SiD Answers to IDAG Tracker Alignment Questions

(June 6, 2009 Draft)

Questions:

- What is your plan for aligning your tracking systems?
- What is the precision required?
- Are there special operations needed for alignment after push-pull prior to data taking, and what time is required?
- How many degrees of freedom need to be considered after a move?
- How do the alignment needs affect the design of your detector?
- Is any real-time monitoring of the tracker alignment envisioned (e.g., related to power pulsing and long term stability?

Responses:

Q1: What is your plan for aligning your tracking systems?

Overall strategy:

The alignment strategy for the SiD outer tracker, vertex detector, and beam-pipe assemblies is based on 1) a small number of robust, rigid elements; 2) precise positioning of smaller components during fabrication and assembly; 3) real-time monitoring of alignment changes, including during push-pull moves; and 4) track-based alignment for final precision. Because alignment at the level of O(few μm) is important to exploiting the intrinsic resolution of the SiD tracking system, determining alignment from several methods with different systematic errors is a prudent strategy. Below we describe the several planned methods that should give us confidence that we understand the detector's alignment to the required precision. But in brief, we expect to achieve ~20 μm relative precision among outer tracker sensor modules in different layers after fabrication and assembly in the full detector. The final precision of a few μm is attained for individual sensor modules from track-based alignment, with real-time FSI and laser-track monitoring providing both a hierarchical bridge from the coarse to the fine alignment and a set of global corrections for time dependent structure motion and deformation.

The first time this full alignment is attempted, we will likely need O(weeks) of collider data to achieve the intrinsic alignment precision, but subsequent full-up alignments following push-pull operations should proceed rapidly, using the FSI and laser-track systems, since the stability of sensor relative positions is expected to be better than the measurement precision of these alignment systems. In other words, a large number of detected tracks will be essential to initial tracker alignment, but will merely provide a cross-check for subsequent alignments. Design luminosity at a center-of-mass energy of 500 Gev (or even an order of magnitude lower luminosity) should nonetheless be adequate for determining alignment. Dedicated running on the Z pole would be useful, but is not thought to be essential for successful tracker alignment.

Fabrication and assembly

Tracker alignment begins during tracker fabrication and assembly. Sensor alignment within each outer tracker module will be measured with respect to fiducials and mounting features of the module. Modules will be solidly anchored with stable relative position to stiff support cylinders and support disks, which are based upon carbon fiber laminate material. That material provides good thermal stability and should give a rigidity for the SiD tracker that is ~50 times higher than that of the CMS tracker. Predicted deflections of the support structures under gravity are small: $< 10\ \mu m$. Modules will be installed in groups with internal alignment of a group controlled to ~ 10 µm. Reference features on each barrel and disk will allow the positions of each group of modules to be known with respect to the reference features to ~ 10 µm. Hence position and orientation of a given sensor should be known to approximately $(10\ \mu m) * 3^{0.5} = 17\ \mu m$. A large coordinate measuring machine or equivalent laser-based equipment will be needed to achieve this accuracy. Frequency scanned laser interferometry during assembly offers the potential for still better knowledge of alignment than the values above. In the end, knowledge of alignment is more important than precision positioning.

We plan to use ball and cone mounts to mate barrels and disks with one another. That type of mount provides a reproducibility of ~ 3 µm. Again, a large CMM or laser-based equipment will be used to measure reference features on each object. Precision should be ~ 10 µm, which implies the precision to which individual sensors are known to ~ 20 µm, although individual groups of sensors will be known relative to one another with slightly better precision.

Within the detector, kinematic mounts will be used to support the outermost tracker barrel from the interior of ECAL. Support via kinematic mounts from some other portion of the detector has also been considered. All other outer tracker elements are supported either directly or indirectly from the outermost barrel. If the kinematic mounts are done correctly, push-pull operations may affect absolute position of the tracker, but should not affect tracker internal alignment.

The vertex detector is supported independently of the outer tracker. Outer support half-cylinders locate all vertex detector elements relative to one another. Relative alignment of elements within either top or bottom support cylinder is likely to be better than half-cylinder to half-cylinder alignment. That suggests the two half-cylinders and detector elements they support may need to be treated as independent objects.

