Study of Interconnection Thermal Reliability and Precise Integration of High Granularity Timing Detector Modules

Master Thesis Defense

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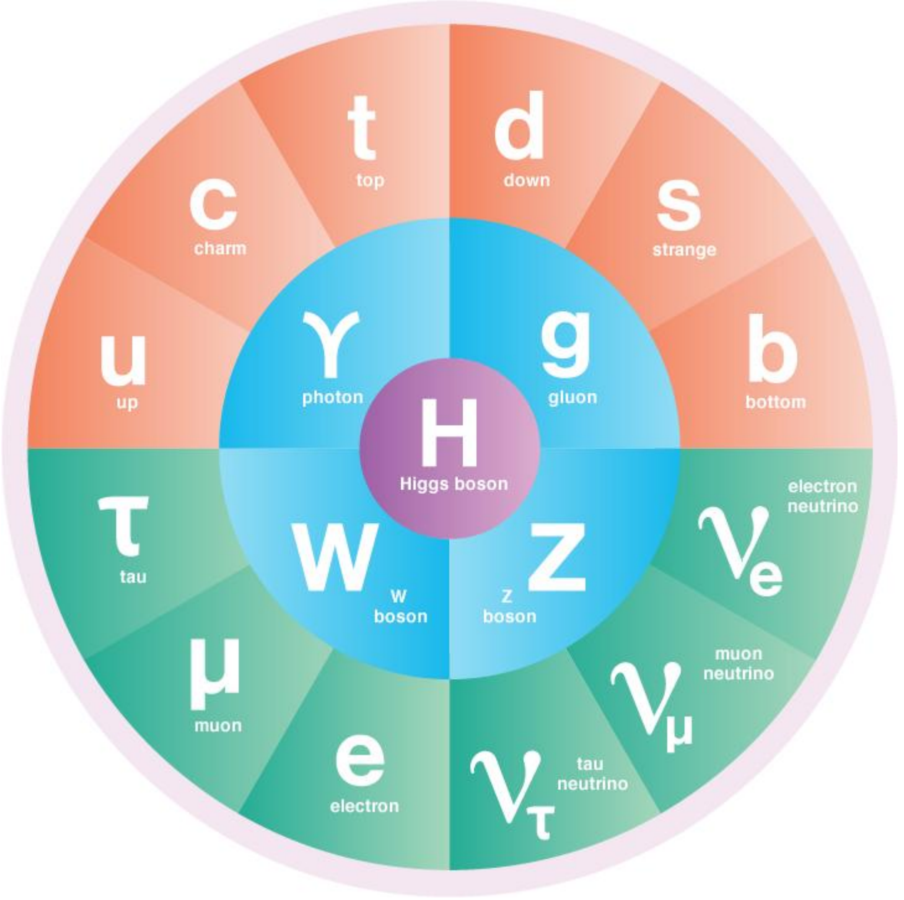
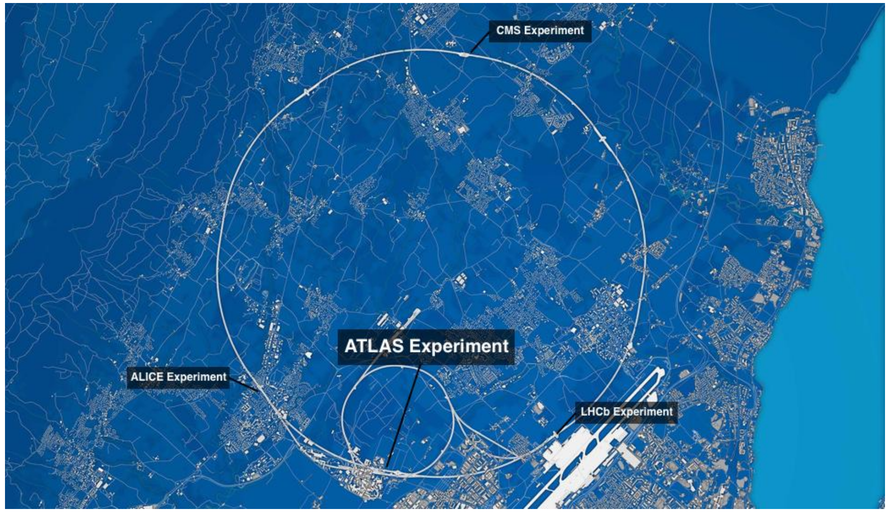
The Standard Model of Particle Physics

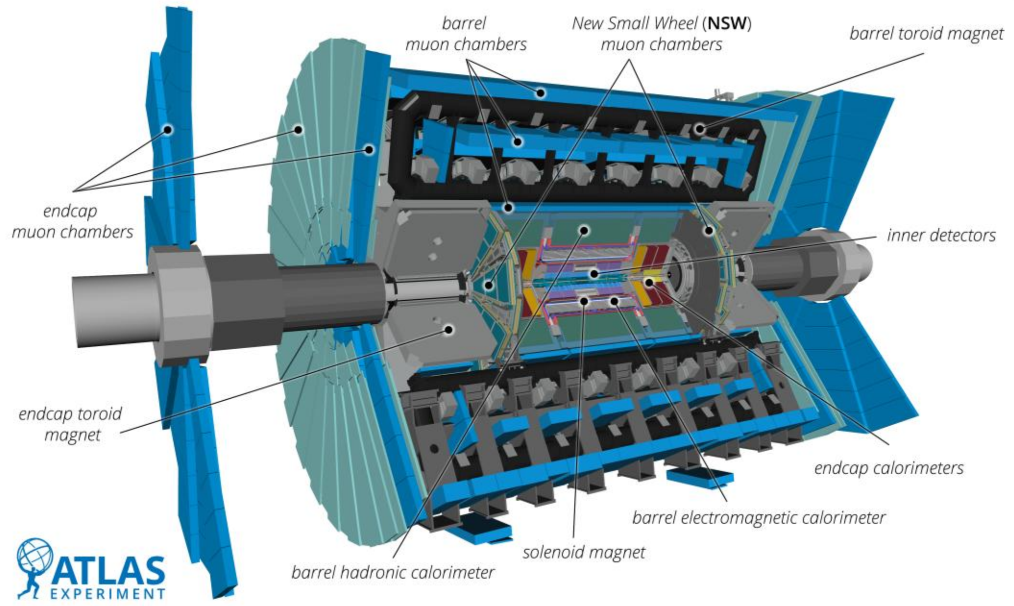
- The Standard Model is the theory that explains the fundamental particles and their interparticle forces
- The particles in the SM includes:
  - Fermions: building blocks of matter, leptons and quarks
  - Bosons: force carriers
- The four fundamental forces:
  - Electromagnetic (γ)
  - Strong (g)
  - Weak ($W^{\pm}, Z^{0}$)
  - Gravity (unexplained in the current SM)
- The Higgs boson:
  - Only particle in SM with zero spin
  - Responsible for granting mass to elementary particles via the Higgs mechanism
  - Discovered in 2012 by both ATLAS and CMS experiments on LHC



The Large Hadron Collider and ATLAS Experiment

- The Large Hadron Collider (LHC):
  - The largest and most powerful particle accelerator
  - Proton-proton collider system
  - Four main experiments: ATLAS, CMS, ALICE and LHCb
- The ATLAS Experiment:
  - One of the two large general-purpose particle detectors at the LHC (the other is CMS)
  - Forward-backward symmetric cylindrical design covering almost 4π solid angle
  - Various sub-detector systems to reconstruct different types of particles
    - Inner detector
    - Calorimeter system
    - Muon spectrometer

