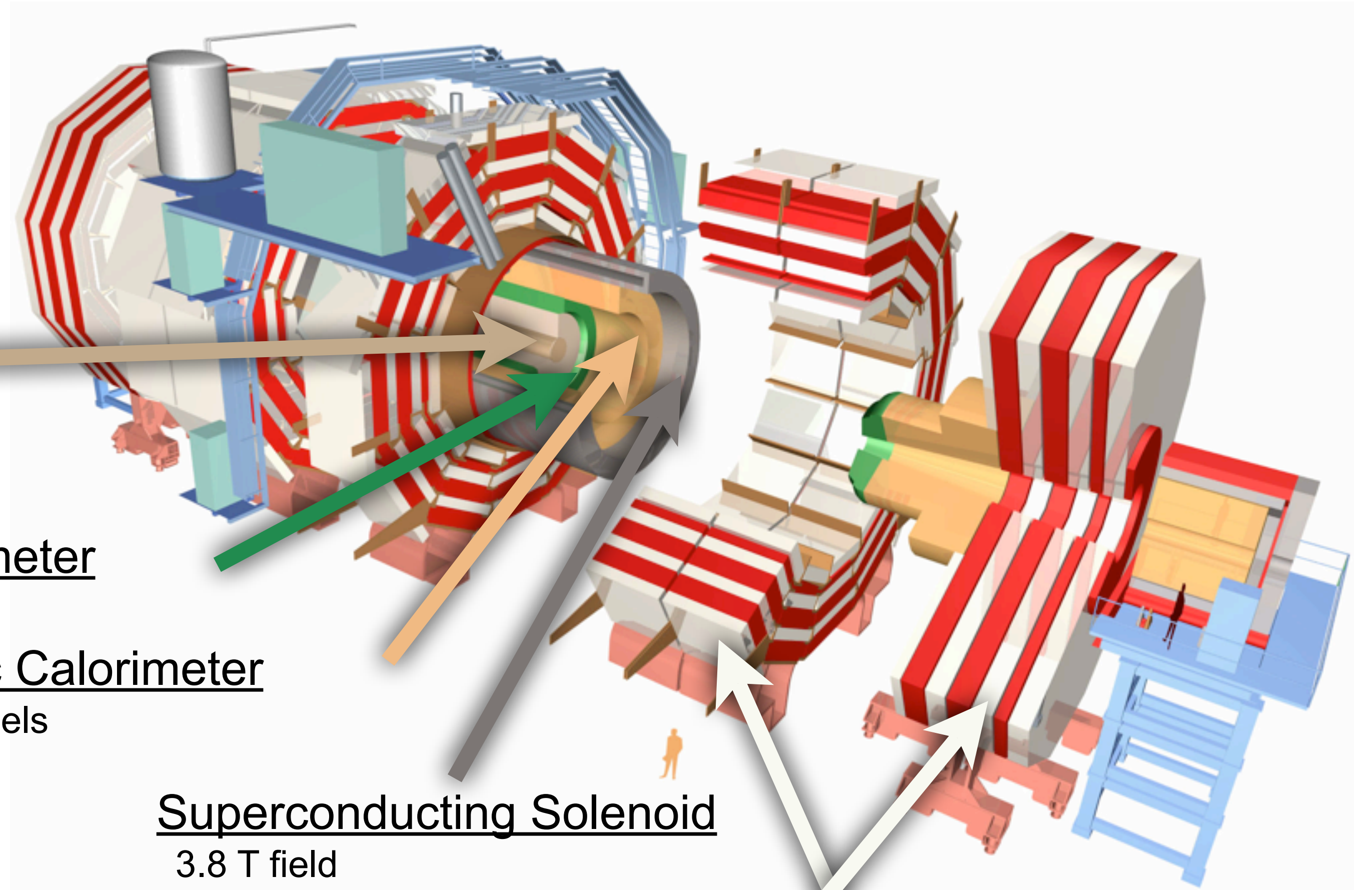
The Upgrade of the CMS Tracker for the HL-LHC

Andreas Mussgiller
DPG Tagung Göttingen
1 März 2012

HELMHOLTZ ASSOCIATION

DESY

The CMS Experiment at LHC



Tracker
76M channels
16588 modules

Electromagnetic Calorimeter
76k channels

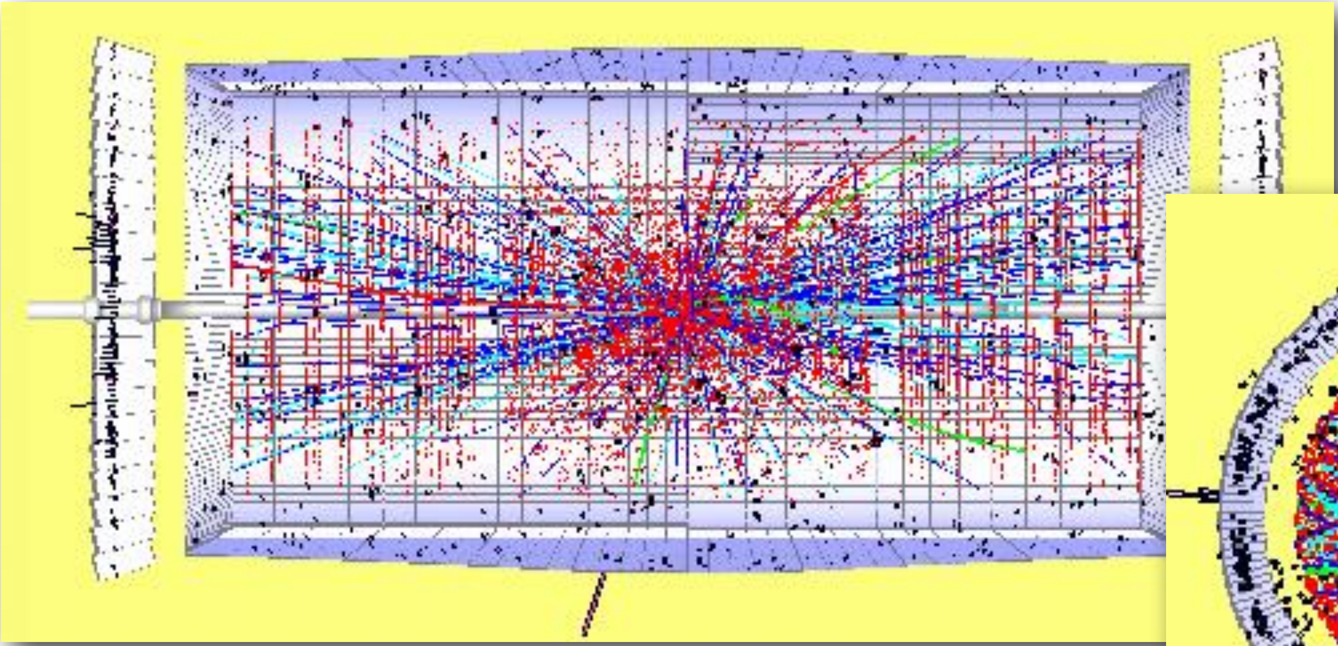
Hadronic Calorimeter
10k channels

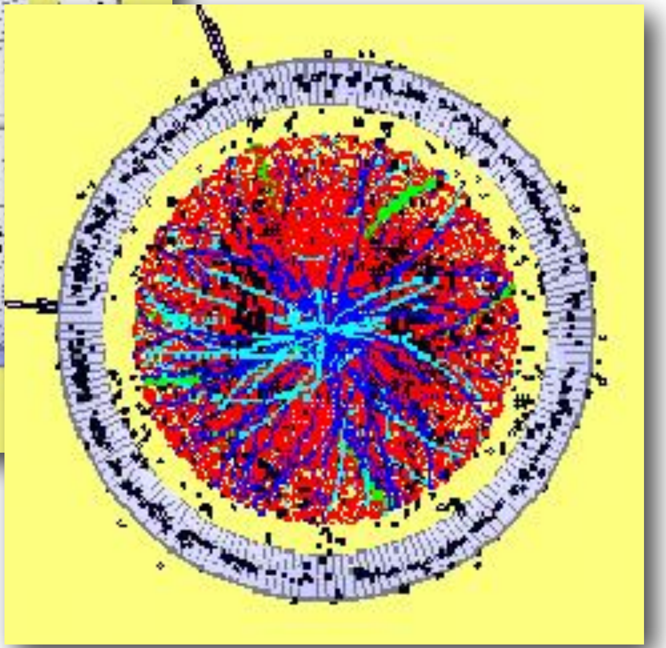
Superconducting Solenoid
3.8 T field

Muonspectrometer
840k channels
1400 chambers

Weight	12500 t
Length	21,5 m
Diameter	15 m

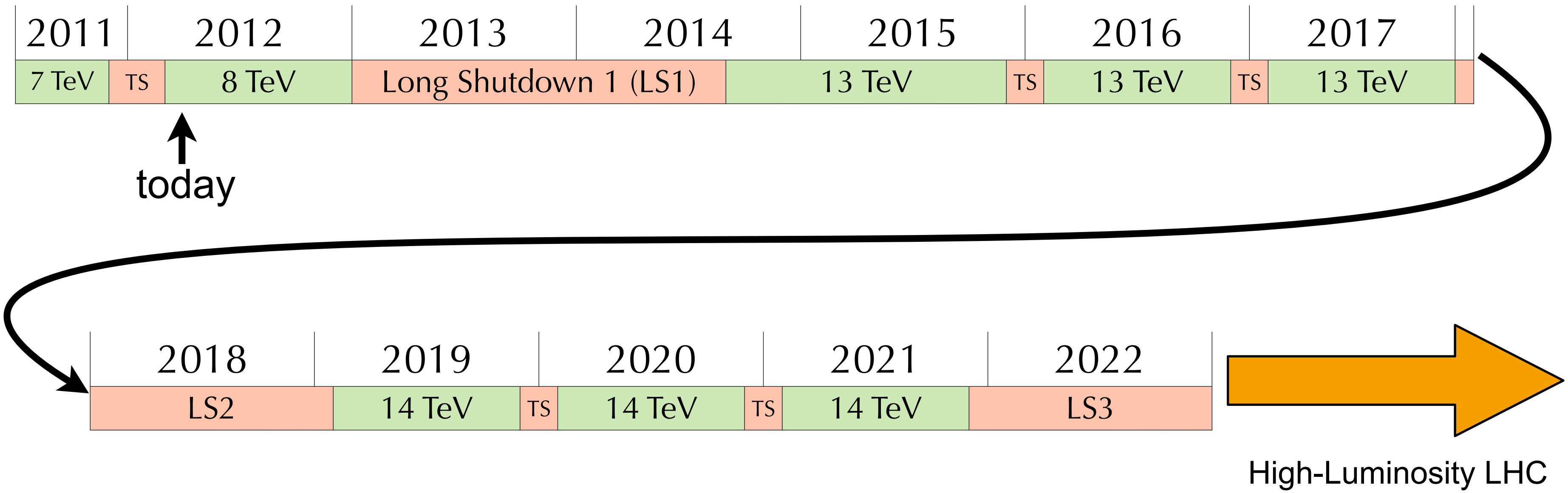
Event at a Luminosity of 10^{34} $cm^{-2}s^{-1}$