Then the tracker would be treated as three pieces: the outer tracker (including all barrel layers and disks), the upper half of the vertex detector, and the lower half of the vertex detector. Within each of these we would hope to provide support which ensures good internal alignment. Alignment of the three pieces relative to one another will be monitored via frequency scanned interferometry (FSI). A combination of frequency scanned interferometry and “laser-track” monitoring of relative sensor positions will monitor internal alignment of the outer tracker. That type of monitoring may not be feasible for internal alignment of the two vertex detector halves due to constraints on the material budget.

After assembly, during data taking, and during push-pull operations, the FSI system will be run nearly continuously, providing ``real time'' measurement of global tracker distortions and of vibration amplitudes and frequencies (up to the Nyquist frequency – O(kHz) of the FSI DAQ sampling).

A deformation monitoring system based on optical fiber sensing techniques is also under consideration. Strain Optical Fiber Sensors (OFS) would be embedded in the carbon fiber supporting structures or/and sensor modules. The OFS would provide real-time strain information during the production, assembly, operation and push-pull operation of the instrumented tracker structures. From a detector integration point of view, using this kind of distributed monitoring requires only the embedding of 120-um diameter optical fibers in the carbon fiber composite; this means that it can be also considered as a suitable technology for the vertex detector.

Frequency scanned interferometry

The FSI system incorporates multiple interferometers fed by optical fibers from the same laser sources, where the laser frequency is scanned and fringes counted, to obtain a set of absolute lengths. This alignment method was pioneered by the Oxford group on the ATLAS Experiment. By defining O(100’s) ``lines of sight'' in the tracker system for absolute distance measurements, we will overconstrain the locations of fiducial points in space, allowing global distortions of the carbon-fiber support structure layers (translation, rotation, twist, bending, stretching, etc.) to be determined to the required precision. Figure 1 shows an extreme example with many lines of sight for one barrel layer from a study done some years ago on an SiD precursor design. The real-time FSI measurements should allow for relevant time-dependent corrections to be applied when carrying out the final step of track-based alignment of individual silicon modules.

With a test apparatus, the state of the art in precision DC distance measurements over distance scales of a meter under laboratory-controlled conditions has been reached and extended. Precisions better than 100 nm have been attained using a single tunable laser when environmental conditions are carefully controlled. Precisions under uncontrolled conditions (e.g., air currents, temperature fluctuations) were, however, an order of magnitude worse with the single laser measurements.

Hence a dual-laser FSI system is foreseen for the tracker, one that employs optical choppers to alternate the beams introduced to the interferometer by the optical fibers. By using lasers that scan over the same wavelength range but in opposite directions during the same short time interval, major systematic uncertainties can be eliminated. Bench tests have achieved a precision of 200 nm under highly unfavorable conditions using the dual-laser scanning technique. Figure 2 shows an example of dual-laser fringes measured on a benchtop single-channel prototype system.

It should be noted that complementary analysis techniques of FSI data can be used either to minimize sensitivity to vibrations in order to determine accurate mean shape distortion or to maximize sensitivity to vibrations below the Nyquist frequency O(kHz) of data sampling, for the same data set. In particular, vibrations due to pulsed operation can be investigated, as discussed below in the response to question 6.

Laser-track method

A separate real-time alignment method with different systematic uncertainties will be provided by a "laser-track" system in which selected sensor modules are penetrated by laser beams to mimic infinite-momentum tracks. This method exploits the fact that silicon sensors have a weak absorption of infrared (IR) light. Consecutive layers of silicon sensors are traversed by IR laser beams, as indicated in Figure 3. Then the same sophisticated alignment algorithms as employed for track alignment with real particles can be applied with arbitrarily high statistics to achieve relative alignment between modules to better than a few microns. This method employs the tracking sensors themselves, with only a minor modifcation to make them highly transparent to infrared light. The modification to a tracking sensor is minimal. Only the aluminum metalization on the back of the sensor needs to be swept away in a circular window with a diameter of few millimeters to allow the IR beam to pass through. Since IR light produces a measurable signal in the silicon bulk, there is no need for any extra readout electronics. This alignment method has been implemented by both the AMS and CMS Experiments.

