Engineering Challenges of the CMS High Granularity Calorimeter

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On behalf of the CMS collaboration

CALOR 2018

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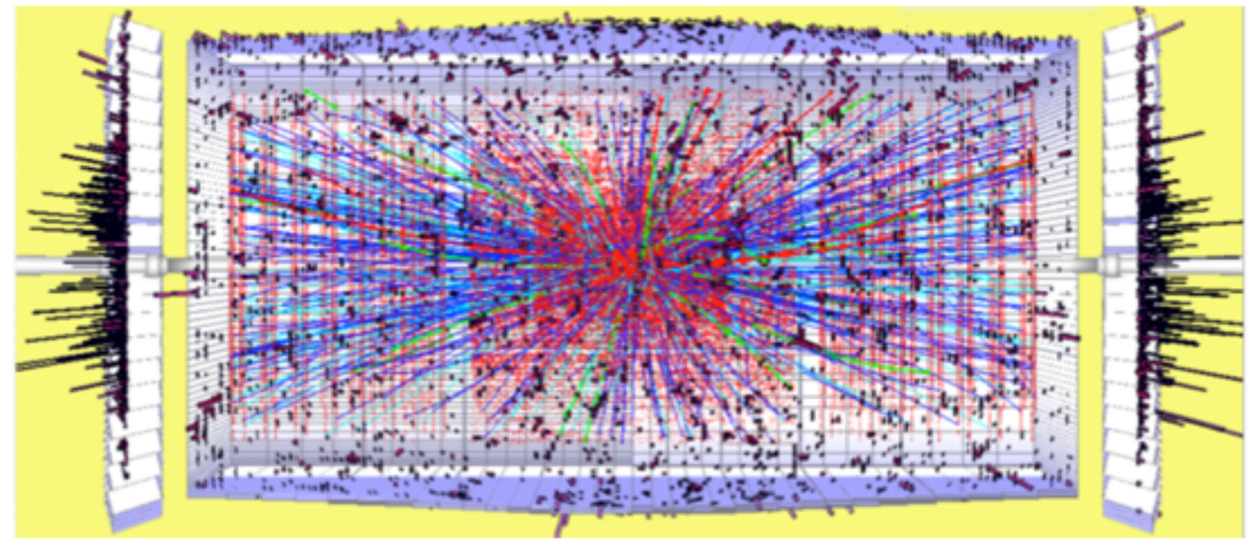
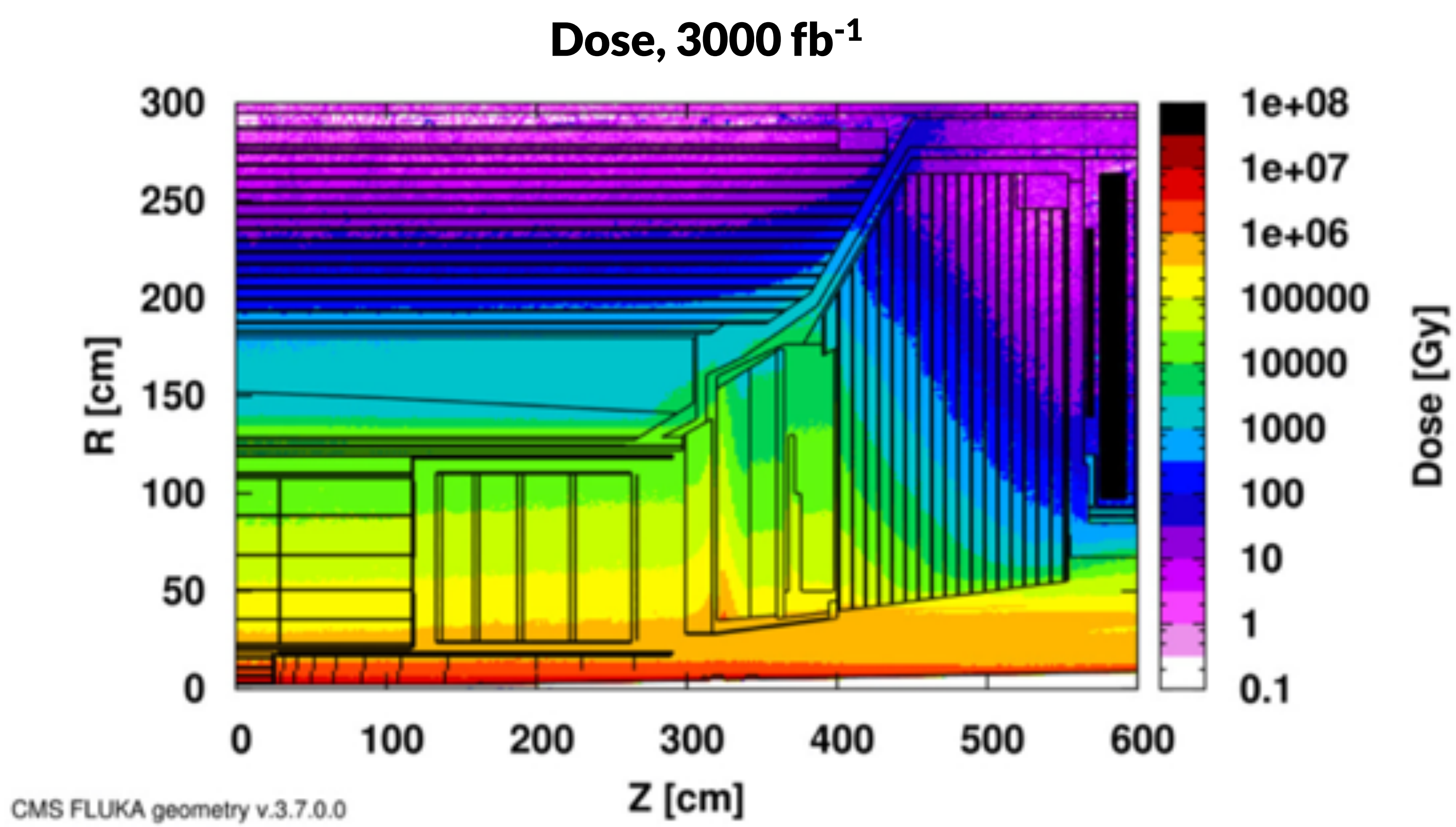
Challenges at HL-LHC

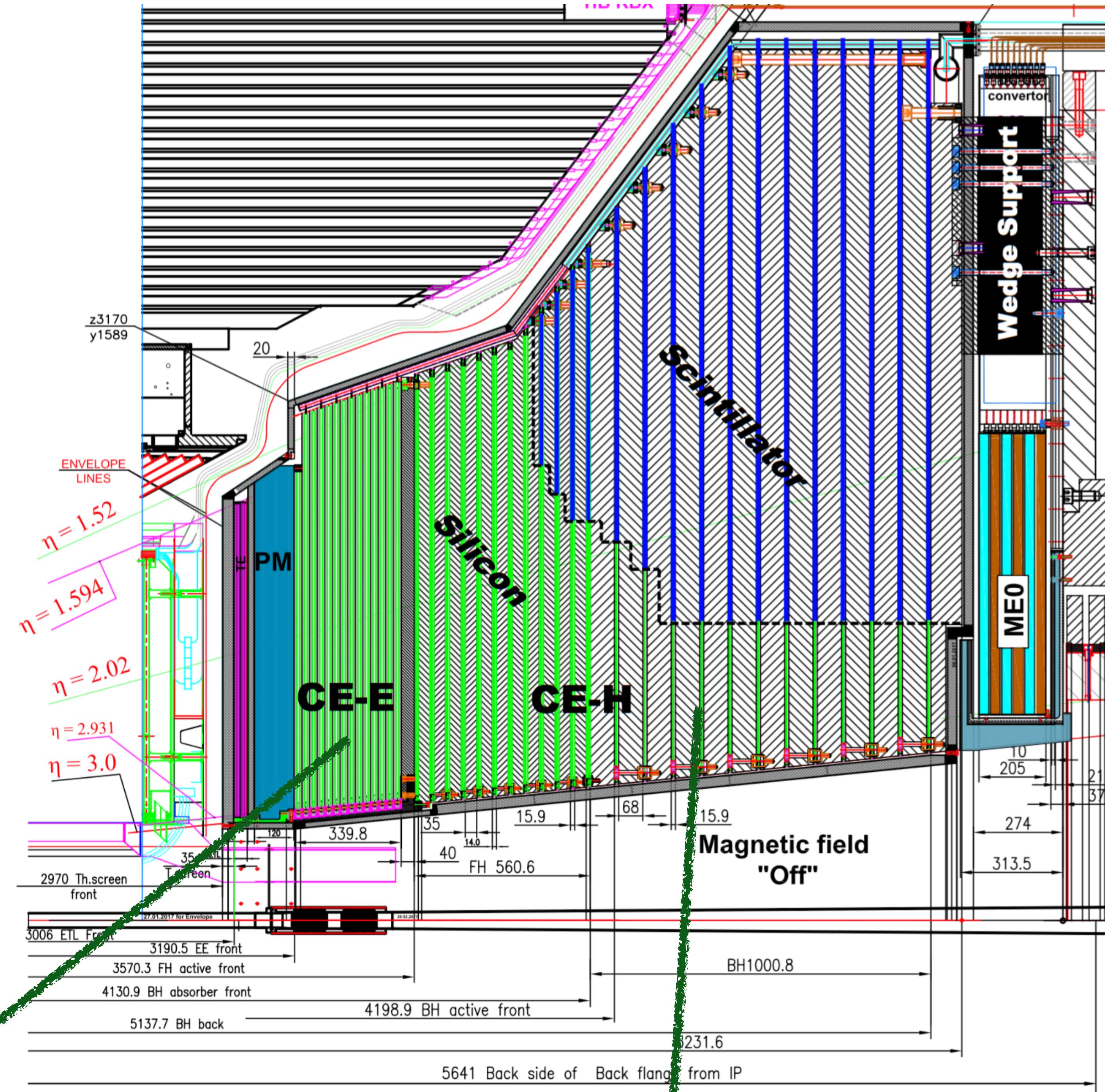
- High Luminosity-LHC plans 5×10^{34} $cm^{-2}s^{-1}$ instantaneous luminosity and 3000 fb^{-1} integrated luminosity
  - High pile-up conditions (Up to 200 interaction per bunch crossing)
  - High radiation dose (150 Mrad, 10^{16} n/cm^2)
- ***The current Electromagnetic and Hadronic Endcap Calorimeter cannot stand the radiation dose and needs replacement***





CMS High Granularity Calorimeter

- A sampling calorimeter
- ~500 m^2 of Scintillators
- *~600 m^2 of Silicon sensors*
  - *Expecting 6M channels*
  - *Expected to dissipate 220kW heat*
- *Will be operating at -30 °C*
  - *To reduce radiation damage*



Electromagnetic section

- *Active element: Silicon*
- *Absorber: Lead, Copper-Tungsten, Copper*

Hadronic section

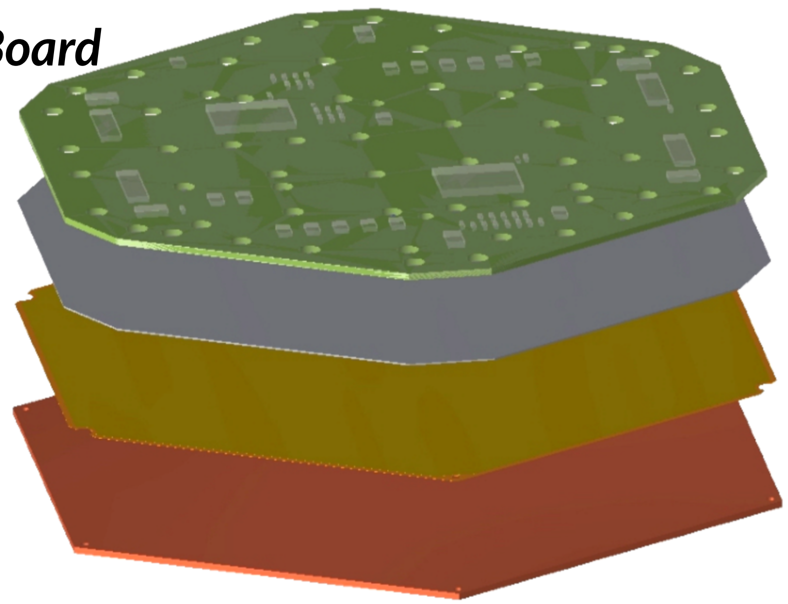
- *Active elements: Silicon and Scintillator*
- *Absorber: Stainless Steel*

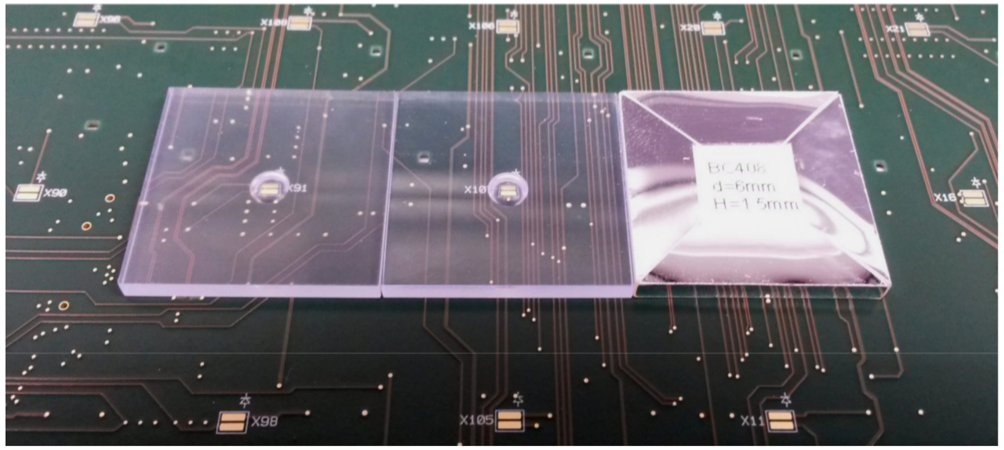
- *See Nural Akchurin's talk*

https://indico.cern.ch/event/642256/contributions/2962409/

HGCal Modules and Cassettes

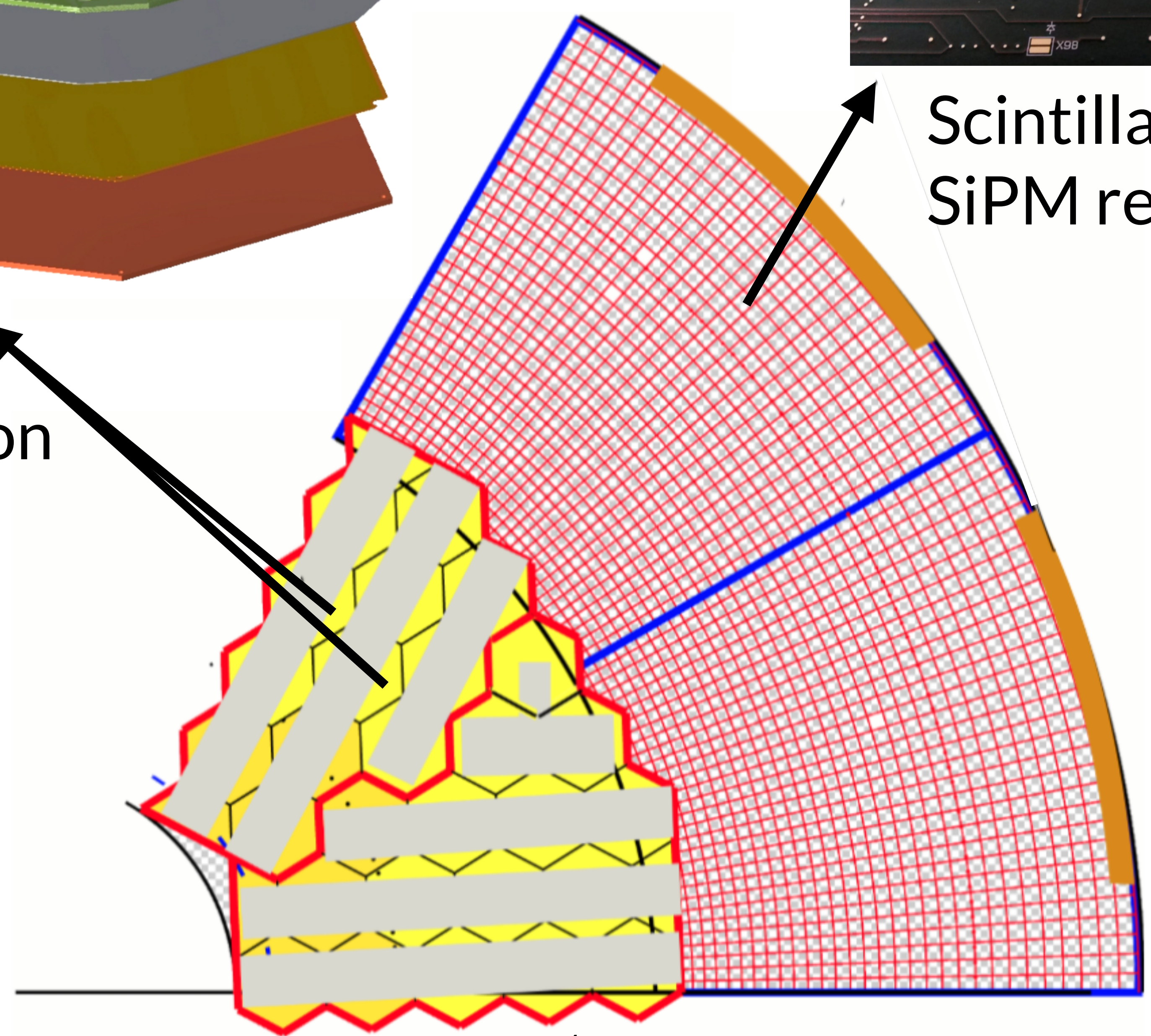
- Cassettes provide support and cooling for the modules





Scintillating tiles with SiPM readout

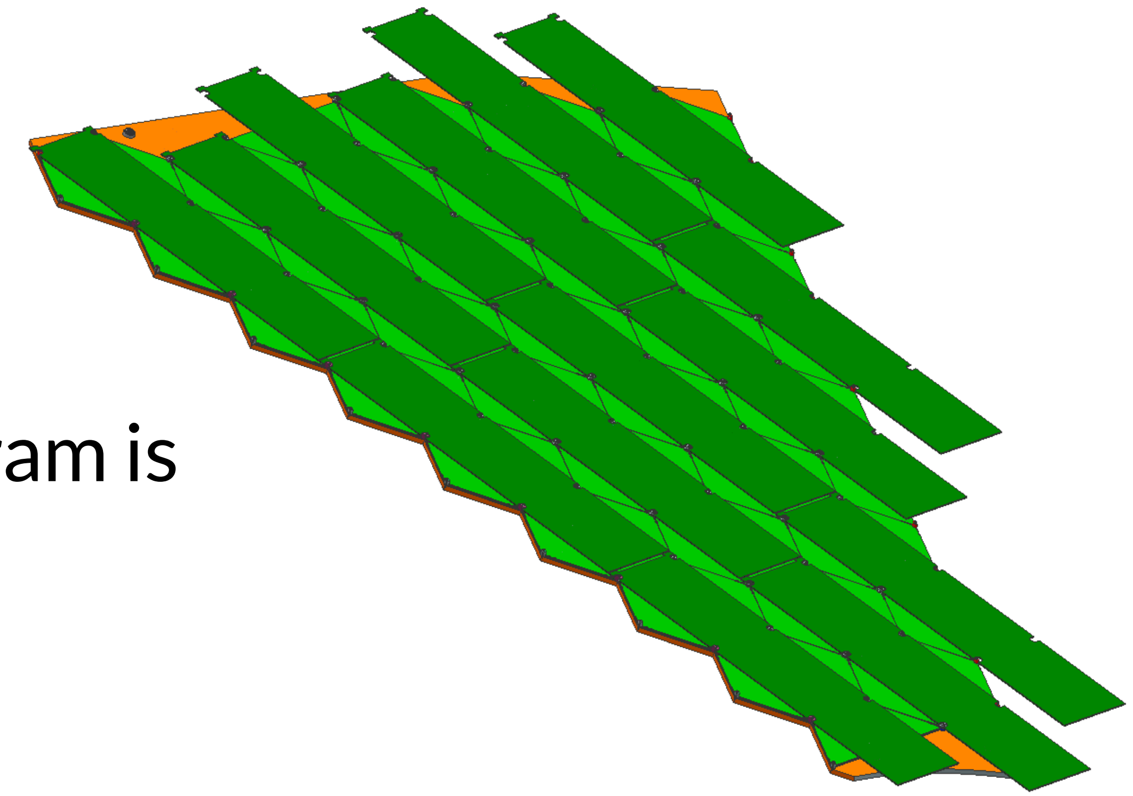
Hexagonal modules based on Si sensors



Addressing Thermal and Mechanical Challenges

Challenges:

