Track-based Alignment in CSA08 and CRUZET

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Outline

- Monte Carlo studies of long-term procedure: CSA08 *(9 min)*
  - answered "last" basic questions about how the procedure will perform with collisions data
- Alignment of stations in CRUZET *(12 min)*
  - based on the long-term procedure
  - real data! production-quality results!
  - aligned constants make sense, agree with external measurements
- Chamber alignment with overlaps *(9 min)*
  - developing procedure for beam-halo sample
  - testing and debugging with CRUZET cosmic rays

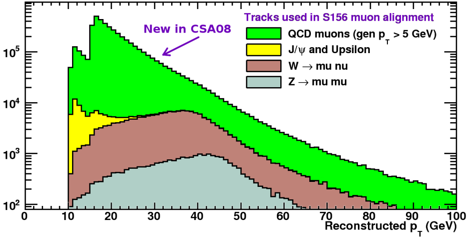
CSA08 Monte Carlo Studies

Goals for CSA08 exercise

- To demonstrate that
  - our long-term procedure works in a realistic simulation
  - we can coordinate with other alignment/calibration groups in a timed test (1 week from "data" to constants)
- To study effects that require huge MC samples in a recent release

Parameters of the study

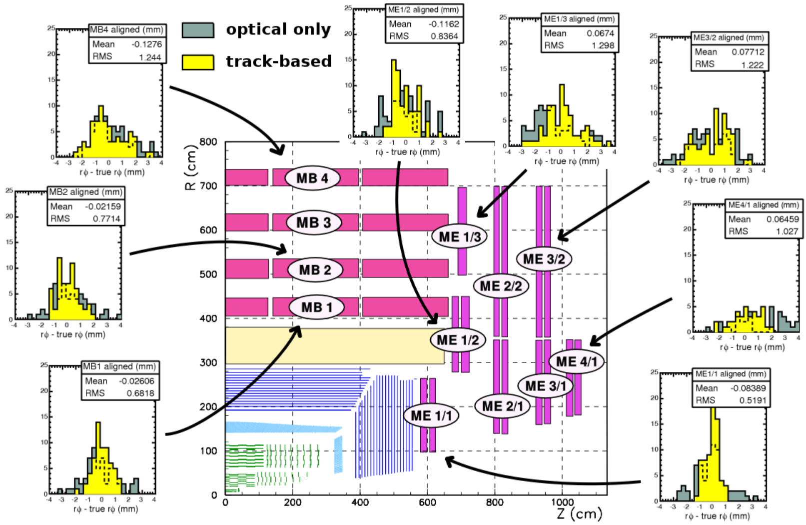
- Long-term procedure: fit tracks to tracker as a reference, minimize residuals in muon chambers
- Align individual chambers in barrel and endcap
- 10 pb^{-1} of inclusive muons, but no cosmic rays/beam-halo



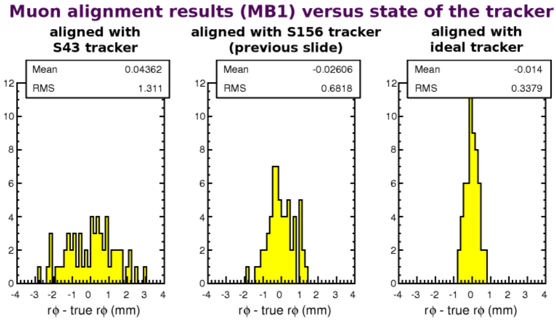
10 pb^{-1} results at a glance

Histograms of aligned positions minus true positions in $r\phi$

MB1: 680 microns ME1/1: 520 microns ME1/2: 840 microns



Key result #1
Strong dependence on tracker misalignment



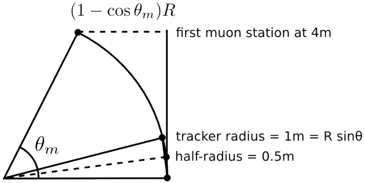
Previous studies used randomly-generated tracker misalignment scenarios	models internal misalignment correlations expected from assembly only
New study uses output of tracker alignment algorithm as input to muon alignment	includes correlations generated by tracker alignment attempt: we see more dependence

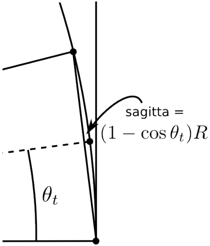
- Alignment performed using tracks from the interaction point
- Tracks that reach a given chamber all pass through the same narrow region of the tracker
- Tracker misalignments are $\mathcal{O}(10\ \mu\text{m})$, effect is 680 μm

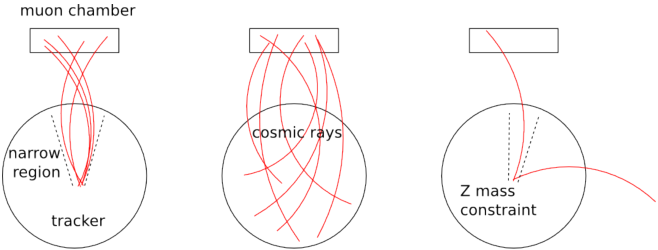
$$\text{Mismeasured } \phi \text{ or } \eta\text{: } 10\ \mu\text{m} \left(\frac{\text{4-6 m inner muon station}}{\text{1-2 m tracker radius/half-length}}\right) = 60\ \mu\text{m}$$

$$\text{Mismeasured curvature: } 10\ \mu\text{m} \left(\frac{\text{4 m inner muon station}}{\text{0.5 m tracker half-radius}}\right)^2 = 640\ \mu\text{m}$$

Why curvature error is quadratic in lever arm:







We need to "average over" the tracker more, so that a muon chamber isn't always seeing tracks mismeasured in the same narrow region

- Easiest and possibly best: align with cosmic rays
- With 100 pb^{-1} or more: constrain $Z \to \mu\mu$ to mix momentum measurements from different regions
- Discussed possibility of using lever arm from muon system to improve tracker alignment

Key result #2

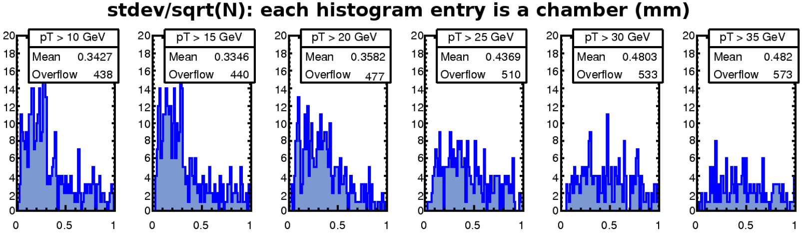
Long-standing question: is it better...