A key parameter to understand the ultimate resolution of this method is the transmittance of a silicon sensor and the diffraction of the light. As a first approximation a silicon sensor is viewed as a stack of perfectly homogeneous plano-parallel layers, each characterized by its index of refraction and thickness. The layers are, however, not continuous, but present local features, so that diffraction phenomena will appear if the size of the obstacle is comparable to the wavelength used. For instance, the strips of the detector, pitched every 10 to 50 μm are good examples of an optical diffraction grating for an incoming beam in the IR. It has been determined that a key parameter determining the overall transmittance of a microstrip detector is the pitch to strip ratio, that is, the fraction of the strip covered by aluminum. The smaller the strip width, the more light is transmitted. It was determined that good transmittance was achieved when the strip width was set to 10% of the pitch. Tuning of sensor thickness was found to contribute up to 5% over the layout optimized value. In bench tests, based on CMS strip detectors, a relative alignment of a few microns has been achieved.

Optical Fiber Sensor deformation monitor

The sensing element of the OFS monitor is a Fiber Bragg Gratting (FBG) sensor operated as an optical strain gauge. FBG sensors have many enhanced features with respect to traditional electrical strain gauges: no need for power or readout cabling, long term stability, immunity to electromagnetic fields, high voltage, extreme temperature and radiation resistant. Concerning its application in tracker systems, one of the most important properties is its light weight since the actual FBG is “written” in a few millimeters section of an optical fiber with a 125 μm diameter. Multiplexing capabilities having many distributed FBG sensors on the same optical fiber are available; this technology also allows for long-range sensing, placing the read-out unit well outside of the detector.

The FBG sensor would be embedded in the carbon fiber structures supporting the modules and the module mechanics itself. The system is expected to reach local deformation sensitivities better than 1 μstrain. The OFS monitor will provide a very fast feedback on full structure deformations during the push-pull operations.

Track-based alignment

The final alignment of individual sensor modules will be track-based, using accumulated statistics from many detected tracks and constrained fitting to determine local position and orientation corrections for that module. (The time to accumulate sufficient statistics for alignment of each individual module is expected, however, to be long enough to require continuous monitoring of global structure motions and deformations via the FSI and laser-track systems and to warrant robust, stable mechanical structures, as discussed above.) Although six parameters are needed, in principle, to describe a rigid module's position and orientation, the most critical parameter by far for microstrip planes is the offset of the module from nominal along the direction normal to the microstrips and in the module plane, since this is the coordinate measured most precisely by the strips. Expected translations in the orthogonal directions should have a negligible effect on track. Rotations of module planes about their normals and about an axis parallel to the strips can lead to small biases in coordinate reconstruction, while rotation about an axis in the module plane and perpendicular to the strips should have negligible effects.

Determining these translations and rotations from minimizing residuals in fitted tracks requires adequate statistics for each module. To determine systematic offsets in the measured coordinate to a precision that is an order of magnitude smaller than the hit resolution requires O(100) tracks per module (assuming systematic variations in hit reconstruction for different strips in the same module are negligible). A study presented at the LCWS2006 suggests that at ILC design luminosity, the sensor modules receiving the least number of tracks [$\cos(\theta) = 0$, outer barrel layer] will be penetrated by $O(10^4)$ tracks per month, making track-based alignment feasible for each separate data-taking epoch between push-pull moves. The fact that a large number of tracks produced will be back-to-back in the x-y plane with approximately equal p_t values should enable more powerful constrained-fit determination of module offsets.

Q2: What is the precision required?

Benchmarking studies, which have been given high priority, have typically assumed perfect detector alignment. Simulation studies to answer this question thoroughly remain to be completed, but studies to date indicate we should aim for 3 μm or better on outer tracker transverse coordinate offsets (barrels and disks) for an assumed hit precision of 7 μm. The answers we can provide now regard the alignment precision which would result in negligible decreases in the extremely good resolution silicon can provide. We expect actual requirements based upon simulation results to be looser.

Vertex detector alignment is further demanding, given expected single hit resolutions for two coordinates of ~3 μm. A coordinate measuring machine can provide a discrete precision per coordinate of ±2 μm, which corresponds to a sigma of 1.15 μm, but monitoring stability of alignment will be critical, both internally via tracks and with respect to the outer tracker via the FSI system. We will aim for 1 μm relative alignment precision for coordinates transverse to tracks.

