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

University of Michigan ILC Group

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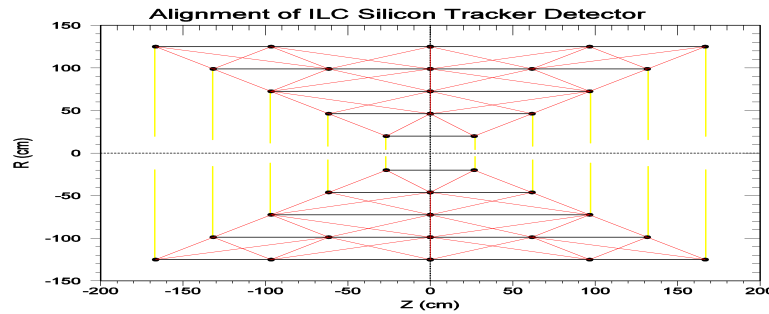
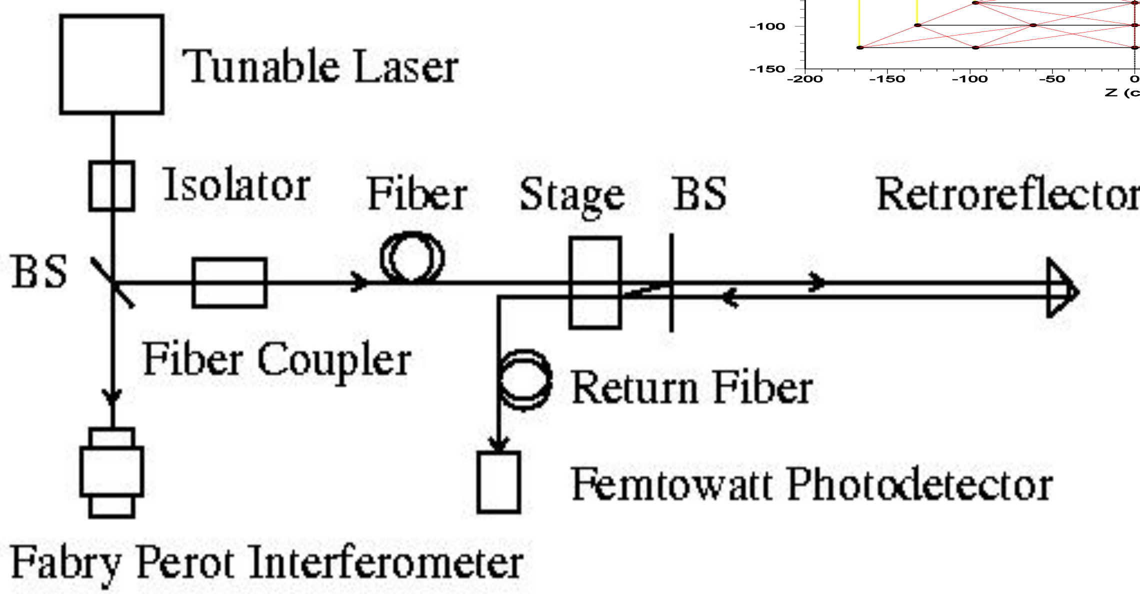
Reminder of Frequency Scanned Interferometry (FSI) Method

- **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 → Achieved sub-micron precision for single-channel setup

Many presentations at LC workshops and two articles:
***Appl. Opt* 44: 3937 (2005); *Nuc. Inst. Meth. A* 575:395 (2007)**

3-year funding gap until resumption of R&D in March 2011 (DOE funding via SLAC MDI and Oregon LCRD)

Gave report on early dual-channel work in Sept 2011 at Granada LCWS

Today: Report on recent multi-channel measurements

*See extra slide for details

Alignment requirements

MDI -- Accuracies for QD0 support:
(March 2009 functional requirements document)
- **50 µm in x, y**
- **20 mrad in roll**
- **20 µrad in pitch and yaw**

SiD tracker – ceiling not well defined, but goal of impact parameter resolution better than ~2 µm in r-φ (100 GeV) suggests systematic alignment errors should be at least as good – challenging!

FSI measurements are longitudinal along lines of sight
- **Transverse precisions depend on projections angles and # lines of sight**
- **Geometric optimization problem**

New infrastructure & measurements - Overview

Have implemented 8-channel, dual-laser system on bench

- But only 7 channels work well (fiber splitter issue)
- Will focus today on 3-channel and 5-channel measurements

Previously used large (~2” diam) glass corner-cube reflectors

- **Now using smaller (0.5”) metal corner reflectors (“cubes”)**

Previously used large commercial stages & clamps for fiber beam launcher

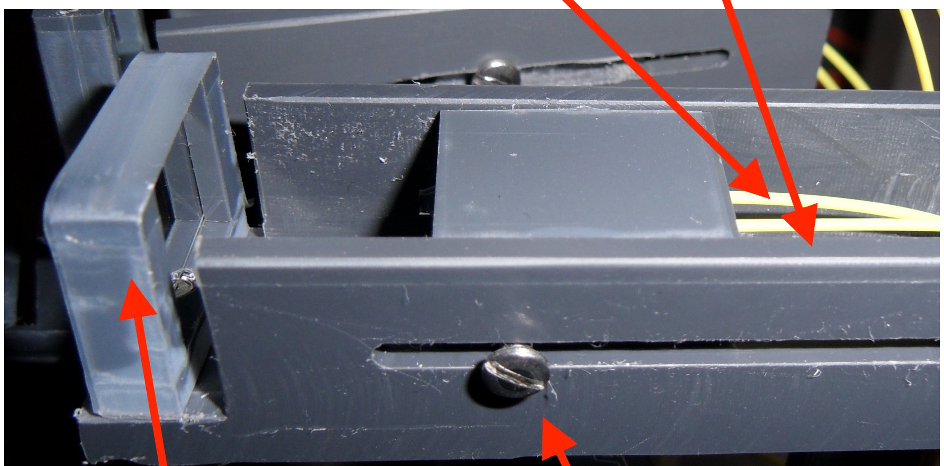
- **Now using compact, customized PVC cartridges with adjustment screws for beam splitters**

New test measurements:

- **Determination of launcher positions relative to (arbitrary) reference point attached to corner cube(s)**
- **Overconstrained measurements of new corner cube test positions**
- **Verification with precision stage – X-Y: ~0.5 µm and Z ~few µm**

New fiber launcher cartridge and corner cube

Return fiber & launch fiber



Beamsplitter
on rotating stage

Pitch angle of fibers
is adjustable

Corner cube(0.5 inch)

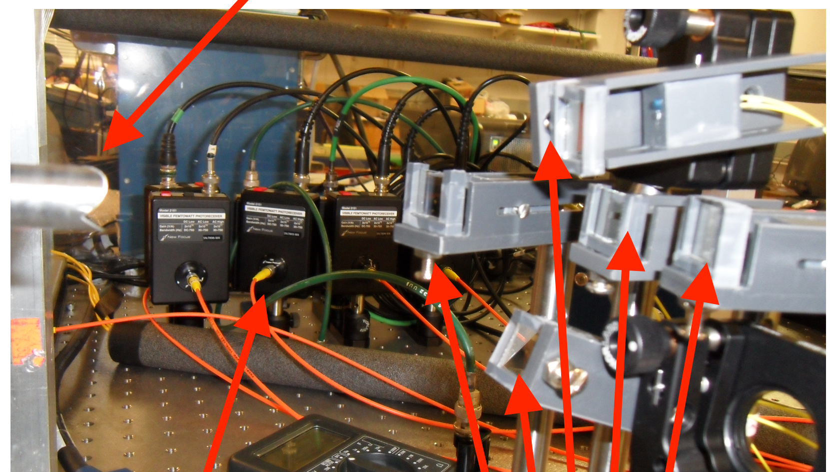
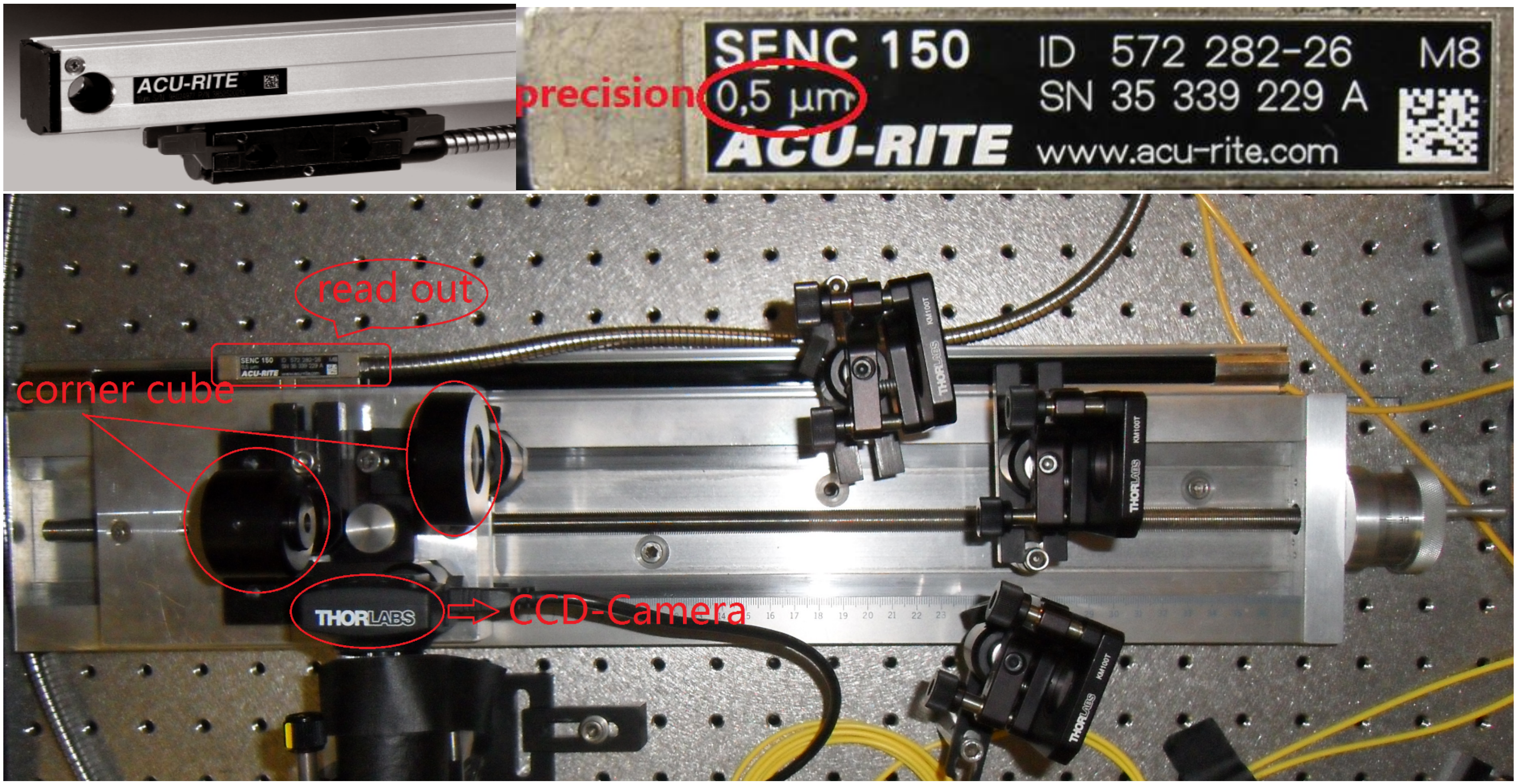


Photo receivers

Five channels
of FSI

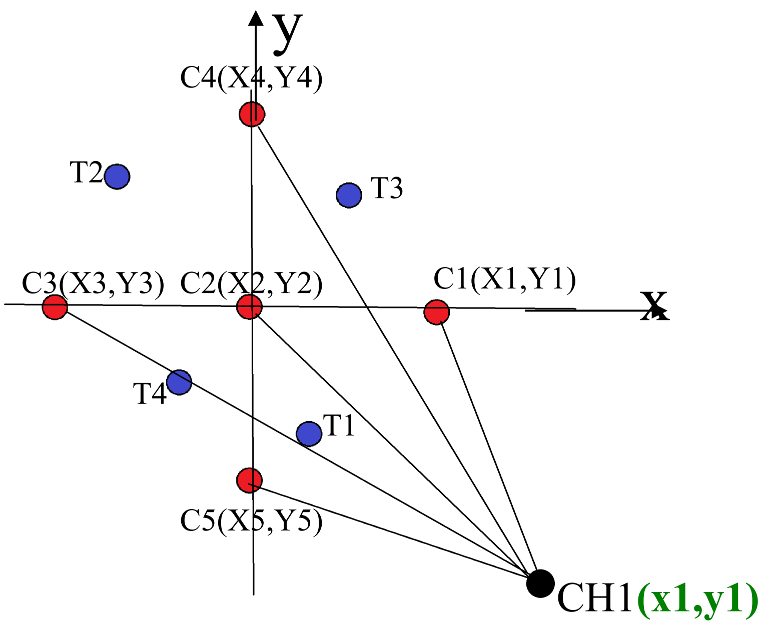
(Configuration for 3D measurements)

Precision 2-D stage (0.5-µm Acu-Rite readouts)