- **Silicon detector has to operate at -30°C**
  - **CO_2 system temperature -35°C**
- **220kW heat load is expected**
- To address the challenges a mock-up program is in place



Goals of the thermal and mechanical mock-up:

- ***Study thermal performance of cassette***
  - Temperature measurements of cooling plate and silicon sensors
  - Comparisons to FEA calculations
- ***Study mechanical properties of the cassette***
  - Demonstrating module mounting scheme
  - Achieving tolerances
  - Investigating ease of assembly
  - Addressing thermal contraction issues

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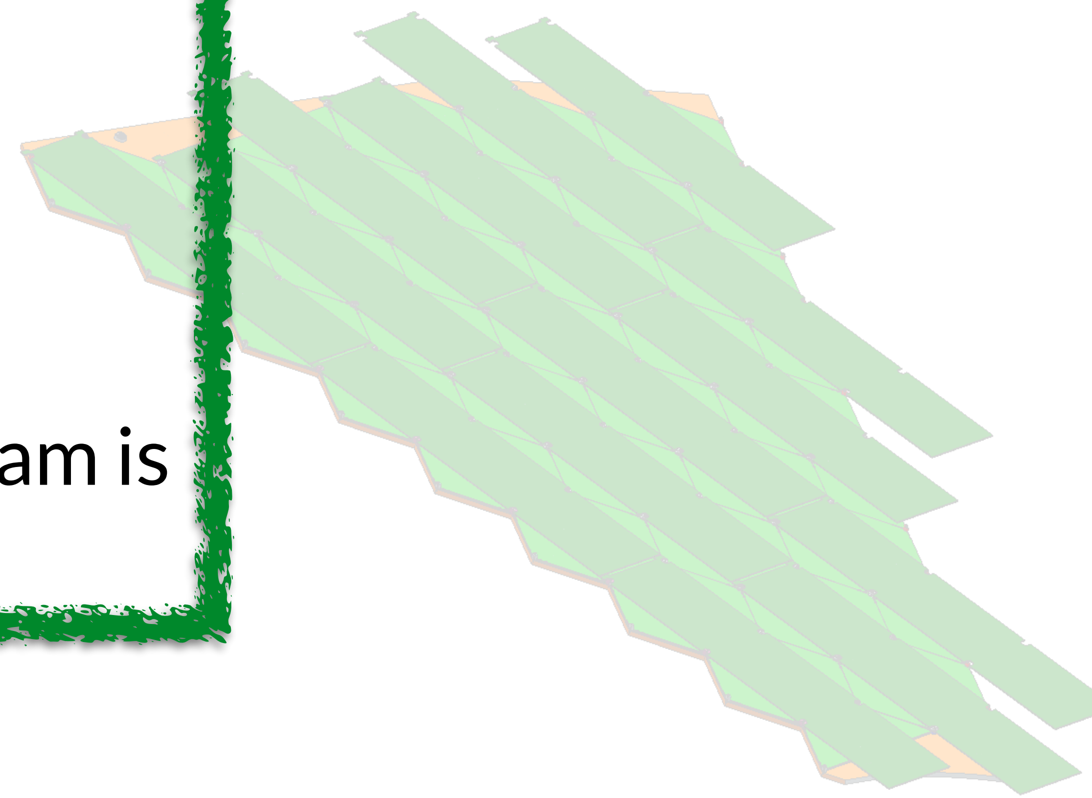

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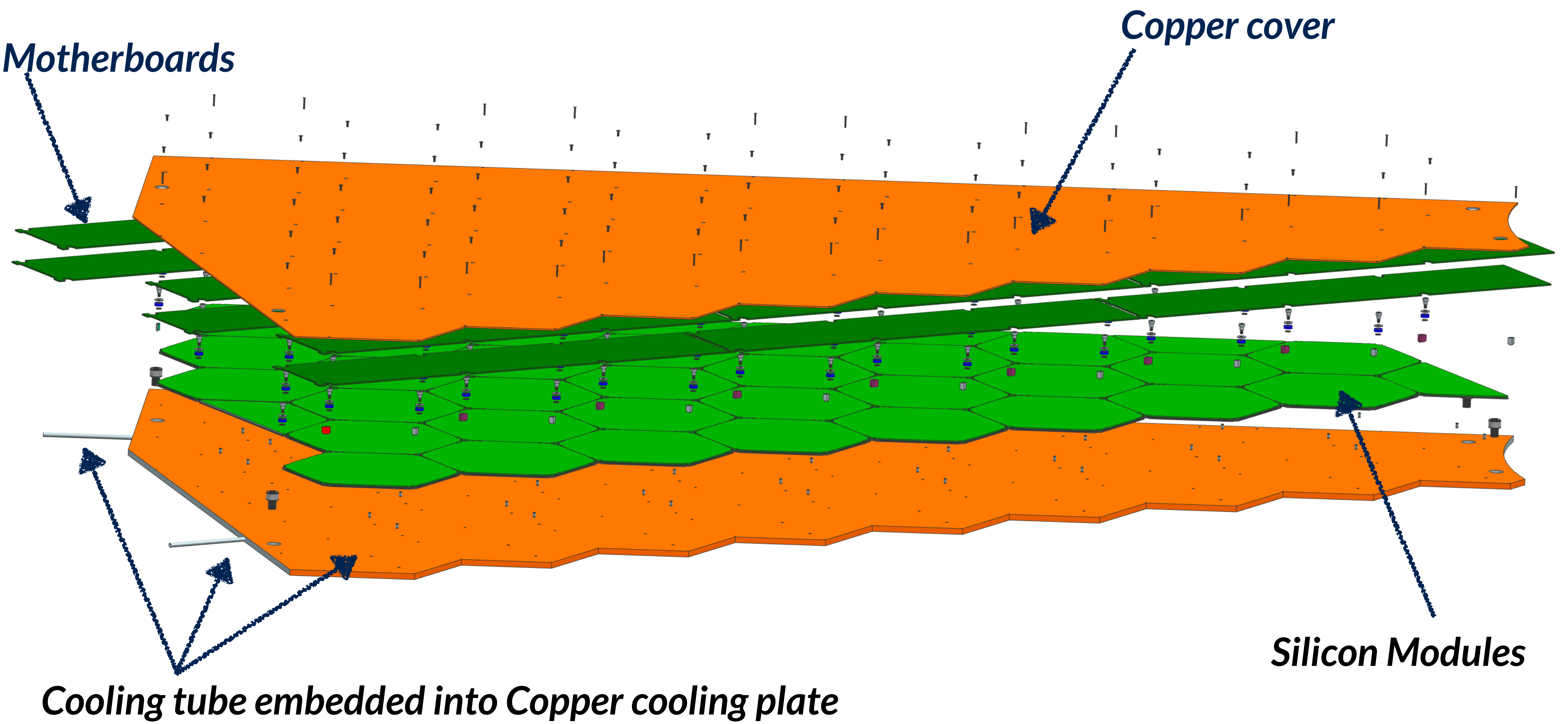
NOT SO EASY!!

Geometry of the 1st Mock-up Cassette

- Designed a 30 degree all Silicon Hadronic cassette
  - ~ 1.5m x 1m in size

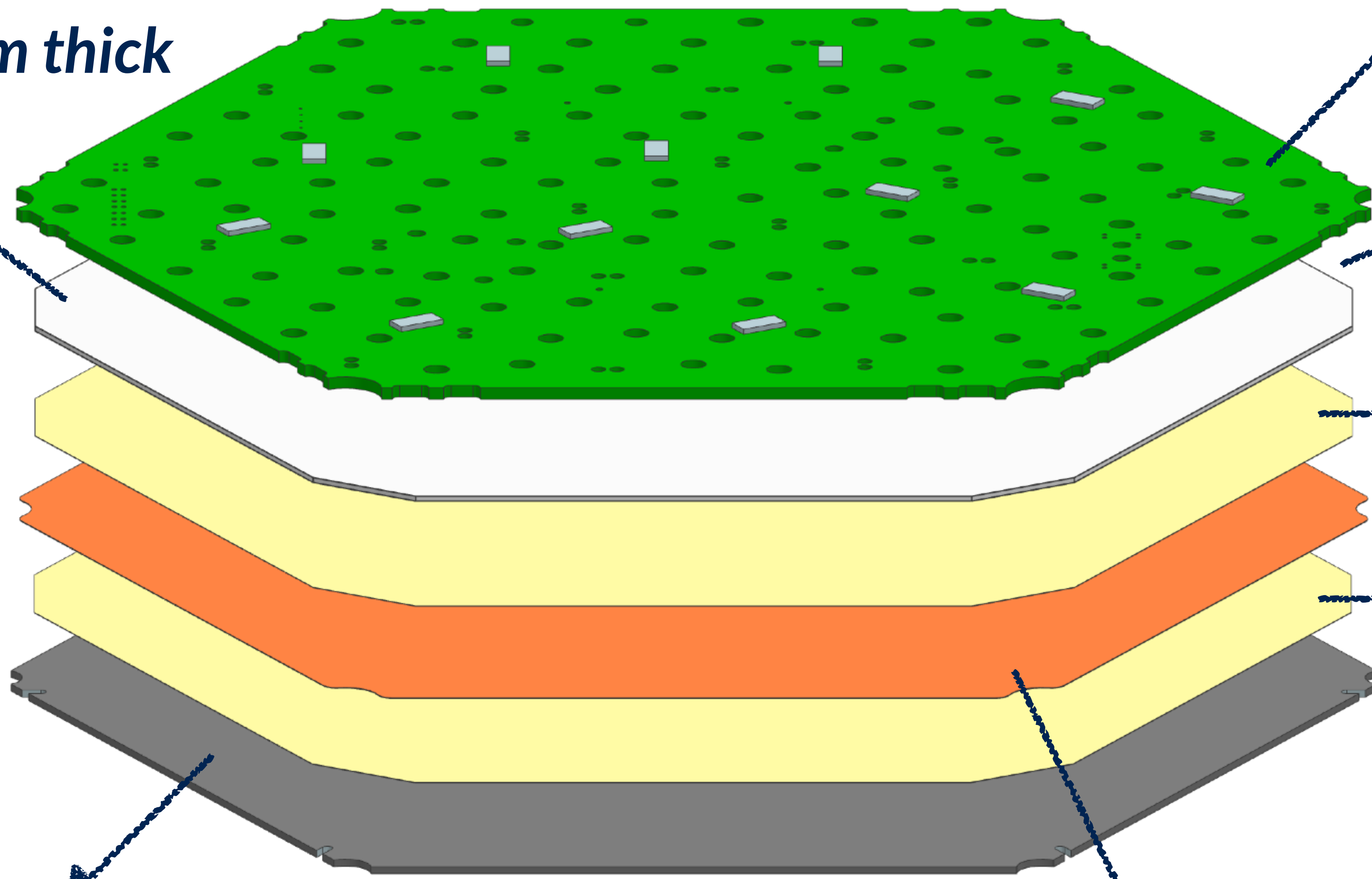


Mock-up Module Layers

Printed Circuit Board; 1.6 mm thick

- *Enables performing thermal studies*

Silicon; 750 µm thick



Glue; 100 µm thick
(Not shown in the picture)

Glue; 100 µm thick

Glue; 100 µm thick

Base plate; 1 mm thick

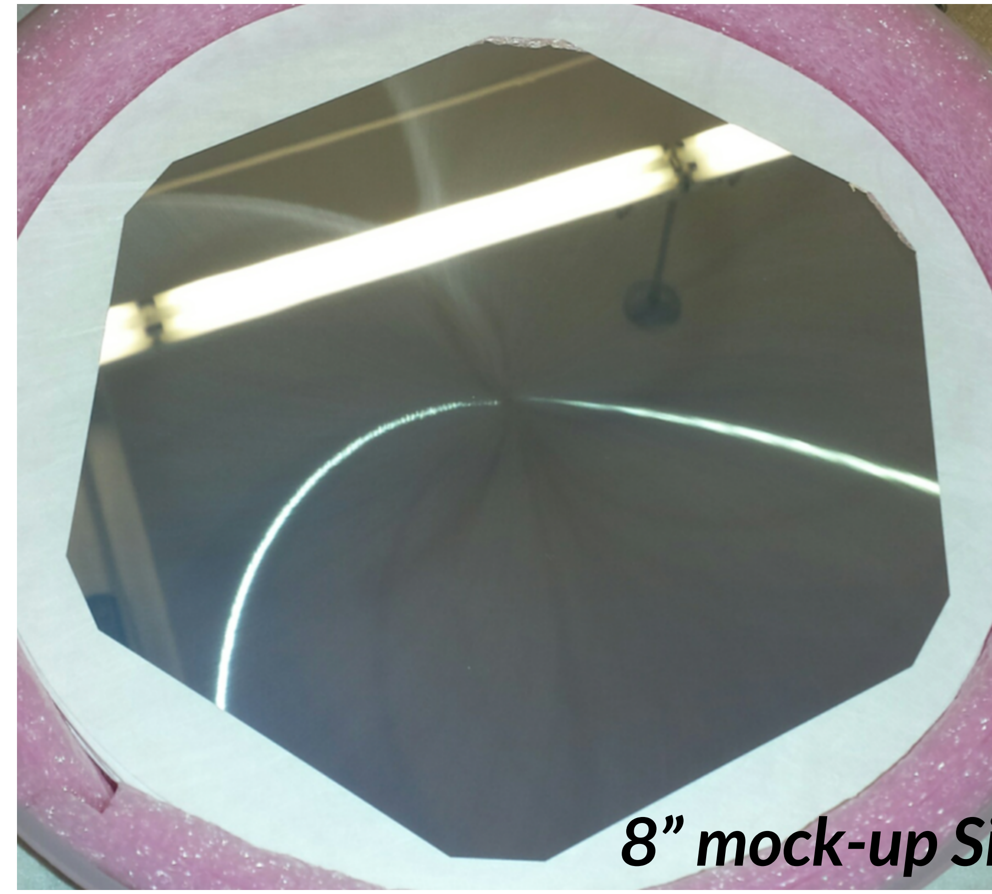
- *Provides support for the active element*
- *Enables mounting*

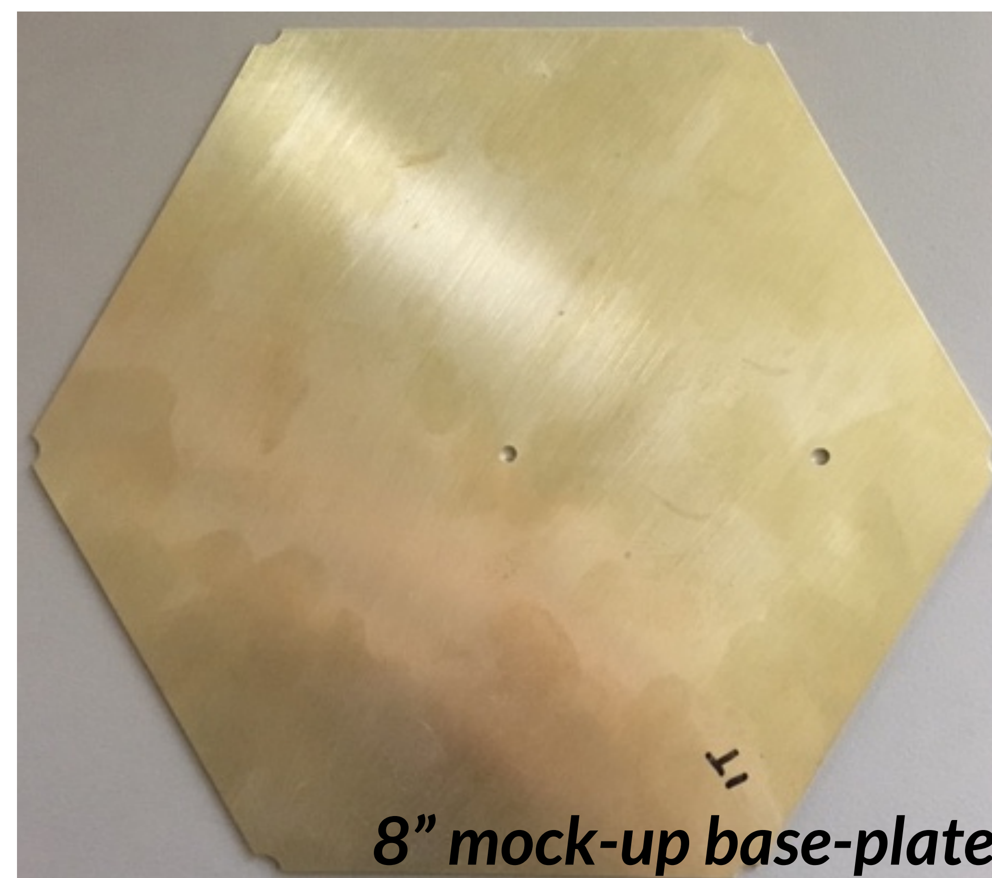
Kapton sheet; 110 µm thick

- *Provides electrical insulation of the sensor back-plane from the baseplate*

Mock-up Si Sensor and Base-plates

- Mockup Si sensors cut from blank 8” Silicon wafers
  - 750 μm thick
  - 320 μm thick (design)
- 1 mm thick base-plates:
  - Material with Coefficient of Thermal Expansion close to that of Silicon:
    - Carbon Fiber (Electromagnetic design)
    - Copper/Tungsten (Hadronic design)
  - Currently investigating economical choices:
    - Brass
    - Stainless Steel
    - Ceramics
- ***Mock-up results are so far based on Brass base-plates***





Module Boards

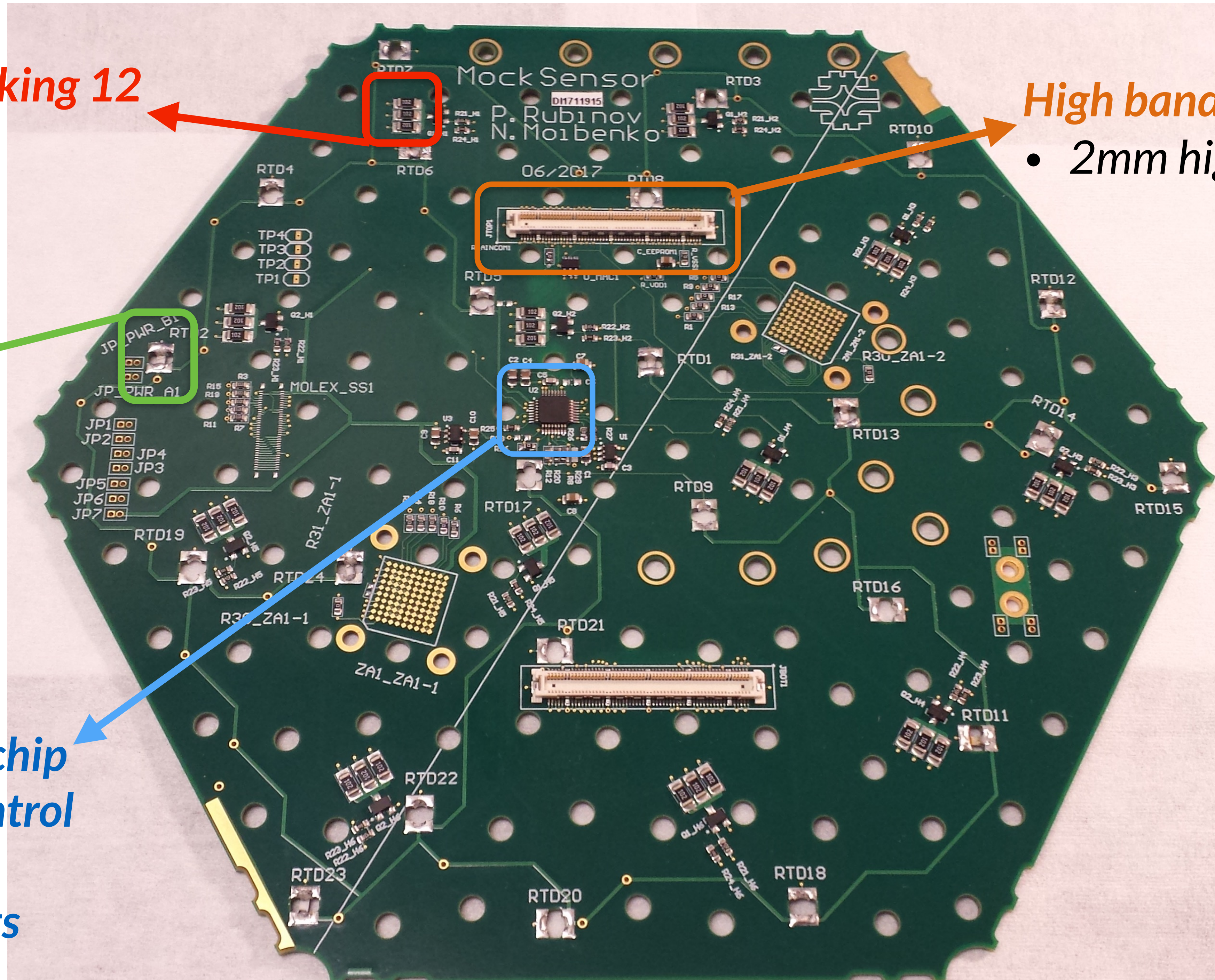
- Mockup of 432 channel module board
    - Designed to *apply heat loads* and *measure temperature of the silicon*