Q3: Are there special operations needed for alignment after push-pull prior to data taking, and what time is required?

During detector moves, alignment of the beam pipe, the ends of the outer tracker, and beam monitoring calorimetry will be monitored nearly continuously relative to the central calorimeter via frequency scanned interferometry. At the end of motion, alignment of the beam pipe, beam monitoring calorimetry, and final quads will be adjusted relative to the outer tracker and central calorimeter. The vertex detector is mounted from the beam pipe and follows its motion. That process should take less than two hours. No adjustments to the position of the outer tracker are anticipated. Tune-up of beam position will be performed at low intensity while monitoring vertex detector and outer tracker backgrounds. The time required depends upon accelerator procedures.

During each move the FSI system will be operational and taking data continuously. Alarms will be set for any motion measured outside of what is expected. Consequently, electrical power will need to be maintained continuously for the laser system, and the optical bench will need to move with the detector. In addition, we envision embedding optical fiber sensor (OFS) in the carbon fiber support structure to measure the deformation of the structure during the move. The OFS system will allow to monitor possible fast vibrations during the push&pull procedure, thanks to its large response bandwith. Again, alarms would be set for measured values outside the expected range.

After the push&pull move, the detector position as a whole will be determined with respect to a fixed external reference frame (like cavern walls) using survey techniques like large scale photogrametry. This is the current procedure followed by the CMS detector before and after the opening of its wheels.

Q4: How many degrees of freedom need to be considered after a move?

Precise answers to this question depend upon R&D on outer tracker, vertex detector, beam pipe, forward calorimetry, and final quad support structures. They also depend upon R&D on cabling, readout fiber optics, pulsed power, and gas cooling. Most of that R&D remains to be done. Answers which follow are best guesses based upon limited information.

Six fundamental rigid-body degrees of freedom are anticipated for outer tracker alignment after a move: two transverse positions per end, an azimuth, and a z-position. Measurement data will be collected to monitor additional degrees of freedom corresponding to shape distortions expected to be quite small (twist, bending, stretching), and to monitor long- and short-term instabilities of the rigid-body degrees of freedom.

Twelve degrees of freedom are anticipated for vertex detector alignment after a move: two transverse positions per barrel end, two transverse positions per support cylinder end, one azimuth per support cylinder end, and one z-position per support cylinder end. An additional four degrees of freedom (two transverse positions of the beam pipe near each LumiCal) will be considered in estimates of support structure distortions.

Q5: How do the alignment needs affect the design of your detector?

Support structures have been designed to minimize distortions and maintain alignment. In the outer tracker, the structure with double-walled support cylinders, concave disk support structures, and nested assembly with annular rings and kinematic mounts is intended to lead to a robust structure which can be treated as a single unit. Kinematic support from the central calorimetry is intended to minimize distortions of that structure under geometry changes of the calorimeters. R&D on prototypes remains to be done, but should allow us to verify that performance is as intended. Tracker sensor modules slightly overlap within layers (and hence are tilted), which provides valuable linking together of sensors within layers for track-based alignment.

In the vertex detector, double-walled support half cylinders are intended to preserve good internal alignment of the entire vertex detector. Since the support structures deflect under beam pipe loads, substantial R&D including measurements of prototypes will be necessary to confirm that the design works well.

Optical fibers will need to be routed carefully into the tracking region for both FSI, laser-track, and OFS systems. The FSI system will require small retroreflectors be mounted on the carbon-fiber support structure, with some retroreflectors residing in the fiducial tracking volume, including on the vertex detector support cylinder. Minimizing material burden will be important. R&D is underway to fabricate lighter retroflectors than the aluminum pellets used in the ATLAS FSI alignment system.

The laser-track method will have an almost negligible contribution to material budget. Laser fiber plus collimators will be placed outside the tracking volume. Alignment sensors for the laser-tracker will have a 1 cm diameter hole in the backside metalization but this will not affect the normal functioning of the detector. Indeed, the extension of the back-metalization does not affect the electrical behaviour of the detector. On the other hand, the OFS system will not increase the material budget contribution. The optical fibers for the sensors are embedded in the carbon fiber structures. Furthermore, they will replace copper lines in the DCS system. As a byproduct, EM noise susceptibility will decrease thanks to this change.