Step 1 - Determining the position of one fiber launcher

Ci = Five calibrated (Acu-Rite) C.C. positions
Ti = Four test points to be determined after calibration



$$L_i = \sqrt{(X_i - x_1)^2 + (Y_i - y_1)^2}$$

FSI_i = distance between Ci and CH1 measured by FSI CH1

$$\chi^2 = \sqrt{\sum_i^5 (FSI_i - L_i)^2}$$

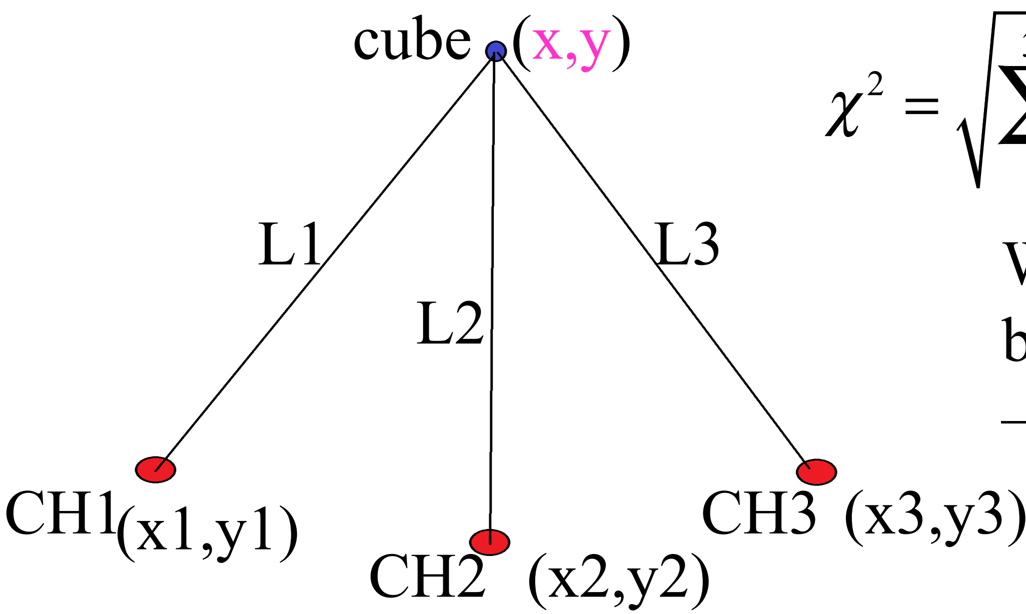
We find the position of launcher 1 (CH1) by minimizing χ^2 w.r.t. (x_1,y_1) – using TMinuit function in Root – Repeat for each launcher

Step 2- Determining the 2-D position of the corner cube

- We use 3 launchers to determine the 2-D position of the corner cube, having calibrated each launcher position in step 1

$$L_i = \sqrt{(x_i - x)^2 + (y_i - y)^2}$$

$$\chi^2 = \sqrt{\sum_i^3 (FSI_i - L_i)^2}$$



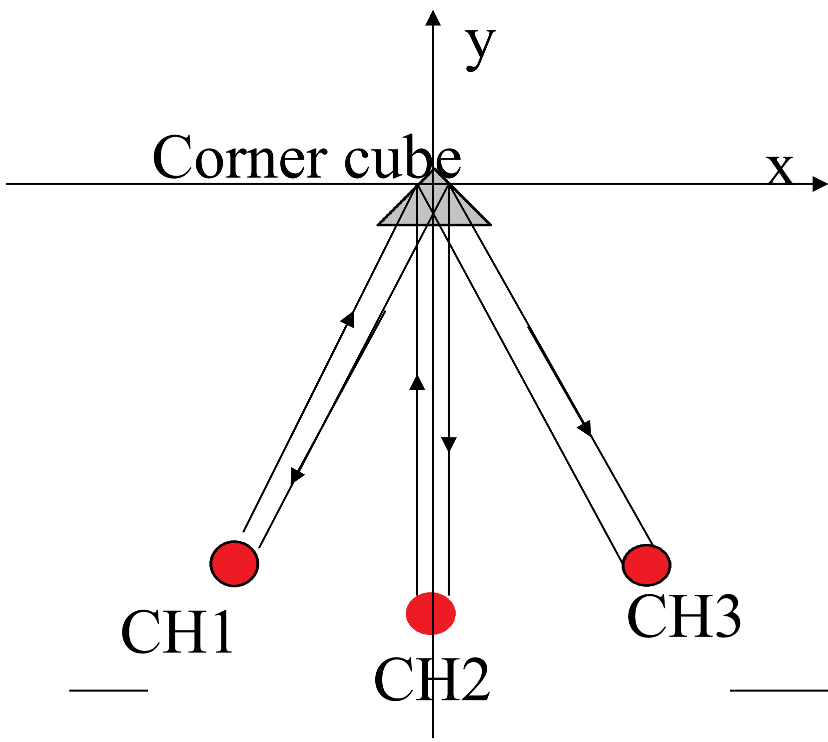
We find the cube position (x,y) by minimizing the new χ^2

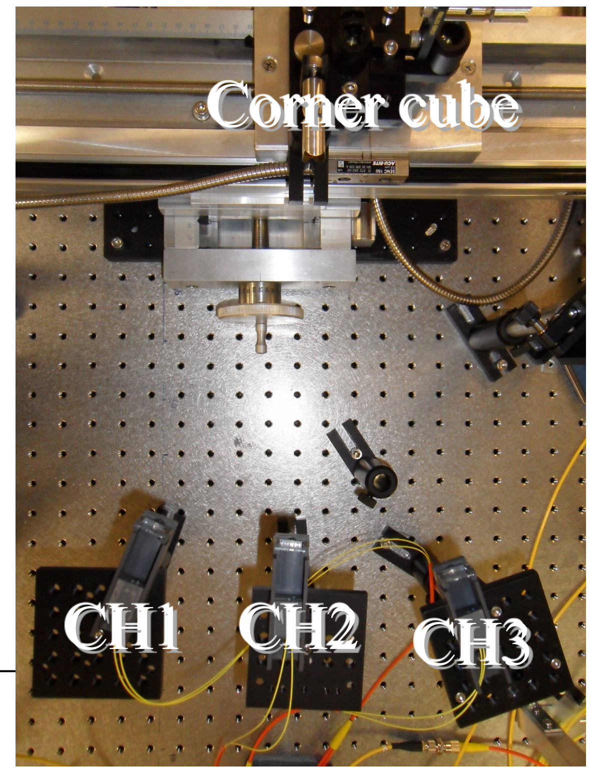
– Repeat for each test position

Results of 1st 2-D test

(1 corner cube , 3 launchers, & four test points)

[microns]	Test1 (x,y)		Test2 (x,y)		Test3 (x,y)		Test4 (x,y)	
ACU-RITE(±½μm)	318	-291	-277	355	318	355	-277	-500
Reconstruction	318.7	-291.6	-276.5	355.8	317.3	355.7	-276.1	-499.8
Difference	-0.7	0.6	-0.5	-0.8	0.7	-0.7	-0.9	-0.2

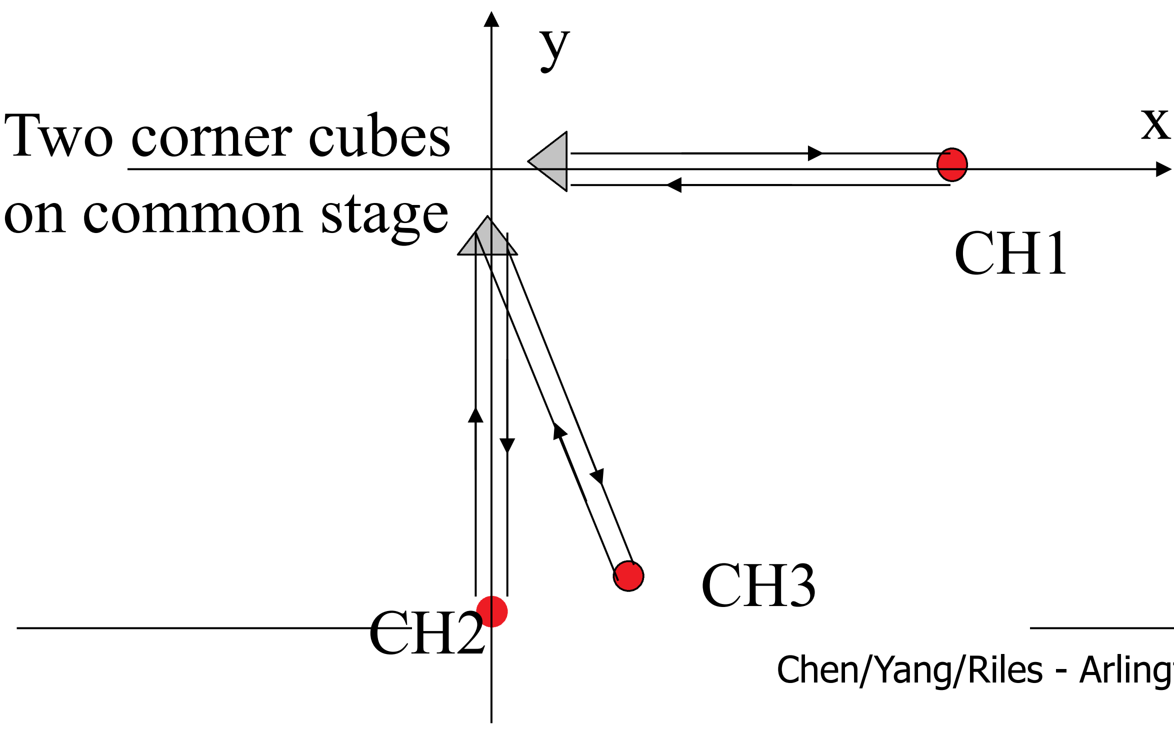




Results of 2^{nd} 2-D test

(2 corner cubes, 3 launchers, four test points)

[microns]	Test1 (x,y)		Test2 (x,y)		Test3 (x,y)		Test4 (x,y)	
ACU-RITE	269	267	-285	267	269	-272	-285	-297.5
Reconstruct.	267.8	267.4	-285.5	267.3	268.1	-272.9	-285.3	-298.3
Difference	1.2	-0.4	0.5	-0.3	0.9	0.9	0.3	0.8

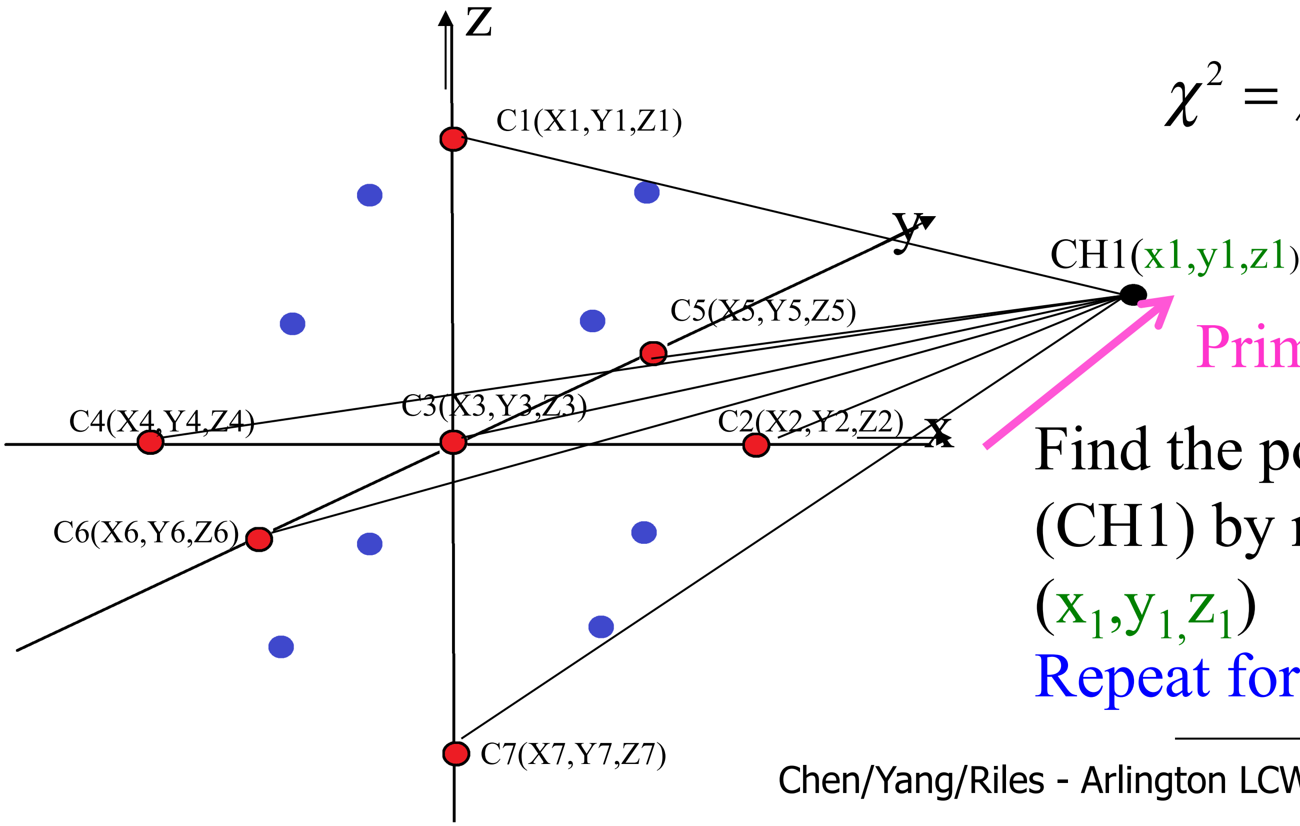


Procedure for 3-D test – Step 1
(7 calibration points)

$$L_i = \sqrt{(X_i - x_1)^2 + (Y_i - y_1) + (Z_i - z_1)^2)}$$

FSI_i : distance between Ci and CH1 measured by FSI CH1

$$\chi^2 = \sqrt{\sum_i^7 (FSI_i - L_i)^2}$$



Primary FSI axis along y

Find the position of launcher 1 (CH1) by minimizing χ^2 w.r.t. (x_1, y_1, z_1)

Repeat for each launcher

Residuals from step 1 (5 launchers)

[micron]	P1	P2	P3	P4	P5	P6	P7	χ^2
CH1	-0.69	-0.64	0.23	0.53	0.24	0.18	0.16	1.2
CH2	-0.15	-0.16	-0.19	0.68	-0.70	0.24	0.28	1.1
CH3	0.73	0.26	-0.66	0.54	-0.76	-0.09	-0.01	1.4
CH4	-0.06	-0.06	0.10	0.15	-0.13	0.030	-0.03	0.2
CH5	-0.60	-0.63	0.23	1.48	-0.71	-0.27	0.50	2.0