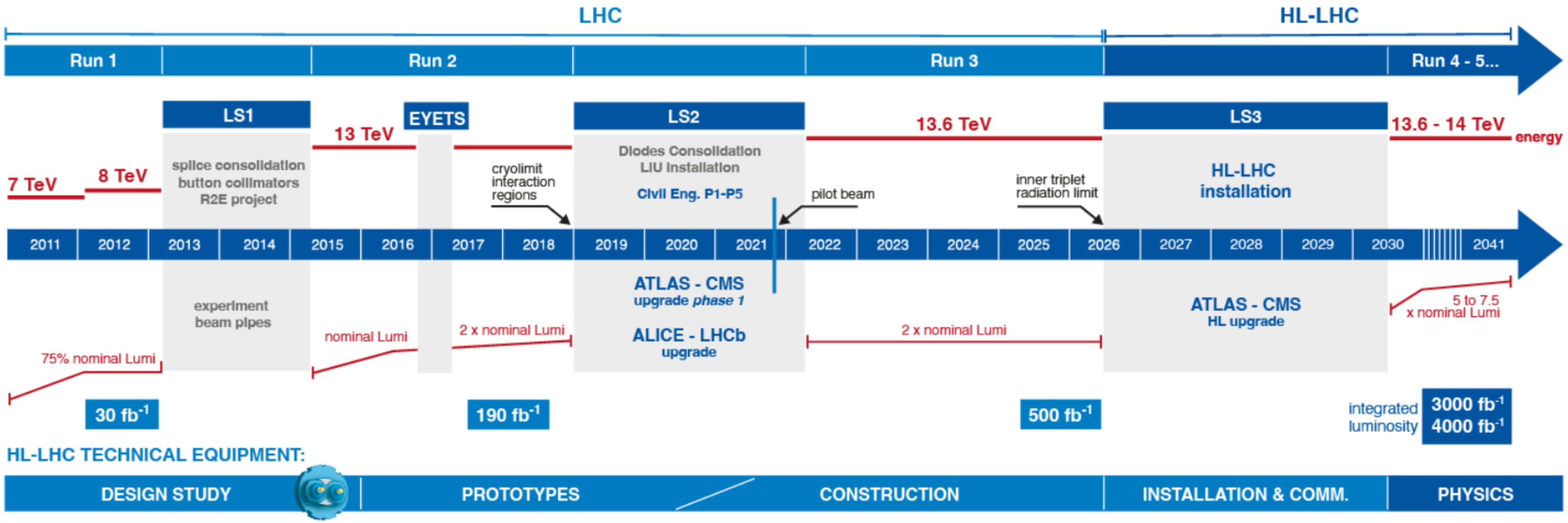




Limitations of the Standard Model

- The Standard Model is still not perfect
  - The nature of dark matter
  - The origin of neutrino mass
  - The matter-antimatter asymmetry problem
  - The mass hierarchies among the fermion generations
  - …
- Experiment directions
  - Precision SM Measurements: electroweak observables, Higgs couplings, rare decays…
  - Vector Boson Fusion (VBF)
  - Vector Boson Scattering (VBS)
  - BSM Phenomena Searches: SUSY, extra spatial dimensions, heavy resonance…

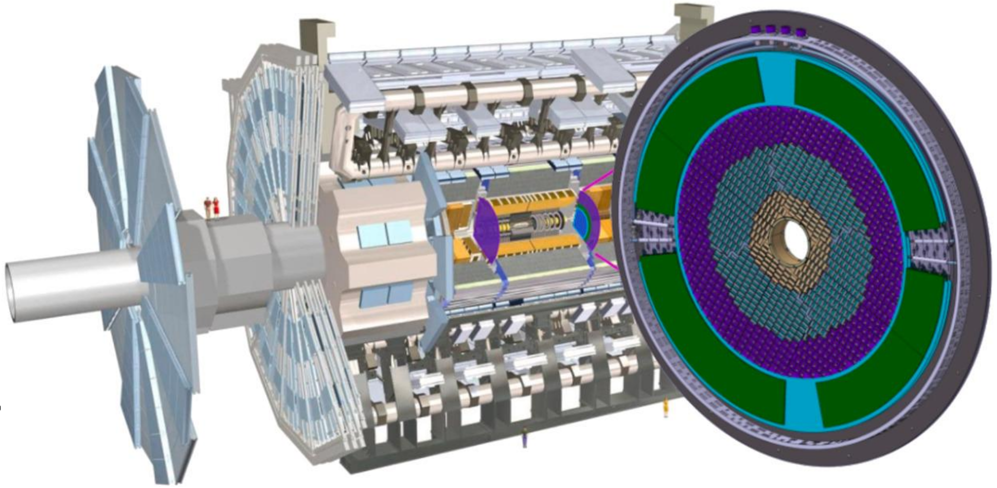
The High-Luminosity Upgrade of LHC

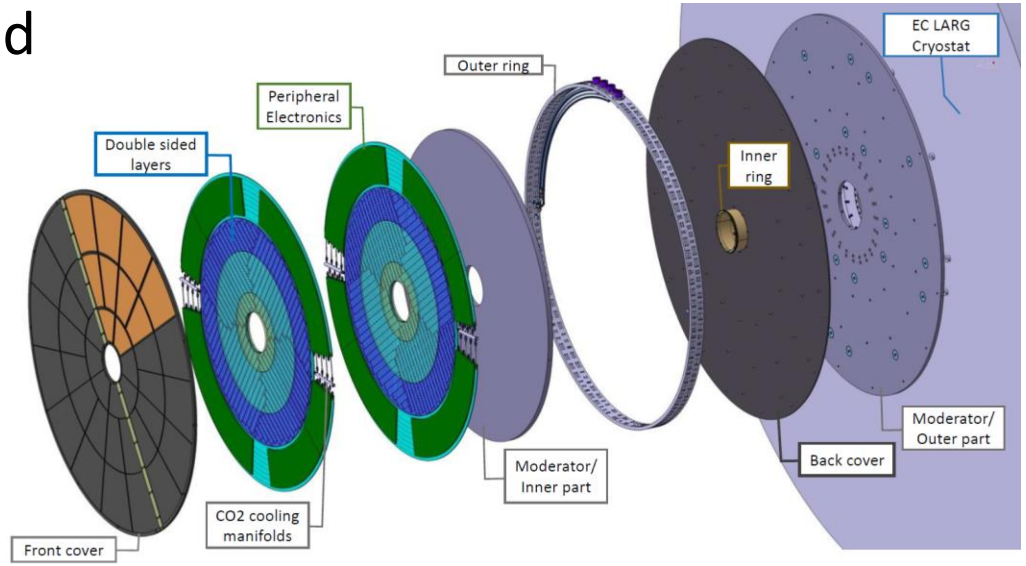


- To explore new physics and develop the SM, CERN plans to complete the HL-LHC upgrade by 2030:
  - Instantaneous luminosity will increase from 2.0 to 7.5 $\times\ 10^{34} s^{-1} cm^{-2}$
  - Average pile-up <μ> will increase from currently 40-50 to 140-200
- To allow the new operation environment, the ATLAS detector will undergo several upgrades:
  - A new all-silicon Inner Tracker (ITk) to replace Silicon Strip/Pixel Detectors
  - High Granularity Timing Detector (HGTD) to deal with pile up
  - New muon chambers: RPC (Resistive Plate Chamber), TGC (Thin-Gap Chamber)
  - Upgrades of the existing systems: Calorimeters, Trigger and DAQ, LUCID…

High Granularity Timing Detector (HGTD)

- Located in the forward region of the ATLAS detector (|η|>2.4)
- Based on Low Gain Avalanche Diode (LGAD) technology to achieve excellent time resolution (~30ps for single track)
- First time to apply LGAD in high energy collider detector system (together with MIP Timing Detector in CMS)
- Operated at -30°C to guarantee timing performance and reduce irradiation effect
- Chinese group makes the major contribution (led by IHEP)



