Alignment issues in large experiments: The CMS system.

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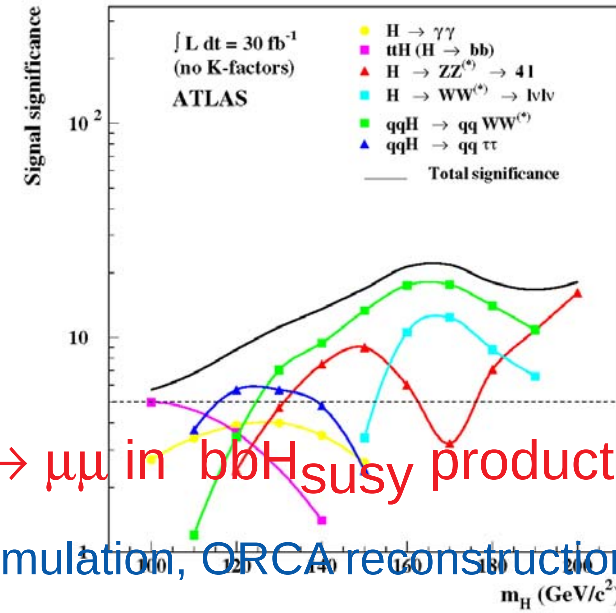
- Physics motivation
- General considerations about alignment
- The CMS alignment

Why … ?

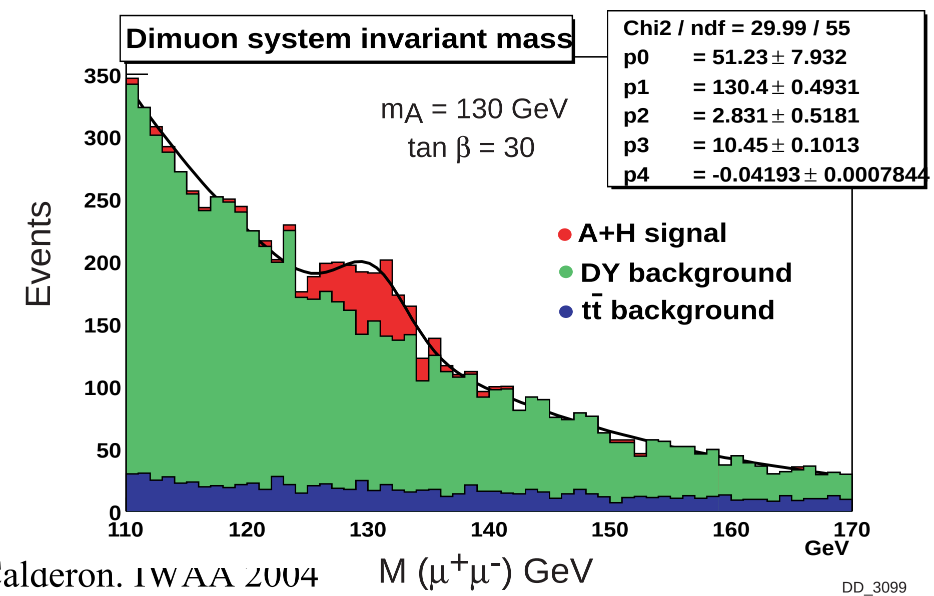
Physics Motivation

- Precise measurement of SM and searches of new physics
  - In LHC major interest in Higgs search
  - Often look for tiny signals on top of large background
- Imply the precise reconstruction of "objects"
  - Tracks
    - muons, hadrons, electrons
  - Calorimetric showers
    - Photons, neutral hadrons
  - Jets
  - Secondary vertices
    - displaced tracks



A/H → μμ in bbH$_{susy}$ production

full simulation, ORCA reconstruction



Why we need to align?

- To achieve these physics goals

  ⇒ detectors consist of a large number of precise and complex sub-units (each of these itself contains many detecting elements)

- Mispositioning of any of these elements

  ⇒ results in bad reconstruction of the particles: wrong properties of the particle or even particles might be undetected

- Problem more acute in large muon systems:

  performance implies alignment accuracies on the order of the detector resolution (tens of microns) between detectors placed in mechanical structures separated more than 10 meters

- Settling, thermal shift, gravitational force and stresses coupled from the magnet system generally deform the support structures (up to a few cm for muon systems)

Different alignment situations

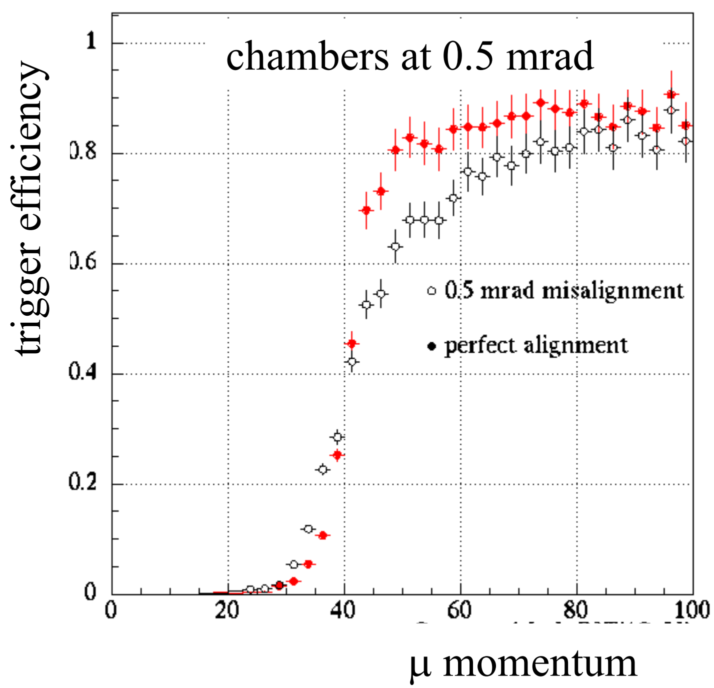
- In many experiments precise alignment needed for two different cases:

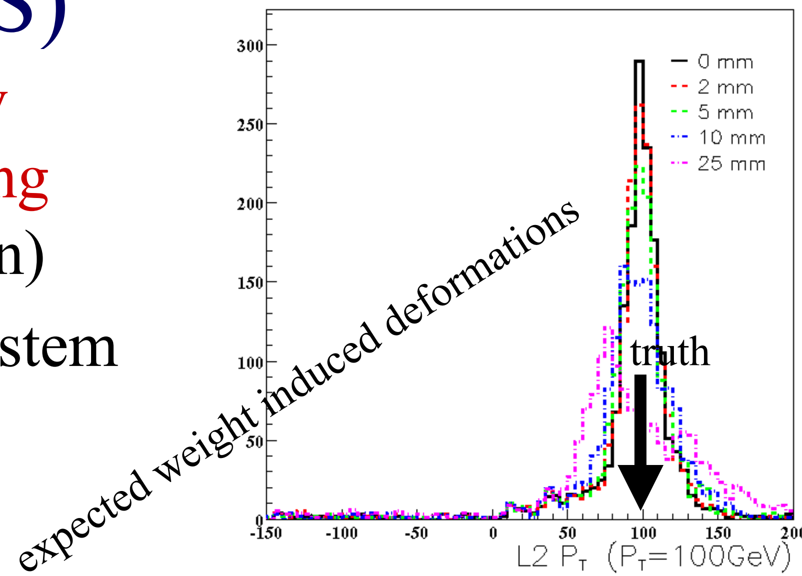
- Precise positioning of Silicon vertex detectors & other tracking devices
  - intrinsic precisions on the range of 10-100 μm
  - alignment errors propagate to the track reconstruction:
    - efficiency loss, degradation of momentum, mass...
  - often critical for vertex/impact parameter:
    - basic in many analyses involving τ or b quark (Higgs search!)
  - problem present at LEP, Tevatron, LHC...

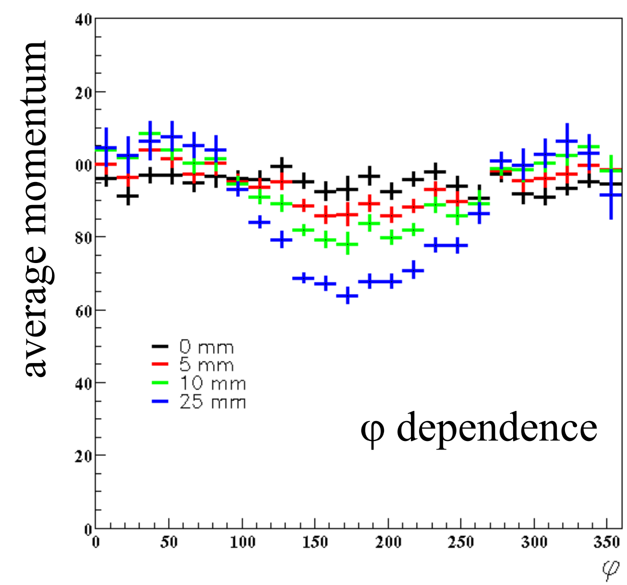
- Alignment of muon spectrometers and w.r.t central tracking system
  - some experiments use the muon system to improve muon reconstruction
  - typical precision of ~ 100 μm
  - L3, CMS, ATLAS
  - for optimal performance of the whole system relative position of muon chambers and central tracker need (sub mm)
  - scale of several meters

Misalignment effect on trigger (CMS)

- Trigger performance is significantly degraded when alignment/positioning errors are included (on-line selection)
- Some examples at Level2 (muon system trigger)







A. Calderón. IWAA 2004

An example from off-line analysis

- *Z'* boson search (CMS, S.Valuev, B.Coussins, J.Mumford)
- effect of weight deformation in the analysis
- mass resolution starts to degrade for survey precisions
  - discovery/exclusion potential degraded

Ideal alignment

expected errors after survey

$\sigma_{mass} = 5.3\%$

3 TeV Z_{SSM}

$\mu\mu$ mass

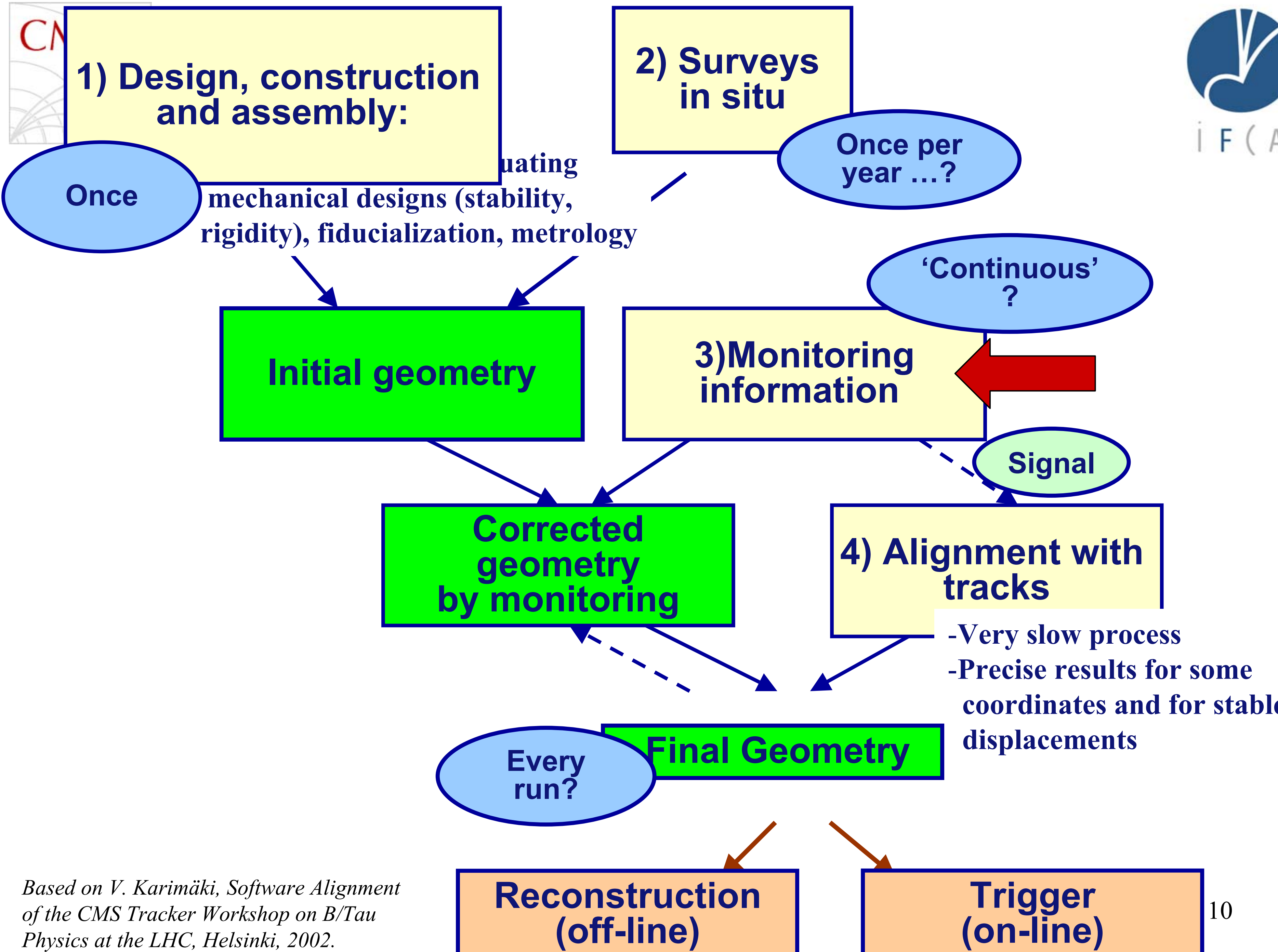
$\sigma_{mass} = 6.9\%$

How … ?

