Lessons learned: calorimeter upgrade R&D for HL-LHC & by Calice

Or: *turning dreams into reality*

Dave Barney, CERN. ECFA R&D TF6, 7th May 2021

With many thanks to numerous colleagues from ATLAS, ALICE, LHCb, CMS and CALICE!

P. Bloch, F. Sefkow, K. Krüger, I. Laktineh, K. Gill, V. Boudry, M. Hansen, F. Ferri, D. Petyt, R. Ruchti, T. Camporesi, S. Moccia, H. Gerwig, R. Zhu, E. Sicking, Y. Kharlov, C. Loizides, M. Lucchini, O. Solovyanov, T. Davidek, I. Korolkov, E. Auffray, N. Akchurin, P. Romeiro, J. Dittmann, D. Tslisov

(if I have forgotten people it is totally my fault!)

And apologies for not covering everything – also entirely my fault!

Outline of talk

- Sensitive materials
- Electronics/PCBs/connectivity/powering
- Mechanical engineering
- Simulation/reconstruction/analysis
- Closing remarks

n.b.: many comments & lessons from LHC experiments & CALICE; most technical examples from CMS HGCAL

"I wouldn't call this R&D but more **T&E: trial and error**"

"The challenges now are **not to forget** for a next generation and to **have the resources** to make it right."

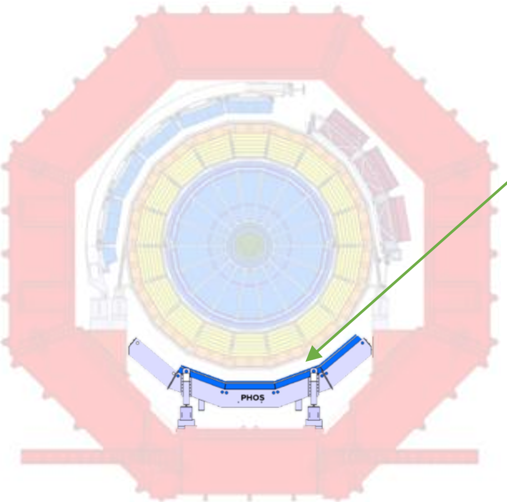
"The main question is: what is best state equation **combining speed, humans and funding** for a given size of project? Work by sociologists needed!"

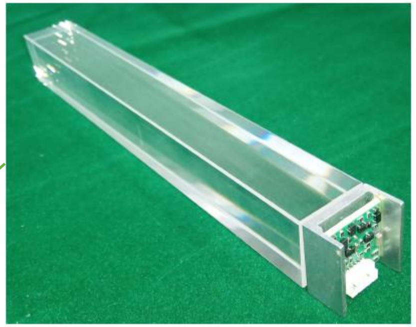
"The difficulty to have **in parallel to operate an existing detector and make R&D for future detectors**: the case we are currently facing for LHC and phase-II upgrades for HL-LHC R&D, and now in addition long term detector: frustration for **many people who would like to do R&D but are fully occupied with operation of current detector**.

Another concern also that it is **easier to attract people for a totally new project** than to update an existing project "

Sensitive materials

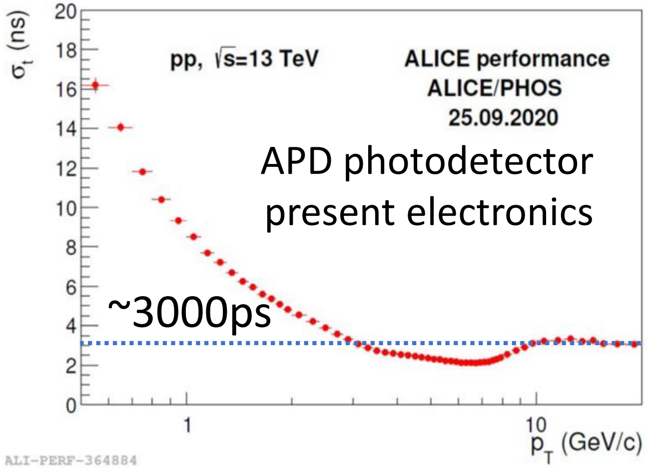
ALICE PHOS: Can be upgraded to provide even better performance during HL-LHC operation

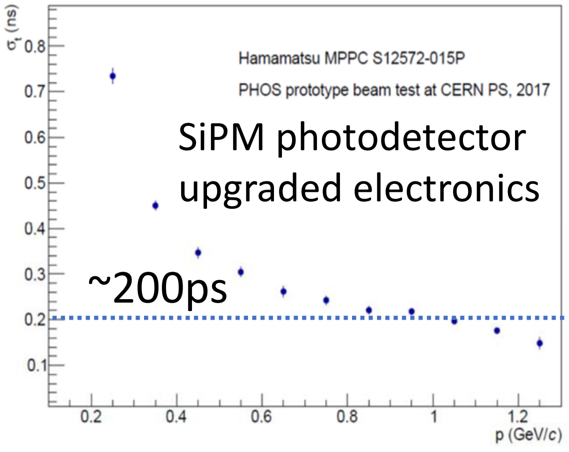




$PbWO_4$ crystals intrinsic timing resolution of the order of ~20 ps
In CMS managed to obtain ~70ps at high energy, dominated by front-end electronics See e.g. https://cds.cern.ch/record/1704542/files/DP2014_011.pdf
But for low energies the **photodetector resolution also plays a major role**

PHOS operates at t=-25°C to increase LY by a factor of 3 with respect to room temperature





Homogeneous crystal calorimeters have the best energy resolution (σ_E/E~1-3%/√E) for low-energy photons/electrons → **will play a role in future colliders**

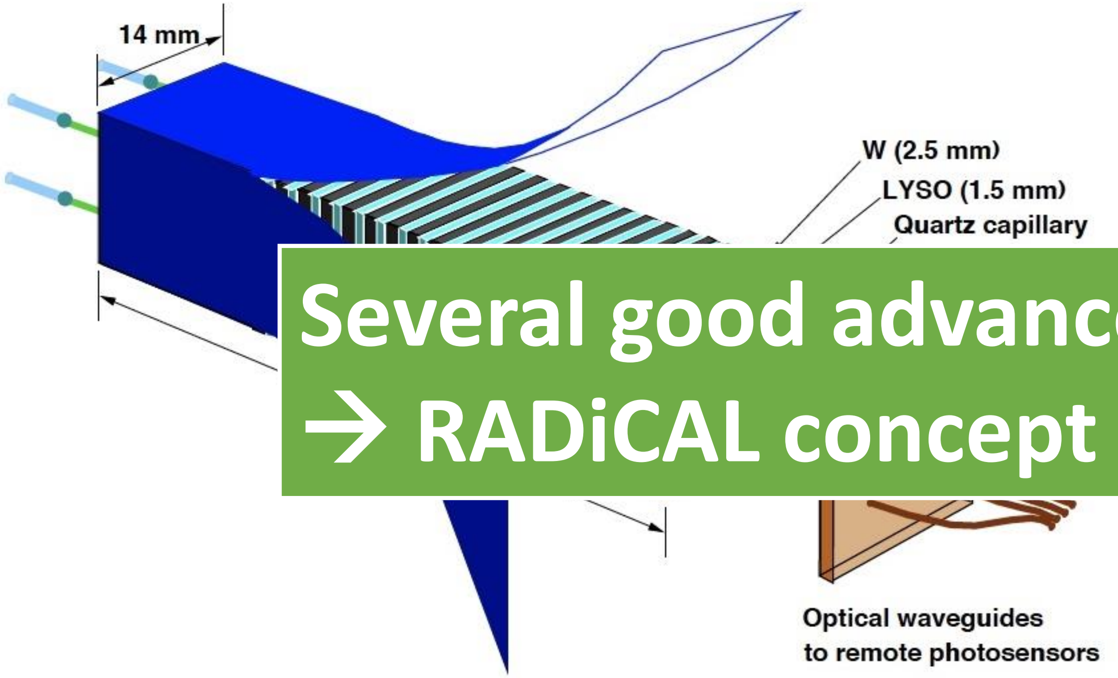
Because of mechanical constraints, PHOS FEE are also embedded into the same air-tight volume as crystals, though FEE are in the warm subvolume. This causes difficulties in FEE maintenance: electronic modules can be replaced or repaired only during LHC long shutdowns once per 4 years.
→ **Would have been much better to host FE electronics outside of air-tight volume**

Significant improvement of timing resolution is possible with the same $PbWO_4$ crystals using the new FEE and new photodetectors → will replace APDs with SiPMs in LS3
→ **was a good move to use a glue that melts ~50ºC and a mechanical structure that facilitates the upgrade**

CMS Shashlik concept: at the downselect (in favour of HGCAL) the Shashlik still needed significant R&D

W/LYSO Shashlik concept had promising energy resolution, with measured (in beams) 10% stochastic and 1% constant terms and very small Molière radius (around 1.4cm). Small LYSO tiles minimize effects of radiation damage

But some technological issues were, at the time, seen as show-stoppers:



- **Liquid wavelength-shifting scintillator in capillaries**:
  - Fear of leaks (2.5l per endcap)
  - Flammability of liquid scintillator
  - Expansion/contraction with temperature changes
- Also tested **GaInP** Geiger-mode photodetectors (much higher band-gap → more radiation resistant in principle)
  - But **in their infancy & no big industrial support**

Several good advancements in past years
→ RADiCAL concept (see talk by Marco Lucchini)

Lessons (similar for non-selected dual-readout option):

Relatively short timescale for upgrade: **mandatory to have no show-stoppers (esp. rad-hardness**, tech. feasibility)

→ have **a set of almost "off the shelf" components** with which to go forwards into development

Potentially-good technologies (e.g. GaInP MPCCs) will not go anywhere without **significant commercial market**

R&D will get more traction if there is potential use in multiple future detectors/colliders etc.

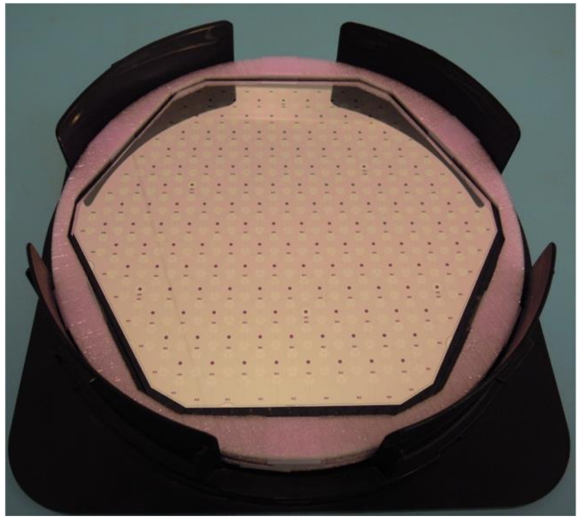
Wise words on Crystal Calorimetry

"Dealing with EM and hadronic damage in $PbWO_4$ crystals at the same time complicates the calibration. **For the former, need to track response losses and recovery on short (minutes/hour) timescales**. Significantly complicates the procedure of deriving and applying corrections.

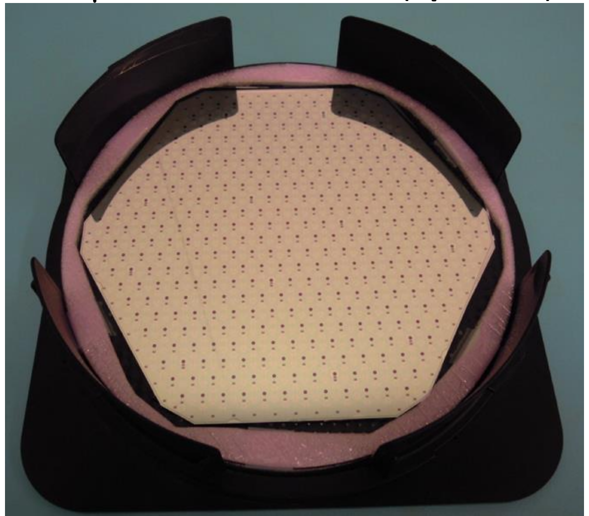
Try to **choose materials with monotonic behaviour** (e.g. LYSO and CsI) that are easier to track, and could in principle be monitored purely using physics events. Make sure you have a **substantial margin for the light output** based on expected irradiation levels."

CMS HGCAL: 8” silicon sensors are a new technology

Low-density 8” sensor
~200 cells of area ~1.1cm^2
300μm & 200μm active thickness (**FZ**)



High-density 8” sensor
~450 cells of area ~0.5cm^2
120μm active thickness (**epitaxial**)



“**one should be careful in making steps which seem a priori innocuous** like going from a 6” line to an 8” line because there are a lot of traps and details to work out, including finding suitable sites for irradiation”

Hexagonal sensor & cell geometry: largest tileable polygon

- **Maximise wafer usage** and aid tiling of endcap ☺
- **edge-effects** due to cut hexagonal cells and sensors 😐

8-inch wafers

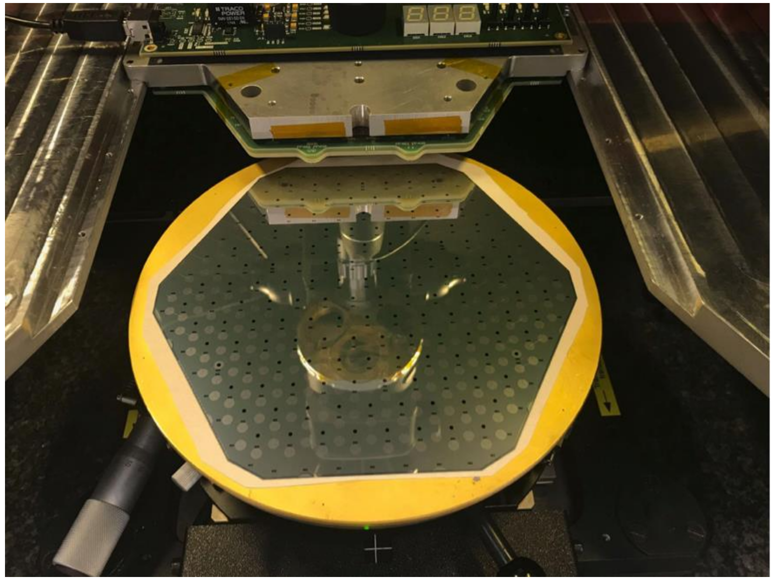
- **Reduces number of modules** w.r.t. 6-inch wafers used in trackers ☺
- New production process
  - Started R&D with three producers: now down to one (HPK) 😐
  - Very thin backside implantation (~1μm)
    → **fragility: one scratch can destroy sensor** ☹
  - Lower oxygen concentration (of bulk) &
    initially higher flat-band voltage (c.f. 6” sensors)
    → **New radiation-hardness qualification required** ☹
- **Connectivity** to large-area PCBs (CTE mismatch) ☹
- Biasing not trivial when glued to baseplate → **cutout in baseplate for wire bonds**

CMS HGCAL: backside fragility of sensors is a serious issue: working closely with HPK to find production solution