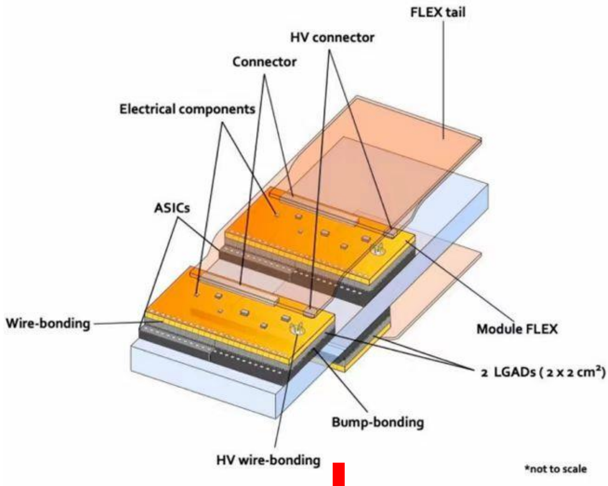


Physics Motivation of HGTD

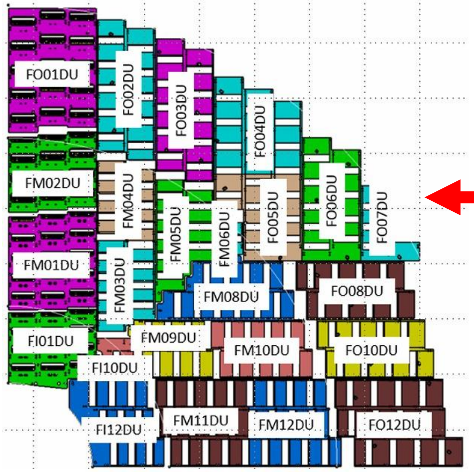
- Assigning Timing Information to Tracks
  - In forward region, ITk gives bad z_0 resolution for low p_T particles
  - Density of pileup vertices surpasses the spatial resolution in z_0 for low- p_T tracks (first time in hadron collider)
  - HGTD: Assign precise time stamps to forward tracks
  - Improve forward jets and leptons reconstruction, essential for processes like VBF and VBS
- Work as a Luminometer
  - Current luminometer LUCID-2 (upgrade for LUCID-3) faces challenges in high pileup conditions
  - High granularity ensures low occupancy per channel and linearity across the full range of luminosities
  - HGTD: Measure luminosity from mean hit count, complement LUCID-3
  - Enable precise cross-section measurement, essential for SM precision measurement and searches for BSM physics

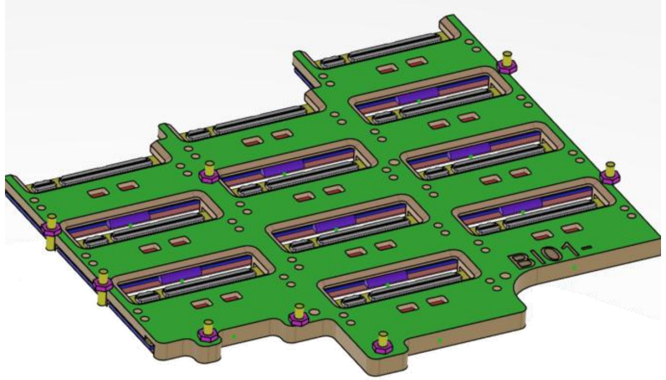
HGTD Module and Detector Unit

- Module
  - 2 readout ASICs (ALTIROC): signal amplification, discrimination, and timestamp recording
  - 2 LGAD sensors: active thickness of 50 µm, pixel size of 1.3×1.3 mm² in 15*15 array, developed by IHEP and IME
  - Interconnection Technology: Dedicated flip-chip bump bonding with tin-silver ($Sn_{3.5}Ag$) bumps
  - Flexible circuit board (module flex): Power supply, signal transmission, wire bonded to ASICs
  - Glue: Araldite 2011 for fixture of sensors to module flex



- Detector Unit
  - 2-15 modules arranged in certain ways
  - Glued to a Support Unit
  - 24 different types for a quarter of one side (24×4×2 in total)





Module Thermomechanical Challenges

- Temperature variation during HGTD operation

Operation temperature: -30℃ ↔ **Assembly temperature: room temperature**

- **Detector commissioning**
- **Module replacements**
- **Data-taking periods**
- **Power off**

- Experiment: thermal cycle, -45°C~40°C
- Target: survive 36 cycles (62 cycles for conservative estimation)
- Impact on modules

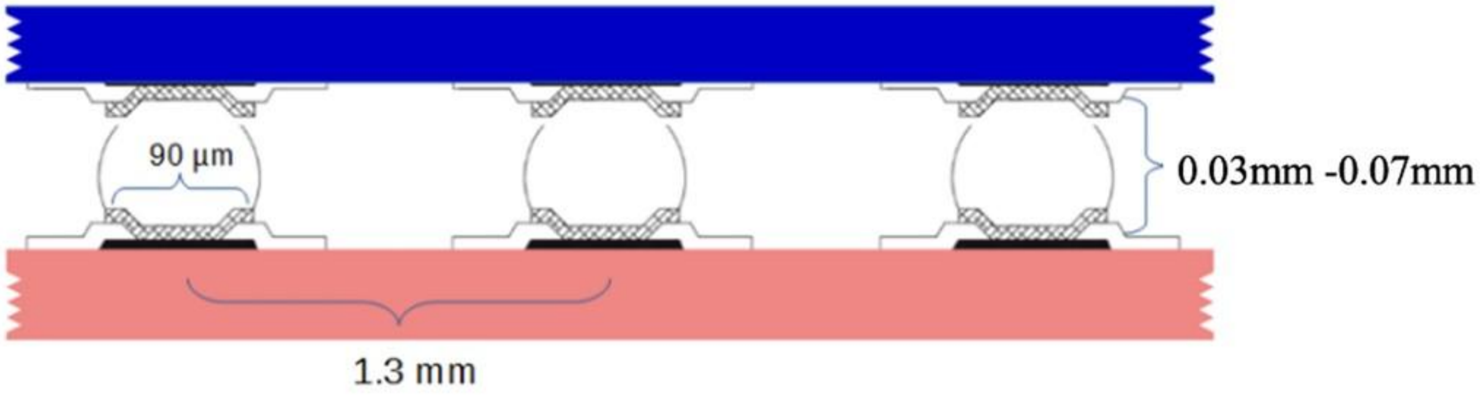
Coefficient of thermal expansion (CTE) mismatch in module components → Thermomechanical stresses accumulate in material interfaces → Cyclic fatigue failures

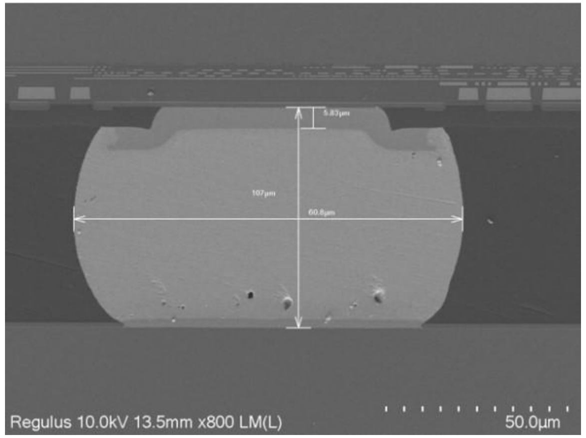
Bump Bonding in HGTD Modules

- Bump material: $Ag_{3.5}Sn$

	Conventional BGA Design	HGTD Module	Concern
Pitch(mm)	0.15-0.50	~1.3	Low I/O density
Bump Diameter (μm)	60-100	90	
P/D ratio	~2.5-5	14.4	Stress concentration

