High Precision Optical Instrumentation for Large Structure Position Monitoring: The BCAM System Applied to the CMS Magnet

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Talk:

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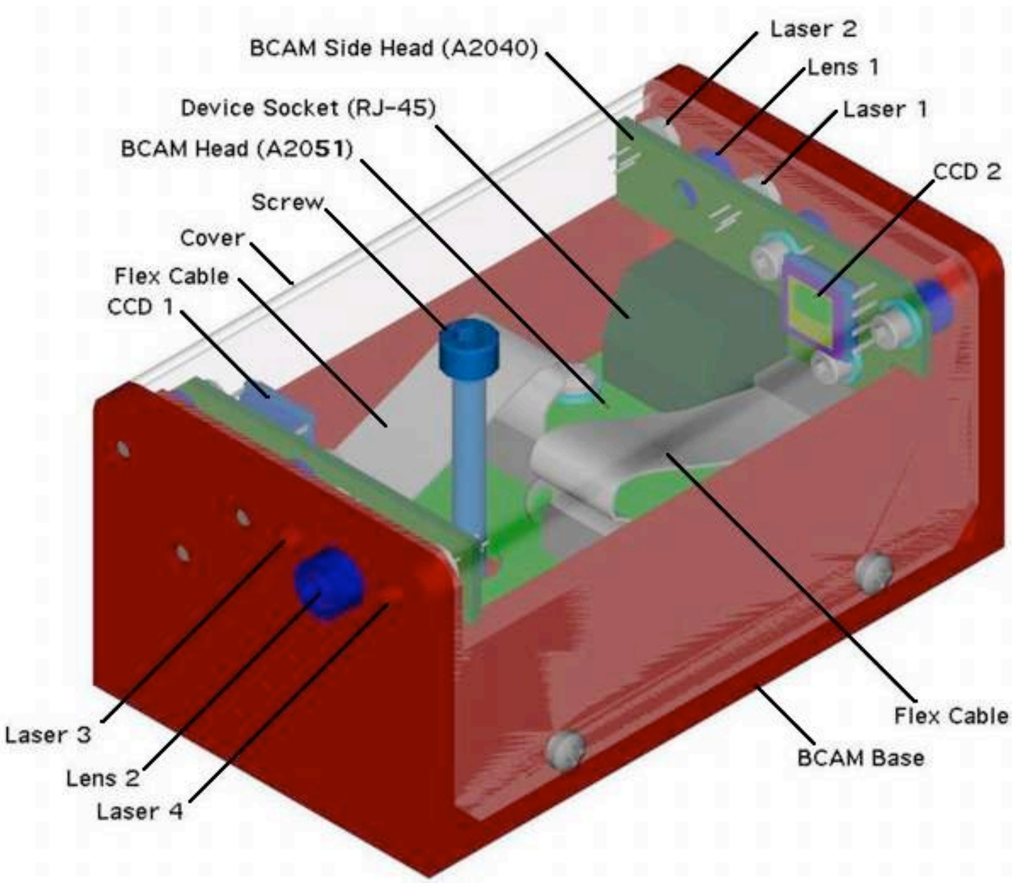
Contents

The BCAM

BCAM = Brandeis CCD Angle Monitor

Designed at Brandeis University for ATLAS End-Cap Muon Spectrometer.



Camera: lens, aperture, 75-mm light path, glass window, image sensor.

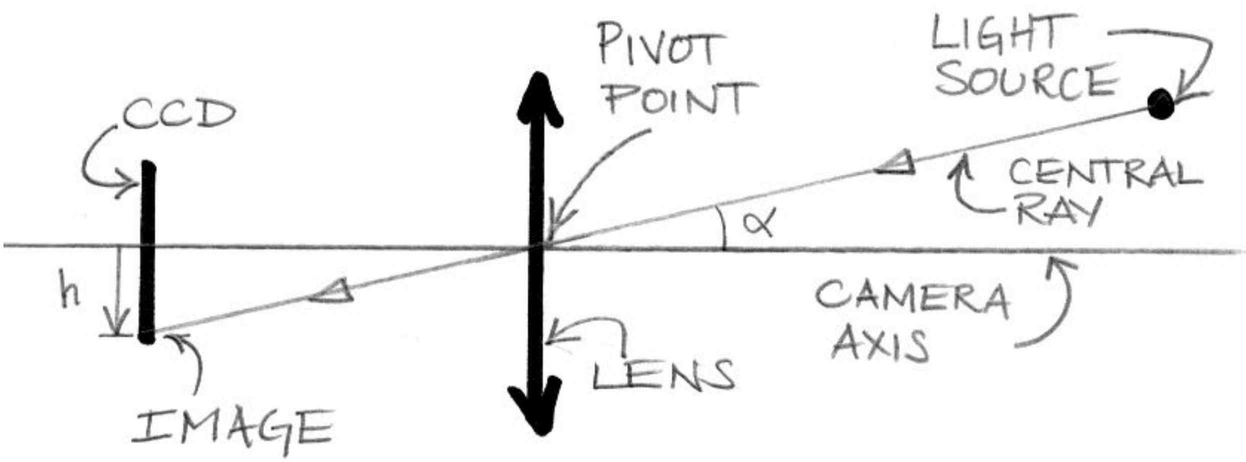
Sources: red laser diodes, thin glass window, no collimating lens.

Readout: LWDAQ hardware via Ethernet and TCP/IP.