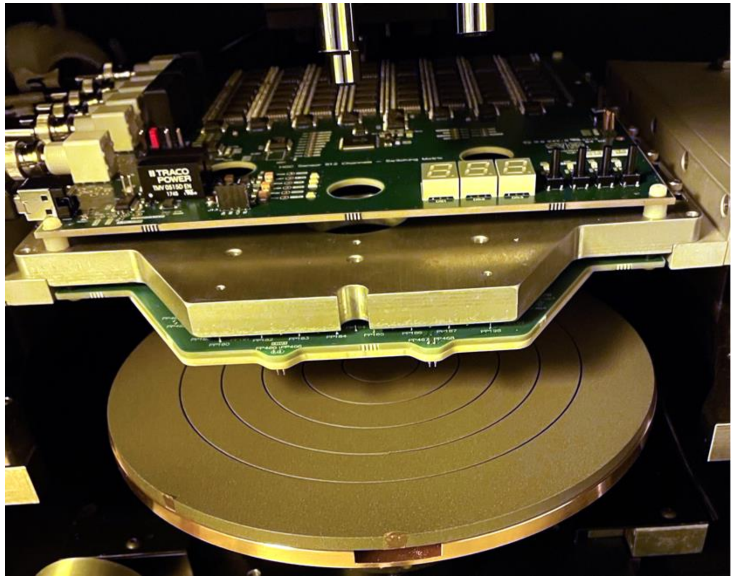
Explored several techniques to mitigate backside fragility for silicon-sensor development phase:

- Adapted sensor design and probe-card design to allow front-side biasing during pre-irradiation tests
- Investigated soft material as chuck cover (lint free paper, Delrin, Teflon)
- Adapted setups to test sensors on dicing frames

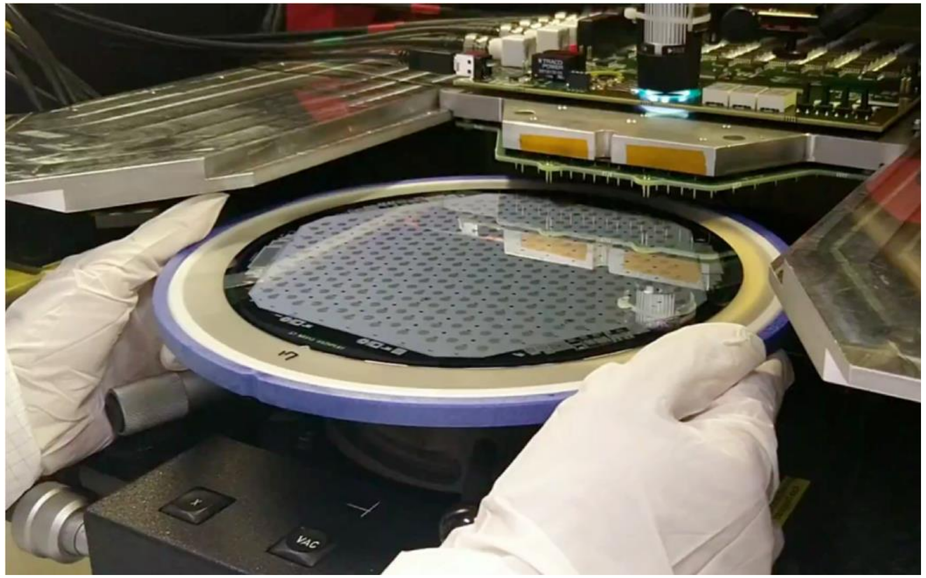
Sensor on clean-room paper



Teflon-coated chuck



Adapted probe station to accept dicing frames

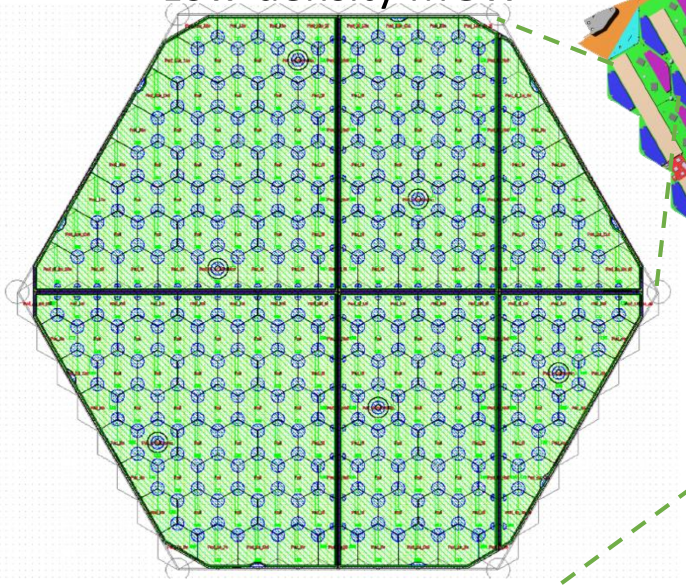


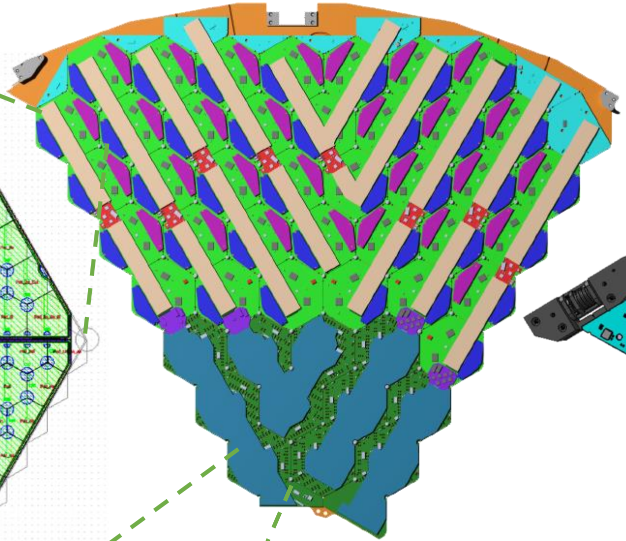
Results from testing sensors on dicing frames are excellent. The procedure to remove the sensor (and test structures) from the frame is lengthy and involves UV light and heating: but should be manageable for the rate we need.

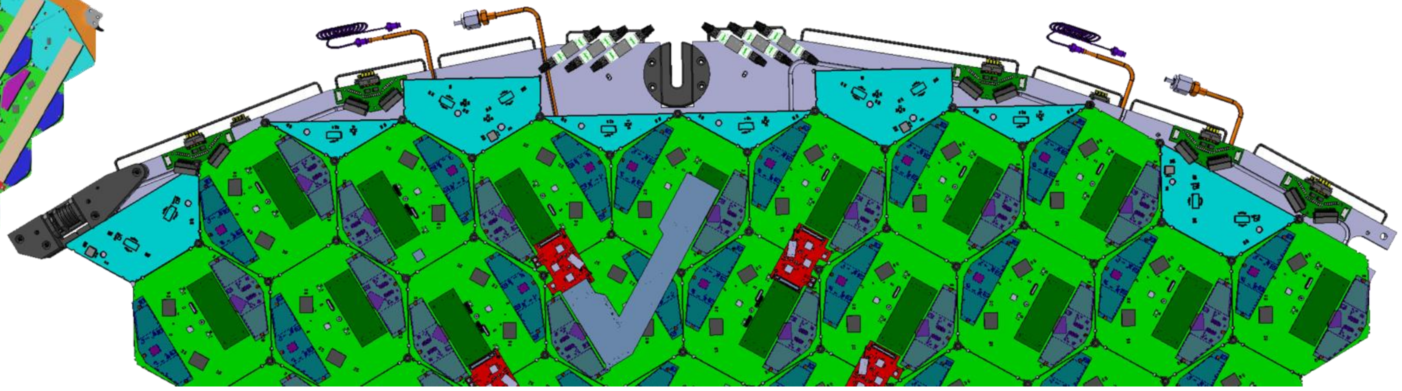
Also working with HPK to see if protective film (e.g. polyimide) can be attached to sensor at fabrication facility

CMS HGCAL: multi-geometry wafers (MGW) to reduce number of mask sets & production types

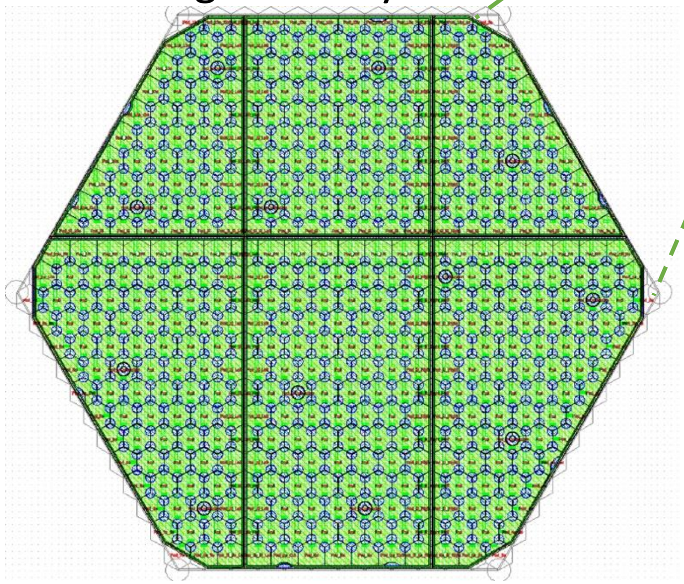
Low-density MGW



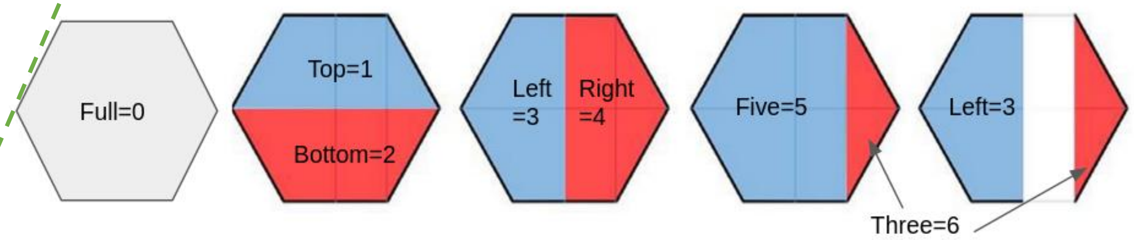




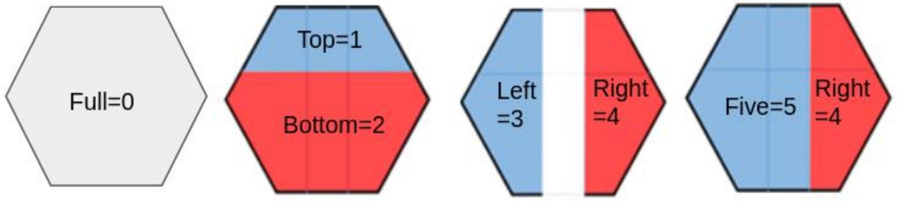
High-density MGW



LD partial sensor layout names



HD partial sensor layout names



Border regions of endcap will be tiled with partial sensors made from **multi-geometry wafers**

Some inefficiencies due to cut lines, but saves masks and silicon
→ **saves money & time!**

CMS HGCAL: irradiation facilities with fast-turnaround time for large-area sensors critical to evaluation of 8”

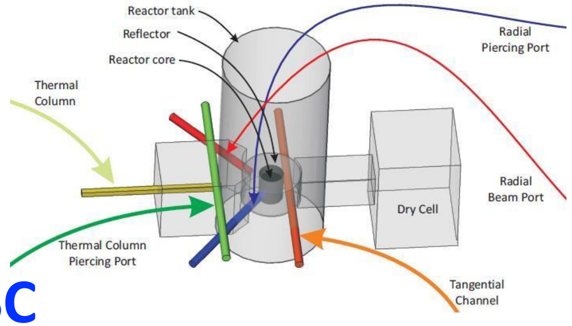
Neutron irradiation: Bulk damage up to very high fluences

- Rhode Island Nuclear Science Centre (RINSC) through **huge work by Brown Uni. (USA)**
  → **only location able to accommodate full 8” sensors**
  → series of 11 irradiations so far: comparisons to JSI ongoing
  qualifying a new facility is a huge effort!
- JSI Ljubljana (Slovenia) and RINSC
  → for test structures (can cover large phase-space with test structures)

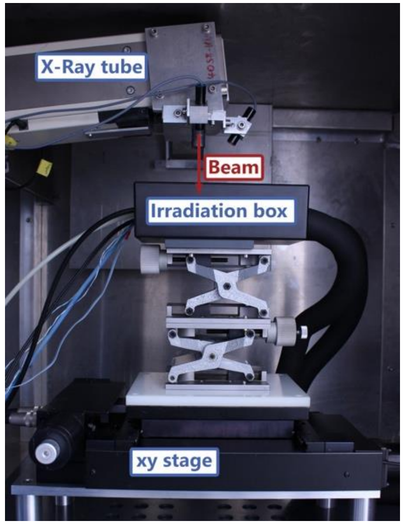
X-rays: oxide-quality studies (MOS, GCD, strip sensors)