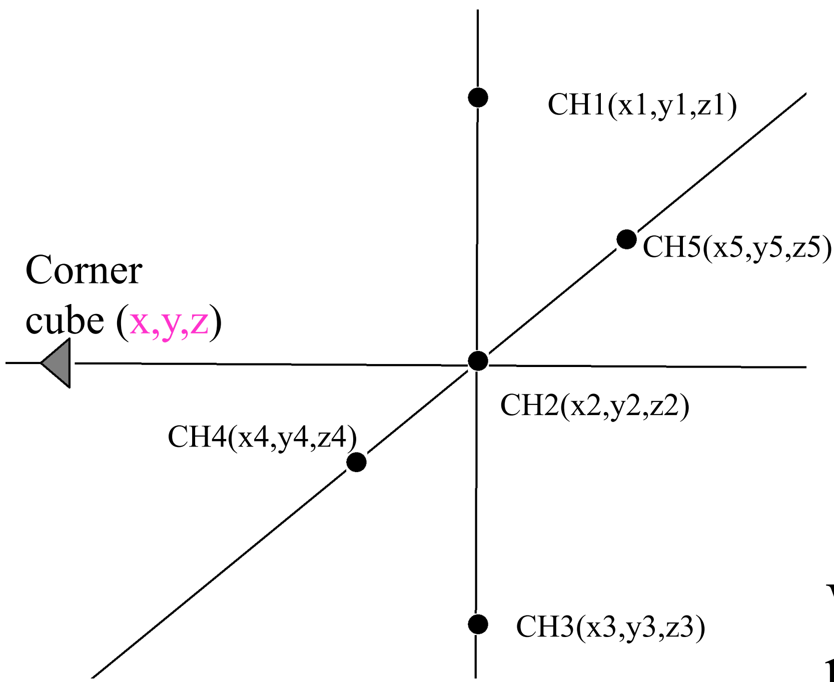
Showing differences between FSI measured distances and reconstructed distances for each of 35 channel-test-point pairs:

$$P_i = FSI_i - L_i$$

Sensitivity of test limited by *a priori* knowledge of calibration point z values (~±2 μm)

Procedure for 3-D test – Step 2
(8 test points – one shown here)

Step 2



$$L_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}$$

FSI_i : distance measured by FSI channel i

$$\chi^2 = \sqrt{\sum_i^5 (FSI_i - L_i)^2}$$

We find the cube position (x,y,z) by minimizing the new χ^2

– Repeat for each test position

Results of 3-D measurements for test point 1

[microns]	Test point 1 (x,y,z)		
Acu-Rite	-209	241	-200
Reconstruction	-208.8	240.9	-196.1
Difference	-0.2	0.1	-3.9

z precision
limited by
graduations on
micrometer
tuning knob

	Test point 1 (x,y,z)			Test point 2 (x,y,z)			Test point 3 (x,y,z)		
ACU	-209	241	-200	-209	-262.5	-200	-223	-234	200
RECO	-208.8	240.9	-196.1	-204.9	-263.5	-195.3	-219.8	-235.4	204.6
A-S	-0.2	0.1	-3.9	-4.1	1	-4.7	-3.2	1	-4.6

	Test point 4 (x,y,z)			Test point 5 (x,y,z)			Test point 6 (x,y,z)		
ACU	-203	214.5	200	239	-262.5	-200	242	-234	200
RECO	-204.1	214.3	201.5	243.7	-263.2	-196.4	245.2	-235.3	205.1
A-S	1.1	0.2	1.5	-4.7	0.7	-3.6	-3.2	1.3	-5.1

	Test point 7 (x,y,z)			Test point 8 (x,y,z)		
ACU	242	241	200	242	241	-200
RECO	244.6	240.4	205.6	242.9	241.0	-197.3
A-S	-2.6	0.6	-5.6	-0.9	0	-2.7

x and z transverse to primary FSI axis
→ Correlated errors

Summary

Status:

- Resumed work in 2011 after long funding drought
- Have established 8-channel testbed in Michigan lab
- Verified 1-D, 2-D displacement measurements with sub-micron precision
- Available equipment limits 3-D displacement test to few-micron precision, but no reason to believe method doesn't work
- Now working with corner cubes and customized beam launchers compact and light enough for MDI application, but not for SiD tracker
- Can tolerate ±3 mm initial misalignment in present setup,
  (up from ±1 mm last year)

Plans & Goals

Short-term plans:

- Additional 3-D measurements in other configurations
- Full FSI simulation with bootstrapping across detector and integration of tracker & magnet alignment monitoring

Goals for future work (if/when funding reappears)

- Increase FSI lengths over which multi-channel system is reliable
- Attain ±1 cm misalignment tolerance (or better)
- Further reduce size & material of retroreflectors & launchers
- Increase bandwidth of measurements

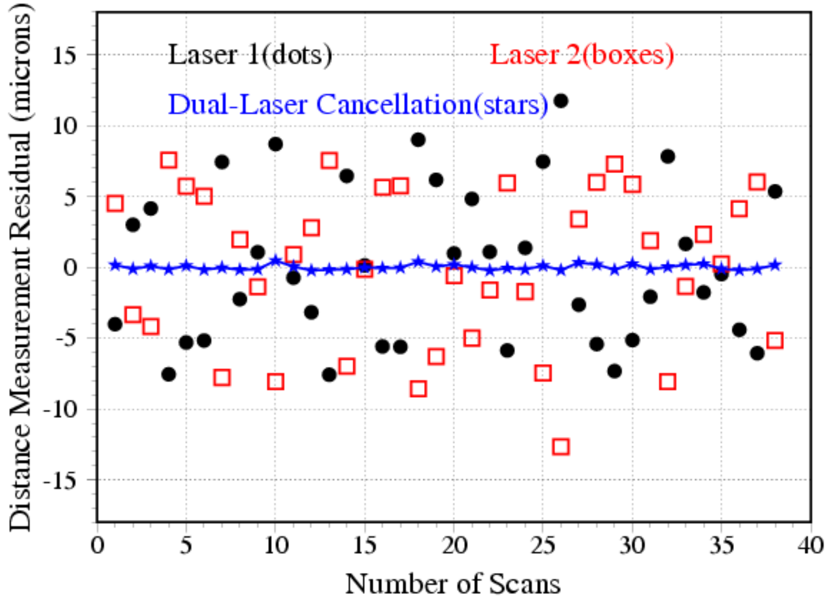
Most of the above would be helped by moving to infrared laser wavelengths, to exploit telecom industry technology

→ Expensive startup to change lasers, optics and photodetectors

Extra Slides

(from previous reports)

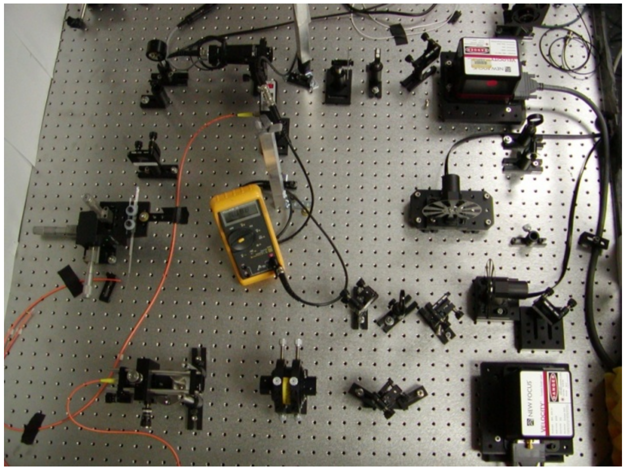
Background on Michigan FSI work



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

Checks:

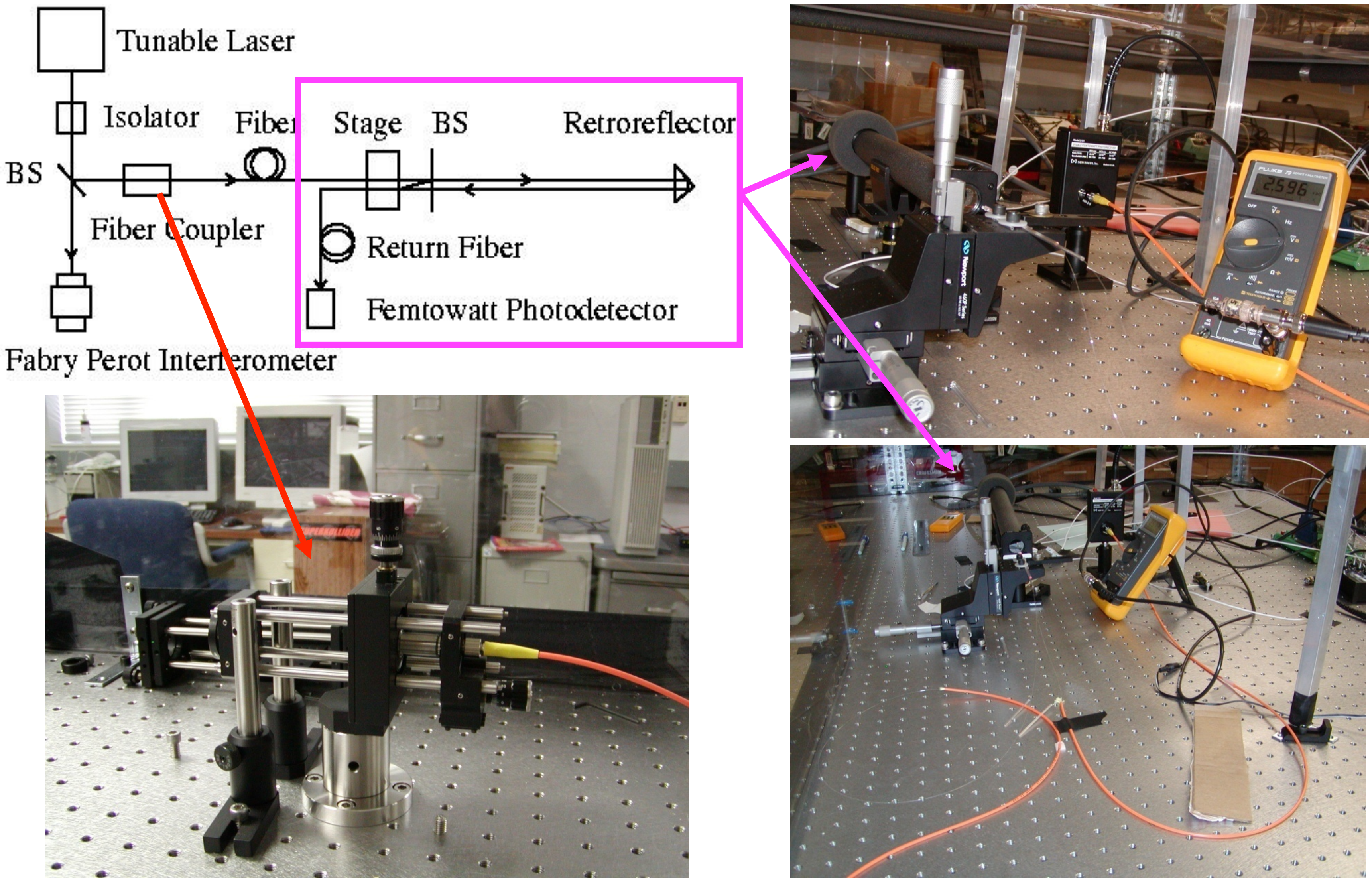
- **Verified micrometer offset of 125 µm**
- **Verified thermal-driven 60 µm expansion**
- **Verified piezo-driven 2 µm displacement**
- **Verified piezo-driven 0.14 µm vibrations**



Caveats:

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

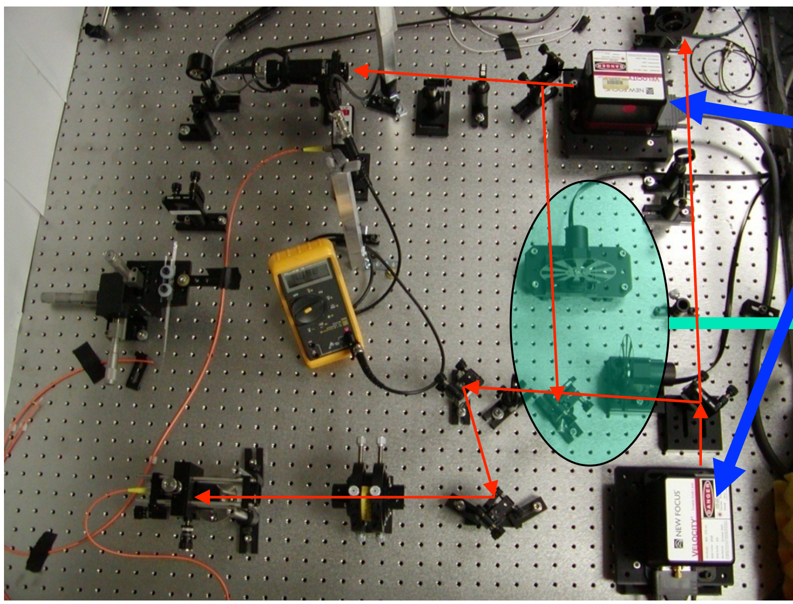
FSI with Optical Fibers (initial setup - single laser)