- to select high-momentum tracks and reduce multiple scattering (minimize standard deviation of residuals)
- or open the floodgates and let in all muons (maximize $\sqrt{N}$)?

Alignment correction is (roughly) mean of residual distribution,

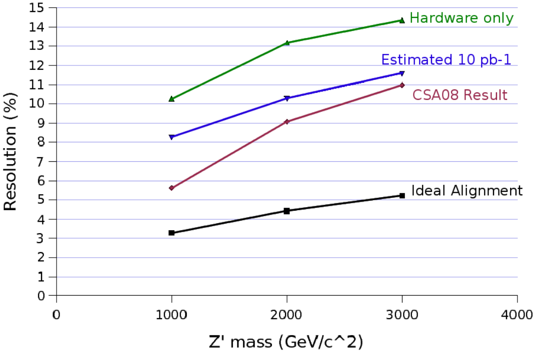
$$\text{uncertainty} = \frac{\text{standard deviation}}{\sqrt{N}}$$

Answer: open the floodgates (minimum p_T of 10 GeV)



Conclusions for CSA section

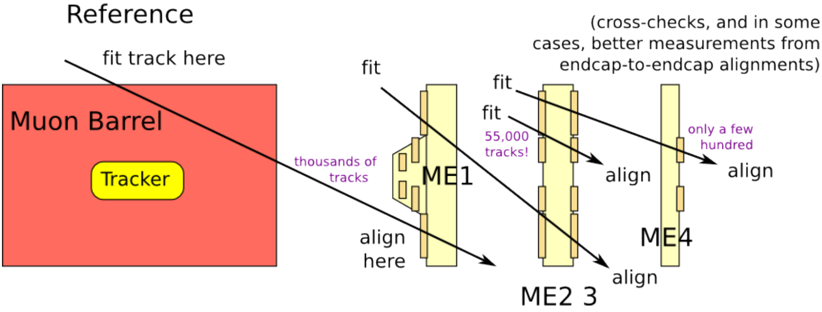
- Long-term alignment procedure is ready for data
- 10 $\mathrm{pb}^{-1} \approx$ all of 2008
- Cosmic rays can improve upon this result
- Makes an impact in benchmark $Z' \to \mu\mu$ analysis:



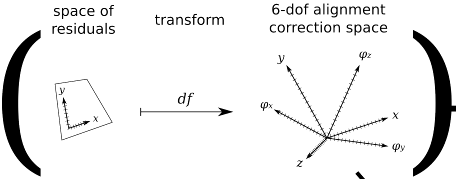
Real Alignment of Stations

Largest and most important part of alignment: find out where the stations are relative to the rest of CMS

- improves track residuals by many centimeters



Similar to the long-term procedure, except that the muon barrel is the reference, rather than the tracker



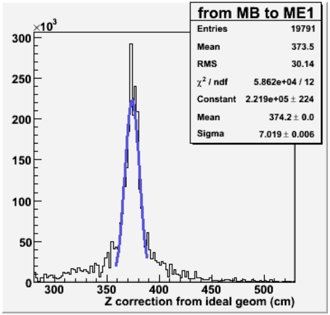
Standard HIP Procedure

weighted mean (with 6x6 matrices) → final result

This Procedure

Make an ntuple,
Fit by hand,
Apply corrections by hand,
Iterate by hand

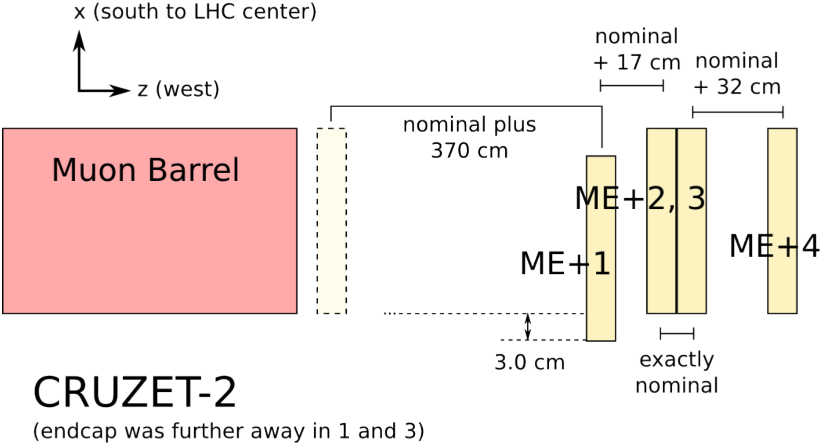
Every hit tells us where it thinks the station is



Histogram of z correction from every hit

- Without a magnetic field, can't cut on p_T
- Bad tracks/hits form a broad distribution
- Good tracks/hits agree on a z position
- Tape-measure agrees, too: 370 cm

Results at a glance: Where were our stations?