- Facilities at KIT (Germany), INFN (Italy) and CERN

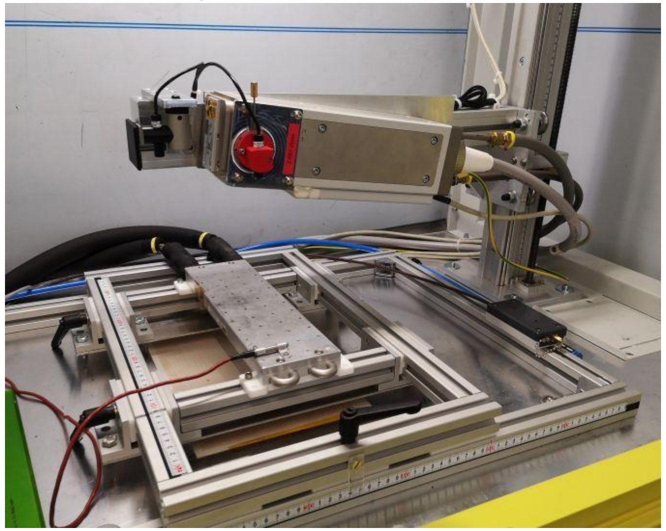
n @ Ljubljana



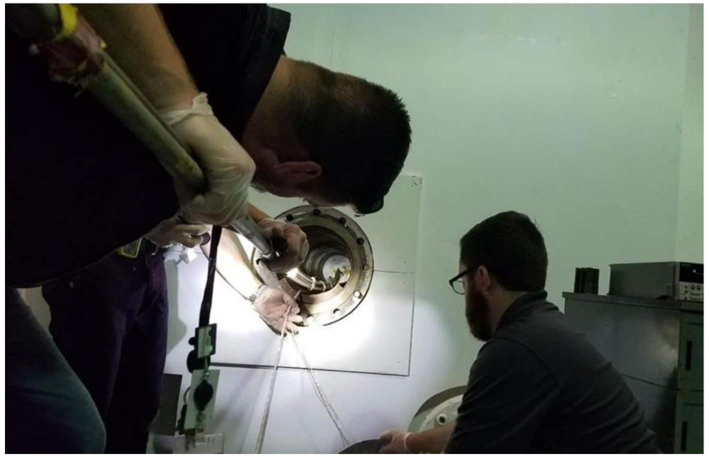
X-rays @ KIT



X-rays @ ObeliX @ CERN

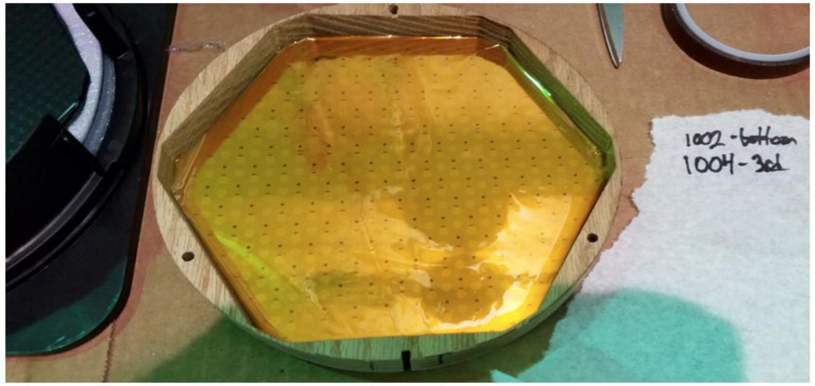


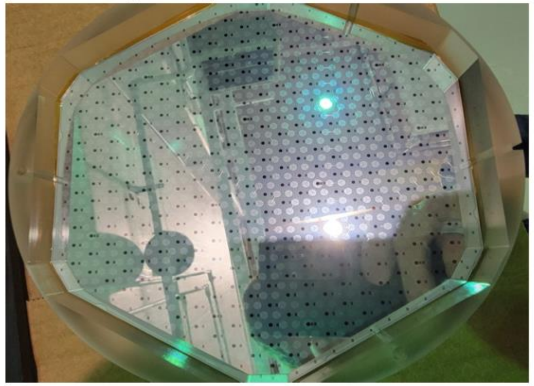
n @ RINSC



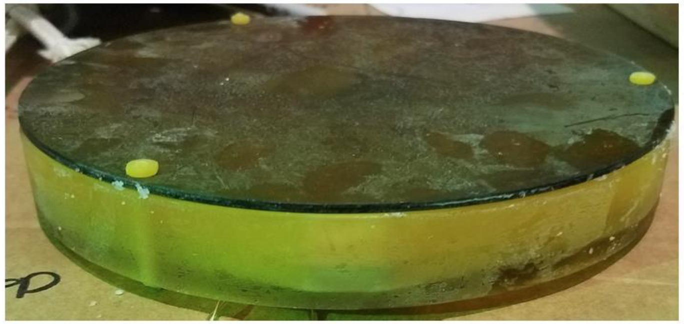
CMS HGCAL: good **relationship** built with RINSC

Stacking of four sensors in wooden or acrylic pucks





Puck, cylinder, beam port



- Irradiation programme in 2020–2021 with 42 full sensors
- Four sensors in a puck irradiated at a time
- Ramped up to one irradiation per week
- Great progress, overcame many initial challenges in view of logisitics, puck material, packaging, handling, T monitoring

Number of irr. sensors	Fluence (neq/cm^2) 6.5E14	1.0E15	1.5E15	2.5E15	5.0E15	1.0E16
d=120 μm	-	-	-	4	4	8
d=200 μm	-	-	-	10(+4)	-	-
d=300 μm	4	4	4	-	-	-

n.b.: irradiations over the past 6 months have shown that **8" sensors have at least the same tolerance as 6" sensors** → To be verified during pre-series phase etc.

Some words on irradiation campaigns

"Irradiation campaigns should consider both **dose and dose-rate** dependencies. CMS HCAL irradiation campaigns were conducted at higher dose rates than LHC operation, and **hid a substantial dose-rate-dependent radiation damage effect**."

"**Read all the published papers** on the subject beforehand"

Some comments on photodetectors (& fibres)

"**Photo-detectors often show unexpected behaviour** in radiation or magnetic field.
e.g. anomalous signals in APDs; sensitivity of HPDs to magnetic field around 2T;
PM tubes suffered from Cerenkov light in the window due to particles from the back.

The lesson for me is that in particular **the photodetectors need to be verified in their final environment** including B field at all intermediate levels and all directions and particles (test beam) in all directions, again such that non-physical events do not come as a surprise after installation. Taking 'triggerless' data will certainly help!"

LHCb: "Having the three sub-systems (PS, ECAL, HCAL) using all scintillator and WLS fibre technology, the ECAL & HCAL **using identical PMTs and FEB**, and using same R/O boards, was (and still is) **very cost and maintenance effective**!"

"It is critical to **look at all links in the signal chain for weaknesses**: photodetectors often show temperature dependence; phototubes may also suffer damage to the photocathode – even from calibration light; fibres and wave-guides can show radiation damage – even at low levels this may be important for high-resolution detectors etc."

Electronics for Calorimeters

LHC calorimeters for HL-LHC: electronics upgrades

Longevity of major experiments is **far beyond initial estimates**;
LHC already at higher-than-planned performance; and **HL-LHC is coming…**

All LHC experiments are changing the calorimeter electronics in LS2 or LS3 (possibly more in LS4)

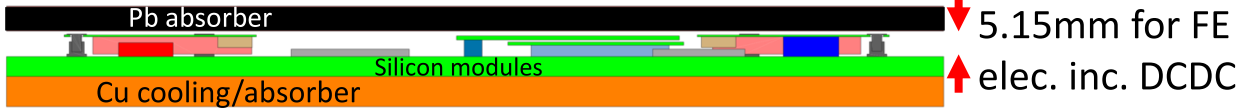
- More requirements on triggering:
  - More bandwidth due to higher rate or "triggerless" readout
  - Larger on-detector buffers to cope with higher latency due to more complex algorithms
- Faster shapers & better clock distribution for higher-precision timing (to help cope with pileup)

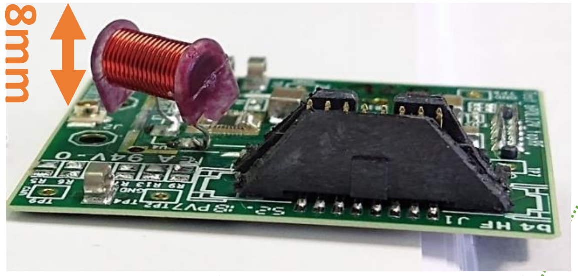
Some general lessons from this upgrade campaign (and some past lessons too!):

- Include **larger-than-needed front-end buffers** to cope with future trigger latency
- As much **flexibility/programmability as practical in FE electronics** to e.g. flag non-physical energy deposits
- Ensure **front-end electronics are as "accessible" as possible**. E.g. ALICE PHOS would have preferred to have them outside of cold volume; some electronics in CMS ECAL barrel are ~impossible to change (below cooling blocks) → **mechanics should – as much as possible – be designed with upgrades in mind**
- **Mezzanine cards on off-detector cards** (e.g. CMS Preshower; new Serenity ATCA cards) facilitate upgrades to more-powerful FPGAs for new algorithms
- Precision timing: always beneficial. **Clock distribution is key**, in addition to fast rise-times of sensors/shapers
- Ability (in labs and beams) to **trigger on non-physical events *if required*** can help avoid costly issues

CMS HGCAL: on-detector DCDC conversion complicated by need to minimize space → development needed!

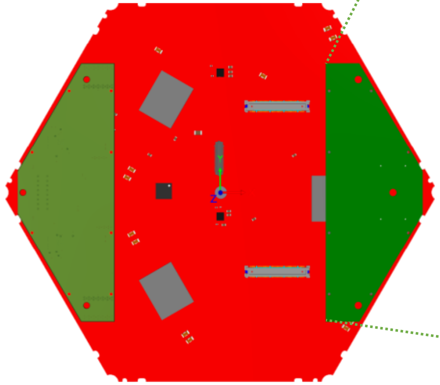
HGCAL silicon-module cassette cross-section

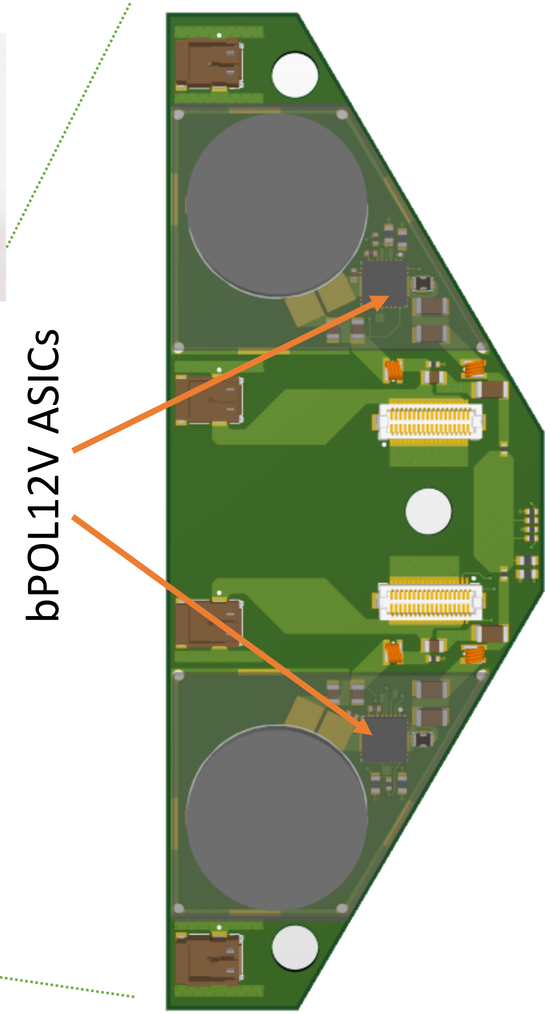




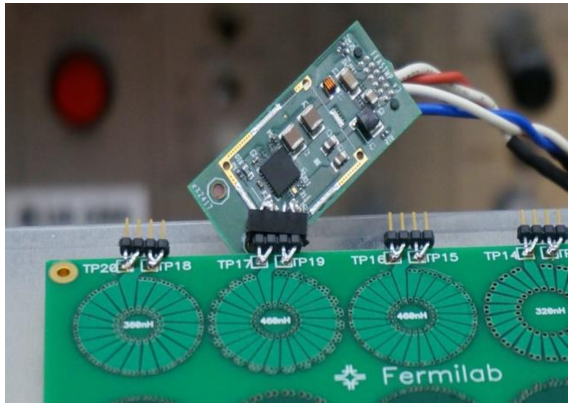
Standard bPOL12V module

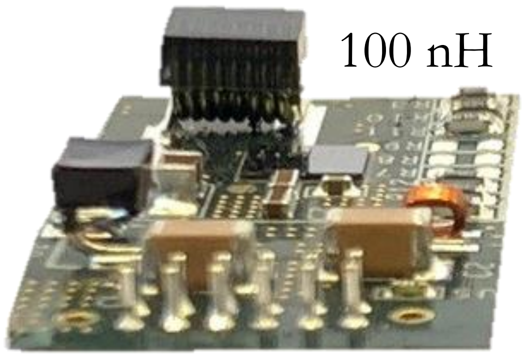
Need custom inductors with low-profile but high inductance to maintain efficiency





Prototype in-PCB inductors



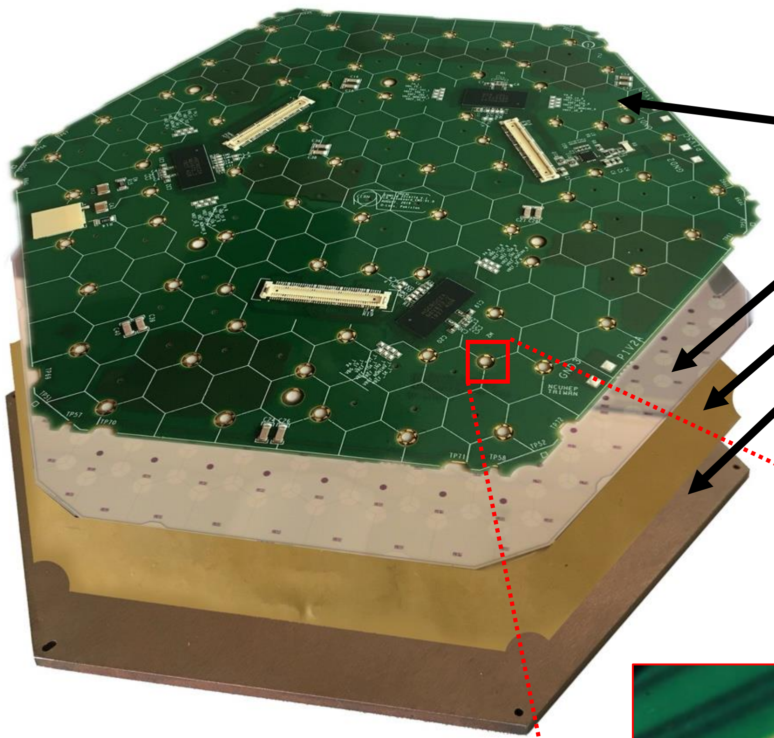


bPOL2V5 module

Alternative to bPOL2V5: rPOL2V5 (resonant switched-capacitor DCDC converter) with much smaller inductor

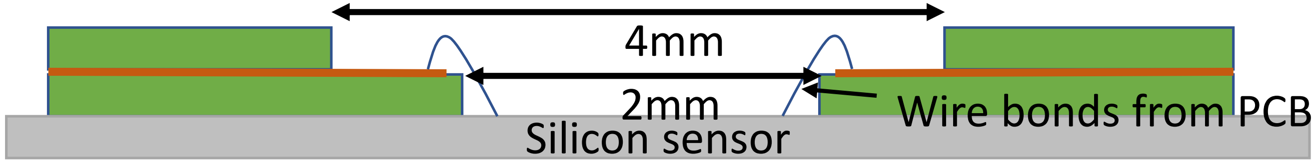
rPOL2V5 module

CMS HGCAL: Medium-area PCBs connected to Silicon

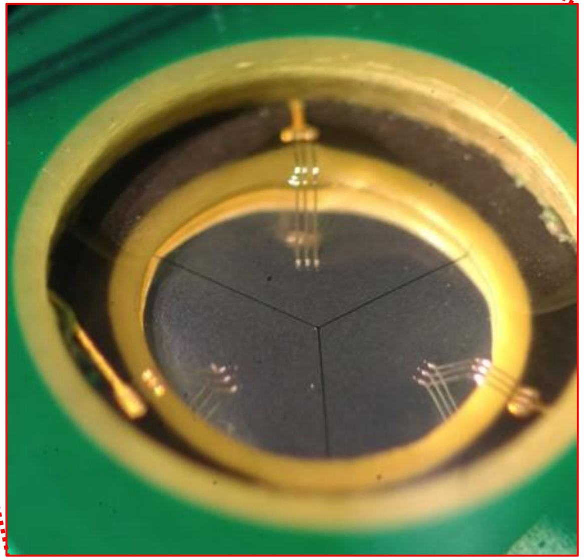


Basic building block of HGCAL silicon region is an 8” (~20cm) hexagonal module: a glued stack of layers comprising:

- **“hexaboard”** PCB containing **HGCROC ASIC**
- **p-type Silicon sensor** divided into smaller hexagonal pads
- **Polyimide+gold sheet** for insulation/grounding
- **Baseplate** (CuW in electromagnetic section; PCB in hadronic section)