- Design luminosity of LHC
- Limit of the current tracker
  - would become inefficient for higher luminosity
- Peak luminosity for 7 TeV running is $3.5 \cdot 10^{33}$ $cm^{-2}s^{-1}$

Preliminary LHC 10 Year Plan



- Several upgrades planned for LS1 and LS2
- High-luminosity LHC era starts in 2023
- Expect $5 \cdot 10^{34}$ cm^{-2}s^{-1} delivered to CMS
- CMS will install a new and improved tracker during LS3

Requirements to the future CMS Tracker

- Higher granularity to deal with increased occupancy
  - Modules will have shorter strips
- Tracker must provide trigger to be used in the Level-1 trigger
  - Input rate to Level-1 trigger needs to stay below 100kHz
- Higher power consumption in the front-end requires new powering scheme
  - DC/DC conversion close to or on the modules
  - Less resistive losses

T63.7

- Use radiation hard sensor material
- Sensors must be kept below -20°C
  - Switch to evaporative CO_2 cooling
  - Need an excellent design to have sufficient cooling while having low mass

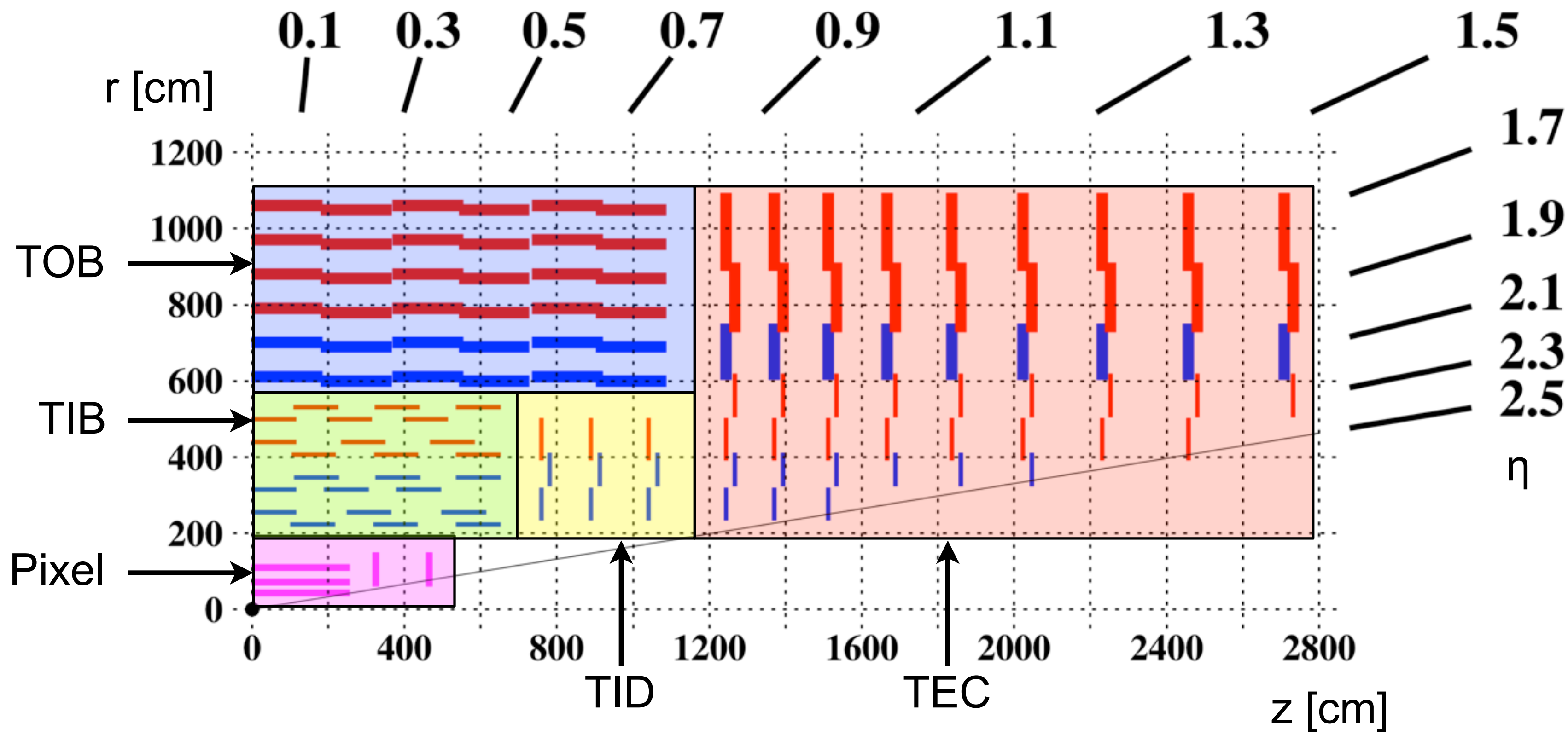
T63.9 T63.10 T67.3 T69.5

- Reduce the material budget
  - Current tracker is rather heavy
  - A performance limitation of the existing tracker

Outline

- Overview of considered module types
- Layout of the future tracker
- Finite element analyses of modules
  - thermal
  - thermo-mechanical
- Measurements
- Outlook

Layout of the current Tracker



single-sided modules — ~10 cm strip length

double-sided modules — ~20 cm strip length

(sandwich with 100mrad stereo angle)

- 15148 modules (excluding pixel detector)
- 27 different module types

Current TEC Module

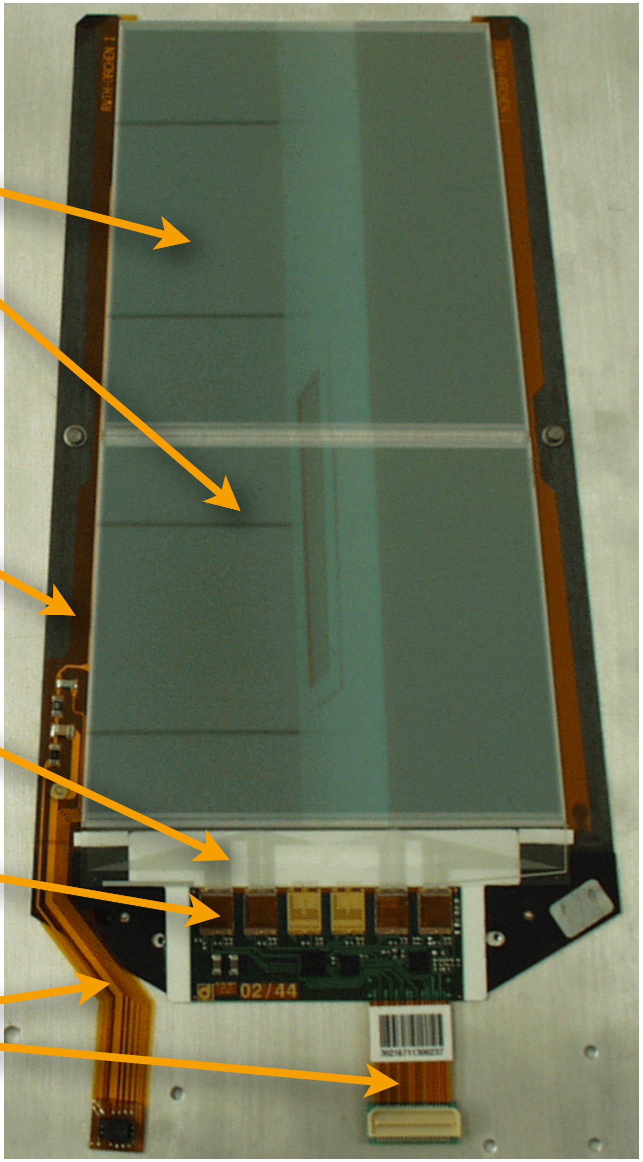
silicon sensors
~20 cm strip length

carbon fibre
support

pitch adapter

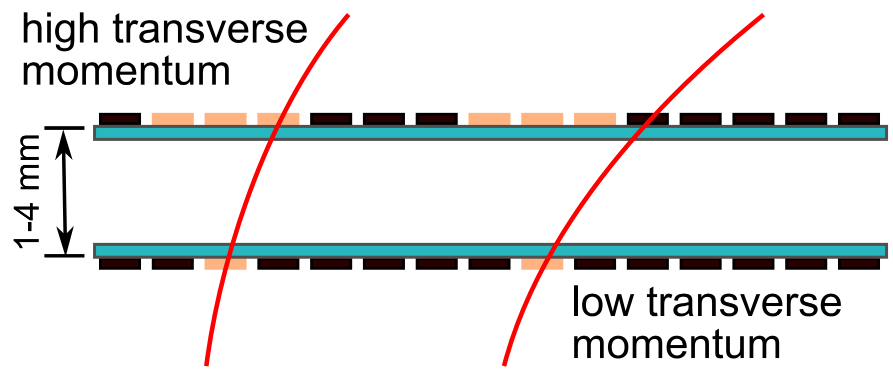
hybrid
front-end electronics
with read-out chips

kapton flat cables
for power and data

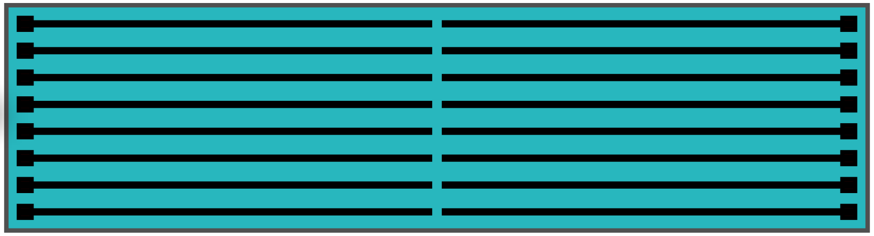


Concept of the future Modules

- Modules will provide trigger signal for high pT tracks
  - will be used in the Level-1 trigger system
- Each module will consist of two sensors at a distance of 1 - 4 mm
  - strong magnetic field of CMS allows for a measurement of pT on the module
  - hits in both sensors are correlated
  - matching hits have to be within a search window
  - distance between sensors depends on module position (r and η)