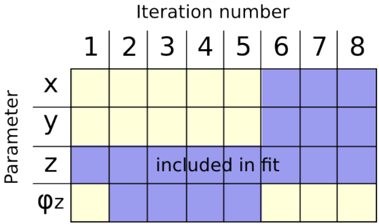


Constants are ready; will upload to database very soon

Procedure details

Best resolution in outer stations from leap-frog approach
"MB $\rightarrow$ 2 $\rightarrow$ 3" means measure corrections between MB and ME2 and between ME2 and ME3, then add them

ME1	ME2	ME3	ME4
MB → 1	MB → 2	MB → 2 → 3	MB → 2 → 3 → 4
direct measurements		take advantage of small lever arms and high statistics	



- ϕ_x and ϕ_y are not additive, but also consistent with zero
- ϕ_z becomes non-additive after applying x and y corrections

Error analysis and consistency

Naïve uncertainty estimate: Gaussian width/$\sqrt{N}$

- x, y: 0.2–0.9 mm, but 0.03 mm in ME2 $\rightarrow$ 3 (high stats)
- z: 0.3–1.6 mm, but 0.07 mm in ME2 $\rightarrow$ 3
- ϕ_z: 0.07–0.3 mrad, but 0.01 mrad in ME2 $\rightarrow$ 3

Consistency checks

Comparison	x (mm)	y (mm)	z (mm)	ϕ_z (mrad)
(MB$\rightarrow$2) $-$ (MB$\rightarrow$1$\rightarrow$2)	-12.8 $\pm$ 0.3	6.4 $\pm$ 0.4	39.9 $\pm$ 0.8	-4.75 $\pm$ 0.12
(MB$\rightarrow$3) $-$ (MB$\rightarrow$2$\rightarrow$3)	-3.4 $\pm$ 0.4	-8.7 $\pm$ 0.5	-15.3 $\pm$ 1.0	-1.06 $\pm$ 0.14
(MB$\rightarrow$4) $-$ (MB$\rightarrow$3$\rightarrow$4)	0.4 $\pm$ 0.8	6.0 $\pm$ 0.9	10.3 $\pm$ 2.4	2.8 $\pm$ 0.3

Statistics-only underestimates the error

$$\sqrt{\frac{1}{N-1}\sum(x_i - \bar{x})^2} = \begin{cases} 7.8 \text{ mm for } x \text{ and } y \\ 28 \text{ mm for } z \\ 3.8 \text{ mrad for } \phi_z \end{cases}$$

But (MB $\rightarrow$ 2) and (MB $\rightarrow$ 3) are double-counted, so this is an overestimate (and dominated by the worst stations)

Cute observations

- Taking conservative $\sigma_{x,y} \lesssim 7.8$ mm, -30 mm shift in ME1 x is significant
- ME2 and ME3 are only 2.3 and 2.0 σ underground
- Experimentally "discovered" that ME2 and ME3 are mounted on the same yoke

$$\left.\begin{array}{rcr} \Delta x & = & 1.3 \text{ mm} \\ \Delta y & = & 2.5 \text{ mm} \\ \Delta z & = & 0.1 \text{ mm} \\ \Delta \phi_z & = & 0.42 \text{ mrad} \end{array}\right\} \text{very small or consistent with zero}$$

Unusually small Δz, only possible if their alignments are linked

Blind analysis: I didn't know (we don't model this relationship in MC)

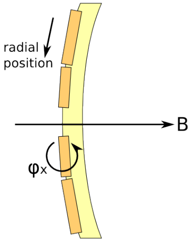
Individual chambers?

Ultimately, we will want to align individual chambers with a method like this

Can we test that now?
Unfortunately, no (few millimeters resolution in CRUZET-2)

Determine collective radial position or ϕ_x?

- Compute chamber-level corrections and merge histograms per station
- Useful for following gross motion of station under $\vec{B}$



CRUZET-3 has ∼5 times the statistics and tracker may provide better-quality tracks

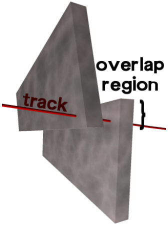
- Alignment converges and makes sense
- Survives internal consistency checks at the level of 7.8 mm (x-y), 28 mm (z), and 3.4 mrad (ϕ_z)
- Non-Gaussian components in residuals identified as irreducible low-momentum tracks: right now, fitting is necessary
- Worth noting: chamber-by-chamber histograms are more nearly Gaussian

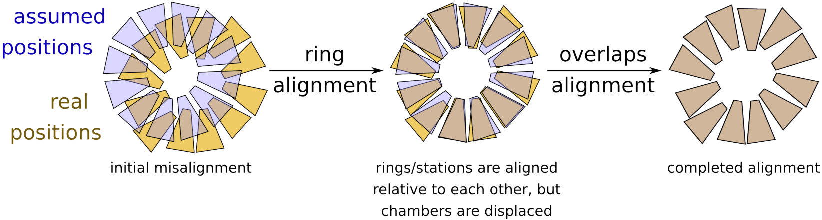
Alignment with Overlapping CSCs

CSC-Overlaps alignment

Determine relative alignment of pairs of chambers using tracks that pass through both

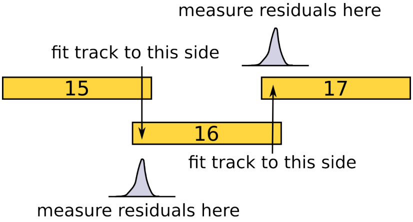
- Very little multiple scattering; simple linear fit
- Align CSC rings internally
- Beam-halo events are ideal, cosmics will work
- Compliments alignment of whole rings/disks from an external reference





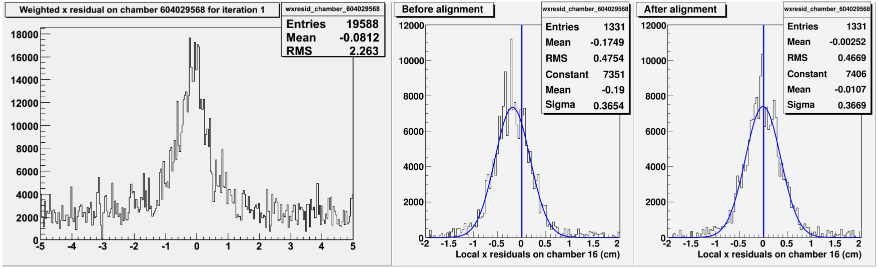
Details of the method

- Get unbiased residuals by fitting to one chamber as a reference, aligning the other
- Measurement propagates around the ring (in this case, to the right)