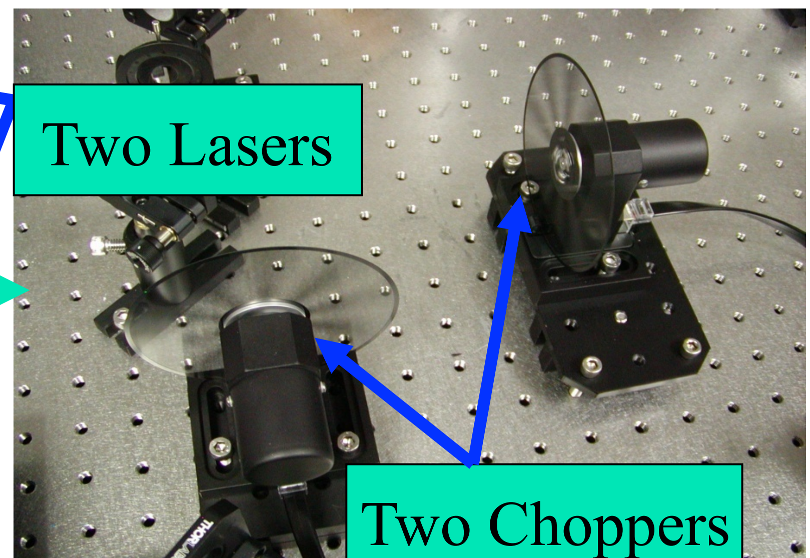


Dual-laser setup (later upgrade)

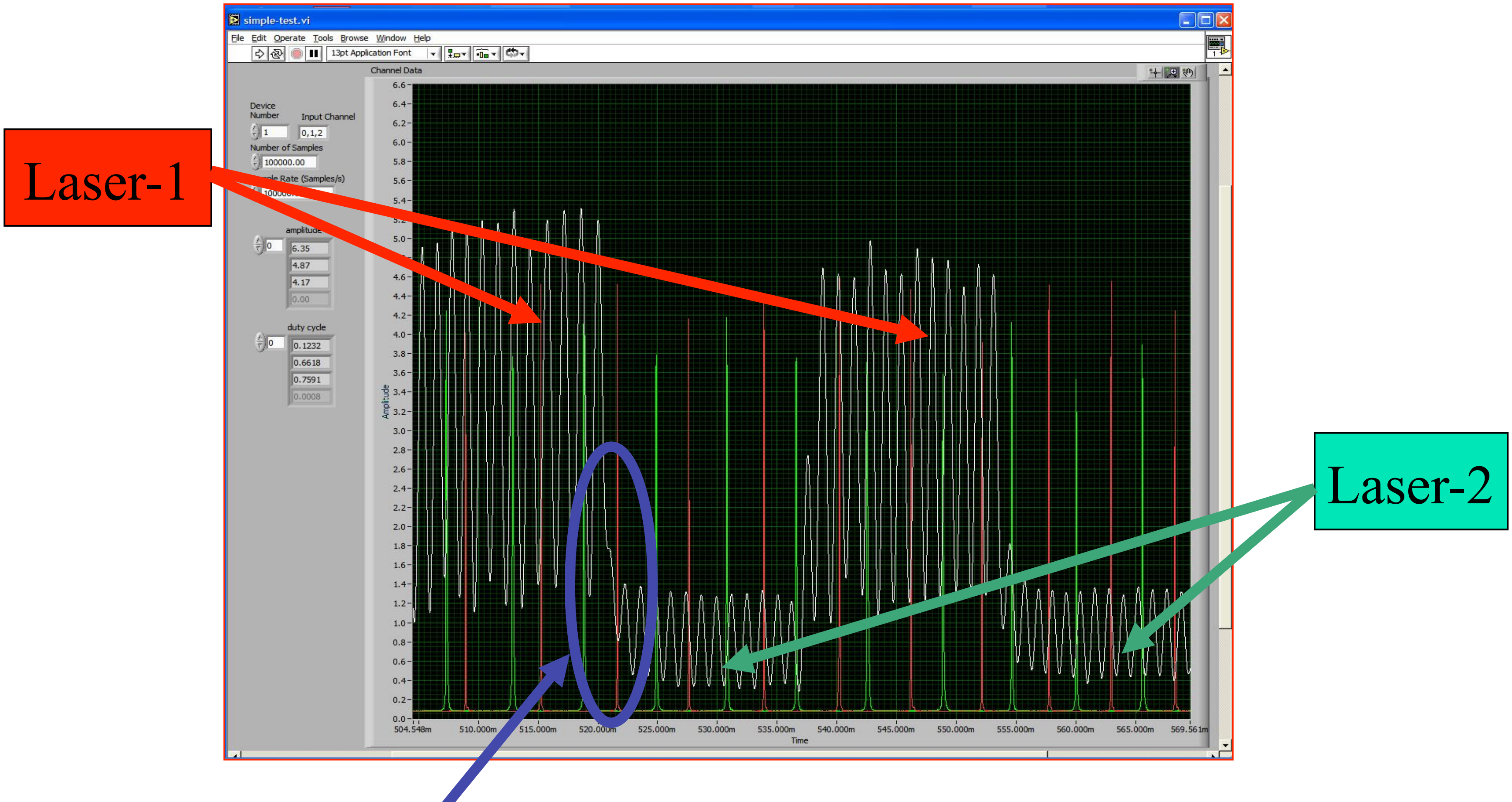
➔A dual-laser FSI was implemented with optical choppers (Oxford group's invention)

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





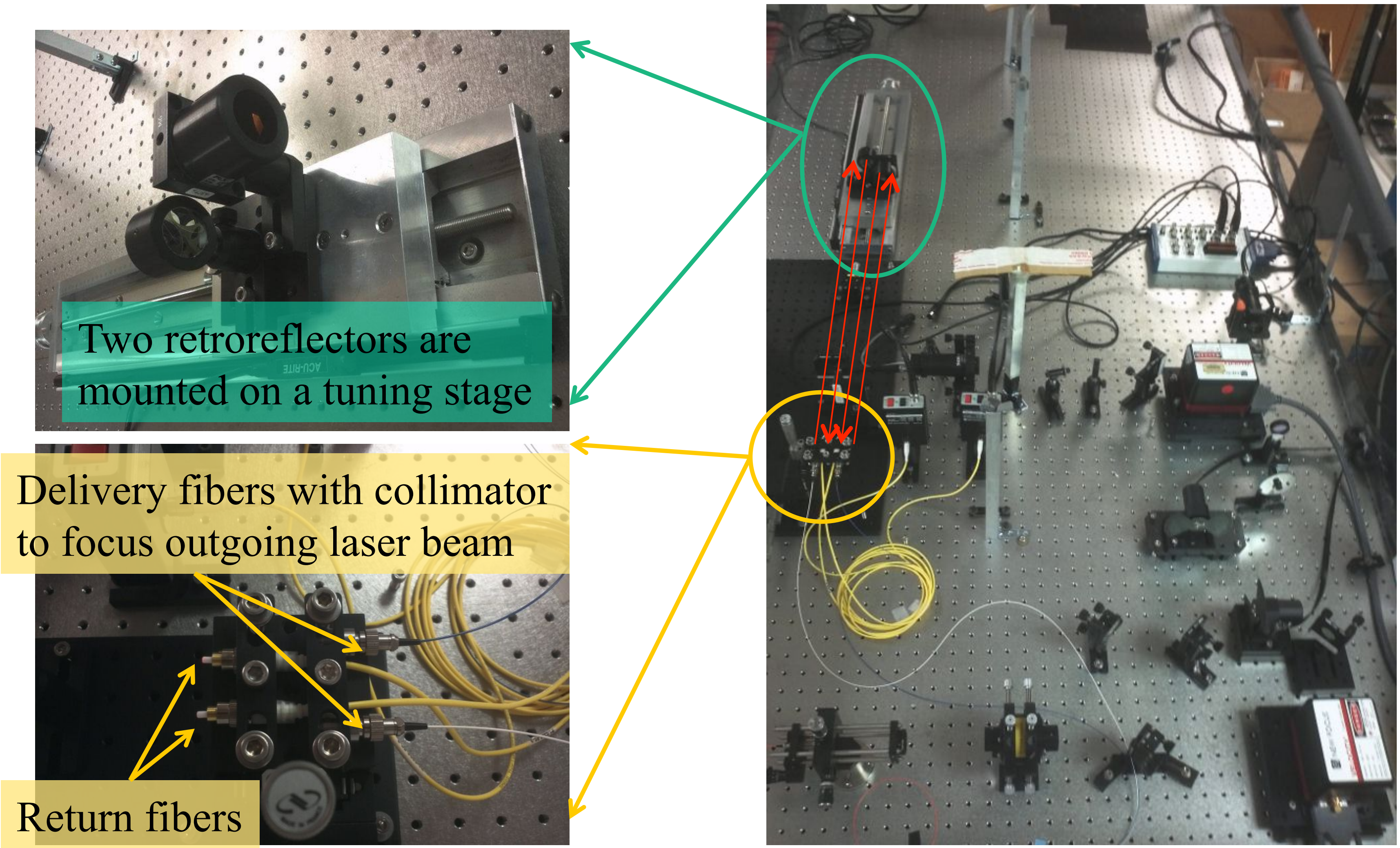
Fringes & F-P Peaks (dual-laser)



