Update on FSI R&D for SiD Final Focus Magnet Alignment

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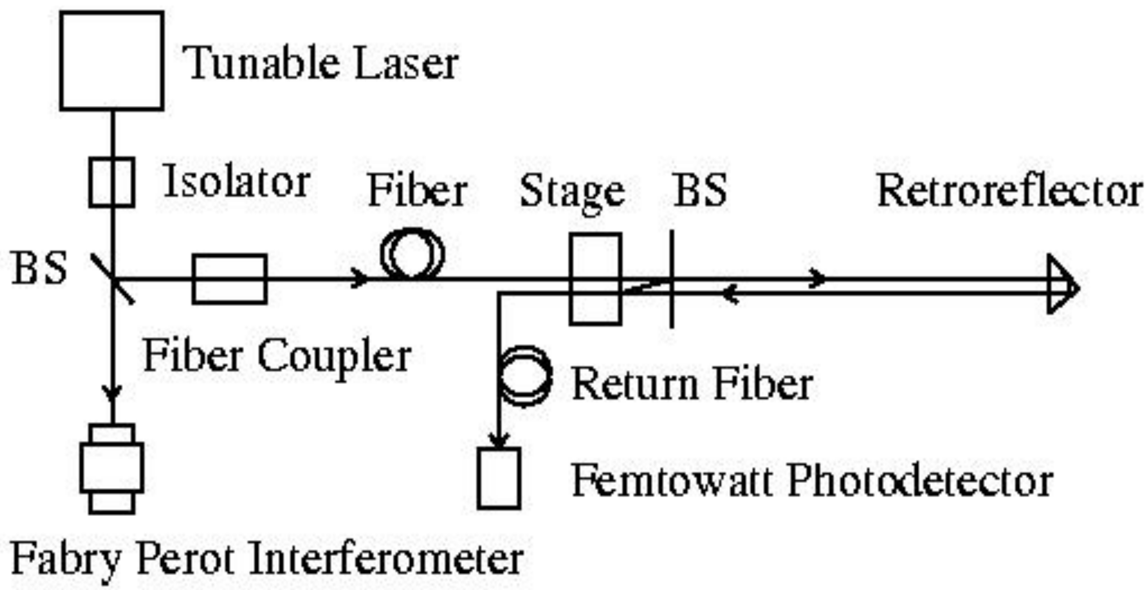
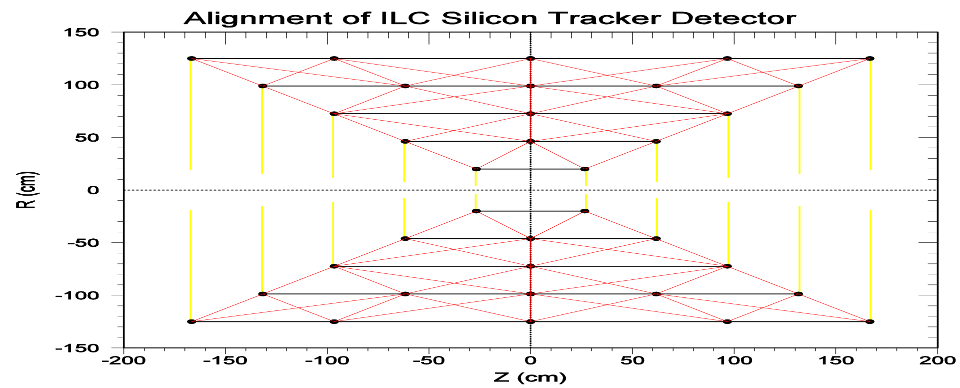
Overview of FSI Method

- Measure hundreds of absolute point-to-point distances of detector elements in 3 dimensions by using an array of optical beams split from a central laser.
- Absolute distances are determined by scanning the laser frequency and counting interference fringes.
- Grid of reference points overdetermined → Infer positions, orientations, distortions



Background on Michigan FSI work

Began R&D work in 2003 on FSI system for an ILC tracker



Applied the principles pioneered by the Oxford ATLAS group

Built basic infrastructure on bench in Michigan lab and came up to speed over ~3 years

Many presentations at LC workshops and two articles:

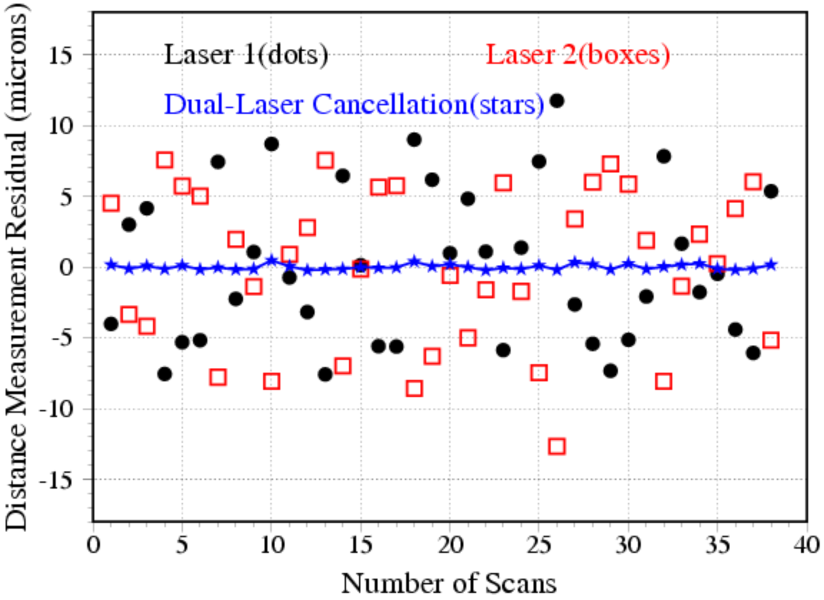
***Appl. Opt* 44: 3937 (2005); *Nuc. Inst. Meth. A* 575:395 (2007)**

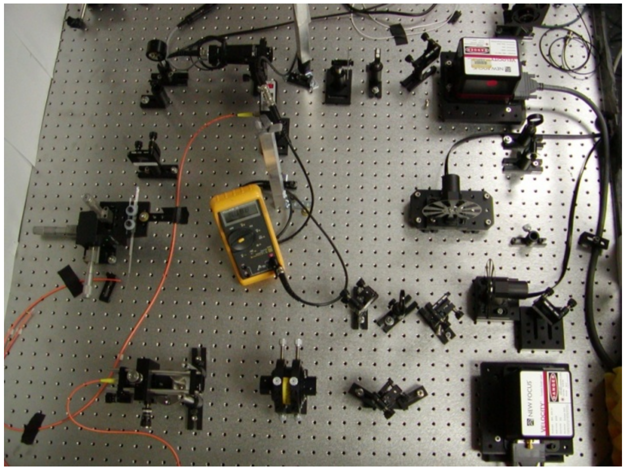
Background on Michigan FSI work

Achieved O(200 nm) precision in hostile environment (air currents, temperature gradients) using dual-laser approach pioneered by Oxford – good robustness

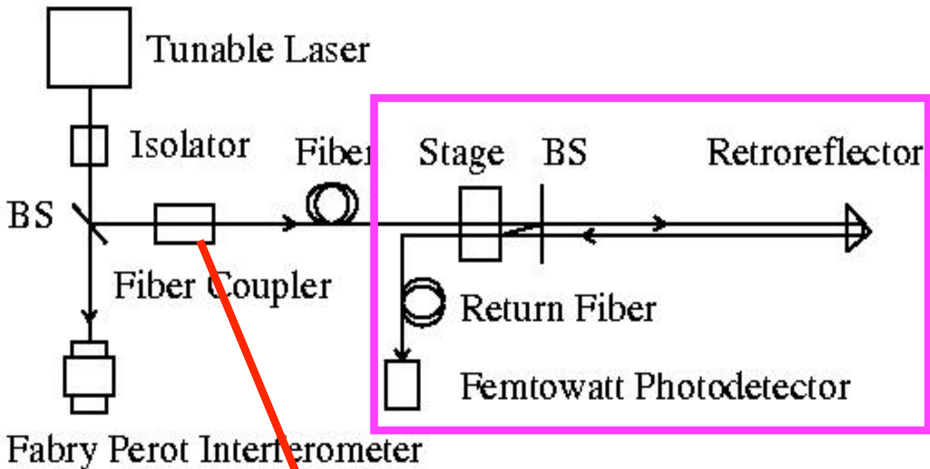
Checks:
- Verified micrometer offset of 125 µm
- Verified thermal-driven 60 µm expansion
- Verified piezo-driven 2 µm displacement
- Verified piezo-driven 0.14 µm vibrations