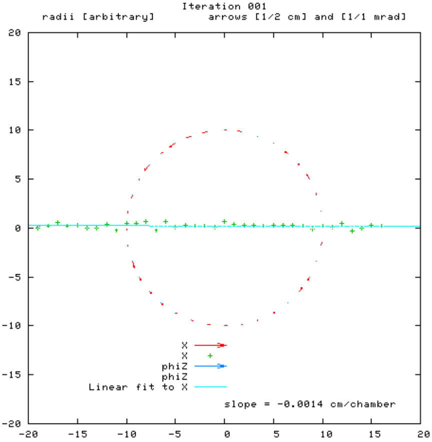
ME+4/1 chamber 16 in CRUZET-1

before quality cuts | after cuts | after alignment



ME+2/2 in CRUZET-1: red arrows and green points are both the $r\phi$ alignment

- propagation is causal (takes exactly 35 iterations)
- ring overcloses by 4 cm due to 1.2 mm systematic error



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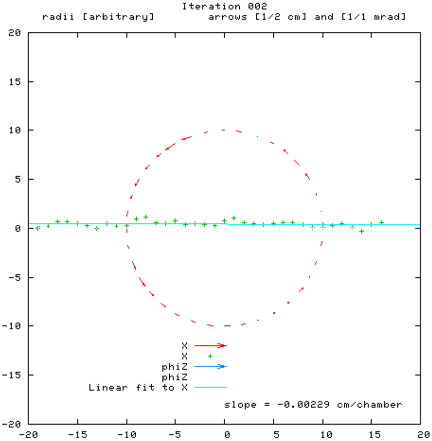

Ring alignment (iteration 3)

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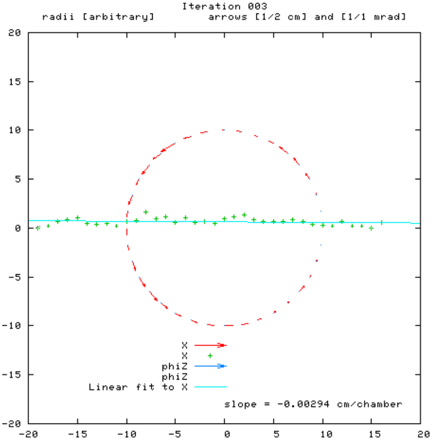

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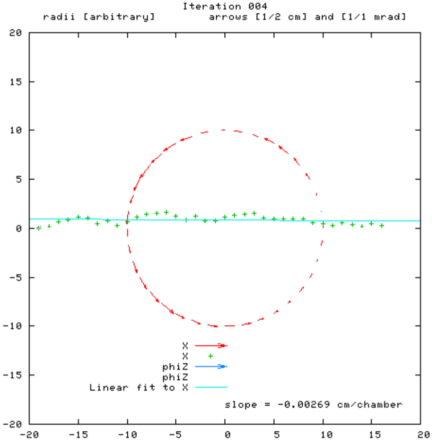

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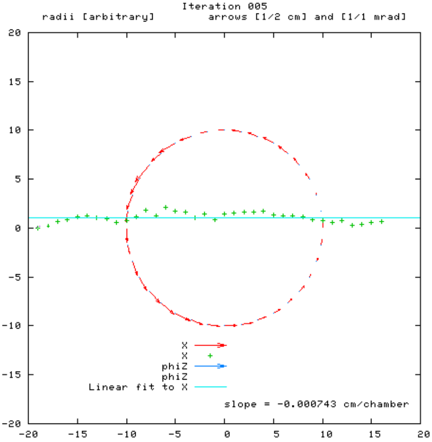

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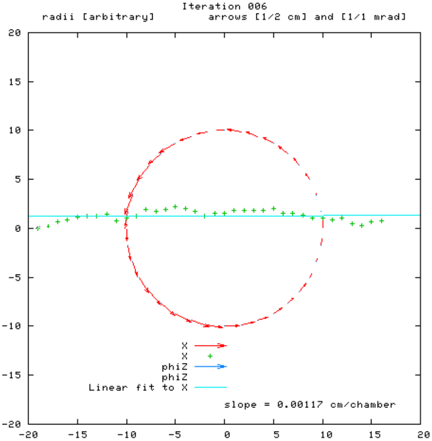

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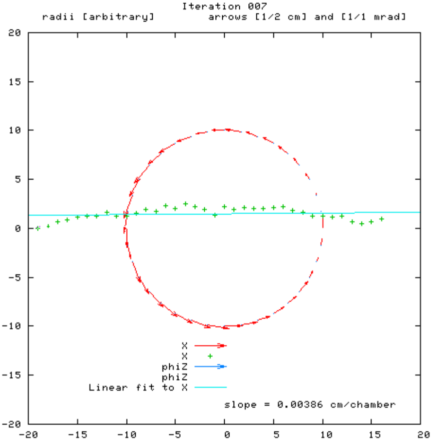

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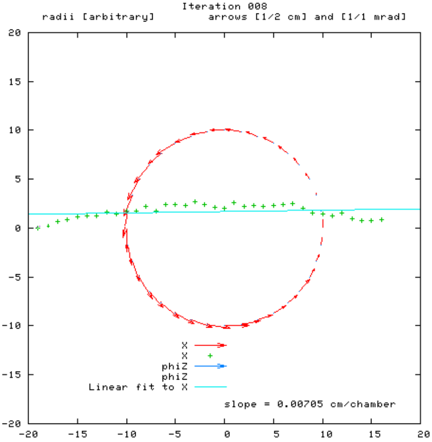