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

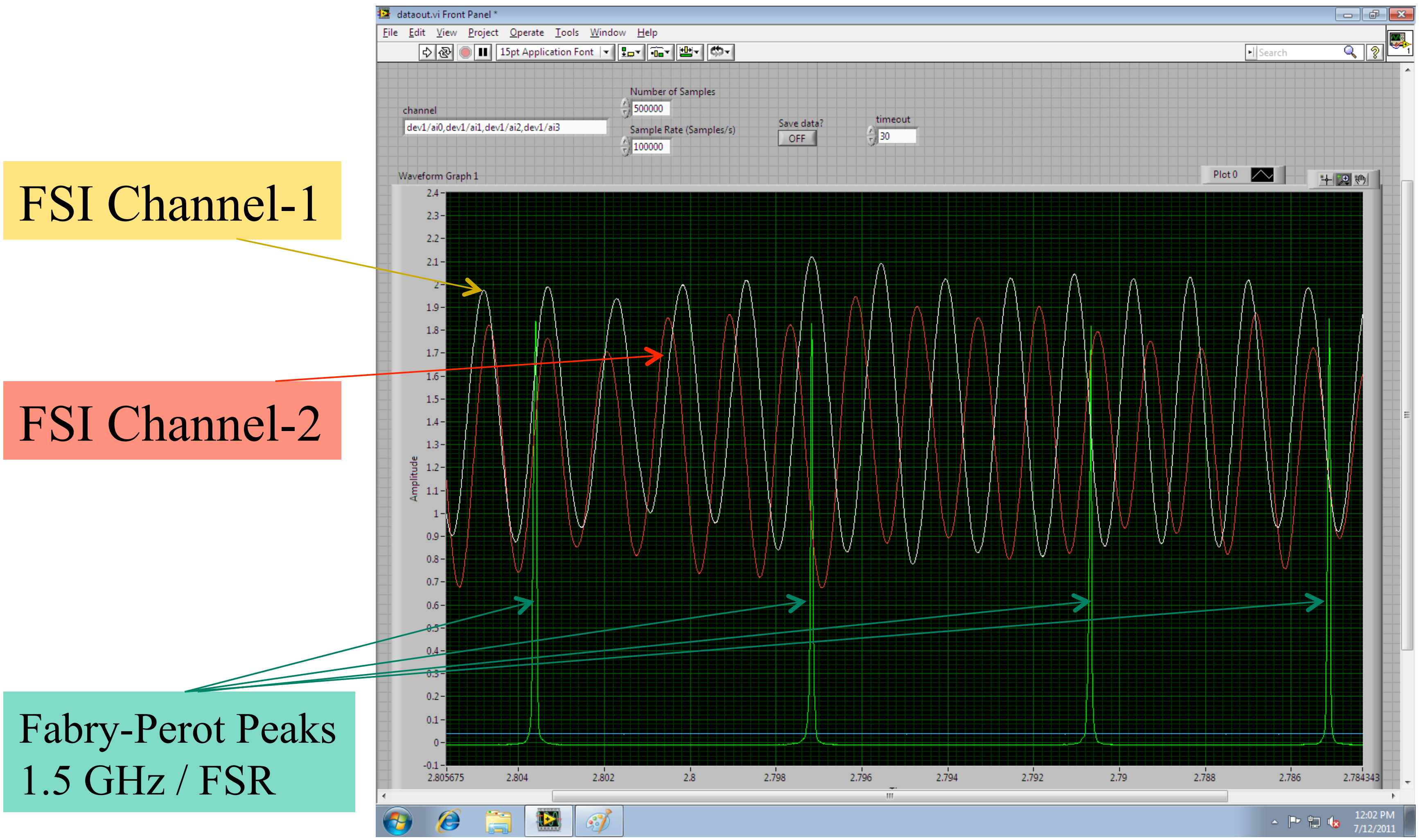
Dual-channel, single-laser

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

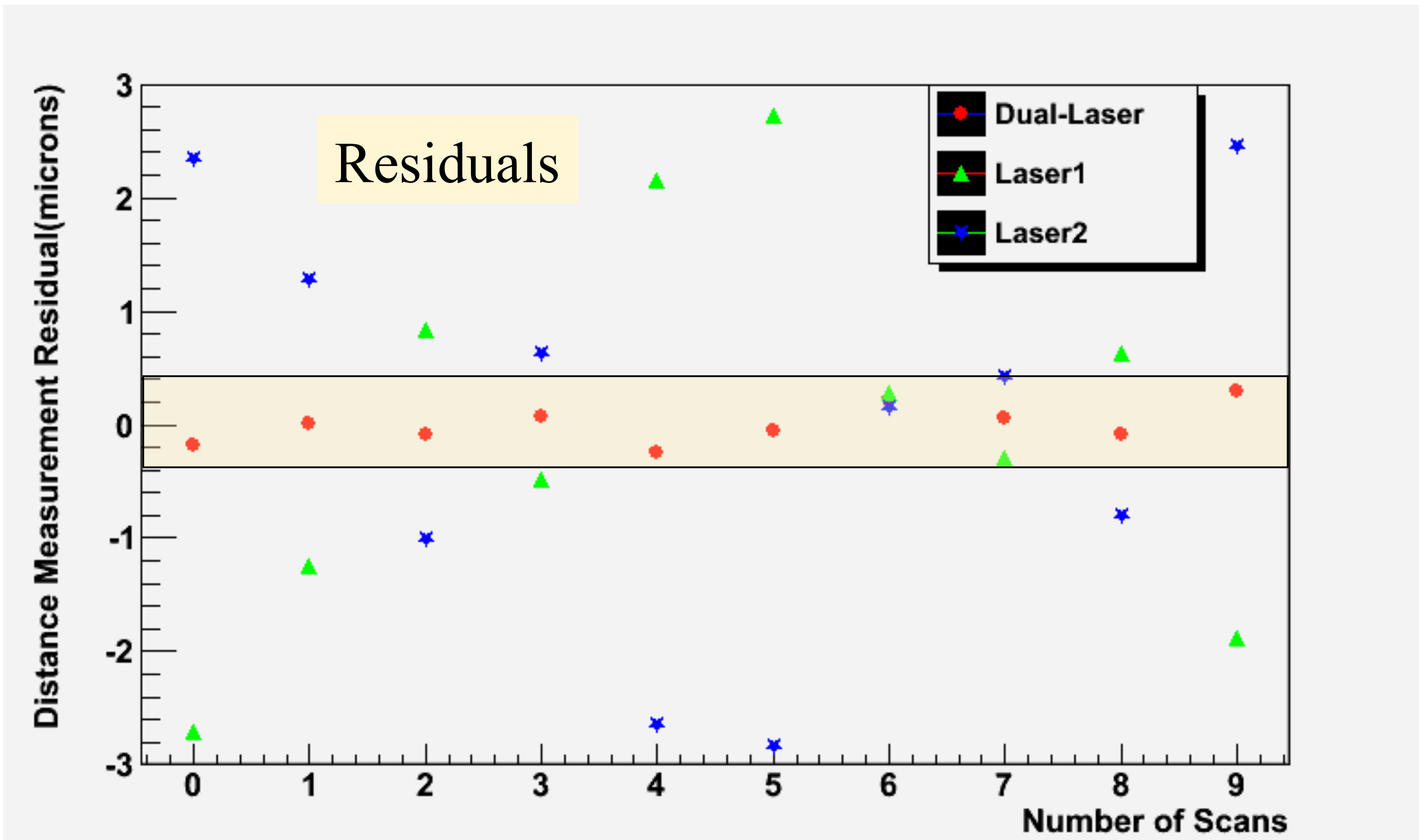
- ➔ Cross-check the distance measurements with two FSI channels and two simultaneous, chopped lasers
- ➔ Using a tuning stage to change position of two retroreflectors simultaneously by amount of (20 ± 2 microns), and check FSI performance. 10 full scan data for each test (R_{dist} ~ 57 cm)

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)



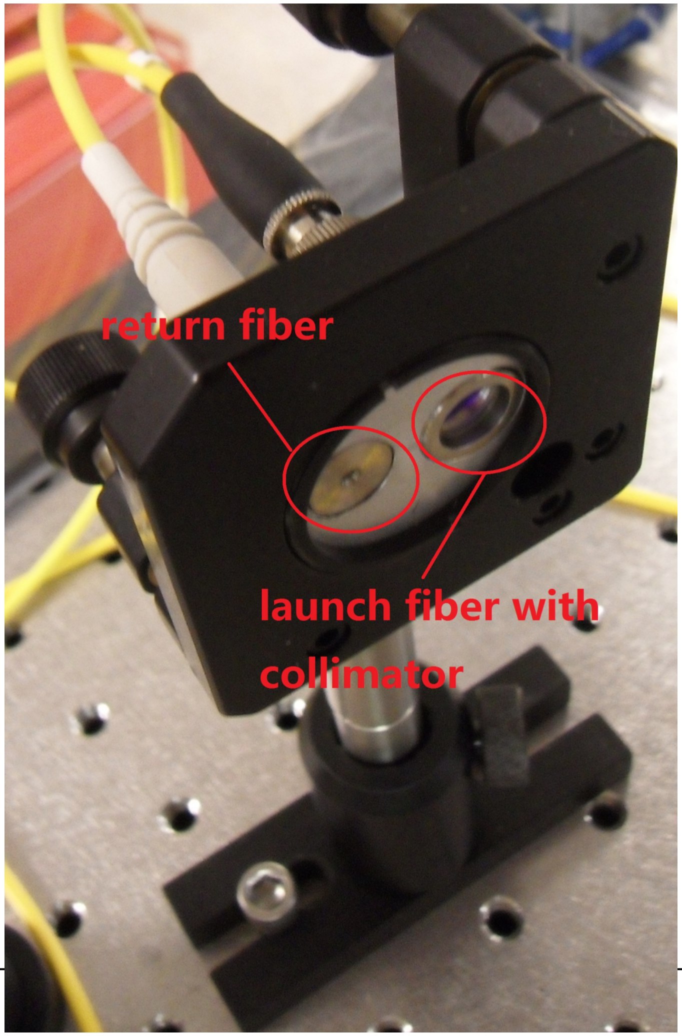
Dual-channel, dual-laser

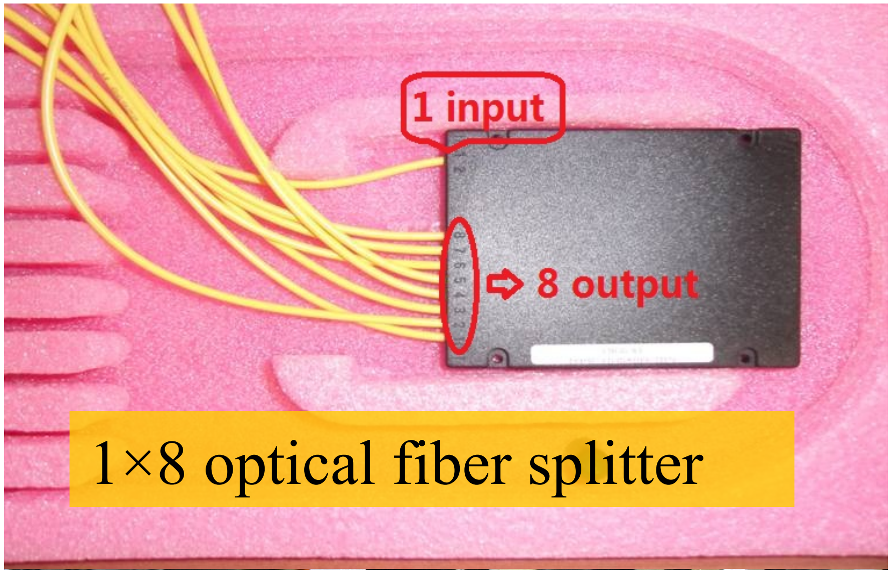
➔ Using dual-laser to cancel the drift errors, better precision for distance measurement can be achieved (0.2-0.3 microns).

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

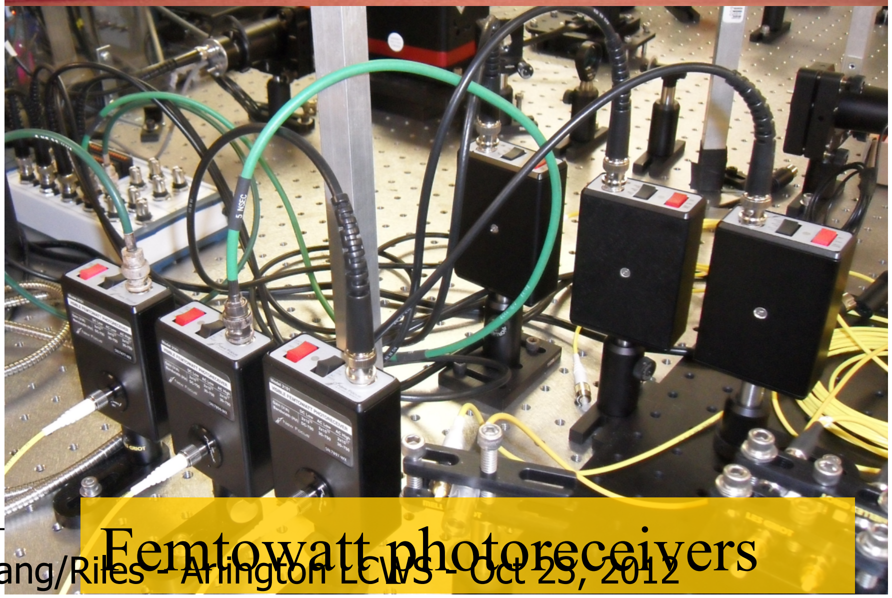
Cross checks and moving to multiple channels