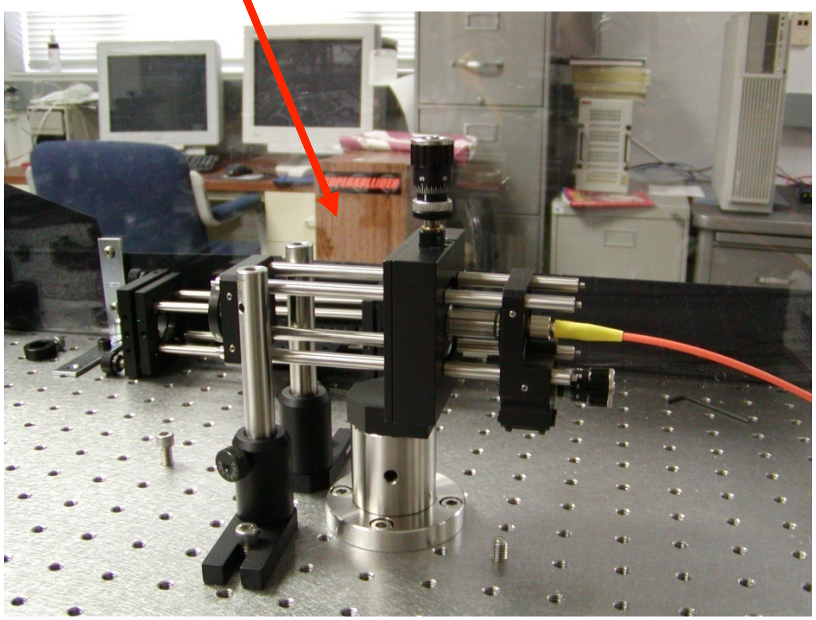
Caveats:
- Single-channel system
- Used (large) commercial retroreflectors locked to table
- Manual alignment

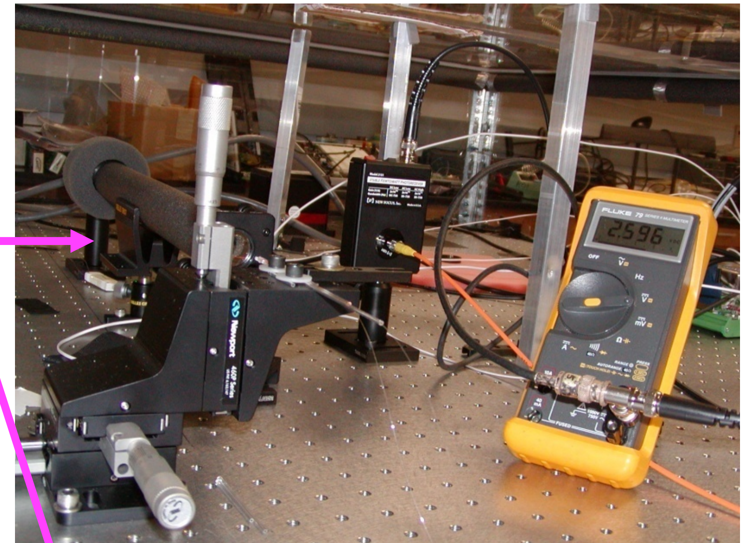


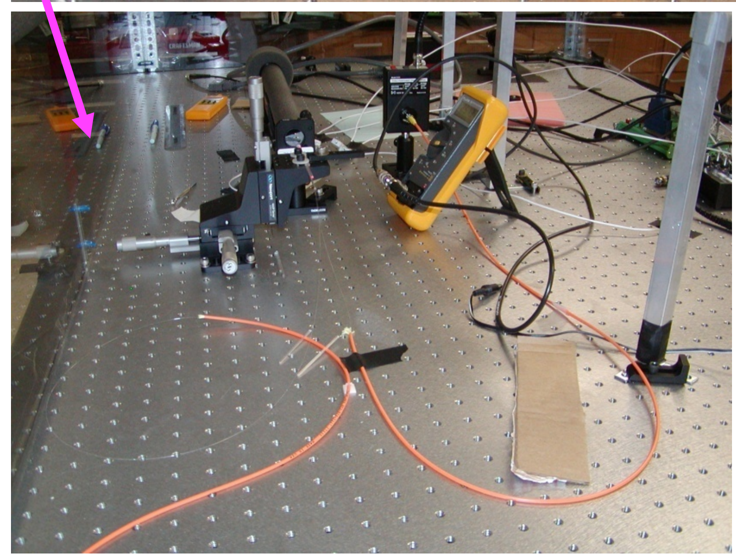


FSI with Optical Fibers (initial setup - single laser)