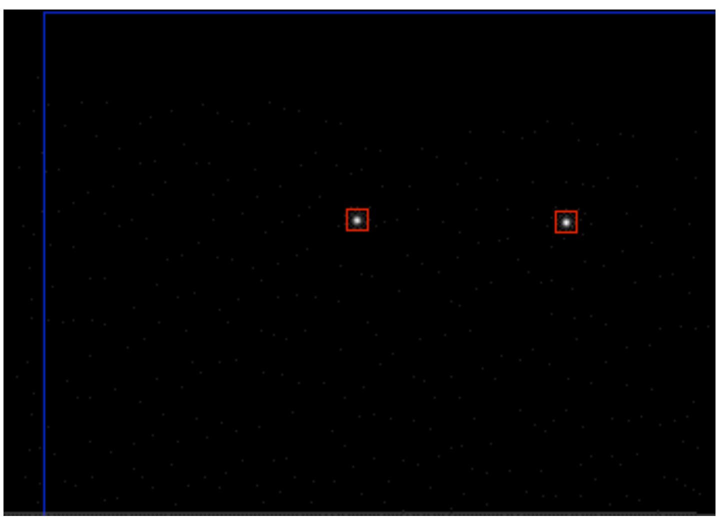
Analysis: LWDAQ software for Windows, Linux, and MacOS.

Camera and Source Models

Camera behaves like a thin-lens camera.



Sources behave like point sources.



Field of View: 40 mrad × 30 mrad

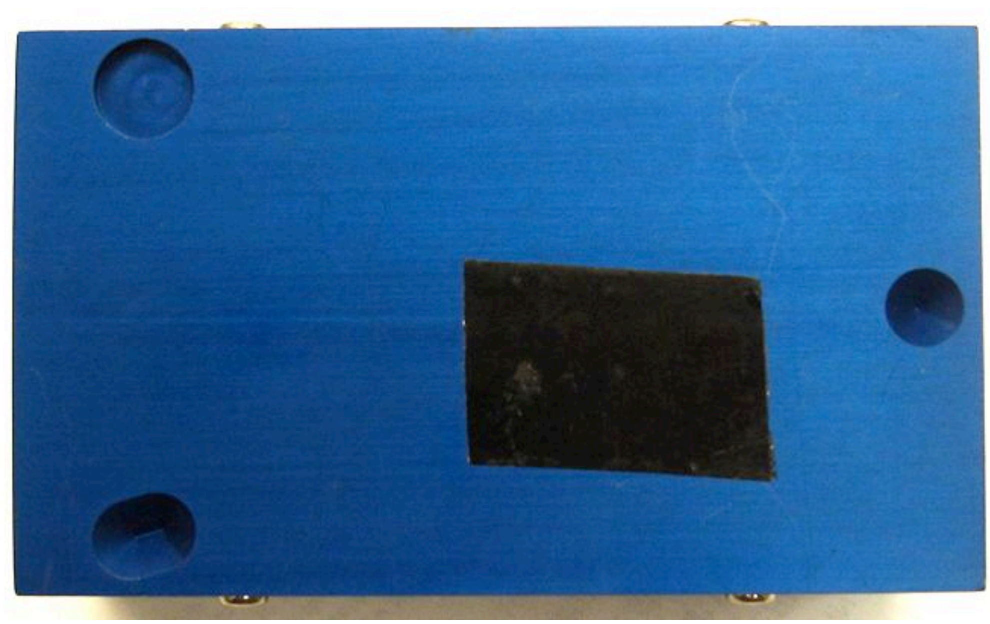
Relative Accuracy (across field of view): 5 μrad

Absolute Accuracy (with respect to mount): 50 μrad

Kinematic Mount

BCAM mounts kinematically on three steel balls.

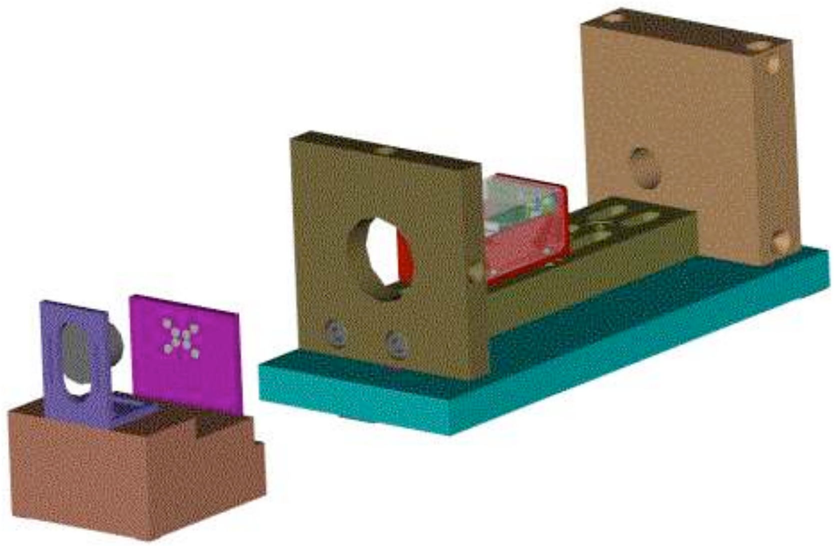
Fastened with a single screw through the chassis.



Coordinates of three balls define a *mount coordinate system*.

Calibration

Calibrate cameras and sources using a roll-cage and CMM.



1. Measure roll cage in four orientations with CMM.
2. Mount BCAM in roll cage.
3. Rotating BCAM camera views reference sources at ranges 1 m and 2 m.
4. Reference camera views rotating BCAM sources at range 1 m.