Factorize the alignment task into:

- **Local or internal alignment**: Of individual subdetectors, so they may be considered as rigid bodies or blocks (6 degrees of freedom) / Position of individuals elements within a detector. (Vertex detector)
- **Global alignment**: spatial relation of these blocks to each other /Position of the various detectors with respect to each other. (Muon spectrometer w.r.t. tracker).
- The position of the experiment with **respect to the beam**

Ref.: M. J. Price, "Alignment of experiments"
CAS-CERN Accelerator School: Measurement and Alignment of Accelerator and Detector Magnets.
Apr. 1997, Anacapri, Italy.



Based on V. Karimäki, Software Alignment of the CMS Tracker Workshop on B/Tau Physics at the LHC, Helsinki, 2002.

3) Monitoring information

To be presented in the CMS Link system

Several techniques:

- **Distance monitors:**
  - **FSI**: precision 1μm, range tens cm - 1 m (ATLAS inner tracker)
    Ref. : A.F. Fox-Murphy et al., NIM A383, 229(1996)
  - **Lasers proximity sensors**
    - Triangulation (L3 muon chambers)
    - Intensity
  - **Electrical proximity sensors**: precision ~ 10 μm (range 50 mm) (L3, CMS)
    - Capacitives
    - Potentiometers

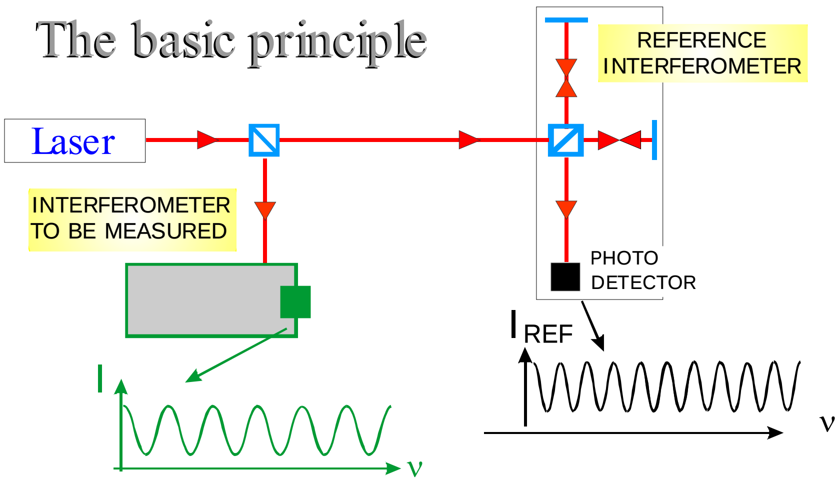
- **Colinearity monitors:**
  - **RASNIK**: precision ~ 3 μm (range 5m) (L3,ATLAS, CHORUS, CDF)
  - **Semitransparent a-Si:H sensors**: (CMS)
  - **STAMP** (ATLAS), **COPS** (CMS)

- **Angular measurements:**
  - **Inclinometers (CMS)**

FSI (Frequency Scanning Interferometry)

- **FSI** is a precise technique for multiple simultaneous absolute length measurements.

Absolute Distance Interferometry



•**Basic principle:**

-A common **tunable laser** system is used for the **interferometers to be measured** and also for the **reference interferometer** (thermally stabilized).

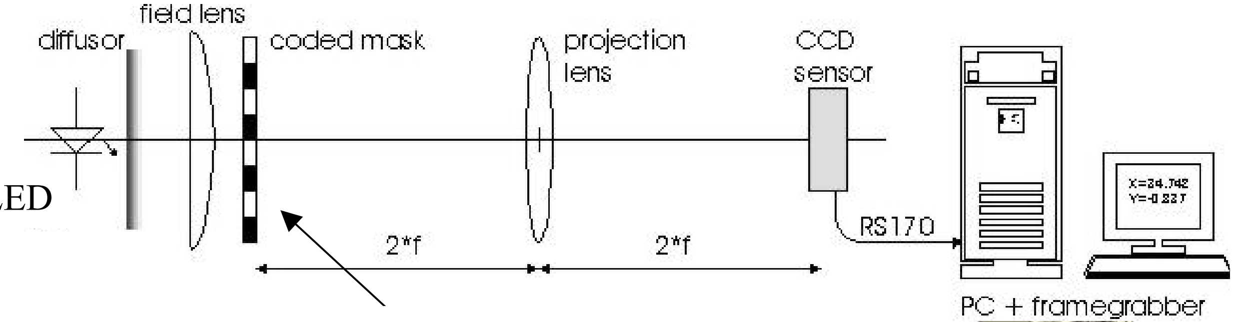
- The optical **frequency** is simultaneous **scanned** in all interferometers.

- Each length is measured by **comparing** the **phase change** in each measured interferometer with the phase change in the reference interferometer.
- The ratio of phase change gives the ratio of lengths.
- Typical **precision 1 micron**

Ref. : P. A. Coe et al
"Frequency Scanning Interferometry in detail", IWAA 2002
"S. M. Gibson et al" Multiple, simultaneous length measurements" IWAA 2002
A. Mitra et al "Combination of FSI with other novel optical tools", *IWAA 2002*

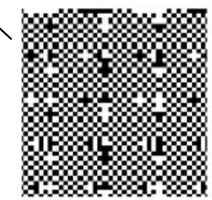
CCD-RASNIK

Matrix LED



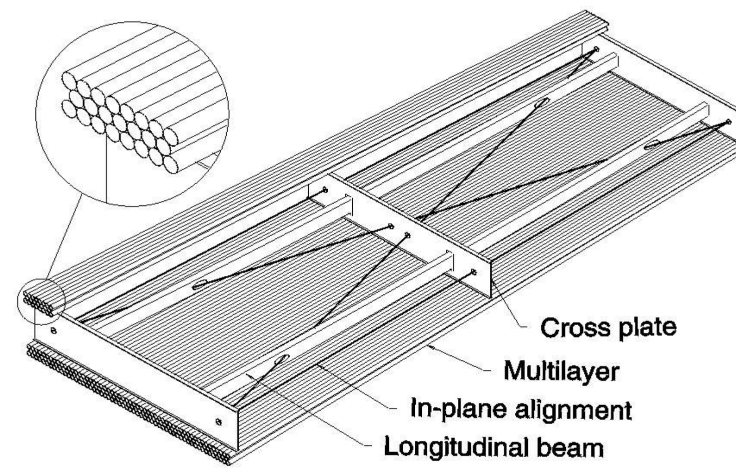
- 3-point colinearity monitor.
- Each elements close to the measurement points.
- Range limited by the mask size

Coded Mask



- **Precision Image**: provides (X,Y) point positions from Black-White transitions (in the CCD)
- **Z Coordinate** provided from Image Scale Factor
- **Rotations Z** coordinate provided from image tilt.

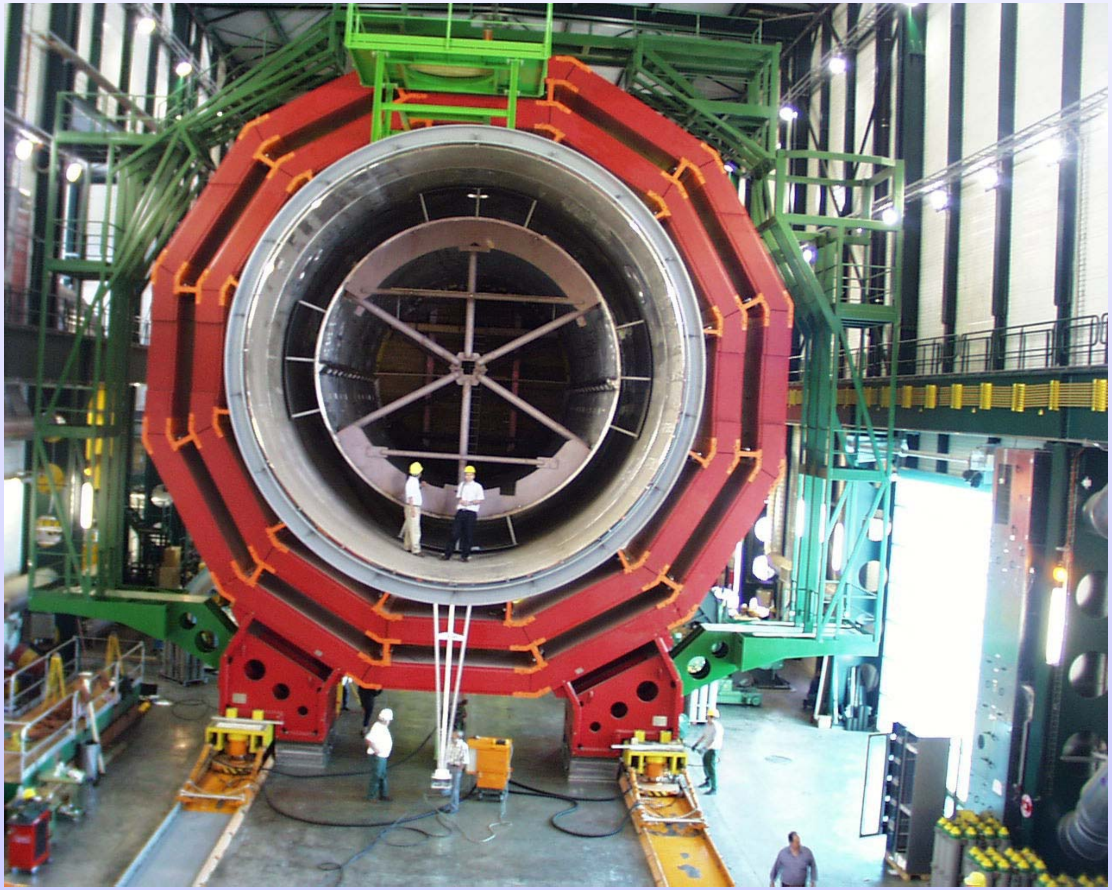
CCD-RASNIK technique is used in the alignment of ATLAS muon chambers.



Transverse resolution ~ 1 μm (at 5m)
Longitudinal resolution ~ 30 μm

An example ...

