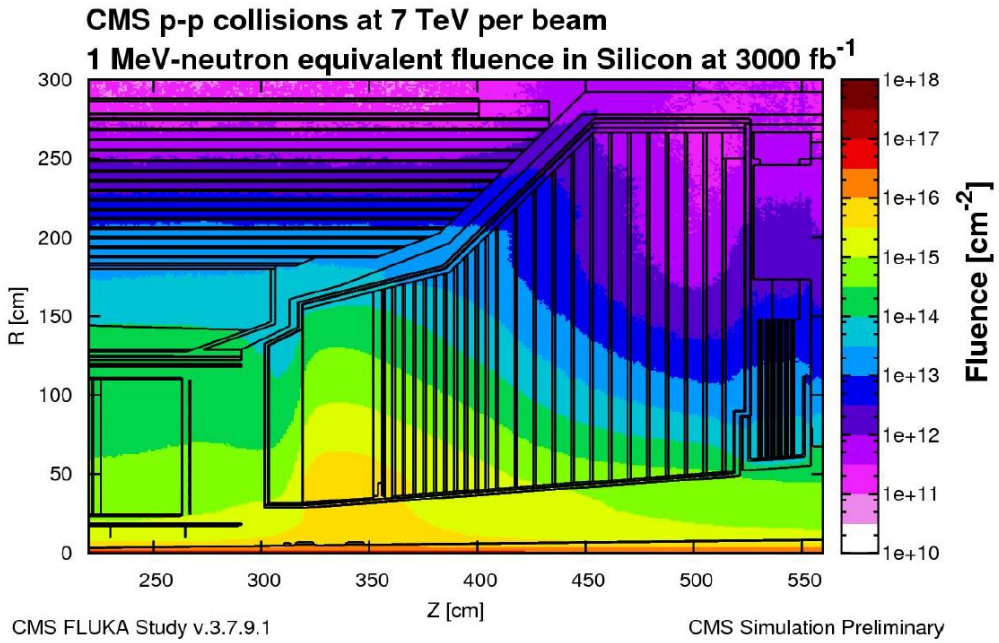
Status of the CMS-HGCAL Module Assembly Center (Beijing) and qualification

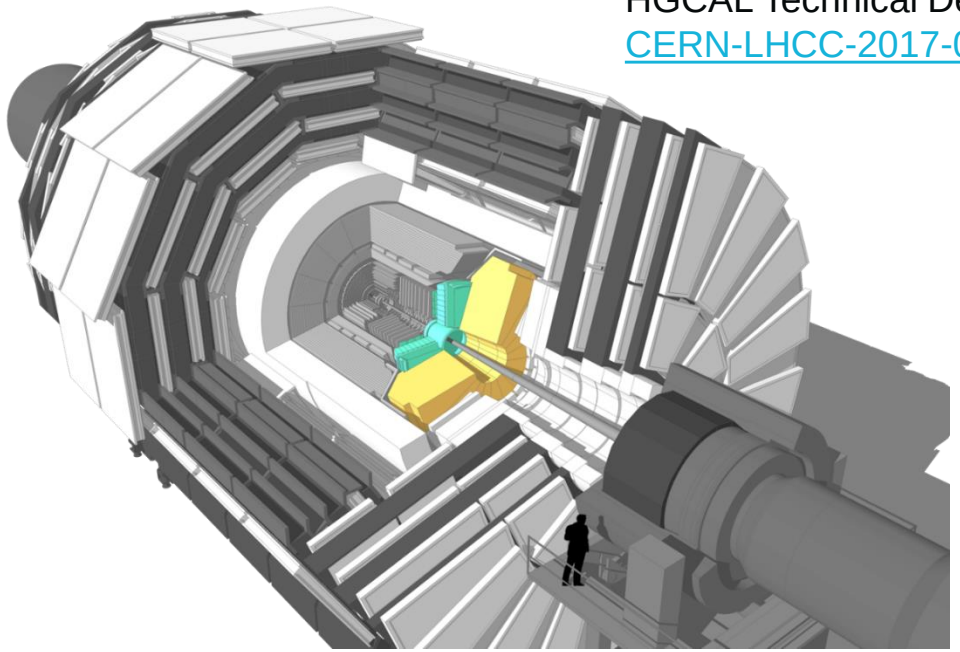
Yong Liu (Institute of High Energy Physics, CAS),
on behalf of the CMS-HGCAL IHEP Team

The 7th China LHC Physics Workshop, Nov. 25-28, 2021

CMS-HGCAL project: motivations



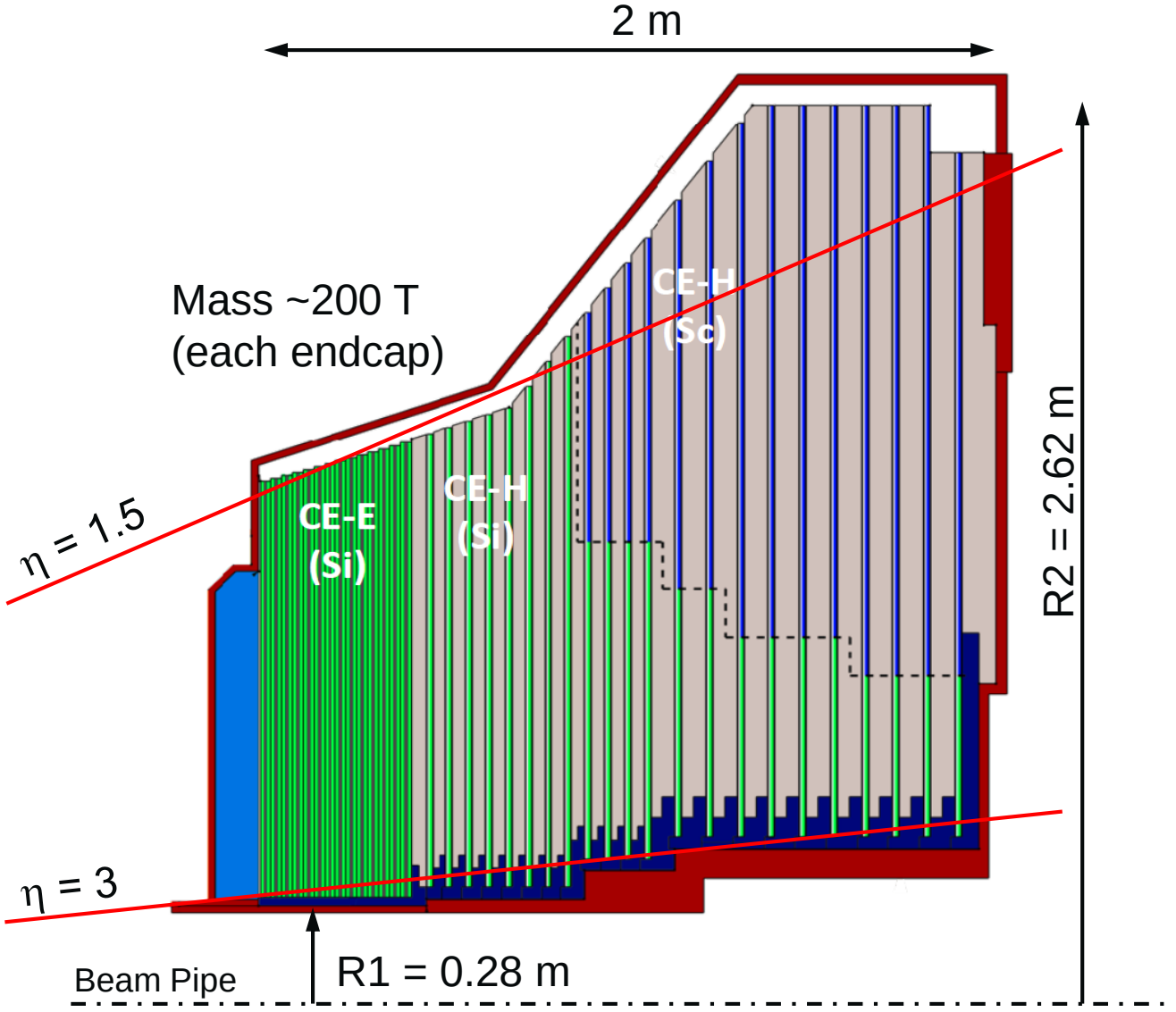
HGCAL Technical Design Report:
CERN-LHCC-2017-023



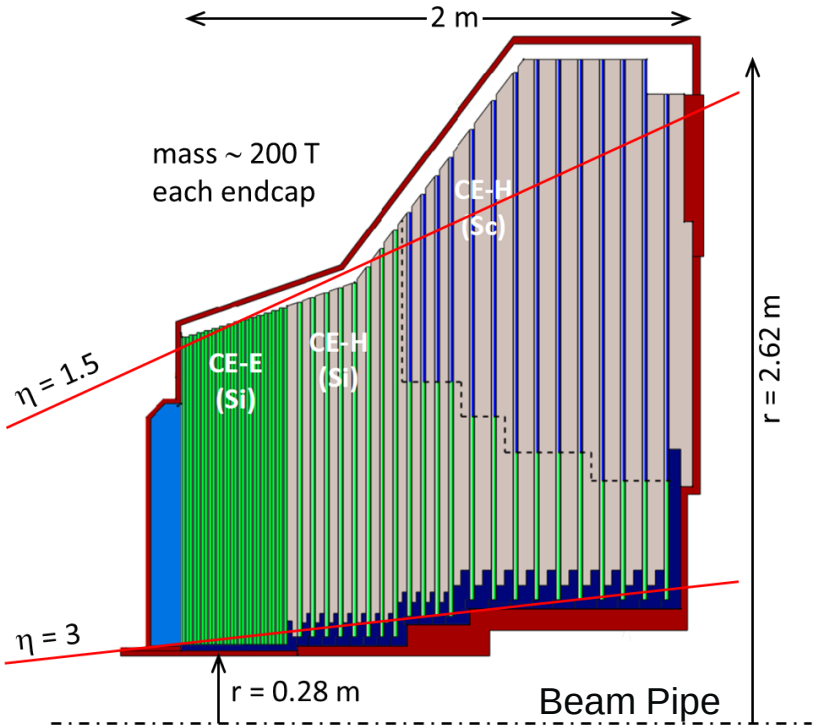
- CMS endcap calorimeters: Phase-2 upgrade
  - Harsh environment at HL-LHC: high pile-up, high radiation level
  - Required to replace the existing endcap calorimeters
  - Construct a High Granularity Calorimeter: HGCAL project