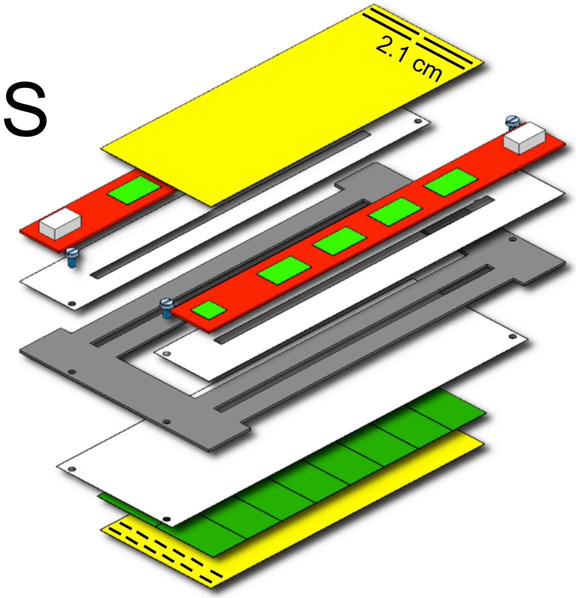
- Increase granularity, i.e. shorter strips
  - read out at both ends of the strip



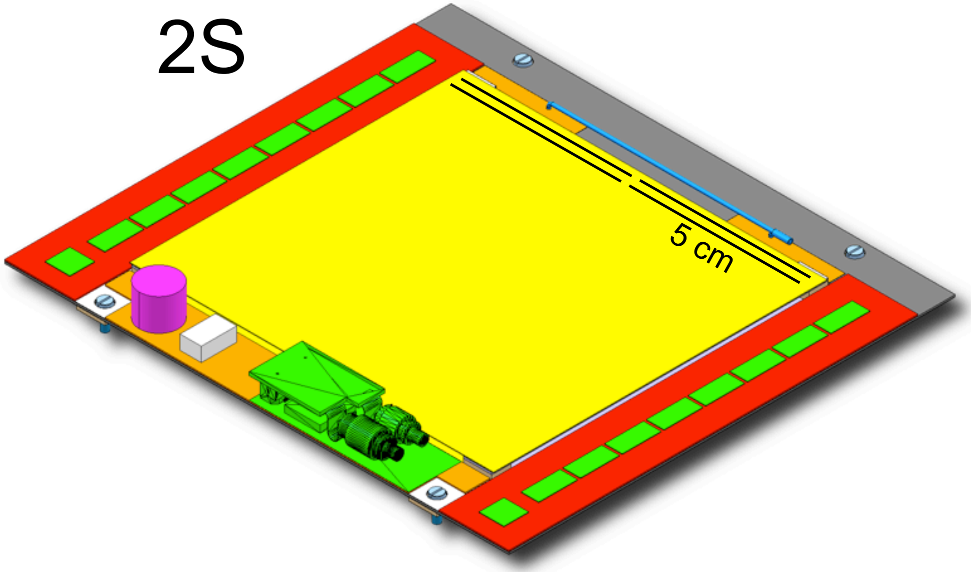
- Only two different module types throughout the tracker
  - with a few different sensor spacings
  - makes the module design much more easy

Considered Module Designs

PS



2S

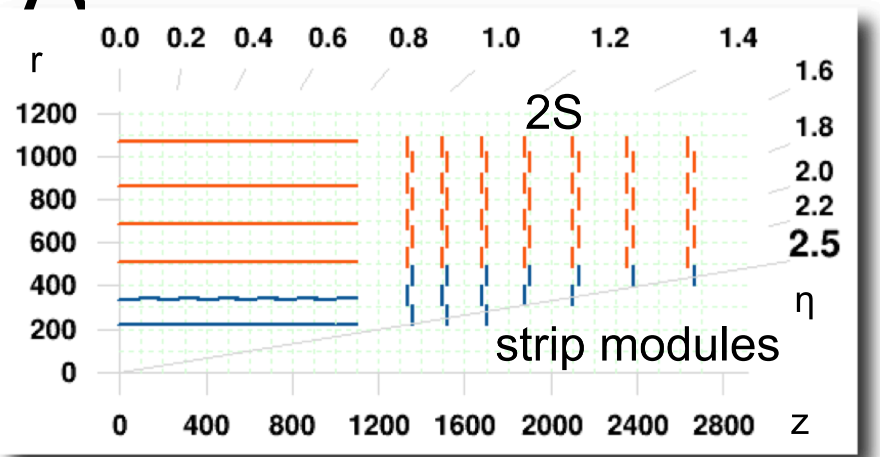


- Sandwich of a pixel and strip sensor
  - 4.2 cm x 9.4 cm active area
  - 2.1 cm long strips (100 µm pitch)
  - 1.5 mm x 100 µm pixels
- Trigger capability implemented in pixel read-out chips
- Provides 2D information

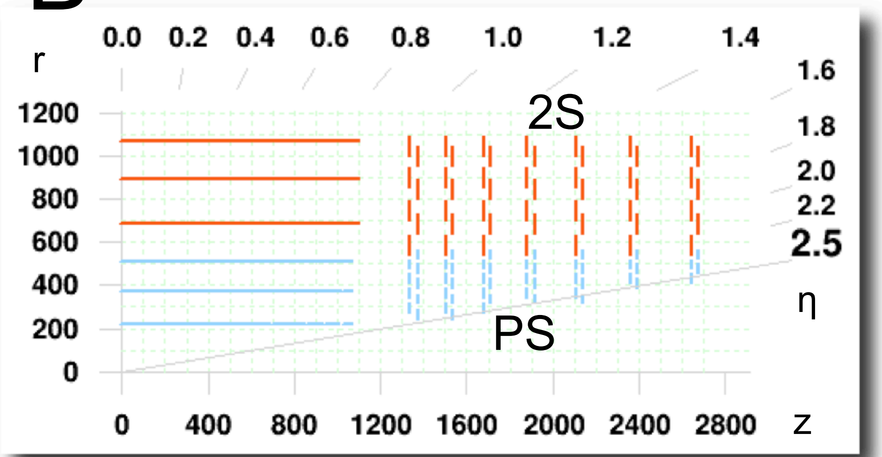
- Sandwich of two strip sensors
  - 10 cm x 9.2 cm active area
  - 5 cm long strips (90 µm pitch)
- Trigger capability implemented in read-out chips
  - CMS Binary Chip under development in the UK

Tracker Layout Options

A barrel & end-cap design

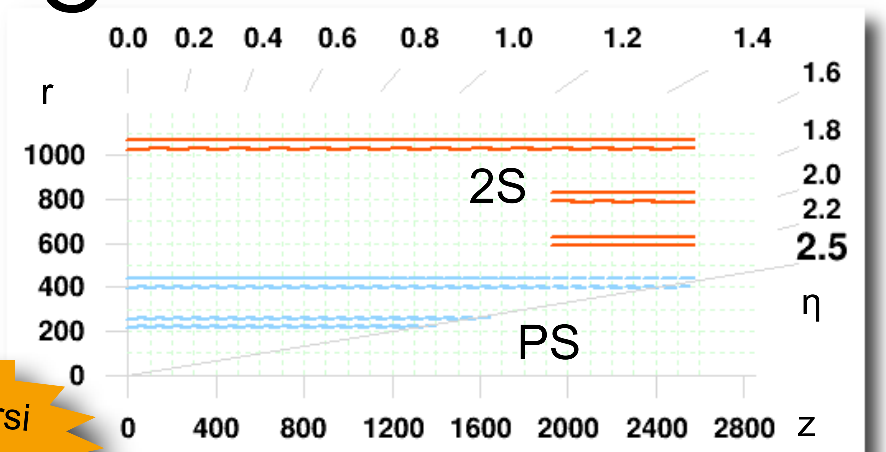


B barrel & end-cap design



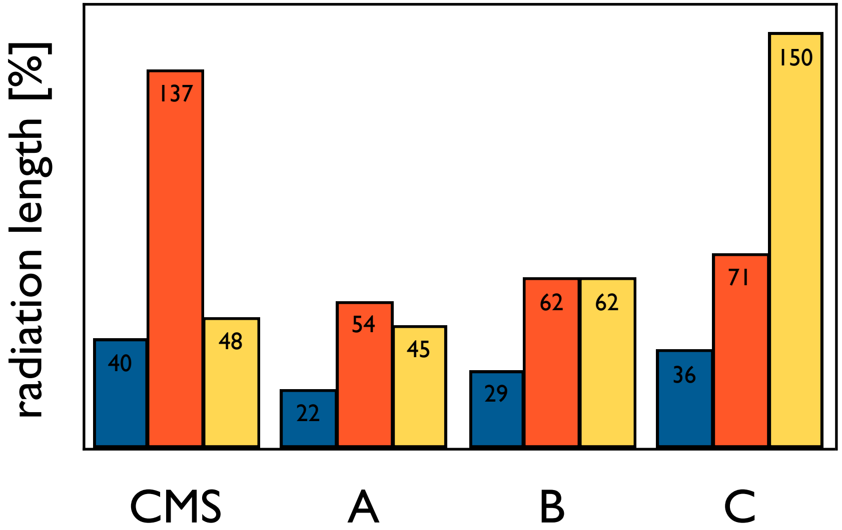
- A: standard strip modules at r < 50 cm
- B & C
  - PS modules at r < 50 cm
  - 2S modules at r > 50 cm
- More design options under investigation