Mount of launch fiber with collimator and return fiber



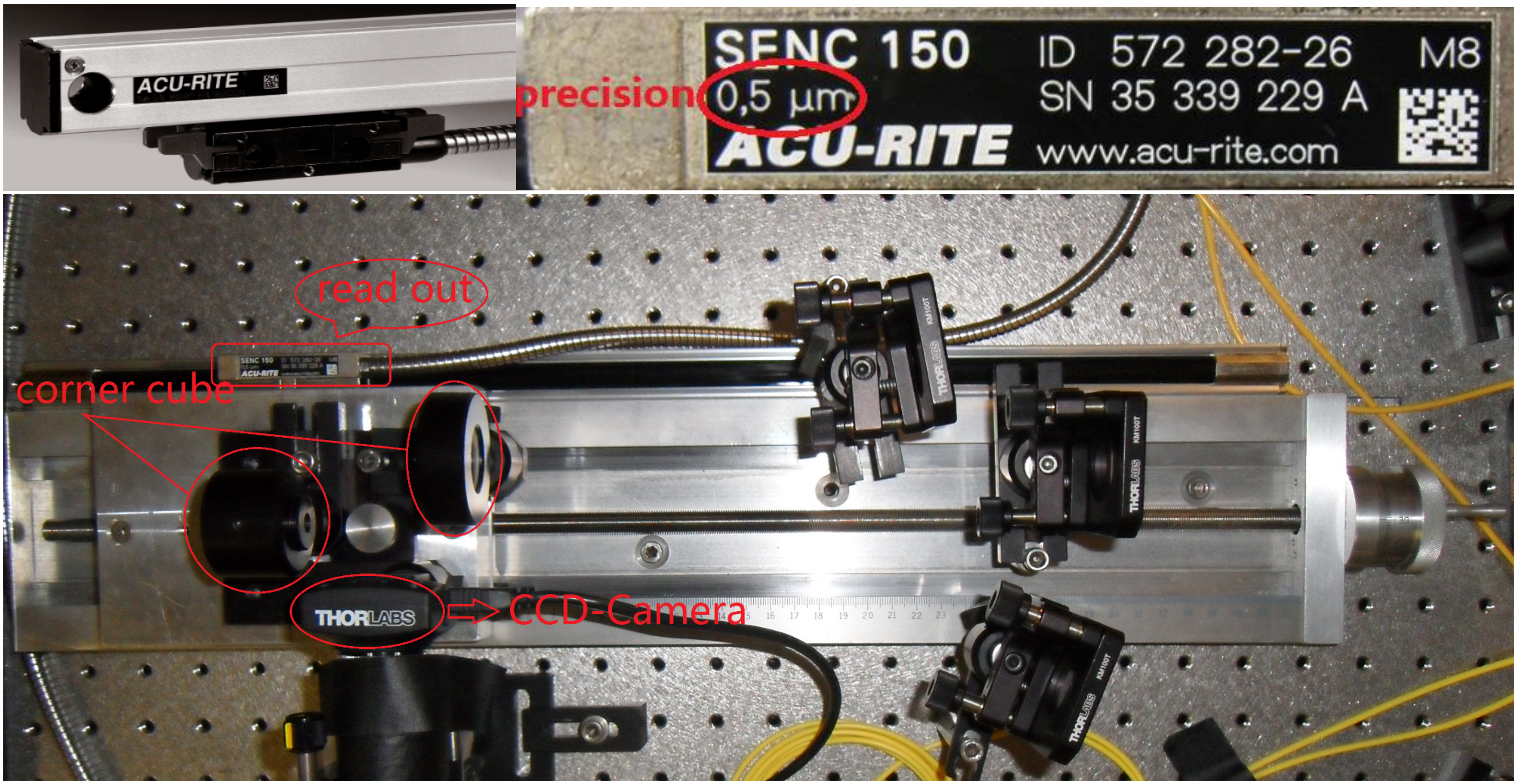


1×8 optical fiber splitter

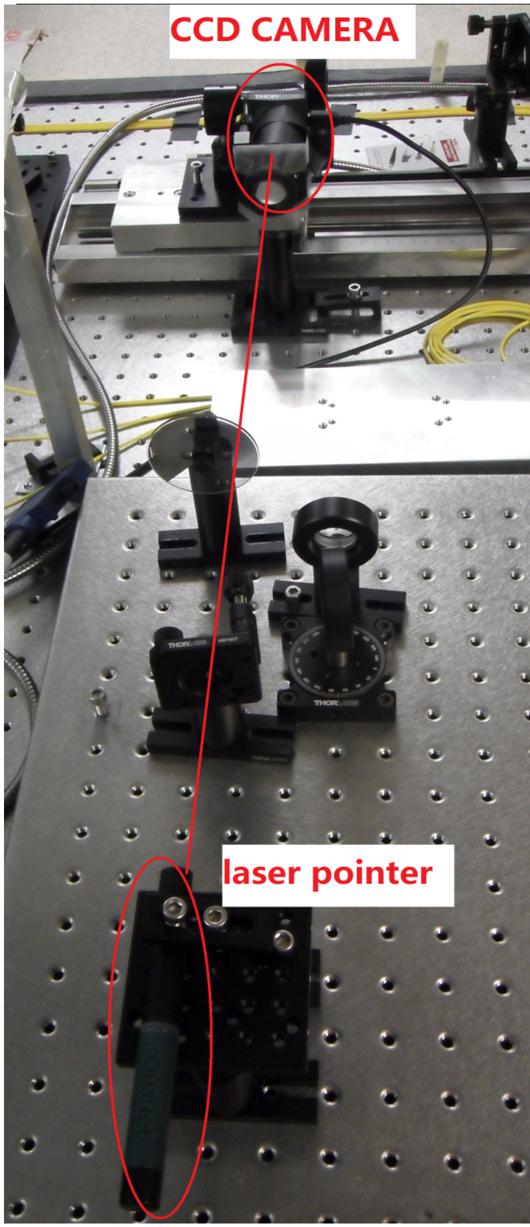


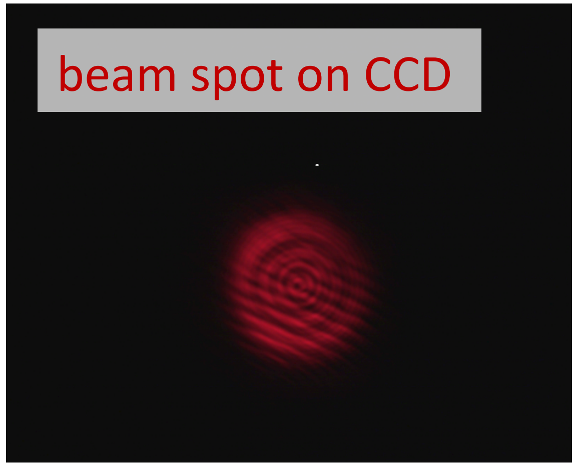
Femtowatt photoreceivers

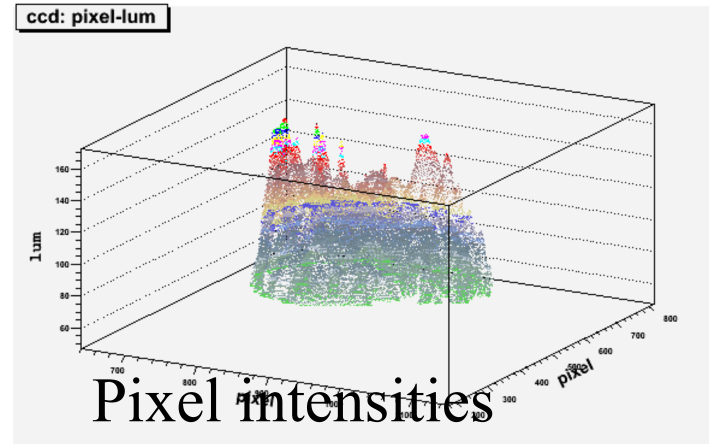
Bought 0.5-μm Acu-Rite readouts for tuning stage



Another cross check – tranverse CCD camera





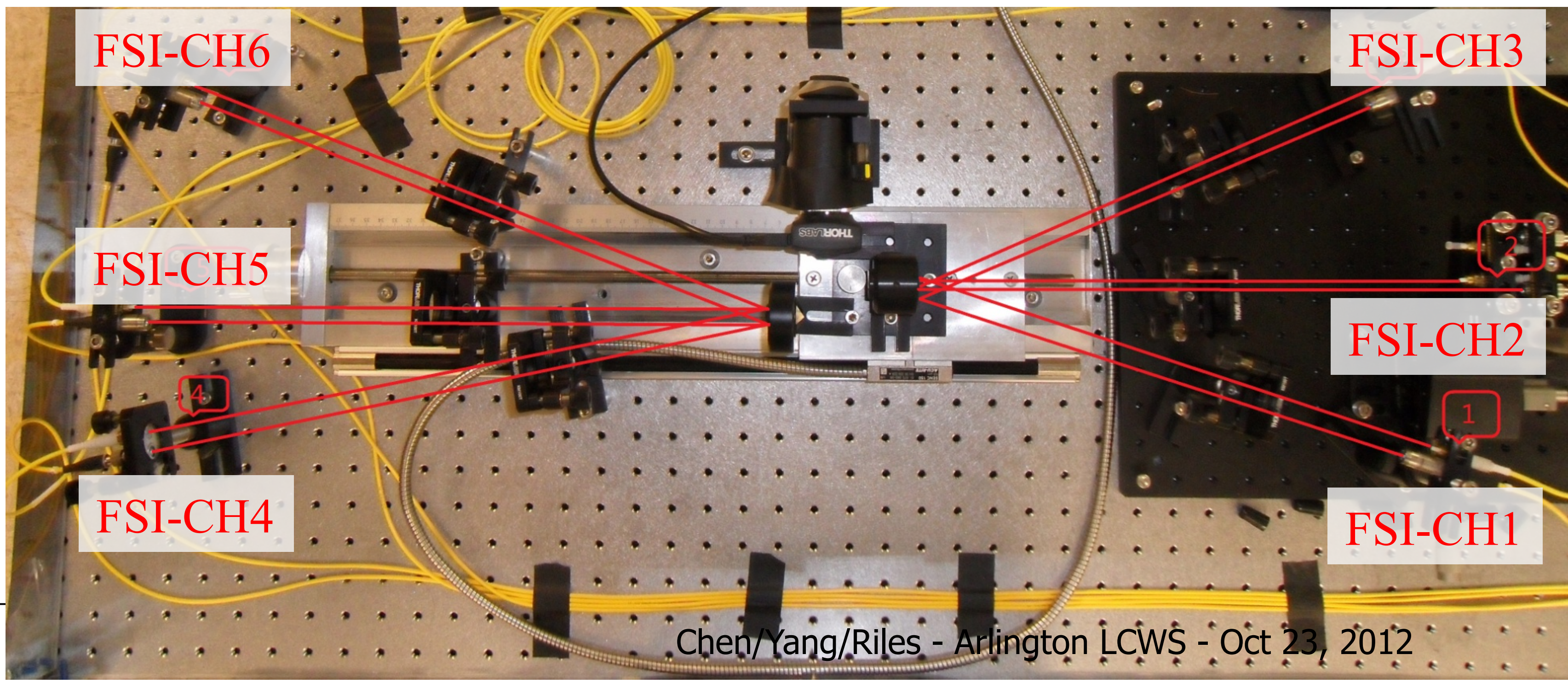


➔The camera and retroreflector are mounted on the moveable plate, so their positions changed together.

➔ Beam centroid measures position change of the camera – and the retroreflector.

First multi-channel test – 1-dimensional displacement

- Cross checks of position(distance) change:
  - ACU-RITE: 98.00±0.71 microns
  - CCD-CAM: 98.21±0.41 microns
  - FSI-CH2: 98.13±0.52 microns
  - FSI-CH5: -98.02±0.30 microns (opposite to FSI-CH2)

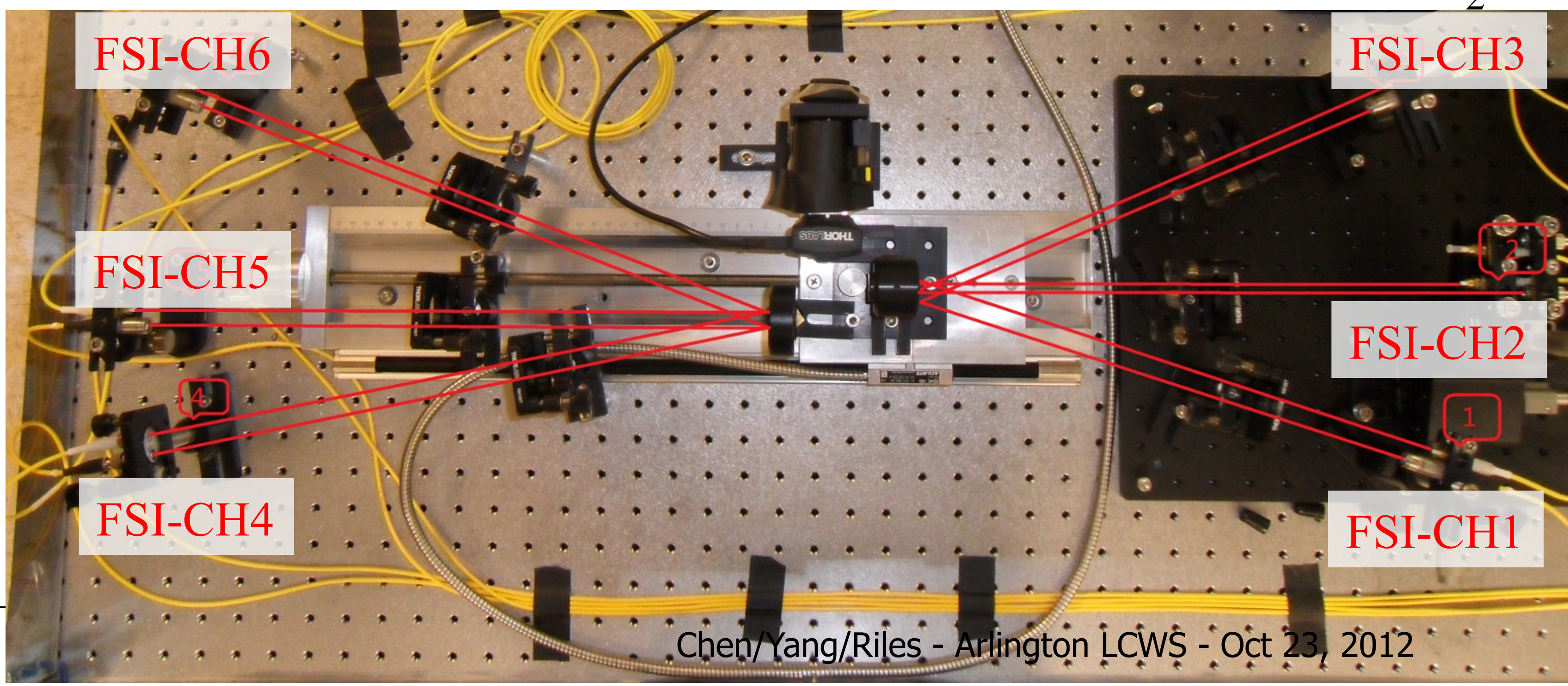


First multi-channel test – 1-dimensional displacement

- Off-axis FSIs measure angle-dependent displacements:
  - Position change for FSI-CH1: Δd_1=93.64±0.35 μm
  - Position change for FSI-CH2: Δd_2=98.13±0.52 μm

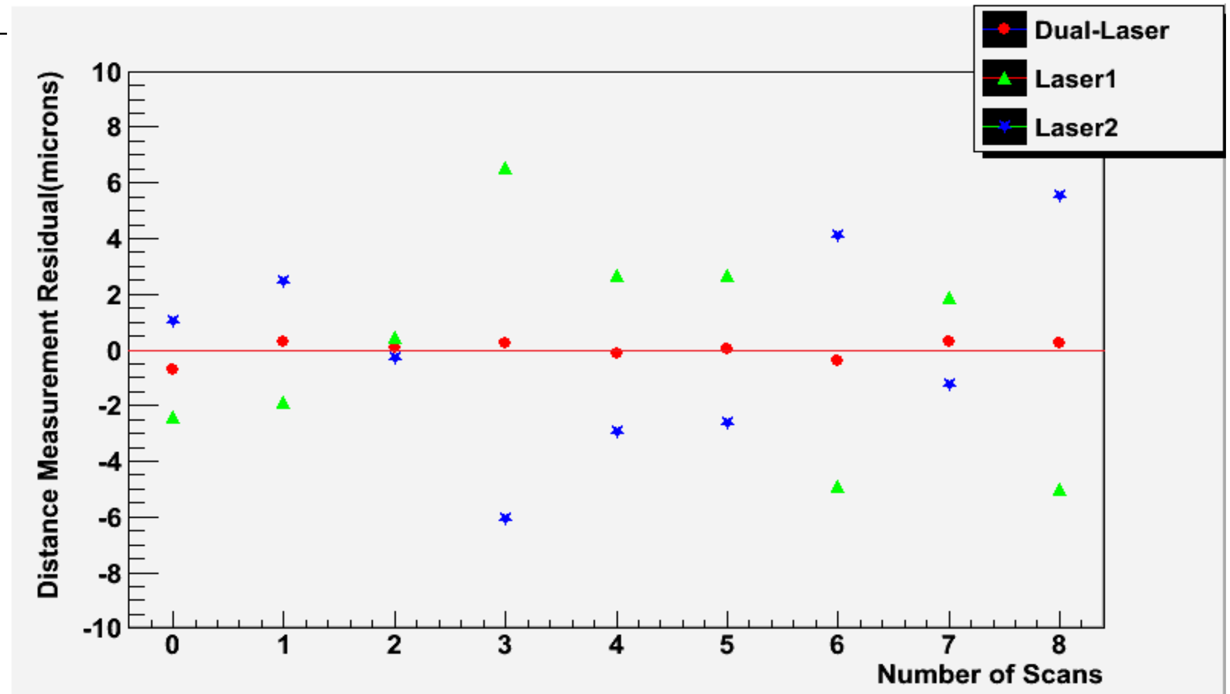
  Angle between CH1 and CH2 :