12 heaters mocking 12 read-out chips

High bandwidth connectors
- *2mm high rigid*

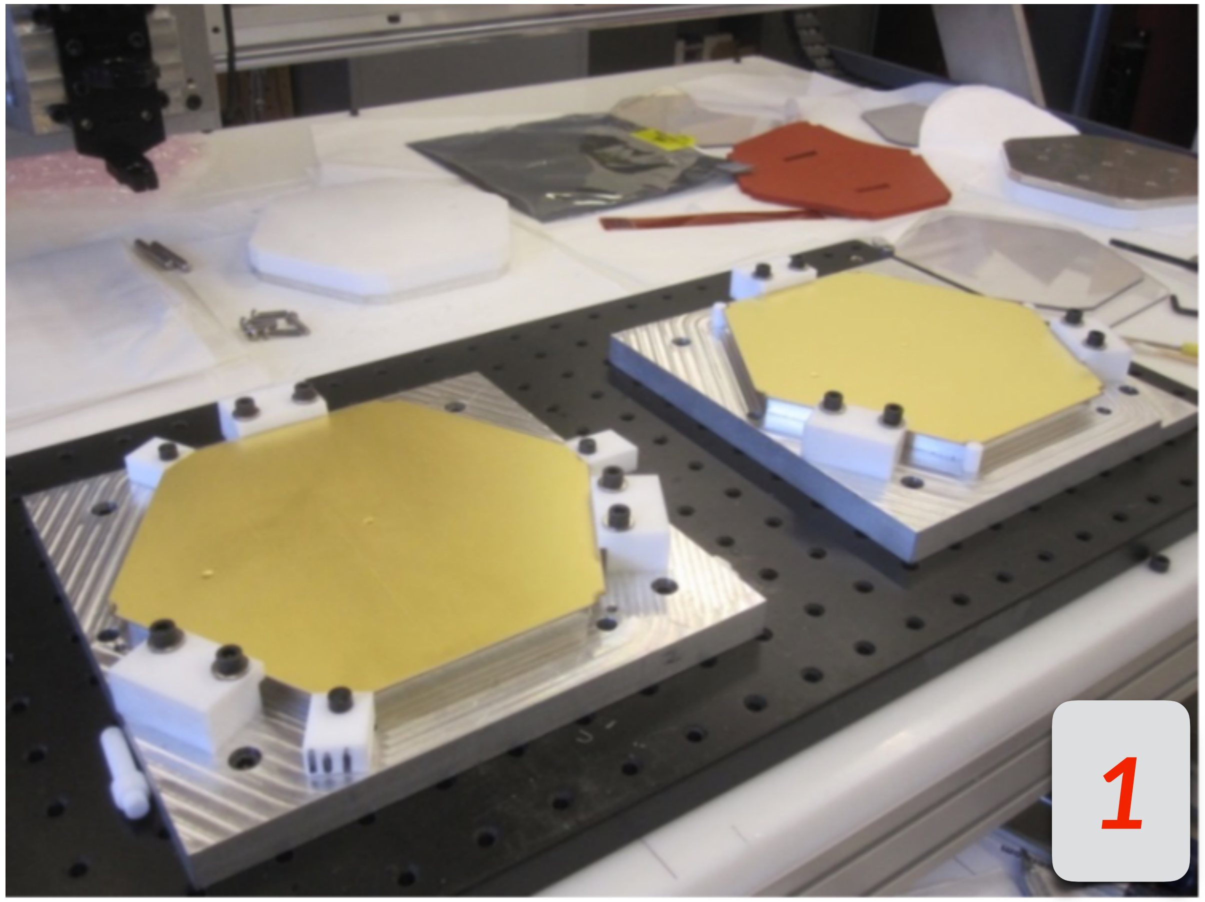
8 RTDs in contact with Silicon

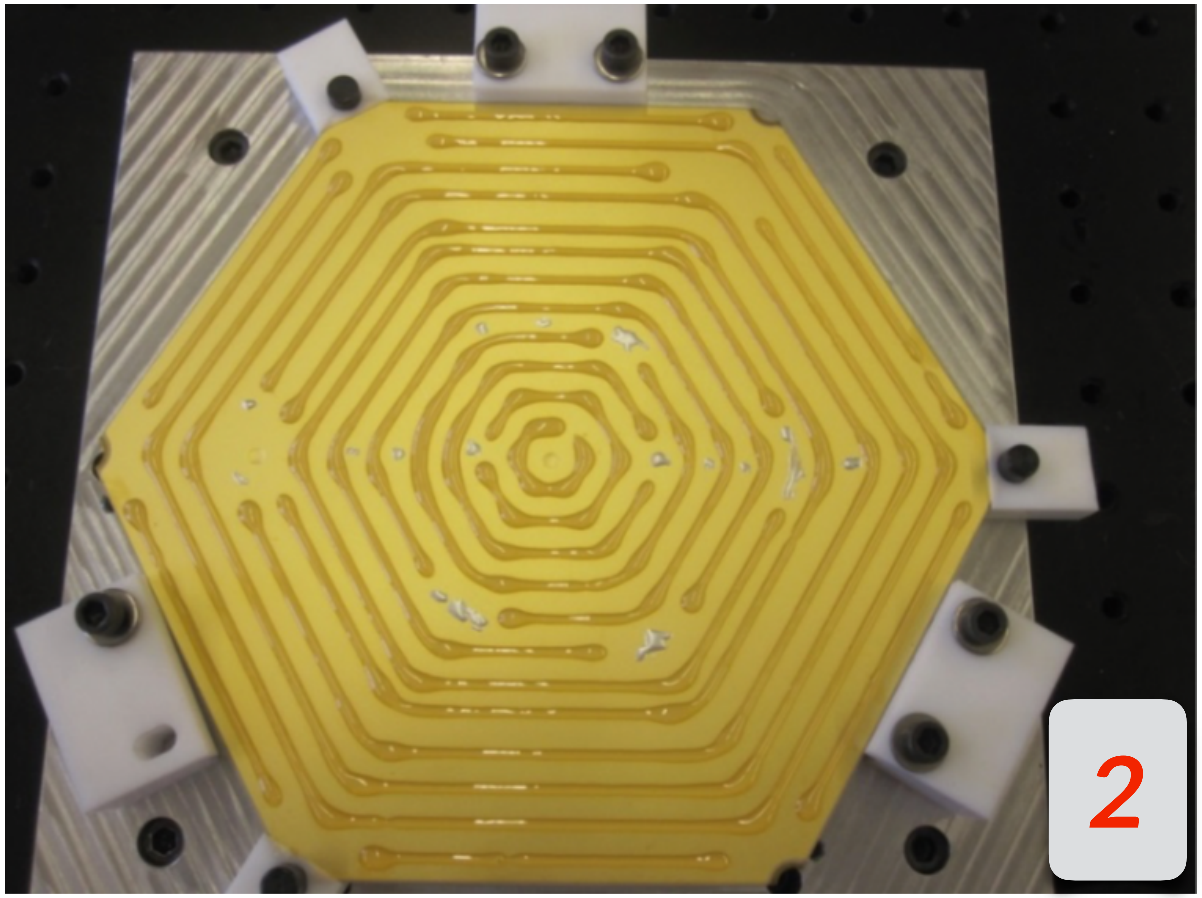
ADS124S0x chip for heater control and temp measurements