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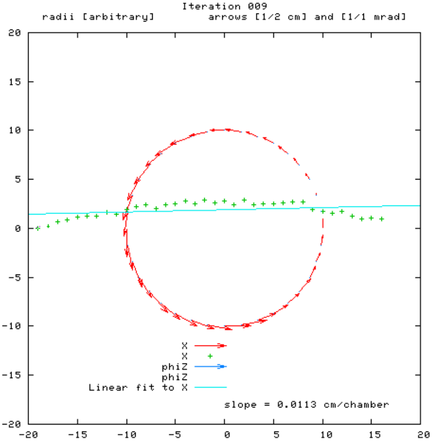

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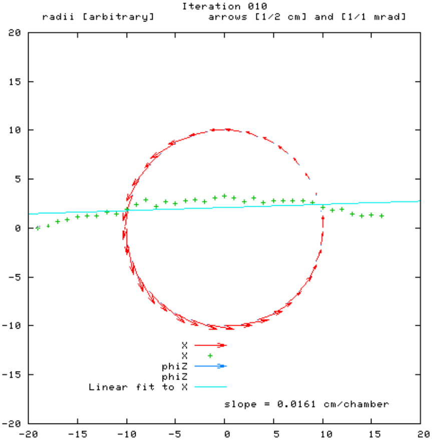

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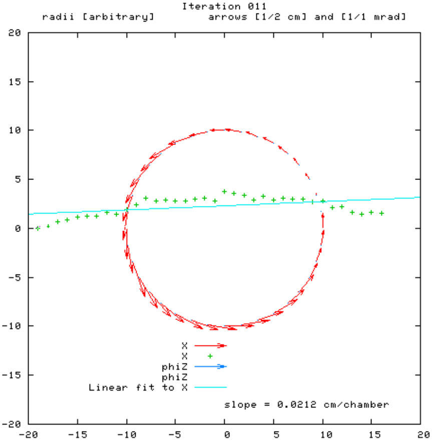

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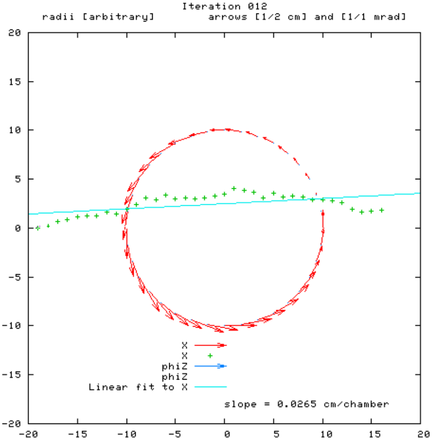

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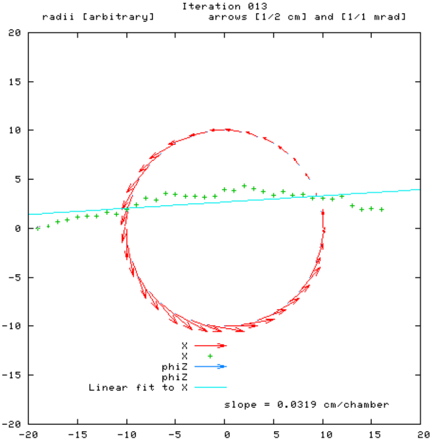

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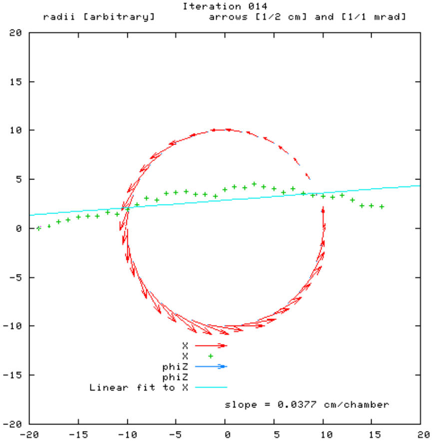

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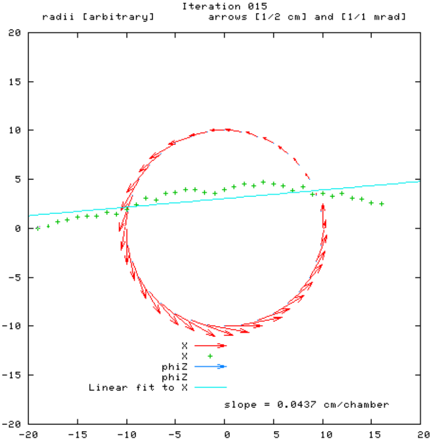

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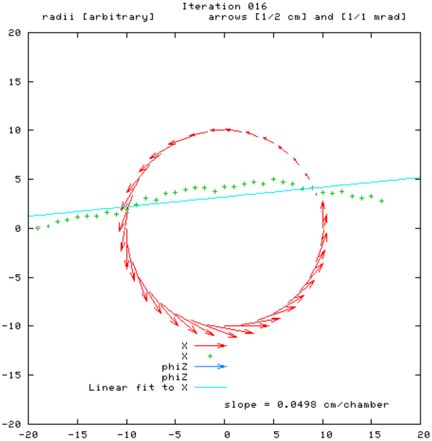

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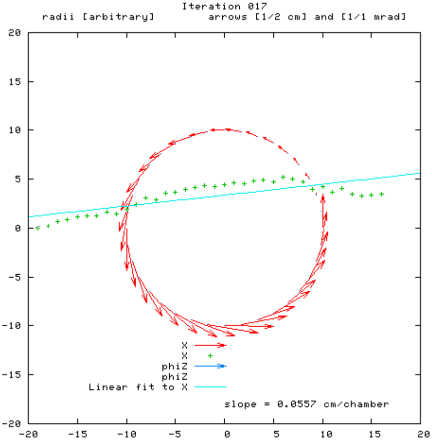