The Compact Muon Solenoid Alignment

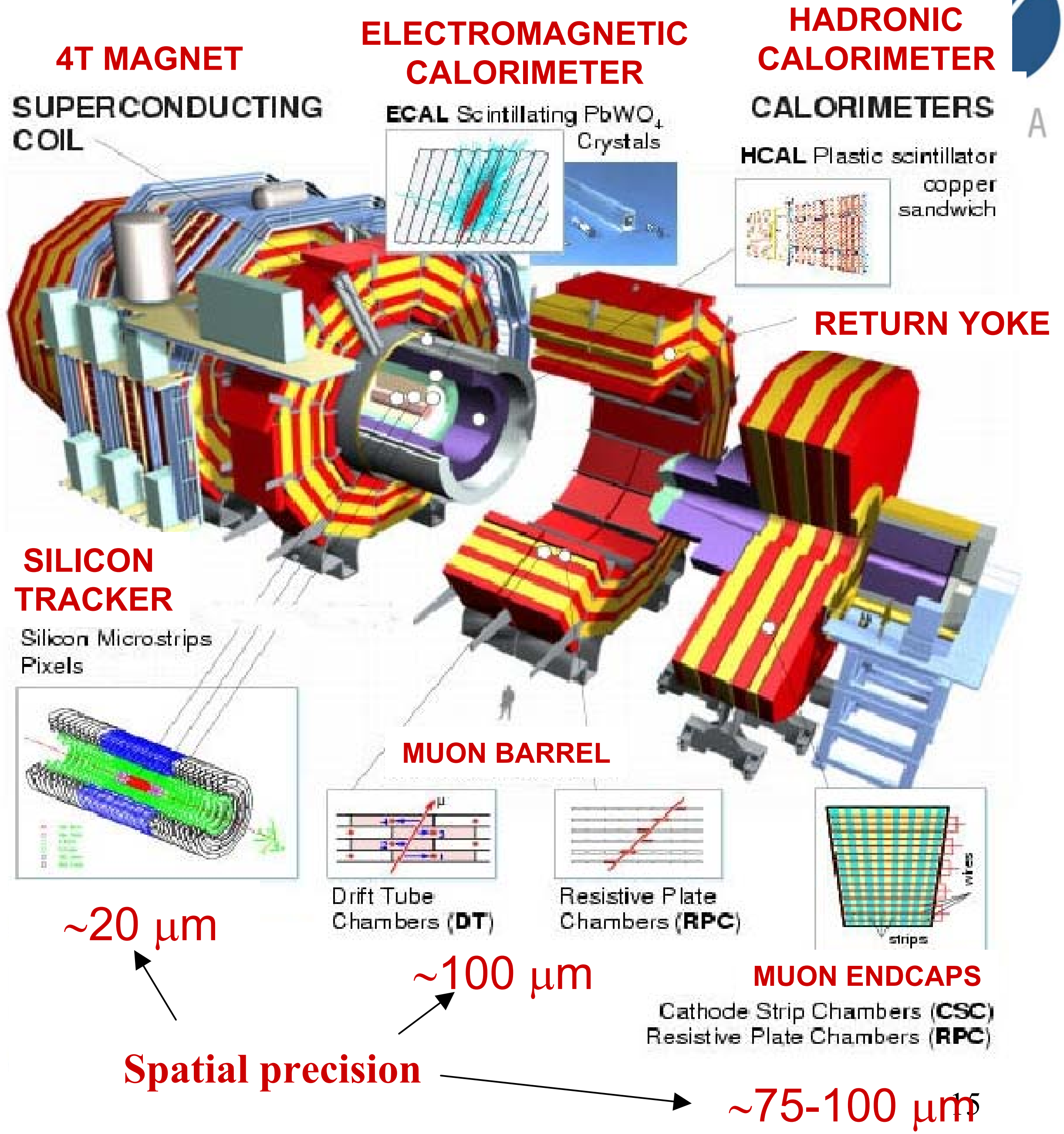


CMS

Weight:	12.500 t
Diameter:	15.0 m
Length:	21.6 m
B Field:	4 T

Design Criteria

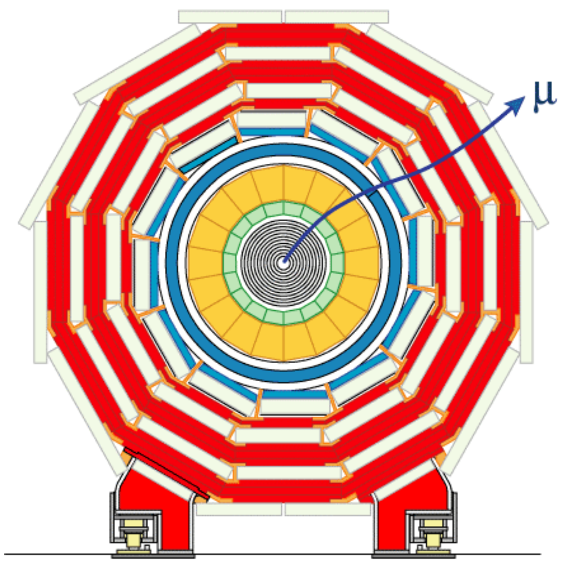
- Very good lepton ID (e y μ)
- And tracking system (B=4T) to measure the particle p
- Detectors capable to operate with high radiation levels (up to 1MGy in 10 years)
- Fast response technologies (beam crossing time 25 ns)
- Good detector hermeticity



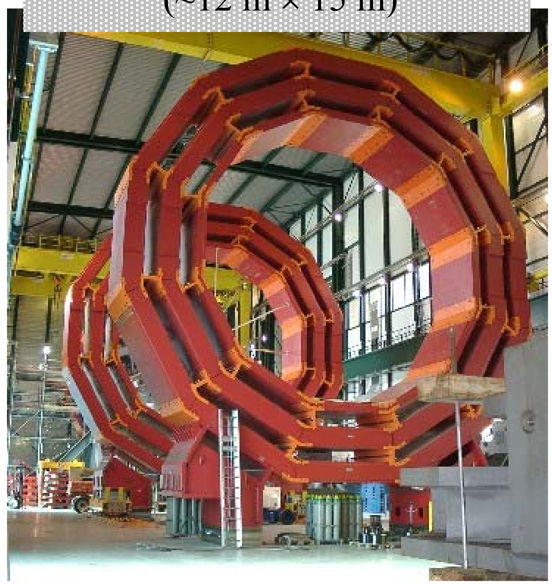
Muon spectrometer: Geometry

- Muon chambers are sandwiched in the return yoke.

Muon Barrel
-5 wheels/ four layers each
-250 chambers

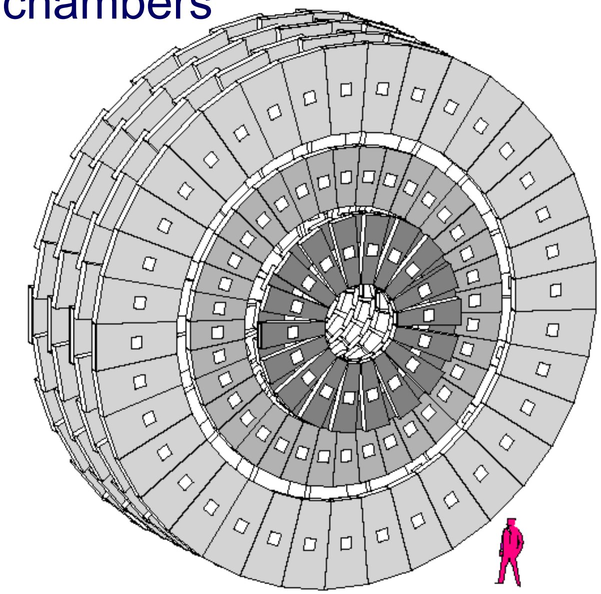


Barrel support structure
(~12 m × 15 m)



Wheel: three concentric iron layers.

Muon Endcap
-6000 m^2 sensitive area (all planes)
- 540 chambers



Endcap support structure

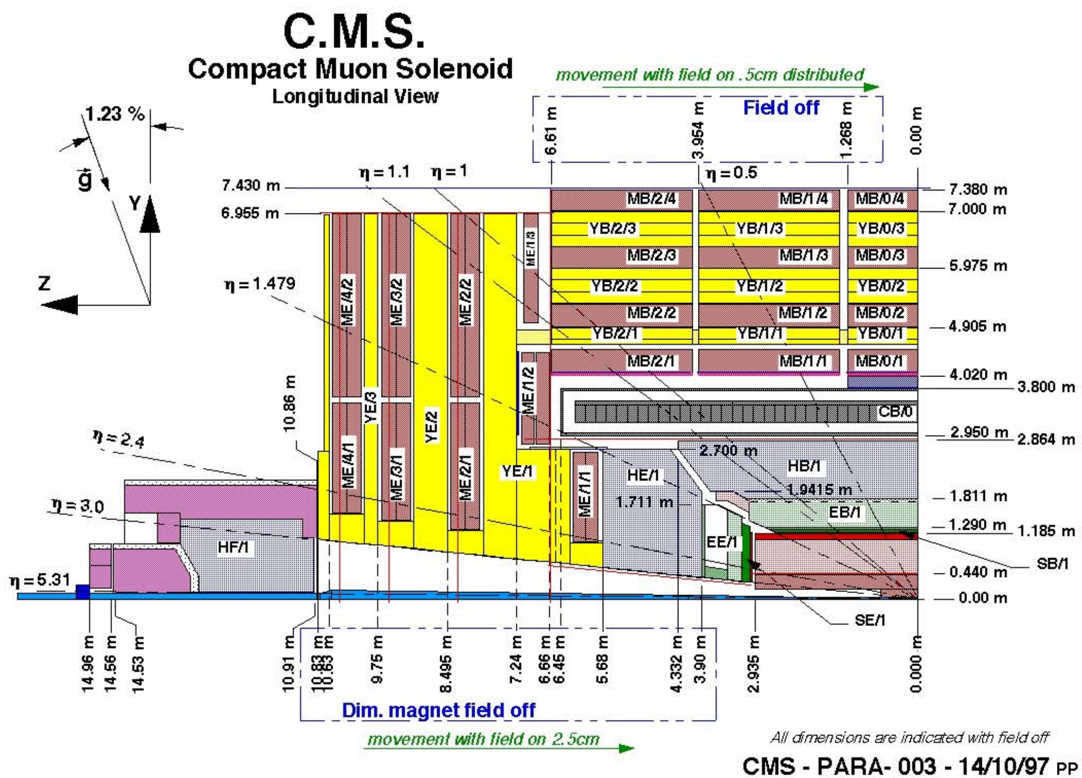
Mechanical structures: large dimensions and not rigid enough for the requirements.

A precision Alignment !

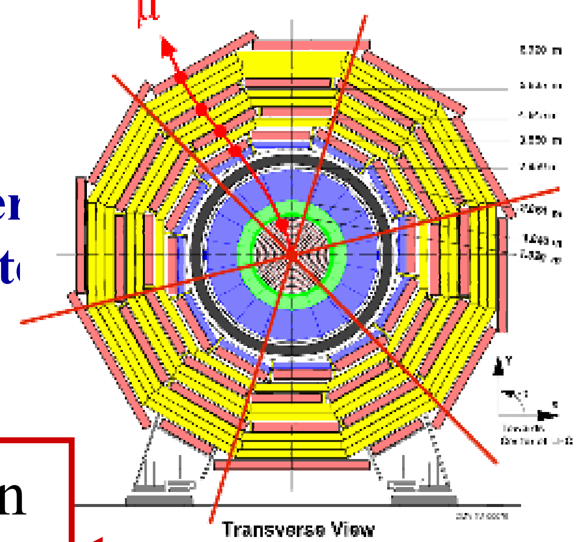
Alignment System: Requirements

- Maximum expected motions:
  - ~1-3 cm B on/off
  - < 500 μm operation (Temp. and humidity)
- Maximum allowed misalignment (not degrade P measurement)
  $\sigma_{R\Phi}$ = 200 μm, Barrel
  $\sigma_{R\Phi}$ = 200 μm, Endcap

  At level of mm in R, Z
- Radiation resistant and non-magnetic materials.



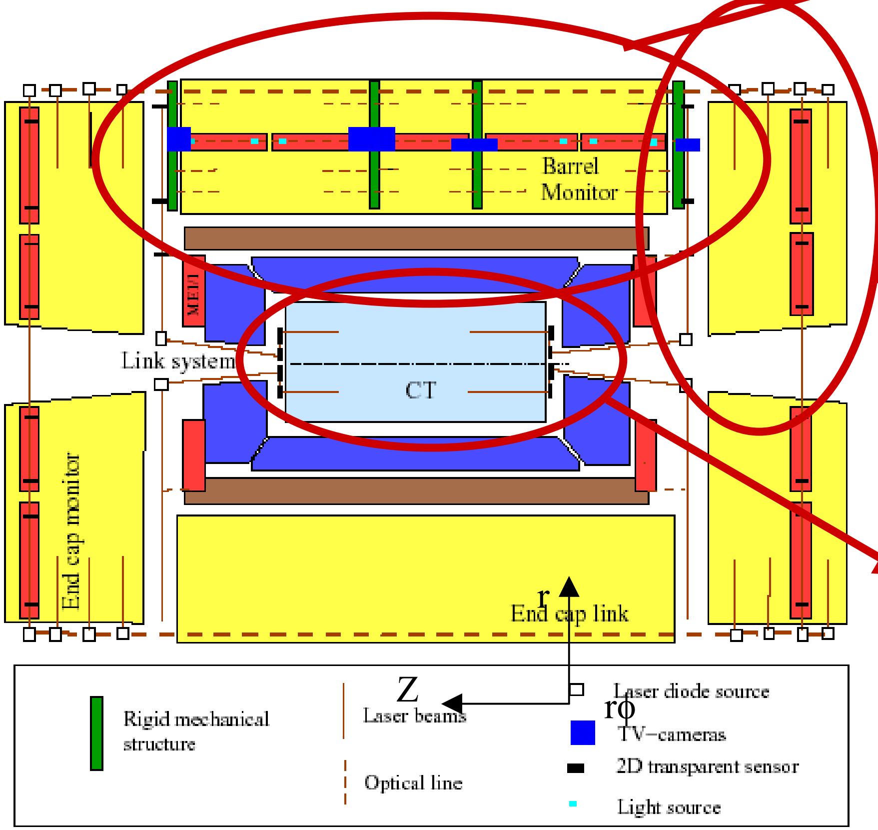
Alignment System



Aim

Tracker internal alignment, monitor the muon chamber relative positions (barrel and endcap) and with respect to the tracker.