Stepped holes in PCB for wire-bonding. Step provides protection to bond wire (which is also encapsulated)



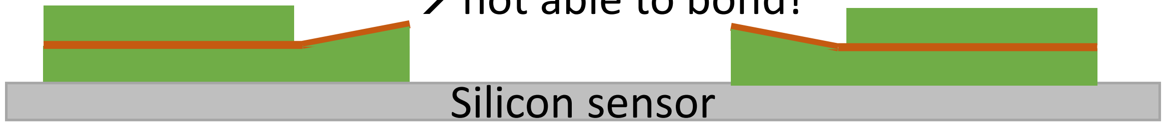
Reason for choosing this method of connection:

CTE mismatch between PCB and silicon: bump-bonding (*a la* pixel detectors) would result in transverse stresses that would shear the soldering:

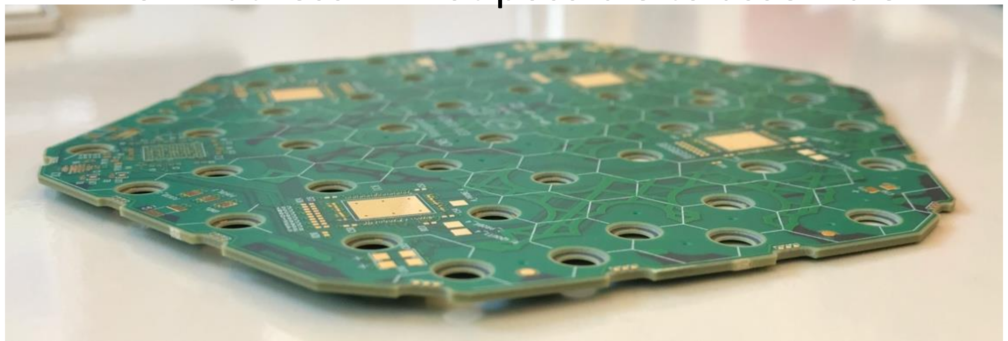
20cm PCB shrinks ~3mm more than silicon from ~250°C to -30°C

CMS HGCAL: Medium-area PCBs connected to Silicon – several problems seen

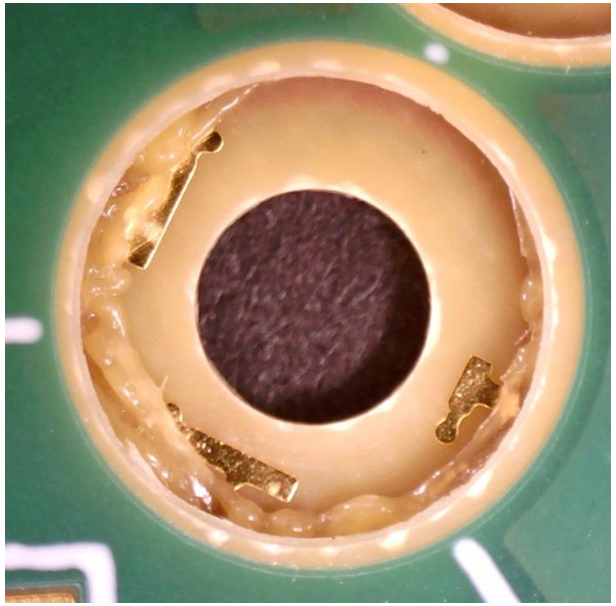
Slope of bond pads
→ not able to bond!



Non-flatness → not possible to assemble



Glue covering bond pads



Very poor surface finish

We have worked - **for three years** - very closely with CERN, three PCB producers and one assembly company to overcome these issues.

Lesson: developing relationships with industrial partners is mandatory for many "easy" items such as PCBs.

Ideally we would continue with these companies for the production phase but this cannot be guaranteed

R&D into alternative large-area silicon-to-PCB connections important for future HGCALs!

E.g. **Anisotropic Conductive Films/Pastes** (still issues with CTE mismatch); **PCB materials with ~same CTE as silicon**

Comment on large-area PCBs

"I know companies that make large PCBs
I know companies that make high-density PCBs
(sometimes they are the same company).
But **no company makes high-density large PCBs**"

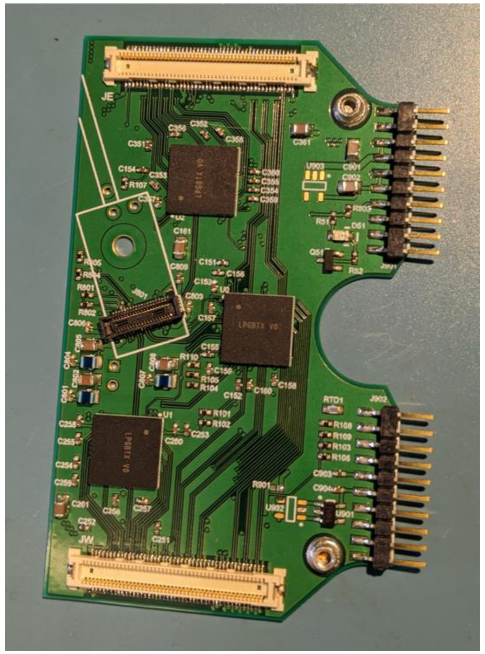
CALICE 13-layer iRPC board

1m long

Rather simple packages
(possible to solder by hand)

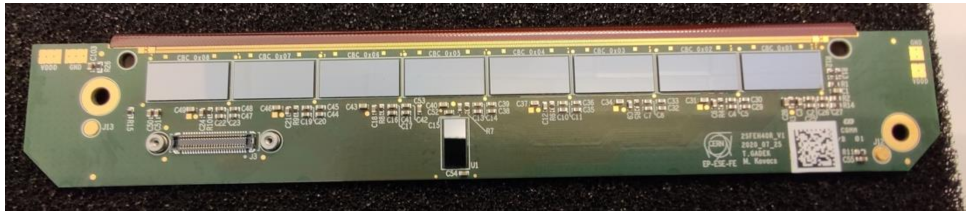
CMS HGCAL "engine" 8-layer board

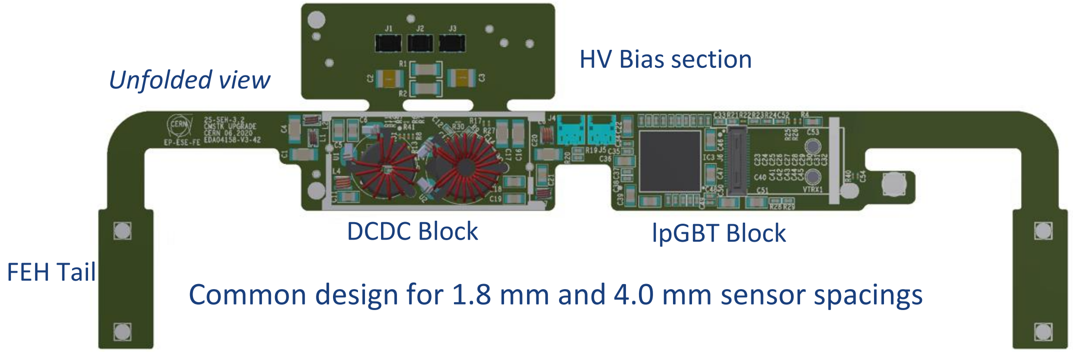
75mm



Contains 3 lpGBT and
connector for VTRX+

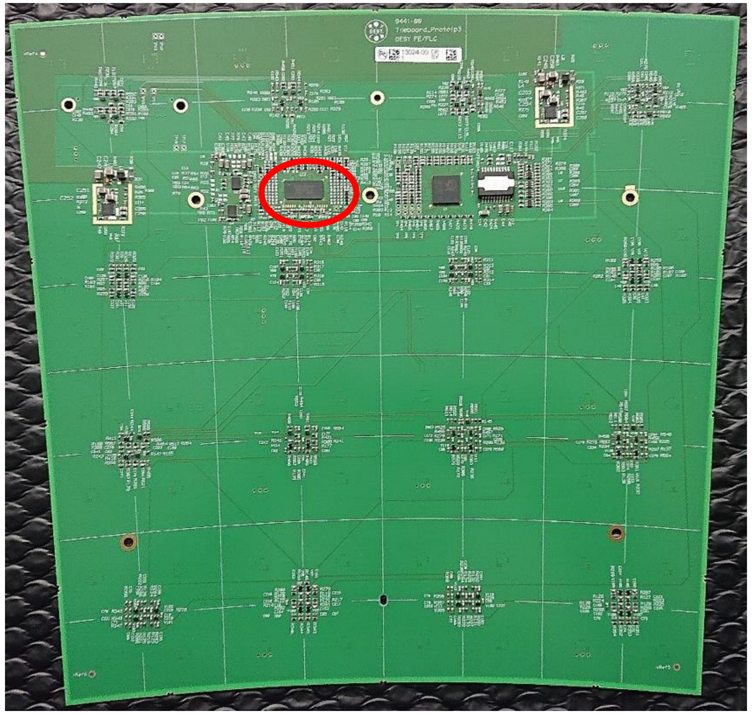
CMS Tracker hybrids





CMS HGCAL: large PCBs – difficulty (and cost) related to fine-pitch BGA packages & fast links

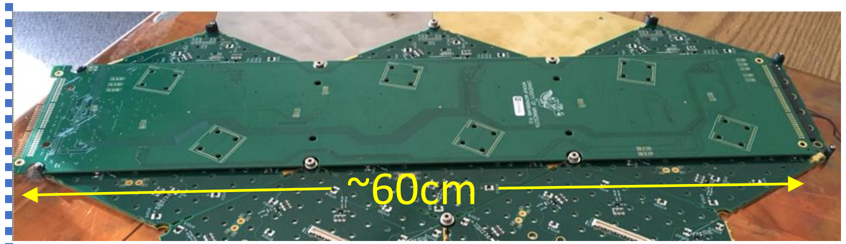
HGCAL "Tileboard" for SiPM powering/readout: HGCROC ASIC package has 0.6mm pitch & μvias → modifying package to be 0.8mm pitch will **increase yield and reduce cost by ~25%**



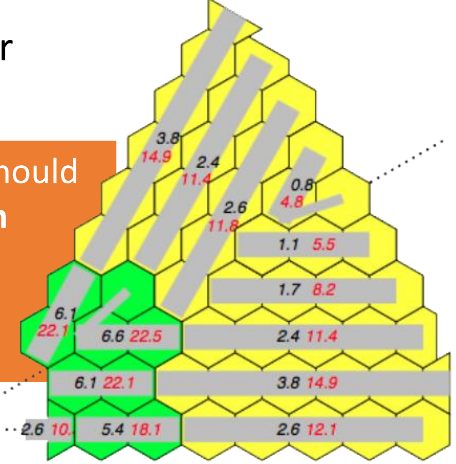
~30cm

~30cm

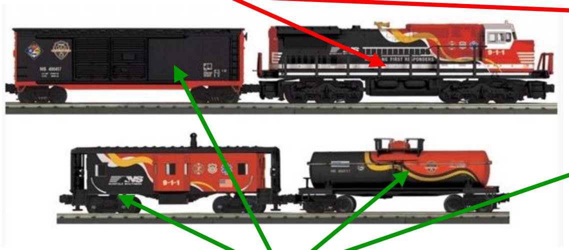
HGCAL "motherboard" for silicon modules: contains data-concentrator ASICs, lpGBT chipset, VTRX+, possibly DCDC converters etc.



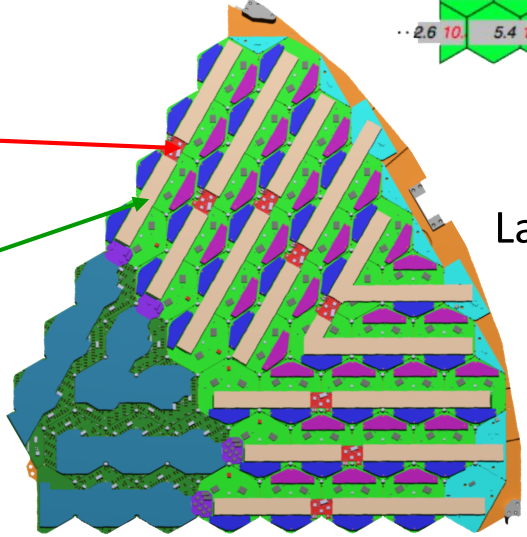
1.28/2.56/10.24 Gbps should be good to **~75/30/5 cm**
Tens of motherboard designs needed for HGCAL → **expensive!**



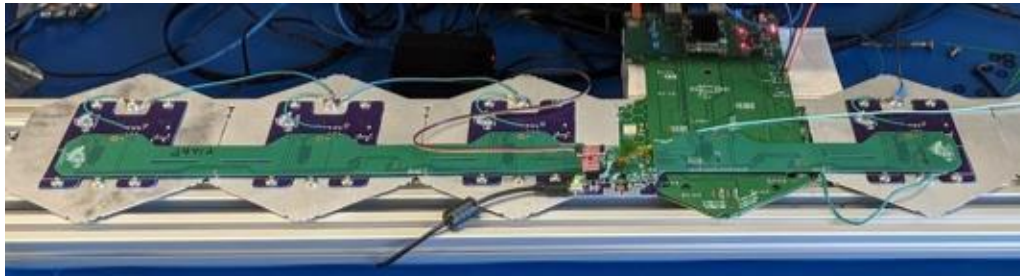
Revised concept:
Single "**engine**": lpGBT+VTRx+



Multiple "**wagon**" types
- mostly passive



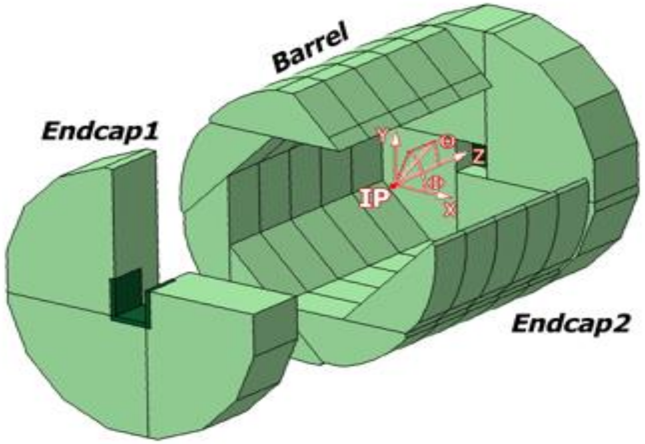
Latest layout



Test "string" of module emulators, two wagons and one engine

CALICE: Large-area PCBs/readout with multiple-cell connection scheme to maintain granularity but reduce channel count