Determine camera parameters in mount coordinates:

1. pivot point location (3 parameters in mm)
2. axis direction (2 parameters in mrad)
3. image sensor to pivot point distance (1 parameter in mm)
4. image sensor rotation (1 parameter in mrad)

Determine source parameters in mount coordinates:

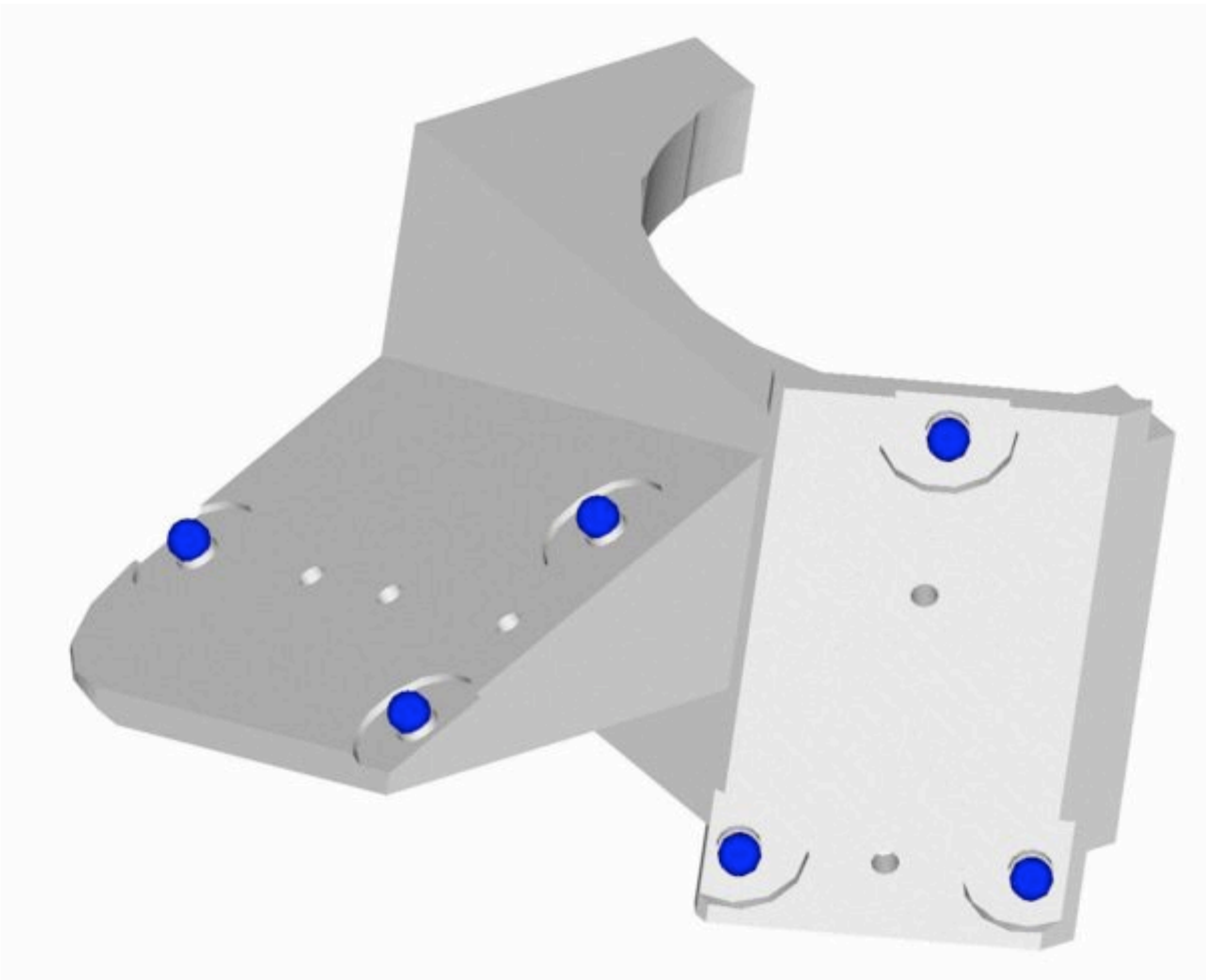
1. light source location (3 parameters in mm)

Mounting Plates

Two or more BCAMs share a *mounting plate*.

Reference balls on plate define its *plate coordinate system*.

Any rigid object with mounting balls acts as a mounting plate.



Measure plate with CMM to 2 µm.