Ring alignment (iteration 18)

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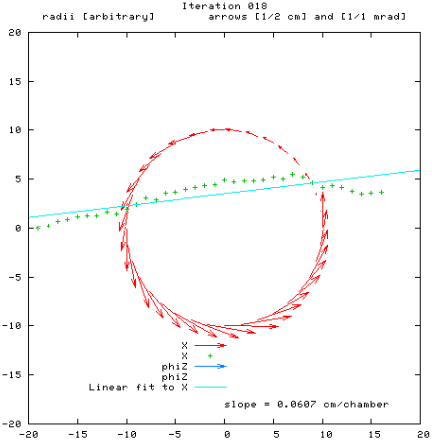

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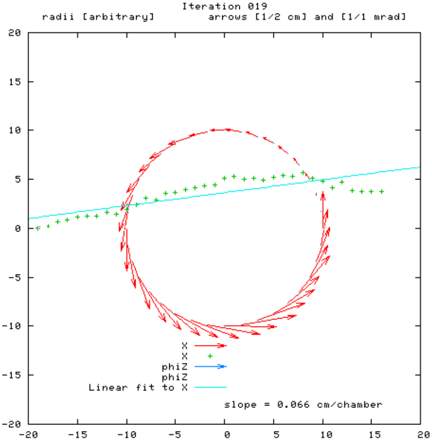

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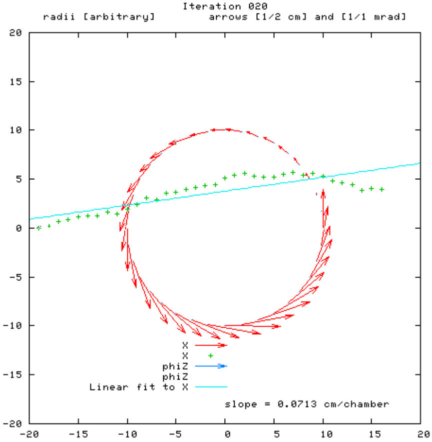

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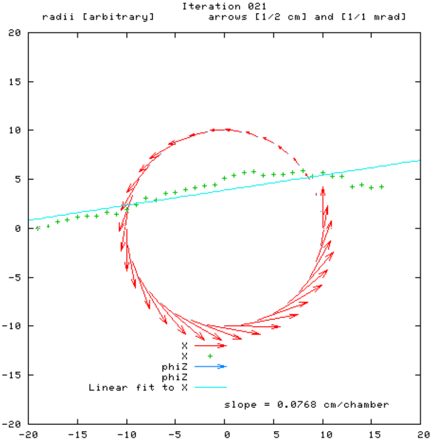

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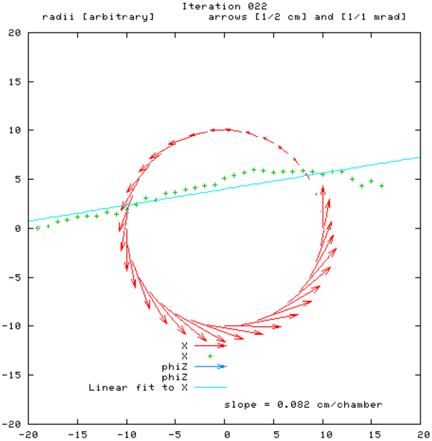

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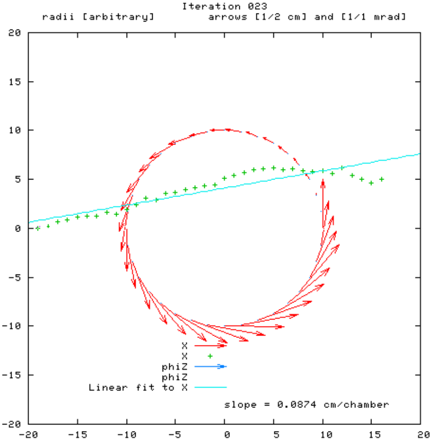

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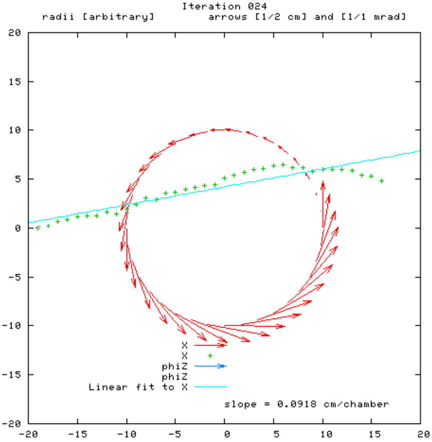

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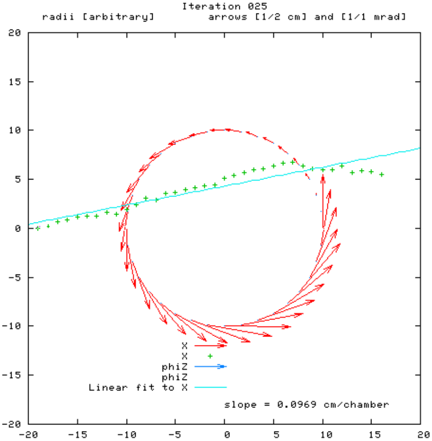
- propagation is causal (takes exactly 35 iterations)
- ring overcloses by 4 cm due to 1.2 mm systematic error



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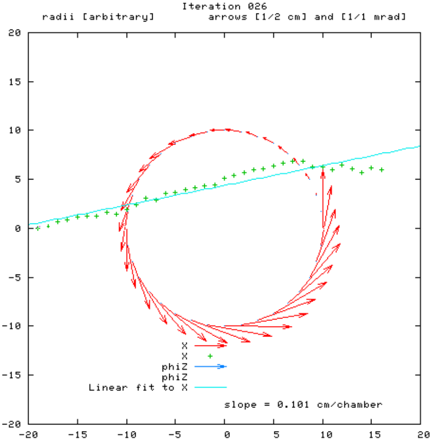