ILC, CEPC: SDHCAL calorimeter baseline Based on iRPC gaseous detectors

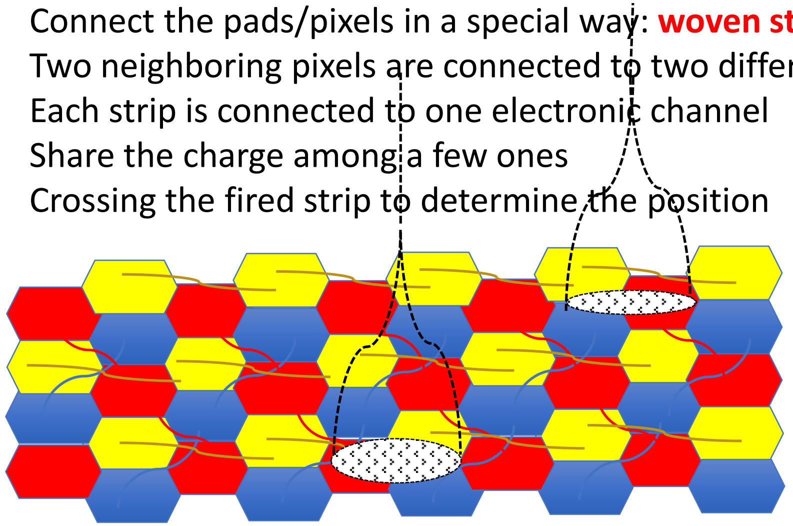


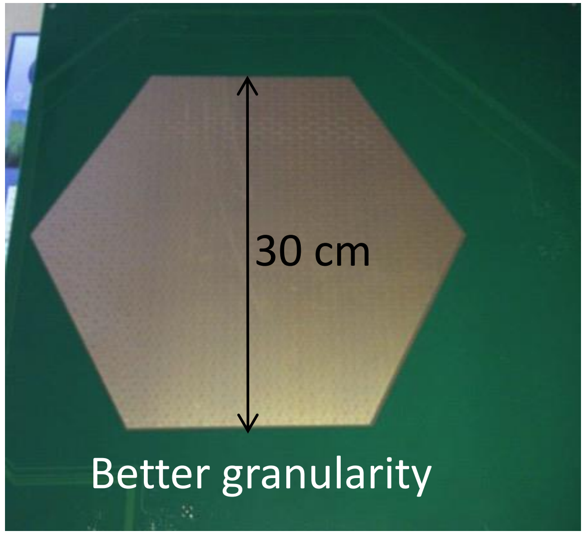
- **SDHCAL** is one of the HCAL baselines FOR BOTH with **tens of millions of channels**
- Only about 10^3 will be fired for each collision. So the channels are idle almost all of the time but will continue to consume power and to produce heat, necessitating in case of circular collider **active cooling** → **reduced PFA performance**

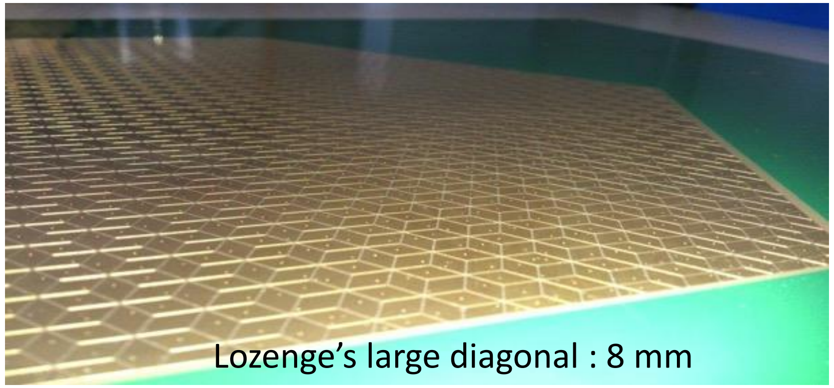
Q: how to keep granularity but save power?

Possible A: take advantage of low occupancy and combine multiple cells into readout channels

- Connect the pads/pixels in a special way: **woven strips**
- Two neighboring pixels are connected to two different strips
- Each strip is connected to one electronic channel
- Share the charge among a few ones
- Crossing the fired strip to determine the position







Some comments on electronics for calorimeters

"Having a good **supply of previous-generation chips** is extremely useful for testing detector concepts"

"Keep **A LOT of spare components**, including the full modules: use them for tests"

"**Cross-detector ASIC development** a la RD53 will be beneficial"

Holistic approach: "The **consequences of readout electronics being integrated and 'married' so closely to the active material for highly-granular calorimeters…tend to be underestimated**. Many people seem to view the electronics somehow separate from the rest of the detector: you can develop it separately; you can start building the large structures already before the electronics are ready; you can replace the electronics later. I think it is **fundamental to the success of a project that people are aware that this is not true** (any more), and that you **need to make sure that the electronics is ready early enough**."

Some more comments on electronics for calorimeters

"(ATLAS) TileCal was designed with many genuine solutions, with minimum of dead space, **readout redundancy** (two channels reading one cell) and **removable on-detector electronics which thus can be extracted and repaired**. This helped us a lot to keep very high data-taking efficiency (more than 99% during Run-1 and Run-2). But people were **surprised at how often this operation was needed** (during commissioning & long shutdowns)."

"**Think about future upgrade** (e.g. increasing granularity by x4) already at the original design. If you get funds for x4 RO channels, you better have a **plan how to implement it with minimal effort!**"

"The original idea was that the front-end electronics will be "sealed from access" and only a group of highly skilled technicians and physicists will access it very rarely. **The real life was quite the contrary**."

"The redundancy turned out not to be fully sufficient as **some electronics failures disabled the whole module**. This is addressed in the Phase-II upgrade, where **each module will be readout with fully independent 4 units** (called minidrawers)"

A couple of words on connectors…

"**Connectors of all the types will be the major disappointment** - **minimize the number** already at the design"

"…some connectors were (perhaps) **not originally designed for frequent on/off** and workarounds had to be applied during commissioning and long shutdowns."

"Beware **obsolescence of low-profile connectors**: the commercial market moves much faster than us!"

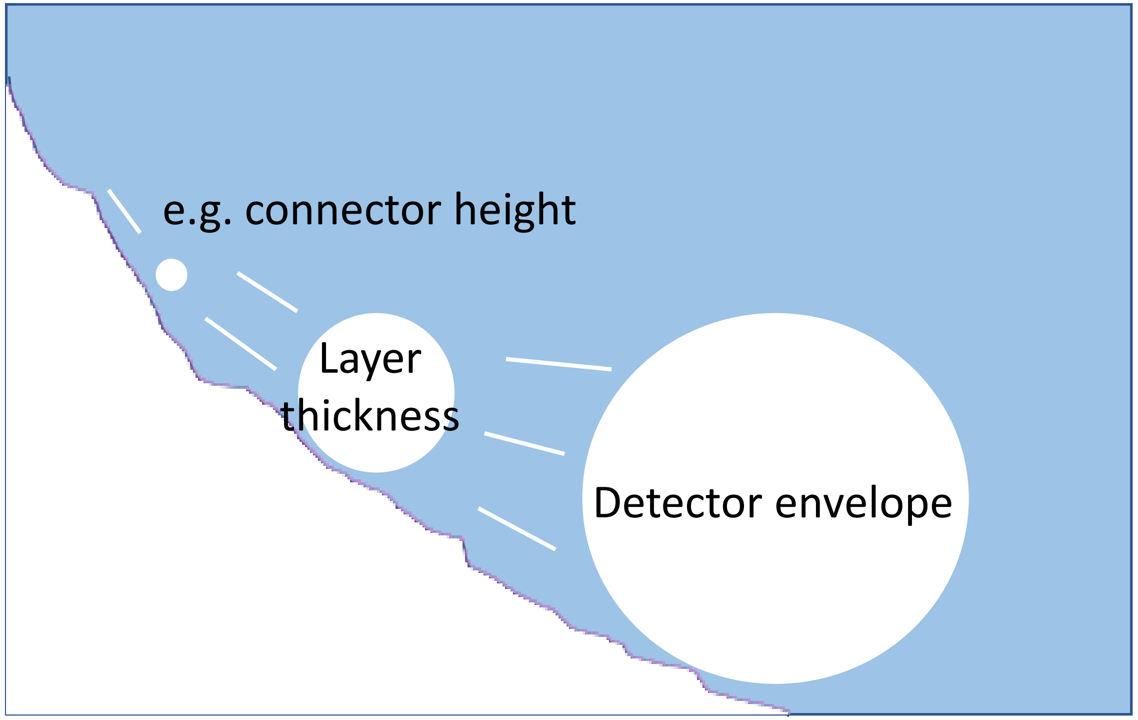
"**Obsolescence** of connectors is **a real problem if you update an existing detector**. Buy spares!"

Mechanical Engineering for Calorimeters

CMS HGCAL

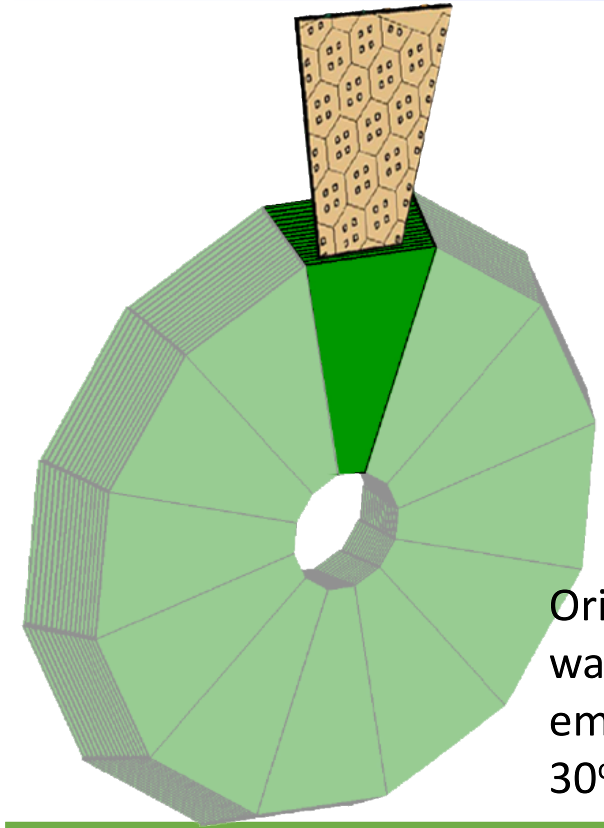
Comment on engineering of highly-granular calorimeters

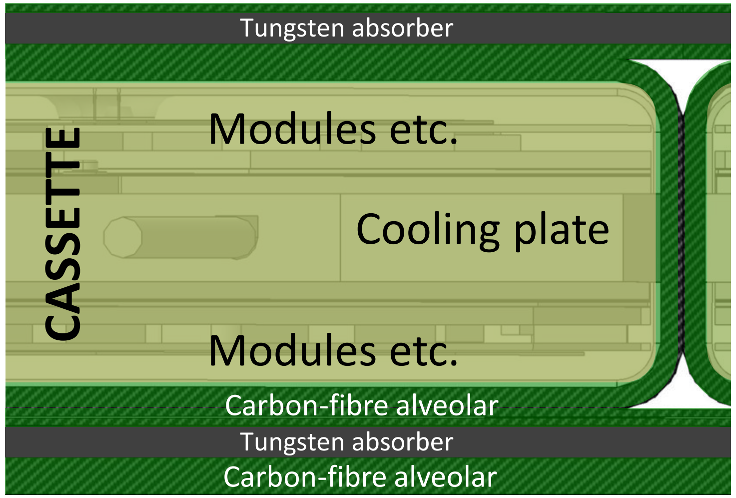
"any small change of e.g. height of an electronic component creates a snowball effect that changes the whole mechanical design. Must have a holistic approach between physicists and engineers (mechanical, electronic and software)"



Software tools for overall layout optimization are extremely useful – not only for mechanics but also bandwidths of links etc.

CMS HGCAL: Alveolar structure with embedded W absorbers → self-supporting Pb-absorber cassettes

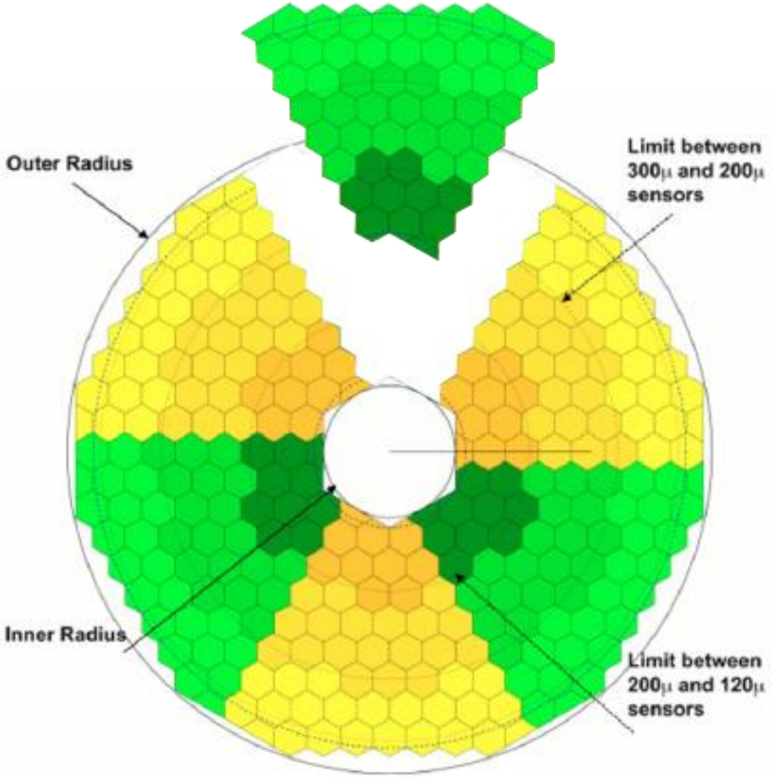


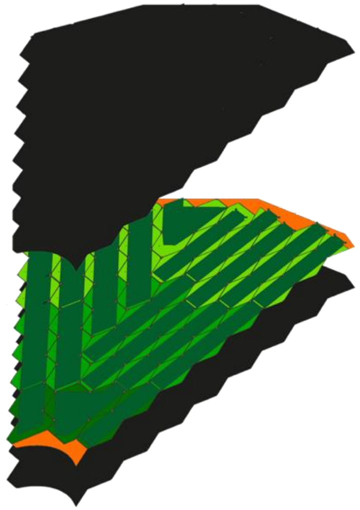


Original electromagnetic compartment was based on CF alveolar structure with embedded W absorber (*a la* CALICE) with 30° trapezoidal double-sided cassettes

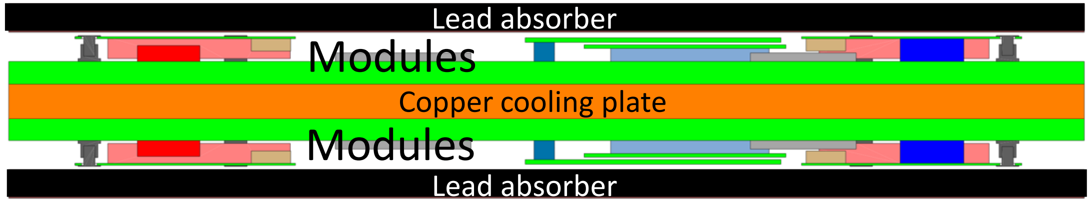
Difficulties/concerns included:

- Fragility of CF alveolar structure during insertion
- Edge-effects of hexagonal modules in cassettes
- Fixed size of "pockets" in alveolar structure
  → **difficult to accommodate any changes in component heights**
- Cost of W absorber (including machining)