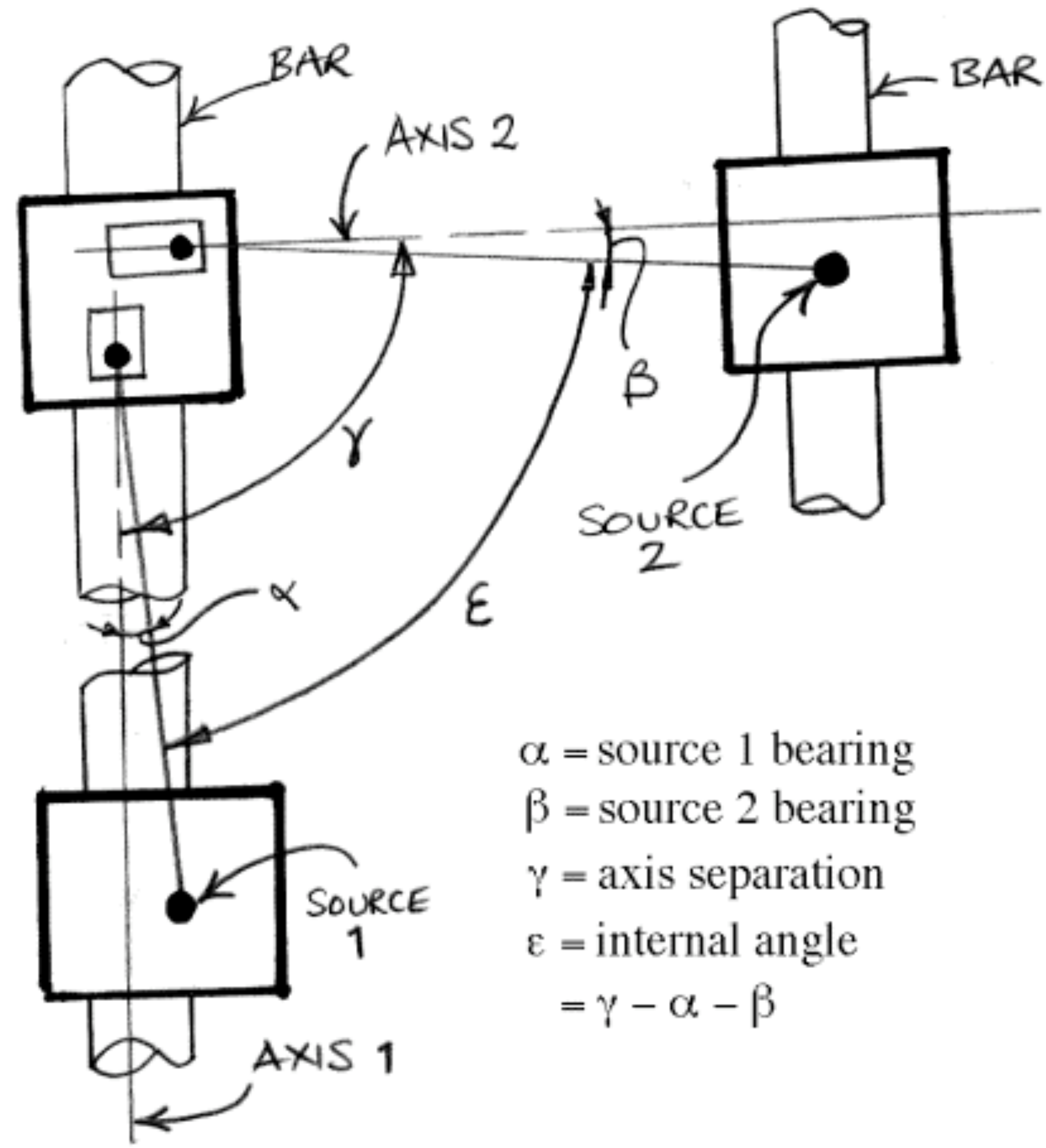
Relative orientations of mounts known to 30 µrad.

Large Angles

Cameras look at sources on other plates.

Cameras on each plate cooperate to measure large angles.

Large Angle Accuracy: relative 7 μrad, absolute 70 μrad.



α = source 1 bearing

β = source 2 bearing

γ = axis separation

ε = internal angle

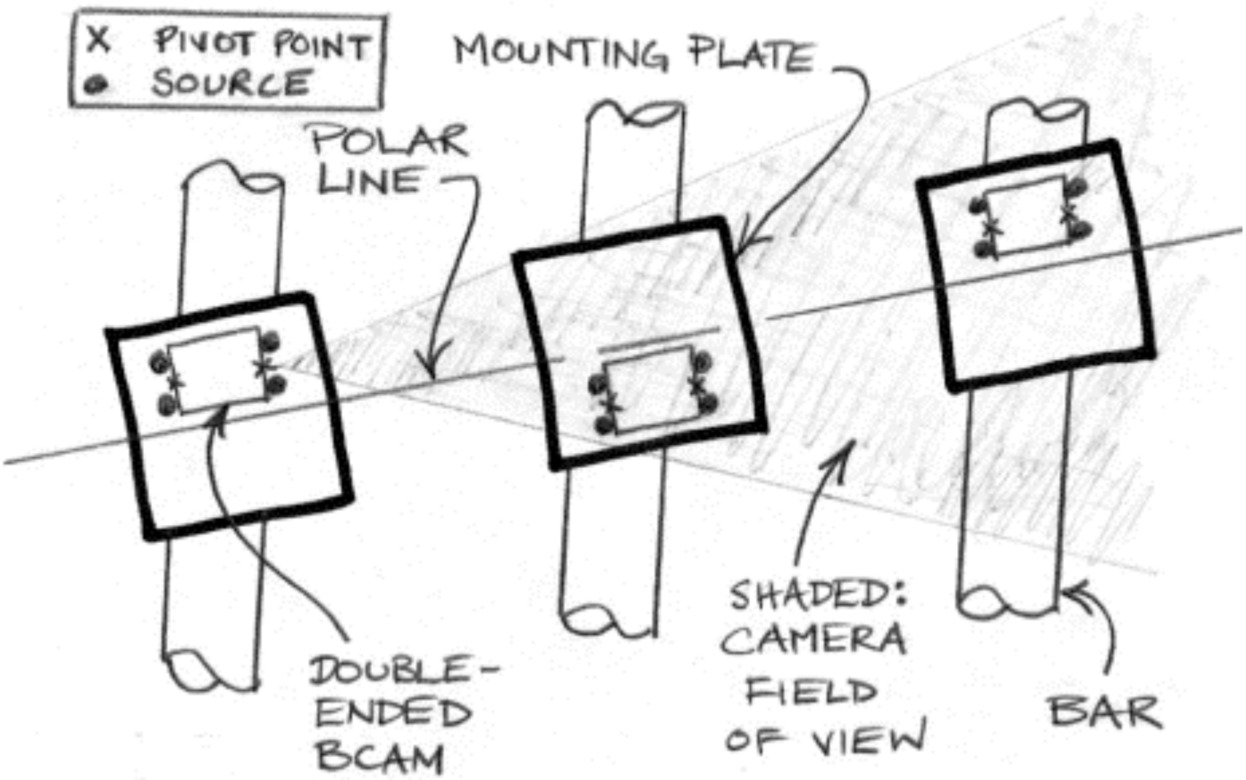
$= \gamma - \alpha - \beta$

Sagitta or Straightness

Cameras look up and down a corridor.