Structured in 4 subsystems



Internal Muon Barrel Alignment

Internal Muon Endcap Alignment

Internal Tracker Alignment

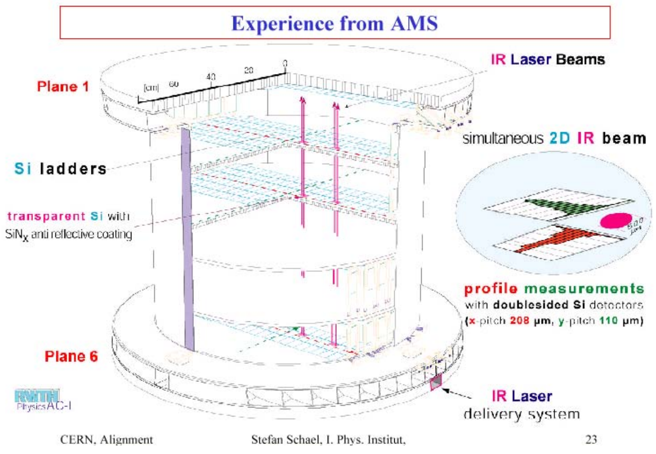
The Link System

Internal Tracker Alignment

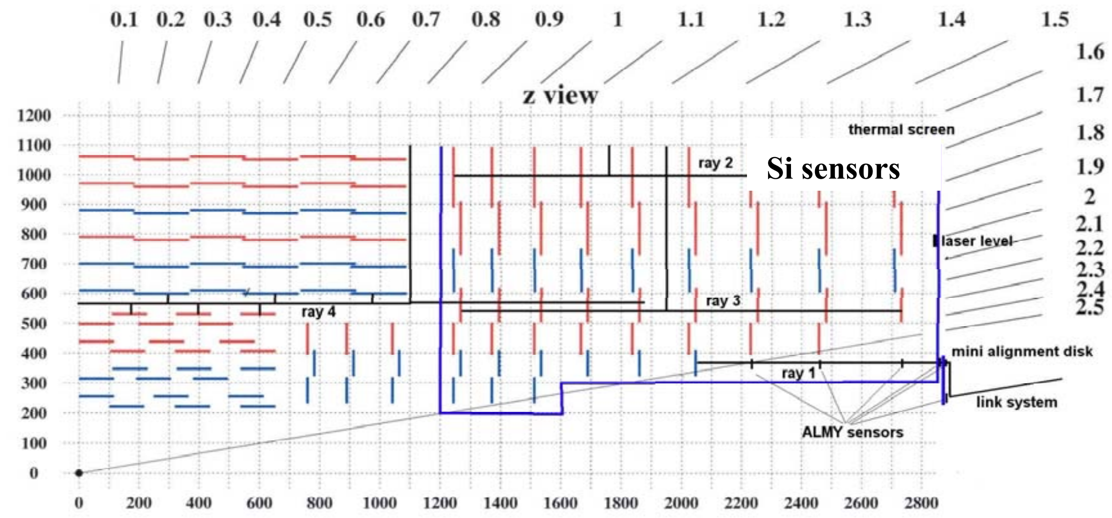
Combined {
- hardware alignment (precision ~ 100 μm)
- alignment with tracks (improve precision up to ~ 10 μm)

- Internal alignment endcap dics (50 % petals, rest using track overlap). σ better than 100 μm
- Relative alignment Endcap-Barrel: 8 optical connections , σ ~ 100 μm

AMS

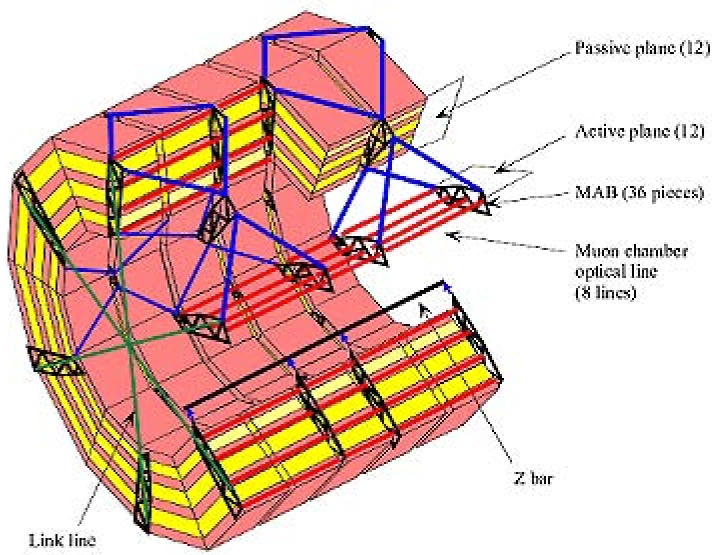


➢ **TKAL uses Si-modules as alignment sensors and Tracks to achieve 10 μm align. accuracy**

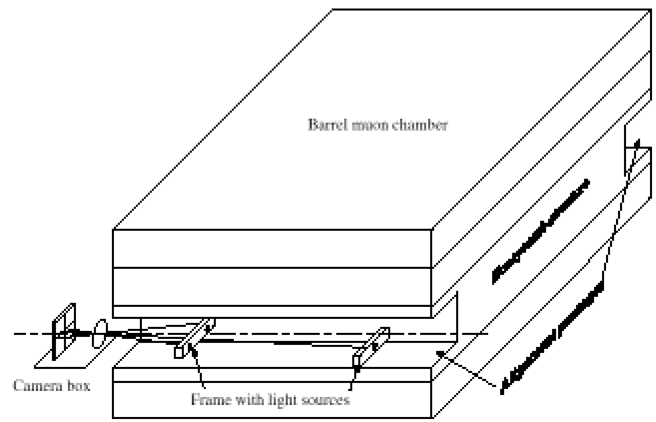


Internal Barrel Alignment

Position between muon chambers trough a mechanical reference structures so-called MABs (Module for Alignment of Barrel)



6 active planes RZ, 6 pasive planes



- Light sources in muon chambers are detected by the MABs.
- Relative position between cameras using triangulation techniques.

Photogrametry techniques

Mechanical structure MAB

Length about 4m

Good Rigidity **(50 μm/50 μrad)**

Wires → External reference points ↔ Light sources

50 μm (Wires → External reference points)

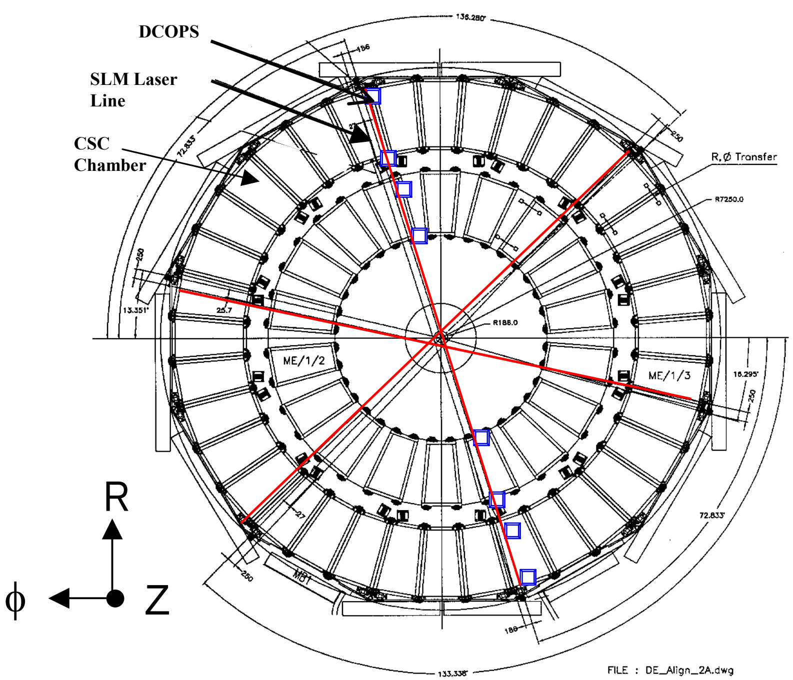
Measurements: **60 μm Rϕ**, **300 μm Z** (External reference points ↔ Light sources)

Overall Precision **σ ~ 200 μm**

Internal Endcap Alignment

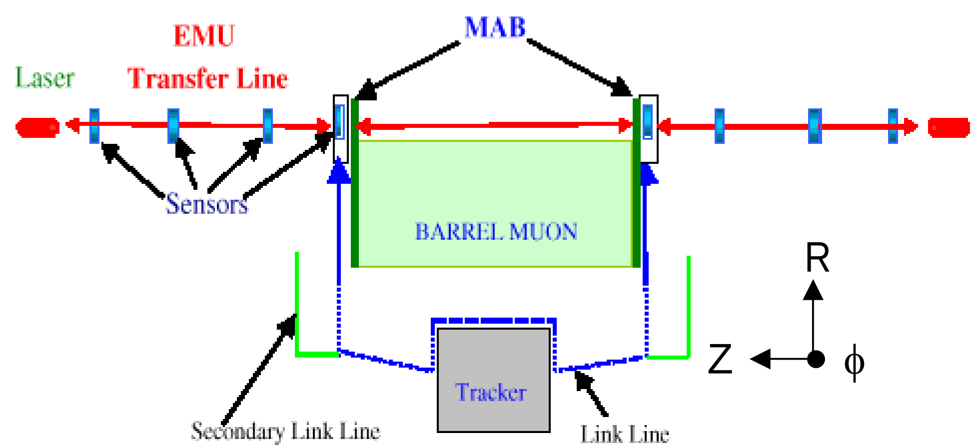
• Measure and monitor Cathode Strip Chambers (CSCs) (Muon chambers) positions in each endcap and also the connection between endcaps.

3 SLM laser lines: CSCs position inside each station.



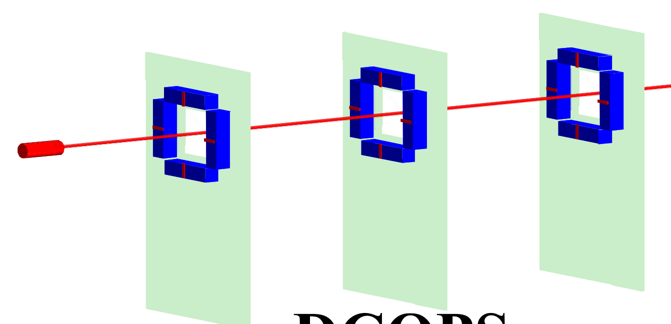
(ϕ,R) transfer via **6 Transfer Line** at maximum R through MABs and several muon chambers.

Multipoint alignment system



Componets:

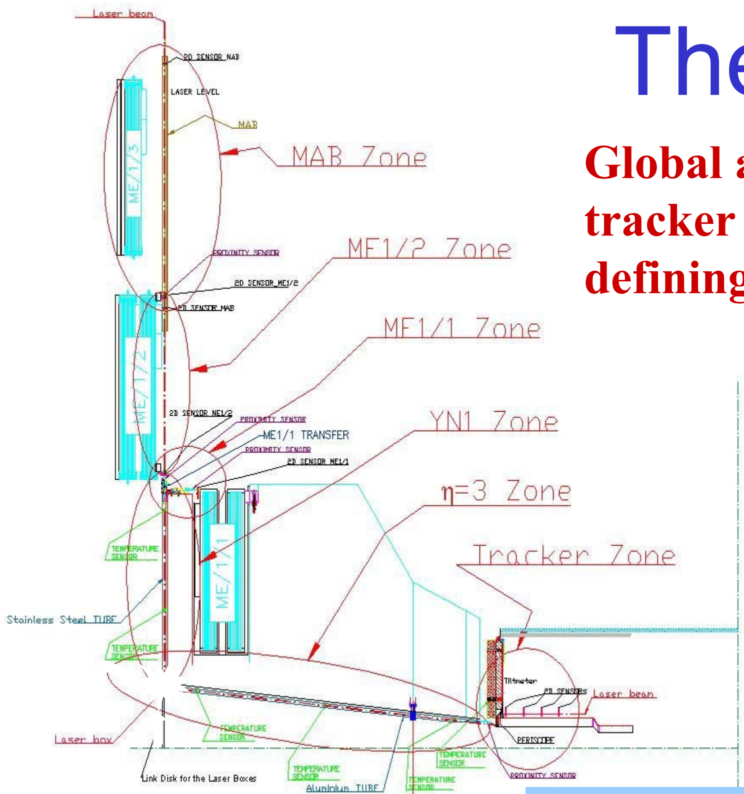
- Laser 670 nm
- CCDs square geometry
- Displacement sensors:
  - optical
  - potentiometers



DCOPS

Precision ~ 200 μm

The LINK System



Global alignment of CMS, transports central tracker coordinate system to Muon chambers defining a common system.