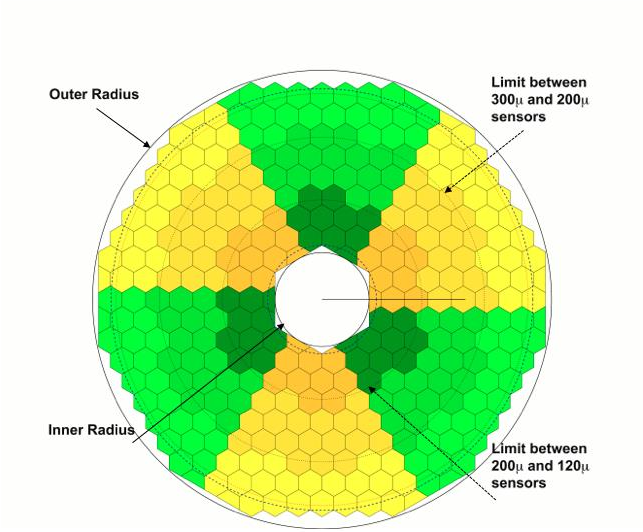
CMS HGCAL project overview

- Key Parameters (updated from the TDR)
  - HGCAL covers $1.5 < \eta < 3.0$
  - **Full system maintained at -30℃**
  - ~640 m^2 of silicon sensors
  - ~370 m^2 of scintillator tiles
  - 6.1M silicon channels: 0.5 or 1.1 cm^2 cell size
  - 240k scintillator-tile-SiPM channels
  - Data readout from all layers
- ~31k Si-modules: including spares
- Active layers and elements
  - Si-sensors (full and partial hexagons) in CE-E and high-radiation region of CE-H.
  - SiPM-on-Tile in low-radiation region of CE-H
- Electromagnetic calorimeter (**CE-E**)
  - **Si**, Cu/CuW/Pb absorbers
  - 28 layers, 25.5 X_0 (~1.7λ)
- Hadronic calorimeter (**CE-H**)
  - **Si** & **scintillator**, steel absorbers,
  - 22 layers, ~9.5λ (including CE-E)

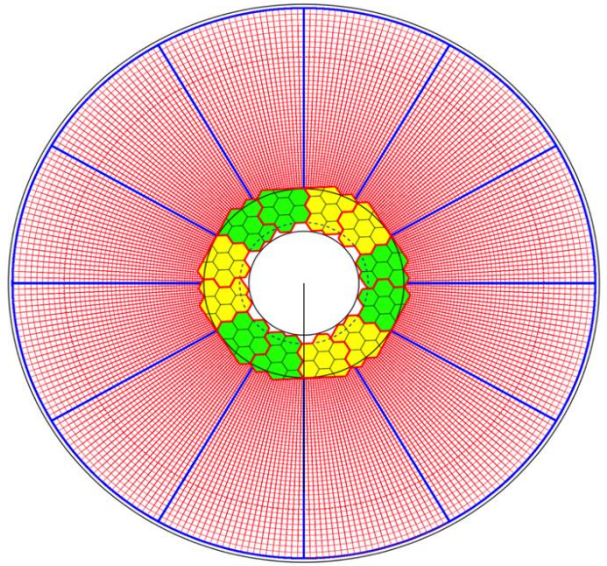


CMS-HGCAL: active layers



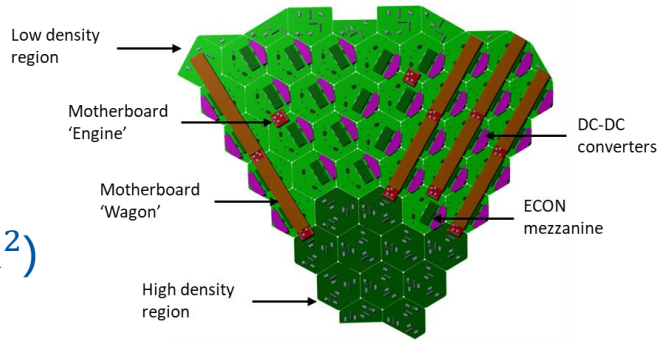


CE-E 9th layer

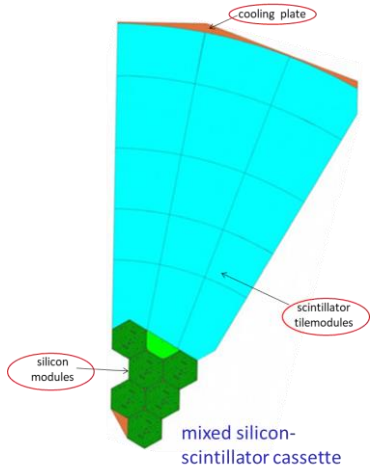


CE-H 22nd layer

- Silicon-only layers in CE-E and CE-H
  - 3 types: 120 μm, 200 μm, 300 μm thick
  - Pads: high density ($0.5\ \mathrm{cm}^2$), low density ($1.1\ \mathrm{cm}^2$)
- Mixed layers: silicon and scintillator-SiPMs
  - Boundary optimized based on radiation tolerance



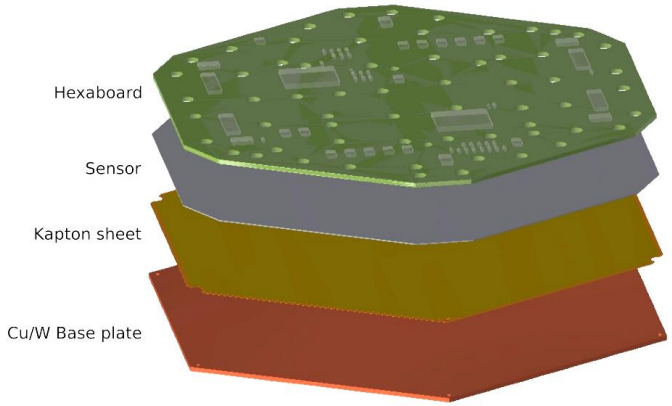
all silicon cassette

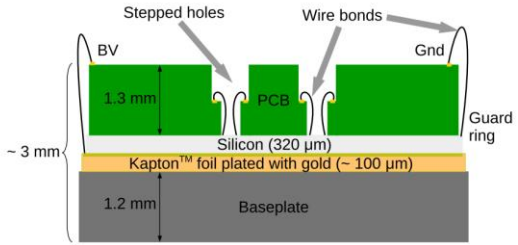


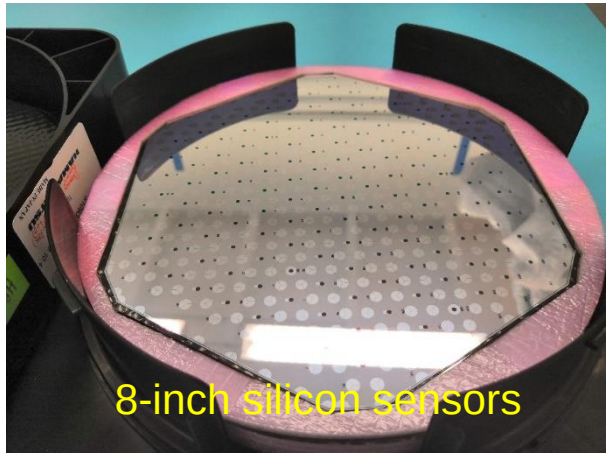
mixed silicon-scintillator cassette

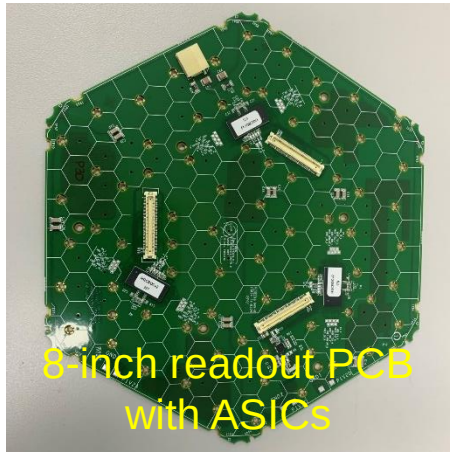
CMS-HGCAL: silicon and scintillator modules

Silicon modules



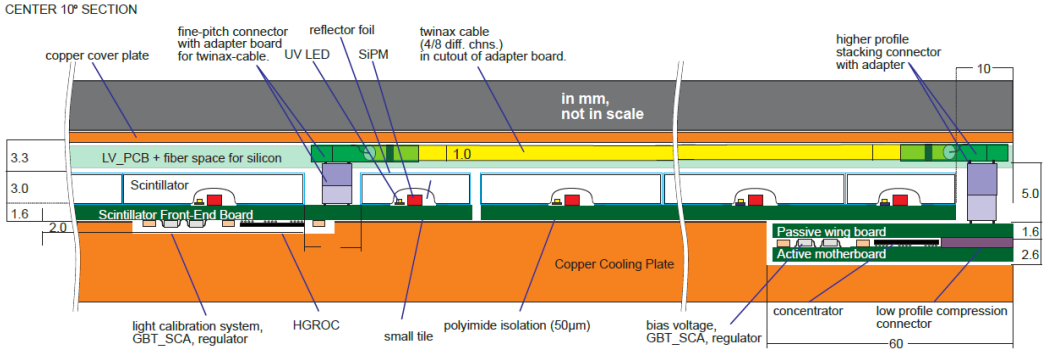


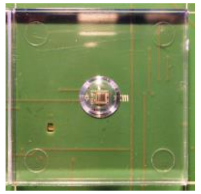




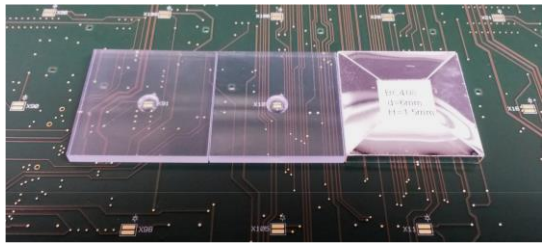
HGCAL China team focus on the silicon modules

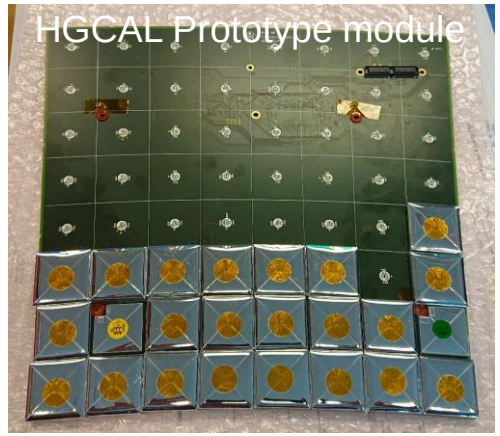
"SiPM-on-Tile" Modules





"SiPM-on-Tile" design: scintillator tile directly coupled with SMD-SiPM

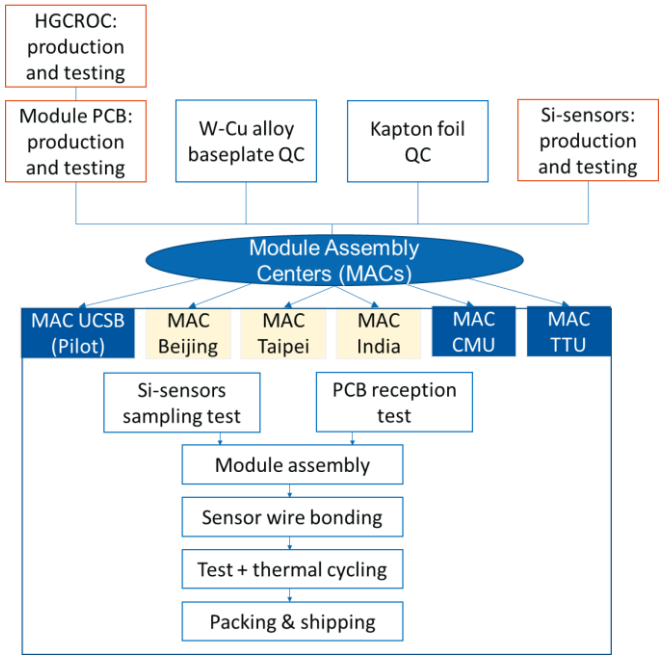




"SiPM-on-Tile" design demonstrated by CALICE-AHCAL prototype, adopted as the **baseline** for CMS-HGC scintillator part