$$\theta_{12} = \arccos(\frac{\Delta d_1}{\Delta d_2})$$



First multi-channel test – 1-dimensional displacement

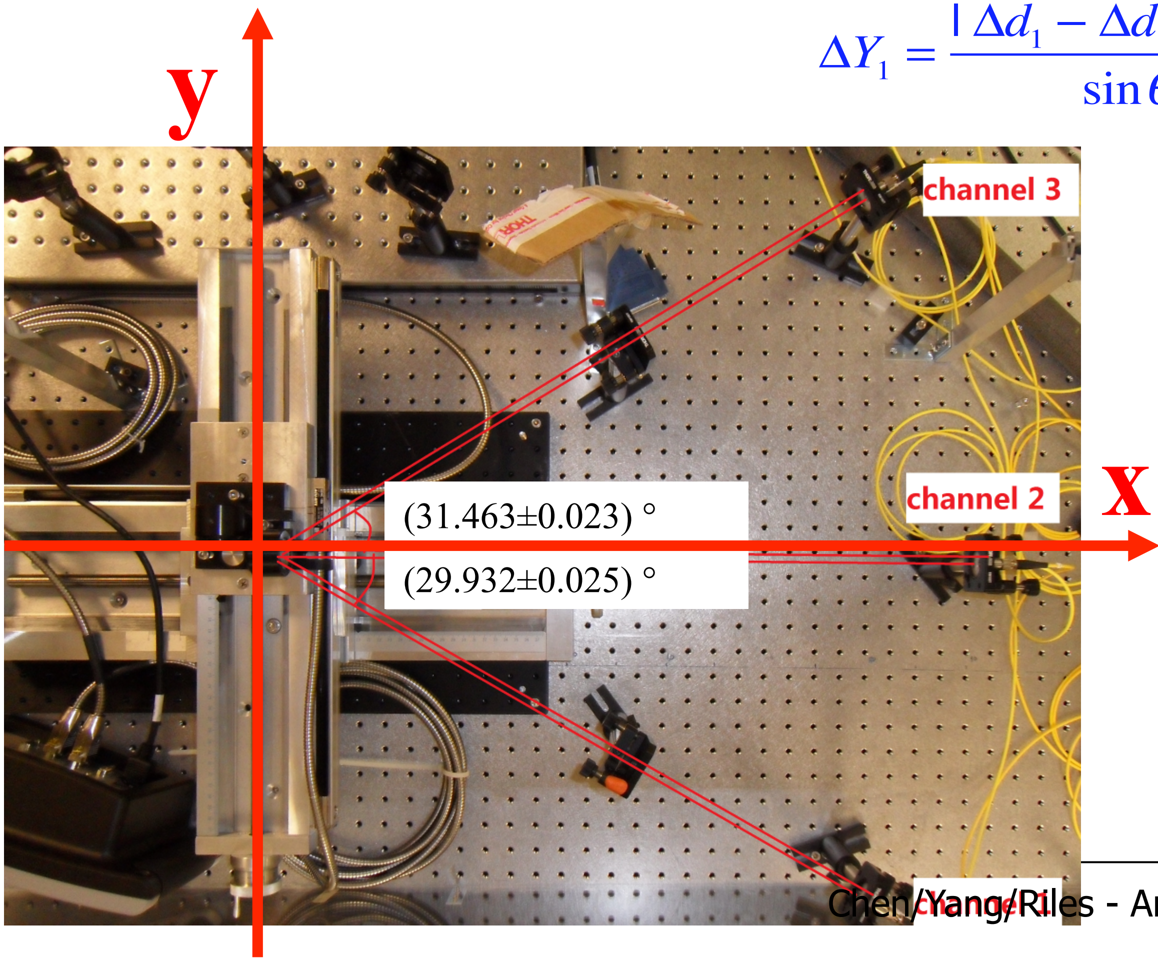
Example of dual-laser scan results for one channel & position



FSI-CH	Position #P1	Position #P2	#P2 - #P1	Angle
1	257745.75 ± 0.27	257839.39 ± 0.22	93.64 ± 0.35	1-2： 17.°
2	221944.12 ± 0.35	222042.28 ± 0.38	98.13 ± 0.52	
3	253345.42 ± 0.23	253435.93 ± 0.28	90.51 ± 0.36	2-3： 23.°
4	186128.35 ± 0.12	186032.28 ± 0.26	-96.07 ± 0.28	4-5： 12.°
5	247669.31 ± 0.20	247571.29 ± 0.23	-98.02 ± 0.30	
6	247605.55 ± 0.24	247513.32 ± 0.25	-92.22 ± 0.35	5-6： 20.°

Second multi-channel test – 2-dimensional displacement

- Determination of 2D position change using 3 FSI channels:
  - using FSI CH2 to measure position change in X direction
  - using FSI CH1 and CH3 to measure position change in Y direction



$$\Delta Y_1 = \frac{|\Delta d_1 - \Delta d_2 \cos\theta_{12}|}{\sin\theta_{12}}, \Delta Y_3 = \frac{|\Delta d_3 - \Delta d_2 \cos\theta_{23}|}{\sin\theta_{23}}$$

$$\Delta Y = (\Delta Y_1 + \Delta Y_3)/2$$

Position change (microns)

In X direction:
- ACU-RITE: 100.00 ± 0.71
- FSI-CH2: 99.63 ± 0.13

In Y direction:
- ACU-RITE: 100.50 ± 0.71
- FSI-CH13(ΔY): 100.56 ± 0.53

  FSI-CH1(ΔY_1): 99.09 ± 0.37

  FSI-CH3(ΔY_3): 102.03 ± 0.97

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)

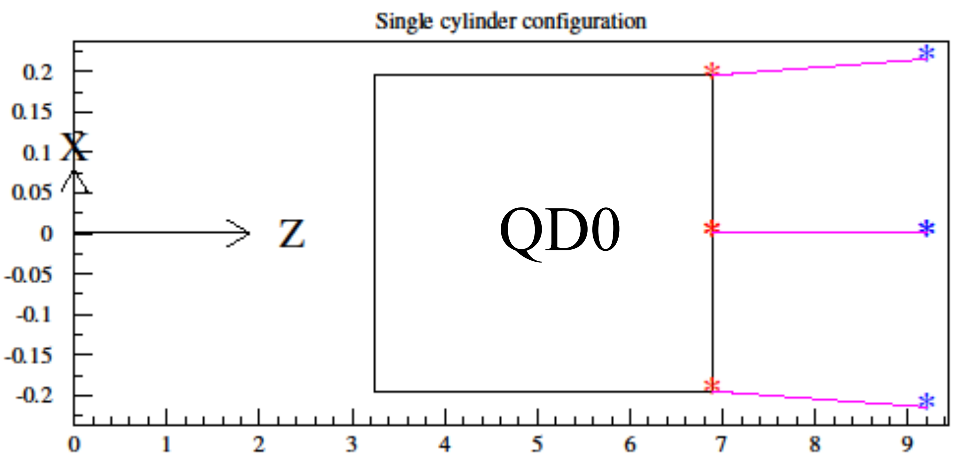
Monitoring alignment of QF1 to bedrock should be relatively easy:
- **Bedrock nearby with many good lines of sight from wall / floor to QF1 sides**

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

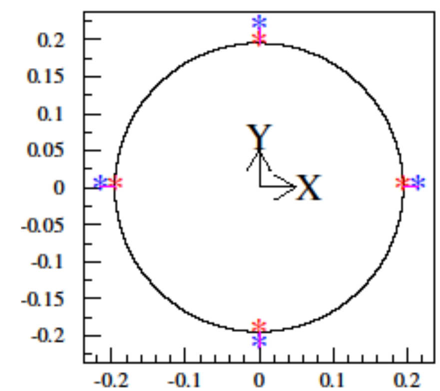
Initial stab at simulations: (quick rework of old tracker simulation)
- **Align e+ and e- sides separately (without bridging gap)**
- **In longer term will pursue bridging gap with lines of sight through open SiD tracker (bootstrap from both ends)**

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)



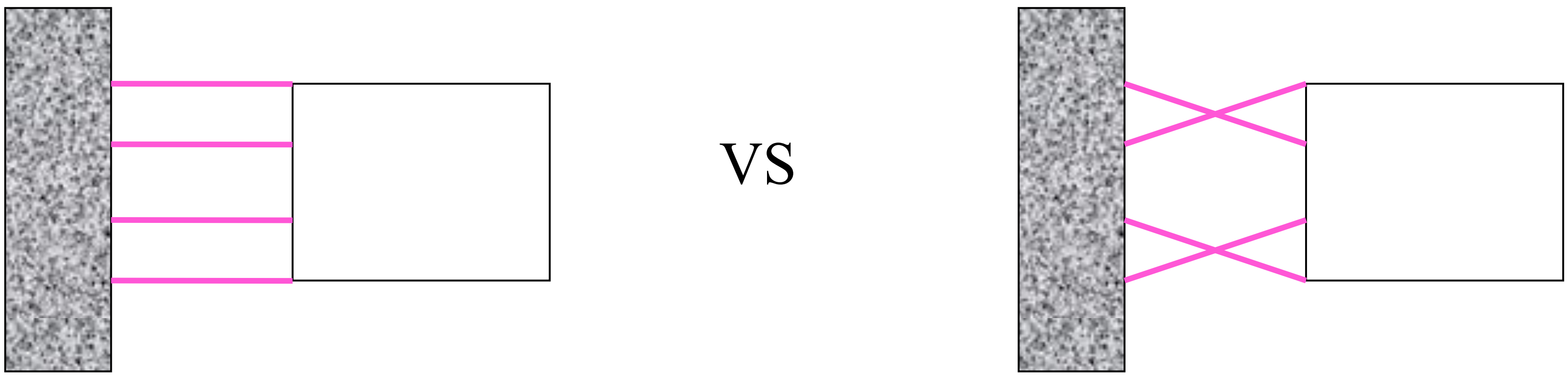
Example:
- N=4
- Option A
- Back end only



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**



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)**

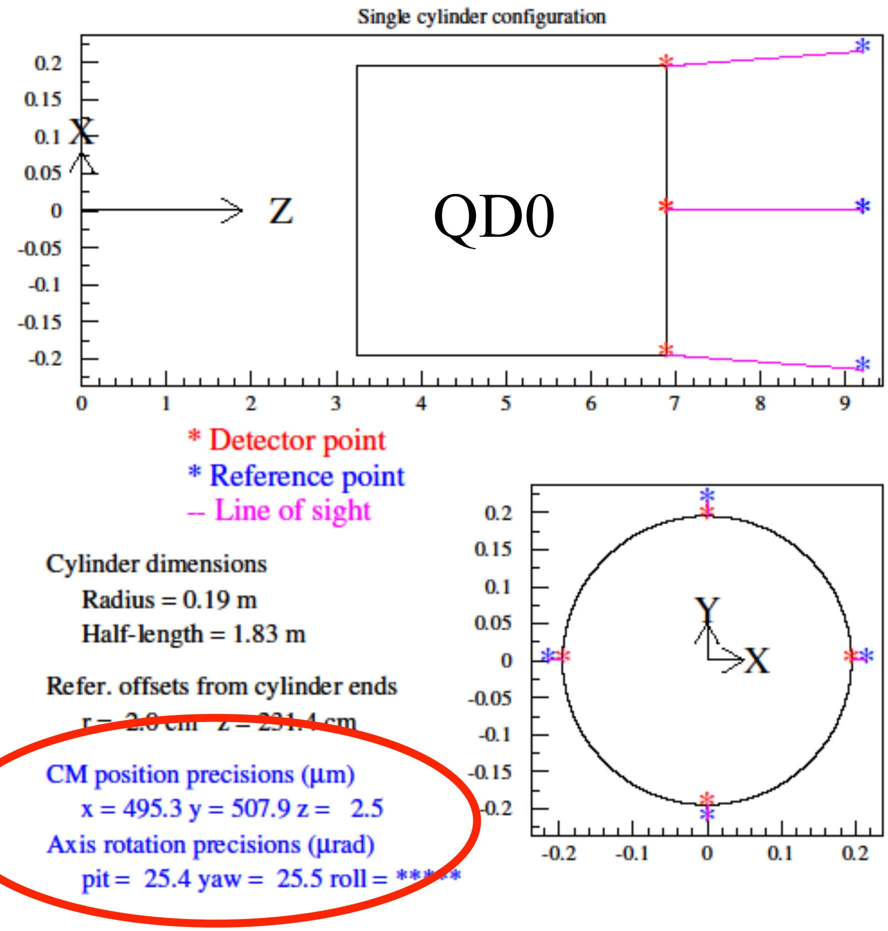
- **Diagrams shown for X-Z and X-Y projections**

- **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

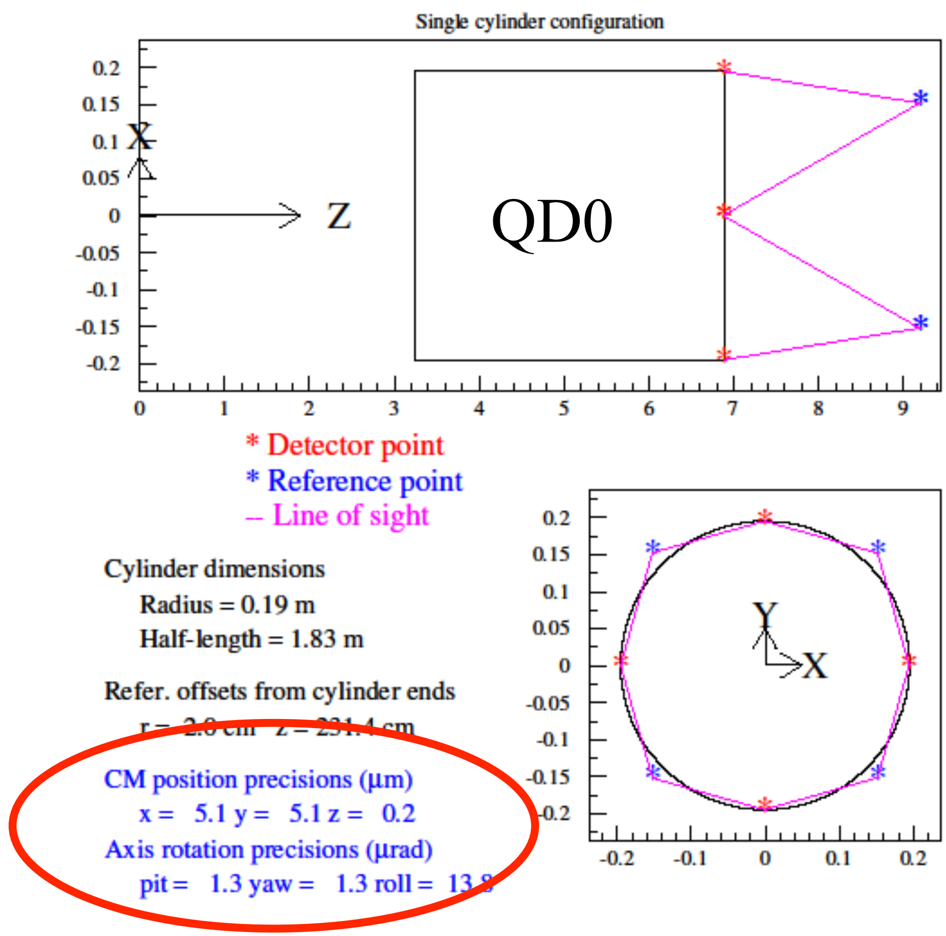


Tolerances not met!