Q6: Is any real-time monitoring of the tracker alignment envisioned (e.g., related to power pulsing and long term stability)?

Outer tracker alignment will be continuously monitored by frequency scanned interferometry, both during data taking and during push-pull moves.

At least six types of measurements are anticipated:

- Transverse and longitudinal positions of the ends of each outer tracker barrel layer at approximately eight azimuths
- Transverse positions of each barrel layer for at least eight azimuths and additional z-locations along the layer
- Overall length of each barrel layer for at least eight azimuths
- Transverse and longitudinal positions of each disk near its outer periphery for at at least eight azimuths
- Beam pipe transverse positions just inboard of each LumiCal location
- Transverse and longitudinal positions of each vertex detector support cylinder at each end (approximately four azimuths).

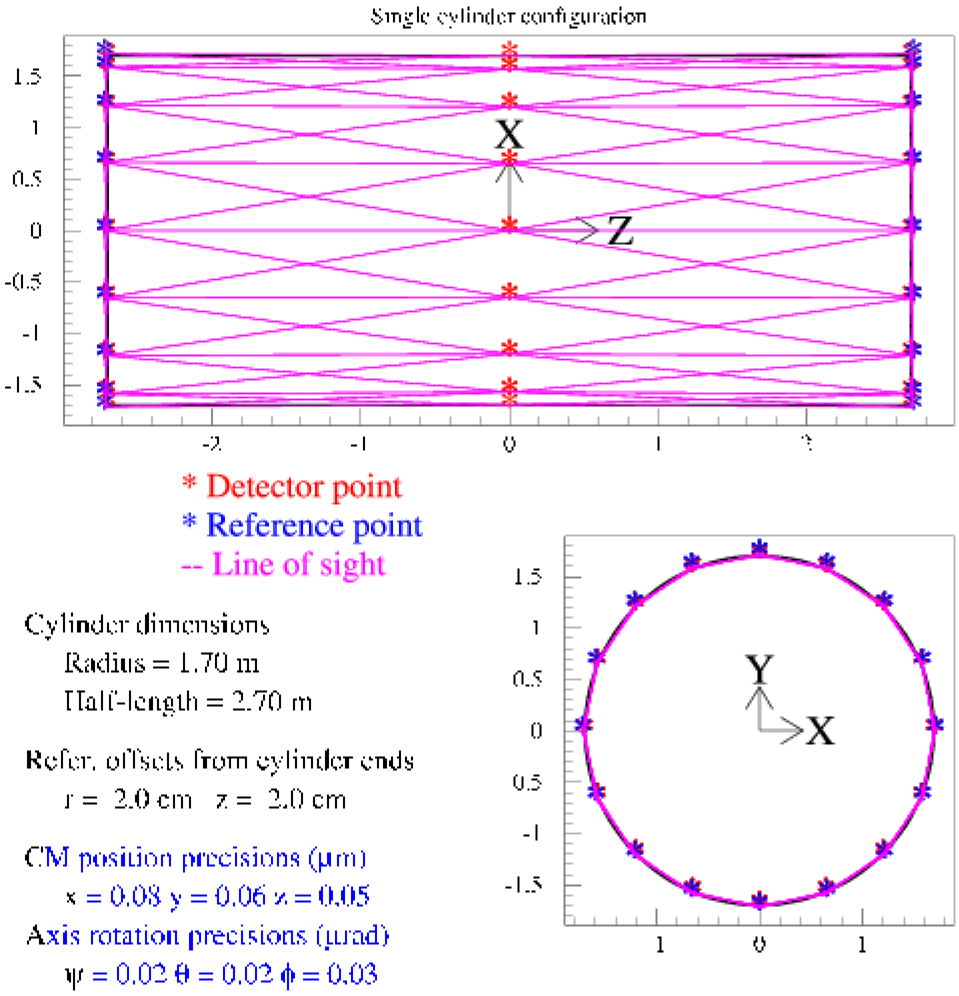
In addition, laser-track monitoring sensible to movements with a time scale of seconds is planned for a subset of the sensor modules. This will allow a quick observation of relative movements between different support structures (barrel layers and disks). Its optimal layout will depend on the modularity of the support structure. An all silicon outer tracker makes integration of a laser-track system very easy. However the layout of the laser-track must try to strengthen those weak modes that affect particle track alignment. The optimal layout is under study at this moment.