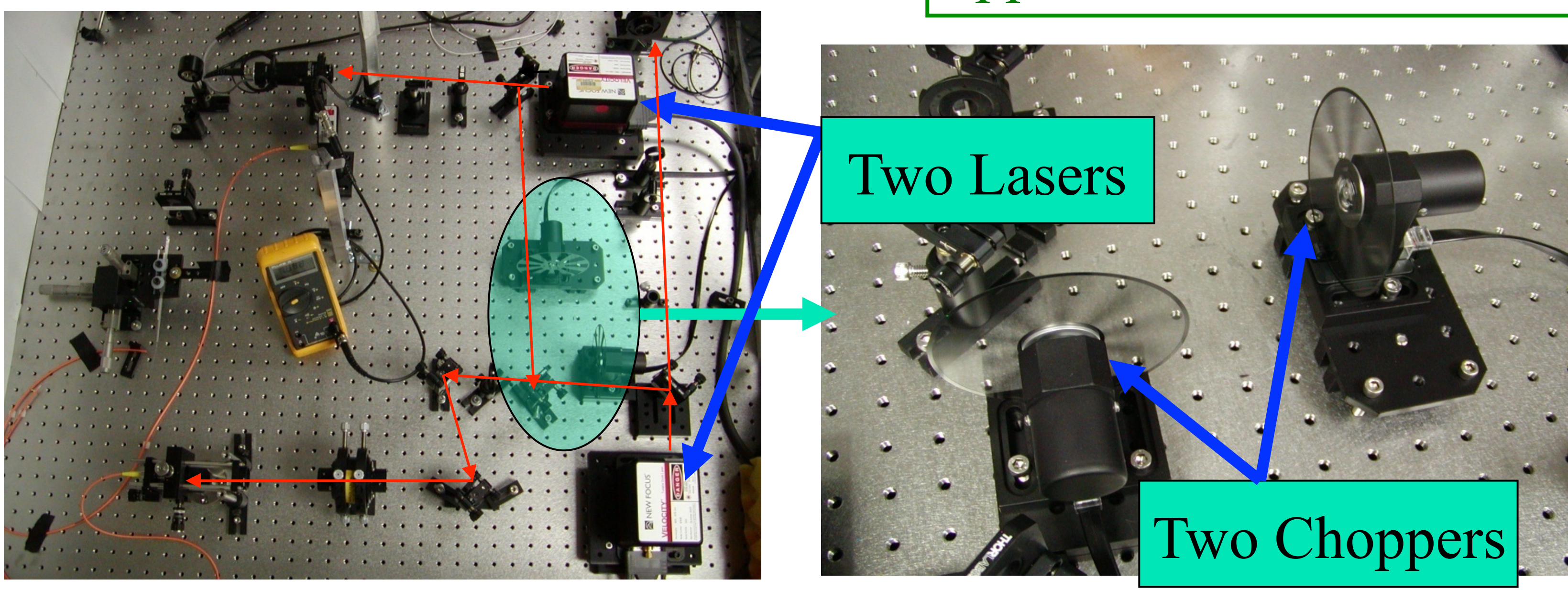




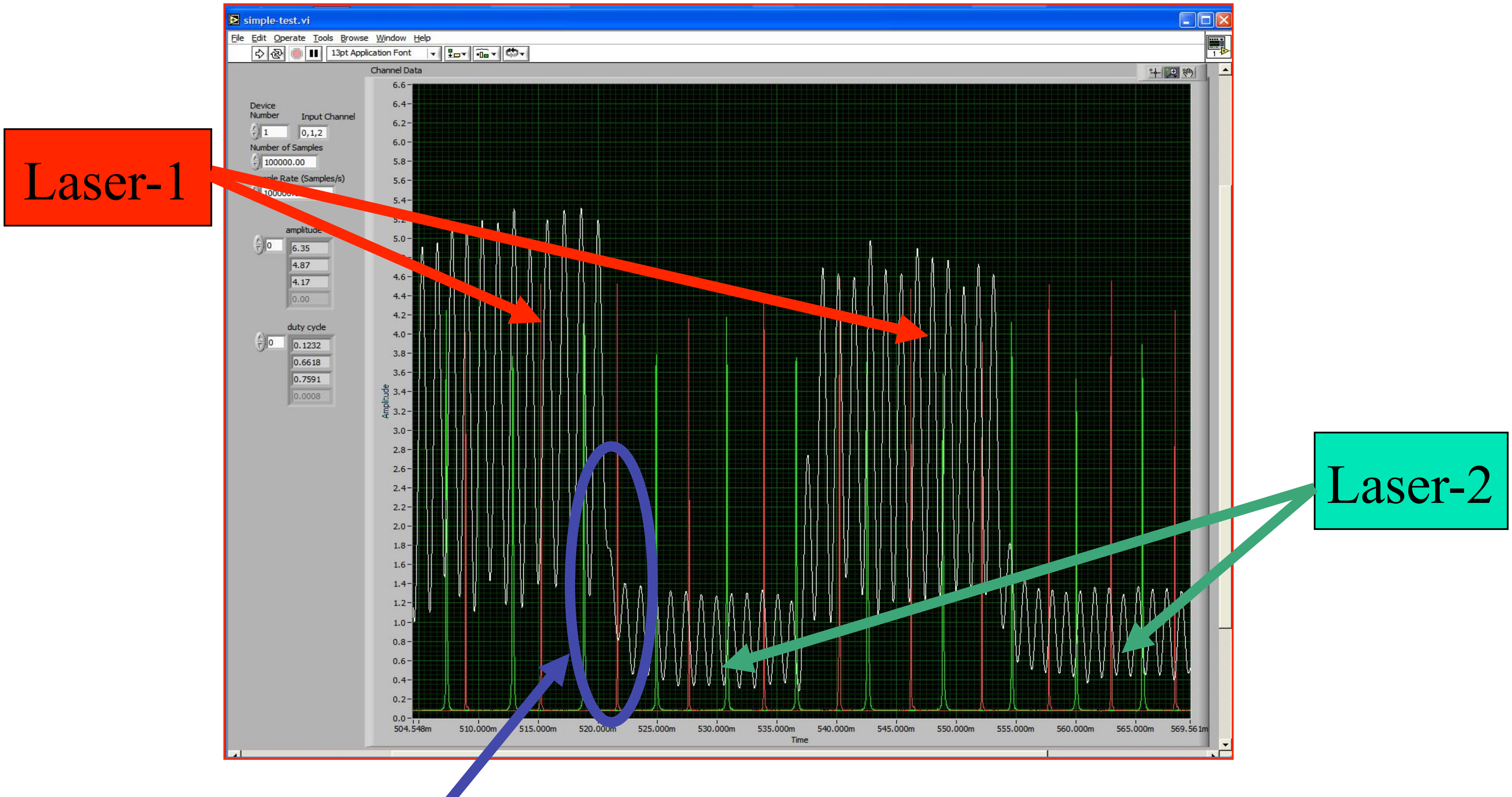
Dual-laser setup (later upgrade)

➔A dual-laser FSI was implemented with optical choppers
(Oxford group's invention)

Systematic errors in distance measurement due to environmental disturbances largely cancel if laser frequencies are scanned in opposite directions



Fringes & F-P Peaks (dual-laser)



Chopper edge effects and low photodiode duty cycle per laser complicate measurement.

Background on Michigan FSI work

Funding dried up ~3 years ago after U.S. congressional actions

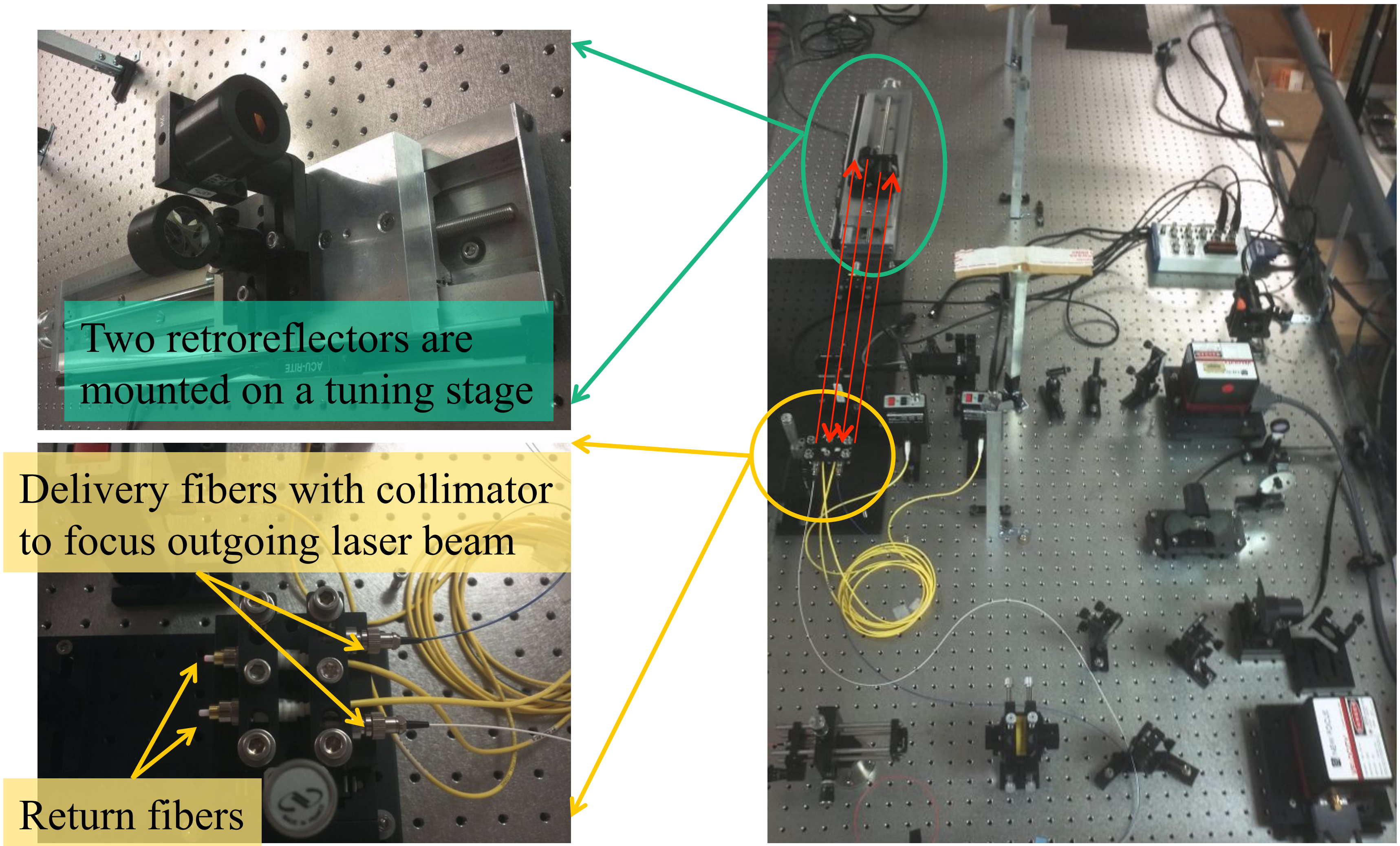
Modest work since then:
- **Looked at lightweight retroreflector arrays**
- **Talked with rapid prototyping companies, but didn't have funds to proceed**
- **Experimented with metallic coatings on PMMA using campus facility**
- **Some simulation work by undergraduate**
- **"Inherited" 3-D translation stage with tens of cm range and submicron precision in 2-D**
- **But project largely mothballed on optical table in Michigan lab**

Funding resumed this year (for both MDI and tracking R&D)

Today – report on some recent work:
- **Progress toward a multi-channel testbed**
- **Simulations**