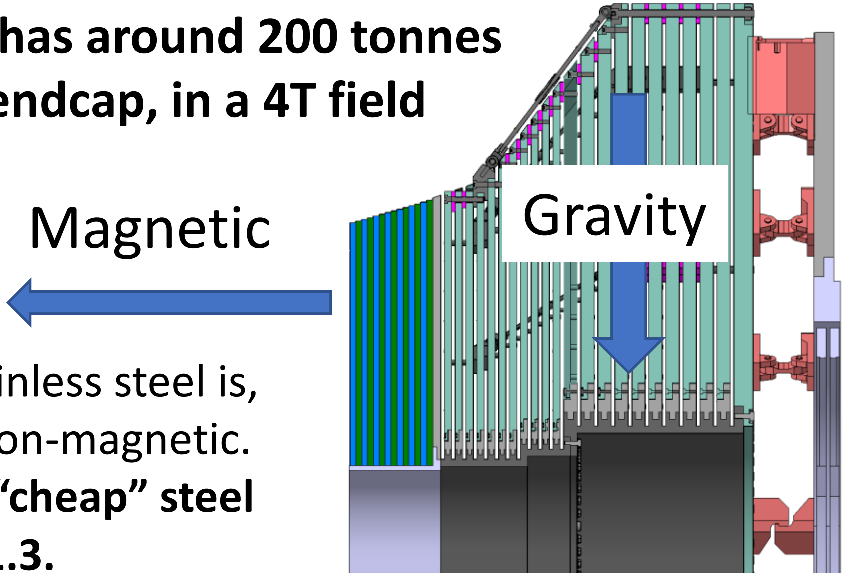
Present cassette shape follows hexagonal modules

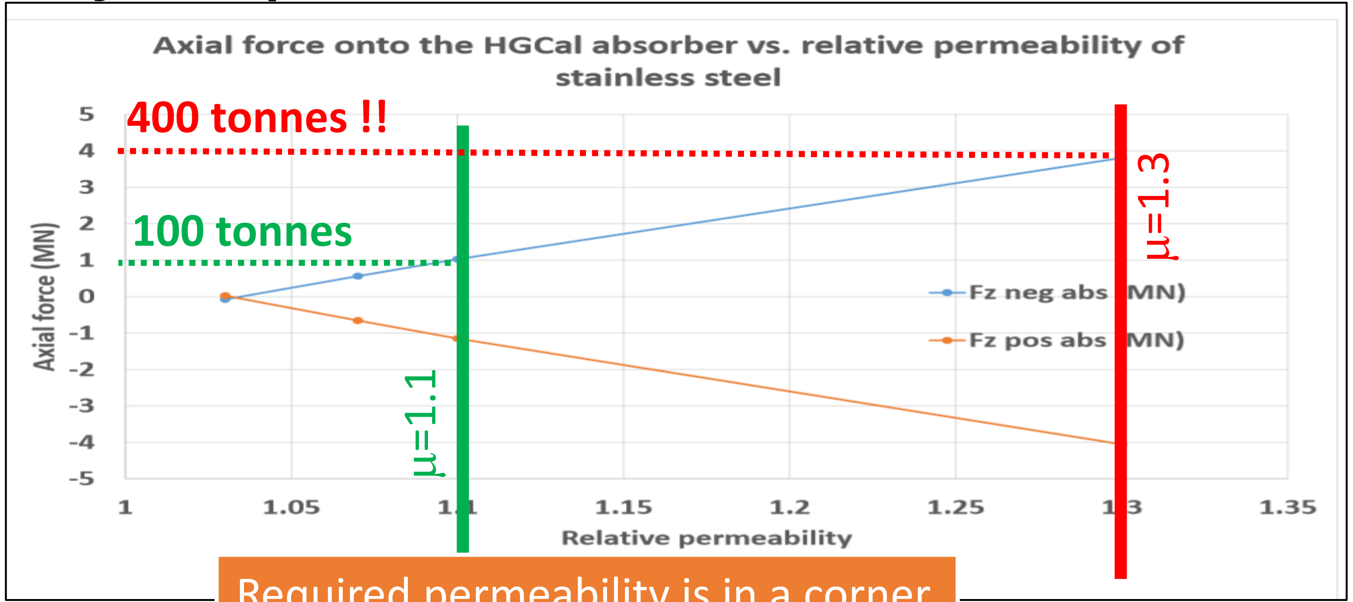


Final design has **no alveolar structure**. **Self-supporting** cassettes with a mixture of **Pb, Cu and CuW** absorbers → approximately **same R_M** as original design

CMS HGCAL: stainless-steel absorbers may be expensive due to permeability requirements

CMS HGCAL has around 200 tonnes of steel per endcap, in a 4T field



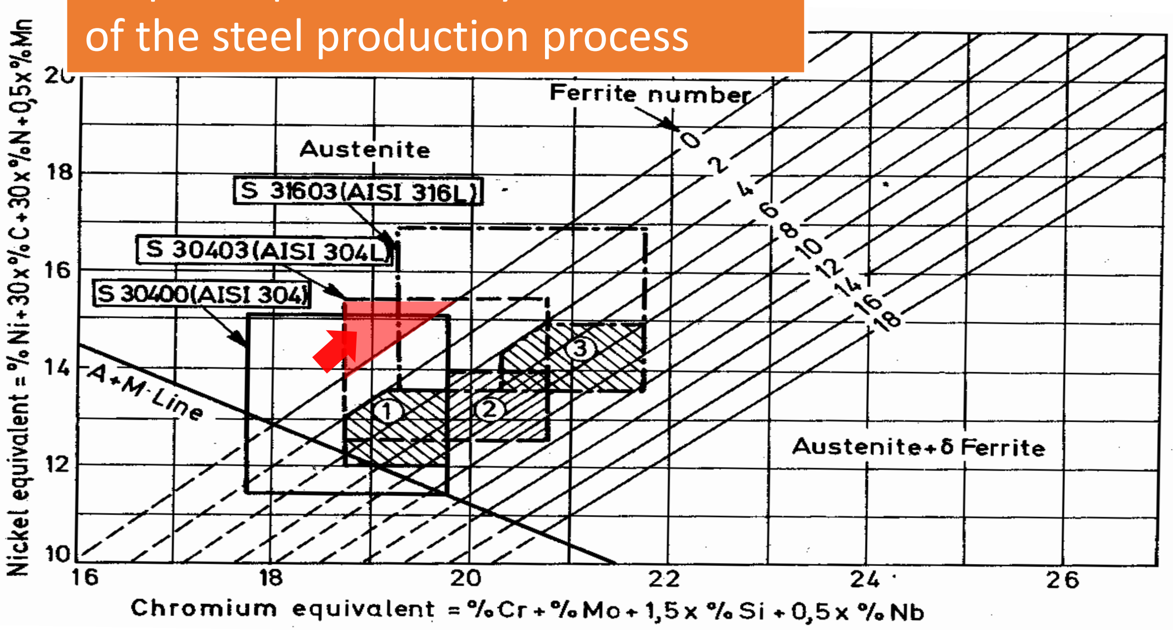


Austenitic Stainless steel is, in principle, non-magnetic. But standard **"cheap" steel may have μ~1.3.**

CMS HGCAL support structure designed for **F_{axial} ~100 tonnes**

Upshot: steel meeting strict permeability specifications may be much more expensive than standard steel!

Required permeability is in a corner of the steel production process

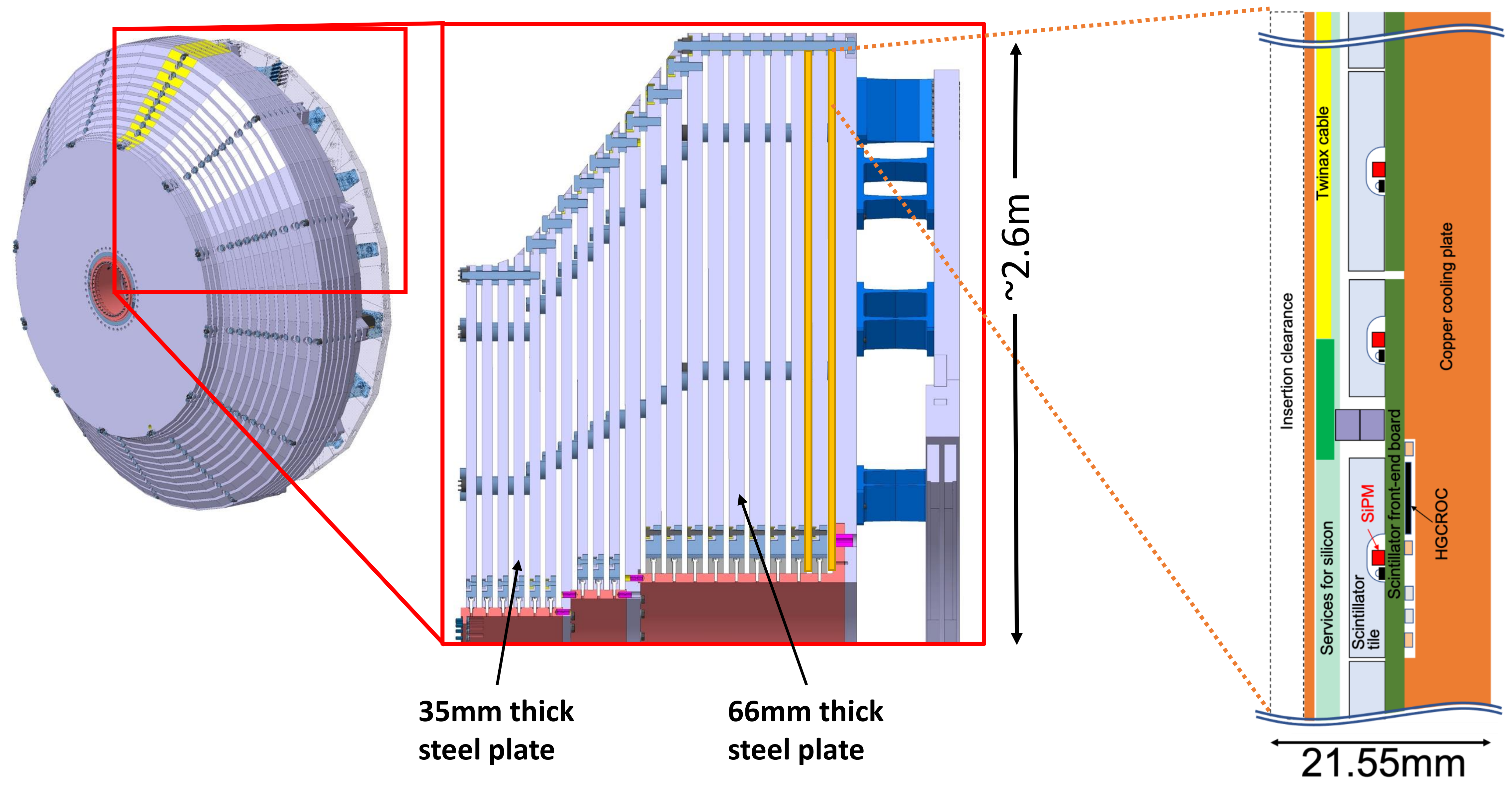


"**Choosing the right steel-making route** (like ingot casting) & controlling the scrap ***may* lead to low permeability** steel: would need to include sampling of each delivery"

"low-cobalt steel is also expensive"

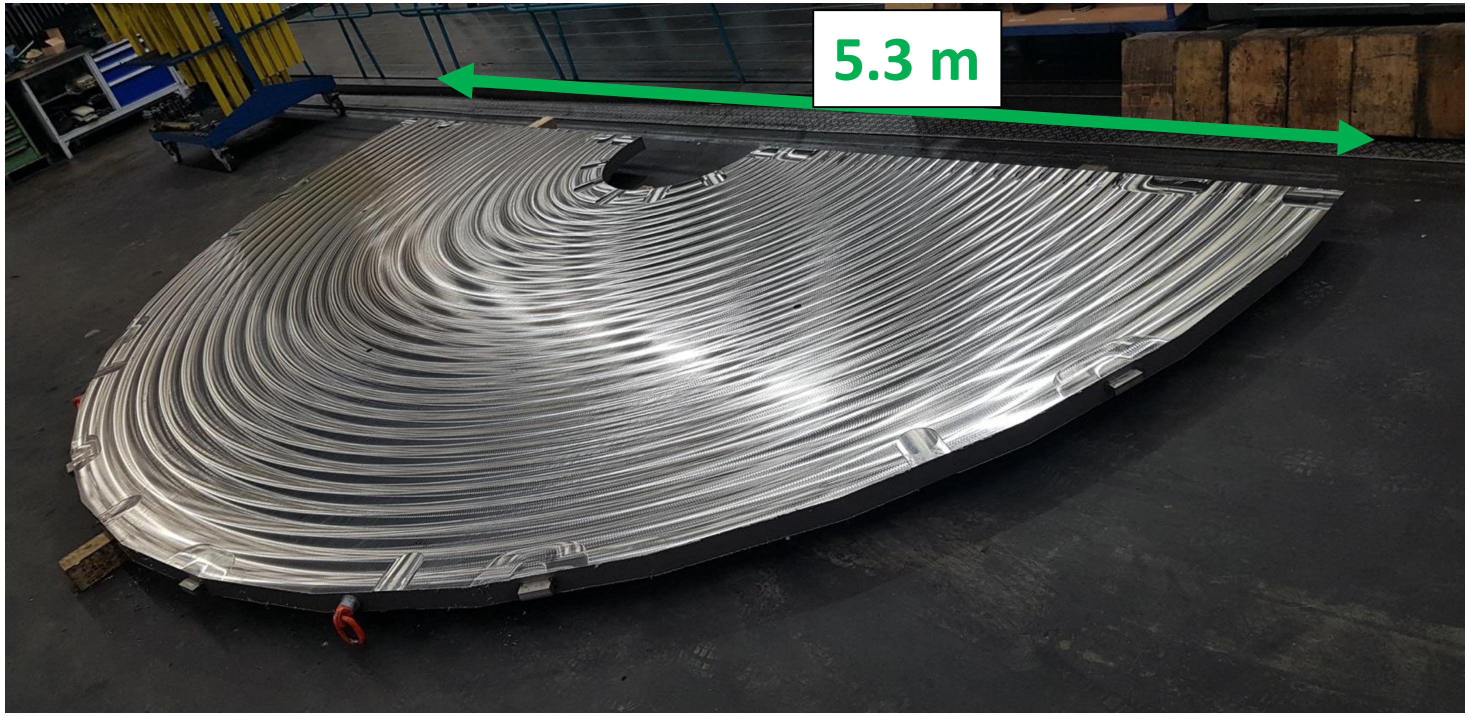
"This **stainless steel casting is some sort of cooking**: you might have the recipe, but the final dish can be excellent or complete @$^@ - depends on the chef's expertise!"