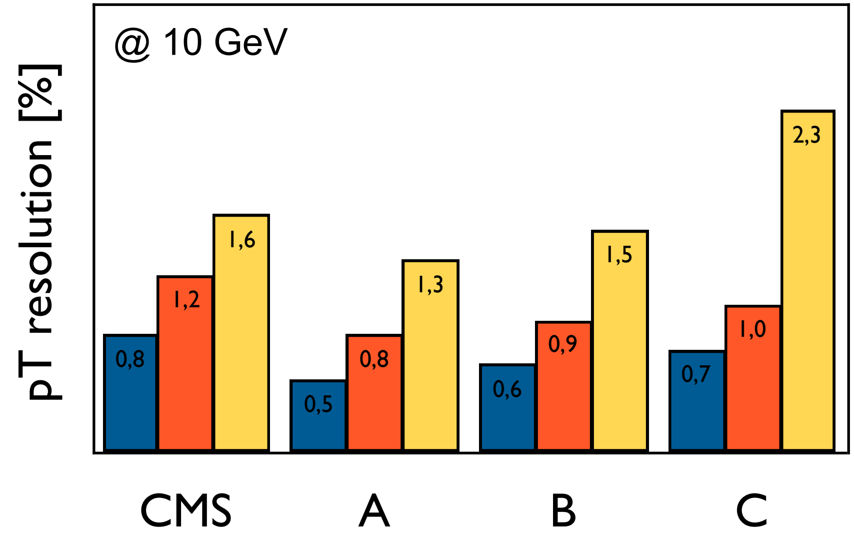
C long barrel design

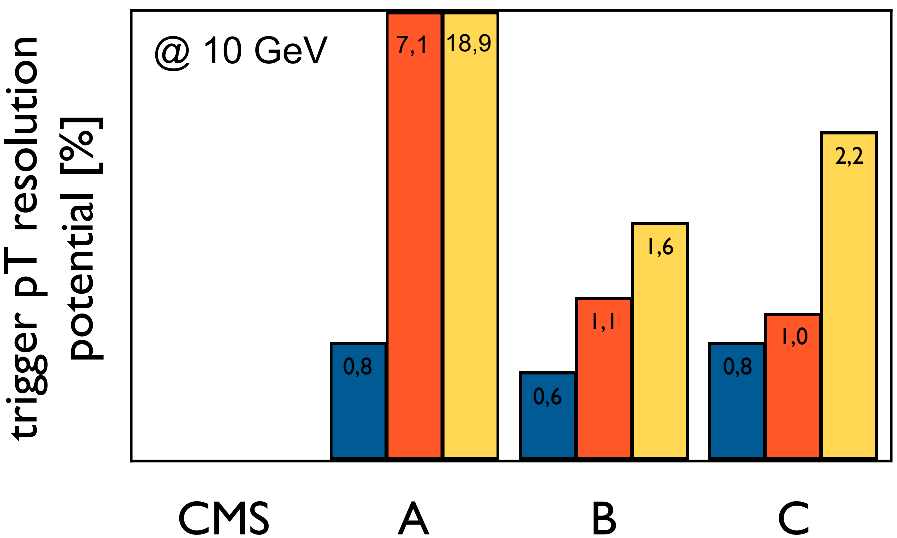


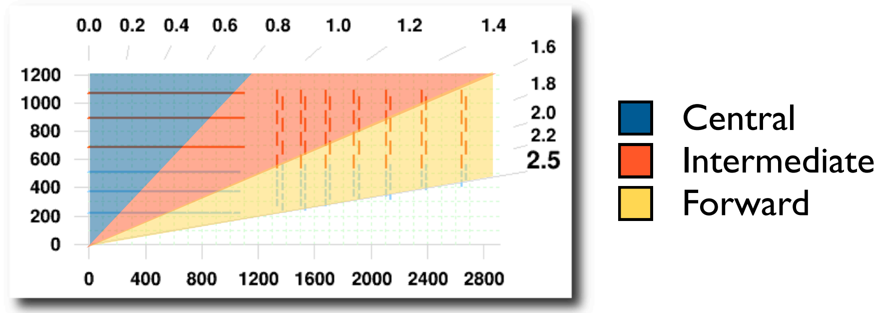
Studies by S. Mersi et al. (CERN)

Layout Comparison



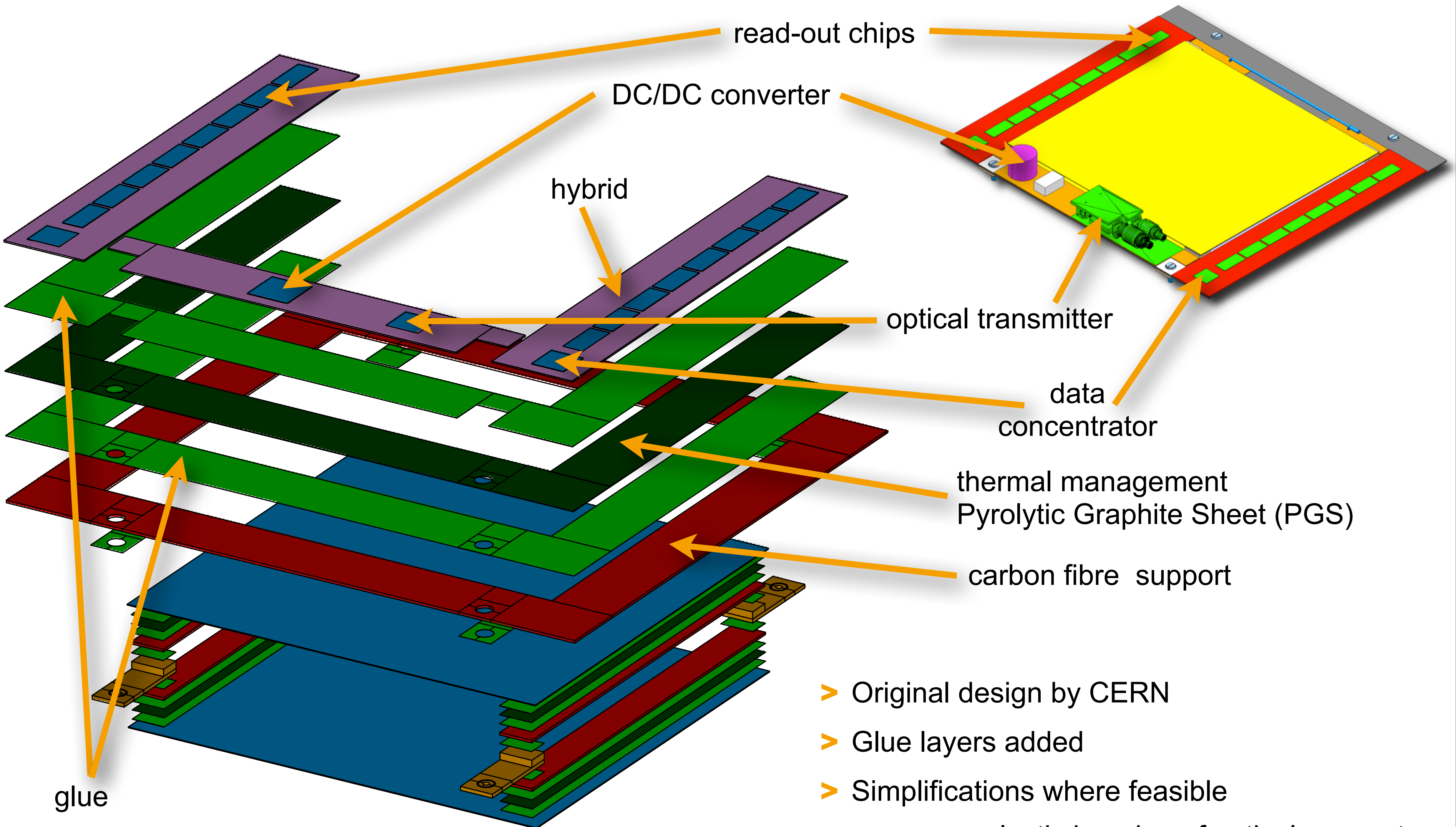






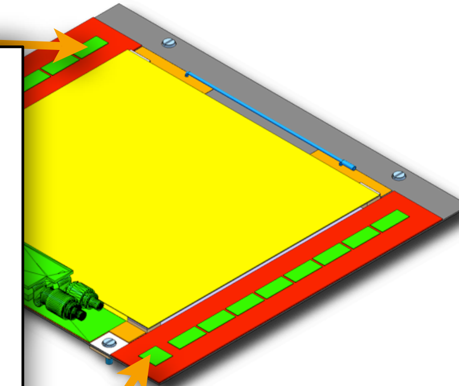
- Preliminary result suggests layout with PS and 2S modules in a barrel & end-cap configuration (B)
  - low material budget
  - good tracking and trigger performance