First Simulations

8 lines:

- N=4
- Option B
- Back end only



All tolerances met!

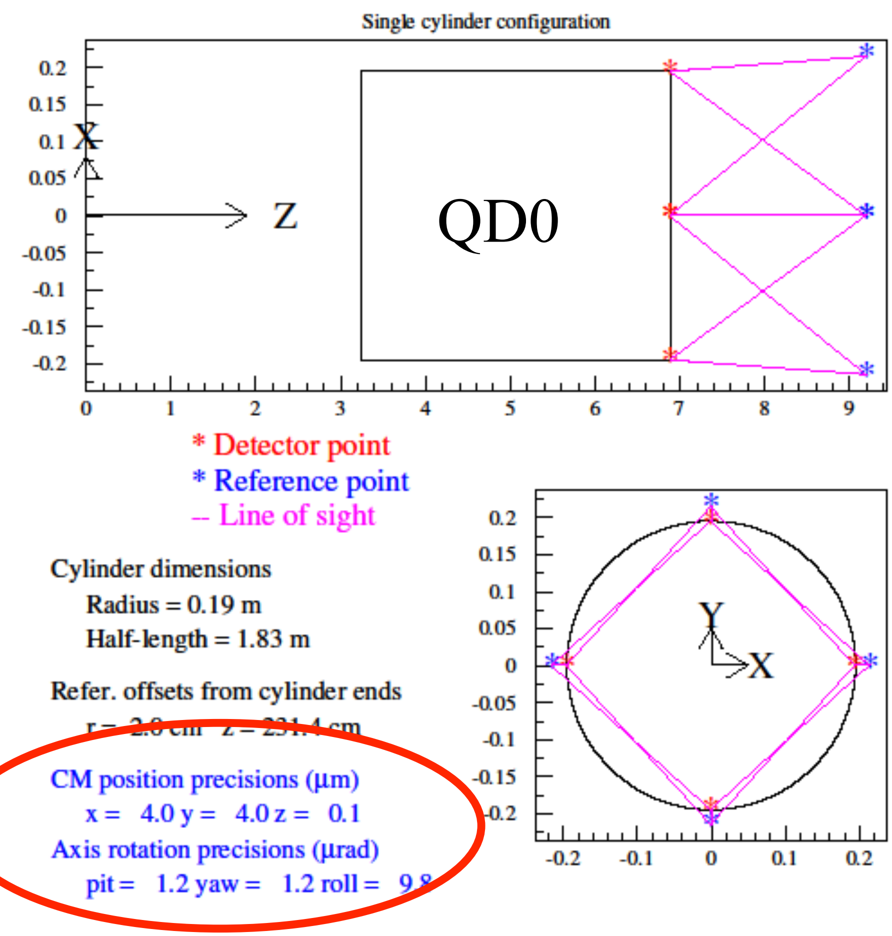
First Simulations

12 lines:

- N=4
- Option C
- Back end only

But can we really align from one end only?

Prudent to monitor other end too…



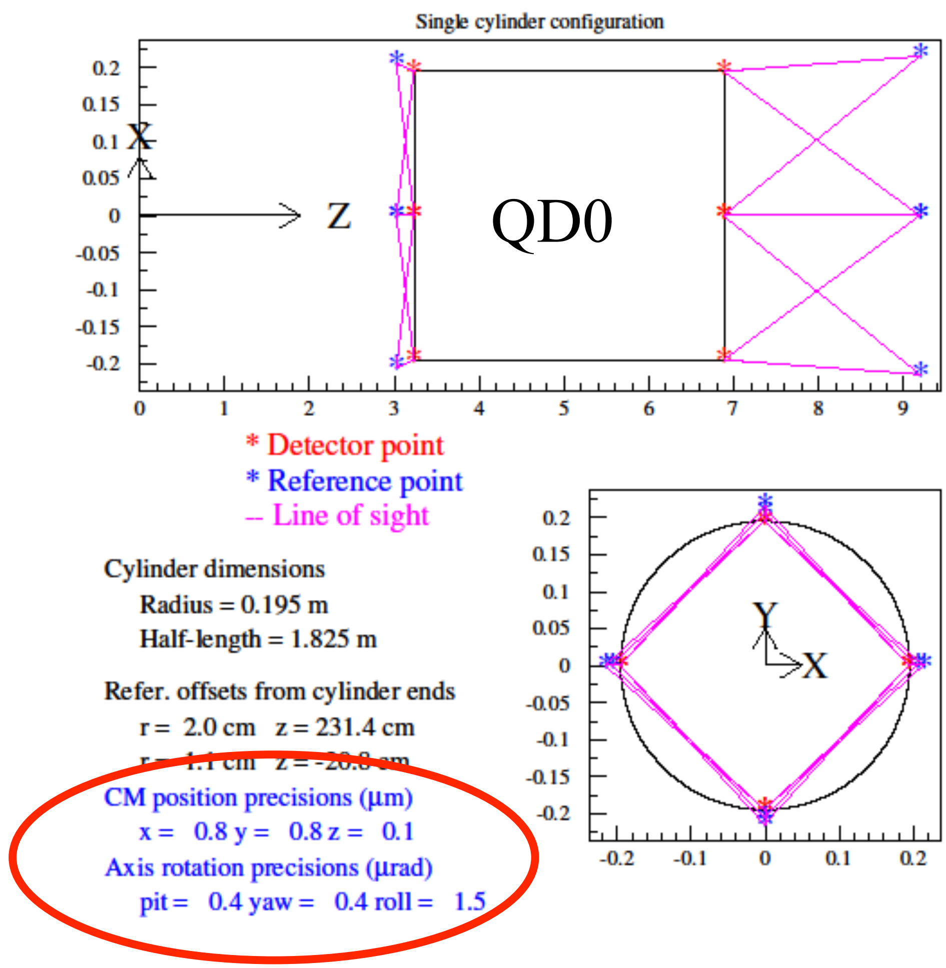
All tolerances met

First Simulations

24 lines:

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

Now back off to Option B…

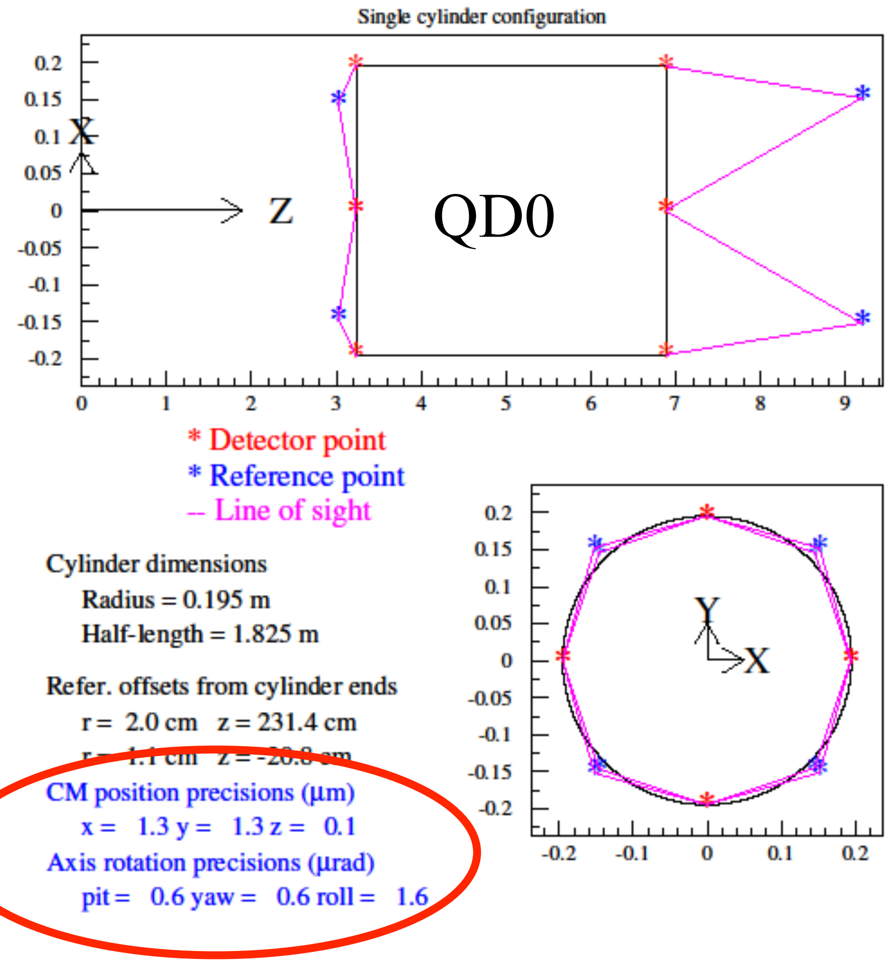


All tolerances met

First Simulations

16 lines:

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

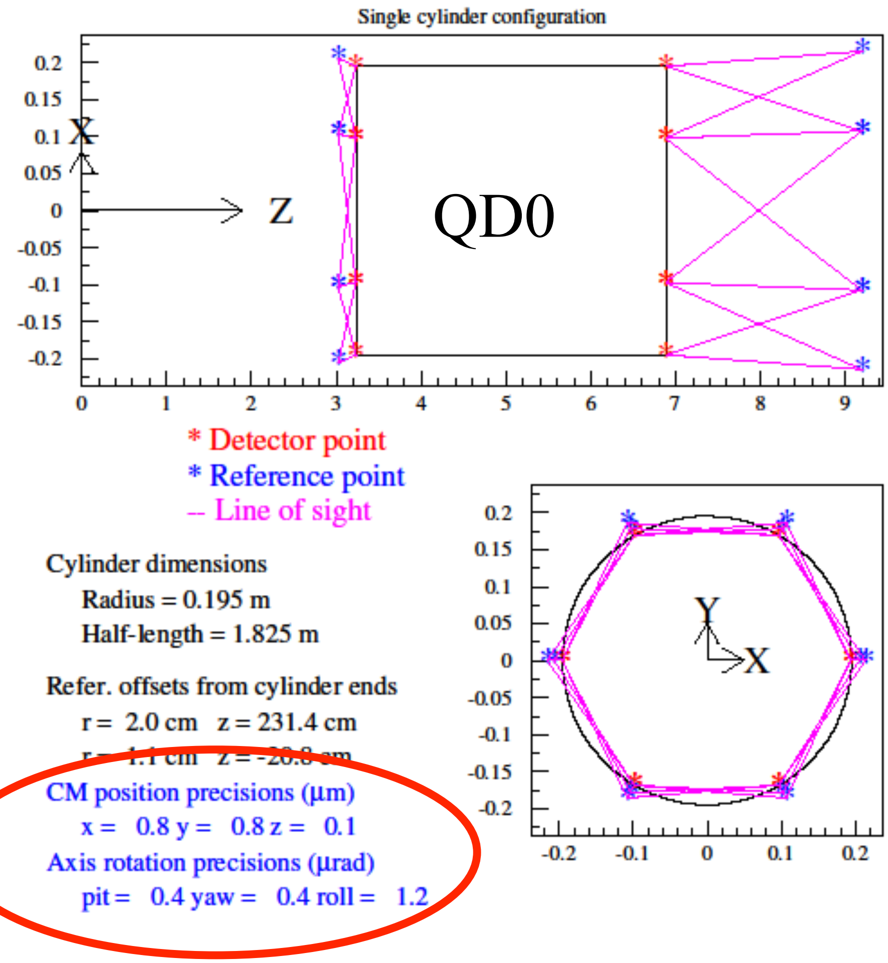


All tolerances met

First Simulations

Deluxe (36 lines):

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



All tolerances met

First Simulations

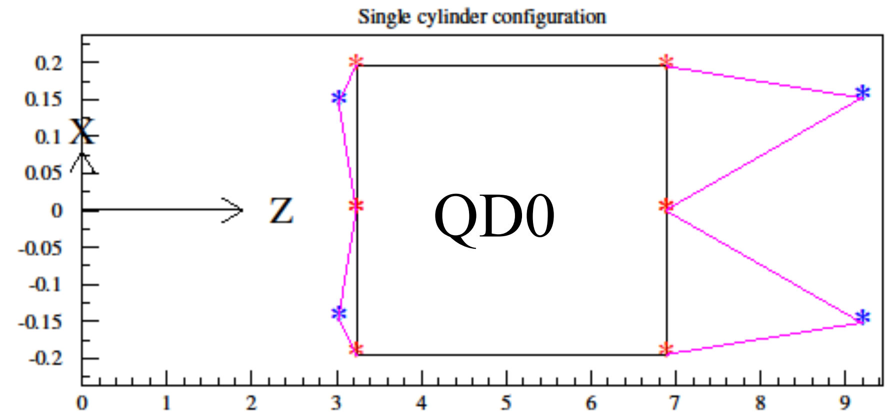
Conclusion:

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



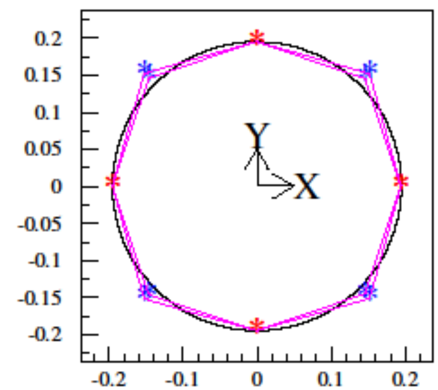
* Detector point
* Reference point
-- Line of sight

Cylinder dimensions
Radius = 0.195 m
Half-length = 1.825 m

Refer. offsets from cylinder ends
r = 2.0 cm z = 231.4 cm
r = 1.1 cm z = -20.8 cm

CM position precisions (μm)
x = 1.3 y = 1.3 z = 0.1

Axis rotation precisions (μrad)
pit = 0.6 yaw = 0.6 roll = 1.6



Caveats:

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