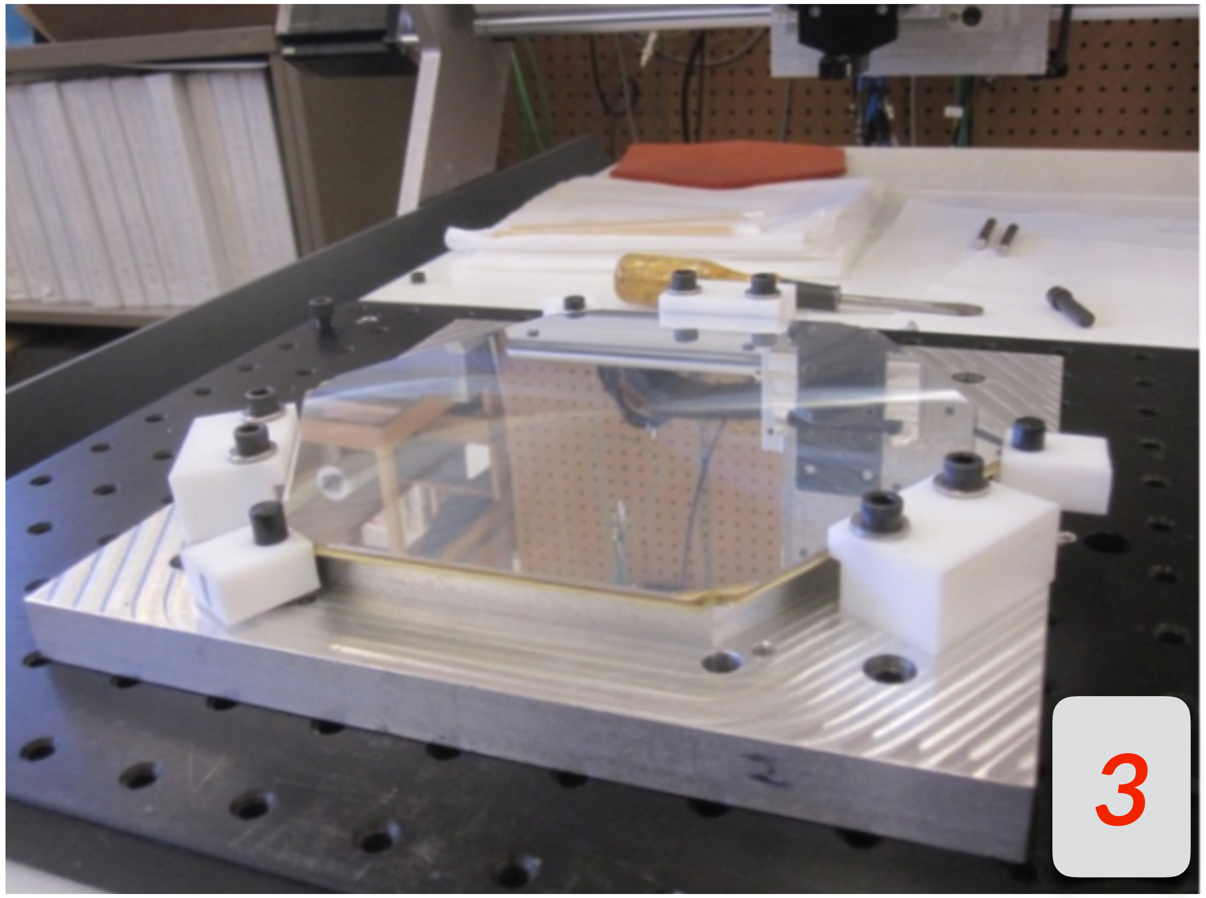


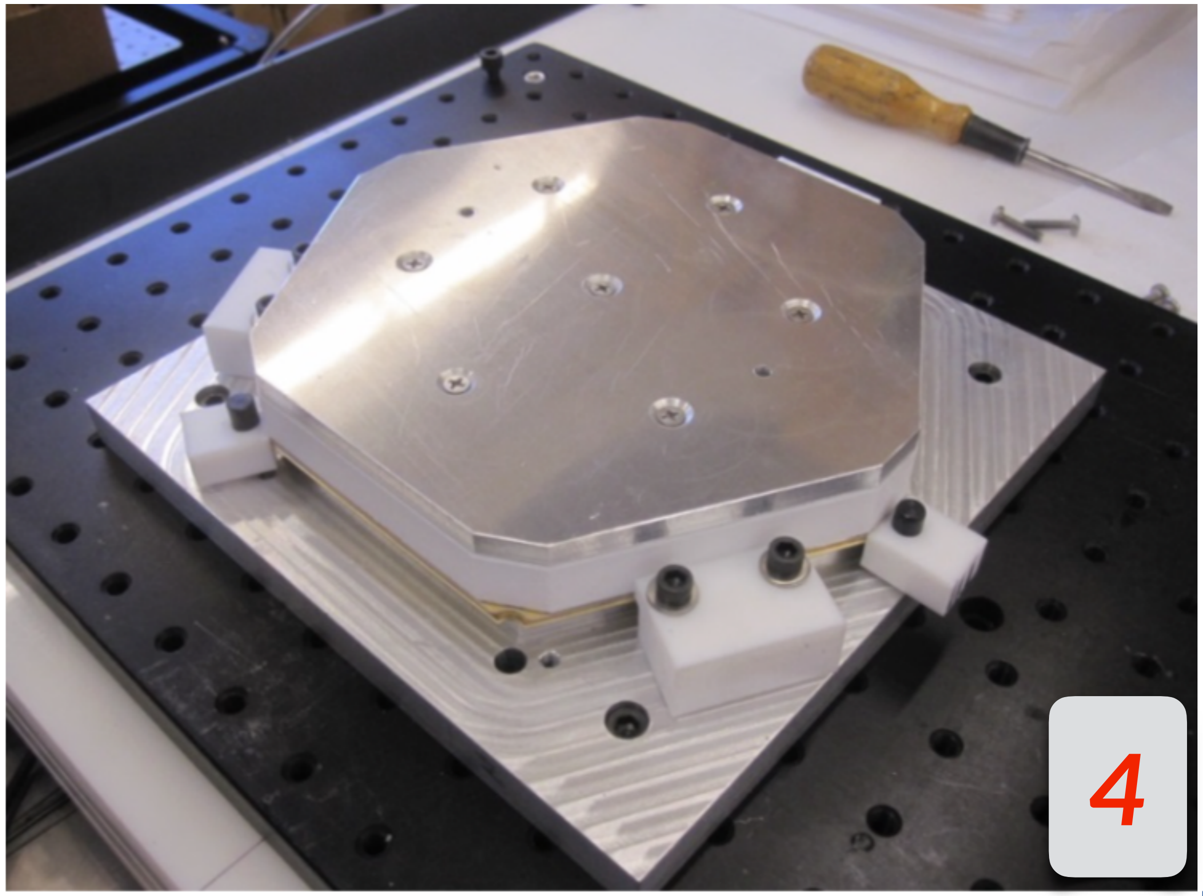
8" mock-up module board

Mock-up Module Assembly

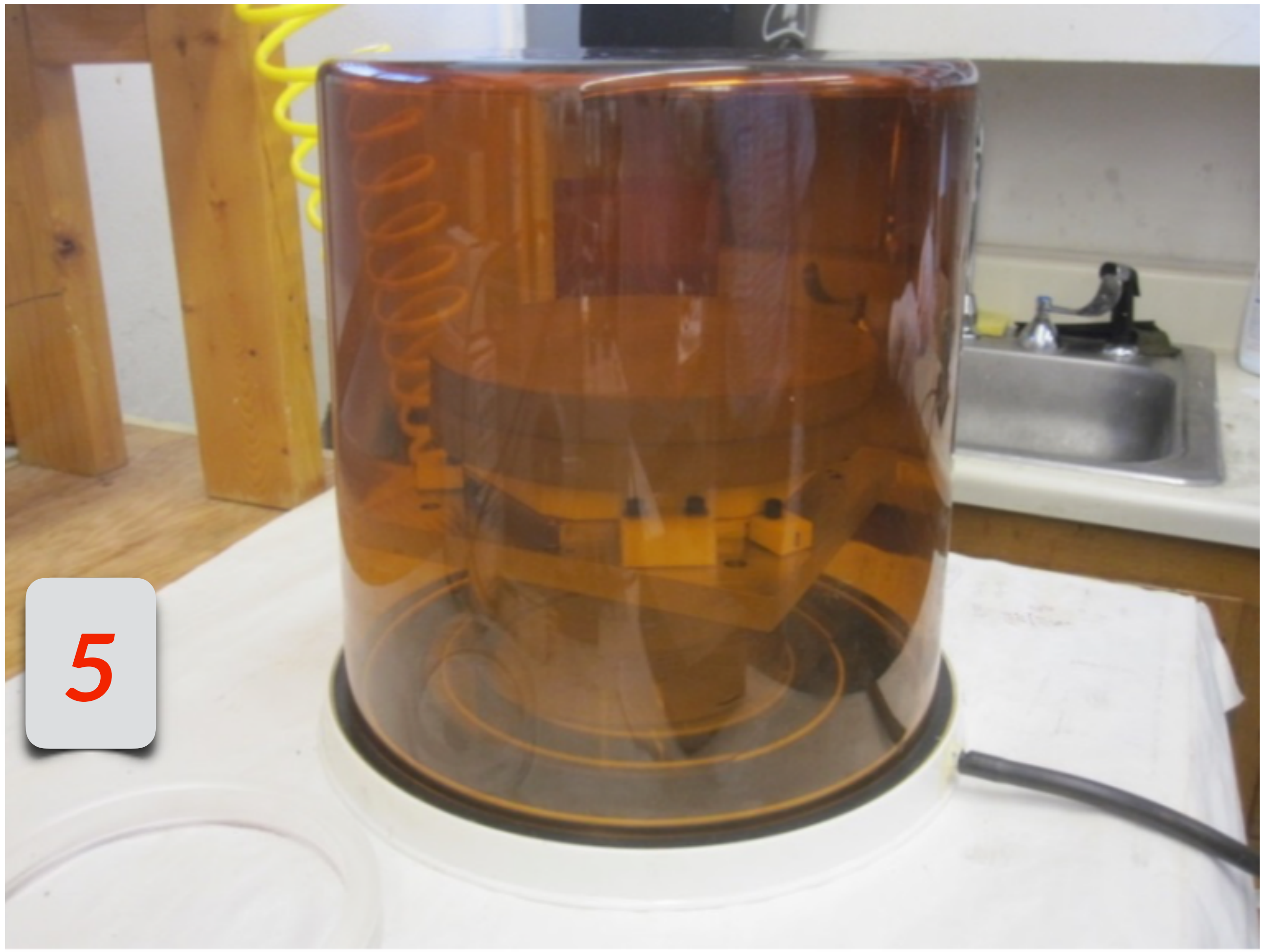








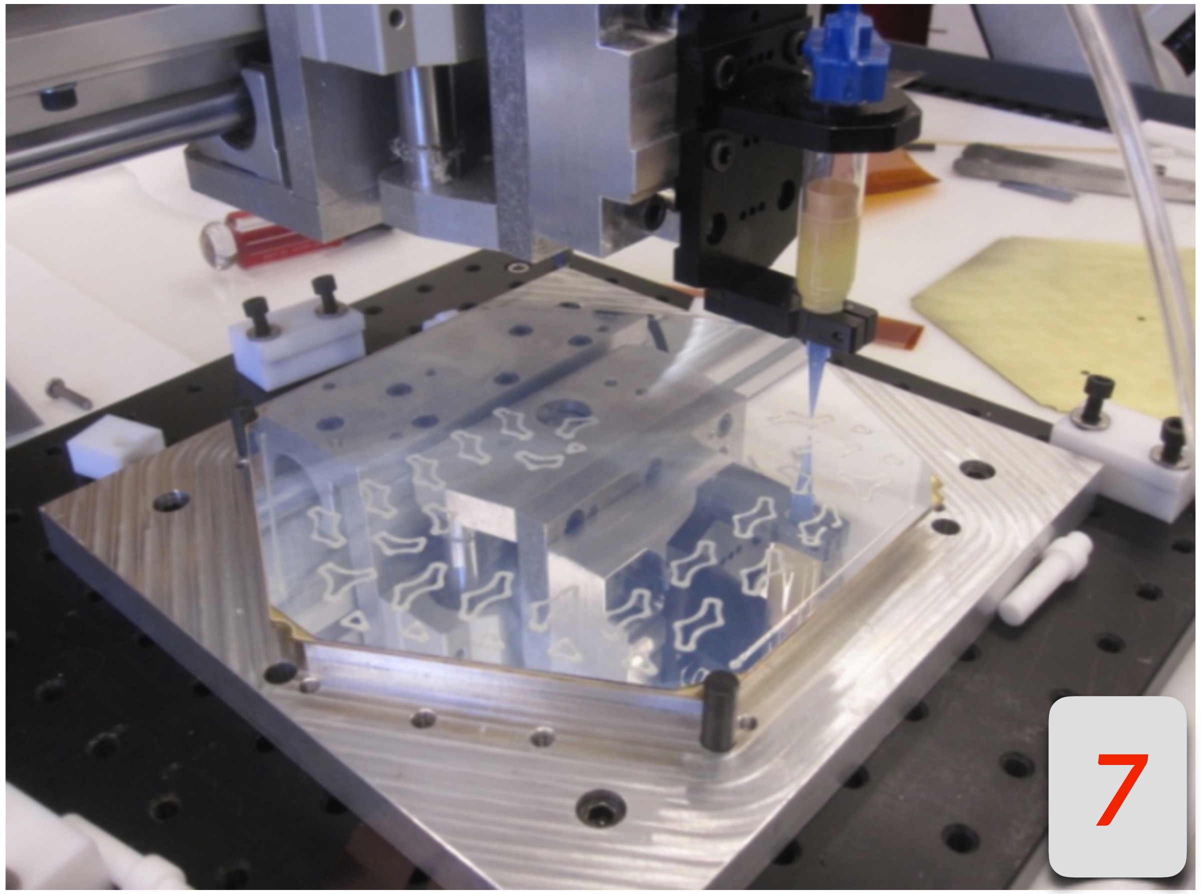
Mock-up Module Assembly

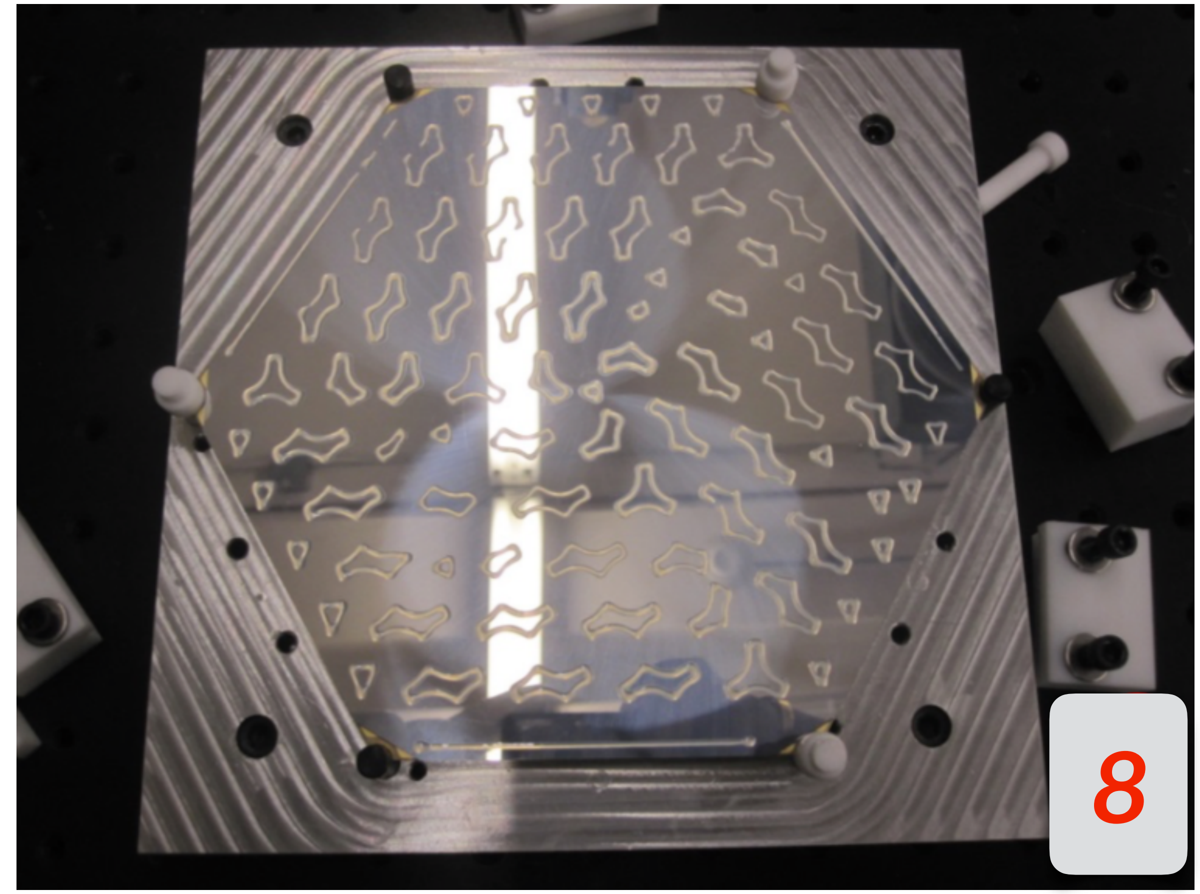


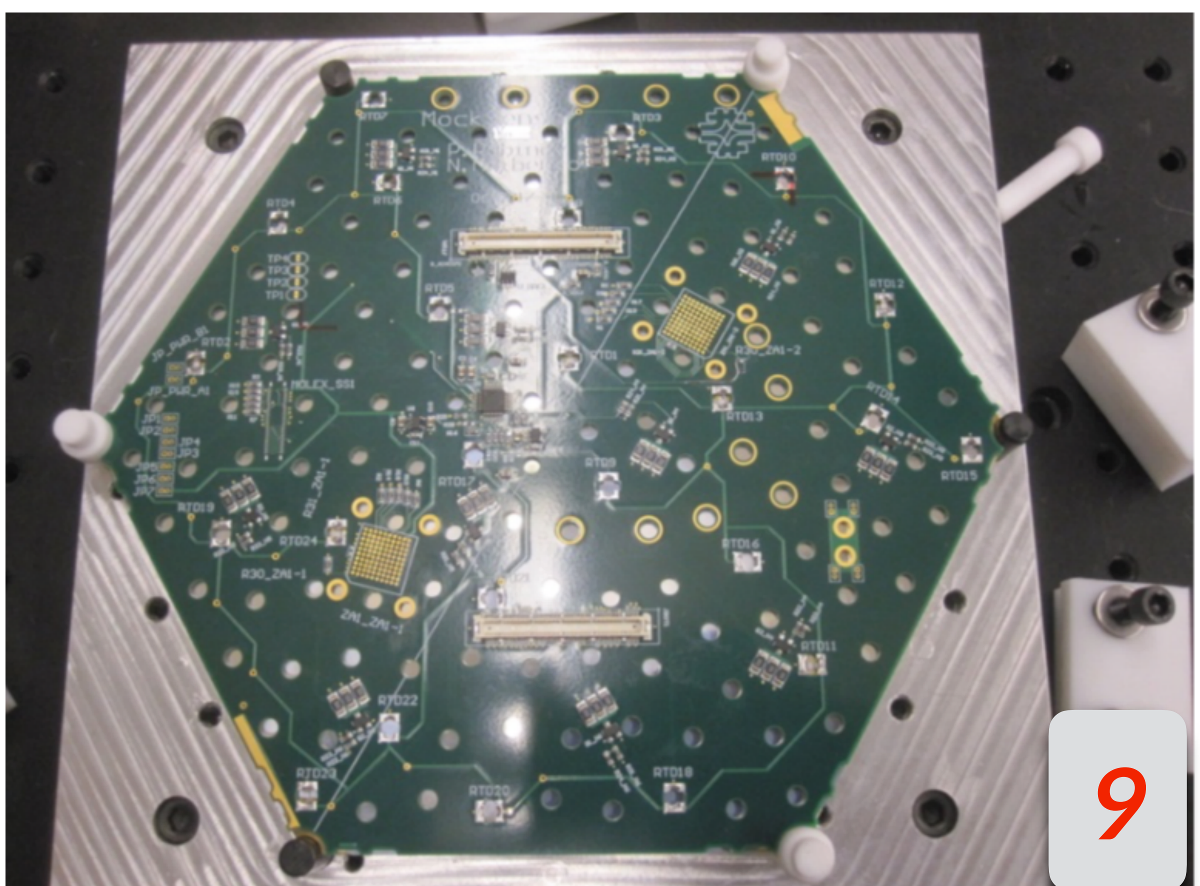
- The assembly is placed for 30 minutes in vacuum to remove the air bubbles

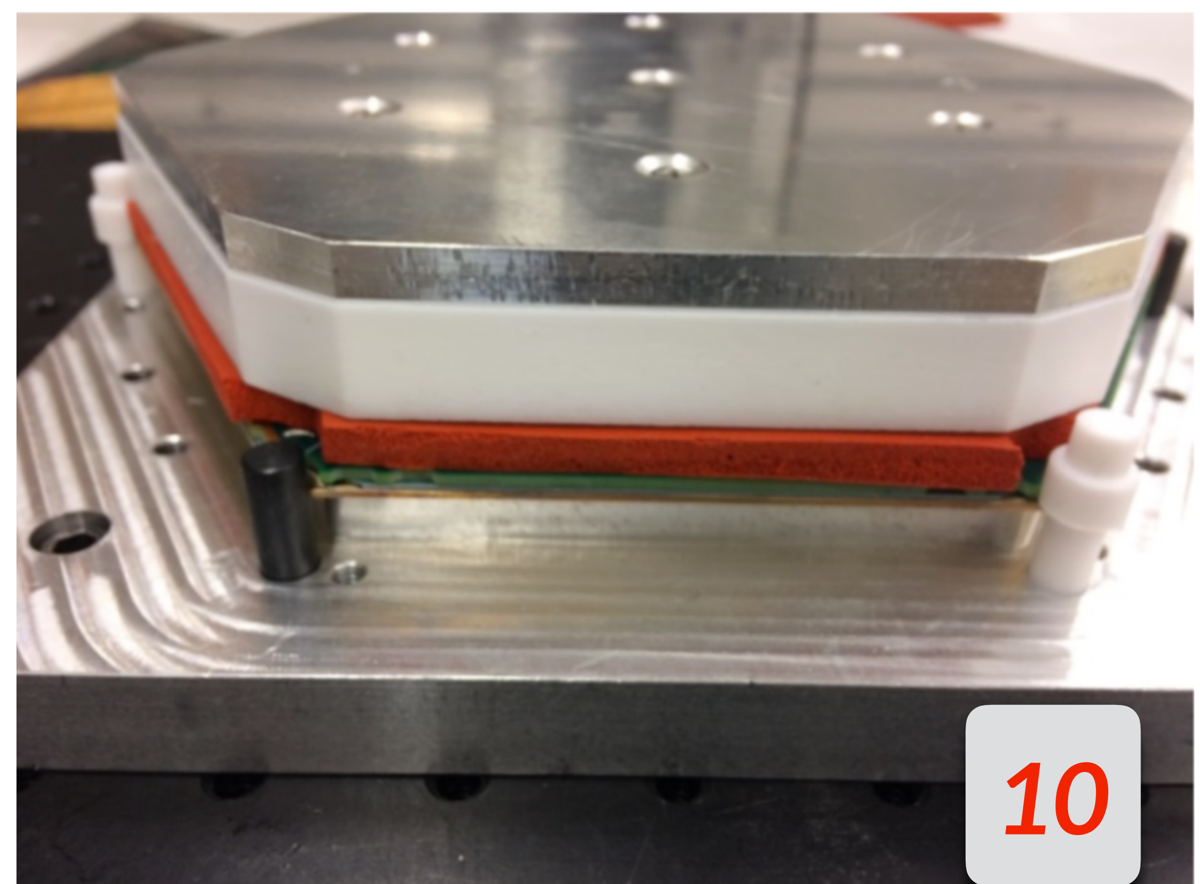
- The assembly is placed in an oven at ~40°C for the epoxy to cure (3 hours)

Mock-up Module Assembly



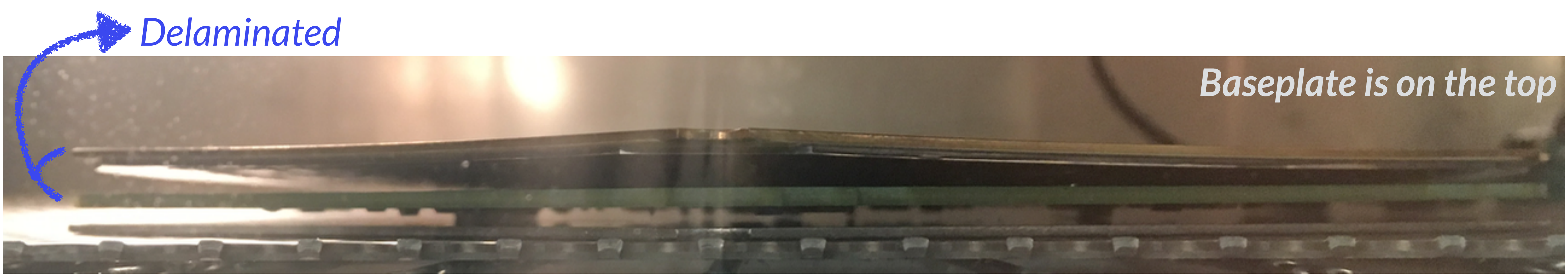






Initial Gluing Challenges in Module Construction

- Coefficient of Thermal Expansion of Brass module baseplate and PCB: $12 \times 10^{-6}\ K^{-1}$ and $19 \times 10^{-6}\ K^{-1}$
- Coefficient of Thermal Expansion of Silicon: $2.8 \times 10^{-6}\ K^{-1}$
- At -30 °C, the Brass baseplate and the PCB are pulling the silicon sensor in opposite directions
  - The glue has to resist the stress
- 3 modules with insufficient amount of glue had the PCB delaminated at -40 °C and the sensor cracked
- After insuring sufficient glue is applied no more failure was observed



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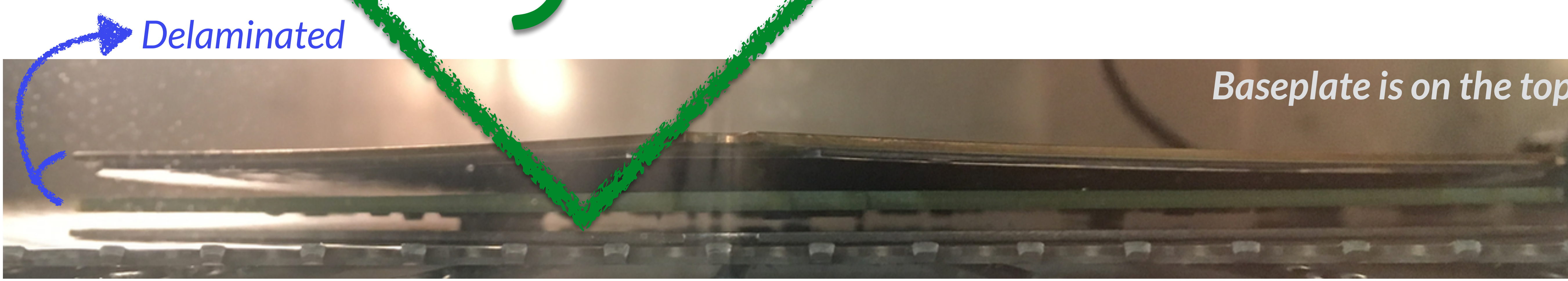
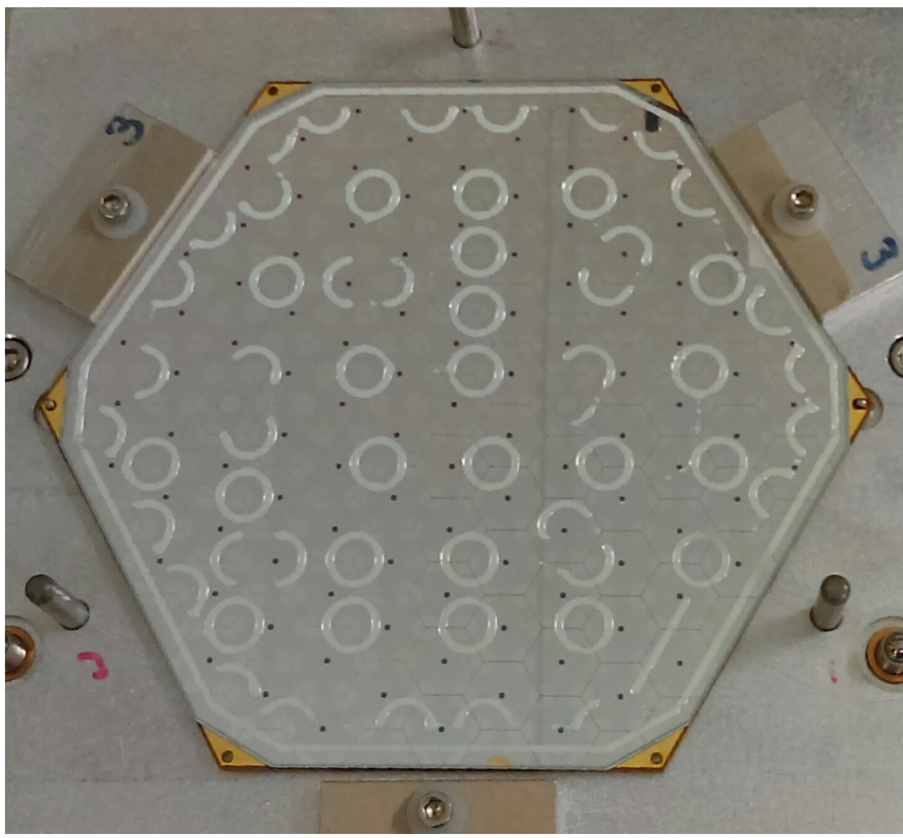
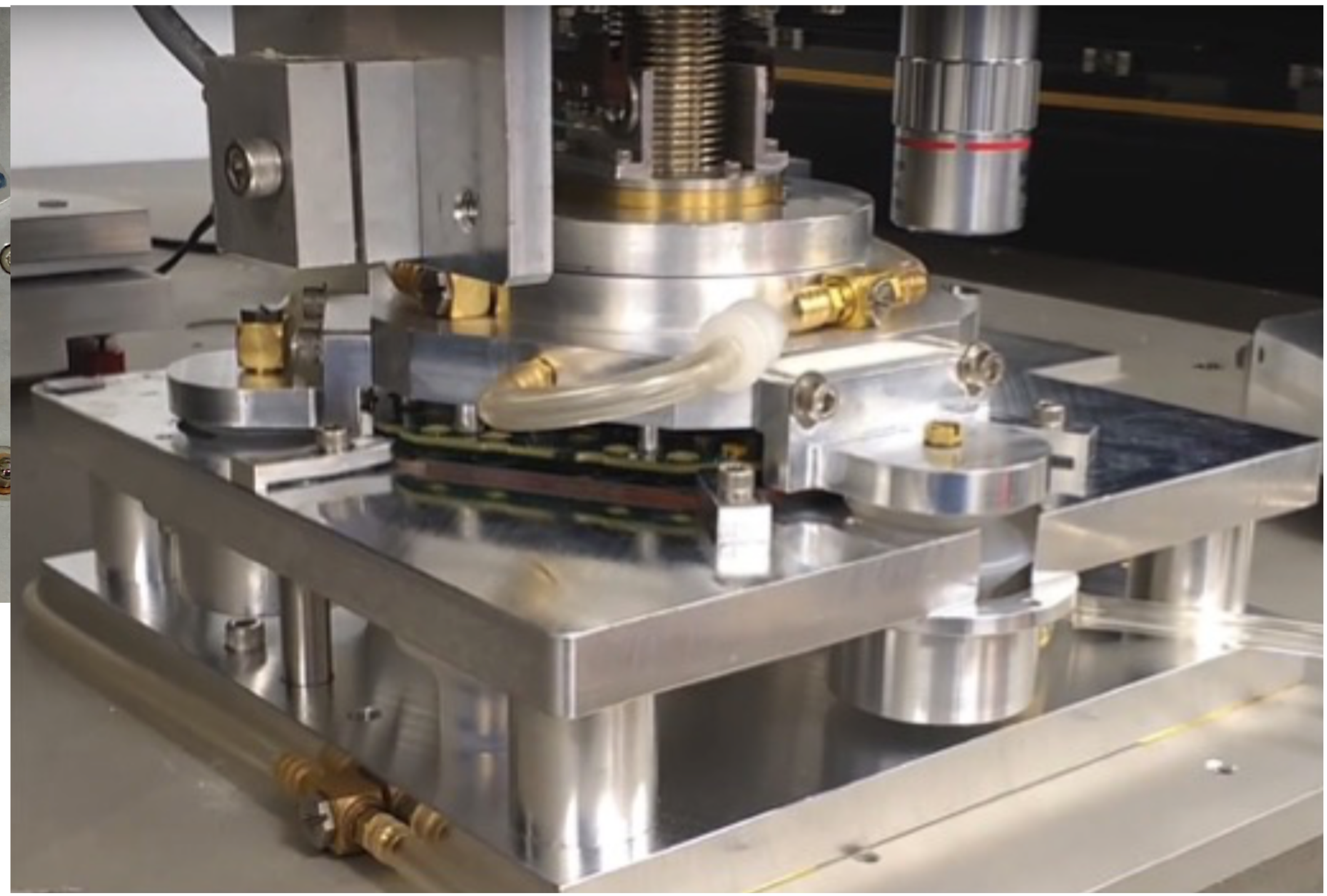
SOLVED!