Laser system

- laser diodes (at 690 nm)
- Optical fibres & collimators

Sensors: type & technology

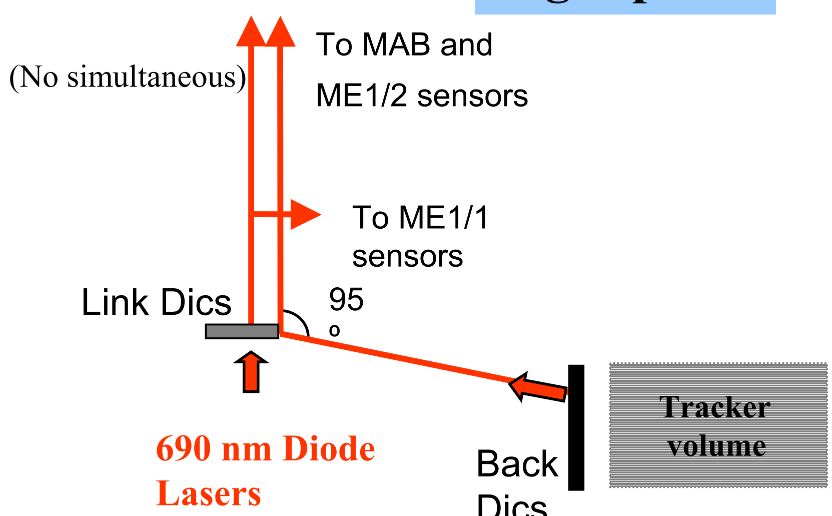
- Photo-sensors
- Inclinometers
- Displacement sensors
- Temperature sensors

Optics (definition of the light path)

- Beam splitters
- Prisms: Rhomboid prisms and pentaprisms.

Light paths

R-Z Plane



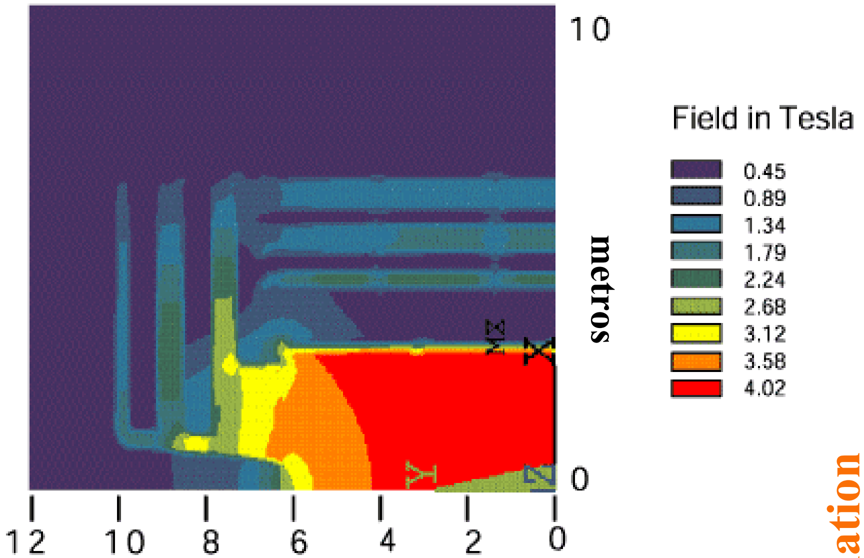
Mechanical components.

-CF supporting structures (MABs, Link wheel, bars)

Front-End & DAQ electronics

Most are commercial after an extensive and often non-trivial checks of performance characterization (also in the adverse environment: magnetic field and radiation)

LINK System: environment

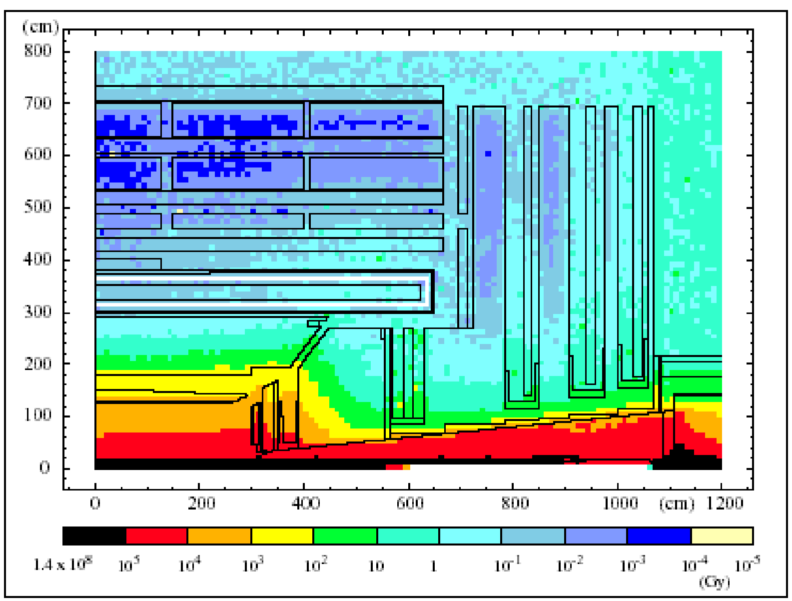


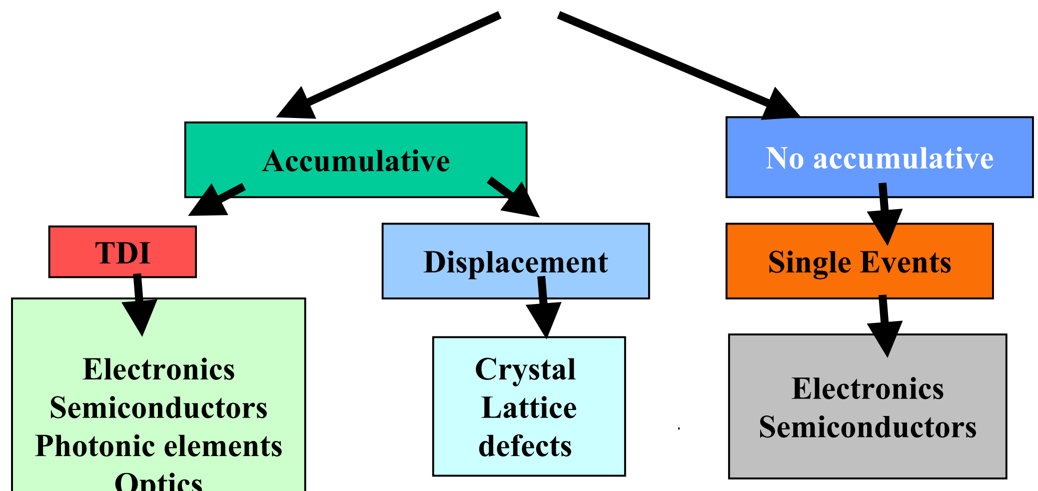
Magnetic Field

- 4 Teslas
- Gradients up to **600 Gauss/cm**
- Complex field map

Radiation environment

- Hard radiation environment
- Photons, neutrons, charged hadrons
- Dose: **1- 100 x 10^3 Gy (10 years)**
- Fluence **5 x 10^{10} - 2 x10^{14}** n/cm^2 (10 years)



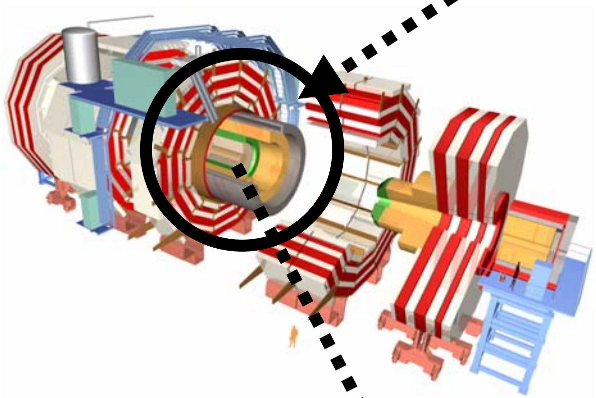


Laser system (I)

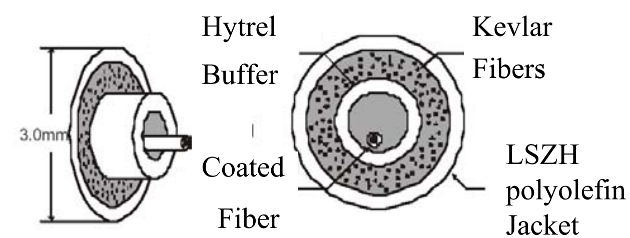
2. Single-mode optical fibers (distribute the laser light inside the detector)

1. Diode Lasers (Out of CMS)

2. Single-mode optical fibers (distribute the laser light inside the detector)



•Radiation tolerance



b) Radiation.induced absorption (RIA)

γ and n irradiation ⇒ Formation (or activation) of 'colour centers', which absorb light at particular wavelengths. One order of magnitude higher in visible range than in infrared. At Tracker < 1dB/m up to 100 kGy dose and 2 10^{14} n/cm^2 in 10 years. (1dB : 80%)

3. Fiber Collimators (inside CMS) (generate a gussian beam at every measuring point of the light path)

Complete characterization:
active measurements under gamma and neutron irradiation.

Photosensors

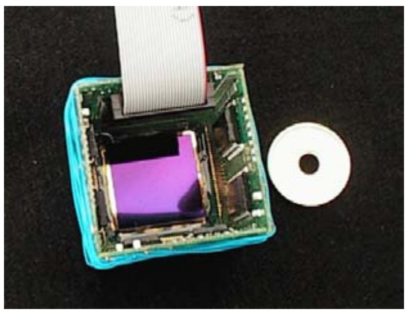
Amorphous silicon on a glass substrate

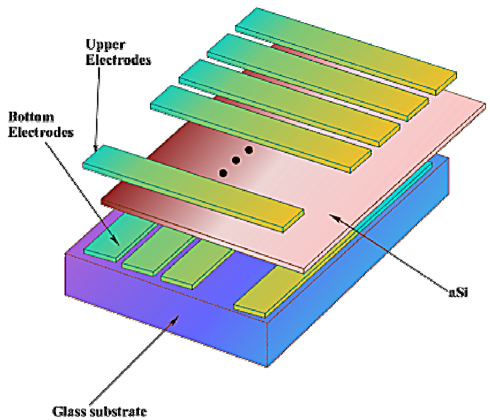
Two studies

Silicon on a ceramic substrate

Non commercial option (BASE LINE)

First design in MPI, Munich. Developed at the Institut für Physikalische Electronik (Stuttgart University)

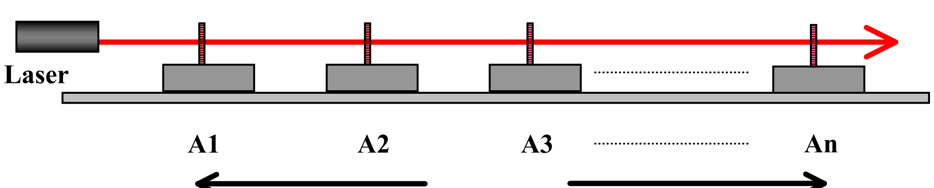




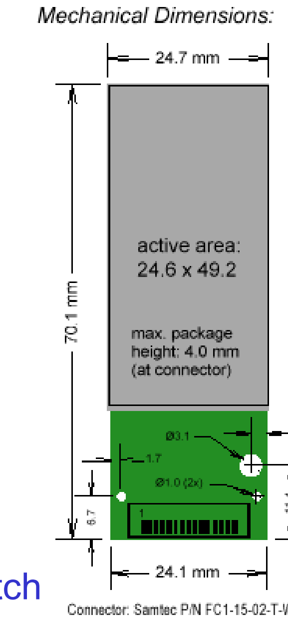
Specifications:

- a-Si:H sensor (DPSD)
- Active area: 30 × 30 mm^2
- Strip number: 64 × 64, 430 μm pitch
- Substrate thickness: 0.5-1 mm
- Radiation resistant

Multipoint Measurement: Semitransparent Sensors Array



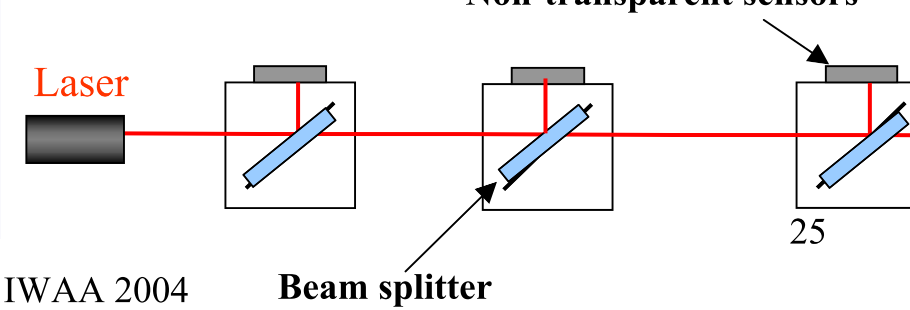
Commercial option



Specifications:

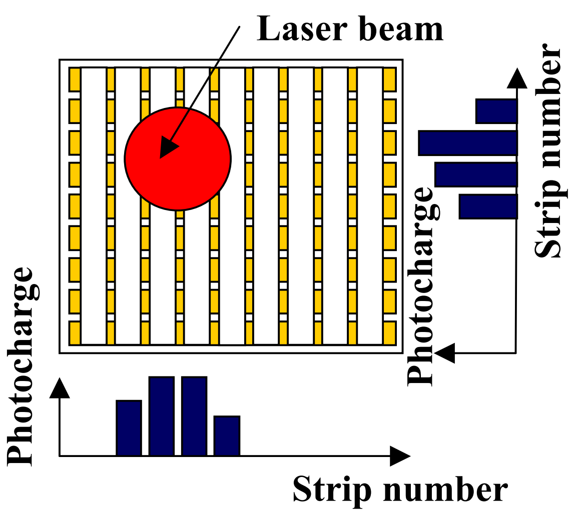
- 2D CMOS image sensor
- High active area (24.6x49.2 mm^2)
- Pixel matrix : 512×1024, 48 μm pitch
- Radiation tolerance

Developed: optomechanics + electronics

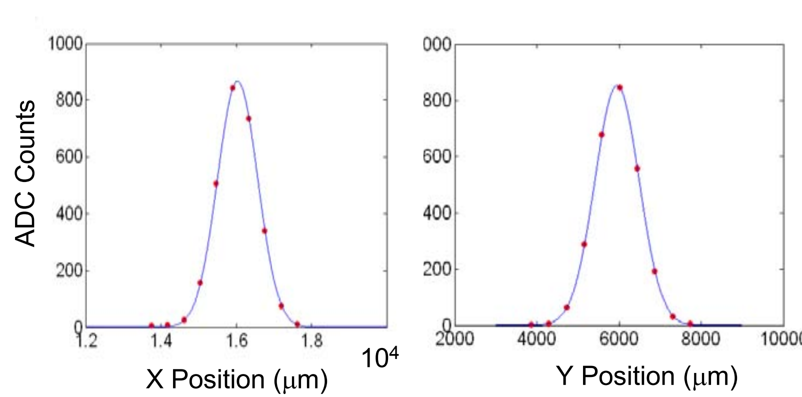


Almy sensors (I)

Signal reconstruction



Position of a light spot: center of gravity of the photocharge distribution collected by the 2D grid of photodiodes.



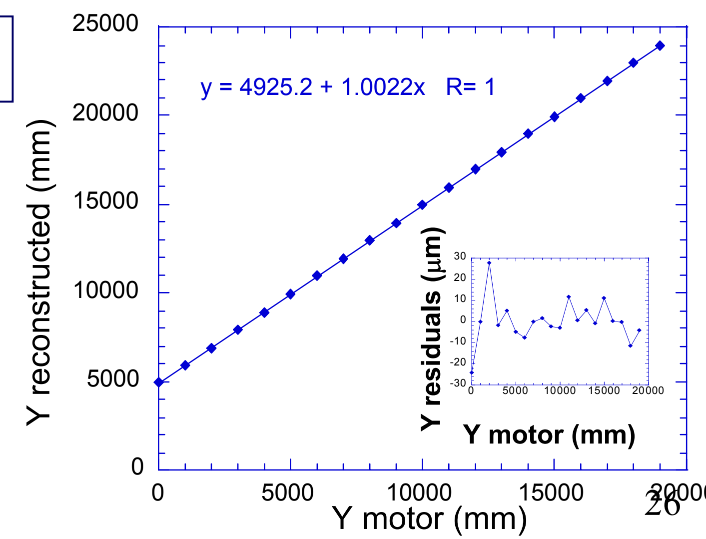
Example of a He-Ne laser spot: photocharge distributions in X and Y directions.

Spatial position reconstruction: linearity test

Linearity and resolution

Compare real displacements with reconstructed displacements from the sensor signal.

Linearity ⇒ resolution $\leq 5\ \mu m$



Almy sensors (II)

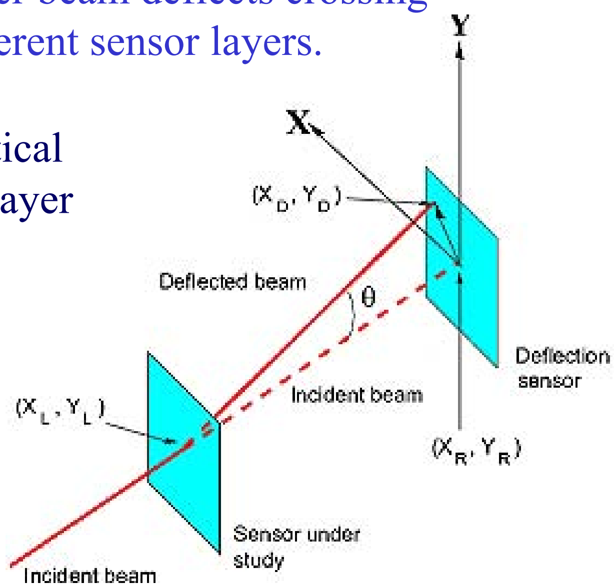
Intrinsic position reconstruction

Distribution of the reconstructed position of the light spot on sensor A2 during a short term stability run. → **σ_x , σ_y < 3 μm**

Deflections

Laser beam deflects crossing different sensor layers.

Measurement of the optical uniformity of the multilayer sensor.

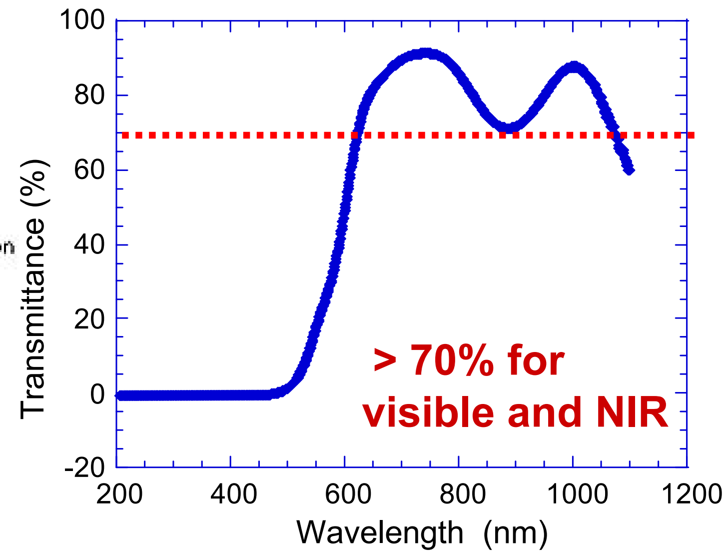


Deflection angles measured

$<\theta_x>$, $<\theta_y>$ < 3 μrad

$\sigma(\theta_x)$, $\sigma(\theta_y)$ < 5 μrad

Transmittance



Ref. M. Fernandez, Transparent detector for the AMS alignment system, IWAA 99

Displacement sensors

System requirements:
- Working range: ~ 2.5 - 5 cm (depends on the CMS region)
- Measurement precision: ~ 80μm
- Radiation and B tolerance

Commercials

Non-contact sensors: laser triangulation sensor

OMRON Z4M-W100

Range : ± 40 mm
Linearity: 1.5%

Characterization test:

- **Stability** (600 min): ± 3 μm
- **Linearity** ⇒ linearity residuals < 25μm
- **Irradiation test**: Changes < 1 % up to 3 Gy & 10^{11} n/cm^2
- **B test**: ~ 30-50 μm

Contact sensors: Linear Potentiometer sensors

SLS130/2K/L/50/1 (Penny Giles)
HLP129/BC1/50/2K/RR (Penny Giles)
s13flp50A (SAKAE)
s18flpa50K (SAKAE)

Range : ± 50 mm
Linearity: between 0.1 and 1 %

Characterization test:

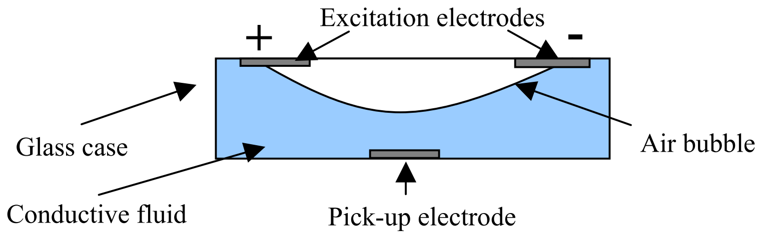
- **Stability** (12 h): changes ~ 0.1 mV
- **Linearity** ~ 50 μm
- **Irradiation test**: Negligible changes < 0.1 % up to 50 kGy & 10^{14} n/cm^2
- **B test**: no effects up to 2T and 0.186 T/cm

Measuring the ϕ angle

Measure angular position and rotational movement of the elements to which they are attached respect to the most stable reference: the vertical gravity vector.

Electrolytic sensor

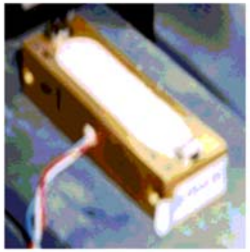
- An enclosed **bubble**, **suspended in a liquid**, will always orient itself **perpendicular** to the **gravity.**



Commercials

Model AGI 756

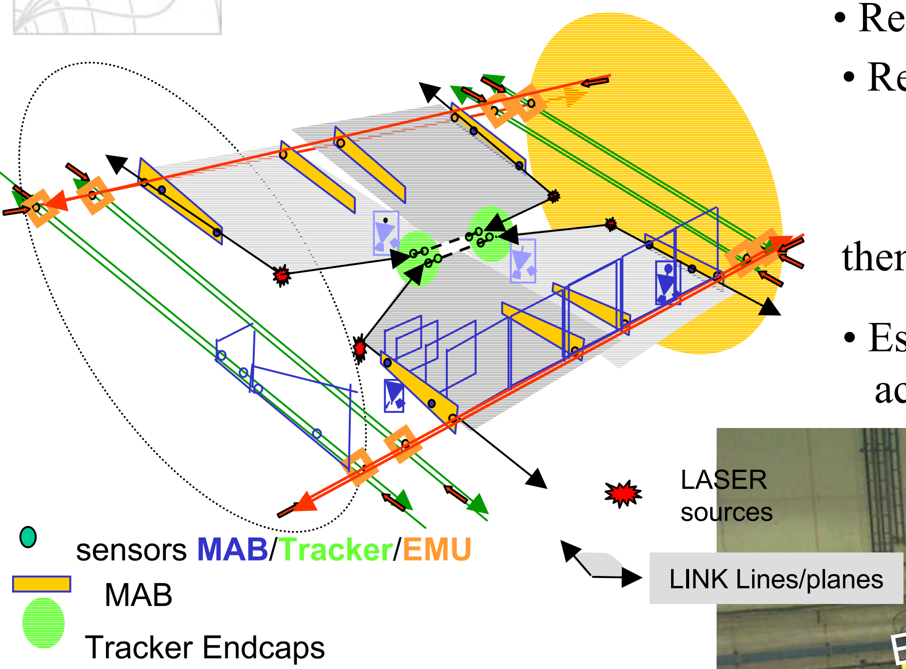
Range : ± 10º
Linearity: 2 %



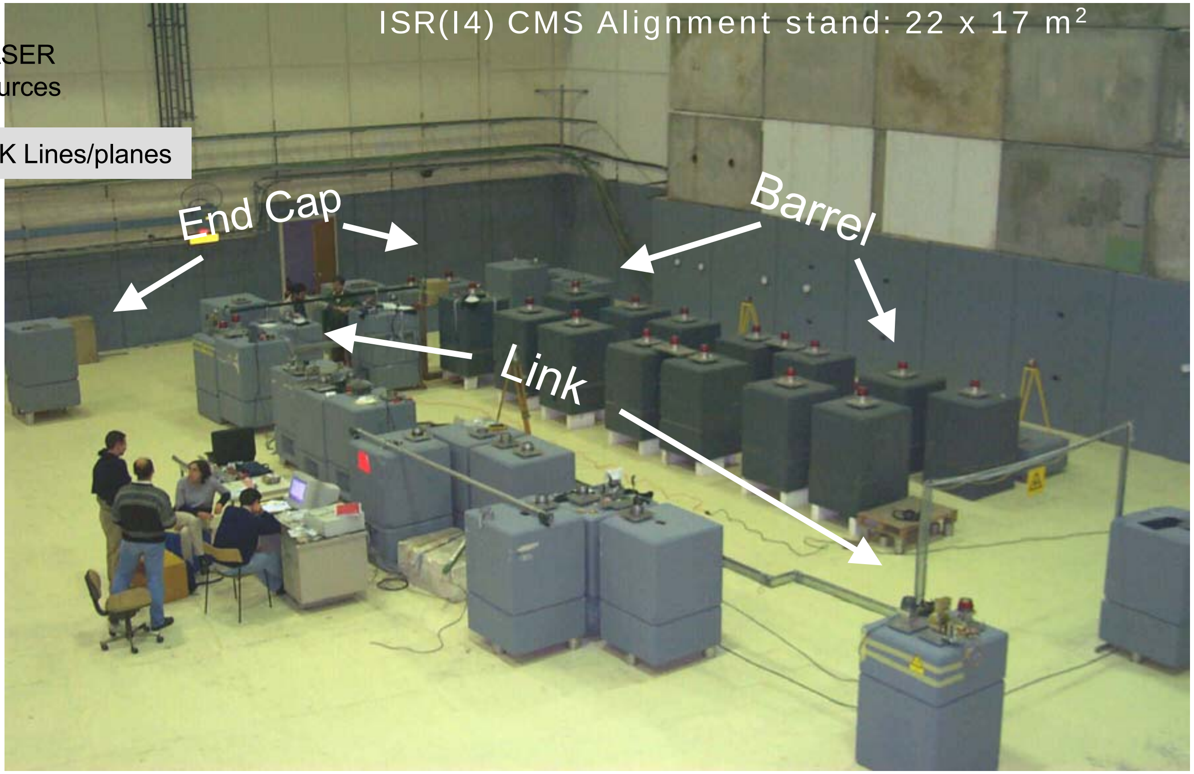
Characterization test:

- **Stability:** settling time (24-48 h after installation) **< 3 μrad in ~ 133 h.**
- **Linearity: residuals < 20 μrad**
- **Irradiation** : **γ up to 50 kGy + 2 x 10^{14} n/cm^2**
  ⇒ No changes
- **B test**: sensitive to field gradients (**< 40 μrad,** located in uniform B**)**

Real scale test



- Real scale version of a half of a CMS R-Z alignment plane.
- Relevant elements for the position monitoring:
  - track zone
  - ½ active plane of Barrel system
  - 2 endcaps lines + connection between them.
  - Link lines
- Estimation the system performance and measurement accuracy.



Absolute reconstruction of the measured positions for the Link system shown a precision ~ 200 μm

Ref. I. Vila, Prototype test of the Compact Muon Solenoid Alignment System, IWAA 2002.

Summary and next steps

- CMS has designed a complex alignment system
  - different component types were selected/developed fulfilling:
    - precision requirements
    - good operation in CMS environment (radiation, field, temperature…)
  - full scale test confirm required precisions
    - ~ 100-200 μm and 15-40 μrad in the relevant coordinates
- all components in production
- final calibration next year
- installation and commissioning in 2005 during CMS magnet test

Factorize the alignment task into:

- **Local or internal alignment**: Of individual subdetectors, so they may be considered as rigid bodies or blocks (6 degrees of freedom) / Position of individuals elements within a detector. (Vertex detector)
- **Global alignment**: spatial relation of these blocks to each other /Position of the various detectors with respect to each other. (Muon spectrometer w.r.t. tracker).
- The position of the experiment with **respect to the beam**

Ref.: M. J. Price, "Alignment of experiments" CAS-CERN Accelerator School: Mearurement and Aligment of Accelerator and Detector Magnets. Apr. 1997, Anacapri, Italy.

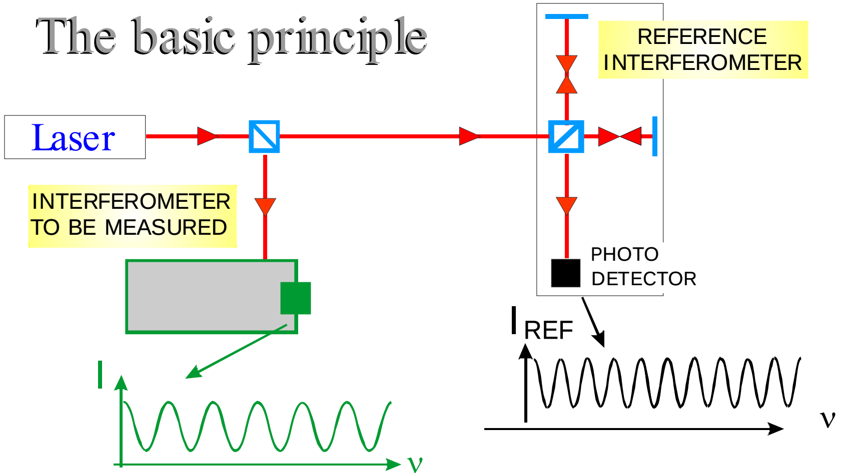
Phases of the alignment:

- At the **design** and **construction** of individual modules: assuring that the the components are located properly.
- During **pre-assembly** and **assembly** of modules in the detector: providing geometrical information on the difference between "as built" and "the theoretical or nominal" with a good accuracy.
- **After installation** of the detector onto the underground area.
- Periodically **during running** of the detector

FSI (Frequency Scanning Interferometry)

- **FSI** is a precise technique for multiple simultaneous absolute length measurements.

Absolute Distance Interferometry



•**Basic principle:**

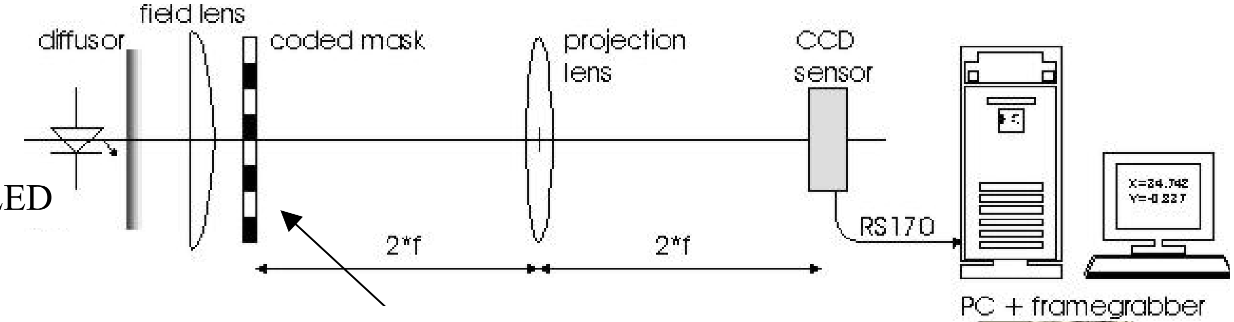
-A common **tunable laser** system is used for the **interferometers to be measured** and also for the **reference interferometer** (thermally stabilized).

- The optical **frequency** is simultaneous **scanned** in all interferometers.

- Each length is measured by **comparing** the **phase change** in each measured interferometer with the phase change in the reference interferometer.
- The ratio of phase change gives the ratio of lengths.
- Typical **precision 1 micron**

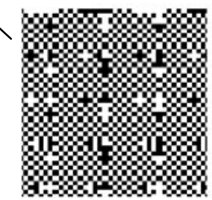
Ref. : P. A. Coe et al
"Frequency Scanning Interferometry in detail", IWAA 2002
"S. M. Gibson et al" Multiple, simultaneous length measurements" IWAA 2002
A. Mitra et al "Combination of FSI with other novel optical tools", *IWAA 2002*

CCD-RASNIK



Matrix LED

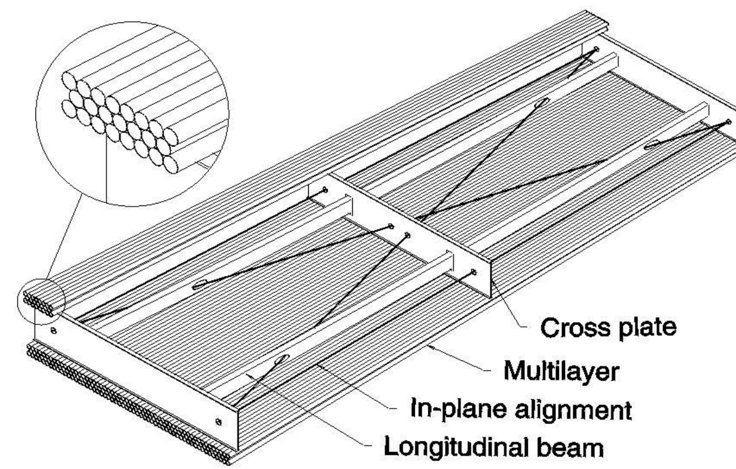
Coded Mask



- 3-point colinearity monitor.
- Each elements close to the measurement points.
- Range limited by the mask size

- **Precision Image**: provides (X,Y) point positions from Black-White transitions (in the CCD)
- **Z Coordinate** provided from Image Scale Factor
- **Rotations Z** coordinate provided from image tilt.

CCD-RASNIK technique is used in the alignment of ATLAS muon chambers.



Transverse resolution ~ 1 μm (at 5m)
Longitudinal resolution ~ 30 μm

4) Alignment with tracks

- **Historically the run-time alignment of particle detectors used the detected tracks to relate the position of the detector elements**
  - track extrapolation is compared with actual hits in sub-detectors
  - multi-parameter fit to the different degrees of freedom
- **However, in many cases this is a very slow process, sometimes implies recording large amount of data**
  - cannot usually monitor displacements occurring in short time
- **Subject to possible biases due to magnetic field or material description.**
- **All in all, for some coordinates and for stable displacements, it can provide precise results**

Combining of Monitoring information +Alignment by tracks

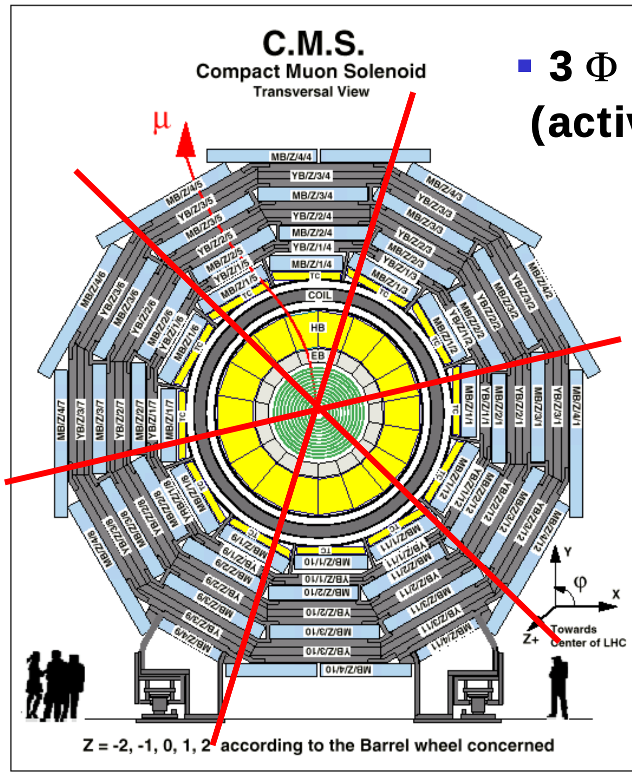
↓

Final geometry

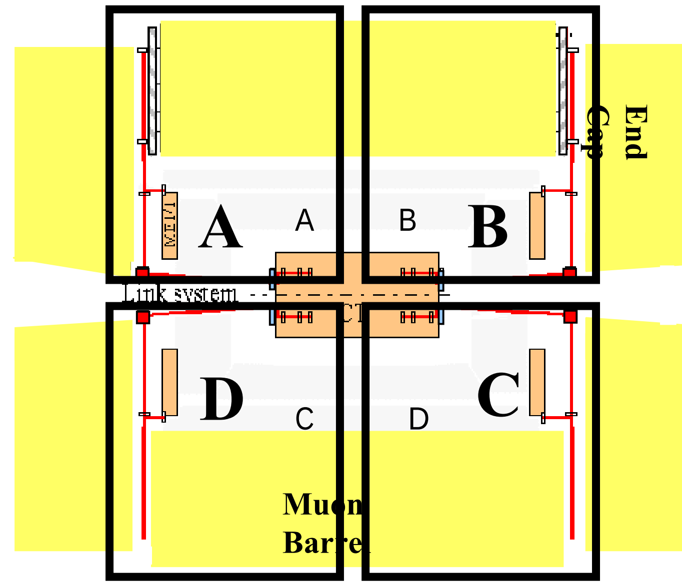
LINK System: geometry

Global alignment of CMS, transports central tracker coordinate system to Muon chambers defining a common system.