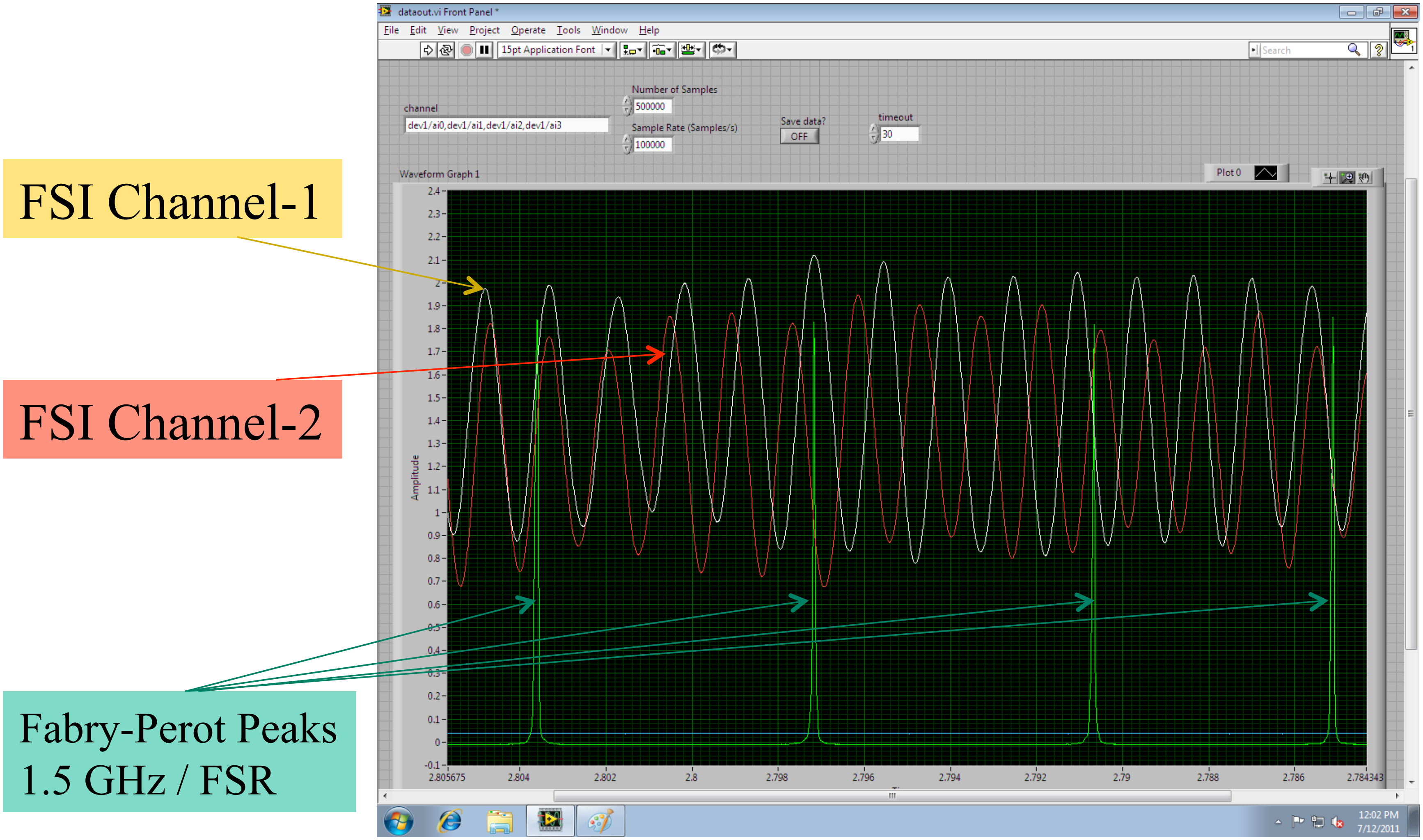
Dual-channel, single-laser

First step: implement & test dual-channel system fed by an optical fiber splitter



Dual-channel, single-laser

Fabry-Perot peaks and interference fringes of two FSI channels



Dual-channel, single-laser

- ➔ Cross-check distance measurements with two FSI channels and two different lasers with full scan data (no chopping)

- ➔ Using a tuning stage to change the position of two retroreflectors simultaneously by amount of (20 ± 2 microns), and check FSI performance. 10 full scan data for each test (R_{dist} ~ 57 cm)

Distance Change (μm)	Laser #1		Laser #2	
	Channel 1	Channel 2	Channel 1	Channel 2
d2-d1	21.48 ± 0.20	21.22 ± 0.21	21.23 ± 0.21	21.39 ± 0.25
d3-d2	20.73 ± 0.33	21.16 ± 0.29	20.61 ± 0.26	20.90 ± 0.21
d4-d3	19.55 ± 0.31	19.52 ± 0.28	19.76 ± 0.31	19.57 ± 0.24
d5-d4	19.99 ± 0.30	19.57 ± 0.31	20.12 ± 0.25	20.10 ± 0.23

→ Standard deviation of 10 sequential scans (closed box)

Dual-channel, dual-laser

- ➔ Cross-check the distance measurements with two FSI channels and two simultaneous, chopped lasers

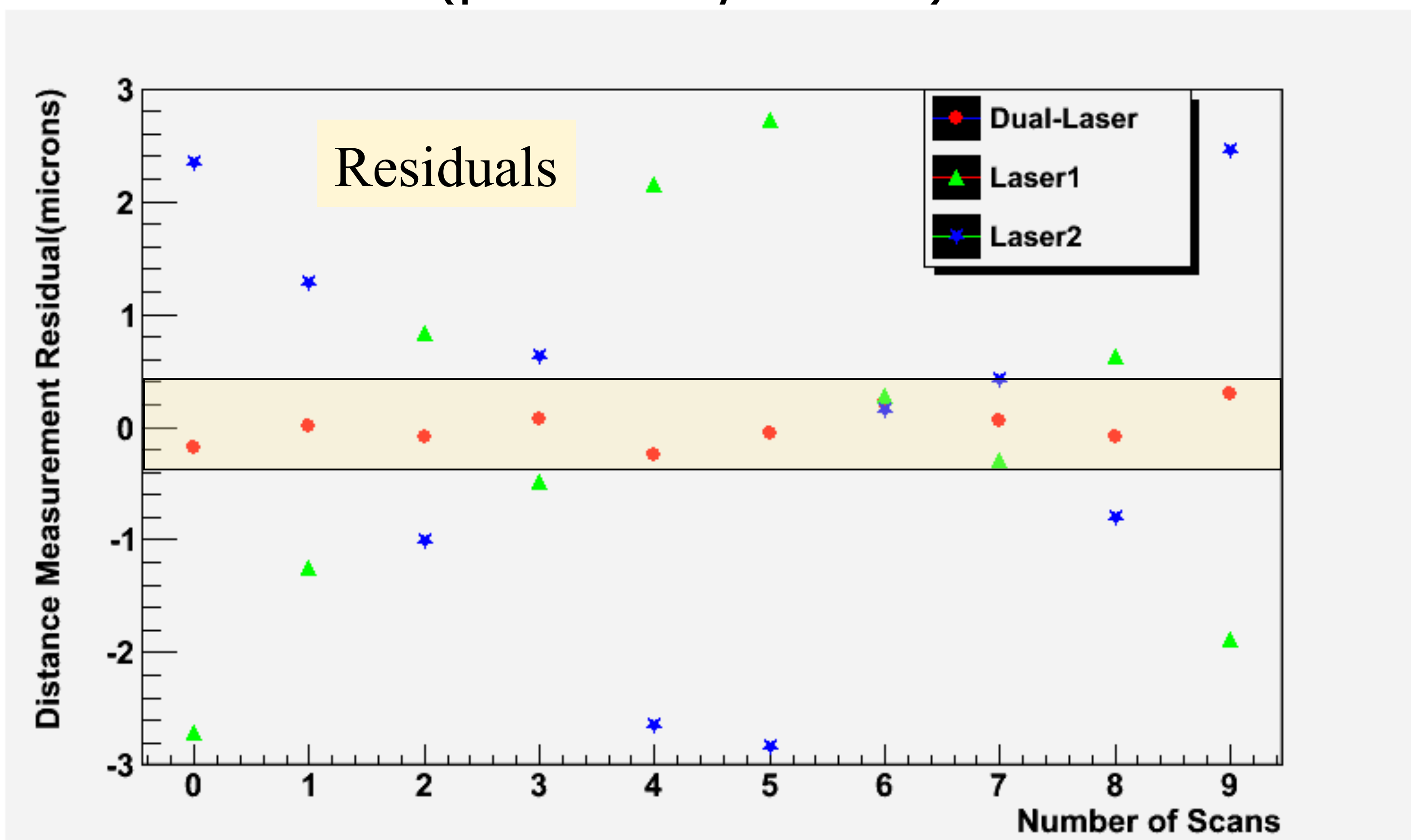
- ➔ Using a tuning stage to change position of two retroreflectors simultaneously by amount of (20 ± 2 microns), and check FSI performance. 10 full scan data for each test (R_{dist} ~ 57 cm)