Significantly higher P/D ratio is subjected to more fragile bumps





Demand for Automated Integration

- 8032 modules need to be integrated into more than 800 Detector Units
- IHEP responsible for assembly of 34% of modules (2730 modules) and integration of Detector Units, in about 2 years
- Integration Challenges:
  - Positioning Accuracy Requirement: micron-level (affects geometric alignment)
  - Manual Assembly: Low accuracy, poor efficiency, and high risk of accidental damage

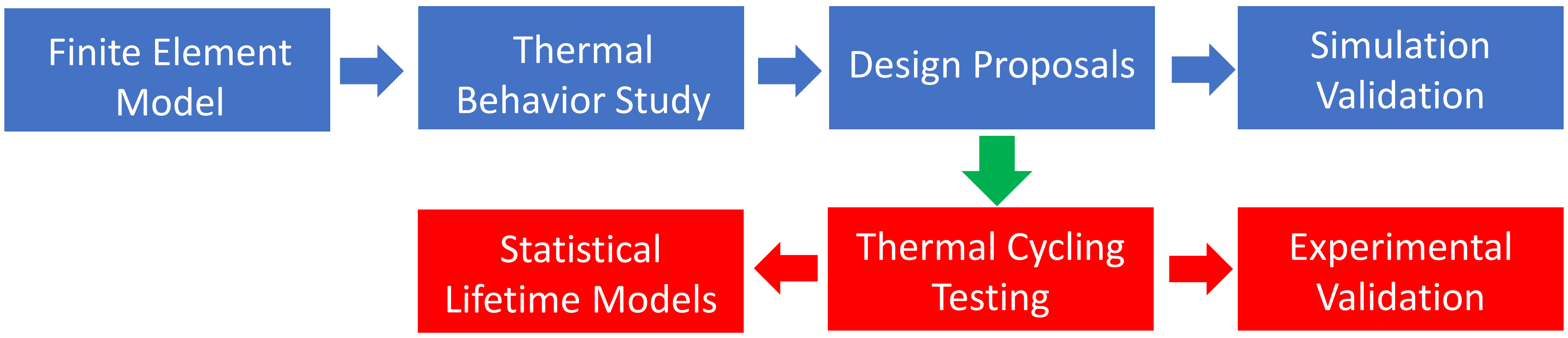
Thermal Reliability Analysis of HGTD Modules

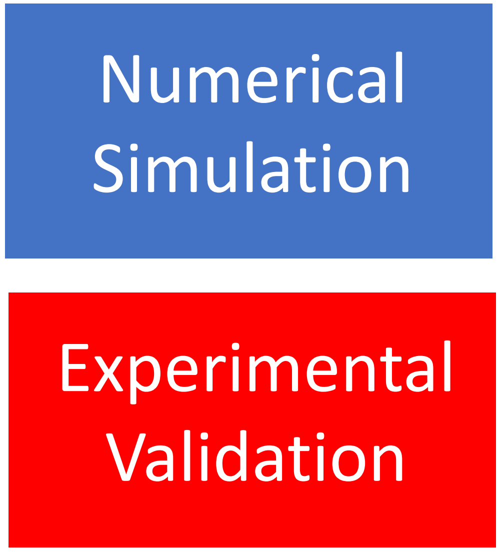
Motivation of the Analysis

- Peer experience of other projects
  - ATLAS ITk: Sensor fractures and bump disconnections observed during thermal cycling in the production phase
  - CMS Silicon Tracker: Experienced similar problem
- Experience in HGTD module R&D
  - Thermal cycling tests on prototype modules showed massive problems
  - Bump disconnection was identified as the major issue
  - Unable to meet HGTD project requirement
- Situation for HGTD project
  - Lack of testing samples in R&D phase
  - Limited time to move to production phase

Research Method

- Numerical Simulation + Experimental Validation
  - Establish a 3D finite element model (ANSYS Mechanical)
  - Simulate and analyze mechanical behavior under thermal load in one cycle
  - Model the module lifetime with mechanical results from simulation
  - Propose and simulate more robust module designs
  - Validate simulation predictions and optimization effects through thermal cycling tests
  - Establish statistical lifetime models



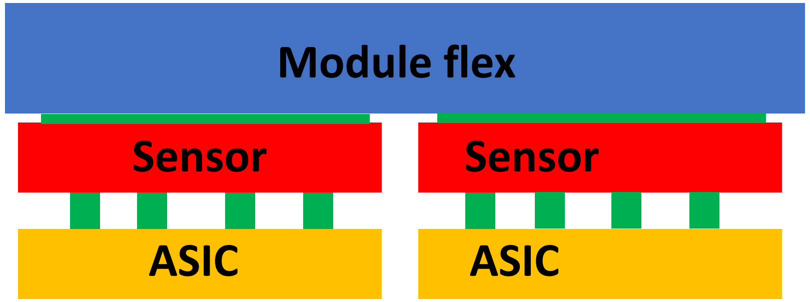


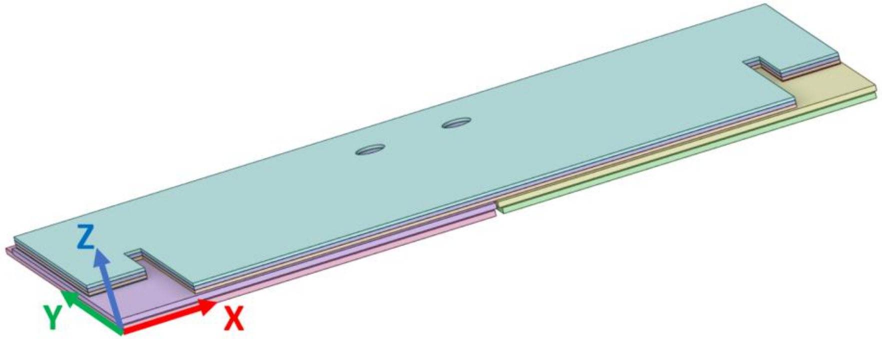
Details of Finite Element Model

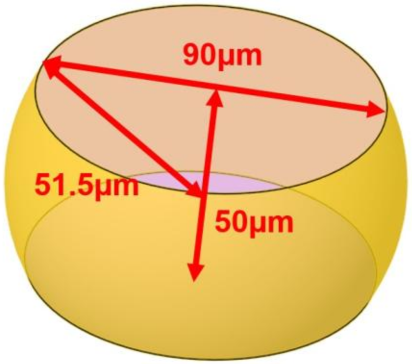
- Key components: sensors, bumps, ASICs, glue, module flex
- Apply reasonable approximation and simplification to cut computational cost
  - Module flex: "polyimide-copper-polyimide“ structure and ignore surface components
  - Generally apply linear elastic anisotropic (except silicon) material properties
  - Use Anand viscoplastic model to model temperature-dependent behaviors of $Sn_{3.5}Ag$
  - Approximation in temperature settings of thermal cycle
  - Neglect gravity
- Local mesh refinement on the bumps (80-90 elements per bump)
- Bounded contact between different layers
- One vertex fixed to prevent rigid body motion