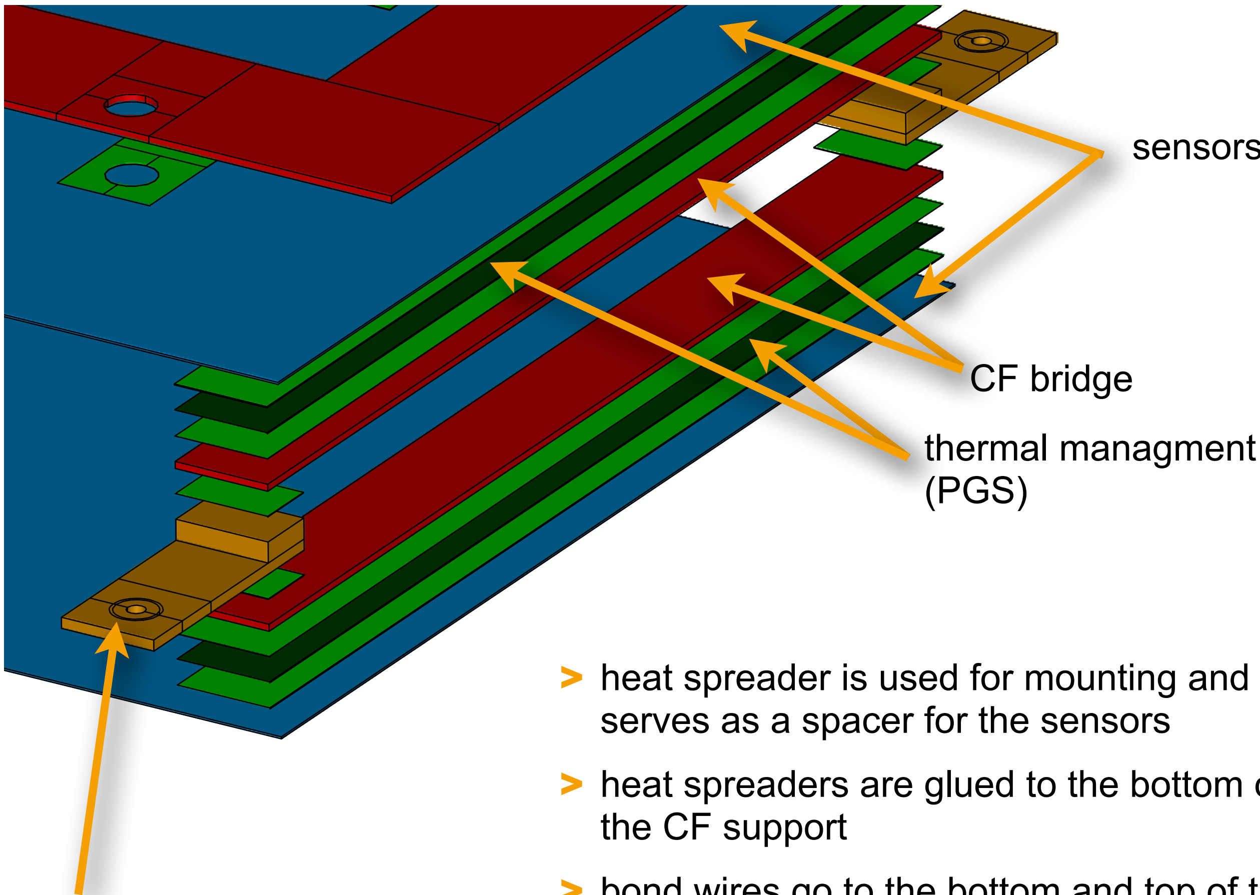
Finite Element Model of the 2S Module



- Original design by CERN
- Glue layers added
- Simplifications where feasible
  - e.g. plastic housing of optical connector is not modelled

Finite Element Model of the 2S Module (cont.)





- heat spreader is used for mounting and serves as a spacer for the sensors
- heat spreaders are glued to the bottom of the CF support
- bond wires go to the bottom and top of the hybrid

r

rator

nagement
aphite Sheet (PGS)

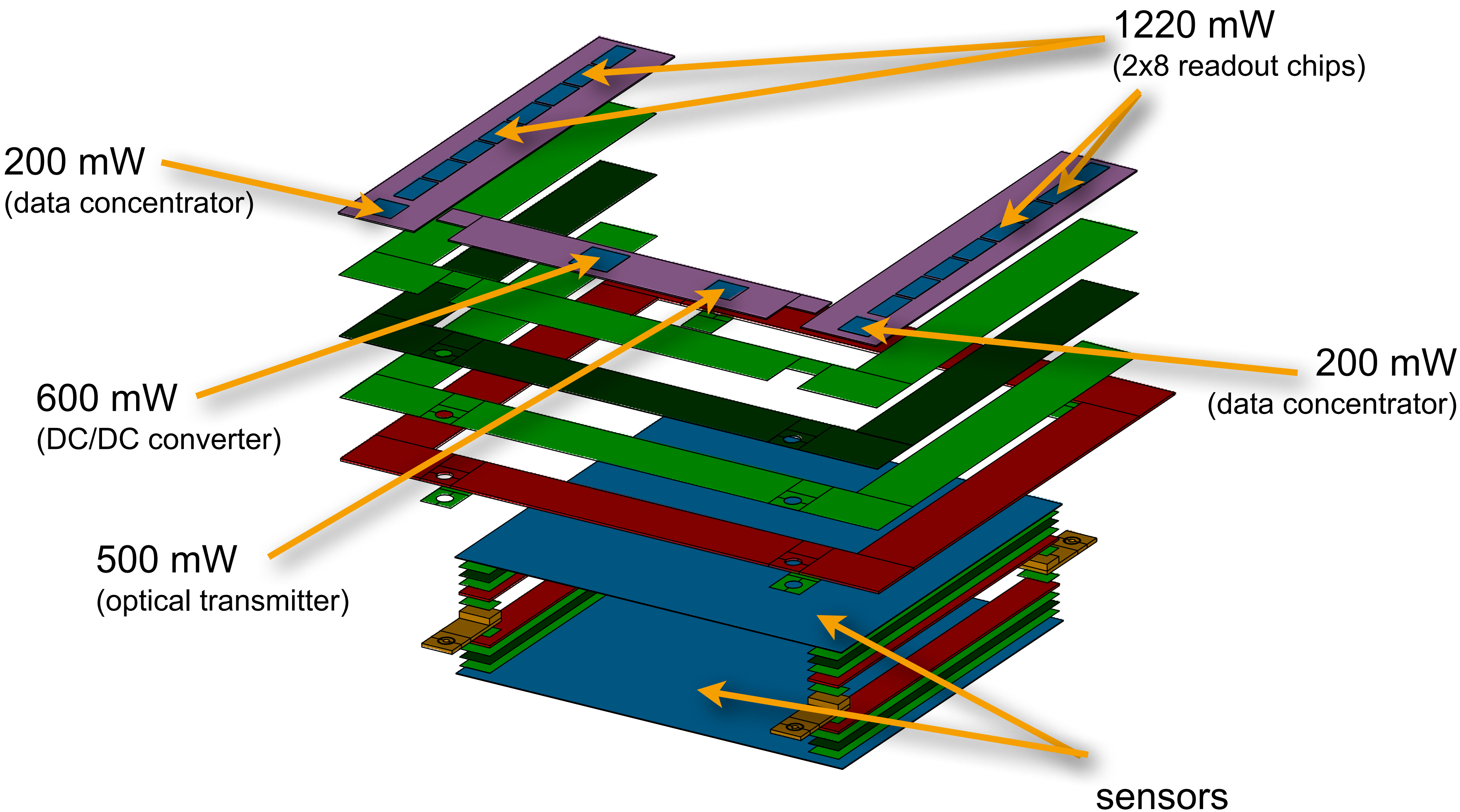
by CERN

ed

where feasible

e.g. plastic housing of optical connector is not modelled

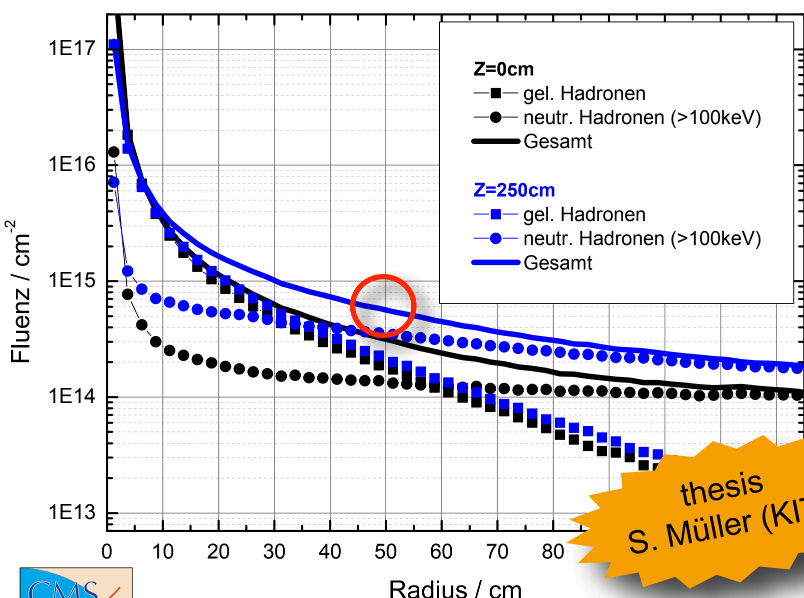
Thermal Loads



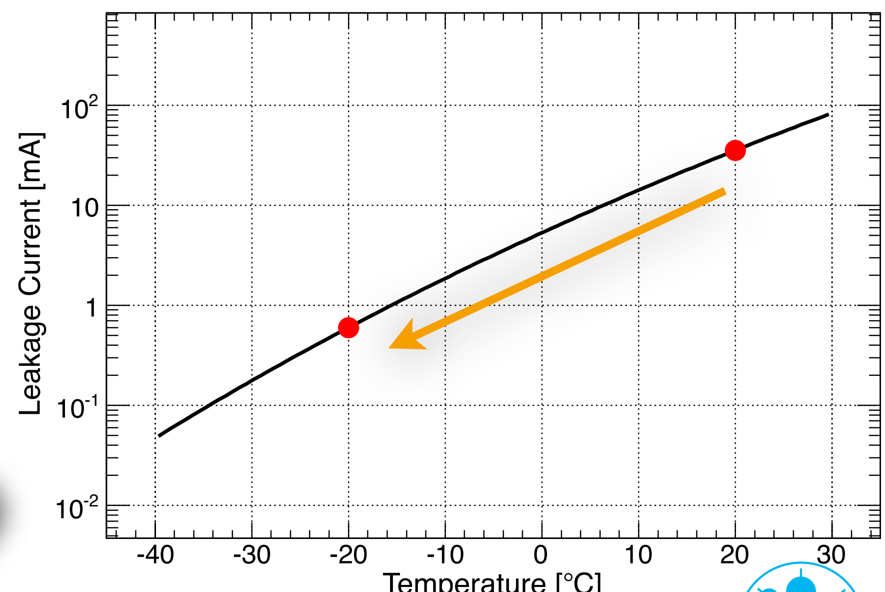
> Total power of front-end electronics: 2.72 W