CMS HGCAL: Flatness/uniformity of 5.3m Ø steel plates is critical to accommodate cassettes



CE-H Cassette structure

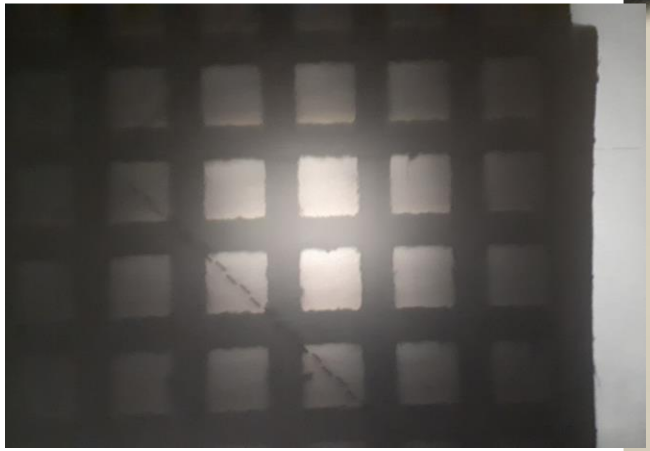
CMS HGCAL: absorber flatness specification difficult to achieve on large scale (for reasonable cost)



- Two C shaped plates 66mm and 35mm thick after machining → **requested 0.5mm flatness**
- For the 66mm plate: starting thickness = 75mm; for the 35mm plate starting thickness = 45mm → **123 hours of machining!**
- Machining relieves the plate stresses → **initial bow of 9mm!** → **turned five times to control the flatness**
- Company suggested to start with even thicker material (about 20 mm more than final thickness) → increased cost, time…
- **0.5mm (for the 66mm thick) and 1mm flatness (for the 35mm thick) achieved**
- **0.5mm flatness too ambitious** and time consuming (& therefore expensive)
- **1mm flatness now the specification → incorporate this into cassette design**

LHCb SPACAL: excellent recent experience with 3D-printed tungsten absorber for ultra-compact calorimeter

- R&D on single cell 3D-printed tungsten prototype
- Produced 1.5x1.5 cm^2 cells up to 10 cm long
- Smooth surface mandatory not to damage scintillating-fibre crystals
  - First company produced 100mm pieces **but too rough inside**
  - **Very good roughness** of Ra= 5 µm achieved with 2nd company; so far only up to 50mm length **(equipment is normally for dentistry!)** → two pieces stacked



Rapport de contrôle

EDMS.2457848 - J3067845

LHCb

bloc longueur 50 mm

Résultats de mesure

Contenu	Mesuré
Rugosité 2D <Rugosité_1>	
Profil=R_ISO - Section=[1]	
Ra	5.0423um
Rq	6.5405um
Rsk	0.5161
Rp	22.5633um
Rv	17.1012um
Rz	39.6644um
Rt	51.3316um
RSm	0.1774mm
Rpk	9.9100um
Rvk	4.8479um

Mean roughness (→ Ra)

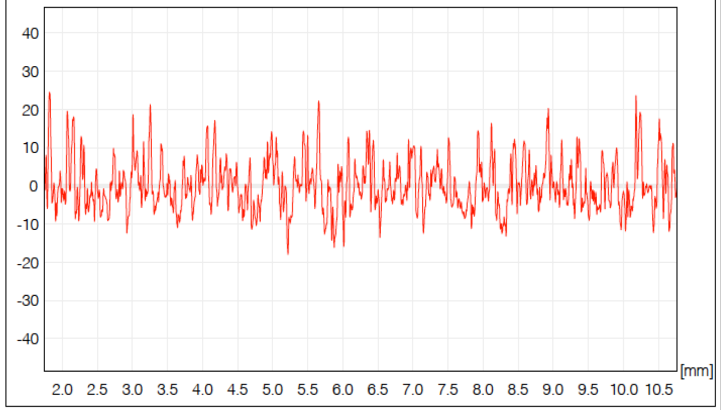
Total height of profile = distance (max-min) (→ Rt)

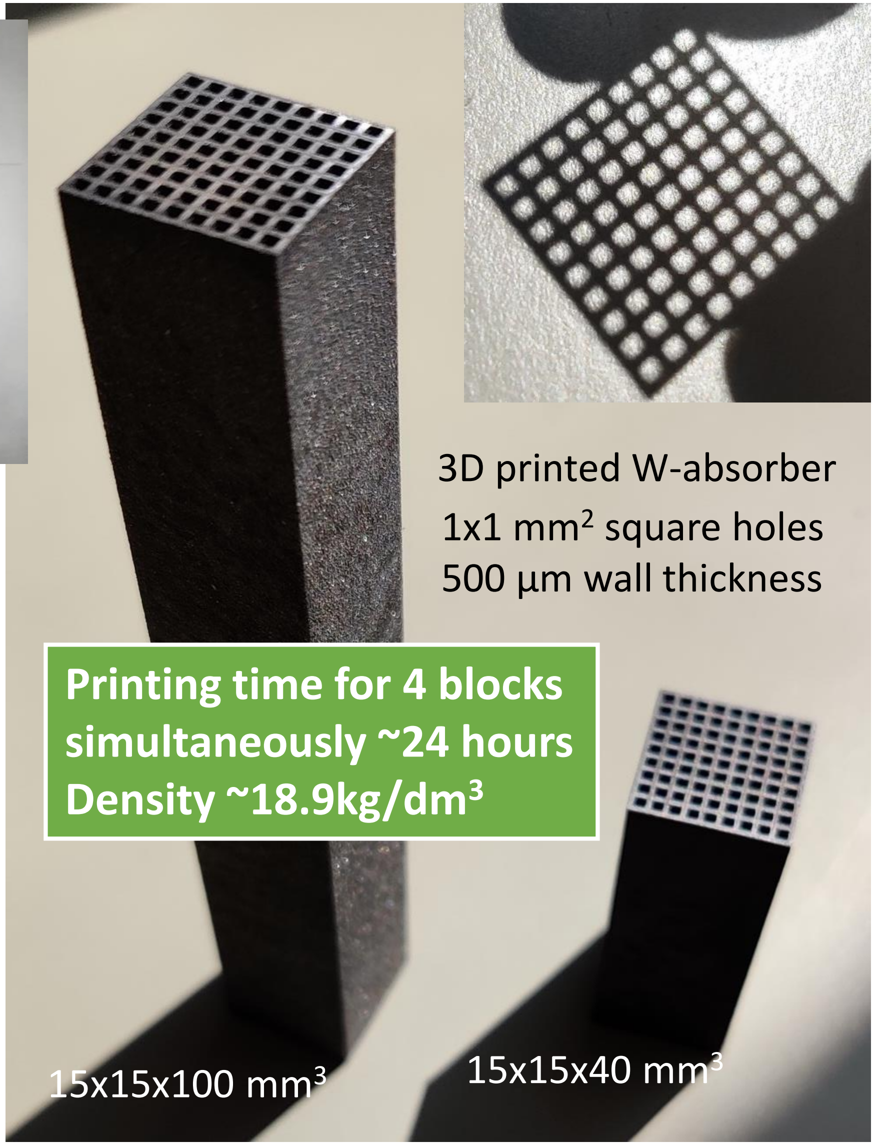
Results from new blocks, Dec. 2020

FACE A

mesure 2

Profil=R_ISO - Section=[1] X Mag x20 Z Mag x1000 <Rugosité_1>





3D printed W-absorber

1x1 mm^2 square holes

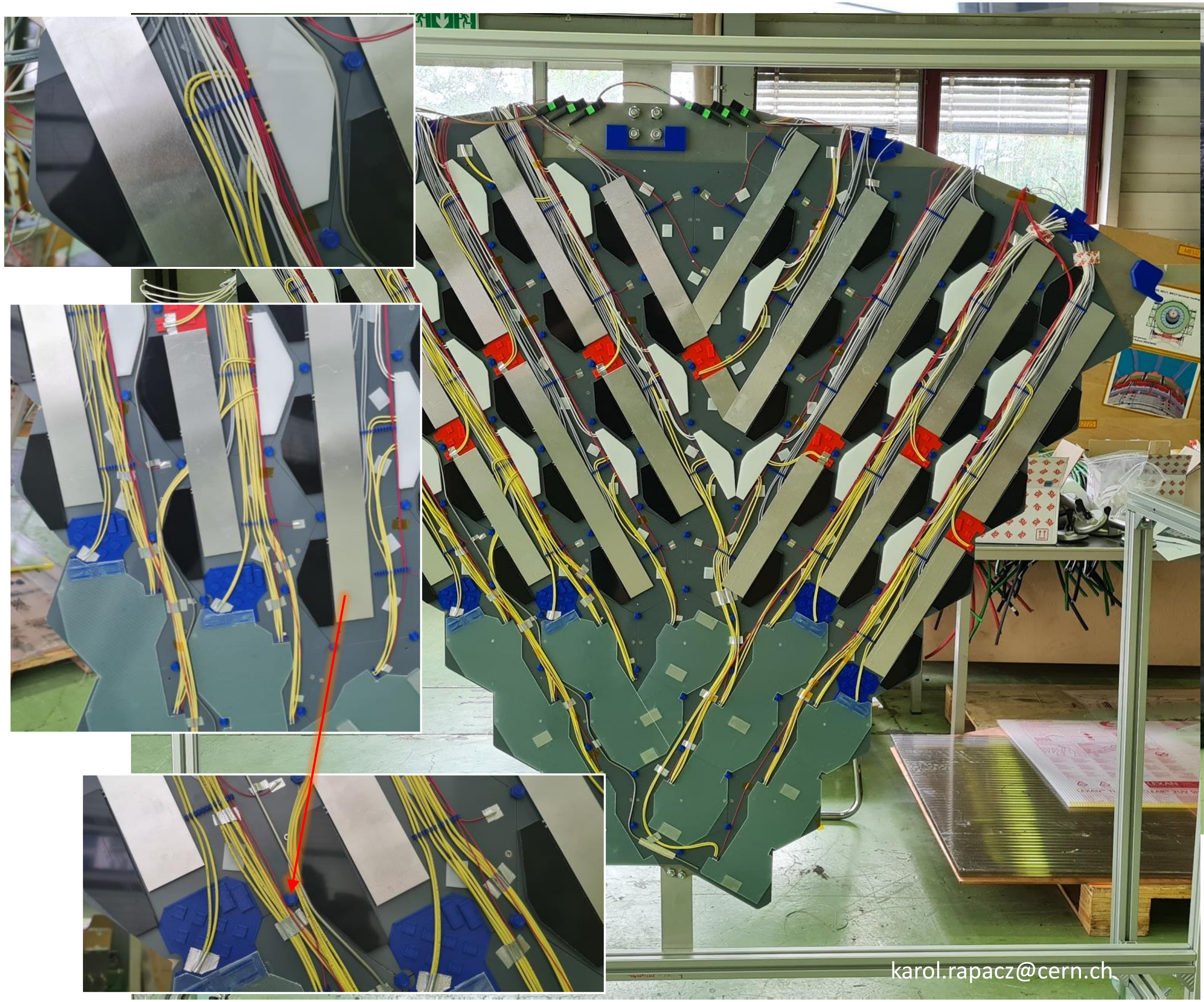
500 µm wall thickness

Printing time for 4 blocks simultaneously ~24 hours
Density ~18.9kg/dm^3

15x15x100 mm^3

15x15x40 mm^3

And so many things to do with integrating a real calorimeter…



Cables in the region between barrel and endcaps

Some comments on basic mechanical engineering concepts for calorimetry

"**Fight for an envelope at the moment of its definition** - calorimetry is about shower containment - you want it to be at least adequate. **Keep protecting your envelope later,** try to expend. The service crack region is a fantastic opportunity to fill with sensors. We did so in ATLAS (TileCal) filling the cracks with scintillator plates.

- The innermost of them provide major ATLAS triggers for all the low Lumi runs.
- The further-out counters provide very competitive luminosity measurements including from the vdM scans."

"Very useful to make your design such that **any element, including mechanical modules, is possible to replace.** We actually did so, but lost this capability when other sub-detectors have blocked our structure. That has unpleasant consequences for the upgrade."

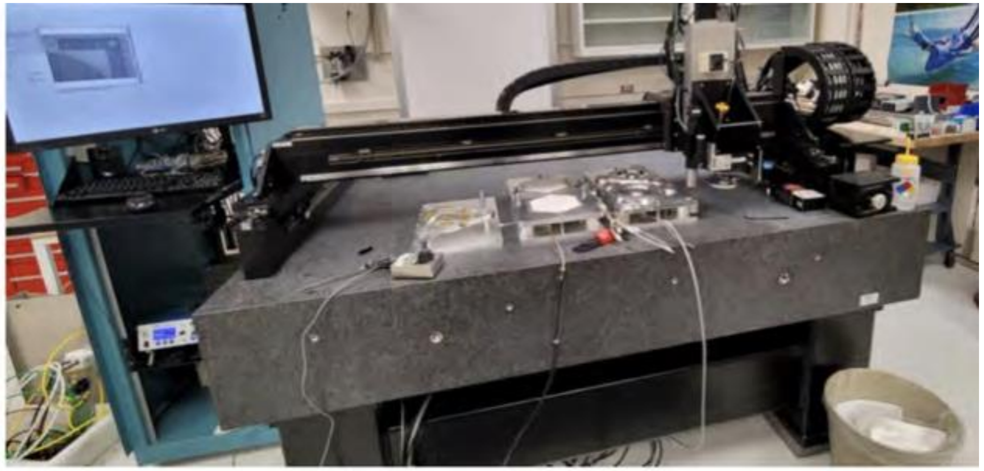
Comment on engineering of highly-granular calorimeters

"On the tool side, the integration is more and more a heavy topic: having a tool set allowing to make complete optimisations would help. By full, I mean **a unified parametrised version of the detector** (radius, cell size, mechanical structure, heat production and transfer, signal precision), or at least automatic bridge to model managers (GEANT4, Catia, Thermal, Comsol or Magnetic simulations, ... I don't really know of a DAQ simulation, yet) would help optimise the optimisation process. This is a bit underway with KEY4HEP, but there is quite some way to go, I think."

Automation of module assembly

CMS HGCAL: module assembly profits from experience assembling CALICE & Tracker modules – but needs work!

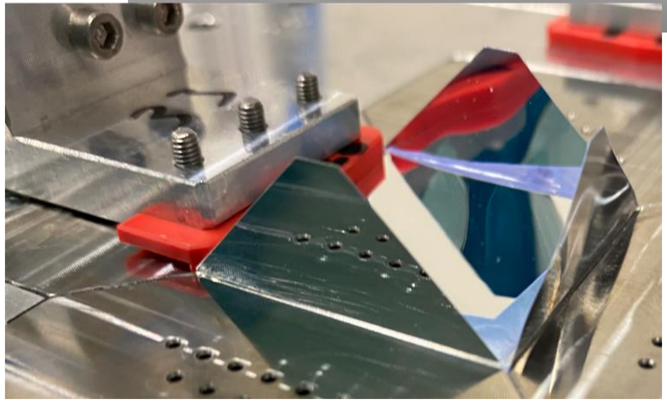
Industrial “gantry” modified for assembling Si modules

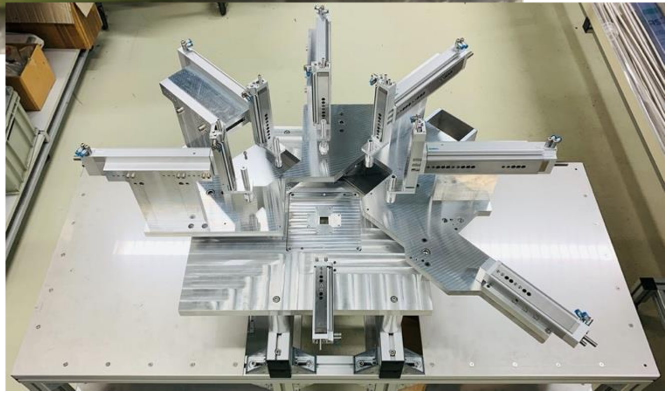


Gantry does glue dispensing and assembly, through dedicated dispensers and vacuum pickups

For scintillator tiles: need to wrap them individually

Machine for cutting foils





Automated folding of foils around tiles

Getting these things right takes a lot of development effort!
→ **don’t underestimate the R&D required for automation!**

Operation, calibration and monitoring

Comments on operation/calibration/monitoring

"BUILD IT AT YOUR OWN RISK, YOU ARE RESPONSIBLE FOR ANY HARM OR DAMAGE THAT YOU SUFFER AS A RESULT"

Decoded: Some calorimeters need **long-term babysitting** by large teams of people **to maintain their performance**. This includes operation of well-understood and stable monitoring systems, regular calibration (MIPs, ϕ-symmetry, standard candles – π^0, Z^0 etc.)