Each camera makes a sagitta measurement.

Sagitta Angle Accuracy: relative 7 μrad, absolute 7 μrad.



Geometric Reconstruction

Input:

1. Position of light spots on image sensors.
2. Camera calibration parameters.
3. Source calibration parameters.
4. Plate measurements.

We expect BCAM systems to produce twice as many measurements as necessary.

We determine geometry by steepest descent fitting.

We use ARAMyS, developed at CERN by Christoph Amelung.

Output:

1. Positions and orientations of plates.
2. Quality of each input parameter.

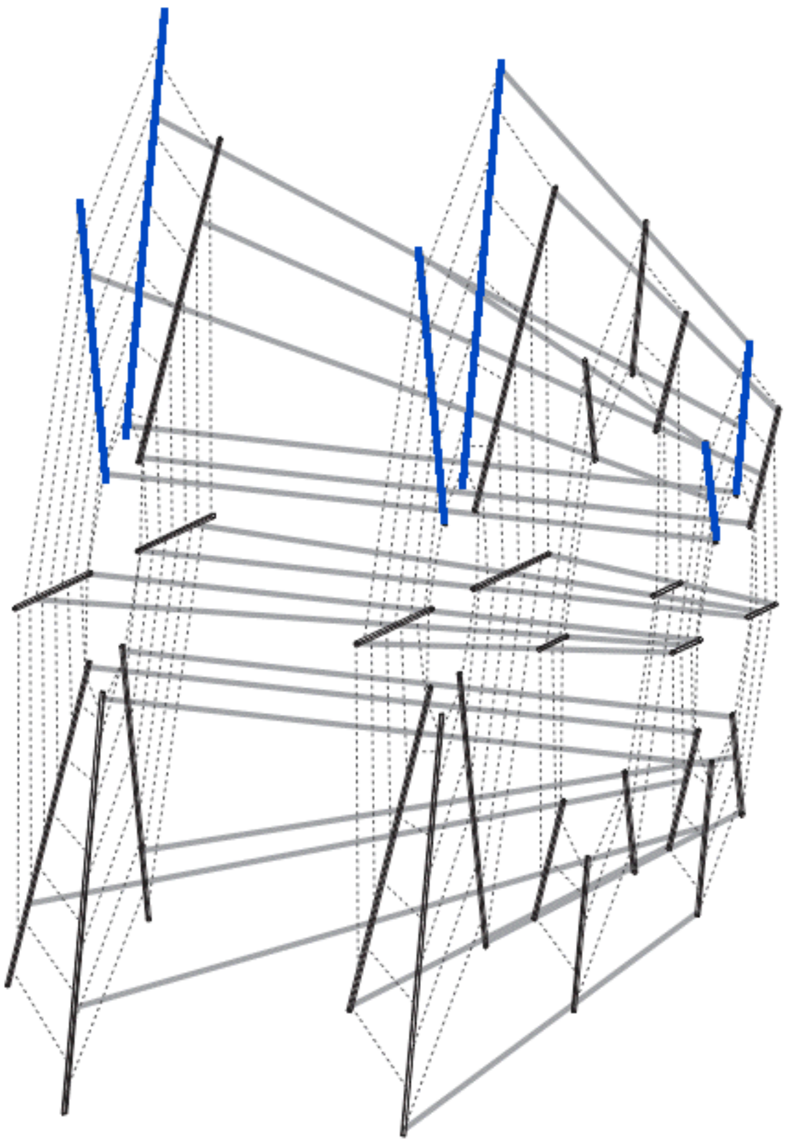
We reject measurements with extraordinary errors, and fit again.

ATLAS

Now building ATLAS End-Cap Alignment System.

Contains a grid of bars that hold BCAMs.

Longest camera-source range is 16 m, longest bar is 9 m.



Blue bars are those implemented in H8 Test Stand.