Multipoint alignment system (Straightness monitor)

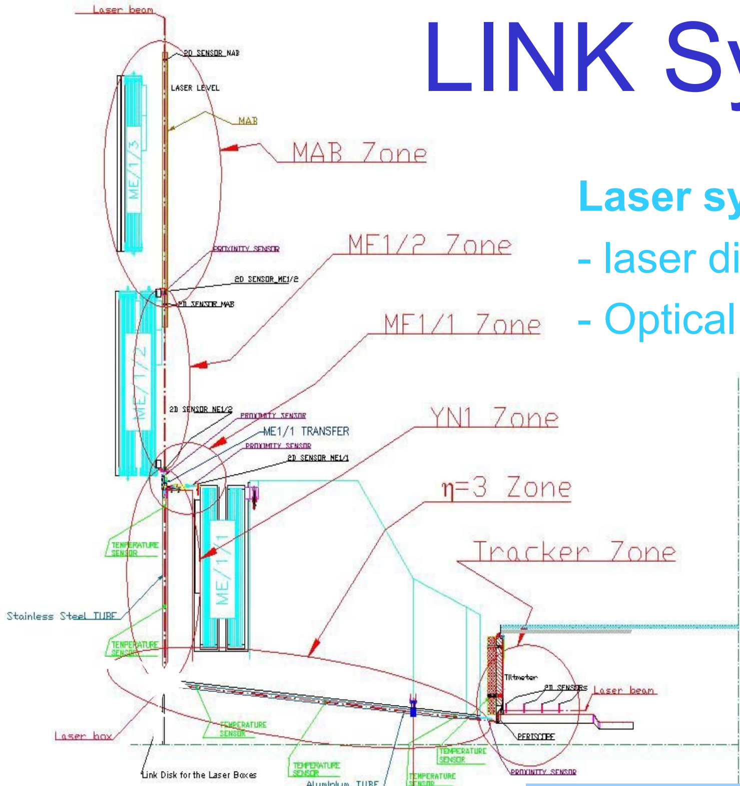


- 3 Φ linking planes (active planes)



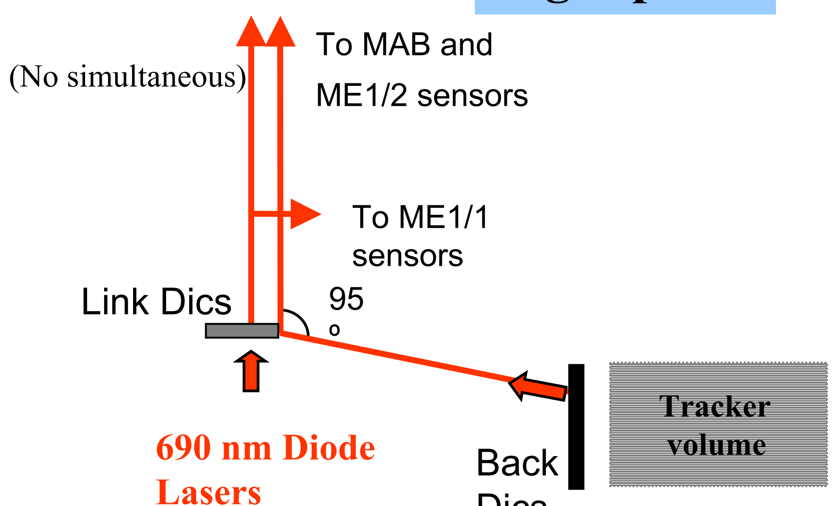
- Basic units 1/4 plane, connecting (by laser beams) tracker y muons
- Layout follow the CMS subdetectors geometry.

LINK System: components



R-Z Plane

Light paths



Laser system

- laser diodes (at 690 nm)
- Optical fibres & collimators

Sensors: type & technology

- Photo-sensors
- Inclinometers
- Displacement sensors
- Temperature sensors

Optics (definition of the light path)

- Beam splitters
- Prisms: Rhomboid prisms and pentaprisms.

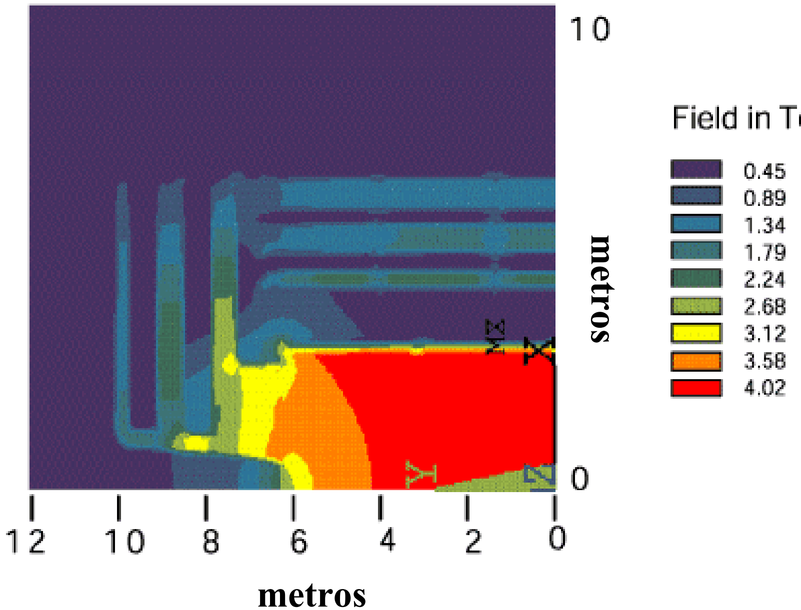
Mechanical components.

-CF supporting structures (MABs, Link wheel, bars)

Front-End & DAQ electronics

Most are commercial after an extensive and often non-trivial checks of performance characterization (also in the adverse environment: magnetic field and radiation)

LINK System: environment

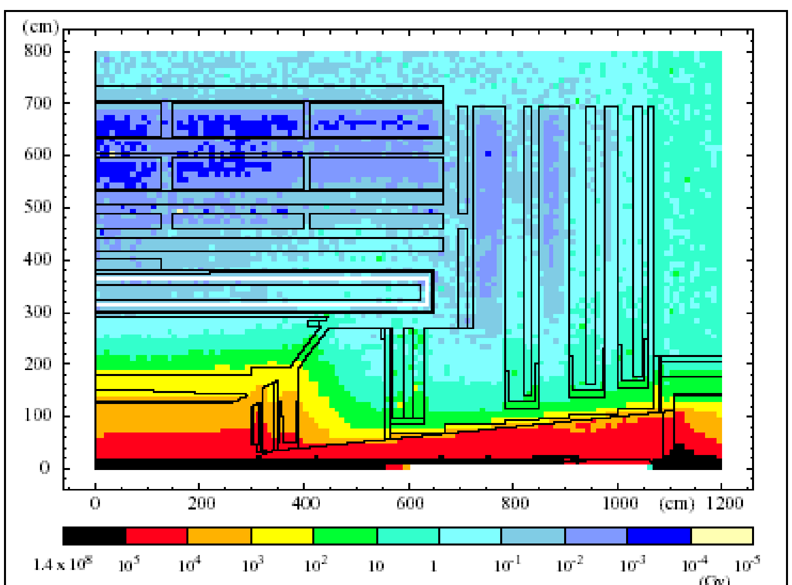


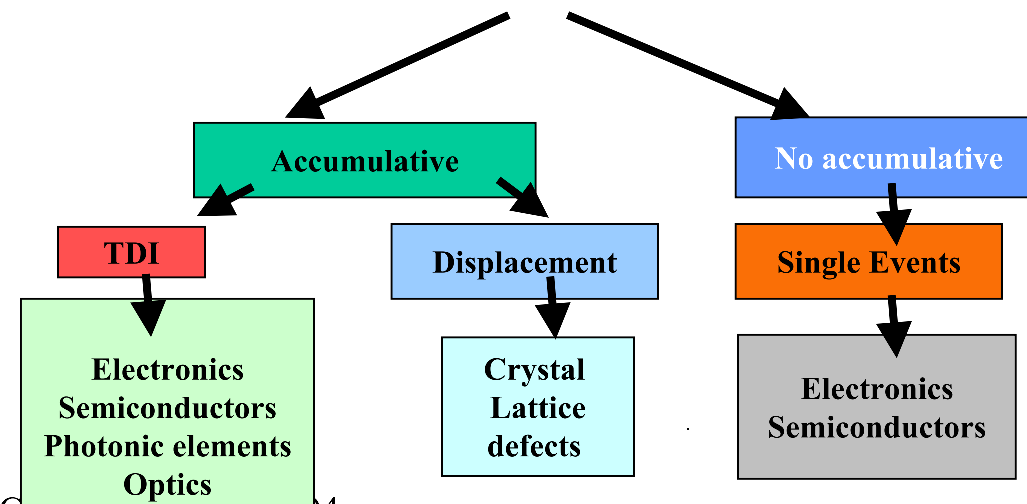
Magnetic Field

- 4 Teslas
- Gradients up to **600 Gauss/cm**
- Complex field map

Radiation environment

- Hard radiation environment
- Photons, neutrons, charged hadrons
- Dose: **1- 100 x 10^3 Gy (10 years)**
- Fluence **5 x 10^{10} - 2 x10^{14}** n/cm^2 (10 years)

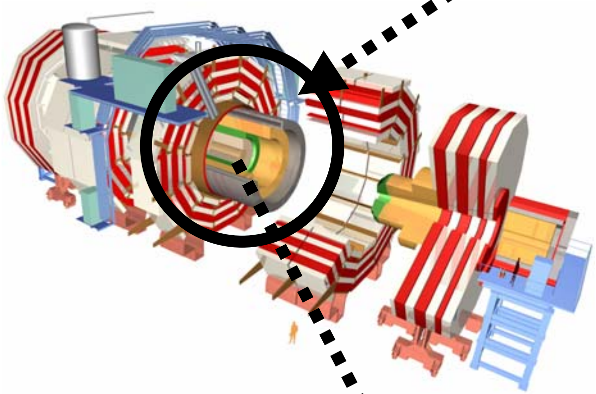




Laser system (I)

1. Diode Lasers (Out of CMS)

2. Single-mode optical fibers (distribute the laser light inside the detector)



3. Fiber Collimators (inside CMS) (generate a gussian beam at every measuring point of the light path)

1. Diode Lasers (Out of CMS)

Several commercial samples from two manufactures:

- **MONOCROM**
- **Schäfter+Kirchhoff**

at different wavelengths were tested.

- **Total lasers: 18**
- **Wavelength driven by the sensitivity of the photosensors:**
  Working wavelength 690nm
- **Output optical power 30 mWatt.**
  (due to losses in optical fibers and optics)
- **Power modulation**
- **Optical power stability better than 1%**

3. Fiber Collimators (inside CMS)

- **Commercial**
- **Gaussian spot w/o distortion along the working path (2 to 10 m)**
- **Hard-rad and non-magnetic materials (Titanium, fused silica lens)**

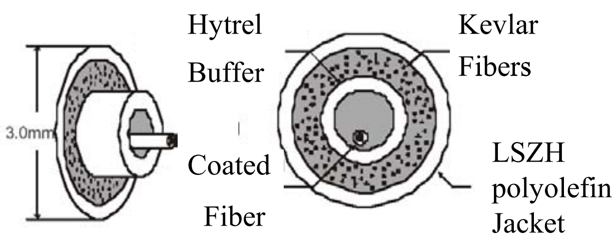
Laser system (II)

2. Single-mode optical fibers (distribute the laser light inside the detector)

- **Single mode optical fiber cables at working wavelength (690nm). Gaussian beam at the output of the fiber.**
- **FC/PC connections.**

Fibre	Reference	Diameter (μm)	M.F.D. (μm)	Cut- Off Wavelength (nm)
3M – I	FS-SN-3224	125/250	4.0	620
3M – II	FS-SC-5624	125/250	6.6	950
Corning	HI 1060	125/245	6.2	920
OFS	CF04247-02	125/245	4.3	620
Nufern	S630	125/245	4.2	570

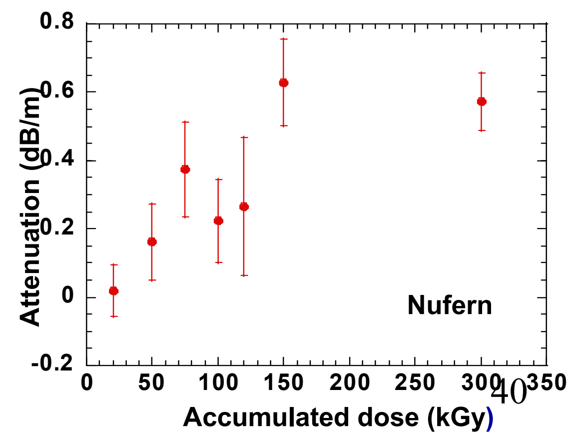
•Radiation tolerance a) Rad-hard materials: **Pure Silica Core**
Silica cladding
Acrylate Coating
(OK CERN safety test)



b) Radiation.induced absorption (RIA)

γ and n irradiation ⇒ Formation (or activation) of 'colour centers', which absorb light at particular wavelengths. One order of magnitude higher in visible range than in infrared.
At Tracker < 1dB/m up to 100 kGy dose and 2 10^{14} n/cm^2 in 10 years. (1dB : 80%)

670 nm
Dose rate: 140 ± 14 Gy /min



Complete characterization:
active measurements under gamma and neutron irradiation.