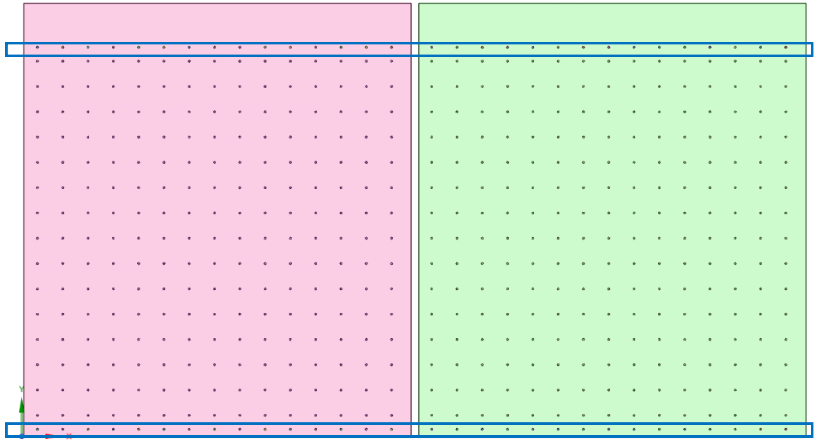
Module Layout in Simulation

	Material	Thickness (µm)
ASIC	Silicon	300
Bump	$Ag_{3.5}Sn$	50
Sensor	Silicon	300
Glue	Epoxy resin	50±30
Module flex layer1	Polyimide (Kapton)	175
Module flex layer2	Copper	200
Module flex layer3	Polyimide (Kapton)	175



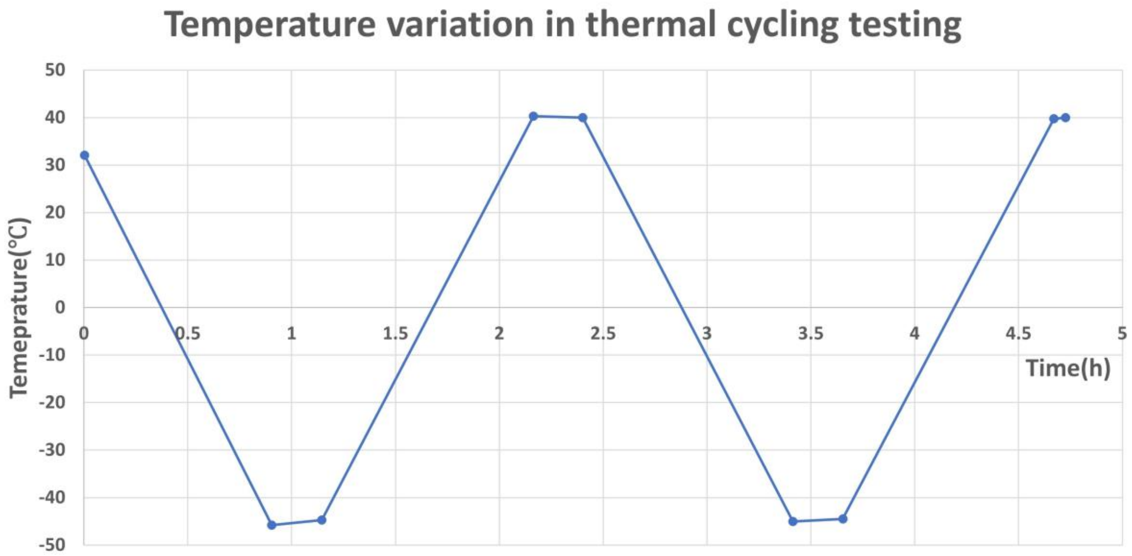


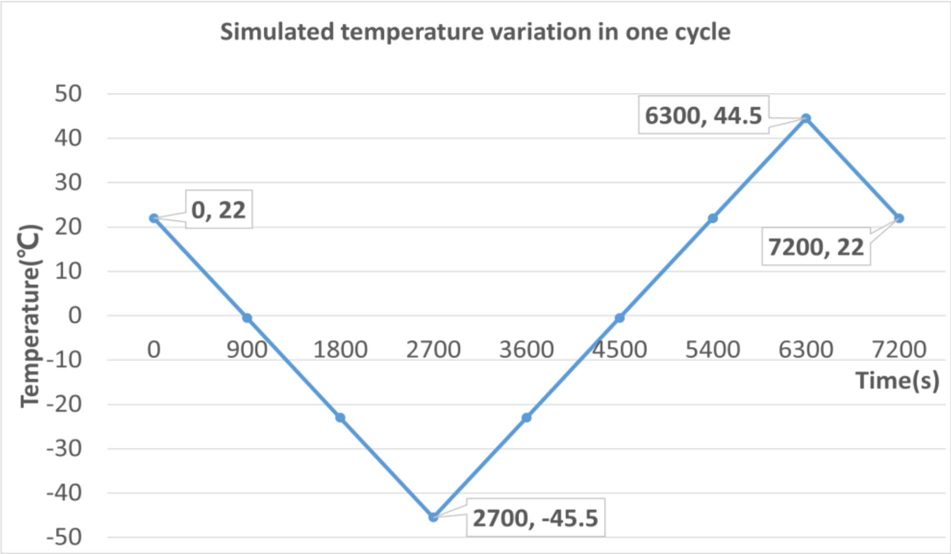




15×15 bumps on LGAD pads + 15×2 bumps on top/bottom edge (guard ring)

Load of Thermal Cycle Conditions





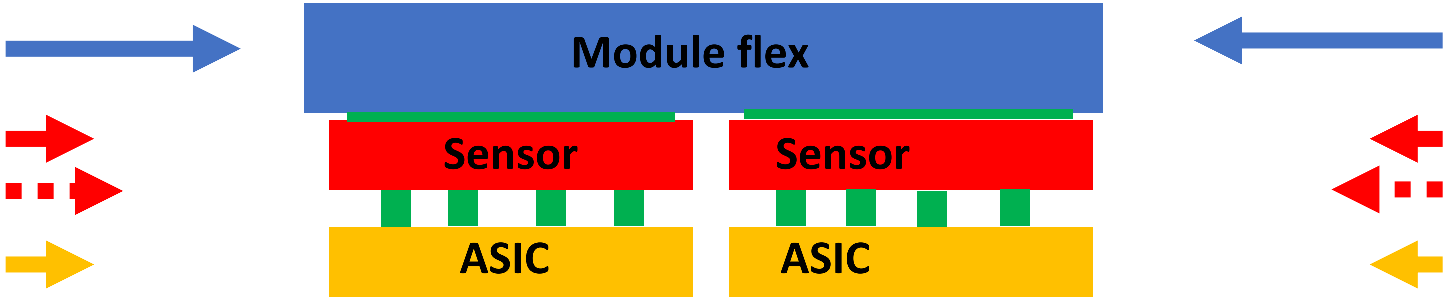
- Testing: 2.5h, -45℃~40 ℃, about 15mins at peak temperatures
- Simulated: 2h, -45.5℃~44.5 ℃, no peak holding time, 24 load steps
- Temperature load directly apply to the full model (temperature change slow enough)
- HGTD operation time=36 (62) cycles, leave enough safety margin

Lifetime Prediction Model for Bumps

Modified Coffin-Manson equation: $N_f = \frac{1}{2}\left(\frac{\Delta\epsilon}{2\epsilon_f'}\right)^{1/c}$

- Commonly used in estimating solder joint reliability within certain temperature range (including **ITk pixel module simulation**)
- Parameter explanation:
  - N_f: average lifetime (50% probability failure, unit in cycles)
  - $\frac{\Delta\epsilon}{2}$: cyclic strain amplitude/ half maximum total mechanical strain in one cycle
  - $\epsilon_f' = 0.325$, fatigue ductility coefficient
  - c: fatigue ductility exponent, relative to thermal cycle setup:
    - $c = -0.442 - 6 \times 10^{-4}\bar{T} + 1.74 \times 10^{-2}\ln(1+f)$
    - $\bar{T}$: average solder temperature in one cycle, -0.5℃ in the setup
    - f: frequency of thermal cycle, in unit cycles/day, 12 in the setup
    - ➢ c=-0.3971
- Set up the relationship between lifetime (prediction) and mechanical strain (simulation result)
- **Use the minimum N_f among all LGAD pad bumps to represent the N_f of the hybrid/module**