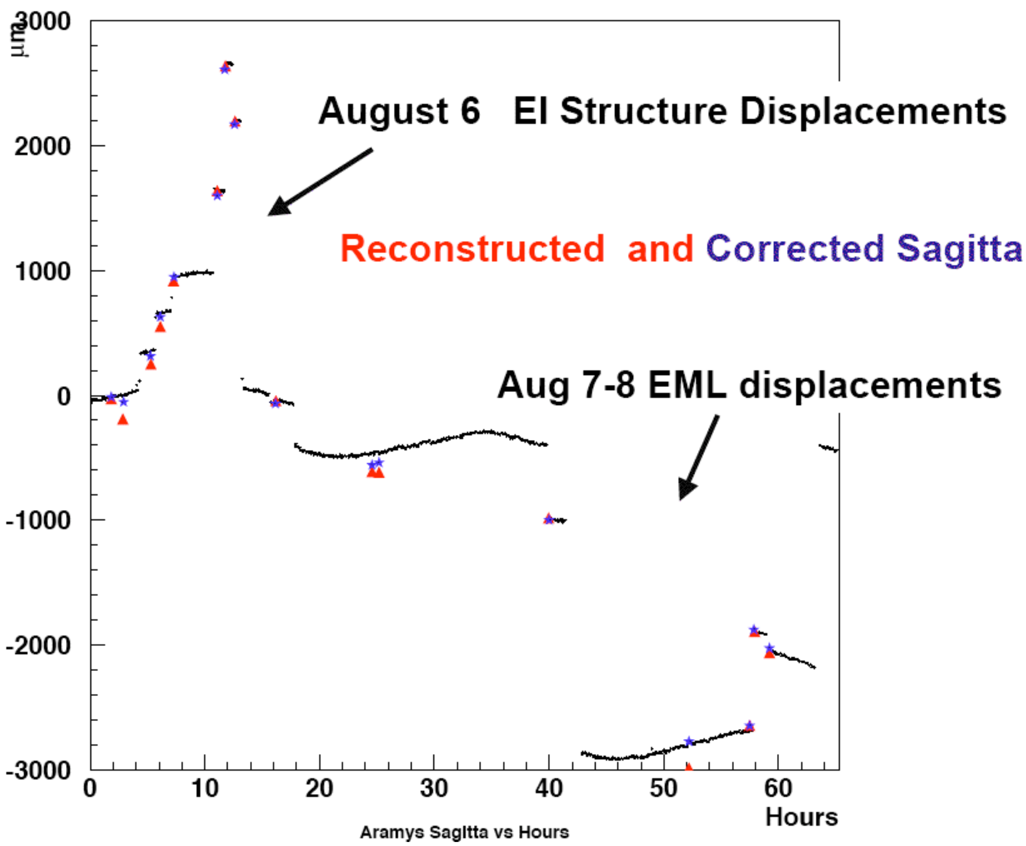
H8 Test Stand

Named after its location at CERN.

A full-size subset of ATLAS geometry in operation from 2001 to 2005.

Photogrammetry and particle beam verified BCAM performance.

Results reported in [Reference Bars for the Alignment of the ATLAS Muon Spectrometer]().



36 BCAMs installed, rejected measurements from 2 cameras.

Relative Accuracy: < 20 μm.

Absolute Accuracy: < 200 μm.

Retroreflectors

A BCAM will see its own sources reflected in a retroreflector.

A retroreflector costs about the same as a BCAM (≈$300).

Advantages of Retroreflector:

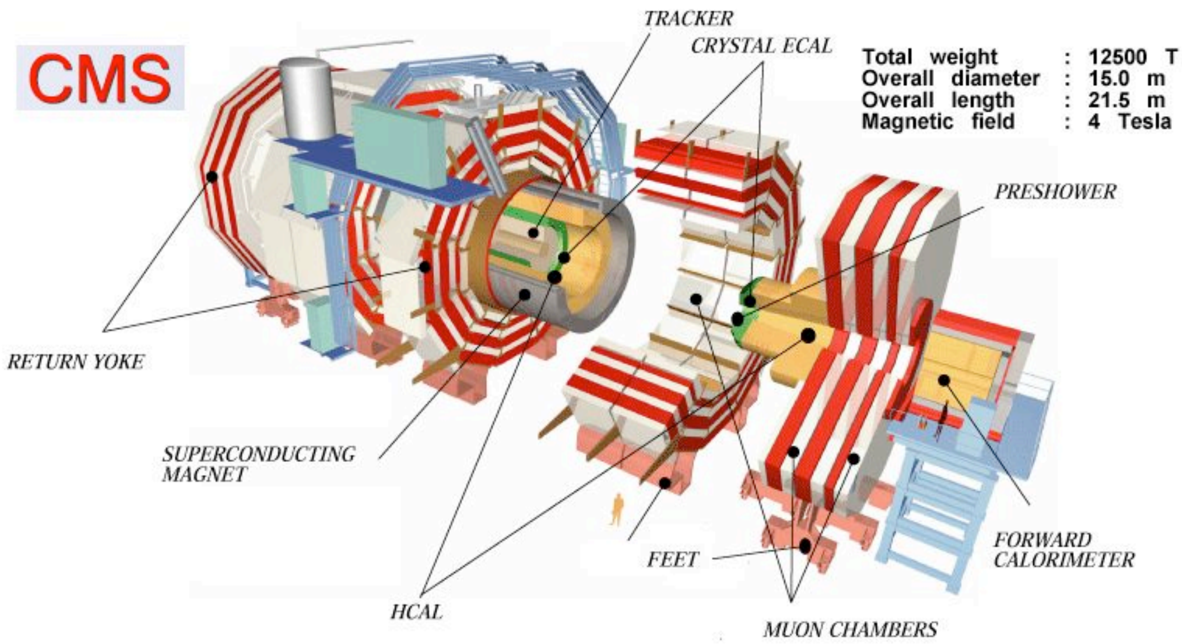
- Need only one BCAM.
- No cable.
- Radiation resistant.

Disadvantages of Retroreflector:

- Have only one BCAM.
- No complimentary measurement.
- Accuracy degraded by doubling the optical path.

CMS Closure

CMS made up of disks.



Disks slide together on rails.

Need to monitor disk positions to 1 mm transverse to motion.

Neet to monitor in real-time during closure.