Module Assembly Center (MAC)

- HGCAL: ~31,000 silicon modules
  - Module assembly chain established
- Module Assembly Center (MAC)
  - 6 MACs world wide: 3 in Asia, 3 in US
  - Each MAC expected to assembly ~5000 silicon modules
  - MAC-Beijing: a dedicated silicon lab on IHEP campus: focus of this talk



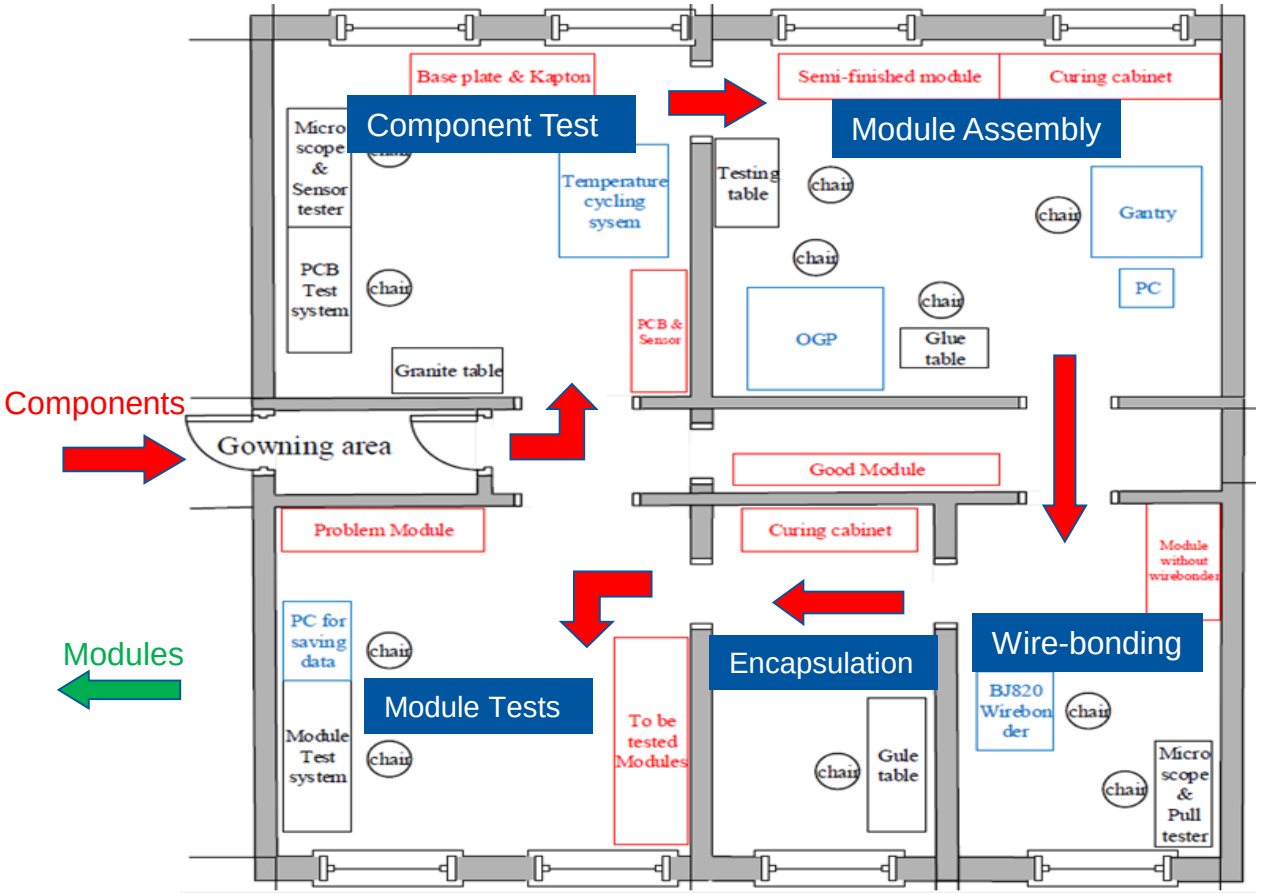
CMS-HGCAL IHEP Team (partial members, May 2021)

Not shown in the photo:
Staff: Mingshui Chen, Jin Wang, Congcong Wang
Graduate: Jialin Guo
Postdocs: Émilien Chapon, Fabio Monti
New members: Xiao Zhao (postdoc), Xiaonan Hou, Zhenxuan Zhang (graduates)

Alumni: Huajie Cheng, Yubo Li

MAC infrastructure development at IHEP

- Lab and assembly chain fully established
  - Clean rooms, key equipment and components, services (vacuum, compressed air, dry air)




Main gantry and OGP

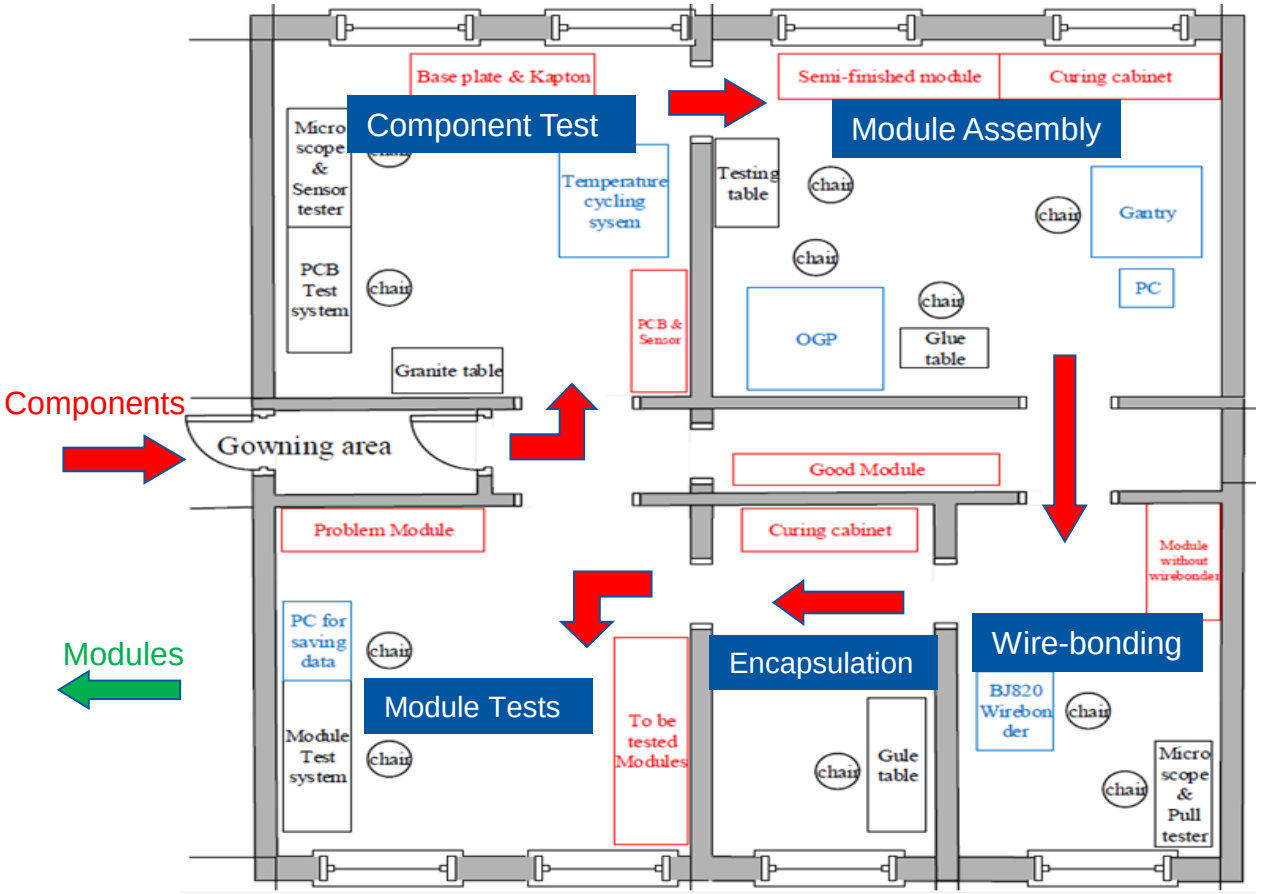

Wire-bonder

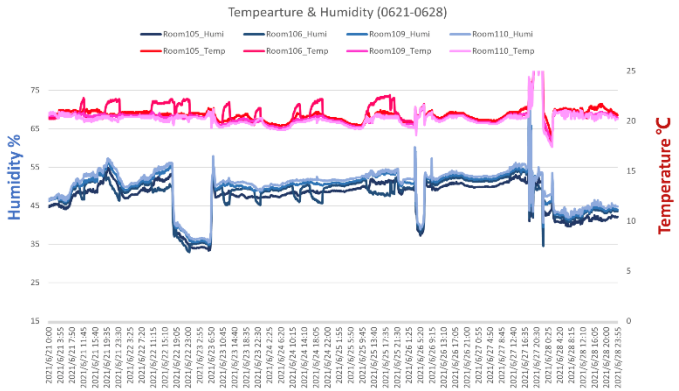

Silicon-module test stands

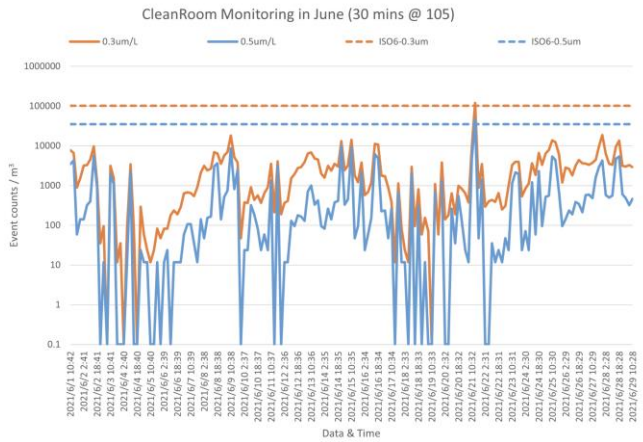

Pull tester and mini gantry for wire-bonds encapsulation

MAC infrastructure development at IHEP

- Clean rooms: Class-1000, 140 m²
  - Temperature: 21 ± 1℃; relative humidity: 45 ± 10%







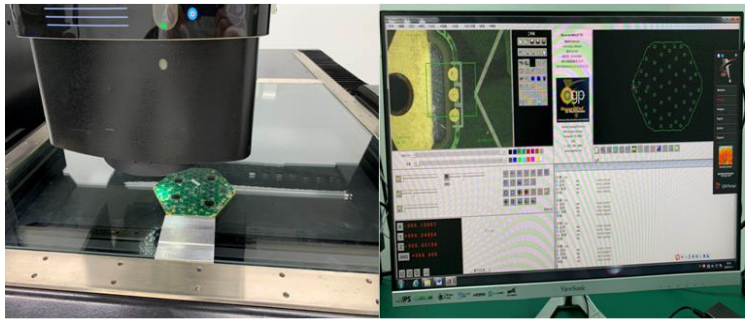
Monitoring of temperature and humidity (within ~1 week): stable running