Module Thermomechanical Behavior



CTE (ppm/℃)

Copper: 18

Polyimide: 20

Silicon: 2.6

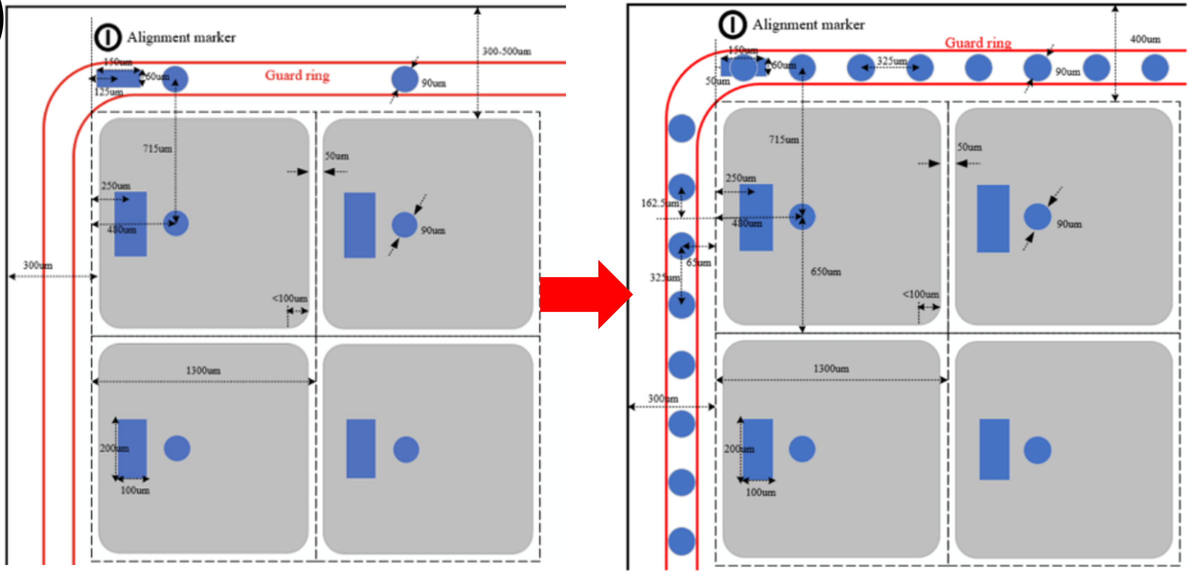
Silicon: 2.6

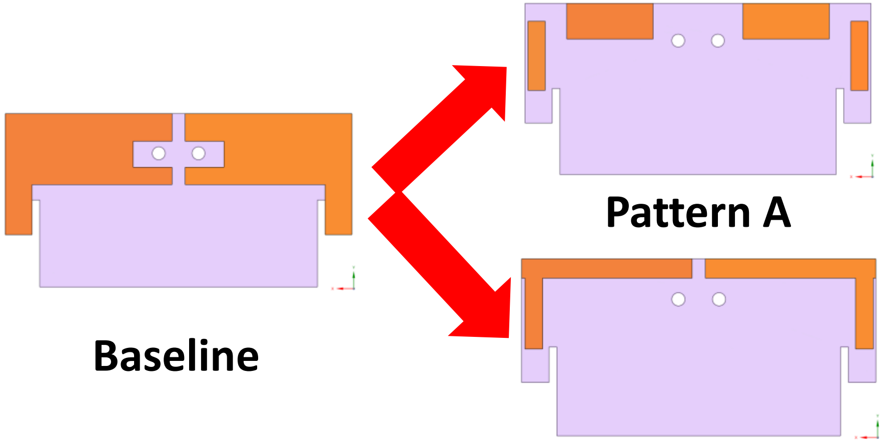
- Origin of shear stress on solder bumps
  - Deformation differs in layers due to different CTEs (represented by arrow length)
  - Bump dimension is small and deformation is negligible
  - Major deformation from module flex passes through sensors to bump upper surfaces
  - Bumps at the corner are under larger stress (far from center leads to larger deformation)
- Possible solutions
  - Thicker sensor (reduce deformation passed from module flex)
  - More bumps (separate stress)
  - Reduce glue coverage (create stress relief regions)
  - Change smaller CTE module flex materials (reduce module flex deformation)

Proposed Design Improvement

- Thick sensor: 300 µm→775 µm (full wafer)
- More bumps: 15×15+15×2 → 15×15+60×4
  - Maintain bumps on LGAD pads
  - Add more bumps on the guard ring
- Optimization of glue pattern:
  - Reduce glue usage
  - Guarantee glue coverage in critical areas:
    - Top edge to support wire bonding
    - Wings part to ensure flatness and fixture into detector
- Alternative module flex materials:

  Copper + Polyimide → Tungsten + Ceramic





Baseline

Pattern A

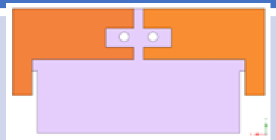
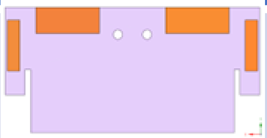
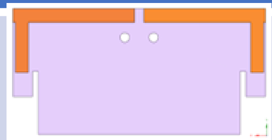
Pattern B

Simulation Validation of Proposals

	Thin, fewer	Thick, fewer	Thin, more	Thick, more
Sensor thickness /μm	300	775	300	775
Number of bumps per hybrid	255	255	465	465
Average lifetime /cycles	16	119	108	393

- Both thick sensor and more bumps help increase module lifetime
- Both thin and thick sensor modules with no additional bumps were produced and tested:
  - Thin sensor modules were the initial version that showed problems
  - Thick sensor modules were the first attempt for improvement
- Modules with thick sensor and additional bumps will be used for production

Simulation Validation of Proposals

	No glue (hybrid)	Baseline	Pattern A	Pattern B
Glue pattern				
Average lifetime /cycles	1240749	393	3029	566
Glue weight /mg	0	18.8	6.6	6.7

- Pattern A shows the longest lifetime, and will be applied for production
- Several modules were produced and tested with this pattern and thick sensor, additional bumps

	Baseline	New proposal
Middle layer material	Copper	Tungsten
Outer layer material	Polyimide	Ceramic
Lifetime /cycles	393	31565

- Match of tungsten and ceramic module flex shows significantly increased lifetime
  - Approximately 10 times cost
  - Technically unfeasible to achieve original thickness (need more space)
  - Lifetime far exceeds HGTD operation span (over-specification)
  - Reserved as a backup plan if necessary

Strategy of Thermal Cycling Testing

- Samples:
  - Several prototype modules with 300 µm sensors (without additional guard ring bumps, predicted average lifetime 16 cycles)
  - More than 20 modules with 775 µm sensors (without additional guard ring bumps, predicted average lifetime 119 cycles)
  - 4 modules with 775 µm sensors, additional guard ring bumps, new glue pattern (predicted average lifetime 3029 cycles)
- Test Process:
  - Modules fixed in protection boxes placed in environment chamber
  - Perform electronic tests at room temperature after every 15/30 cycles
    - Threshold voltage scan with different charges (36 DAC/12 DAC)
    - Radiation source scan
  - **Failure Criterion: A module/hybrid is considered failed if any bump disconnection occurs**

Testing Results and Simulation Validation

- Original 300 µm sensor: Massive failures occurred within 10-20 cycles, consistent with the simulation prediction (16 cycles)
- Improved 775 µm sensor (119 cycles):
  - To achieve more statistics, the results are analyzed as individual hybrids instead of modules (46 hybrids)
  - No failures occurred before 30 cycles
  - Most hybrids didn’t fail till the last cycle done, and they were assumed to “fail” at the last cycle done