Thermal Loads - Sensors

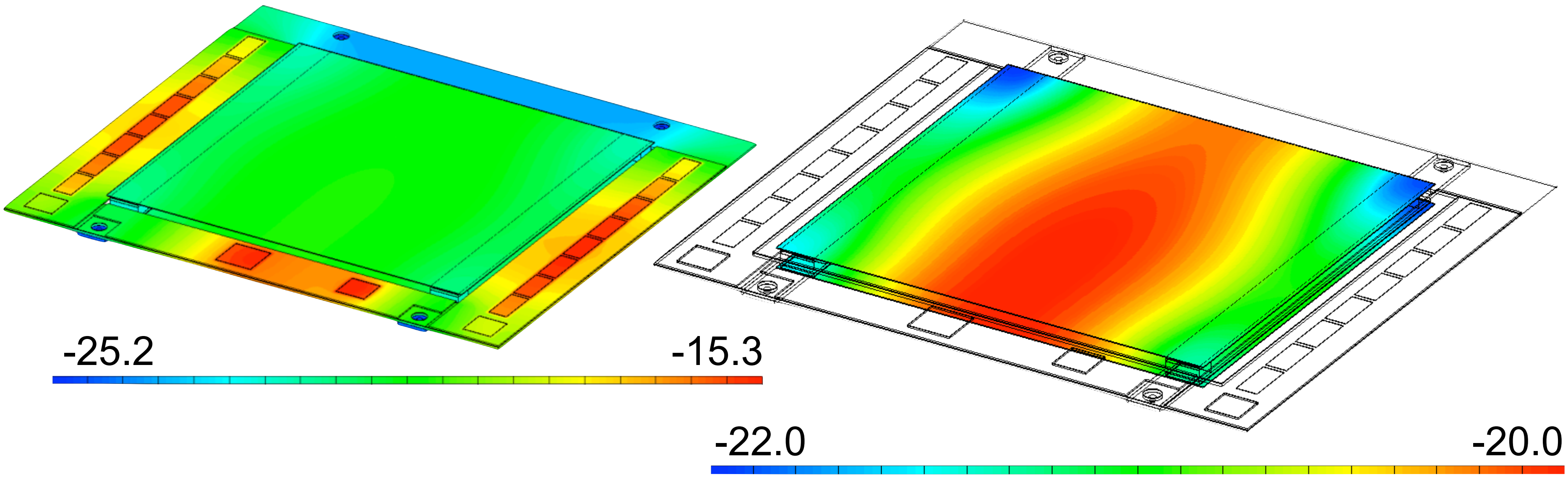
- Power consumption of sensors depend on temperature and radiation damage
  - Use maximum fluence for a given module type and 3000 fb^{-1}: $\Phi = 5.5 \cdot 10^{14}\ 1/\mathrm{cm}^2$
  - Leakage current at RT: $I = \underbrace{5.5 \cdot 10^{14}\ 1/\mathrm{cm}^2}_{\text{fluence}} \times \underbrace{1.84\ \mathrm{cm}^3}_{\text{volume}} \times \underbrace{4.0 \cdot 10^{17}\ \mathrm{A/cm}}_{\text{damage constant}} = 35.4\ \mathrm{mA}$
  - Scale leakage current to -20°C: $I \propto (kT)^2 \exp\left(-\frac{1.21\ \mathrm{eV}}{kT}\right) \quad \Rightarrow \quad I = 0.60\ \mathrm{mA}$
  - $P = 0.60\ \mathrm{mA} \times 600\ \mathrm{V} = 360\ \mathrm{mW}$
- Total power consumption by module: 3.44 W



thesis
S. Müller (KIT)



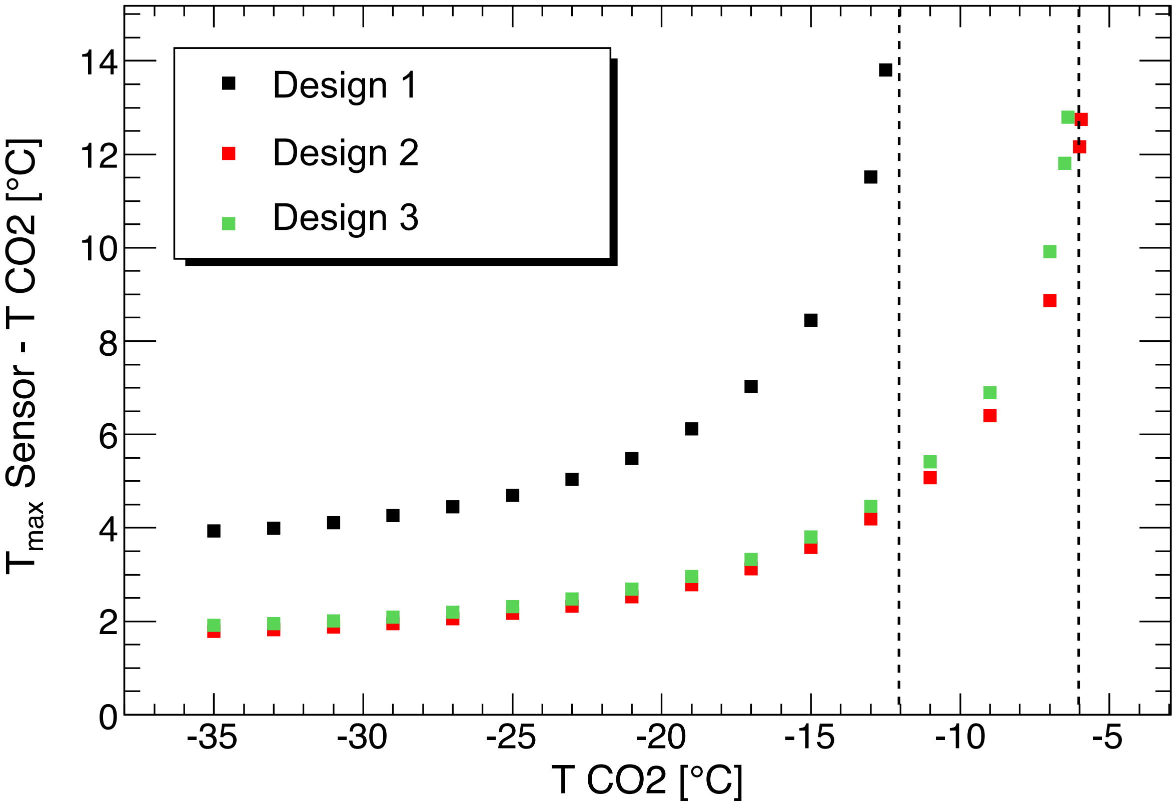
Thermal Finite Element Results - Sensors



- Temperature of cooling contact tuned to get temperature on sensors below -20°C
- Very good thermal coupling between sensors and cooling contact
  - temperature gradient between cooling contact and sensor is only 5.2°C (design goal is 10°C)
  - temperature gradient on sensors is 2°C
- Sensor power consumption is calculated for a uniform temperature distribution
  - power consumption is overestimated ➟ safety margin
- Study is not sensitive to temperature at which thermal runaway occurs

Thermal Runaway

- Leakage current doubles for approximately every 7°C increase in temperature
  - positive feedback behavior
  - for too high temperature cooling will not be sufficient
  - module will not be operable ➟ thermal runaway

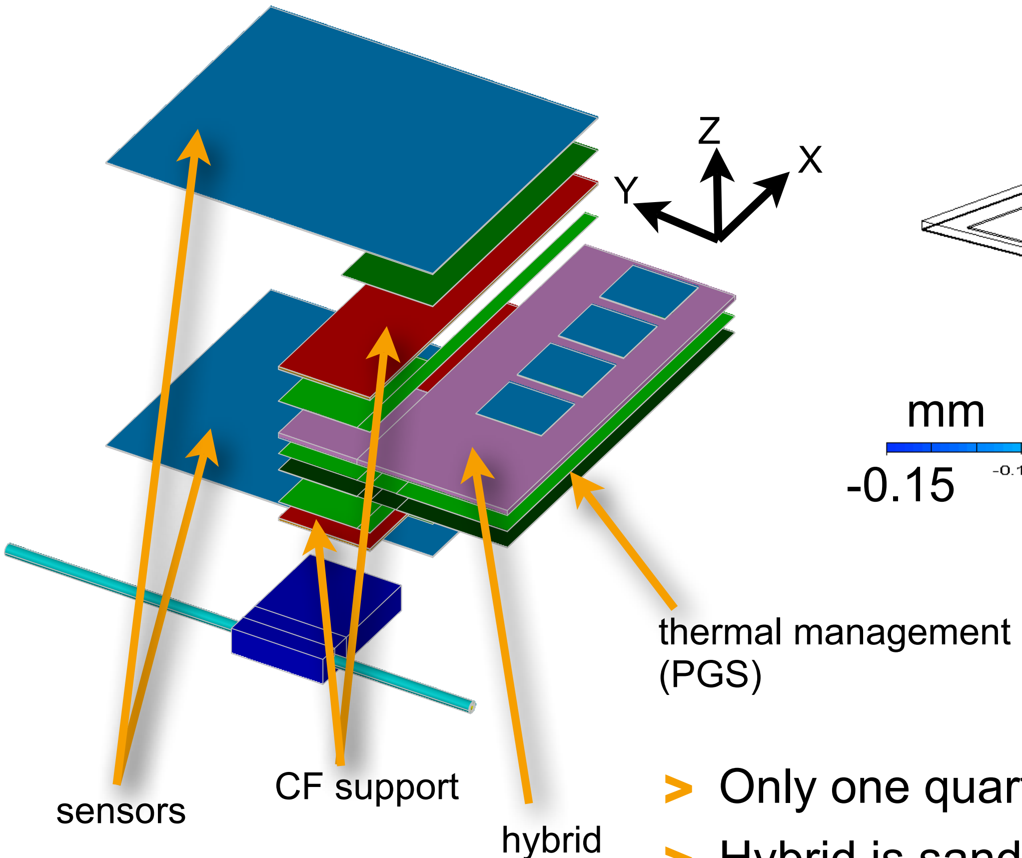


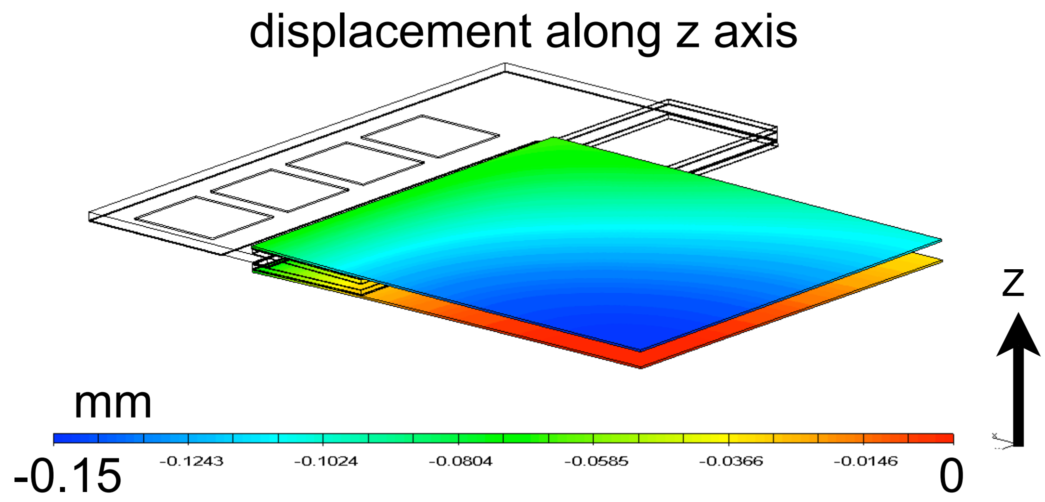
- Plot shows results from an early design phase
- Has to be repeated for the ‚final' PS and 2S module designs