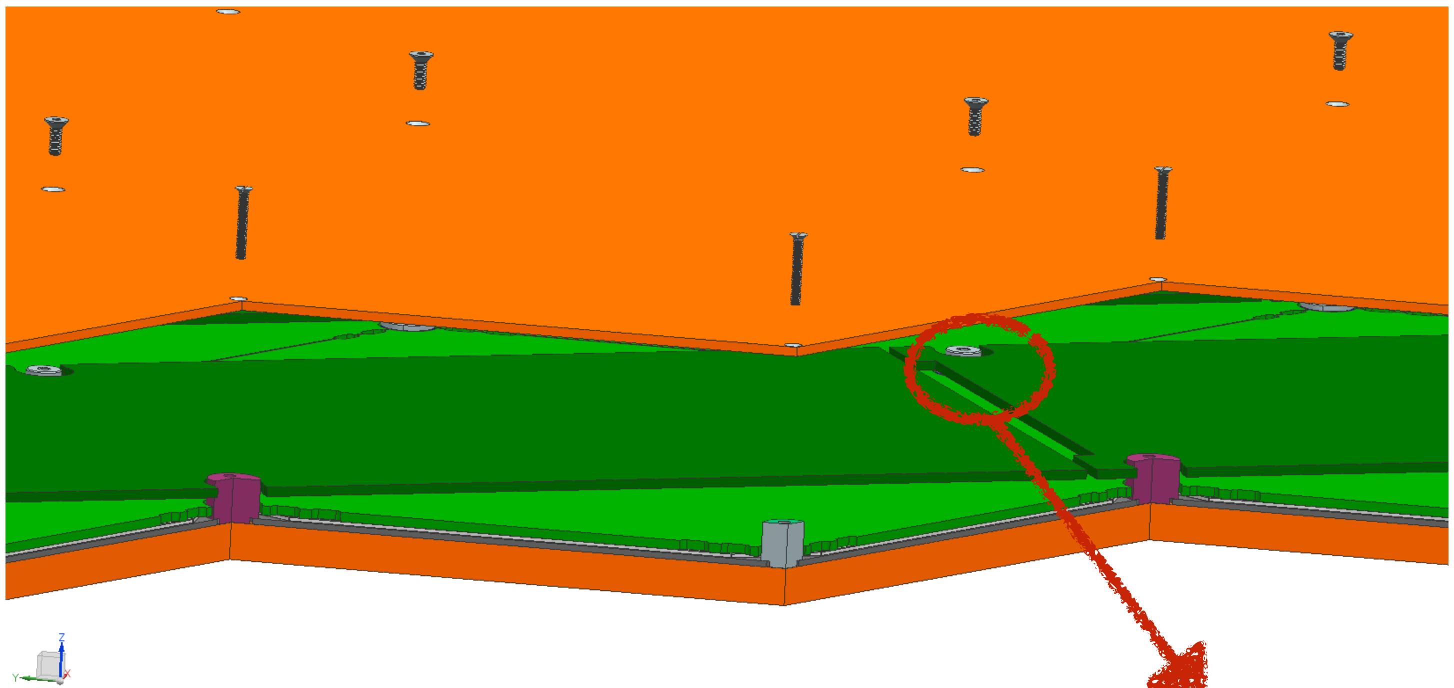
Automated Module Assembly

- A pick-and-place gantry is used for mating the main components of Silicon modules
- Ensures consistent dispense of right amount of glue

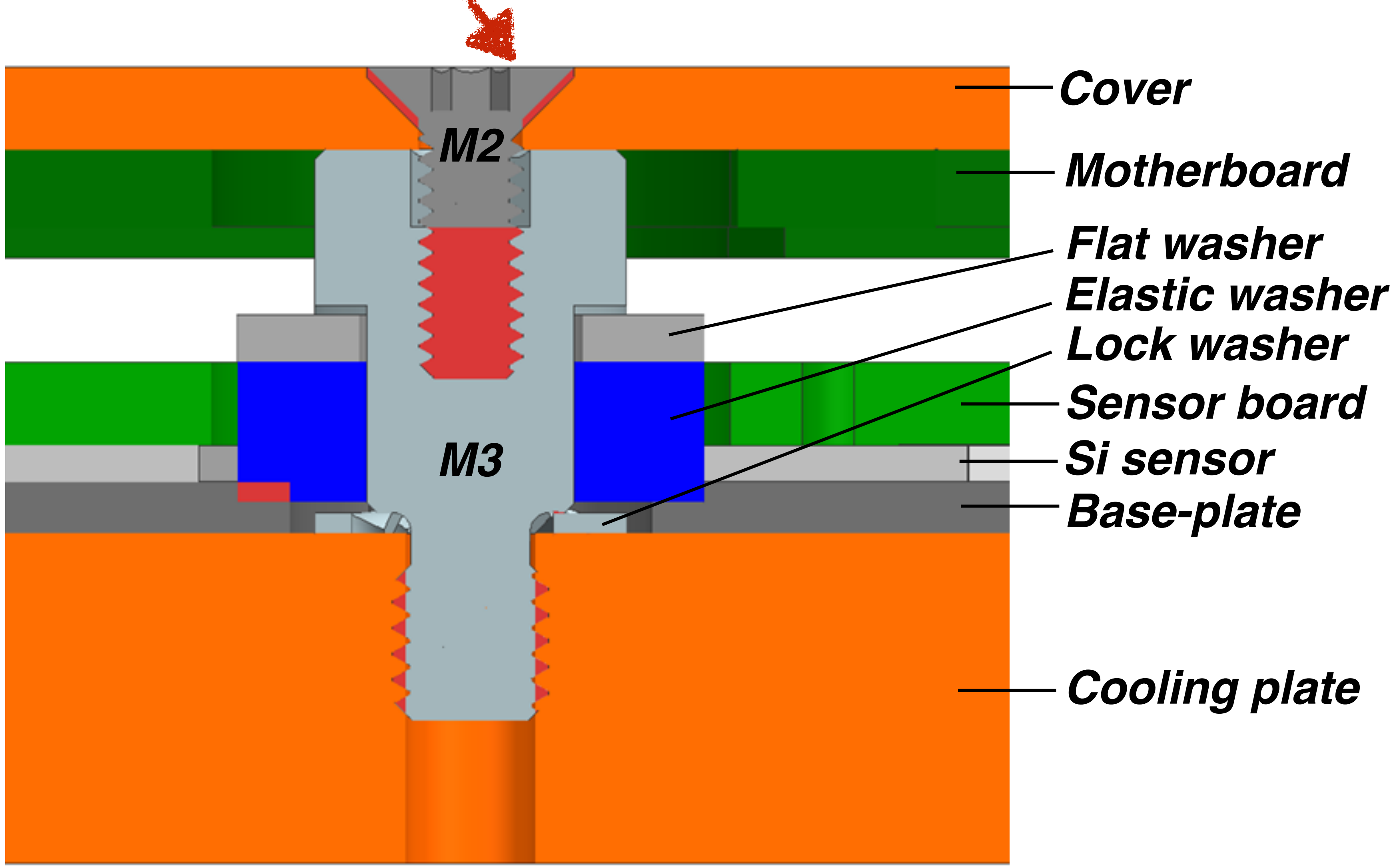




Dynamic Mounting of Modules in Cassettes

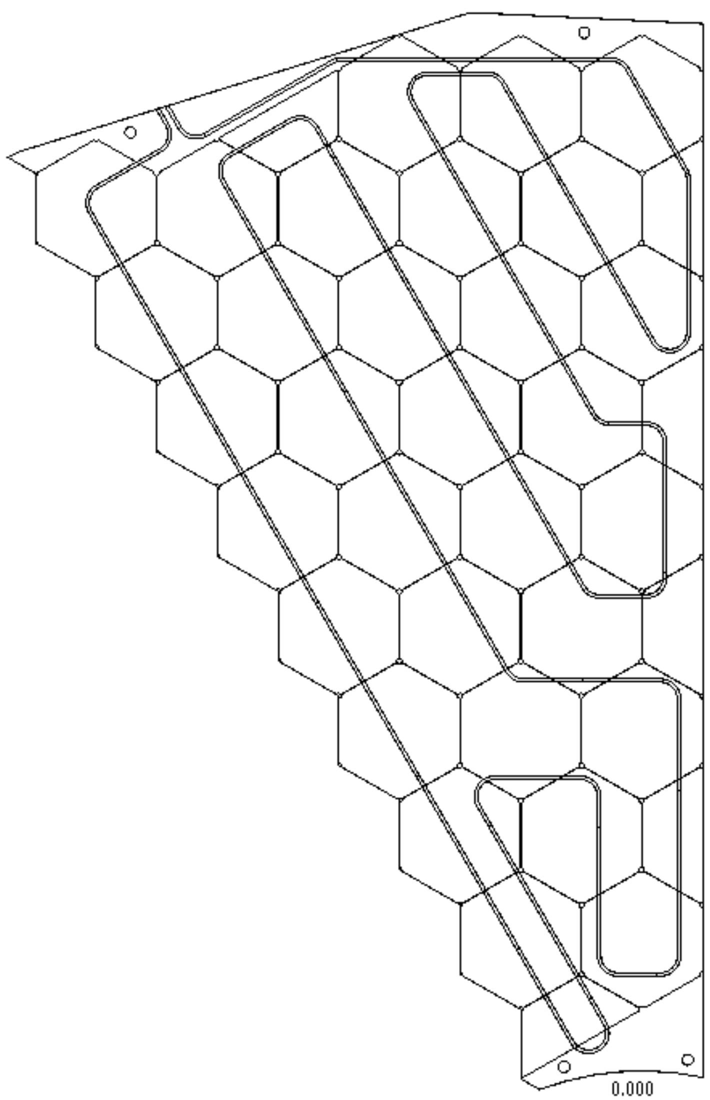


- Lower Coefficient of Thermal Expansion of Silicon module w.r.t. Copper necessitates a dynamic mounting scheme for the modules

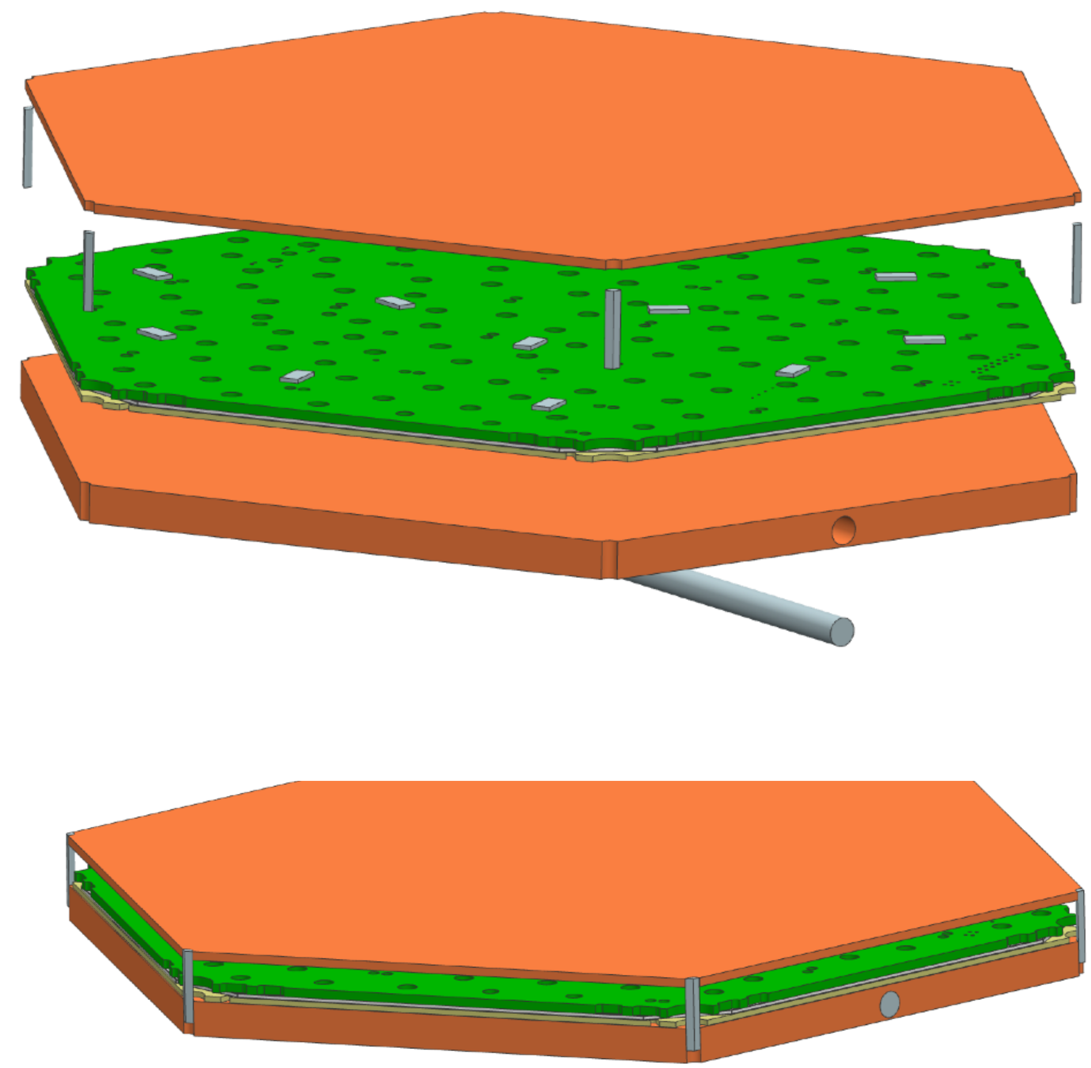


Thermal FEA Simulation Set-up

- The expected performance of the cooling system is calculated based on the combination of FEA simulations in two steps:
  - Full size Copper cooling plate and CO_2
  - Single Silicon module and Copper cooling plate



Full size Copper cooling plate and CO_2



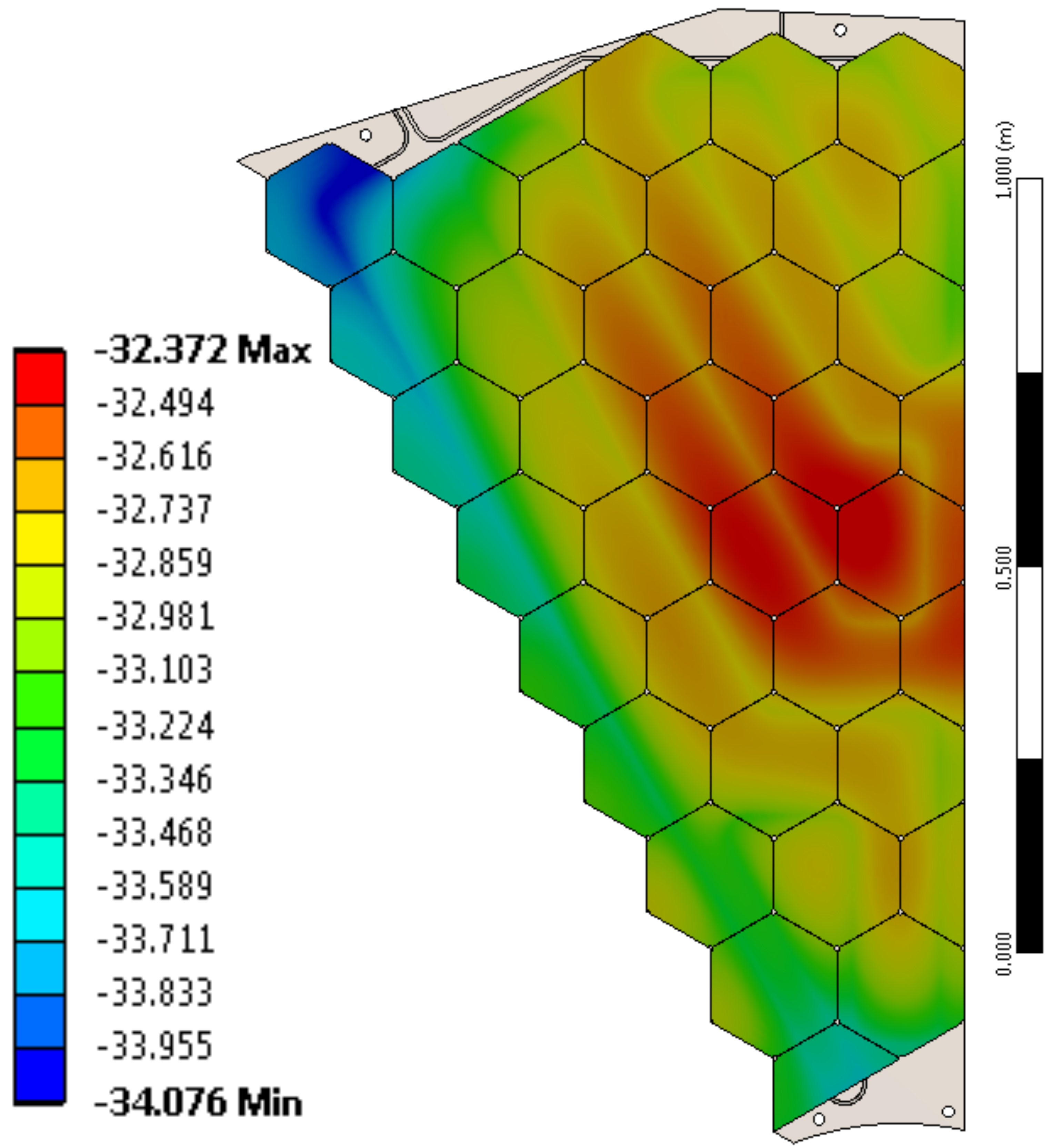
Single Silicon module and Copper cooling plate