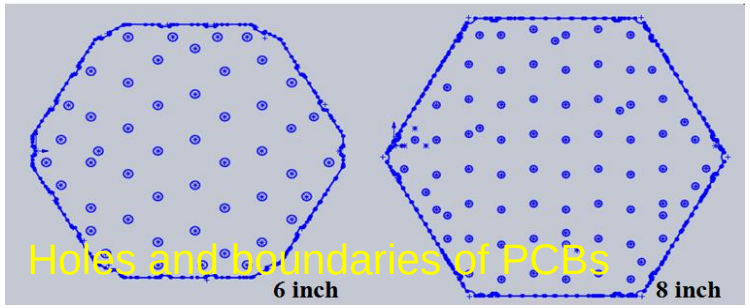
Monitoring of particle level (within ~1 month): better than Class 1000

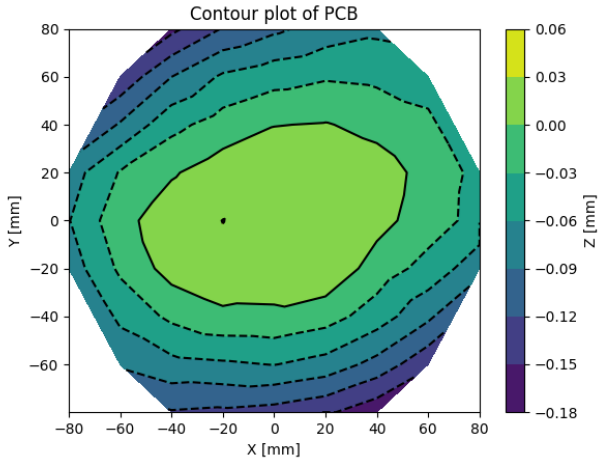
Key procedure in module assembly: component testing

Component Testing → Module Assembly by Gantry → Wire-bonding → Module Encapsulation → Module Testing

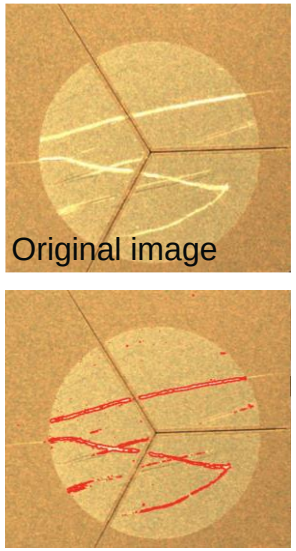
- Component testing: optical gauging product (OGP), without contact
  - Extensive measurements performed for baseplates, PCBs: size, boundaries, thickness, flatness
  - Visual inspection boosted by machine learning: identify and categorize scratches on silicon sensors







PCB planarity measurement (contour)

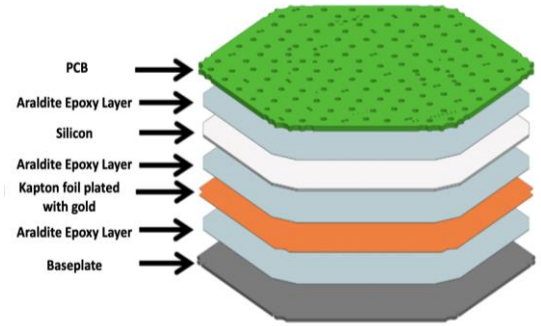


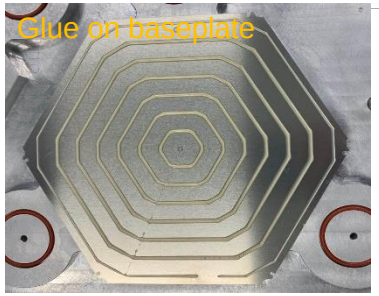
Scratches identified by AI: ongoing efforts

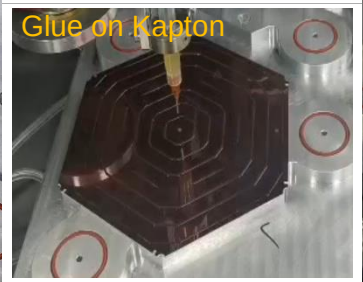
Key procedure in module assembly: gantry operations

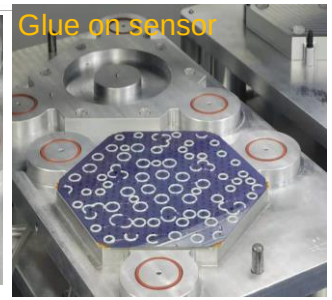
Component Testing → **Module Assembly by Gantry** → Wire-bonding → Module Encapsulation → Module Testing

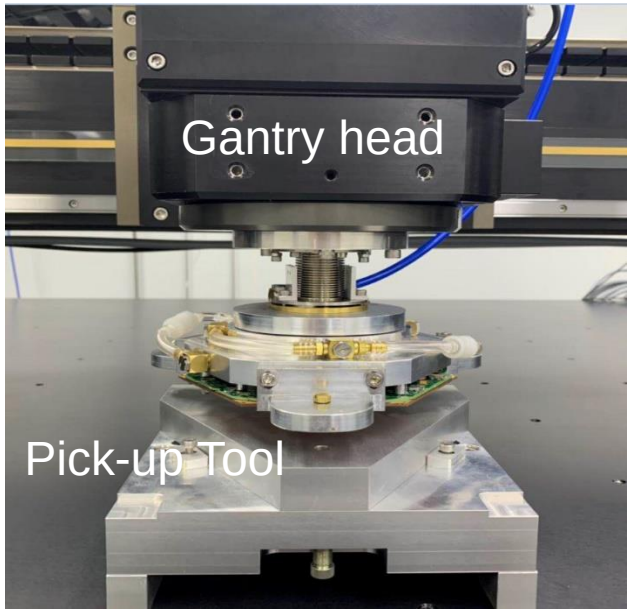
- Module assembly: with the main gantry and tooling (camera, gantry head, fixtures, etc.)
  - Precision pick-and-place movements with components, fine glue dispensing
  - Automated operations with dedicated software







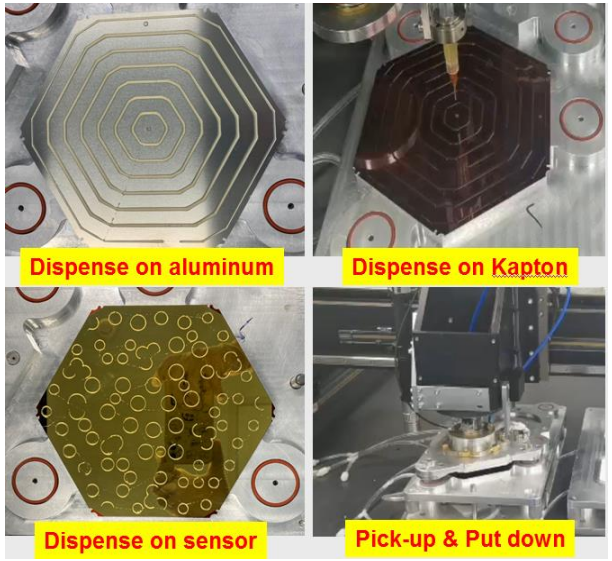


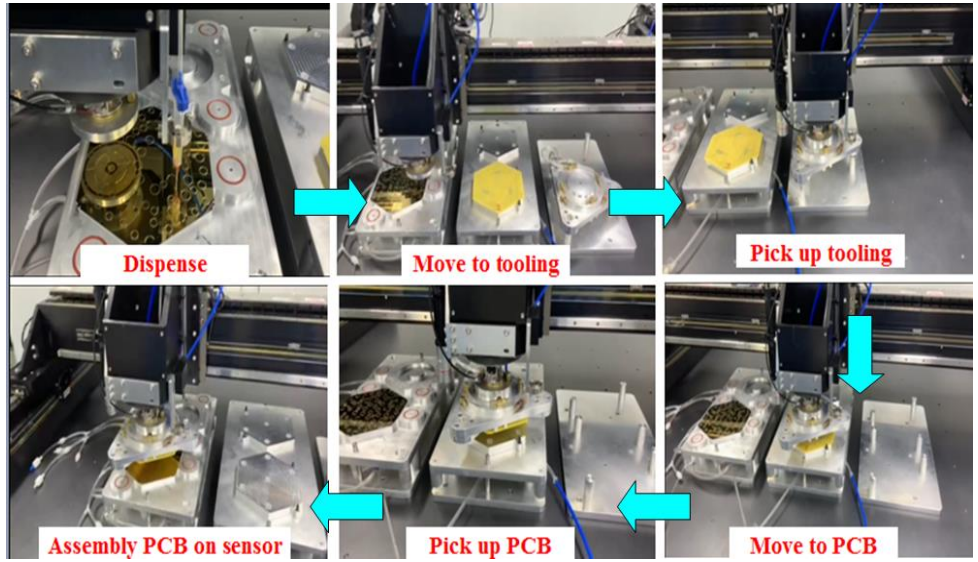


Key procedure in module assembly: gantry operations

Component Testing → **Module Assembly by Gantry** → Wire-bonding → Module Encapsulation → Module Testing

- Module assembly: with the main gantry and tooling (camera, gantry head, fixtures, etc.)
  - Precision pick-and-place movements with components, fine glue dispensing
    - Automated operations with dedicated software
  - Extensive exercises with dummy components: control of glue thickness and spread, placement precision





Details in the talk in the Detector Upgrade parallel session: "**First 8-inch silicon module production and testing**" by Feng Wang (IHEP): stay tuned…

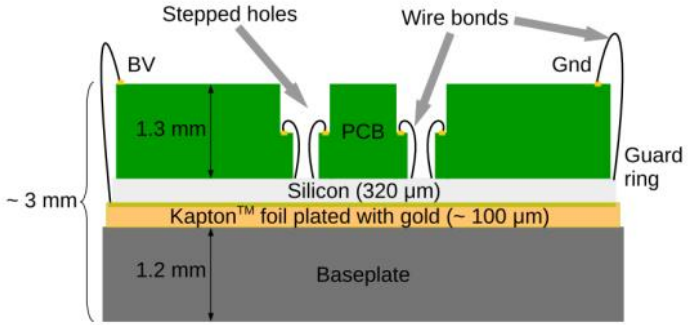
Key procedure in module assembly: wire bonding

Component Testing → Module Assembly by Gantry → **Wire bonding** → Module Encapsulation → Module Testing

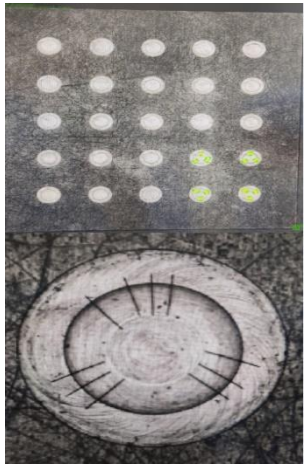
- Wire-bonding: to build electrical connections between silicon sensors and PCB
  - Exercises with dummy sensors and PCBs and optimize bonding parameters
  - Applied optimized parameters for the assembly 8-inch real modules