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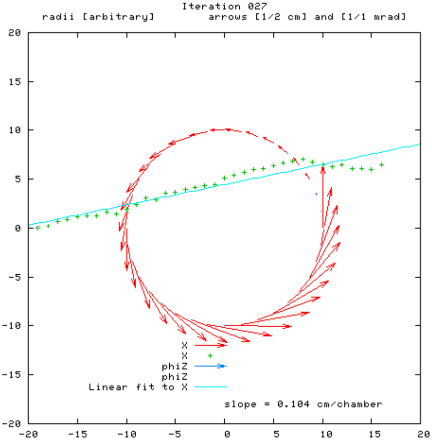

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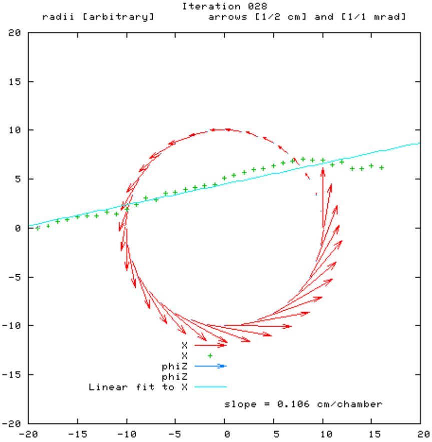

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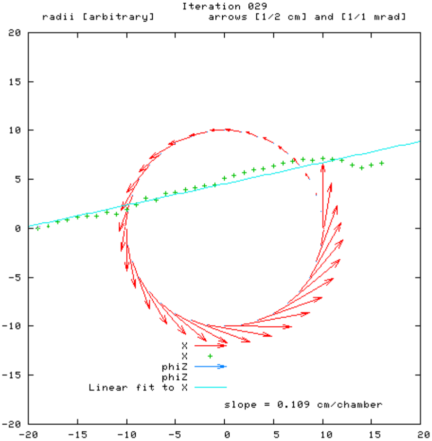

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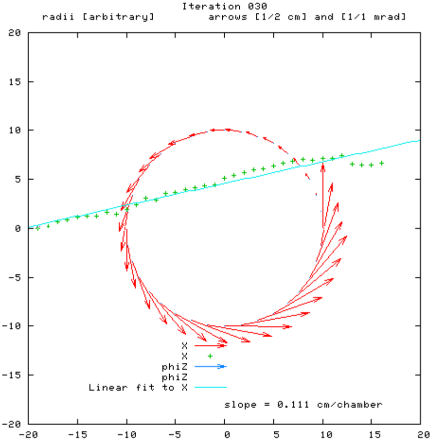
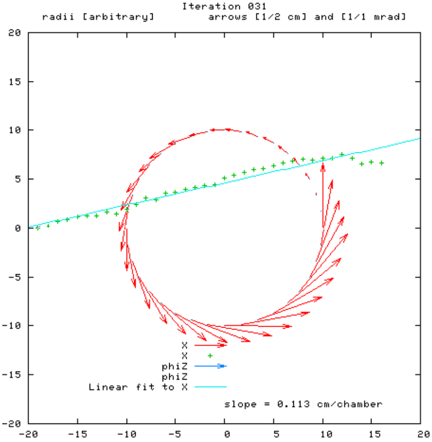


Ring alignment (iteration 31)

ME+2/2 in CRUZET-1: red arrows and green points are both the $r\phi$ alignment

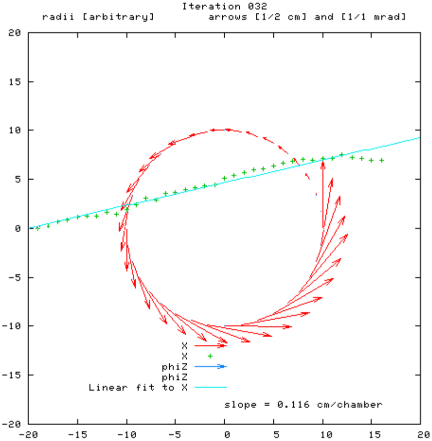
- propagation is causal (takes exactly 35 iterations)
- ring overcloses by 4 cm due to 1.2 mm systematic error



Ring alignment (iteration 32)

ME+2/2 in CRUZET-1: red arrows and green points are both the $r\phi$ alignment

- propagation is causal (takes exactly 35 iterations)
- ring overcloses by 4 cm due to 1.2 mm systematic error



ME+2/2 in CRUZET-1: red arrows and green points are both the $r\phi$ alignment

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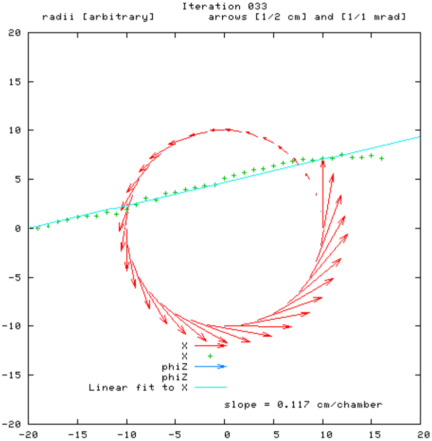

ME+2/2 in CRUZET-1: red arrows and green points are both the $r\phi$ alignment

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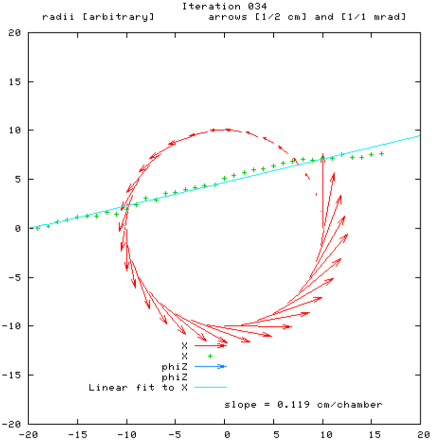