Cooling Plate Performance

Copper cooling plate and CO_2:

- FEA calculations have been made assuming an expected uniform heat load of 200W
  - 6.8 meter long tube
  - 2.197 gm/sec CO_2 mass flow
  - Pressure Drop = 0.8 psi

- ***At most the Copper cooling plate is expected to be 2.5 °C warmer than the CO_2 temperature.***

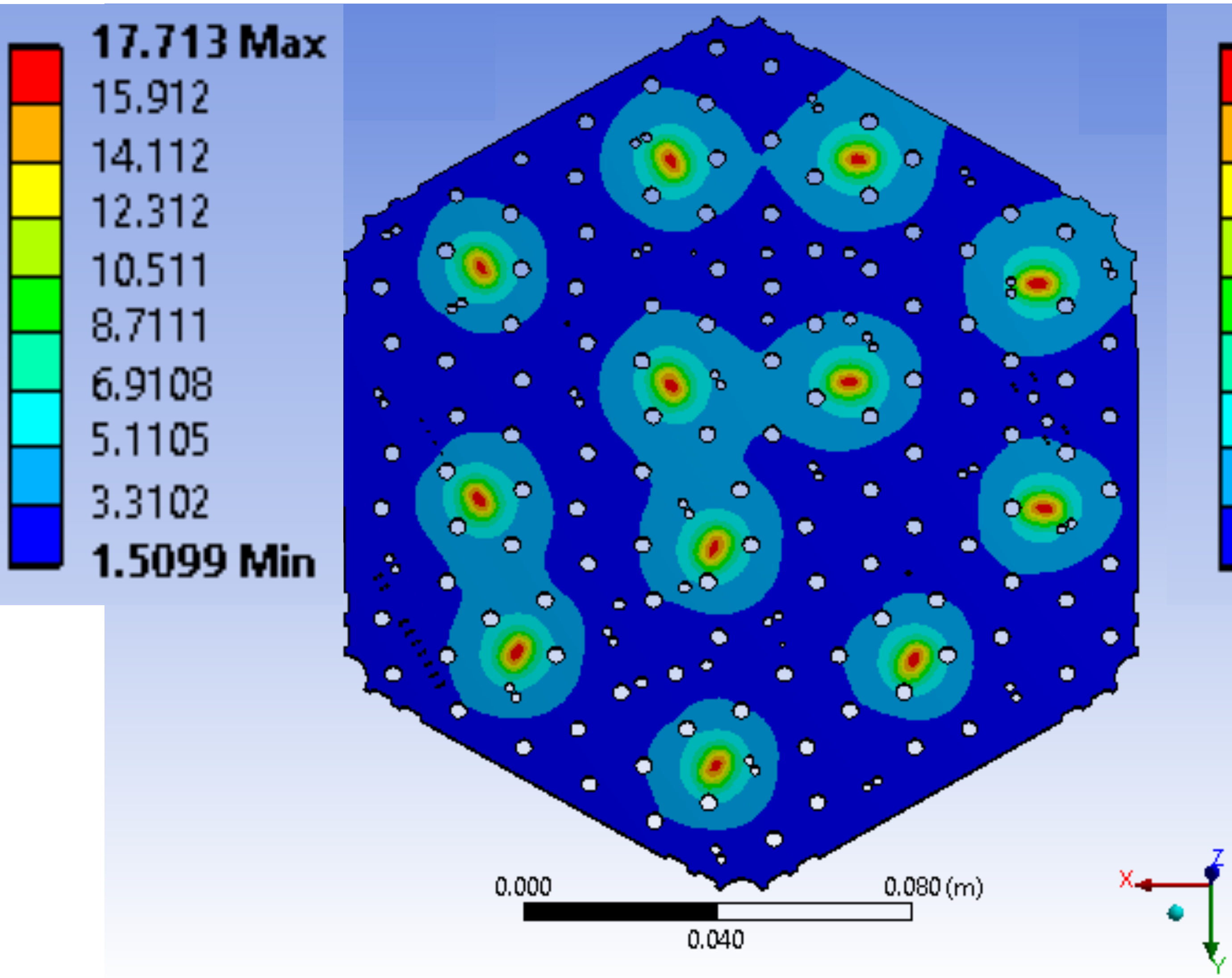


Expected Performance at Silicon Level

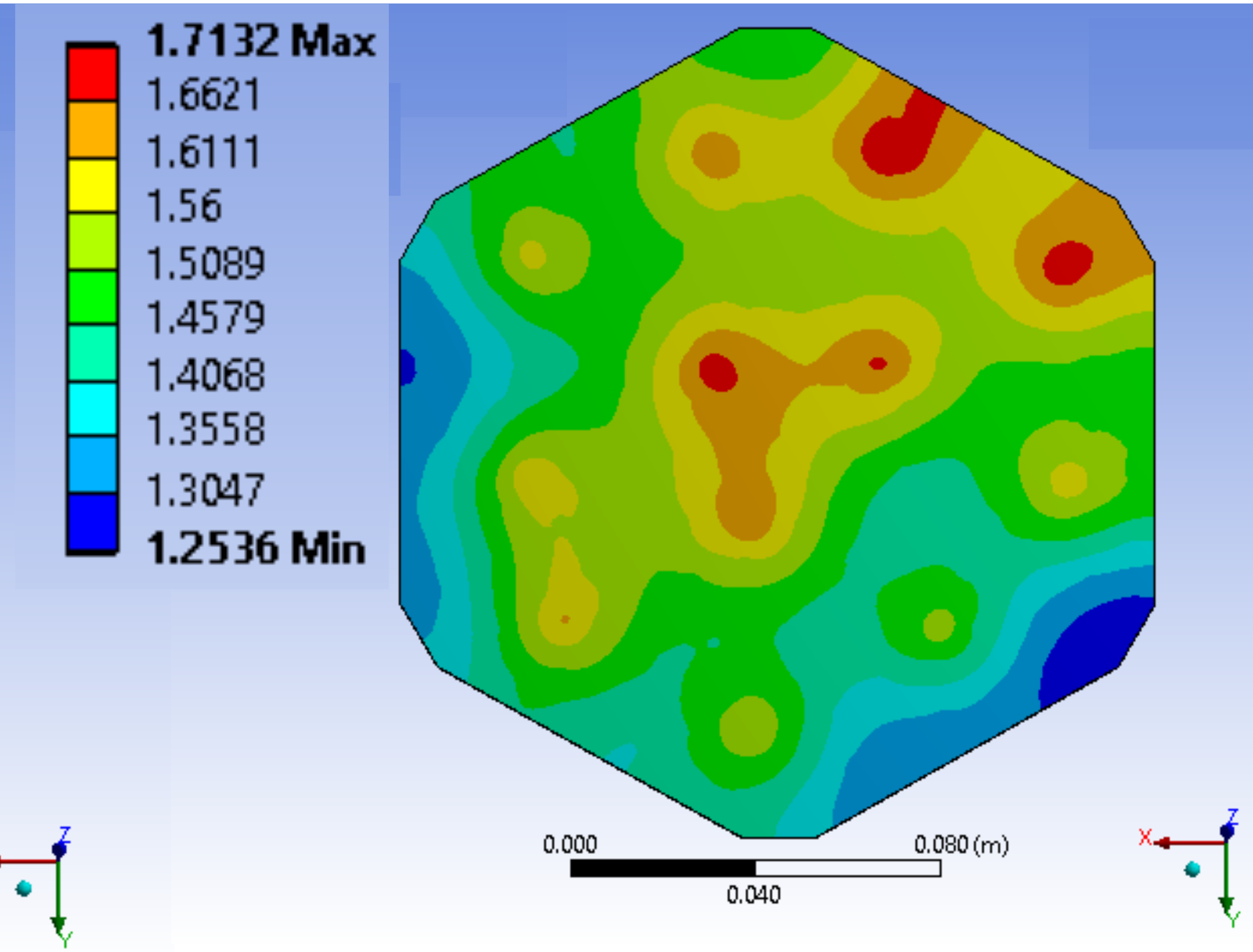
Copper cooling plate and Silicon:

- 6 W heat load is applied though 12 heaters (0.5 W each)

PCB



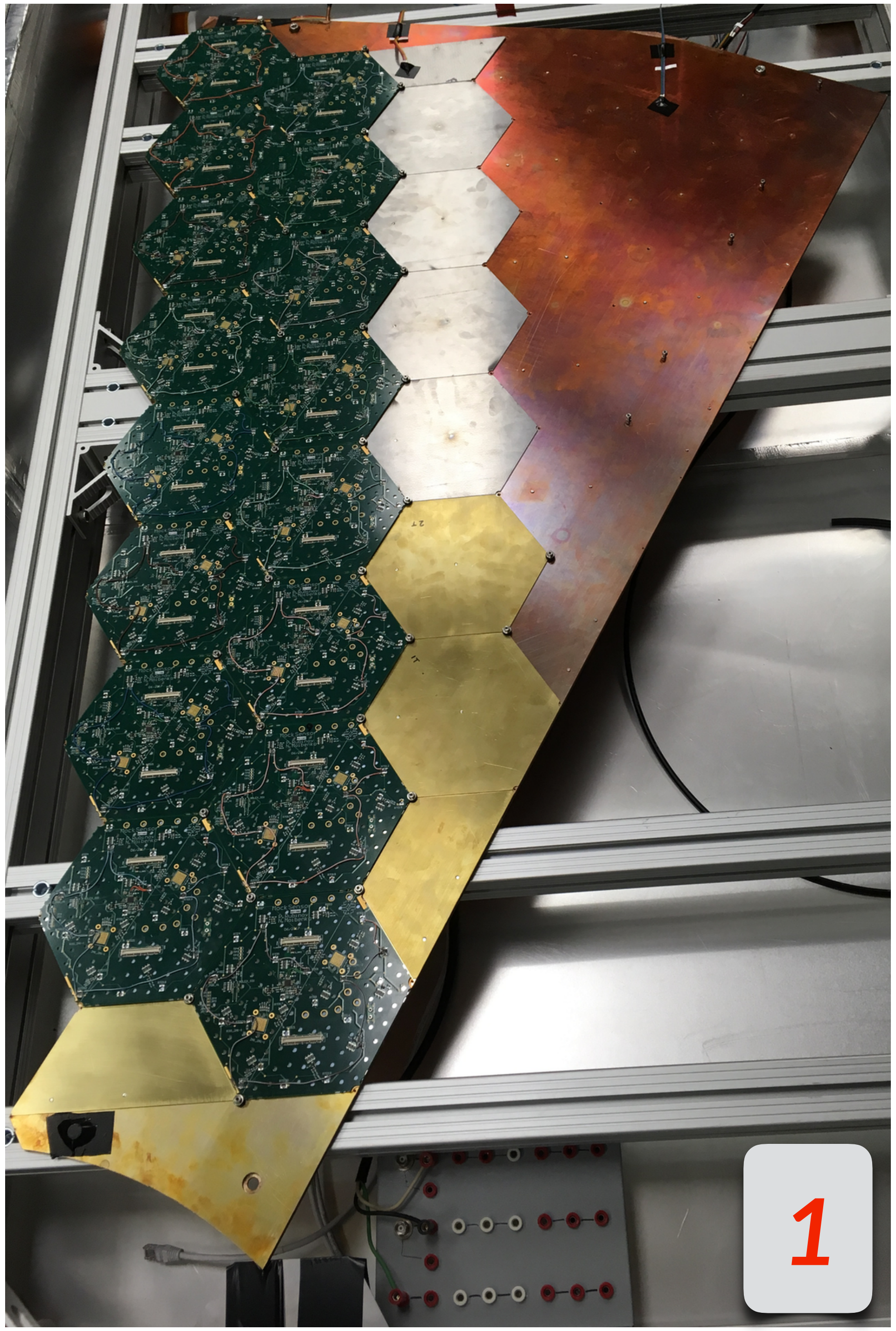
Silicon

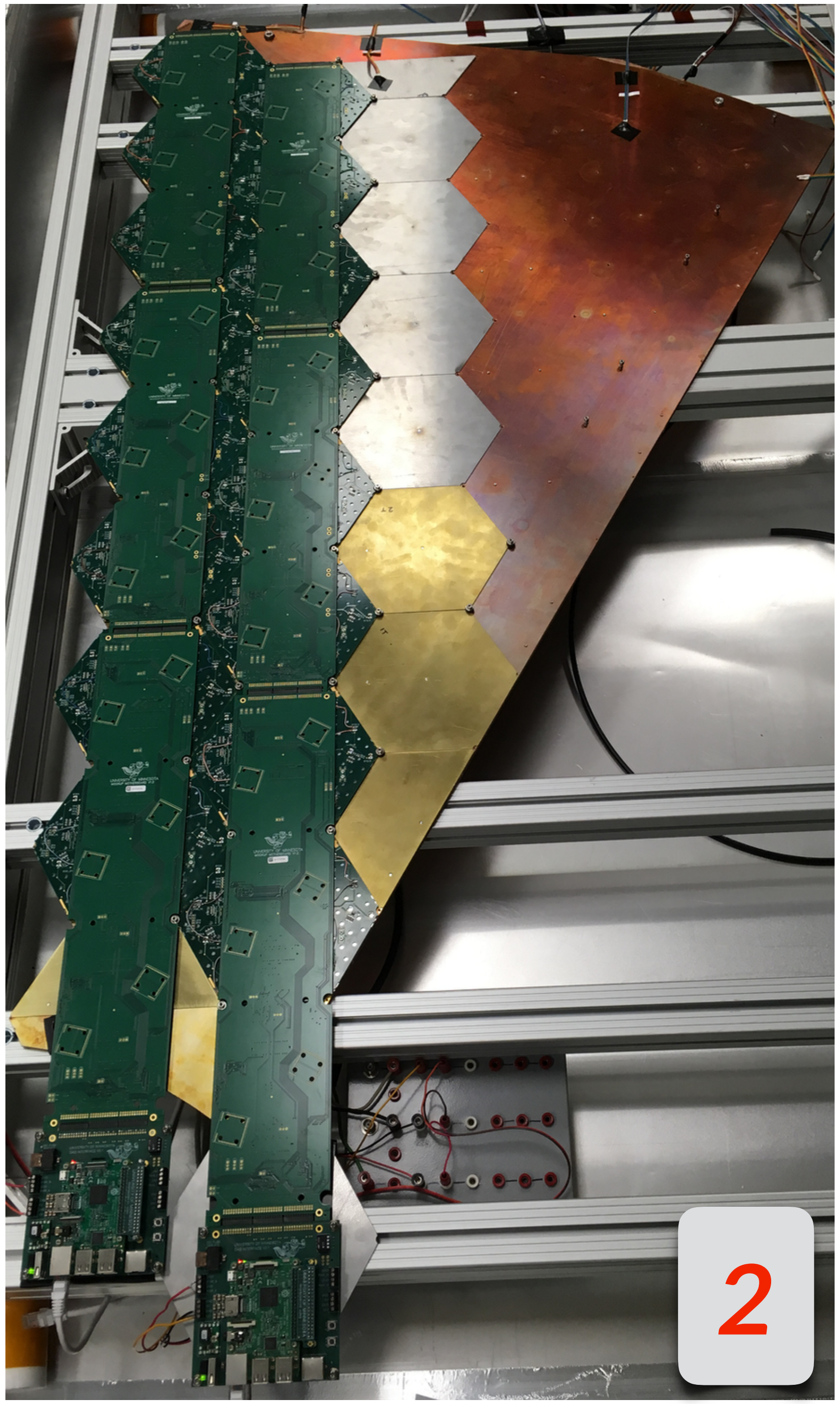


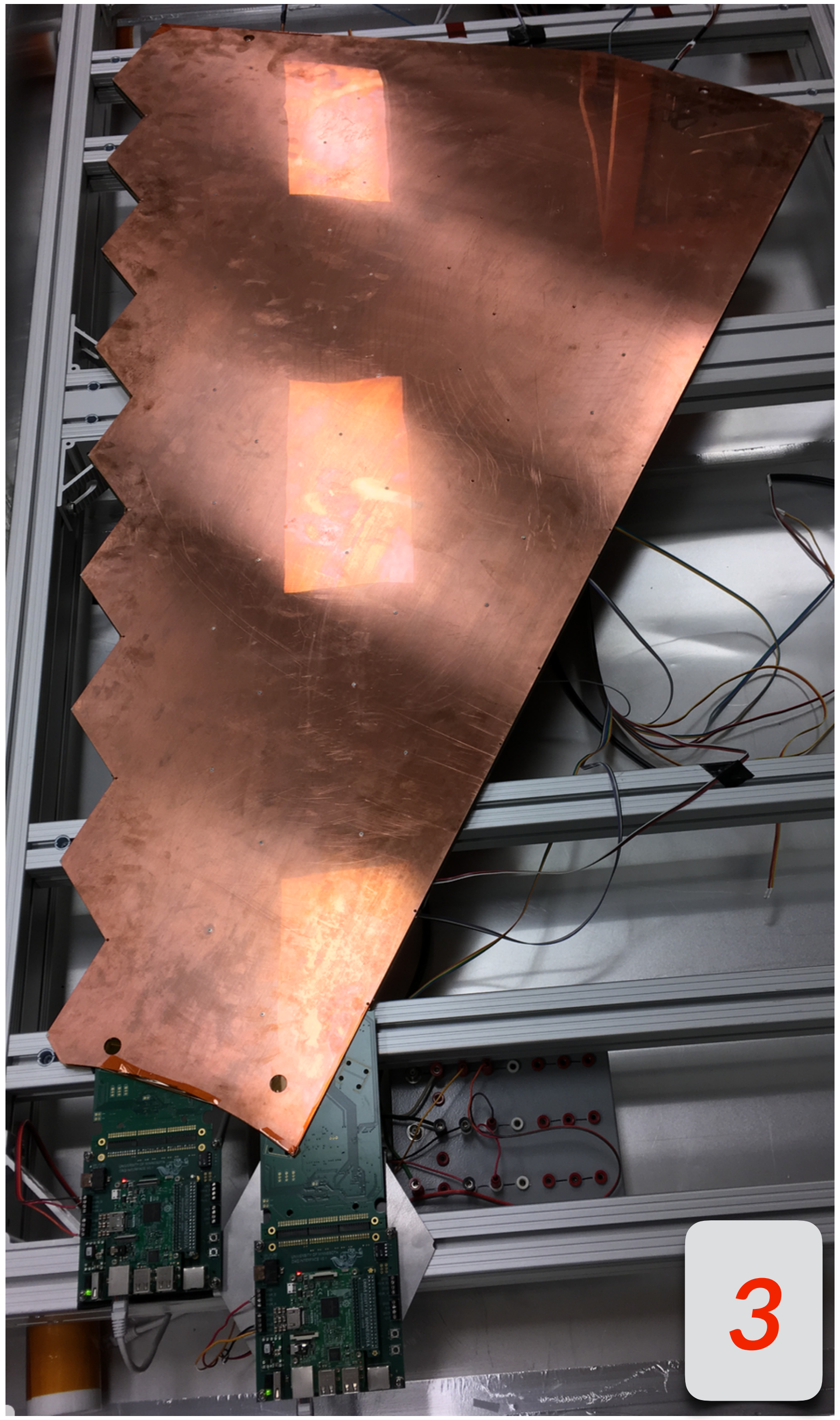
- ***On average the Si is expected to be 1.5 °C warmer than the Copper cooling plate***
- ***As a result all Si sensors satisfy the requirement of being colder than -30 °C***

Assembled the Mock-up Cassette

- The mockup cassette has been fabricated, assembled and cold tested
  - 16 full modules and 6 motherboards