Thermo-Mechanical Finite Element Analyses

- All considered module designs consist of multi-layer sandwiches
  - 2S Module: Al/Be heat spreader - CF support - PGS - hybrid substrate
- Mismatches in the coefficient of thermal expansion (CTE) cause thermal stress and deformation
  - lifetime of sensor can decrease due to stress
  - stress can cause glueings to fail after several thermal cycles
  - deformation can lead to a non-uniform spacing of both sensors in a pT trigger module
- FE Model from thermal studies is used to investigate stress and deformations
  - results from the thermal FEA are used in the stress analysis
  - module is assumed stress-free at room temperature
- Results on the next slide are for an early design stage of the 2S module

Thermo-Mechanical Results

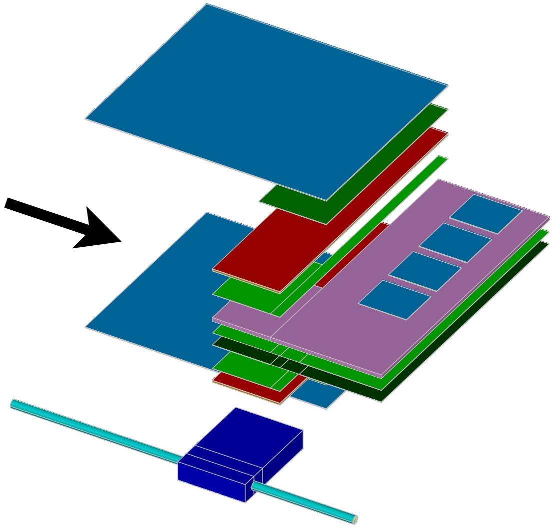


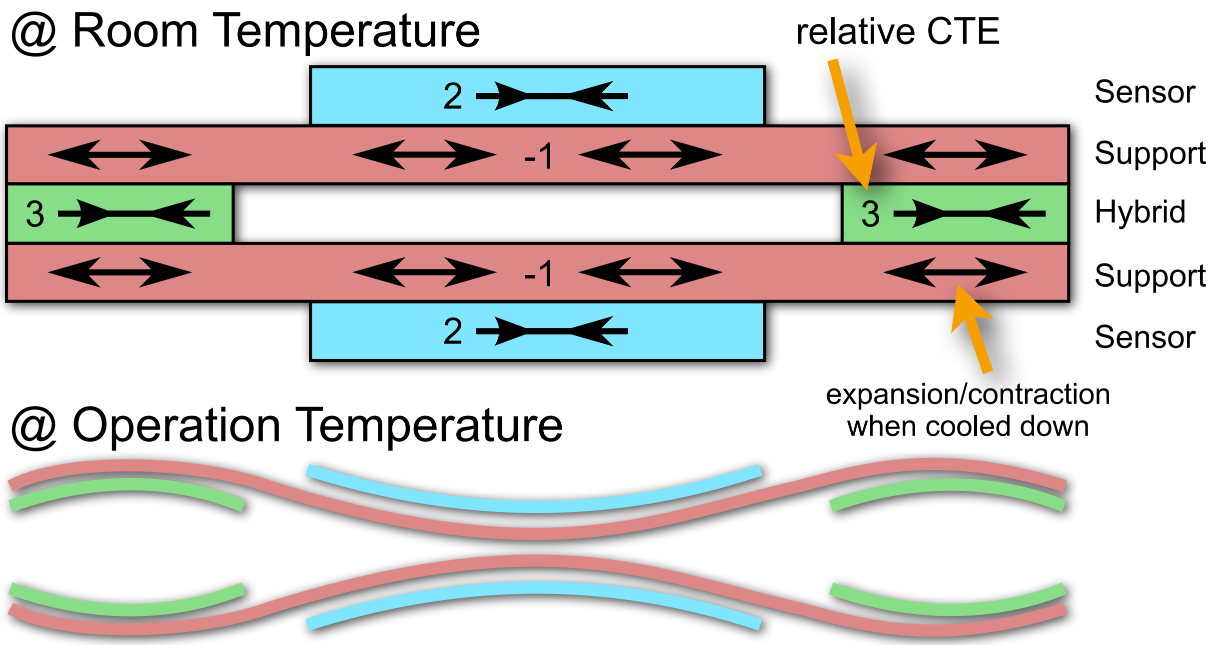


- Only one quarter of the module is shown
- Hybrid is sandwiched between two CF support strips
- Hybrid is L-shaped

- Distance between sensors decreases by 150 µm ➟ 15% for 1 mm spacing
  - strongly affects the trigger performance

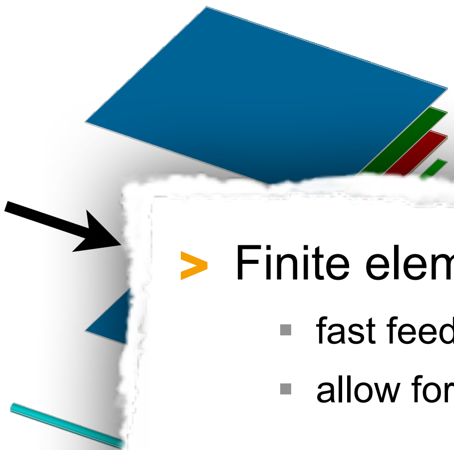
Thermo-Mechanical Results (cont.)





- Edge: bending due to hybrid vs. CF support CTE mismatch
- Center: bending due to CF support vs. sensor CTE mismatch
- Large deformation can be avoided by filling the gap between the support strips
  - too much material reduction can ‚amplify' the effects of CTE mismatches

Thermo-Mechanical Results (cont.)



@ Room Temperature

relative CTE

Sensor

pport

brid

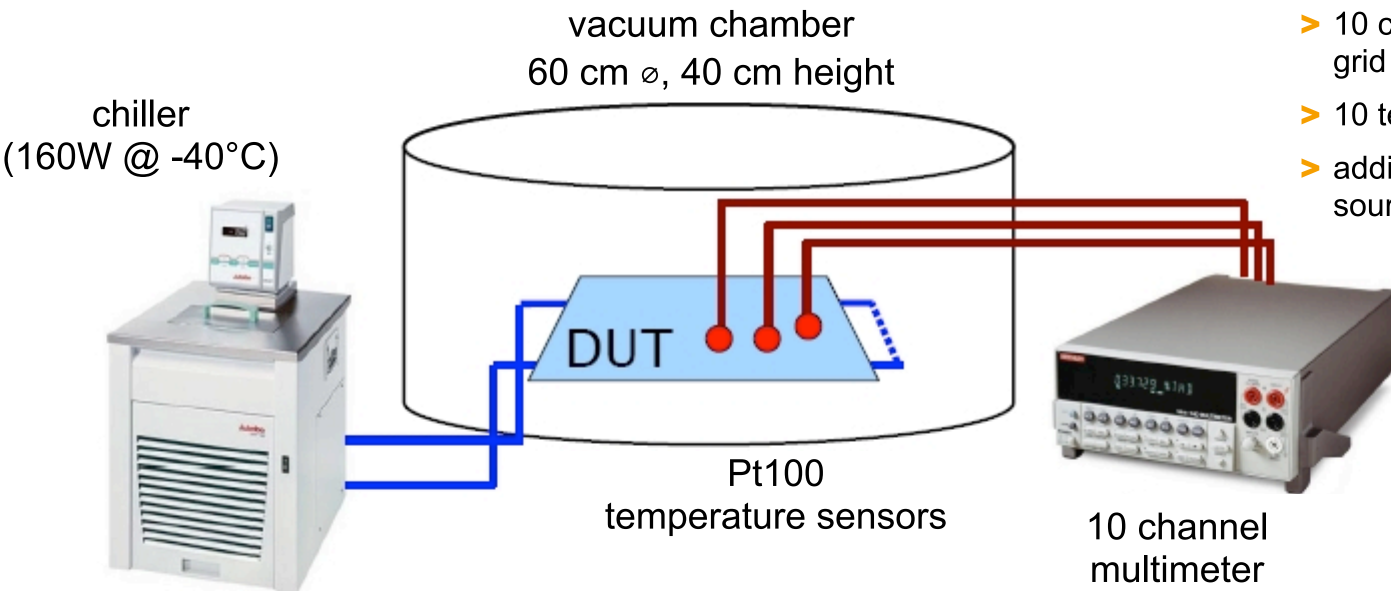
upport

nsor

- Finite element analyses are a powerful tool
  - fast feedback of the behavior and performance of a design
  - allow for a qualitative comparison between design options
- Finite element models are often too perfect
  - e.g. perfect glue layers with uniform thickness and no air entrapments
  - making the model more realistic is a big effort
- Results rely on the material properties used in the calculation
  - often not very well known
- Behavior and performance of design has to be confirmed by measurements

- Large deformation can be avoided by filling the gap between the support strips
  - too much material reduction can ‚amplify‘ the effects of CTE mismatches