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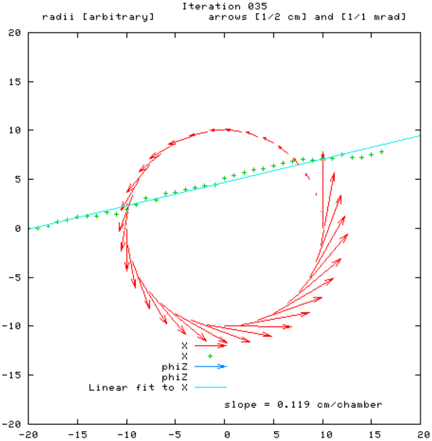

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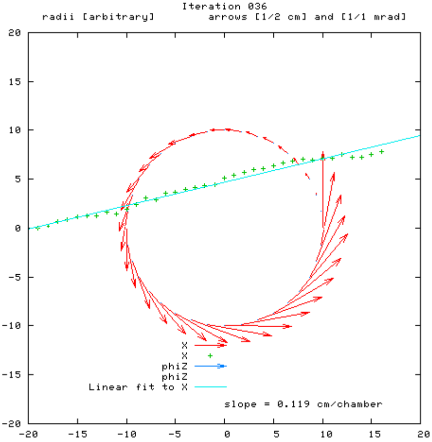
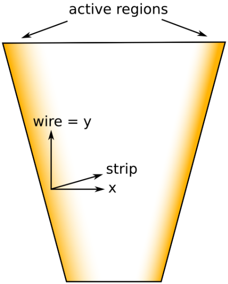
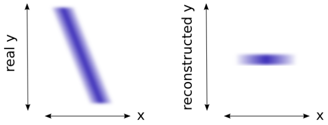


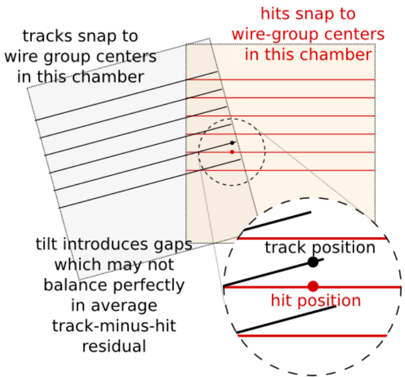
- Same conclusion from CRUZET-2, including more alignment parameters, different rings (though the size of error is different)
- Likely problem is use of x residual, rather than strip ϕ

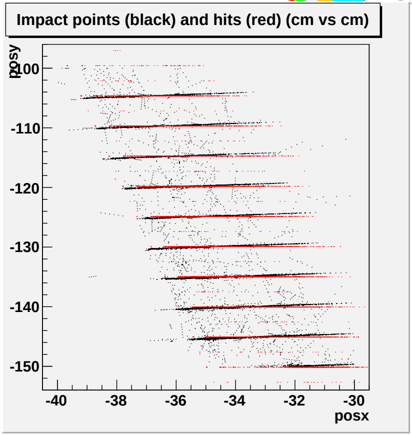




- In our regions, x has a significant component from wire measurement
- Wire measurement is discrete due to ganging: about 3.5 cm to 5.5 cm
- $(s, w) \to (x, y)$ transformation is an irreversible projection
- Aligning with $s = \phi$ would require deep changes to alignment framework: we're starting with a stand-alone implementation to demonstrate the need
- Must modify track-fits as well (also restricted to the edges)

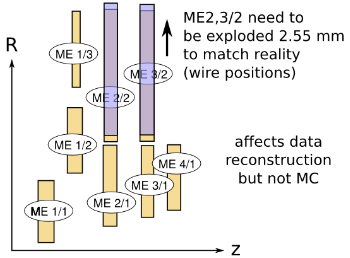
How does this effect work?

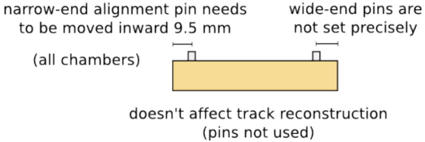




- Asymetric coverage can introduce fake "misalignments" on the order of several millimeters
- Effect would be the same in every chamber of a given ring, leading to exactly the lack of closure we saw

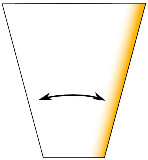
While trying to resolve the overclosure problem, we found two errors in the software description of the detector, relative to integration drawings. Thanks to Tim, Oleg, and Richard!

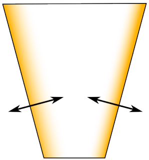




Revised strategies

- strip $\rightarrow \phi$ is simplest
- 1-D alignments can only use hits on one side (convergence)
- can get 2-D from strips alone


strip as φ coordinate


both sides: two linearly-independent degrees of freedom

Conclusions for CSC-Overlaps

- Surprisingly, this the most challenging alignment procedure (including some reasons not described here)
- When the chambers are so close, they “see” the fine-grain details of their neighbors, some of which can cause biases
- We’re modifying the procedure to access the strip data directly for both the track-fits and the hit residuals

Final conclusions: Are we ready for data-taking?

- Long-term procedure is well-established: it will provide an alignment of a half-millimeter or better when it's first needed for physics studies: $\sim$10 pb^{-1}
- Our tools are flexible enough to develop a station-finding algorithm in a matter of days, allows us to think on our feet and respond to what the data tell us
- Station alignment satisfies internal consistency checks, makes sense, agrees with external information where available: I submit that it is correct (can anyone prove me wrong?)
- CSC-Overlaps procedure is subtle because it looks at hits under a microscope. Once we solve the edge-effect type problems, it will be a precise technique.

Hopefully, we'll have lots of beam-halo! (That we can use!)