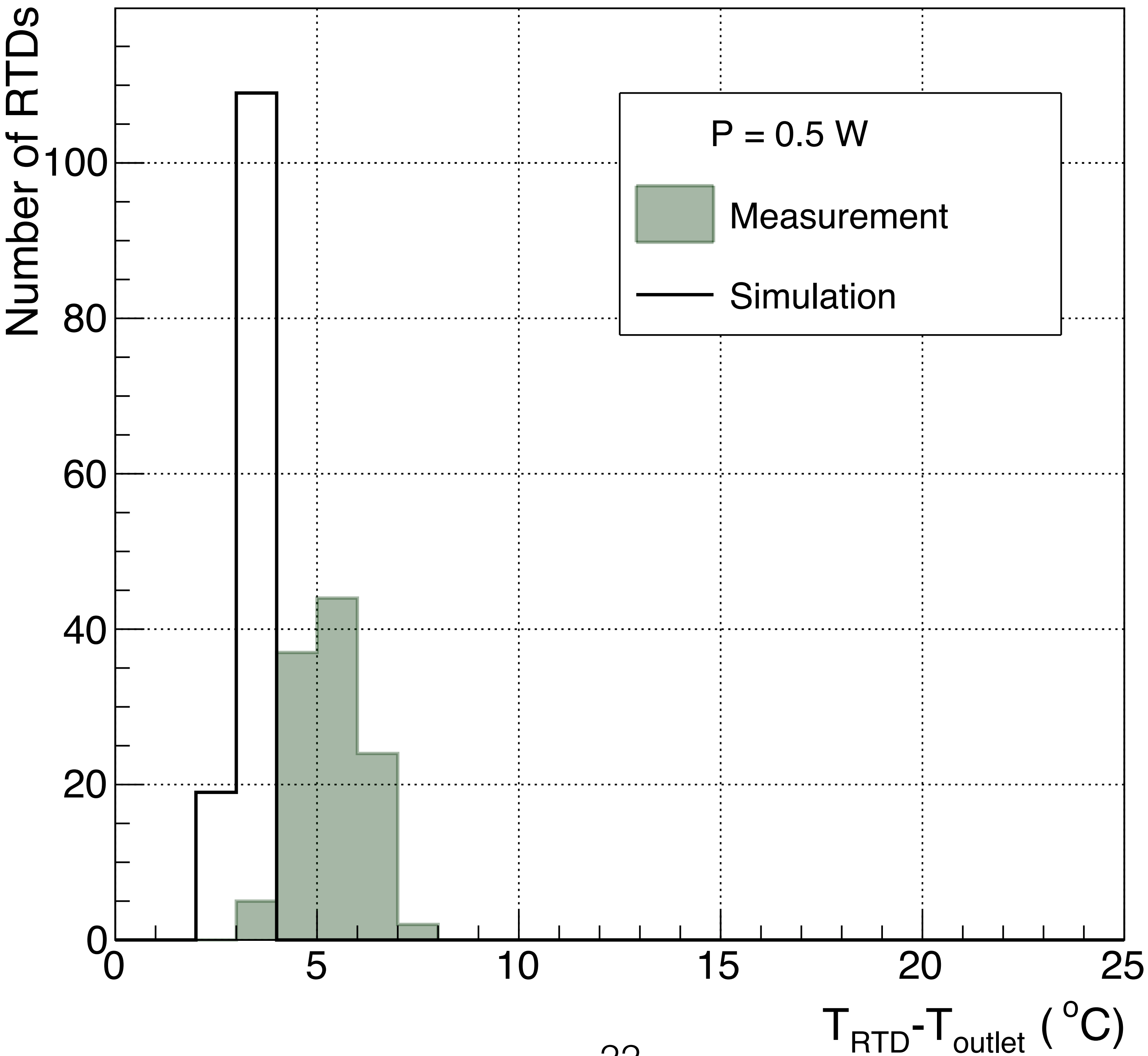






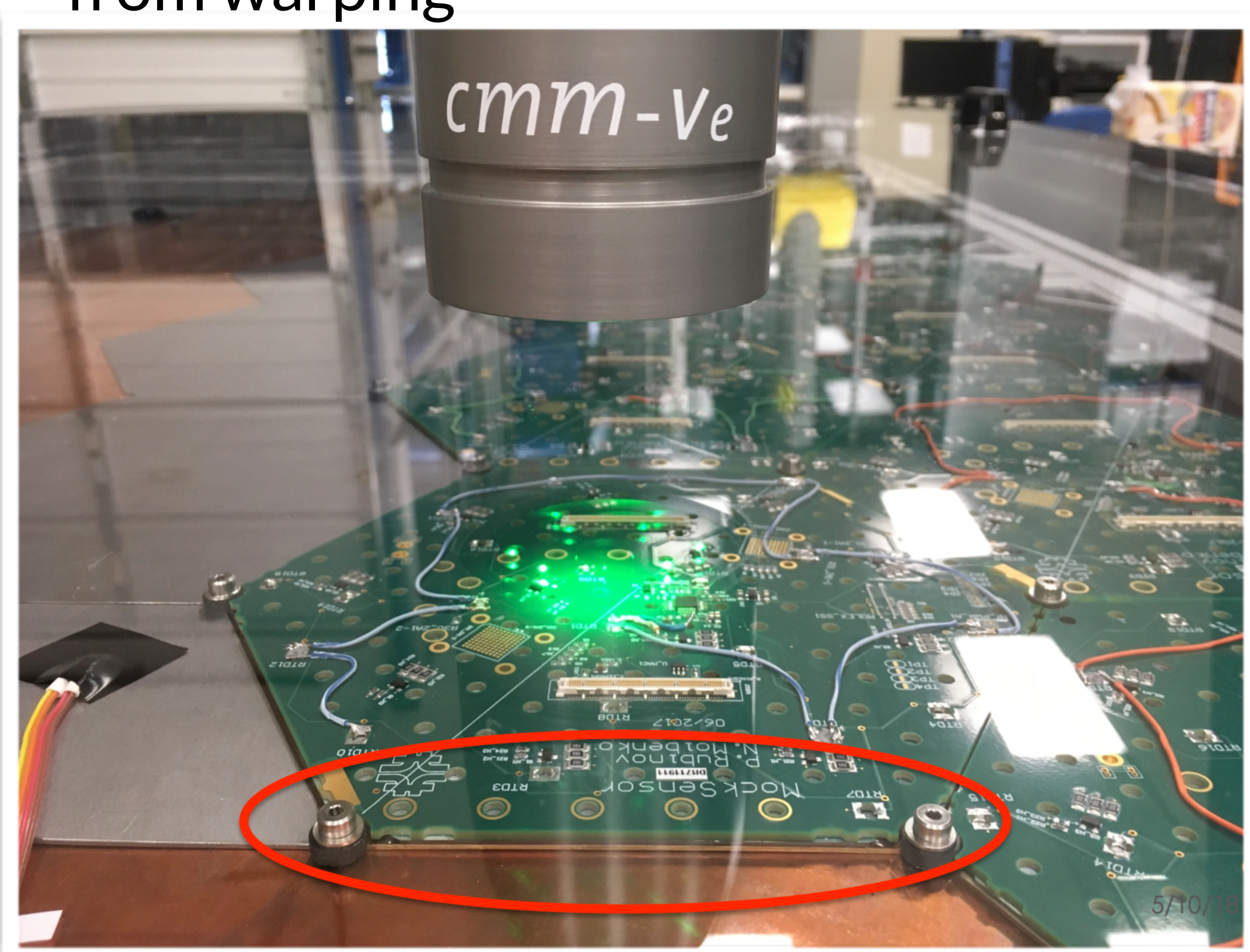
Measurements vs. Simulation

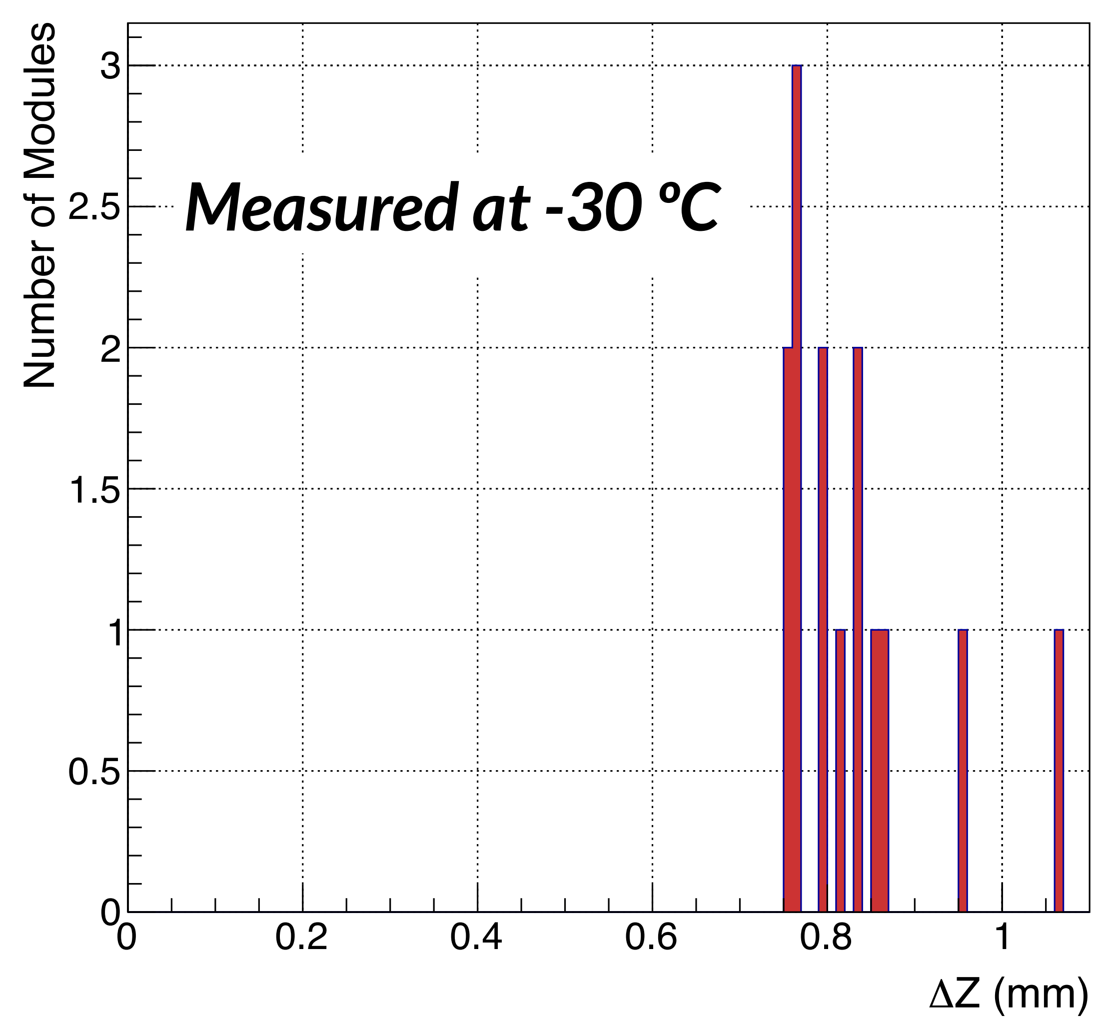
- 6 W heat load applied per module (12 heaters; each 0.5W)
- The Si temperature was measured ~5.2ºC above CO_2 outlet on average for 6W heat load per module



Module Flatness at Cold Temperatures

- Measured the height of the center and 6 corners of the modules installed on cooling plate with the Coordinate Measurement Machine at -30 °C
- The center of the modules is measured ~800 μm higher than the corners at -30 °C
  - The air gap below the warped modules explains why the measured temperatures are larger than expected
- Other base-plate material is being investigated that can prevent modules from warping





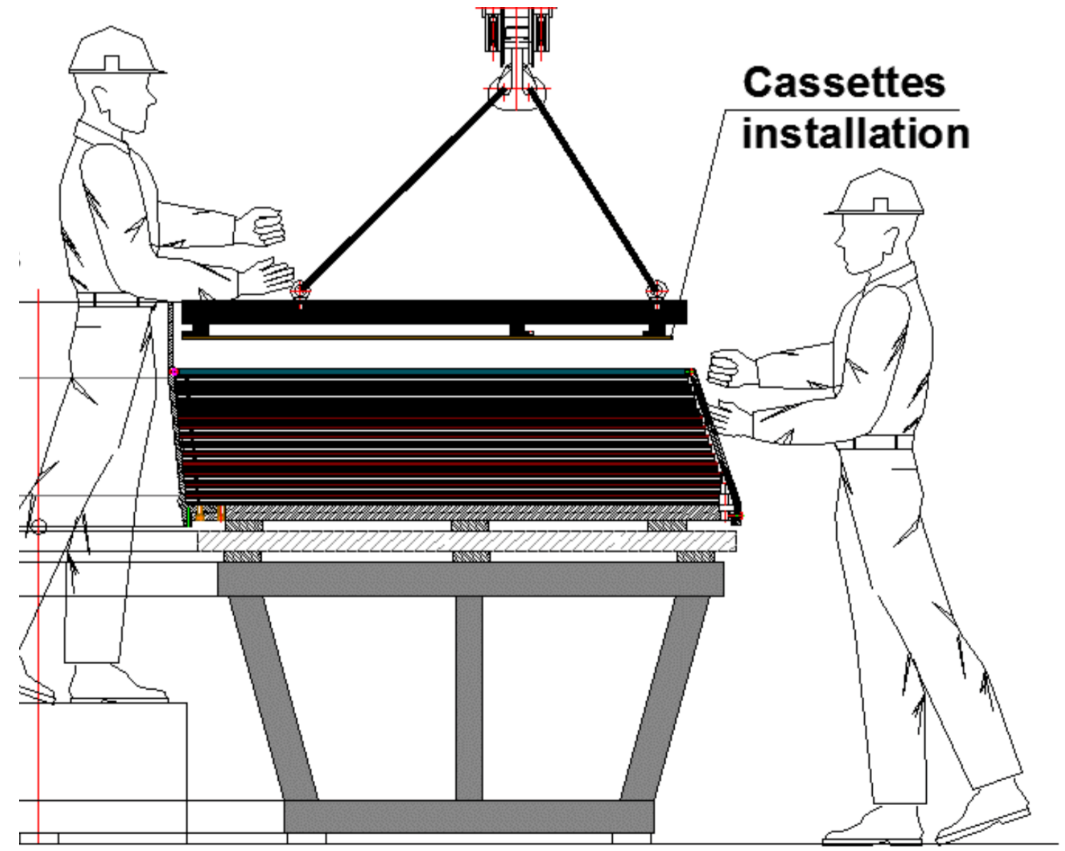
Conclusions

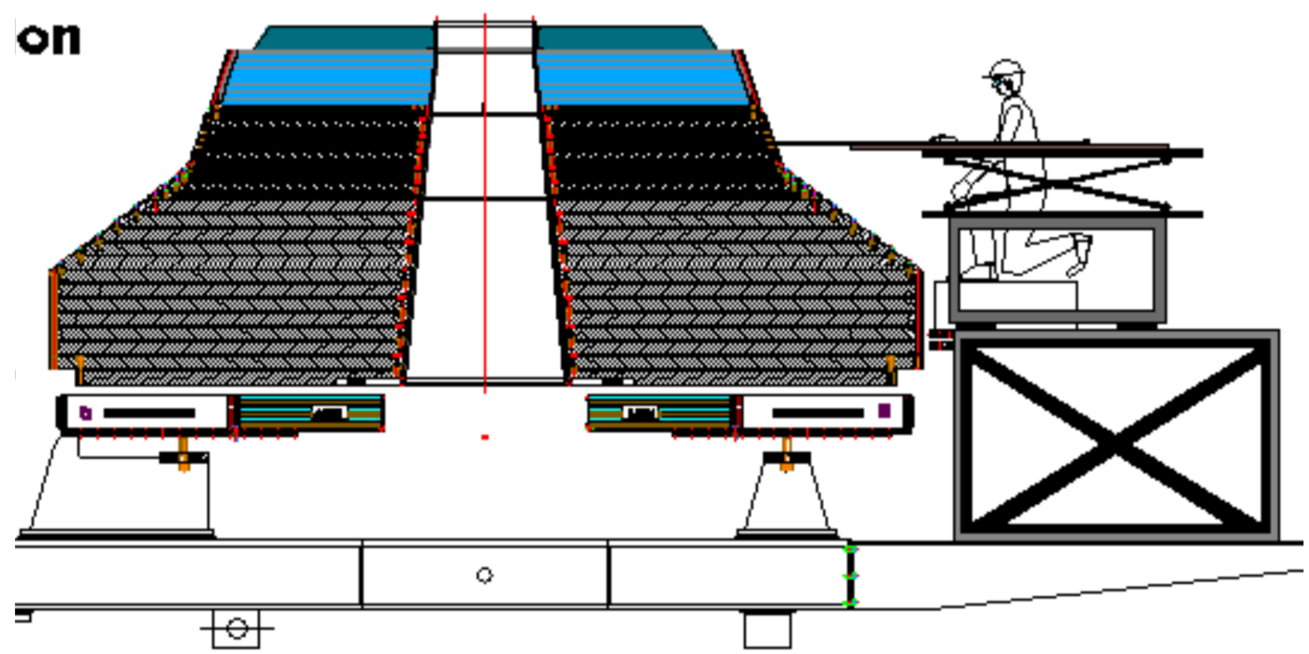
- The CMS HGCal is addressing high pile-up and high radiation dose issues at HL-LHC
  - Radiation hard Si modules
    - Operation at -30 ºC
  - 6 M channels
    - 220 kW heat dissipation
- The thermo-mechanical design must
  - Address challenges of efficient heat removal over large surfaces
  - Safely accommodate the large differences in CTE of most commonly used materials (such as PCBs, most metals, etc.) compared to that of the Silicon sensors
- A baseline design which addresses these issues has been developed for the TDR
  - An extensive set of detailed simulations and tests with full scale realistic mock-ups is currently under way to further optimize this design and arrive at a fully engineered solution

Back-up

CMS HGCal Cassette Installation

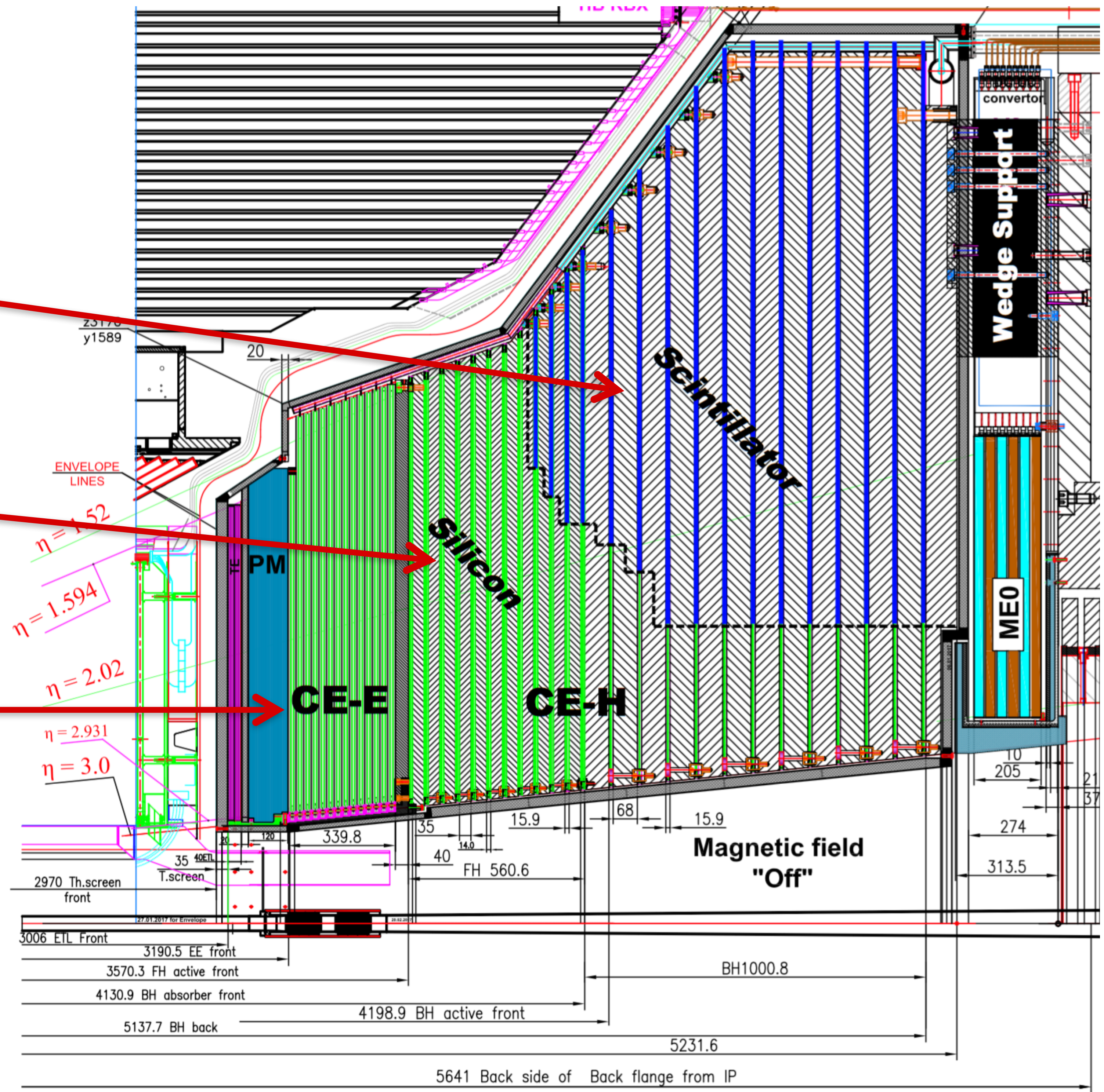
- Cassettes are built around a central copper cooling plate
  - Provides mechanical support and cooling for active elements
- Cassettes are assembled and tested at assembly sites
- Shipped to Point5 and installed into the calorimeter
  - Electromagnetic cassettes stacked
  - Hadronic cassettes inserted