"Beware of the solutions that say - we will recalibrate something weekly. We, for example, can not permit this luxury. **The internal stability is much better than calibration capability.**"

"In TileCal we are **a bit obsessed with calibrations**. We have movable radioactive Cs source, Laser system, System that integrates signals from collisions, and we analyse response to isolated muons. These **'overlapping' calibrations give great information**. **This pays back**, we think that at any moment we are within few % from the target and channel-channel spread is of a few %. This few % may be as low as one. But **this effort is rather costly in manpower**. Very costly. One may want to prioritize."

Comments on operation/calibration/monitoring

"We will still have to face the challenges of tracking PbWO4 response in HL-LHC. One thing that we definitely learned from >10 years of running ECAL is that **maintaining a precise laser monitoring system operating 24/7 providing "physics quality calibrations" is hard work**..."

"In terms of the data taking, when you have many similar channels, it is very **important to be add some internal source identifiers to the data stream**, so in case of wrong re-connection (cables, fibres) during the maintenance, one can figure out correctly the source of the data immediately, and not after some re-processing of the data"

"**Monitoring of as many as possible components during the data-taking** also turned out to be important (a few problems were only discovered during collision data-taking)"

Software & Simulation

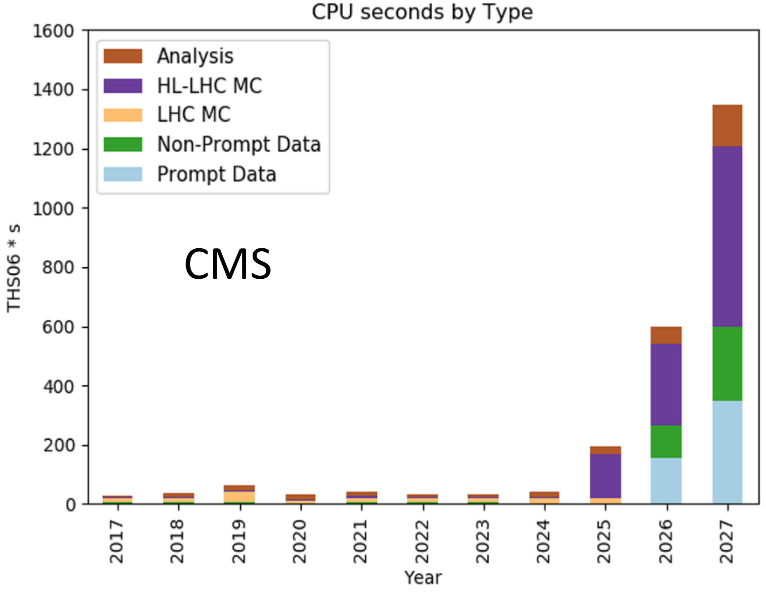
Some comments on software/simulation for HGCALs

"With such a complex geometry and large number of channels* it is **very time-consuming** to vary geometries & measure performance to optimize the calorimeter. And **how exactly do we measure performance**?

→ **need for even-more-accurate and performant fast simulations & reconstruction algorithms**

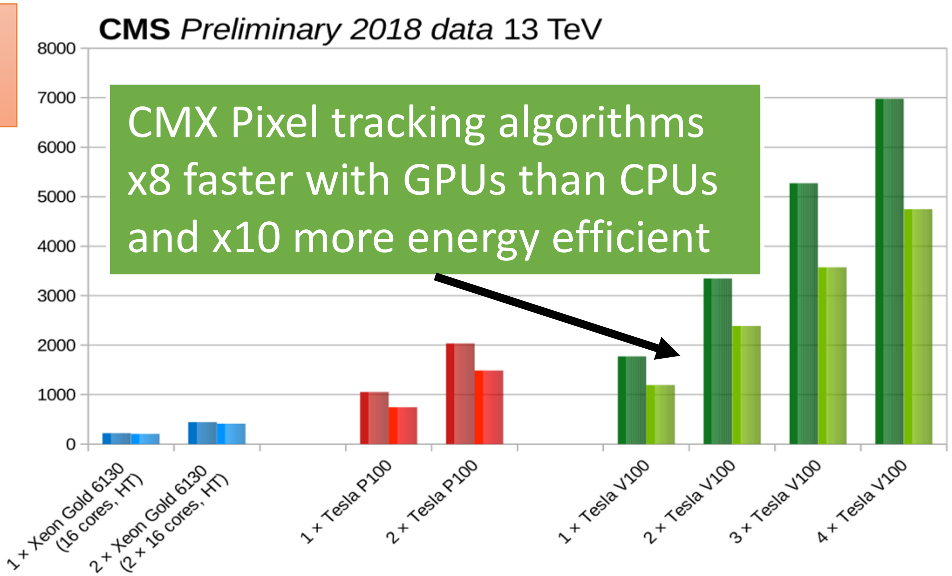
** in high-granularity calorimeters*

Computing needs increase by x30
May get a factor x2-3 from CPU development

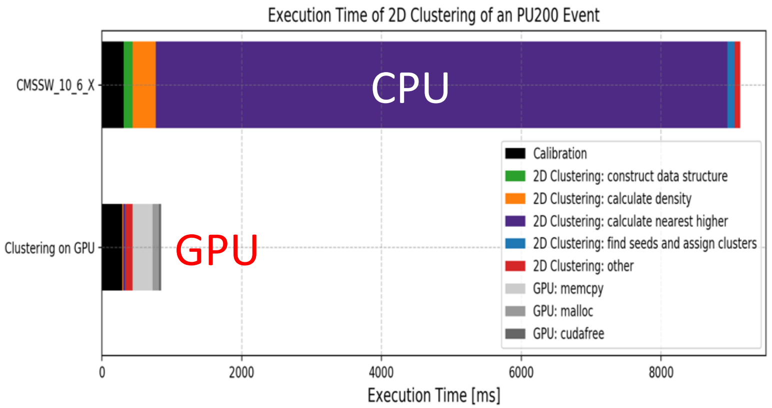


We are currently missing a factor 10 in computing power!

CMX Pixel tracking algorithms x8 faster with GPUs than CPUs and x10 more energy efficient



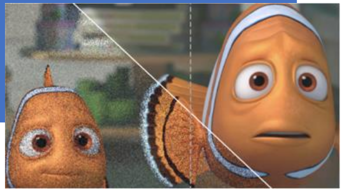
For HGCAL clustering, time for mathematical processing is almost negligible! Overall time is x10 faster for GPUs, limited by data throughput



Aside from hardware R&D, Machine Learning (ML) is one of the fastest-growing areas of software research in HEP and elsewhere

→ **HGCAL pattern recognition etc. is an excellent real-world testbed for ML**

→ need to **utilize our own experts efficiently** and encourage participation from **experts from outside our field**



Test, test and test again.
And again. And a bit more.

Some wise words on testing-time from one of our young CMS colleagues who sadly passed away in 2020

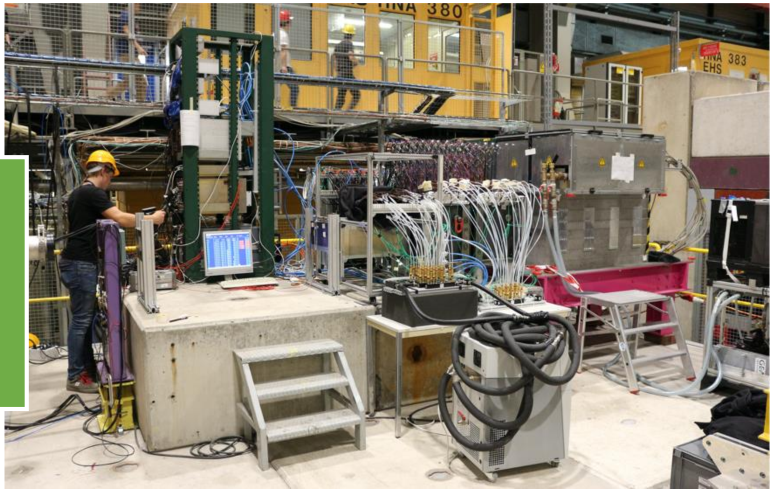
- The CMS HCAL is very complicated and takes **infinite time to fully test and debug**
- Initial QC and short term test can reveal only obvious problems with high probability of appearing and cannot reveal ”rare” problems
- The **longer you operate and the bigger scale of the system** – the more problems you find. Some of them might be critical.
- It is hard to choose a priori ”optimal” time for long burn-in test, but **always better to have longer test than shorter**
- One should plan the Upgrade schedule taking into account ”enough” time for long burn-in test and solving possible issues
- **In case of delay usually people reduce time for burn-in**, which is wrong way! It takes much more time later to fix the problems on already installed equipment.
- **Much better to spend time and efforts on making good stable detector rather than spending much more time and efforts on analysis trying to understand how to recover or correct data from bad unstable detector**

Danila Tlisov

Some closing remarks

- When designing a new calorimeter, the **development phase** is often more critical than the research phase. Challenges can be addressed if there is **adequate flexible engineering support** (electronic, mechanical, software)
  ➔ large laboratories and institutes need **flexibility to hire more engineers/designers** for specific periods, and/or **build working relationships with engineering departments** in their own institutes
- **Building good relationships with industry** for detectors, power supplies, PCB manufacture, absorber production etc. critical for success
- Beam & system tests are not only an opportunity to focus technical developments, but are **critical for training of young physicists and engineers**

One of three winners of the CMS "Thesis Award" 2021



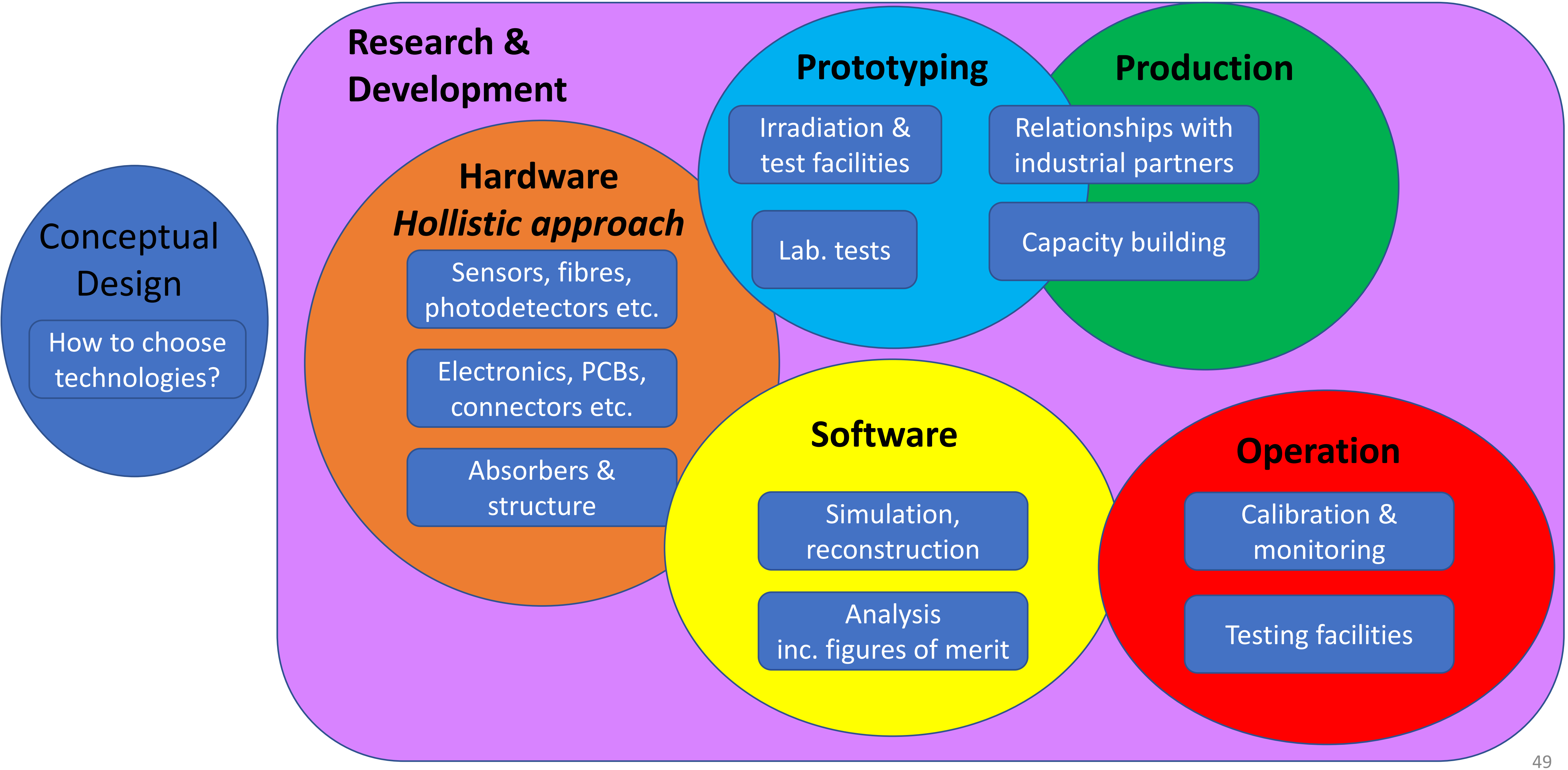
"**Tests, tests, tests, prototypes - never enough**. We did perhaps 20+ beam test campaigns 1995-2004 & about 10 for HL-LHC 2015-2018"

"**Test components from various institutes integrated together** – in many places: more than seems reasonable - never enough!"

A wise person once said:

“there are no show-stoppers; it is all just engineering”

backup


Conceptual Design
How to choose technologies?
Research & Development
Hardware
Hollistic approach
Sensors, fibres, photodetectors etc.
Electronics, PCBs, connectors etc.
Absorbers & structure
Prototyping
Irradiation & test facilities
Lab. tests
Production
Relationships with industrial partners
Capacity building
Software
Simulation, reconstruction
Analysis inc. figures of merit
Operation
Calibration & monitoring
Testing facilities