Bonding machine: Hesse BJ855

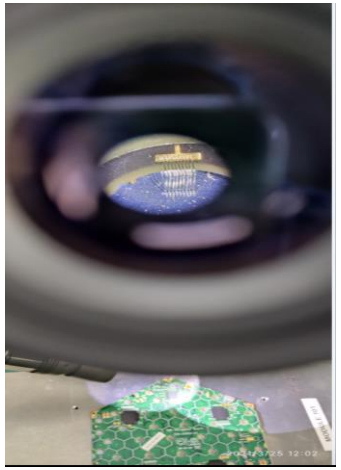
Schematics of wire-bondings of silicon modules (side view)



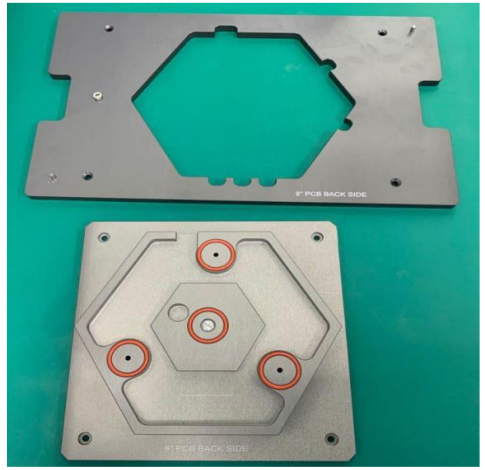
Wires in mock-up with stepped holes



Wires in a real 6-inch module



Wire-bonding Fixtures for 8-inch modules

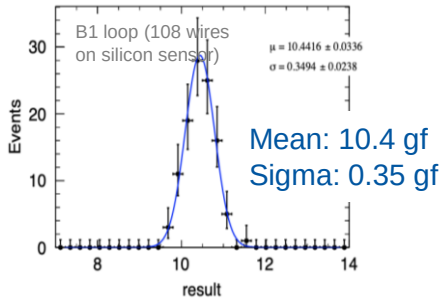


Huiling Hua, "Wire bonder and Pull tester for IHEP HGCal MAC Qualification", CMS China Meeting 2021

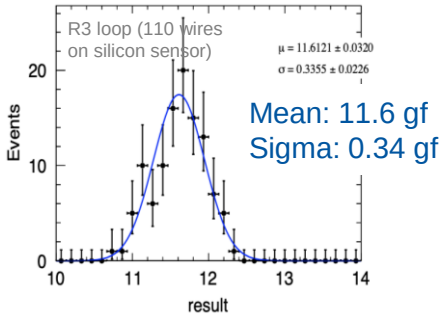
Key procedure in module assembly: wire bonding

Component Testing → Module Assembly by Gantry → **Wire bonding** → Module Encapsulation → Module Testing

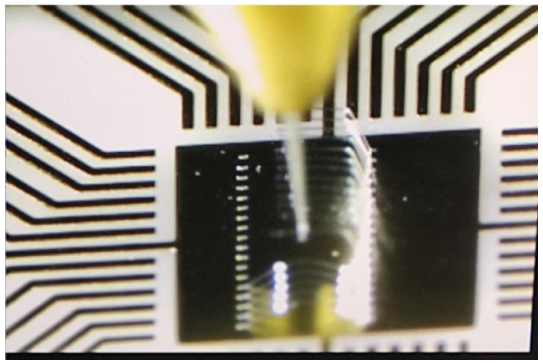
- Wire-bonding quality (by pull tester): wire-bonds can fulfill the strength requirement
  - Destructive pull test: measure the strength of bonding wires and feet
  - Non-destructive test: to extract the correction factor to be applied for destructive pull tests
    - Wire-bond in a triangle form (max. 5gf strength set)

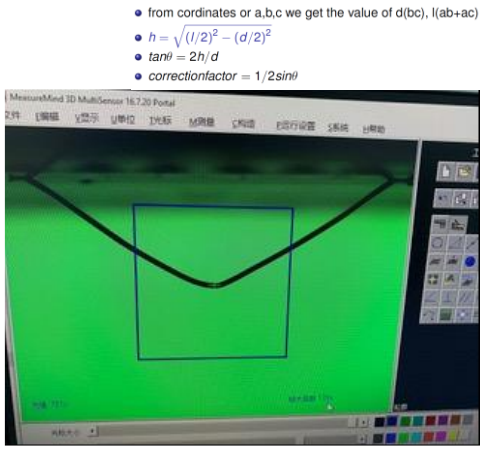


Mean: 10.4 gf
Sigma: 0.35 gf



Mean: 11.6 gf
Sigma: 0.34 gf





Pull strength requirement: for all substrates average pull strength should be >8gf and standard deviation <1.0 gf

Twiki Page: Wirebonder Qualification Reporting Area

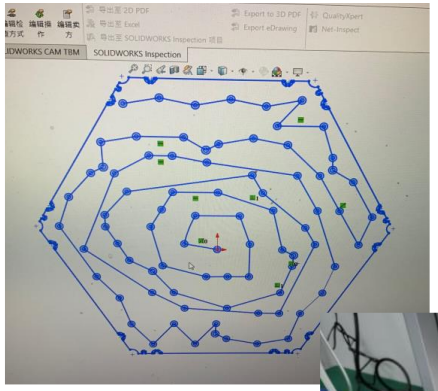
MAC preparations for key procedures (4)

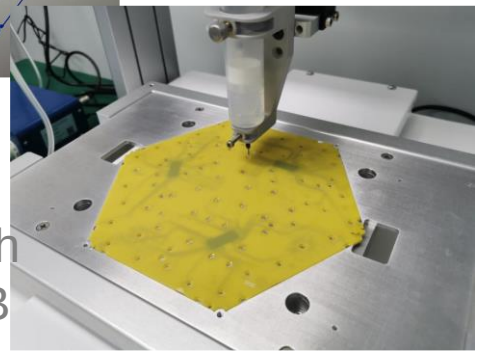
Component Testing → Module Assembly → Wire-bonding → **Module Encapsulation** → Module Testing

- Mini-gantry system: dispense glue to encapsulate the wire-bonds for better mechanical stability
  - Mini-gantry: to dispense glue points into the stepped holes of PCBs, exercises with mock-ups
  - Centrifuge: to remove bubbles in 2-component glue mixture

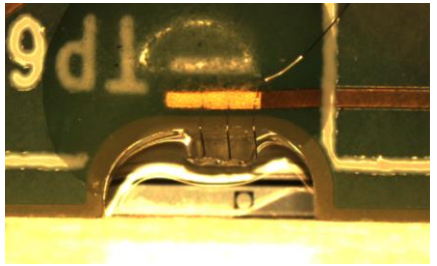
Mini-gantry

Centrifuge


Route of syringe (mounted on the mini-gantry head)

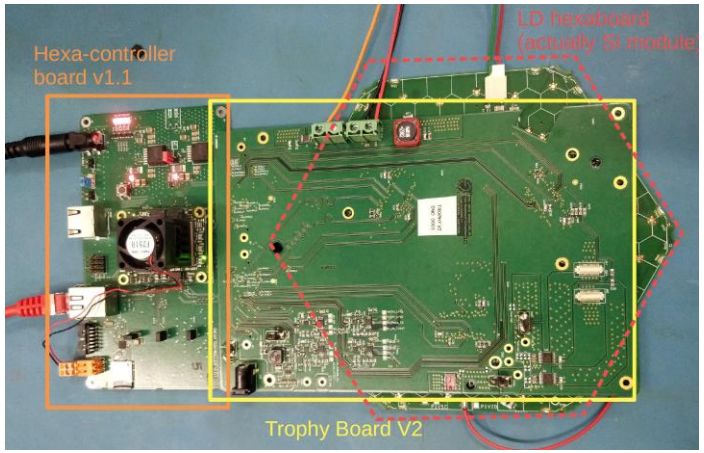

Exercises with mock-up PCB

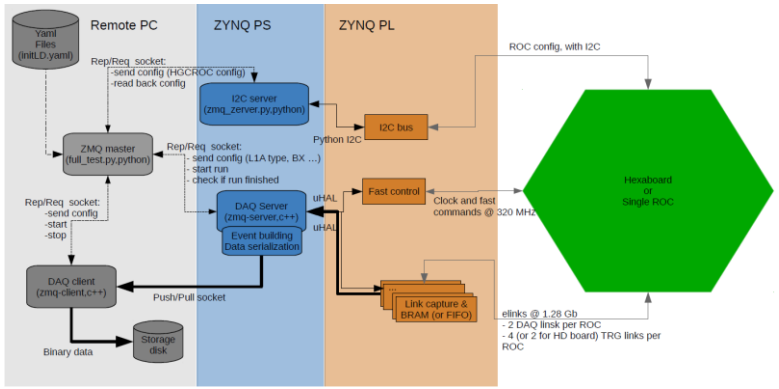
Encapsulation of wire-bonds



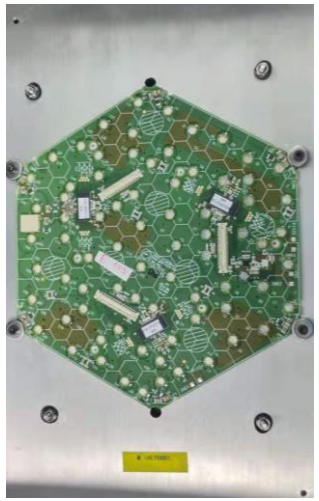
MAC preparations for key procedures (5)

Component Testing → Module Assembly → Wire-bonding → Module Encapsulation → Module Testing

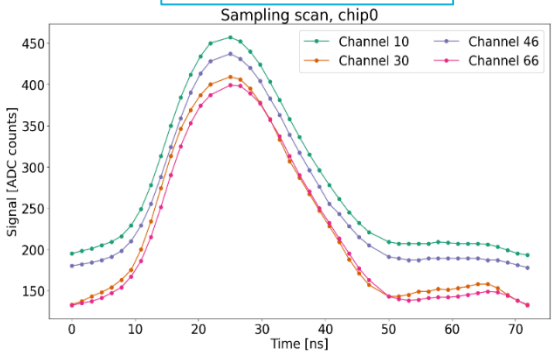




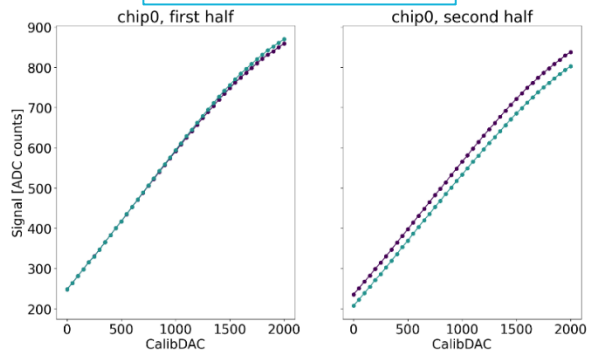
SiModule: “IHEP-001”