HGCal Cassette Types

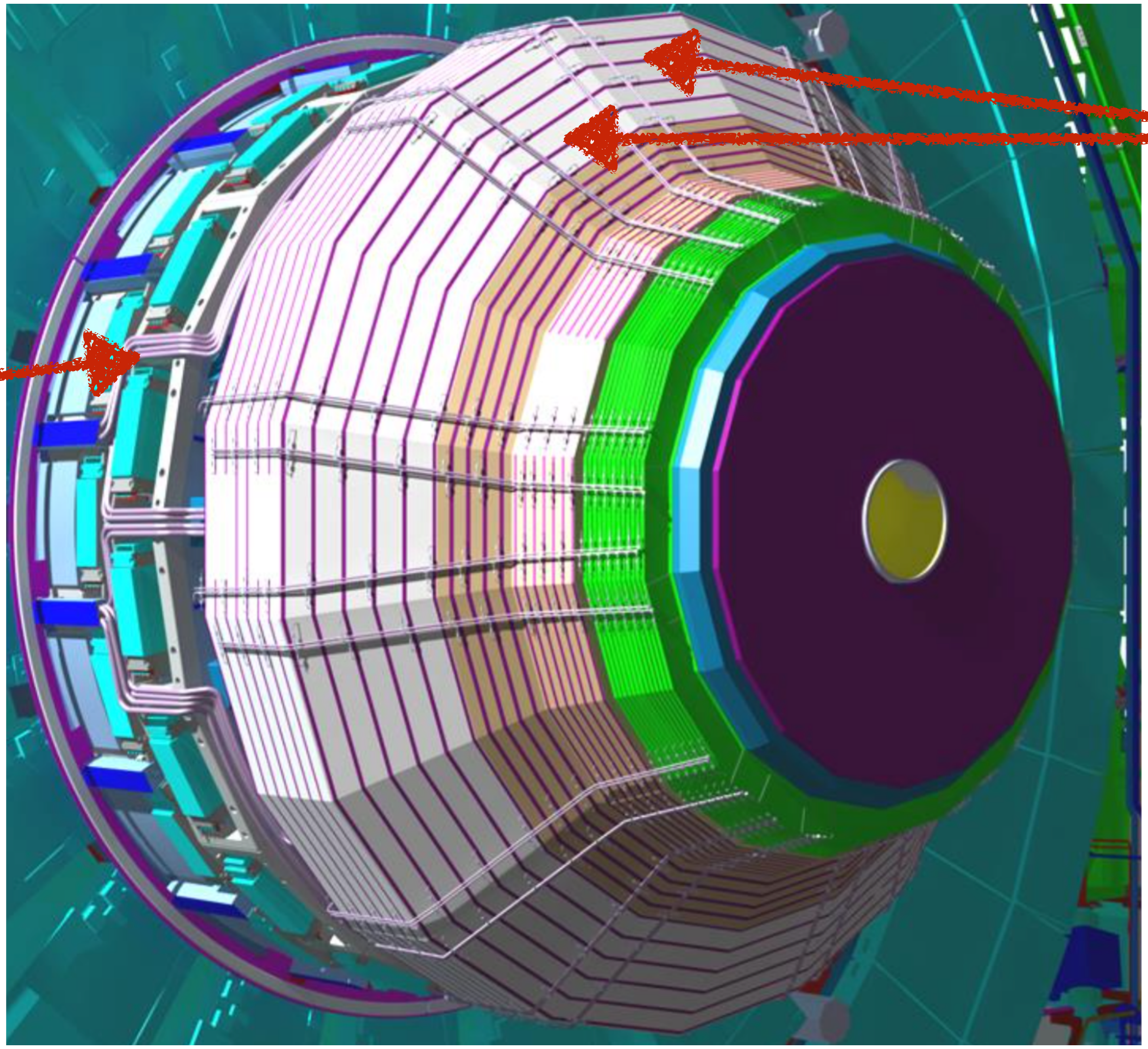
- 3 types of cassettes
- Single-sided Si + scintillator cassettes for CE-H layers 9 -- 24
- Single-sided Si only cassettes for CE-H layers 1 -- 8
- Double-sided Si only cassettes with Pb absorber for CE-E, 14 x 2 layers



HGCal Cooling System

- The cooling of the HGCAL detector is based on bi-phase CO_2
- Rigid vacuum-jacketed stainless steel pipes carry the CO_2 from the refrigeration plants to the detector.
- The flow is fed to the detector cold volume via 24 vacuum-insulated coaxial lines on each Endcap.

Vacuum jacketed coaxial lines over the Endcap suspension system brackets



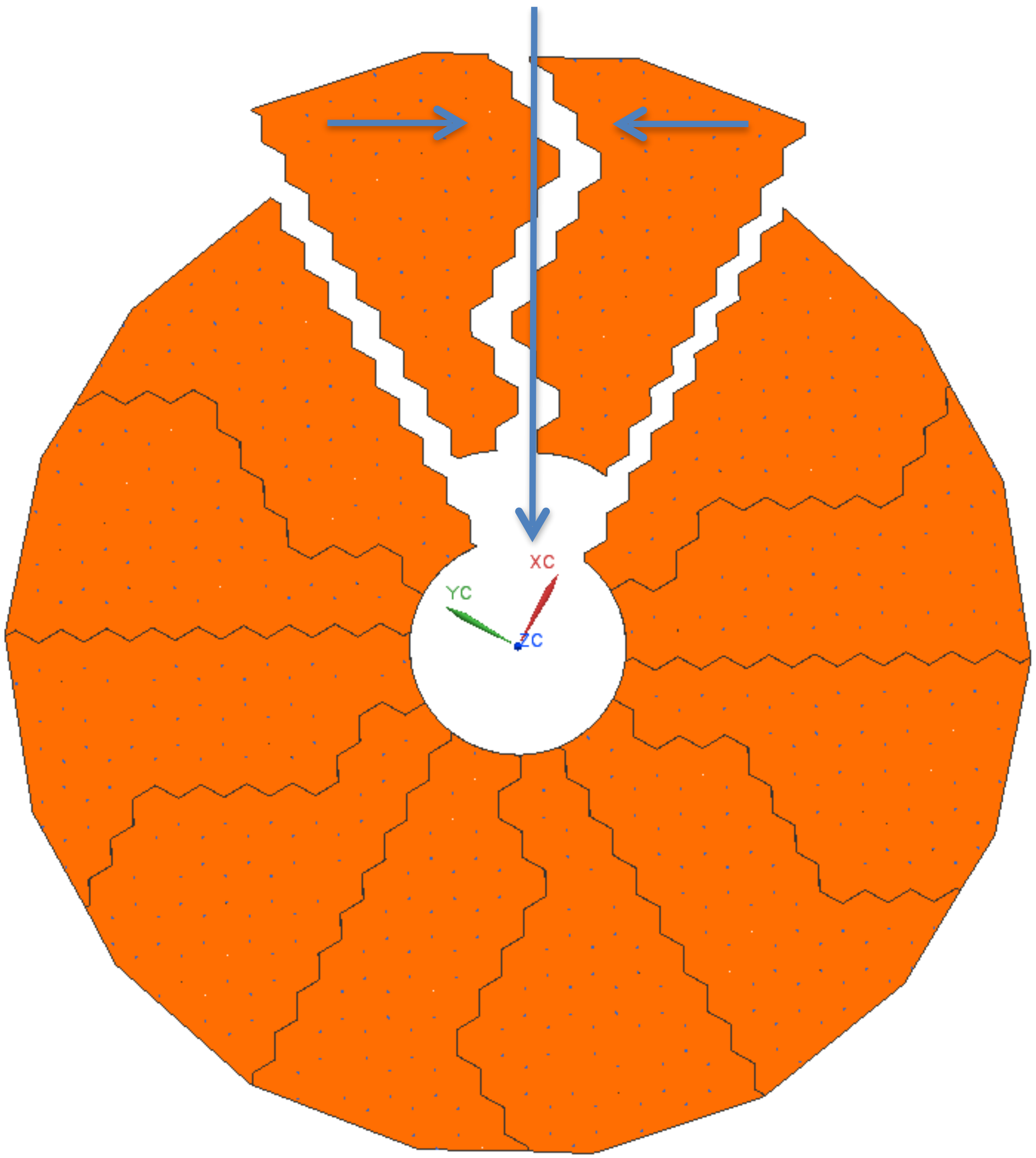
two sets of supply and return lines every 30º

Design Question Being Addressed

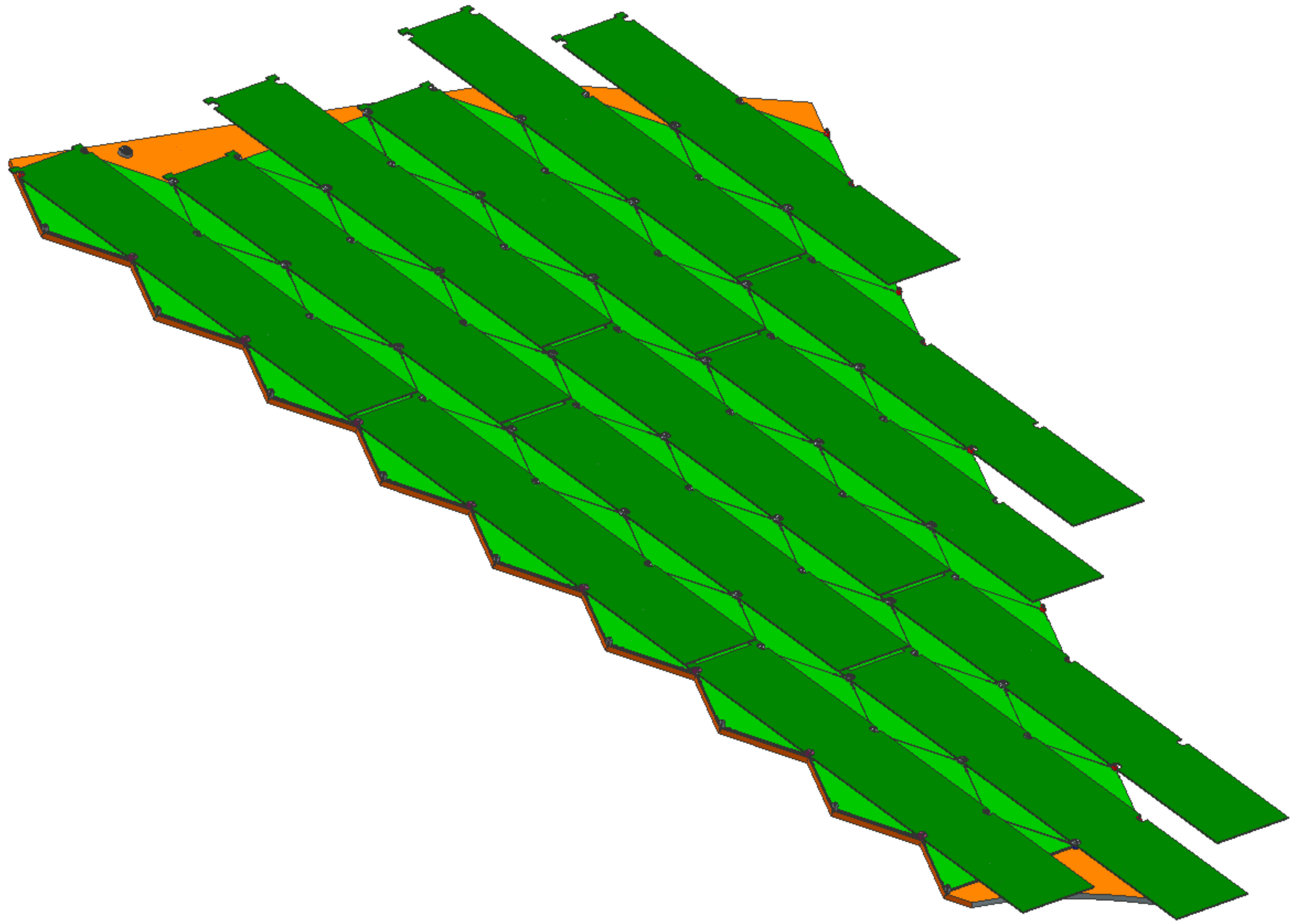
- ***Cassette boundary shape***
  - 30 or 60 degree cassettes
  - Whole modules or half modules at the edge
- ***Mounting scheme of modules***
  - One shared screw for three module corners or individual ones, special mounting on cassette edge, washer design, location of module locating pins
- ***CO_2 cooling pipe shape and capillary design***
  - Operating pressure difference of cooling plant and heat power drives the design
- ***Geometry of motherboards and connections to modules***
  - Single or double row of modules, number of modules per motherboard
  - Rigid, compression, flex cable connectors
- ***Power delivery***
  - Location of DC to DC converters
  - Power bus bar or inside motherboard
- ***Cassette interface patch panel design***
- ***Assembly procedures, tooling and testing***

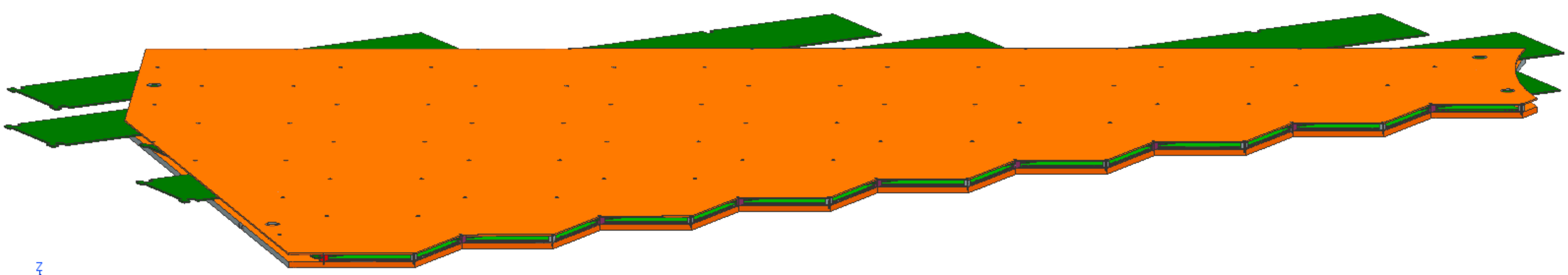
Segmentation of the Cassettes

- The interface between cassettes follows the outline of whole-size modules
- The size of the Electromagnetic (CE-E) cassettes has been chosen to be 60 degrees
- The size of the Hadronic (CE-H) cassettes has been chosen to be 30 degrees to ease fabrication and assembly of components
  - Cassettes can be inserted in pairs as a 60-degree unit
- All cassettes use common design where possible



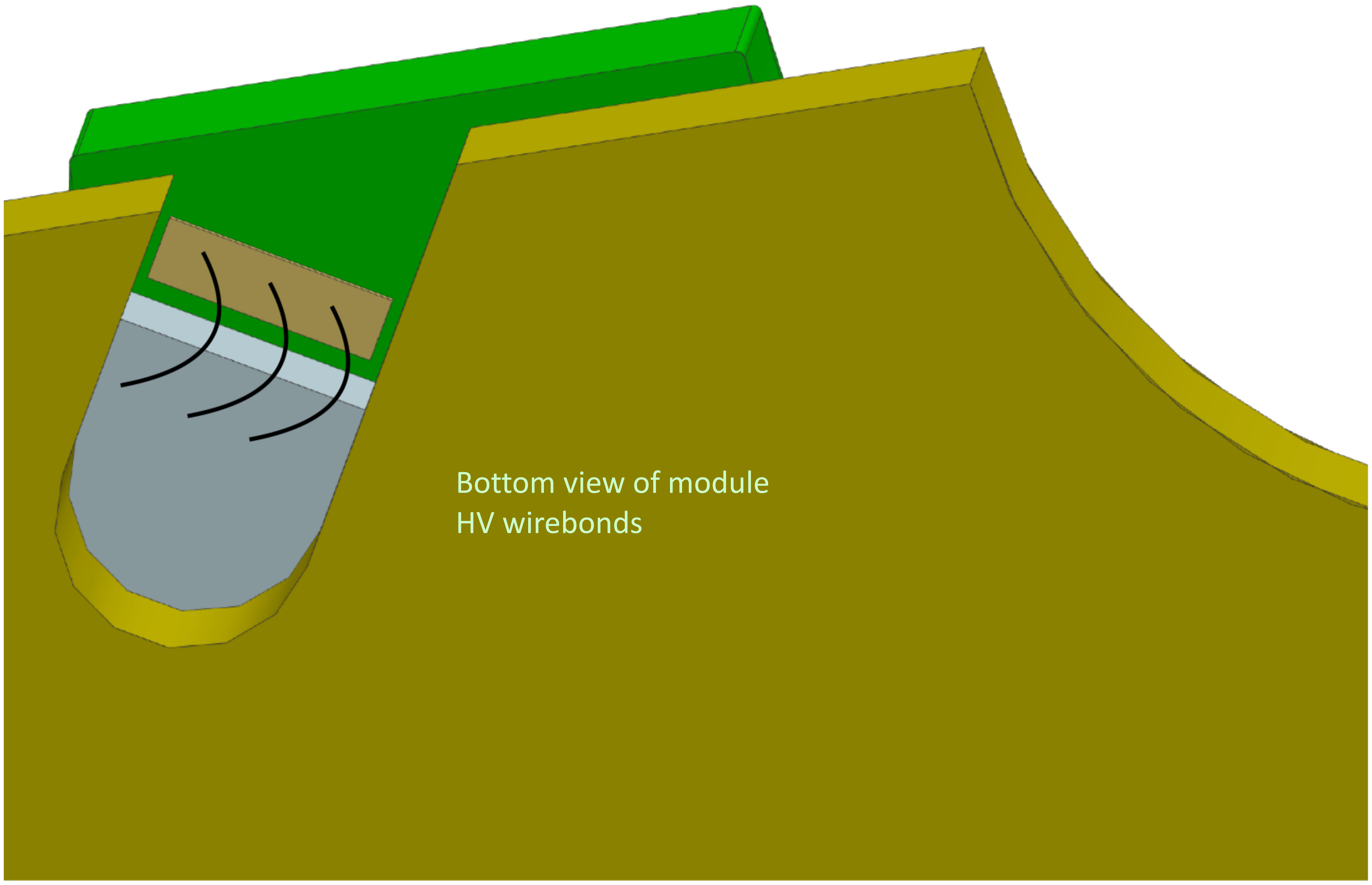
More Views of the Mock-up Cassette





Module Design Modifications

- Introducing new High Voltage wire-bond locations to simplify bonding and potting



Motherboard and DAQ System

- DAQ system available to read order of 50 ADC chips and 800 RTDs
- DAQ is based on Raspberry Pi that communication to ADC chips on SPI bus
- At the end of motherboard chains, a Raspberry Pi carrier board is connected which communicates to the DAQ PC via ethernet