The OFS deformation monitoring system can be also operated continuously. Commercial systems achieve a bandwidth higher than 1 MHz. Both the FSI and OFS systems will be valuable in monitoring possible vibrations from pulsed power operations described below.

In a 5 T solenoidal field, forces and torques acting on radial runs of power delivery cabling can be significant. Moreover, at the ILC the power is assumed to be delivered with a frequency matching the 5 Hz duty cycle of the machine. This interplay of the magnetic field with the cyclic delivery of power can result in vibrations which are transmitted from the cables into sensors and their support structures. These vibrations can be mitigated by delivering the power on flat-lines with three conductor layers. The central layer, for example, would serve to supply power and the two outer layers would serve as power returns. To avoid ground currents and ensure that supply and return currents balance within a cable, some combination of isolation of power sources and isolation of sensor grounds is needed. Then, provided the two return currents of a cable are equal, net force and torque on the cable due to interaction of currents with the magnetic field would be zero. Power/ground isolation would also eliminate issues that arise when portions of the vertex detector are unpowered while other portions are powered..

The power distribution at sensor locations should be optimized. In the barrel, radial current runs within sensors are relatively short, thereby limiting forces and torques associated with the magnetic field. In the disks, care will need to be taken to avoid supply/return current loops within sensors. In both locations, limitation of support structure material lessens the ability of those structures to resist unexpected forces and torques. It is clear that careful design and testing will be necessary to minimize the effect of potential adverse effects of the pulsed power operation on the vertex detector and outer tracker.

In any case, the effects of power pulsing on the detector alignment should be easily monitored with both the FSI and OFS systems, given their high bandwidths and precisions.



Cylinder dimensions

Radius = 1.70 m

Half-length = 2.70 m

Refer. offsets from cylinder ends

r = 2.0 cm z = 2.0 cm

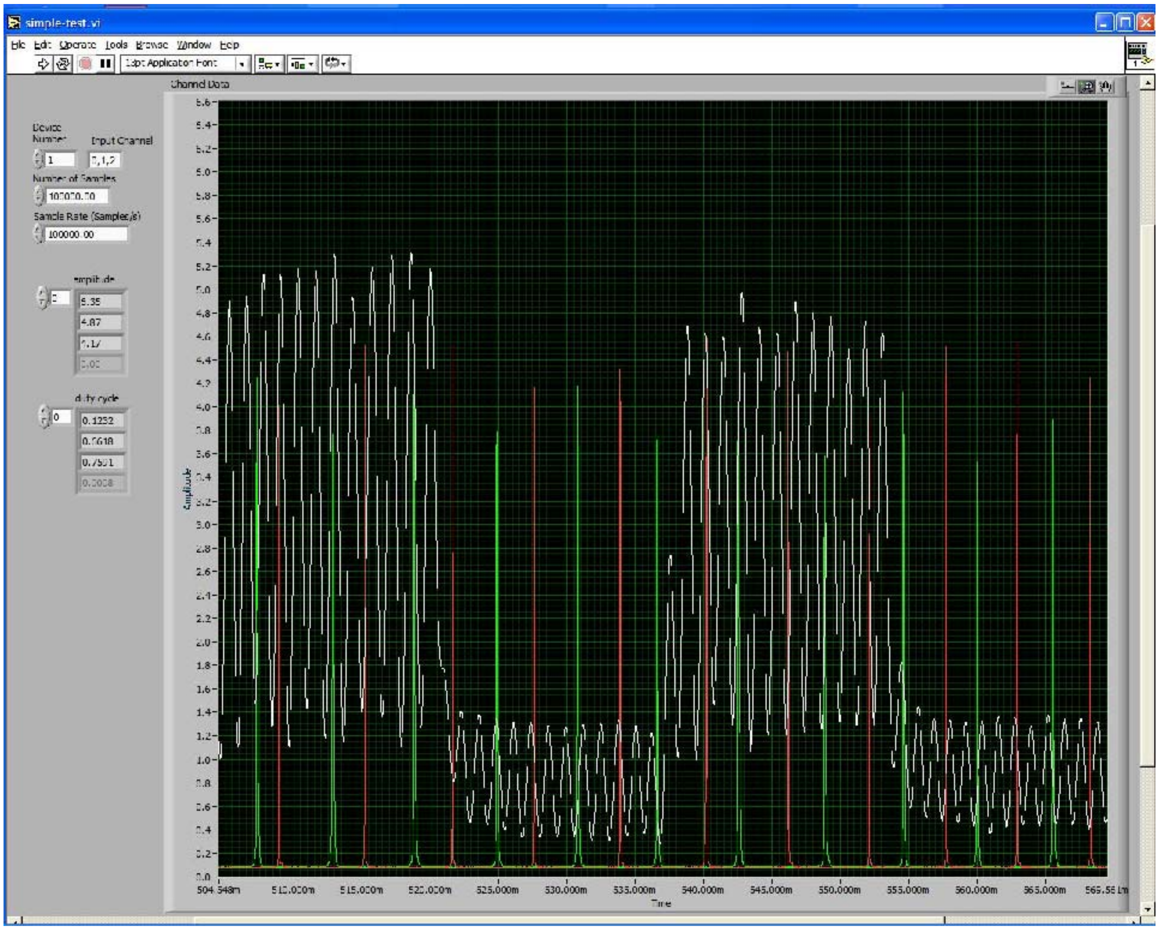
CM position precisions (μm)