Distance Change (μm)	Laser #1		Laser #2	
	Channel 1	Channel 2	Channel 1	Channel 2
d2-d1	21.39 ± 1.63	21.11 ± 1.85	20.10 ± 1.63	21.24 ± 1.62
d3-d2	20.93 ± 1.90	21.47 ± 2.31	19.75 ± 2.05	19.74 ± 2.28
d4-d3	19.02 ± 1.48	19.06 ± 1.70	21.02 ± 1.76	20.69 ± 1.85
d5-d4	20.54 ± 1.13	20.53 ± 1.22	19.40 ± 1.27	20.02 ± 1.27

Larger spreads in individual measurements

Dual-channel, dual-laser

- ➔ Combine dual-laser values to cancel drift errors
- ➔ 0.2-0.3 microns (preliminary results)



Dual-channel, dual-laser

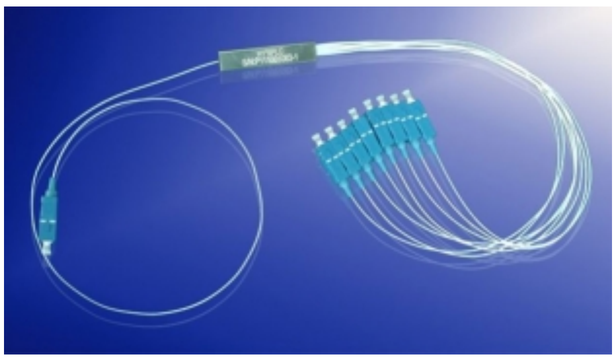
➔ Using dual-laser to cancel the drift errors, better precision for distance measurement can be achieved (0.2-0.3 microns).

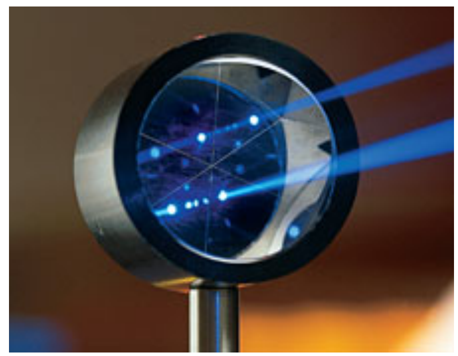
Distance Change (μm)	Dual laser	
	Channel 1	Channel 2
d2-d1	20.75 ±0.35	21.18 ± 0.34
d3-d2	20.34 ± 0.22	20.60 ± 0.24
d4-d3	20.02 ± 0.22	19.88 ± 0.20
d5-d4	19.97 ± 0.23	20.28 ± 0.18

Preparations for multi-channel setup

➔ Have ordered supplies & equipment to support up to eight FSI channels, including:

- optical fiber splitter(1×8), collimators
- optical fibers, beam splitters, retroreflectors
- Femtowatt photoreceivers, fiber launchers etc.



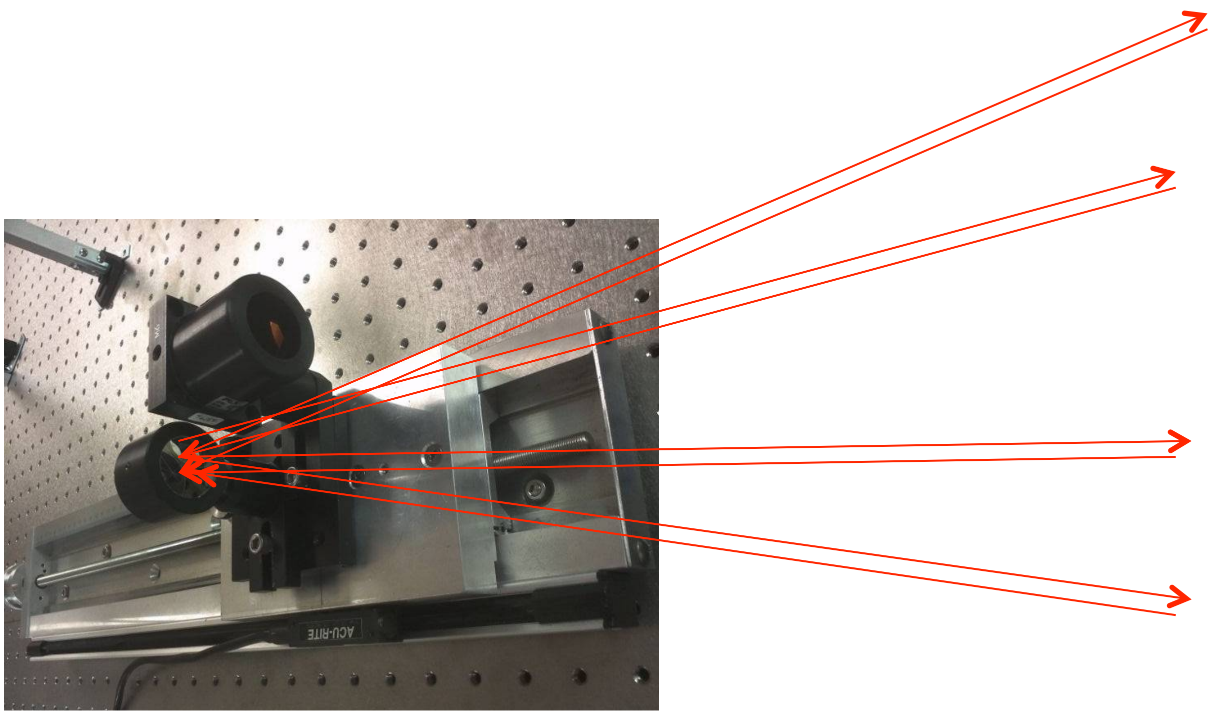


➔ High precision glass scale to monitor the position change of the retroreflectors (~0.5μm).

3-D Position Measurement

➔ Will soon attempt 3-D position & displacement measurement of the retroreflector

➔ Cross-check position change of the retroreflector on the tuning stage using multiple point-to-point distance measurements



Preliminary simulation work

Accuracies for QD0 support in functional requirements document (Mar 09):
- **50 µm in x, y**
- **20 mrad in roll**
- **20 µrad in pitch and yaw**

Have tried some simple simulations of beam launcher / retroreflector layouts (Minuit fitting to a grid of lines "attached" to QD0 ends)

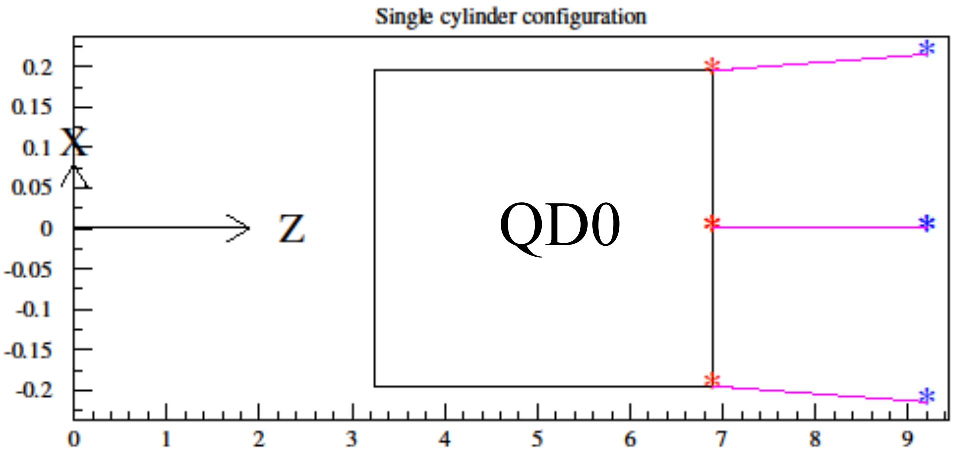
Monitoring alignment of QF1 to bedrock should be relatively easy:
- **Bedrock nearby with many good lines of sight from wall / floor to QF1 sides**