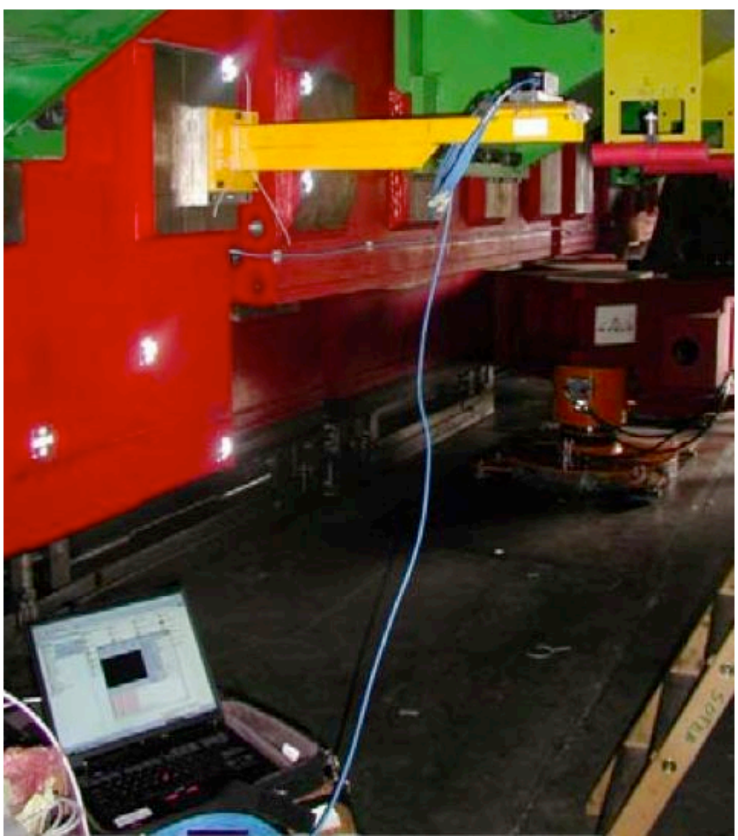
Disks move several meters.

CERN survey group decided to use BCAMs and retroreflectors.

Retroreflector Application

Two alignment corridors pass through all disks at shoulder-height.

BCAMs on outer disks, retroreflectors on inner disks.



Retroreflector Results

Relative Accuracy ≈ 80 µm (exceeds requirement)

Dominant Error Source: CMM measurements, BCAM calibration.

SPHERE	DX (mm) [BCAM - DP]	DY (mm) [BCAM - DP]	DZ (mm) [BCAM - DP]
8	0.03	-0.04	0.01
9	-0.02	0.01	0.03
10	-0.02	0.03	0.00
17	0.00	0.00	-0.01
18	0.00	-0.01	-0.01
19	0.00	0.00	-0.01
23	-0.06	0.01	0.01
24	0.03	0.02	-0.01
25	0.03	-0.03	0.04
32	0.01	0.09	-0.01
33	-0.01	-0.02	-0.01
34	0.00	-0.07	-0.02

MIN (mm)	-0.06	-0.07	-0.02
MAX (mm)	0.03	0.09	0.04
STDEV (mm)	0.03	0.04	0.02

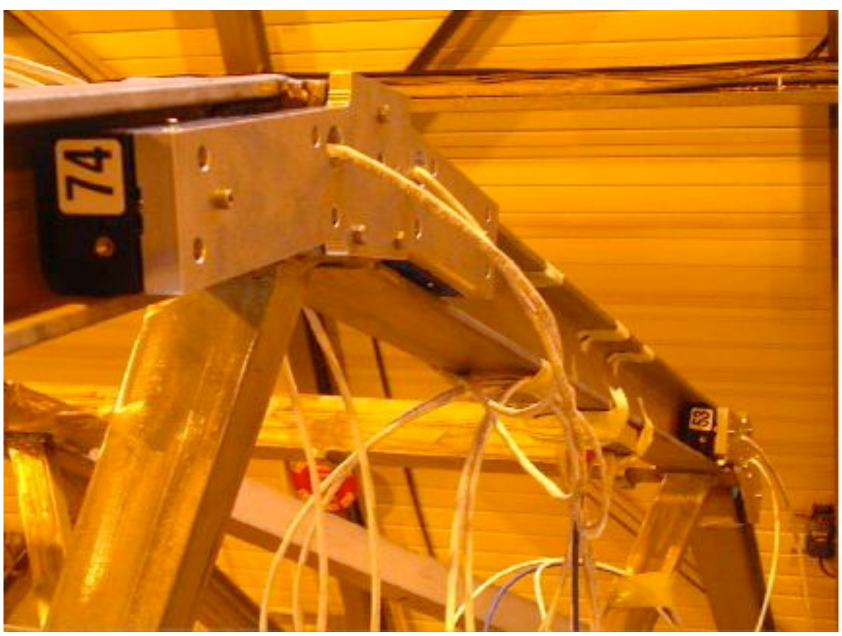
Absolute accuracy ≈ 1 mm (meets requirement)

Dominant Error Source: survey of plates.

ALICE Space Frame Monitor

The ALICE space frame supports its detector barrel.