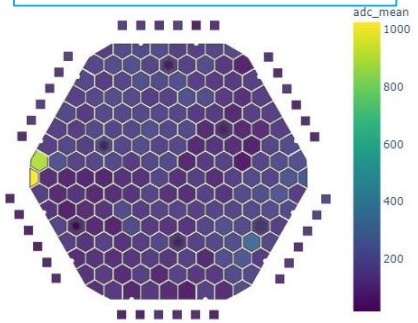
Sampling Scan



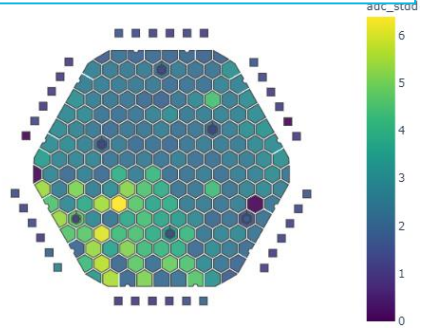
Charge Injection



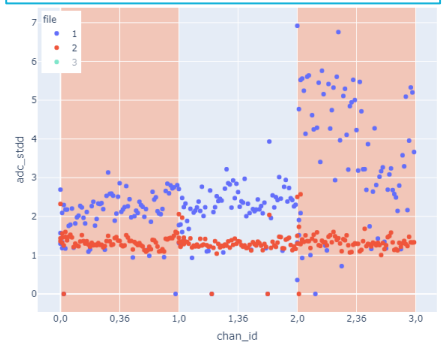
Pedestals: PCB only



Pedestals: PCB+sensor

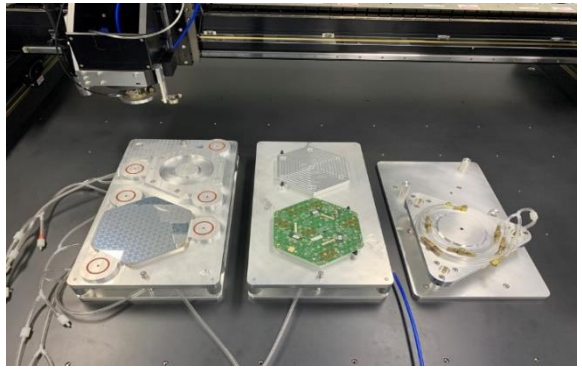


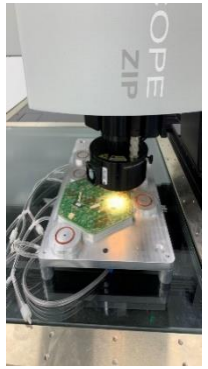
Pedestals: w/wo sensor

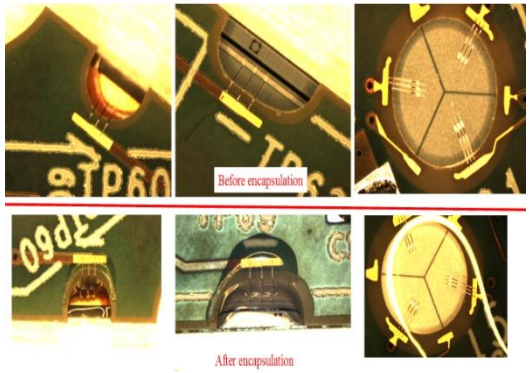


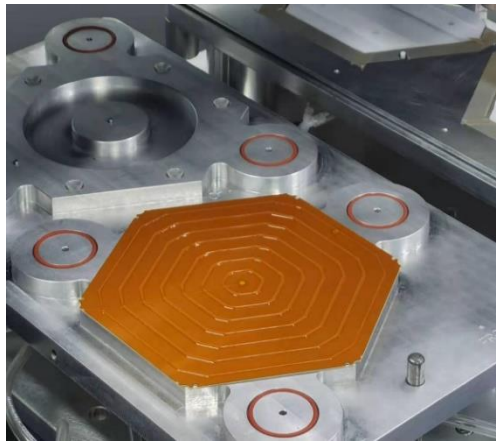
Highlights: the first 8” module assembly at IHEP

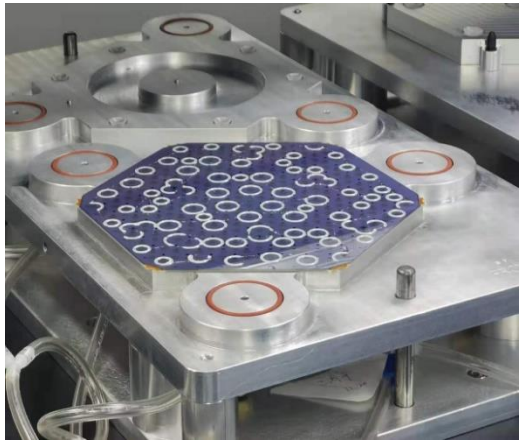
- Successfully assembled the first 8-inch silicon module: **the first MAC to achieve this goal**
  - Applied optimized parameters from extensive exercises of dummy module assembly
  - Full functionality demonstrated in lab tests → validated the 8” silicon module design

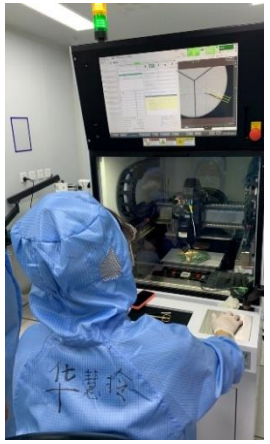


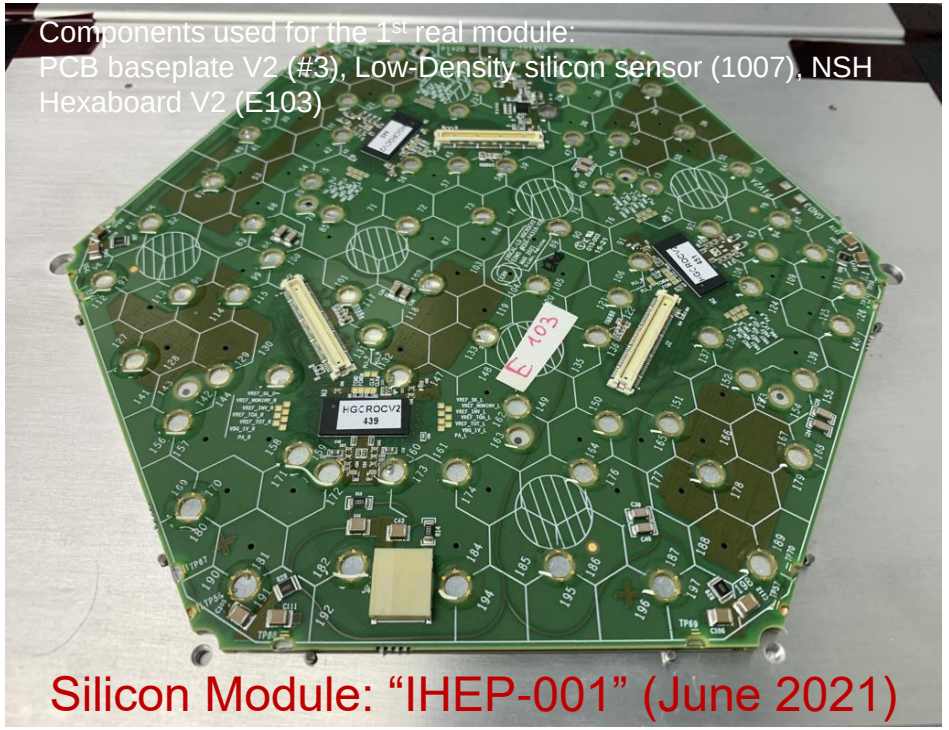






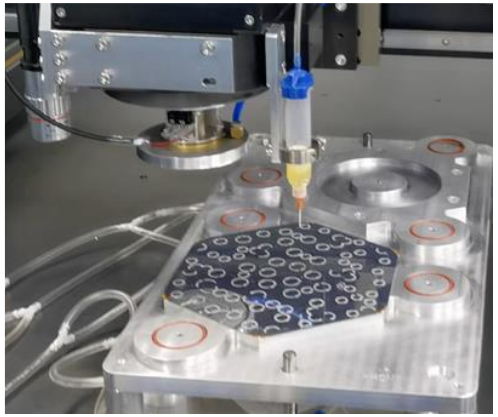


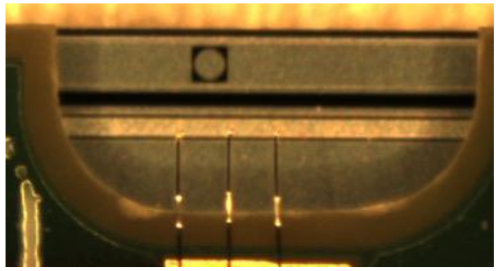


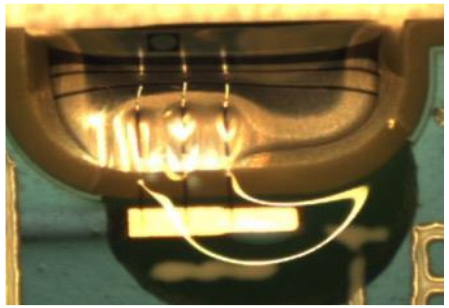


Highlights: the second 8” module assembly at IHEP

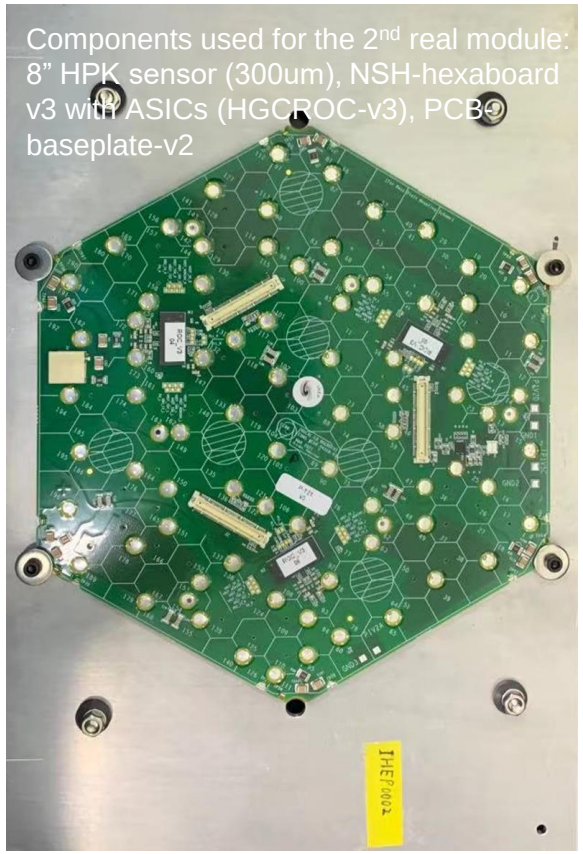
- Successful assembly of the second 8-inch LD module







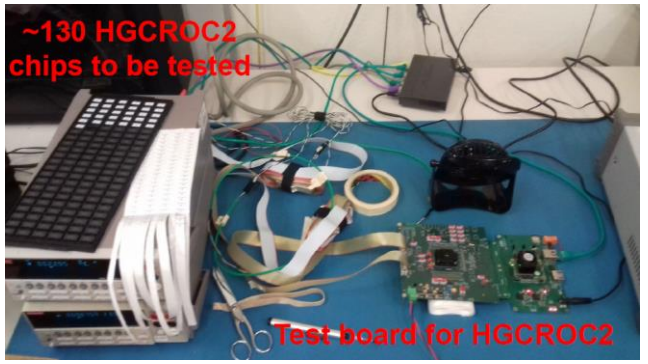
Silicon Module: “IHEP-002” (Sep. 2021)