→ Have focused on QD0 alignment w.r.t. QF1

Initial stab at simulations: (quick rework of old tracker simulation)
- **Align e+ and e- sides separately (without bridging gap)**
- **In longer term will pursue bridging gap with lines of sight through open SiD tracker (bootstrap from both ends)**

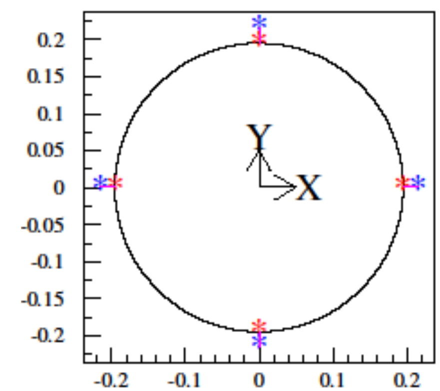
QD0 alignment simulation

- Beam launchers placed on outside of QF1 front ends (~2 cm out in radius)
- Beam launchers placed on inner edge of innermost Hcal endcap layer
- Tried N launchers / reflectors spaced uniformly in φ (N = 4, 6)
- Tried lines of sight for three launcher/reflector combinations:
  - Option A – 1 line of sight / reflector [$\varphi_i^{launch} \rightarrow \varphi_i^{refl}$]
  - Option B – 2 lines of sight / reflector [$\varphi_i^{launch} \rightarrow \varphi_{i-0.5}^{refl}, \varphi_{i+0.5}^{refl}$]
  - Option C – 3 lines of sight / reflector [$\varphi_i^{launch} \rightarrow \varphi_{i-1}^{refl}, \varphi_i^{refl}, \varphi_{i+1}^{refl}$]
- Tried aligning from only back end of QD0
- Tried aligning from both back and front ends of QD0
- Took accuracy on lines of sight to be 0.5 µm (despite 0.2 µm demonstration)



Example:

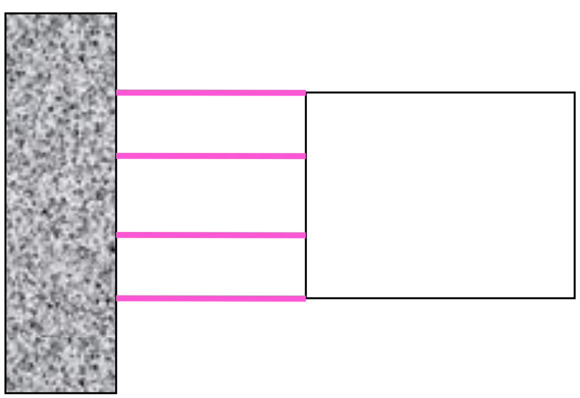
- N=4
- Option A
- Back end only



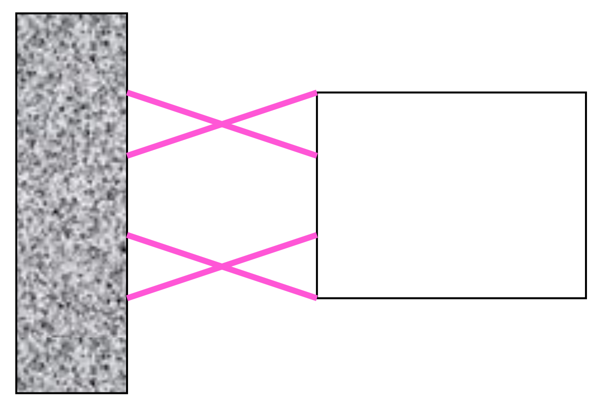
QD0 alignment simulation

Useful analog for thinking about overconstrained FSI fitting:

- **Imagine the lines of sight as steel rods attached to ball joints at each end**
- **Degrees of freedom that allow all rods to move easily are poorly measured**
- **"Cross bracing" good for removing degenerate DOFs**



VS



Preliminary simulation work

Following figures show sampling of layouts tried so far

- **Beams launched**
  from blue asterisks ("reference points")

to red asterisks (retroreflectors)

- **Magenta lines indicate launched beams (arrows omitted)**

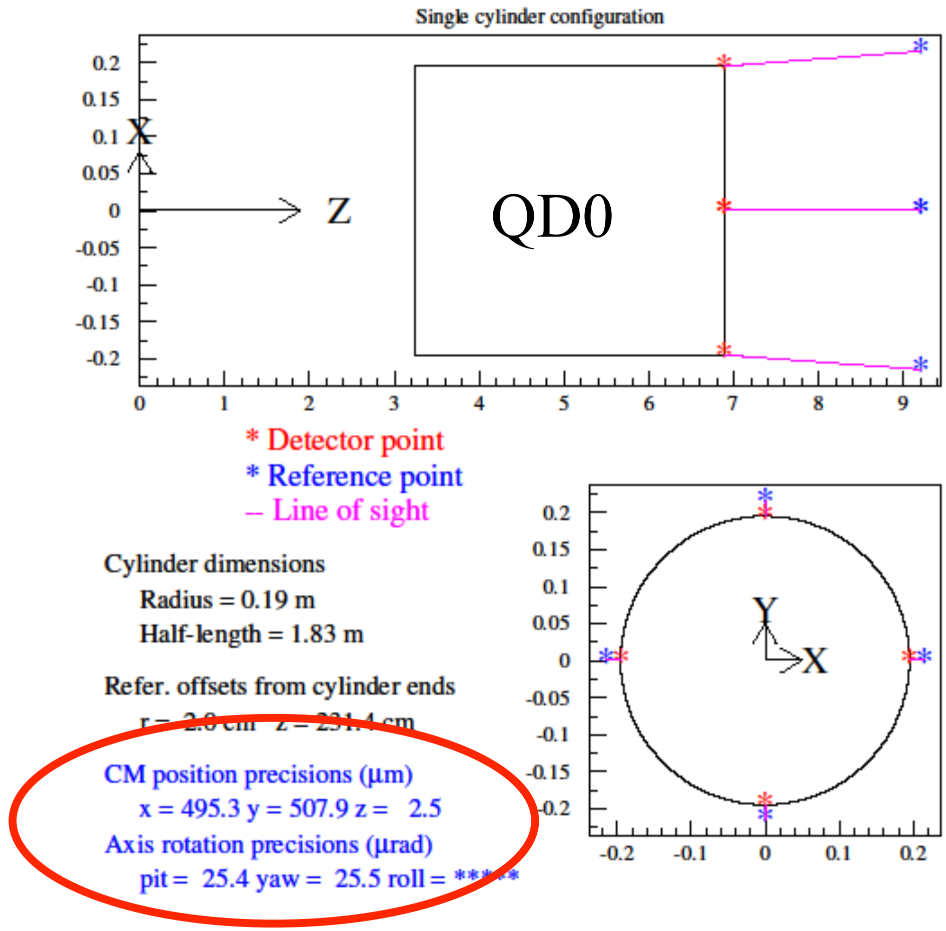
- **Diagrams shown for X-Z and X-Y projections**

- **Minuit fits performed to determine quoted precisions (blue) on QD0 c.m. position and cylinder orientation (pitch, yaw, roll)**

First Simulations

Bare bones: (4 lines)