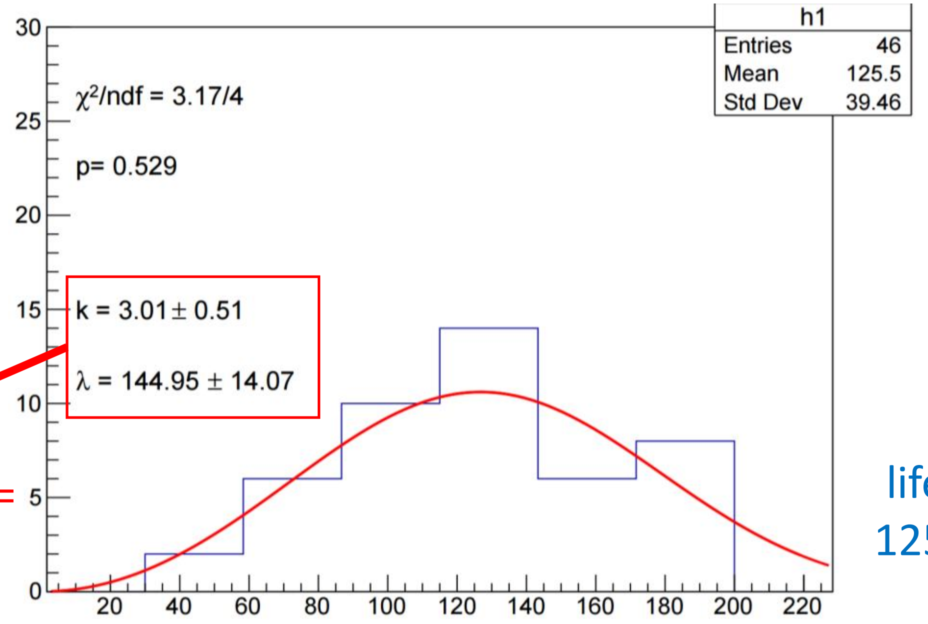
Cycles	0-30	30-60	60-120	>120
Number of hybrids	**0**	**2**	**16**	**28**

  - Failed bumps were observed in the **corner areas**, matching the stress concentration areas identified by simulation
- Production version modules (3029 cycles) : no failures before 120 cycles out of 7 hybrids

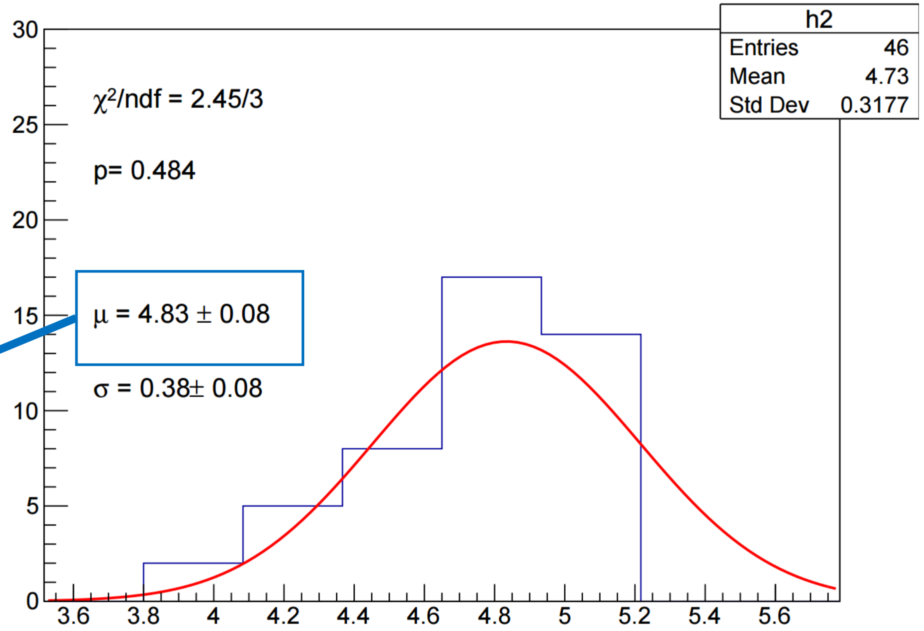
Establishment of Statistical Lifetime Model

- Data Processing Assumptions
  - Failed Samples: Lifetime is the average of "last cycle without failure" and "first cycle with failure"
  - Non-Failed Samples: Conservatively take the "maximum number of test cycles" (right-censored data)
- Statistical Models:
  - Weibull Distribution (left): $f(x,\lambda,k) = \frac{k}{\lambda}(\frac{x}{\lambda})^{k-1}e^{-(\frac{x}{\lambda})^k}$
  - Lognormal Distribution (right): $f(\mathrm{x},\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}}e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}$