x = 0.08 y = 0.06 z = 0.05

Axis rotation precisions (μrad)

$\psi = 0.02$ $\theta = 0.02$ $\phi = 0.03$

Figure 1: Example of lines of sight for one barrel layer, taken from a study of an SiD precursor design, along with achievable fitted precisions on center-of-mass offsets (μm) and pitch/yaw/roll rotations (μrad). This example is somewhat extreme (~100 lines of sight for a single layer) and permits greater positional and pointing precision than is needed.



Device Number: 1
Input Channel: 0,1,2
Number of Samples: 100000.00
Sample Rate (Samples/s): 100000.00

amplitude: 0
5.35
4.87
5.17
0.00

duty cycle: 0
0.1252
0.5618
0.7501
0.0008

Figure 2: Example of FSI fringe display for a single-channel dual-laser FSI system. White peaks indicate interference fringes, while red and green peaks are Fabry-Perot transmission maxima from a chopped, dual-laser system.}

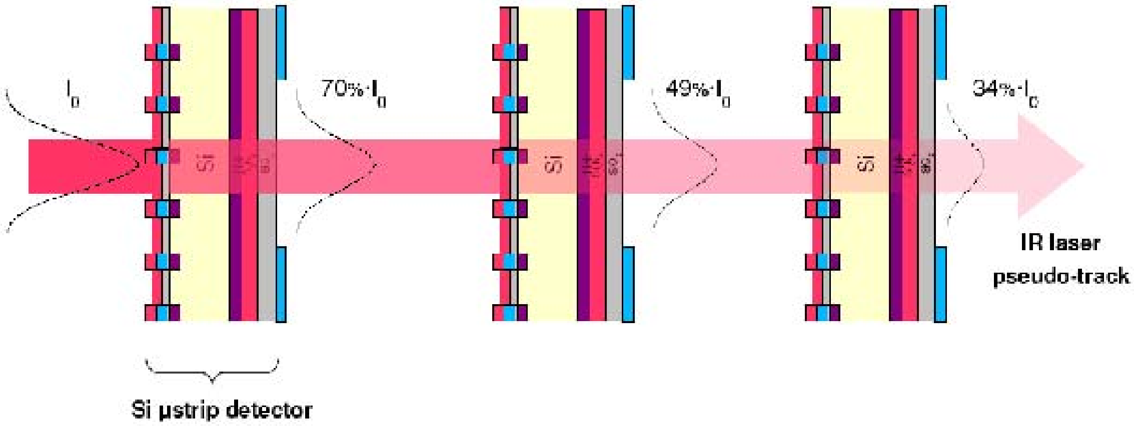


Figure 3: Sketch of the IR alignment method