- N=4
- Option A
- Back end only

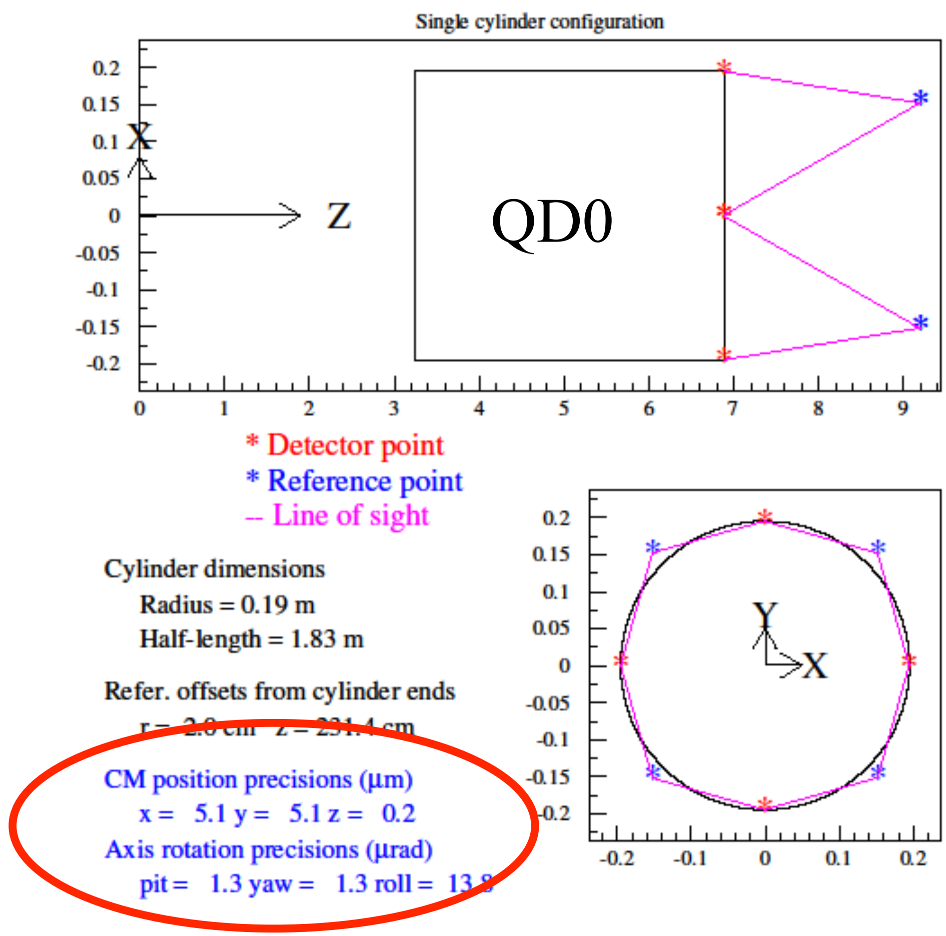


Tolerances not met!

First Simulations

8 lines:

- N=4
- Option B
- Back end only



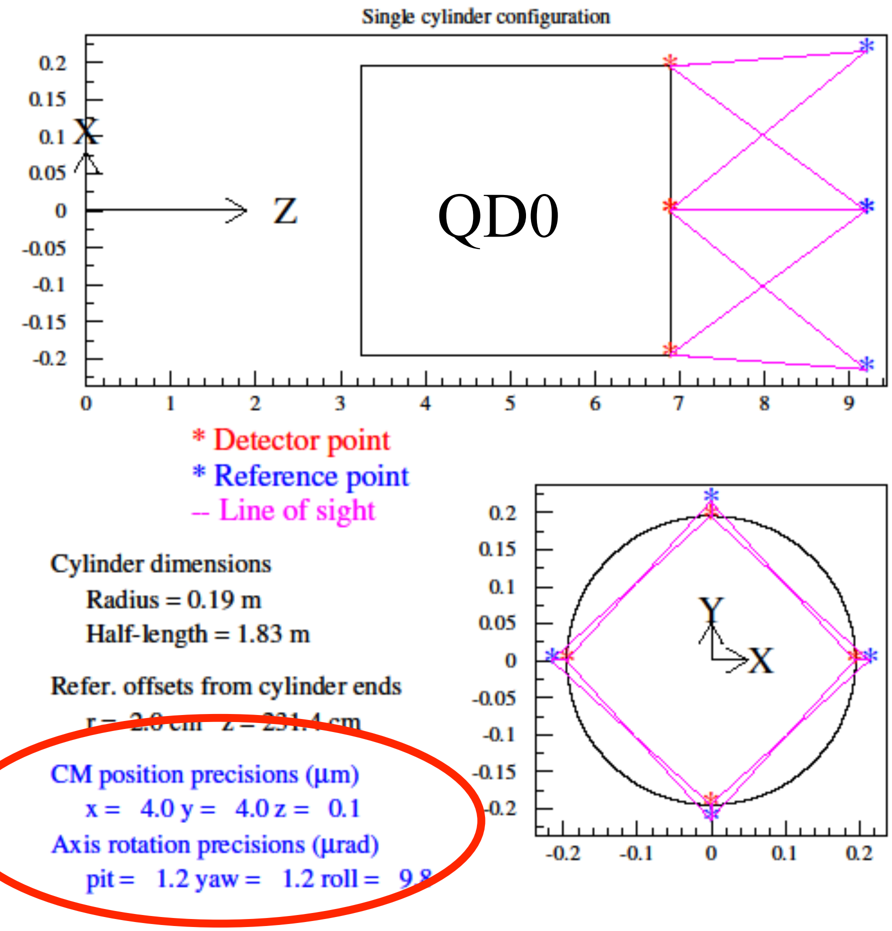
All tolerances met!

First Simulations

12 lines:
- N=4
- Option C
- Back end only

But can we really align from one end only?

Prudent to monitor other end too…

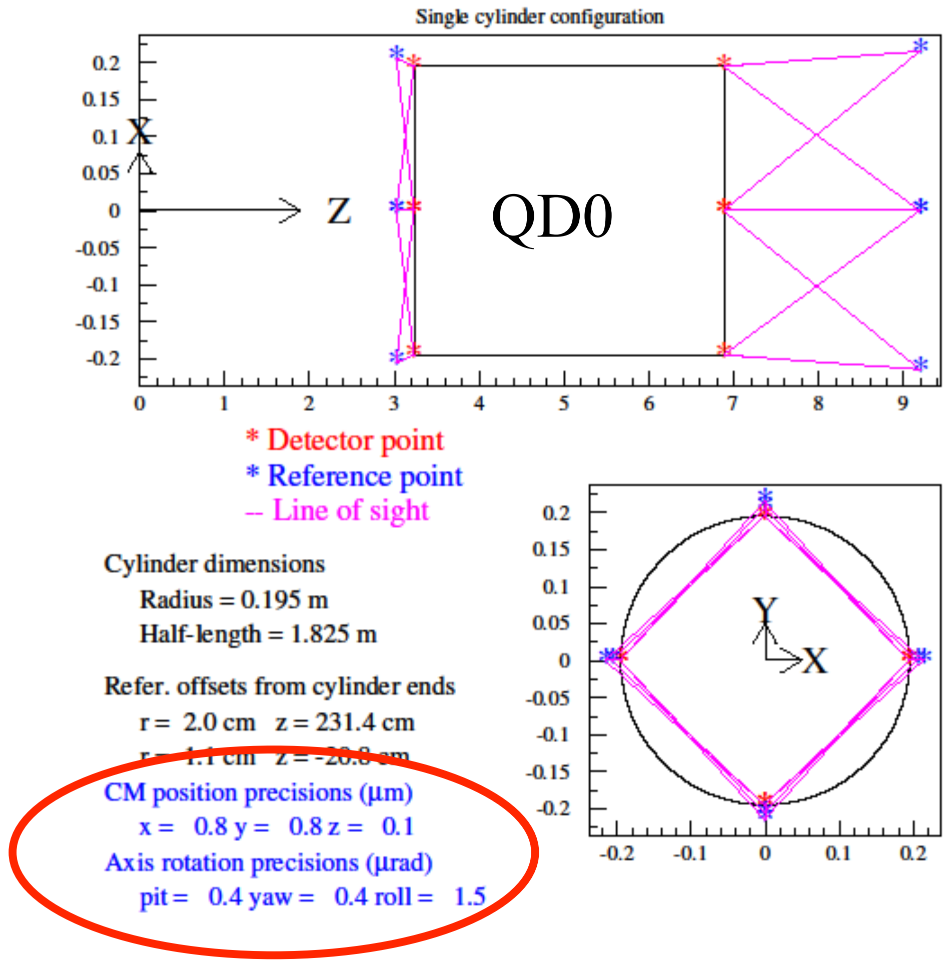


All tolerances met

First Simulations

24 lines:

- N=4
- Option C
- <u>Both ends</u>



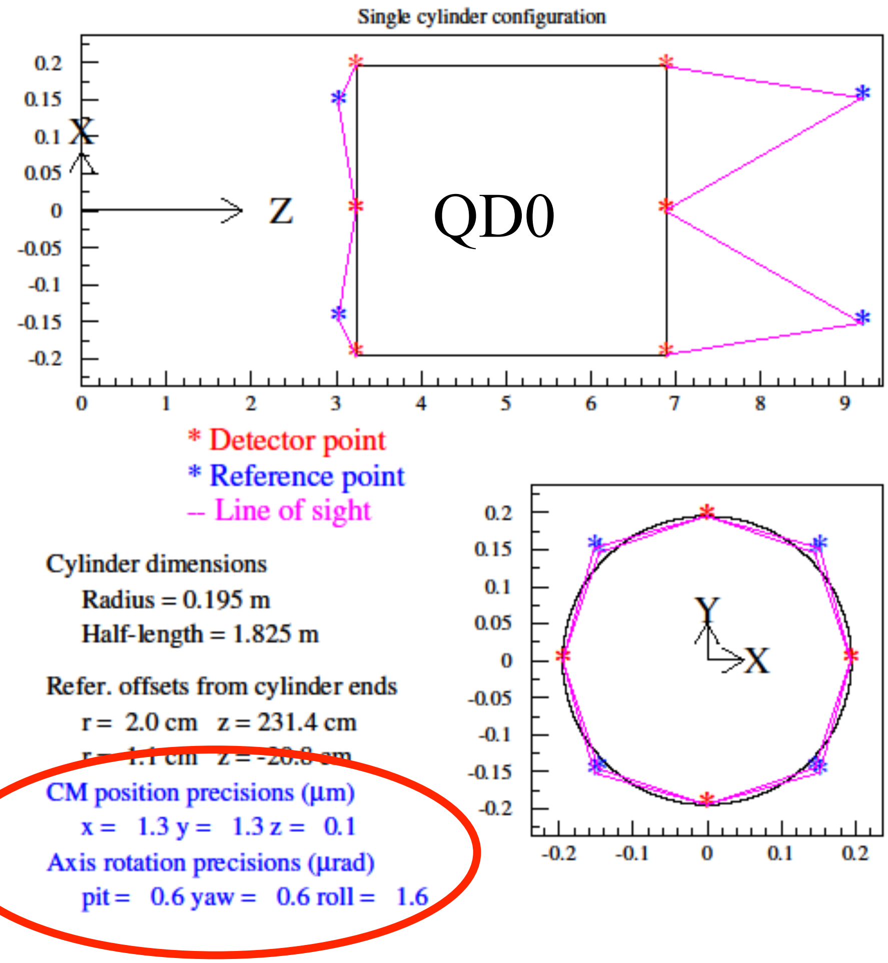
Now back off to Option B…

All tolerances met

First Simulations

16 lines:

- N=4
- Option B
- <u>Both ends</u>

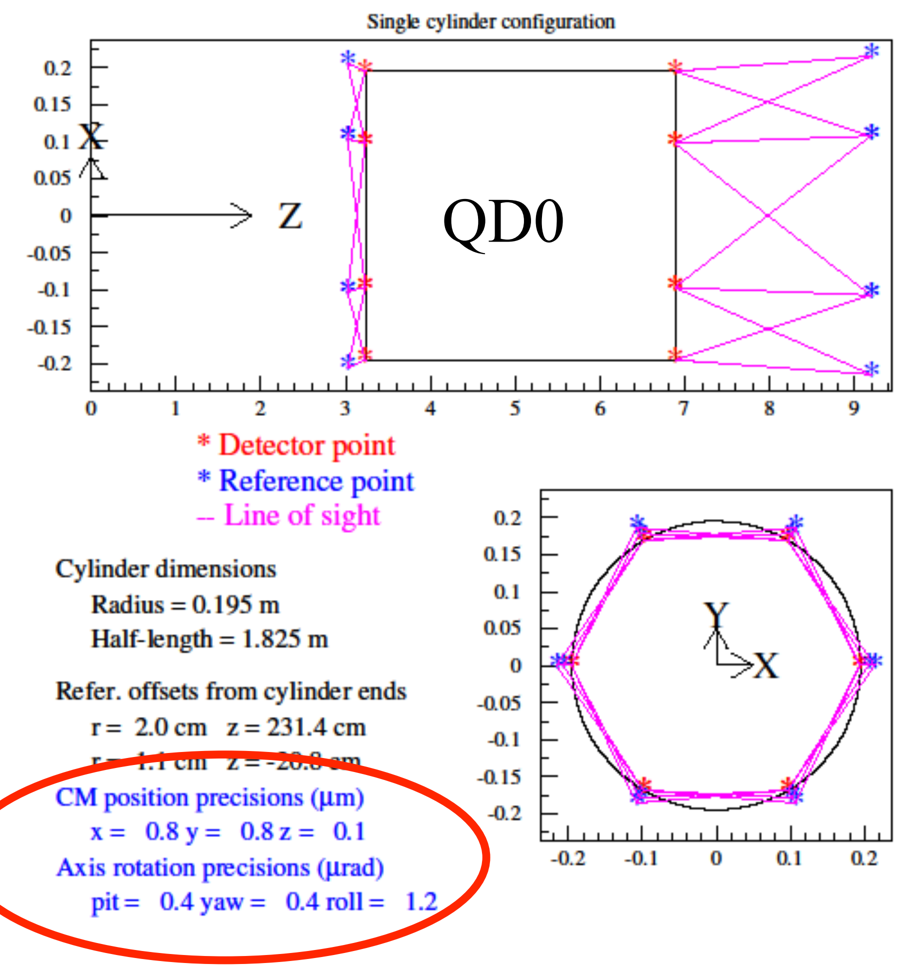


All tolerances met

First Simulations

Deluxe (36 lines):

- N=6
- Option C
- <u>Both ends</u>



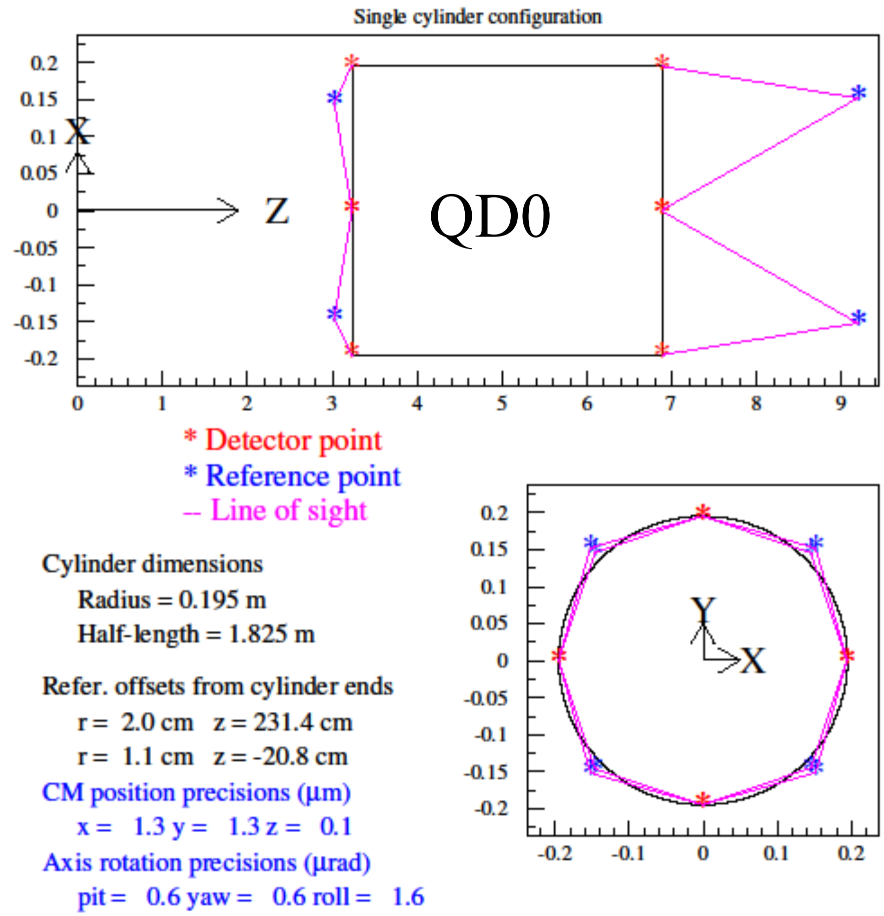
All tolerances met

First Simulations

Conclusion:

16 lines probably fine

- Precision better than needed
- Tolerant of channel loss



→ Need four retroreflectors on each end of QD0
→ Need four launch points (2 beams each) on QF1 and Hcal

Caveats:

- **Assumes reference points on Hcal known!**
- **Bridging detector gap is important → Future simulation**

Summary

Have resumed FSI R&D this year after long hiatus

Dual-channel measurements look promising

Now working on multi-channel testbed

Some issues to be addressed for MDI application:

- Robustness w.r.t. initial misalignment
- Reduction & mounting of retroreflector & fiber launcher
- Transition - optical to infrared (exploit telecom technology)
- Full FSI simulation with bootstrapping across detector gap and integration with tracker alignment