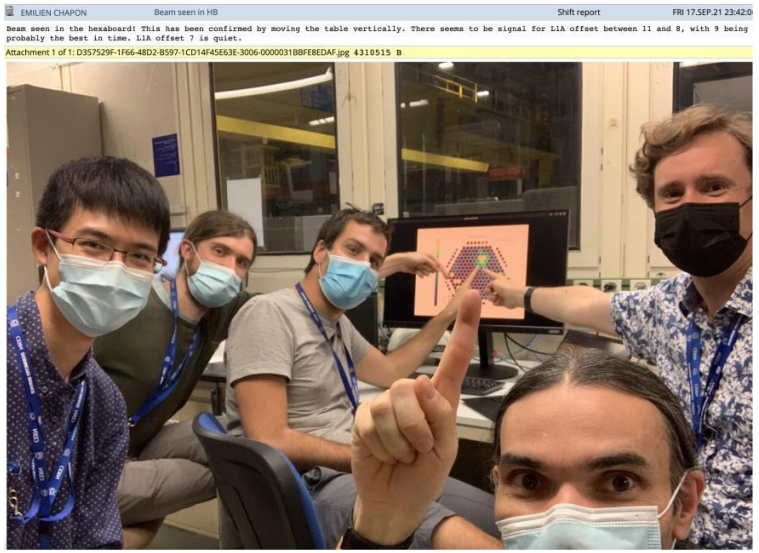


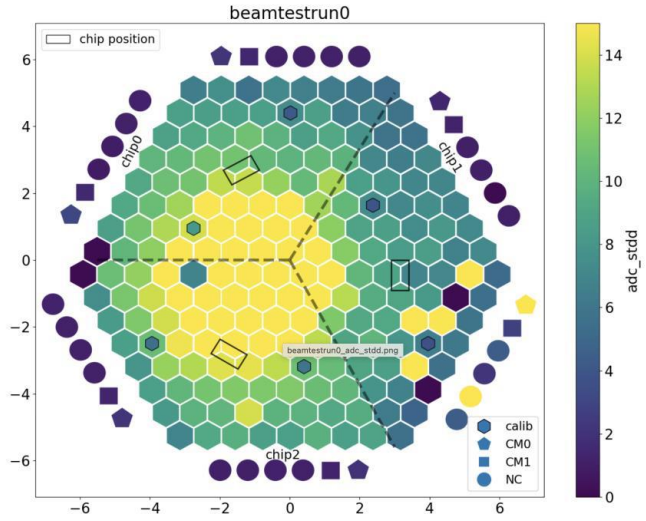
Highlights: HGCAL-IHEP activities at CERN

Émilien Chapon, Fabio Monti (IHEP)

- Qualification of HGCROC2 and hexaboards
  - ~130 HGCROC2 chips tested (in April), some good chips mounted
  - ~20 hexaboards tested (in June) and shipped to MACs
- Recent beam tests at CERN SPS in Sep.-Oct. 2021
  - Test of two silicon modules (HGCROC v2, v3) assembled by IHEP
  - Successfully seen hexaboard response to beam: MIP signals
  - Ongoing studies with data collected with muons, electrons and pions



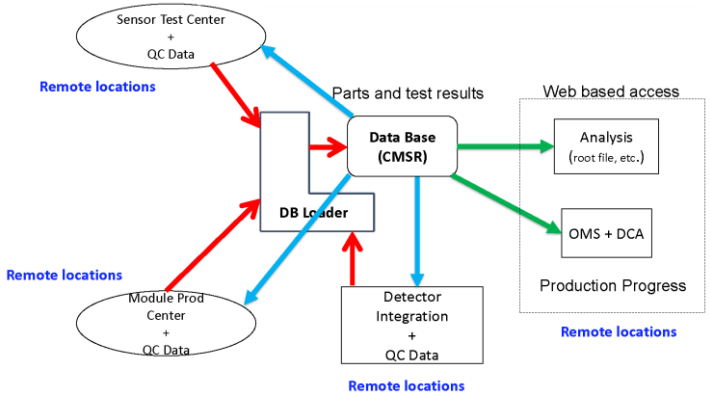


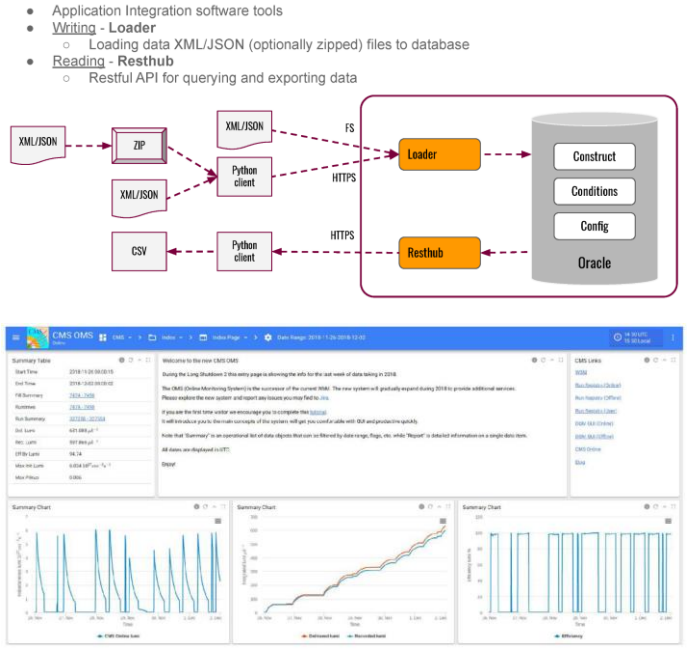


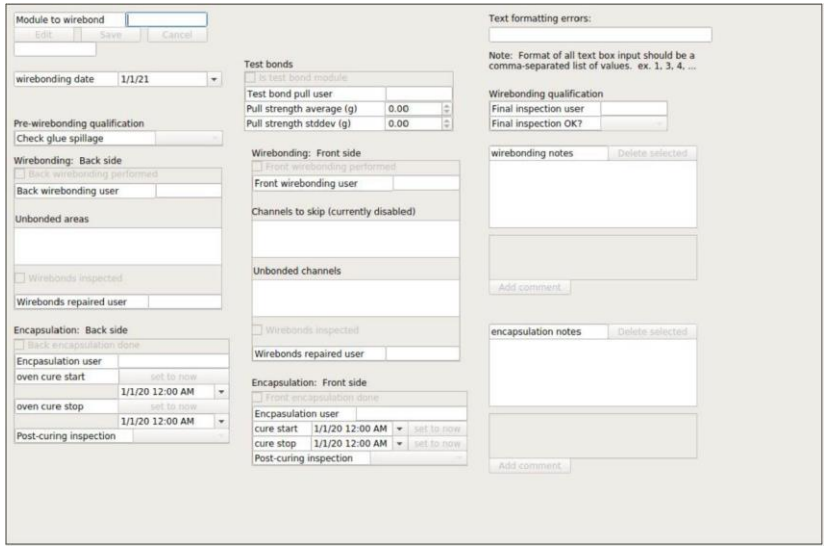
MAC database development for module production

Jin Wang (IHEP)

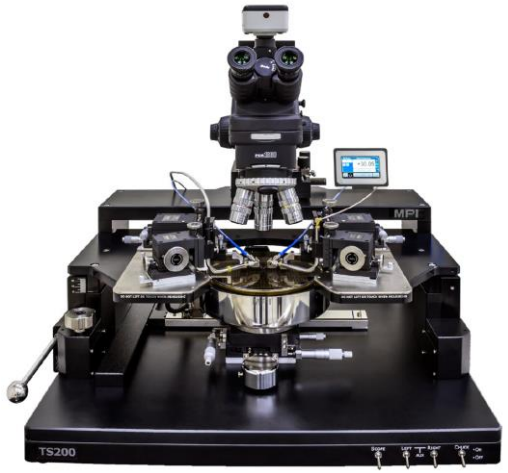
- HGCAL Database: an essential part of HGCAL project
  - Record data of all steps in module production
    - Transmit information between local MAC and HGCAL database
    - Sensors, PCBs, baseplates, tooling; production steps and testing results; shipping
  - New version will be available for MACs to exercise

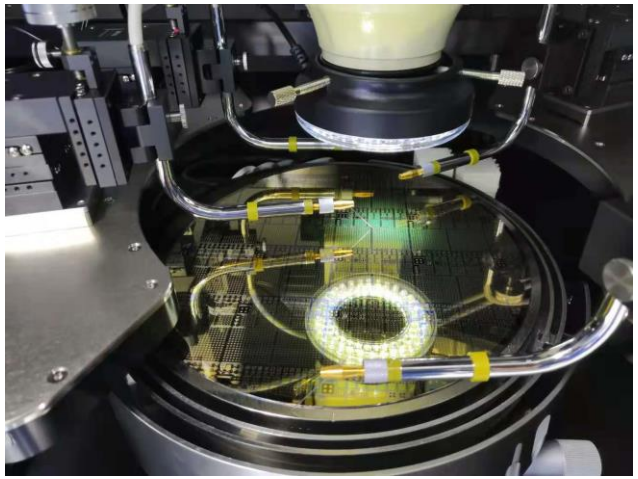


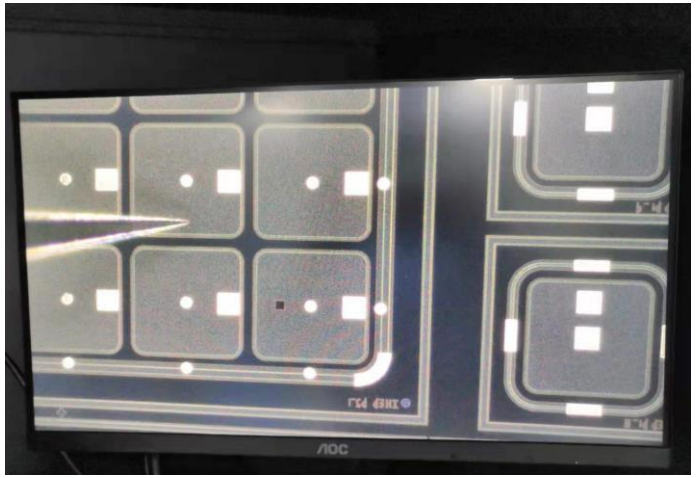


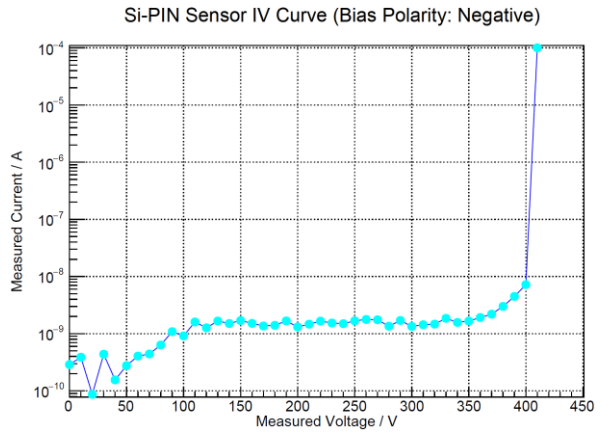


Further developments: silicon sensor test stand

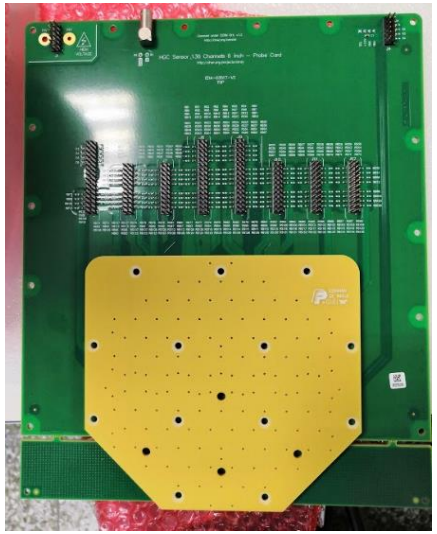








- Dedicated test stand based on probe station
  - Manual probe station (MPI-TS200) for 8-inch wafers
    - First tests done with Si-PIN sensors: IV-curve scans
  - Probe cards
    - 6-inch ready (2 sets), to be tested with full wafers
    - 8-inch to be fabricated
  - Switch matrix ready
    - 512 channels for both 6-/8-inch sensors
- Capability to serve for reception tests of HPK sensors



ARRAY probe card system, NIMA 940 (2018) 168

MAC: path to site qualification

- Huge progress made in 2021
- MAC-IHEP qualified: assembled two live 8” modules (in Jun. and Sep.)