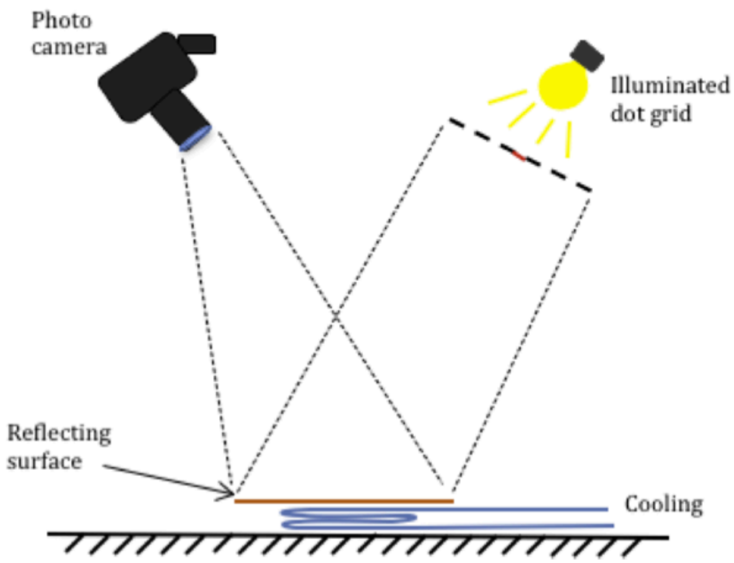
Thermal Measurements

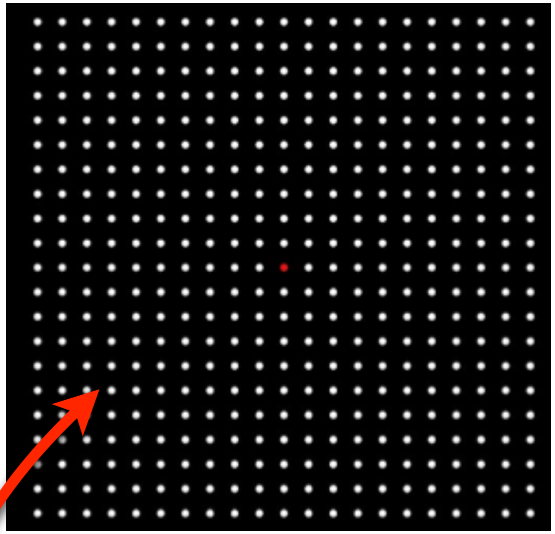


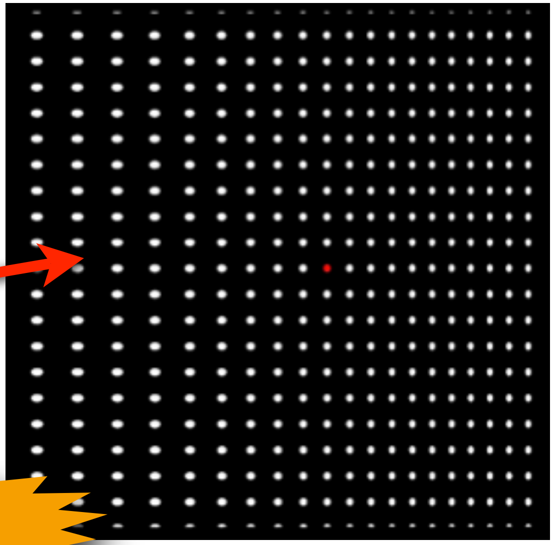
- Conventional cooling with silicon oil
- 10 cm x 20 cm table with mounting grid as a cold mass
- 10 temperature sensors
- additional feed-throughs for power sources

- Study details of the module design with test structures
  - confirm thermal properties of novel material
  - many aspects of the module designs factorize
  - investigate behavior of gluings and thermal interfaces - e.g. pipe to module
  - feed results back into FEA and module design
- Measure thermal performance of prototype modules

Optical Deformation Measurements



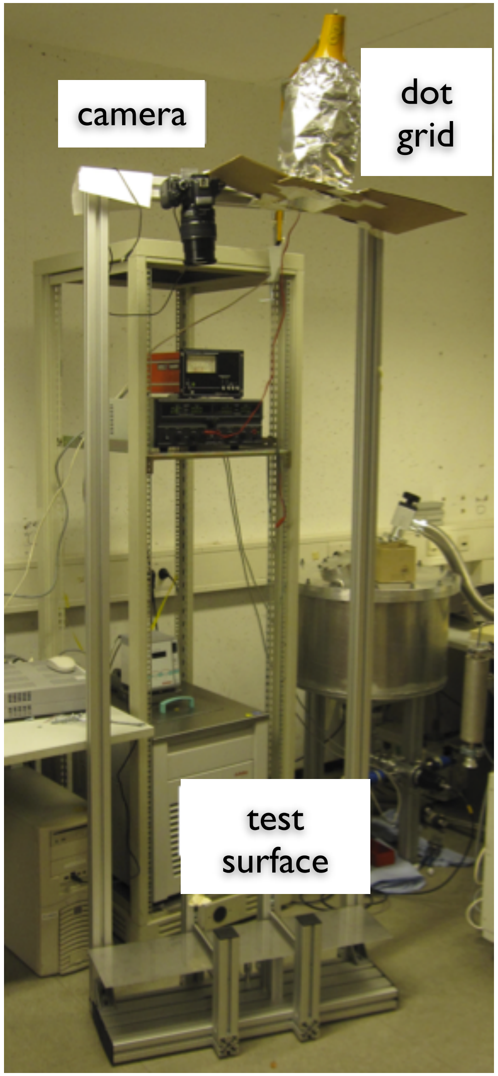




- Camera takes pictures of a back-lighted dot-grid through the reflective surface of the DUT
- Deformation is reconstructed from two images
  - Mirror image off the undeformed surface
  - Mirror image off the deformed surface
- Based on idea by MPI Munich
- Initial tests and final design based on raytracer images

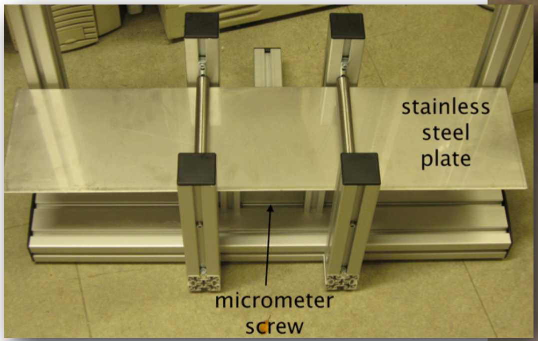
Software by J. Olzem (DESY)

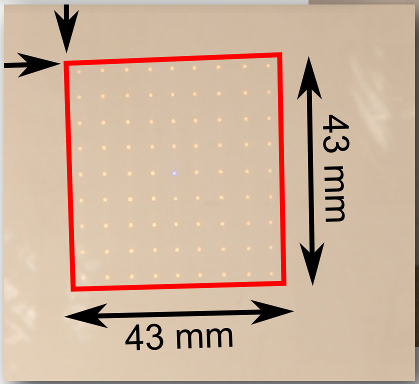
Test Measurements

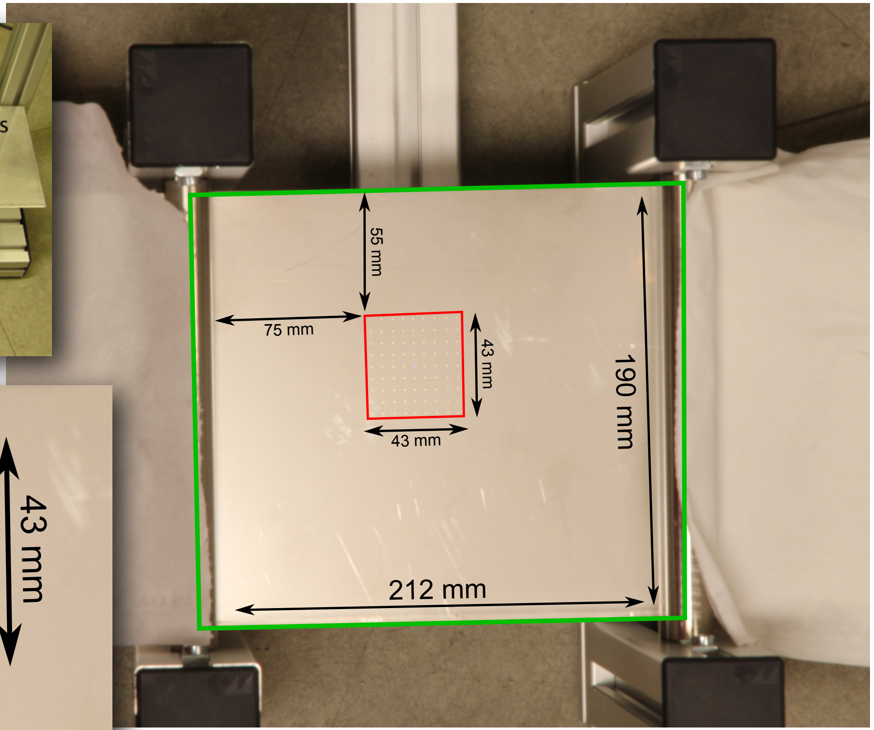


- First test measurements have been performed the DESY summer student programm
- Test surface is a polished steel sheet
- Deformed by a precision micrometer screw
- Test measurements suggest a precision of < 5μm

S. deRijk







Final Design of the Optical Deformation Setup

- Final setup will be able to measure components up to 60 cm x 75 cm in size
  - Illuminated dot grid has to be twice the length and width
  - Total size is 250 cm x 150 cm
  - 5 mm x 5 mm in-plane resolution
- In collaboration with the DESY ATLAS group
  - characterize petals for the ATLAS Silicon Strip Upgrade
- DUTs have to be cooled to their final operation temperature
  - Time between reference image and deformed image may be several hours
- Setup itself must not deform within one measurement
  - DUTs will be placed on a granite table
  - Granite table is embedded in aluminium support structure
- Setup will be flushed with dry air to avoid condensation
- Camera and dot grid will be movable to adjust to size of DUT and reach best precision

Summary and Outlook

- For the HL-LHC era CMS will install an improved tracker
  - higher granularity
  - less material
  - trigger capability

- R&D for the mechanics of the future modules up to now based on FEA
  - Studies have lead to several improvements in the design
  - We are close to a balanced design for the 2S module
    thermal vs. thermo-mechanical vs. material budget performance

- Near-term focus is on the 2S module
  - A detailed list of work packages exists
  - Plan to build a mechanical prototype by the end of this year

- Measurement setups are in preparation
  - Thermal setup will be available for use by the middle of this year
  - Optical deformation setup will be commissioned by April

Backup