120 BCAMs in two rings monitor space frame deformation.

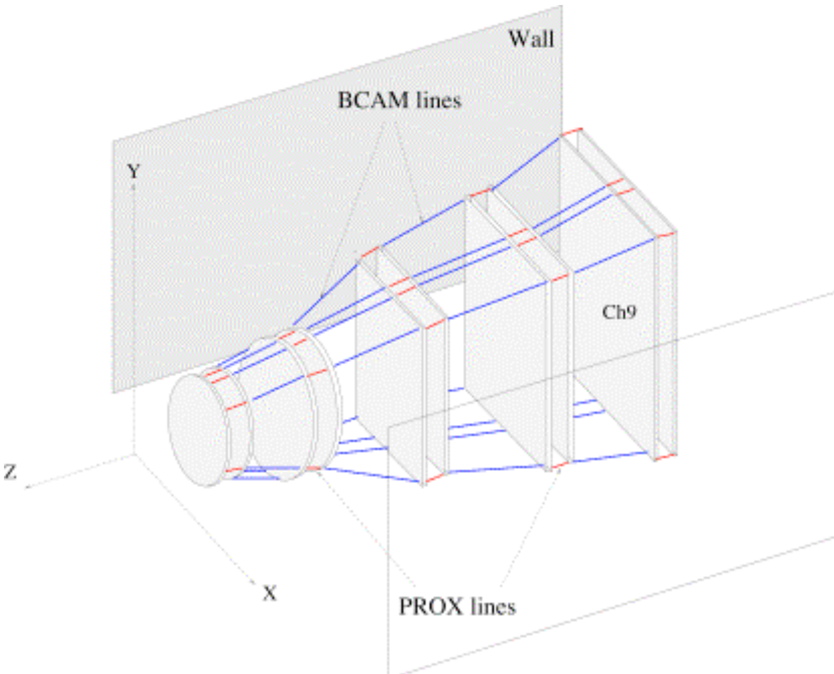


Serial number label visible from viewing BCAM.

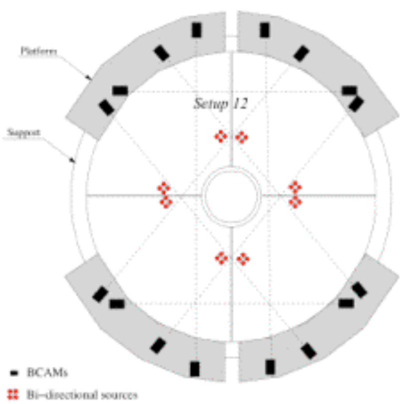
Status: installed.

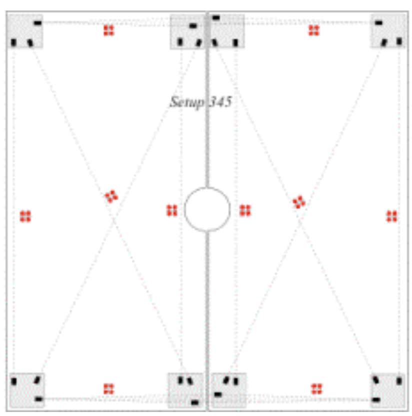
ALICE Geometric Monitoring System

Alignment system for the forward muon spectrometer.



300 BCAMs monitor longitudinal and tranverse displacements.

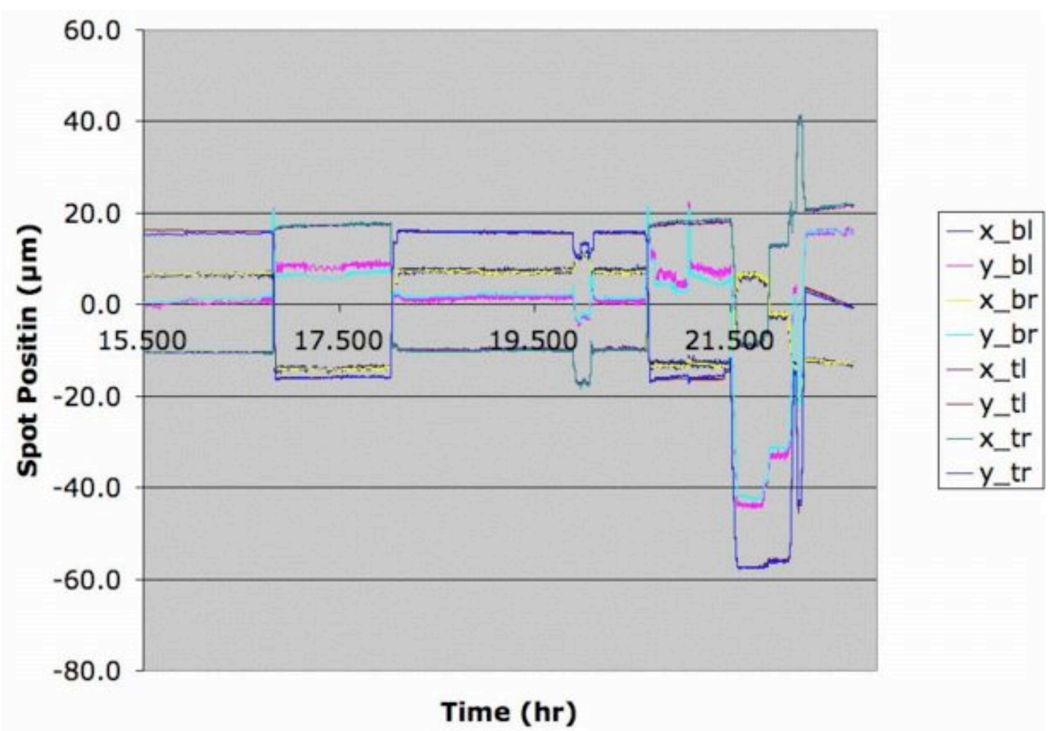




Status: installation in progress.

Mayall Telescope Monitoring

Two BCAMs fastened to telescope structure with C-clamps.



BCAMs monitor telescope strut bending.

Conclusion

1. BCAM relative accuracy 5 μrad across field of view.
2. BCAM absolute accuracy 50 μrad with respect to mount.
3. BCAMs available from Open Source Instruments Inc.
4. Single-ended BCAM costs $300 in 100's.
5. The BCAM User Manaul describes use in detail.
6. The LWDAQ User Manual describes readout in detail.
7. The BCAM Assembly Manual describes assembly in detail.
8. All circuits and software distributed under GNU General Public License.
9. This talk at http://alignment.hep.brandeis.edu/ATLAS/IWAA_06/IWAA_06.html.
10. Speaker will demonstrate BCAMs and DAQ upon request.