- **A lot of progress in key areas in the recent months:**
  - Procurement of the CEH steel and prototyping of the CEE lead sheets. Engineering team welcoming replacements after departures, and looking still for more effort to consolidate the team
  - Cassette design, cooling plate fabrication, and assembly tooling all advancing (*)
  - Silicon V1 prototype testing concluded. V2 sensors received and under test. HPK internal QA/QC much improved. Pre-series full size sensors order is imminent. MGW (partials) prototypes expected from HPK soon
  - Silicon module assembly centres: 3 MACs qualified (UCSB, IHEP, and NTU), 2 are close (CMU and TTU), and TIFR now has a green light to order a gantry
  - SiPM market survey closed. Moulded tile prototyping well advanced. Machined cast tile prototypes made and under test, and tileboards development and test advancing well
  - SiPM-on-Tile light yield results consolidated from different tests. Inputs collected for the optimization of the overall layout, and calibration procedure being studied for end-of-life with lower S/N
  - Tilemodule assembly: automated tile wrapping and tilemodule assembly equipment is working in the TACs
  - HGCROCv3 is under test and the analogue results very encouraging, some issues with new digital elements to be understood, and packaging has suffered delays
  - ECON-T-P1 submitted. ECON-D design well advanced and reviews being planned. Schedule updated to be more realistic. ECON-T-P2 planned. ECON design and verification team stable. Looking how to further consolidate the depth of the team

(*) see additional material

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- Ongoing studies: preparations for module pre-production
  - Assembly of more dummy modules, precision improvement, tooling production

The team behind the first 8-inch module

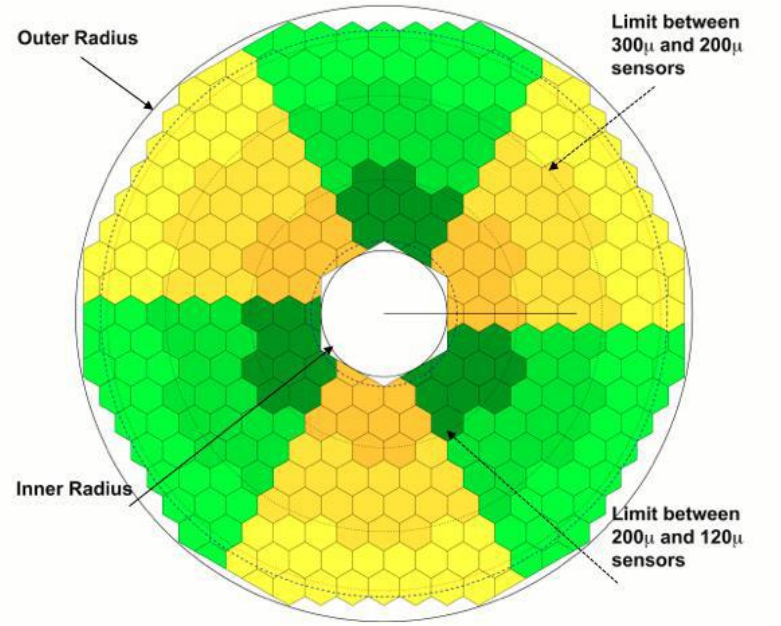
Summary and prospects

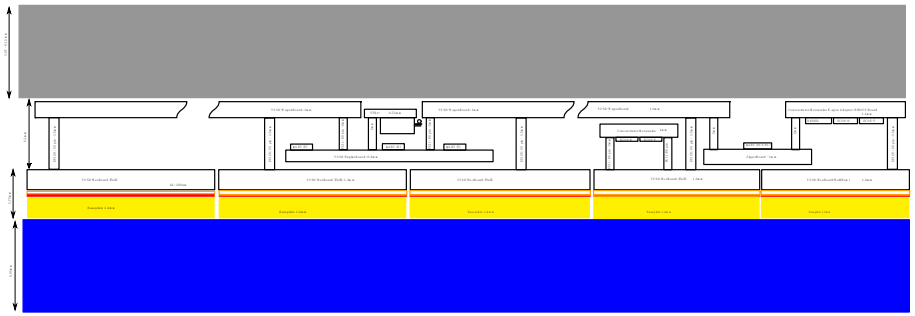
- Steady progress in the HGCAL MAC-Beijing
  - Infrastructure established
    - 140m² clean room, key equipment, test stands, services
    - Finished equipment commissioning and personnel training
  - MAC-Beijing qualified
    - Successfully built two live 8-inch silicon modules, full functionality demonstrated in lab tests
    - Both sent to CERN for beam tests in Sep-Nov. 2021; clear signals seen from beam particles
- Ongoing studies for preparation of module pre-production
- R&D activities at university groups
  - Fudan University: planning to join in module production at MAC-Beijing and future beam tests
  - Tsinghua University: involvements with MAC-Beijing infrastructure development
  - Zhejiang University: partial hexaboard design

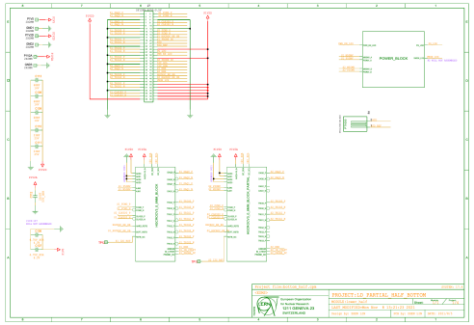
Spare slides

HGCAL activities at Zhejiang U.: partial modules

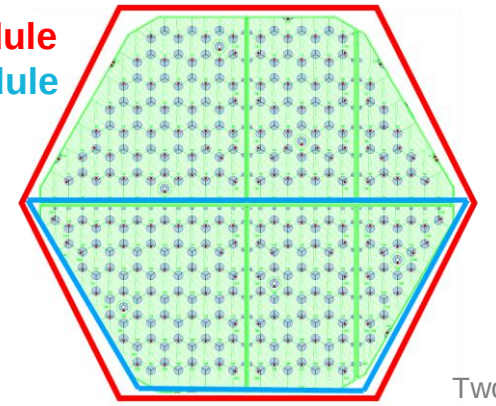
- Complex HGCAL geometry at CMS endcap regions: extra challenges
  - Equipped with both full (hexagonal) modules and partial modules
  - Zhejiang University team: design half modules
    - Schematics done, now working on the layout

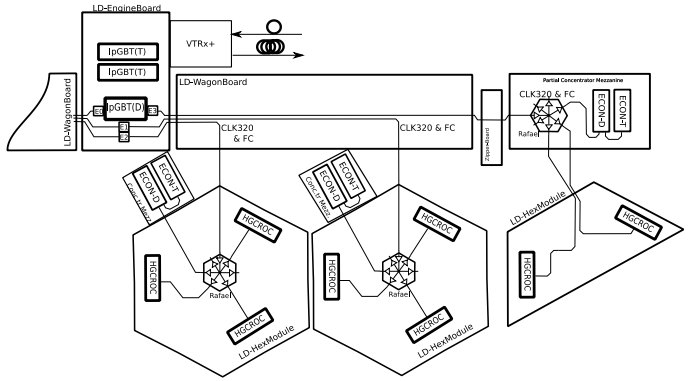






Full module
Half module





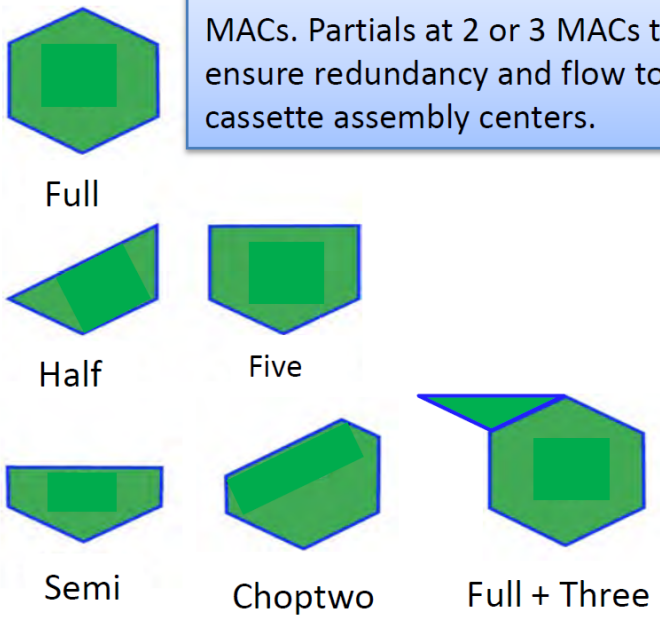
Two HGCROC ASICs on the bottom half of Hexaboard and a Rafael ASIC is on the Partial concentrator to fan out the fast command signal

Full and partial modules: more information

Joe Incandela, "Silicon Modules and MACs", CMS HGCAL Rentrée General Meeting, Aug. 2021

Types and quantities of modules

Full modules will be done at 3-4 MACs. Partials at 2 or 3 MACs to ensure redundancy and flow to cassette assembly centers.



Module Type	300 µm	200 µm	120 µm	Sum
Full	8820	7740	4356	20916
Five	1158	144	0	1302
Choptwo	0	0	312	312
Semi	450	0	312	762
Half	1386	156	84	1626
Full+Three	1092	0	0	1092
Totals	13998	8040	5064	27102

Production plan for current schedule:

- 10 modules/day per MAC with 6 MAC's
- 12 modules/day per MAC with 5 MAC's

Contingent capacity (for the case production reduced to 1.5 years):

- 12 modules/day per MAC with 6 MAC's
- 14 modules/day per MAC with 5 MAC's

Contingent capacity (for the case production reduced to 1 year):

- 20 modules/day per MAC with 6 MAC's
- 24 modules/day per MAC with 5 MAC's

Sensors
HD: high density (120 µm) sensors
LD: low density (200 or 300 µm) sensors

J. Incandela – CMS CE Modules and MACS – Rentree - 30 August 2021

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