Average lifetime=$\lambda\Gamma\left(1+\frac{1}{k}\right)$ = 129±13 cycles

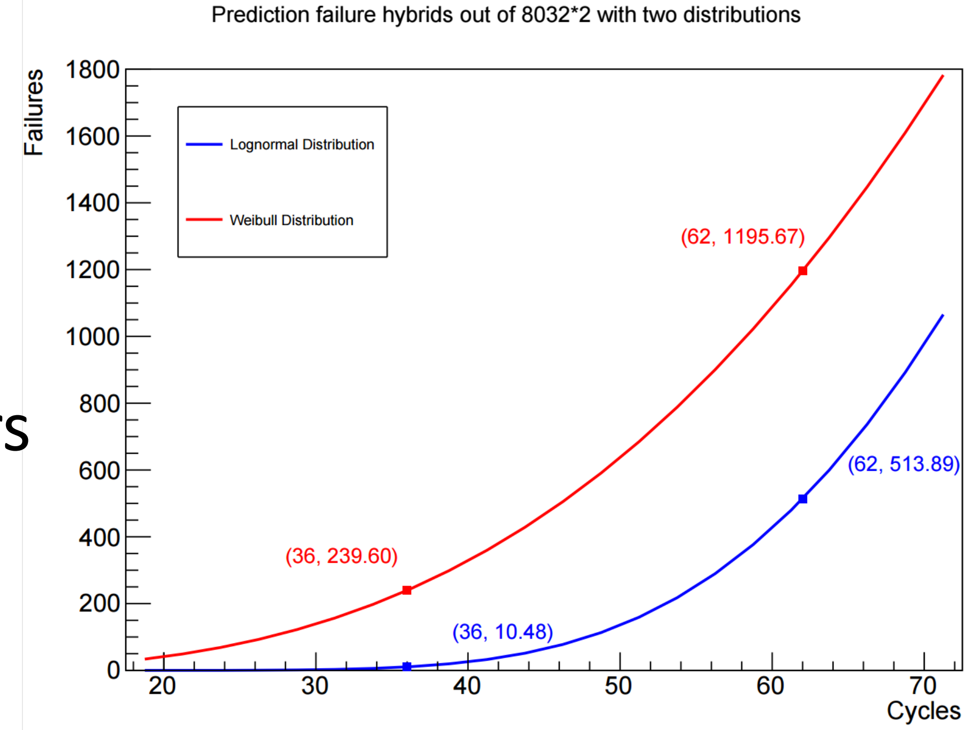


Average lifetime=e^{μ}= 125±10 cycles



Lifetime Prediction Results

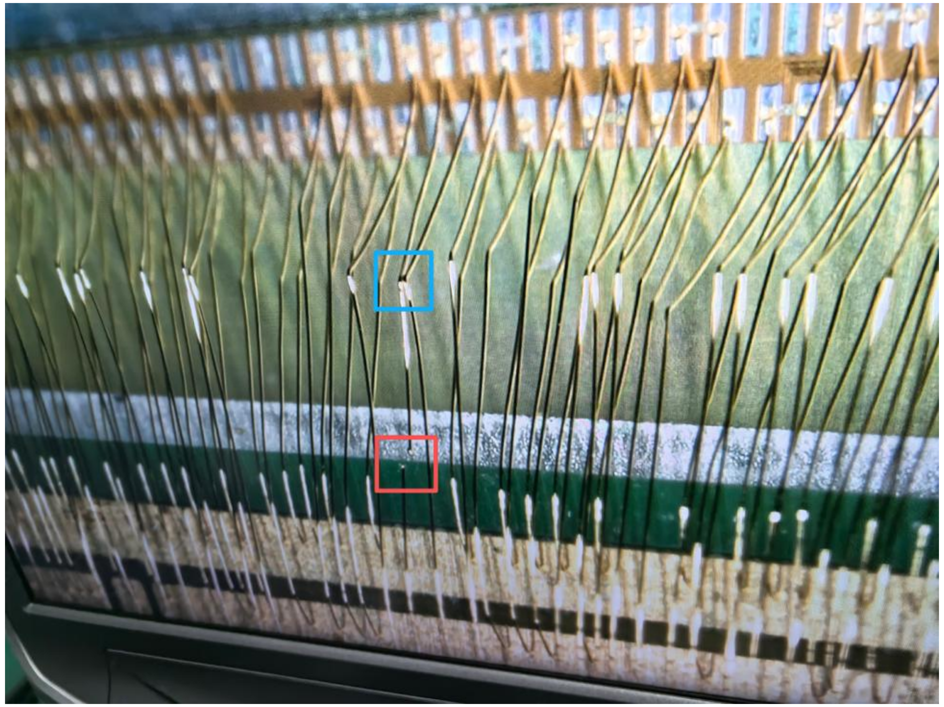
- HGTD Lifetime Requirement: 36 (62) cycles
- Only a very small number of modules will fail during their lifetime, and failures only involve individual bumps, meeting project requirements
- Prediction is based on modules with thick sensors but no additional guard ring bumps and glue pattern optimization



Even if there are 1196 (240) failure hybrids, actual failure ratio in pad is:
1196/(8032*2*225)=0.03%
240/(8032*2*225)=0.007%

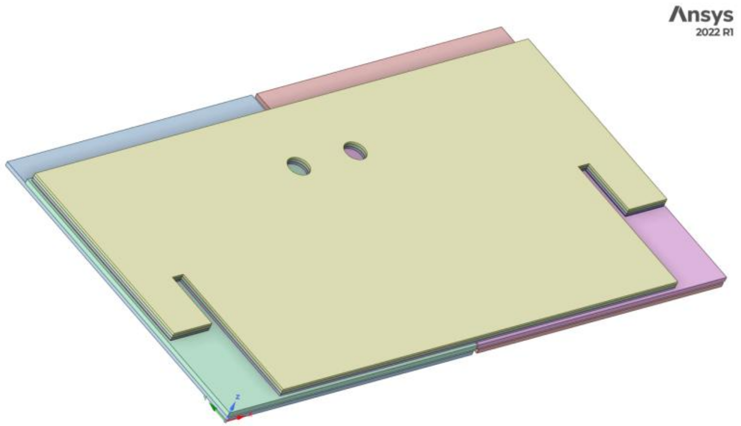
Testing of Production Modules

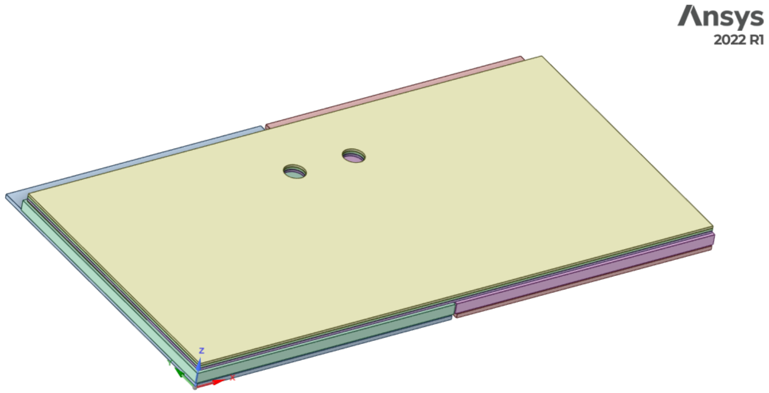
- 4 modules were produced and tested (7 hybrids)
  - **Thick sensors, additional guard ring bumps, optimized glue pattern (3029 cycles)**
  - 1 failed at 150 cycles, 4 failed at 180 cycles, 2 completed 210 cycles
  - All failures are caused by wire bonds touching:
    - Different failure mode from the study in the thesis
    - 2 modules (4 hybrids) recovered after re-wirebonding
    - 1 module (2 hybrids) still not functional, probably ASIC failure



- Statistical model
  - Average lifetime: 201 (lognormal) /210 (Weibull)
  - Failure hybrids out of 8032*2:
    - At 36 cycles: 0/0
    - At 62 cycles: 0/0
- Better than modules with only thick sensors

Module Flex Shape





Lifetime: **393** **102**

$k = 3.01 \pm 0.51$

$\lambda = 144.95 \pm 14.07$

- A rectangle module flex is easier for man is weaker in thermal cycle (denied)

Glue thickness /μm	20	50	80
Average lifetime /cycles	535	393	378

- Module with thinner glue can live a little longer
- Glue thickness within specification (20-80 μm) does not make too much difference in lifetime

Glue Thickness

- Glue thickness in specification: 50±30 μm

Glue thickness /μm	20	50	80
Average lifetime /cycles	535	393	378

- Module with thinner glue can live a little longer
- Glue thickness within specification (20-80 μm) does not make too much difference in lifetime

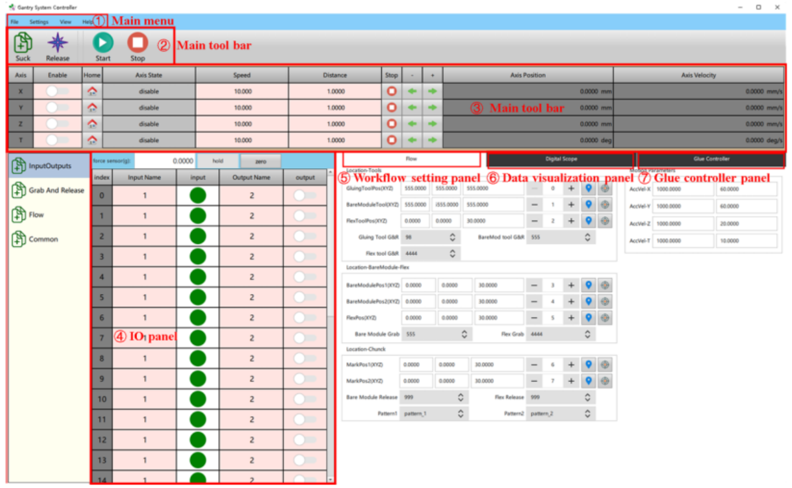
Summary of Thermal Reliability Analysis

- Studied the causes of bump failure through FEM simulation
- Proposed module designs:
  - 775 μm sensor
  - 240 guard ring bumps
  - Optimized glue pattern
  - Alternative module flex materials (backup)
- Experimental validation:
  - Thermal cycling experiments verified optimization effects
  - Simulation precision was validated
  - Weibull/lognormal models realized lifetime prediction
- Conclusion: With the combined strategies, modules are estimated to fully survive the HGTD lifetime

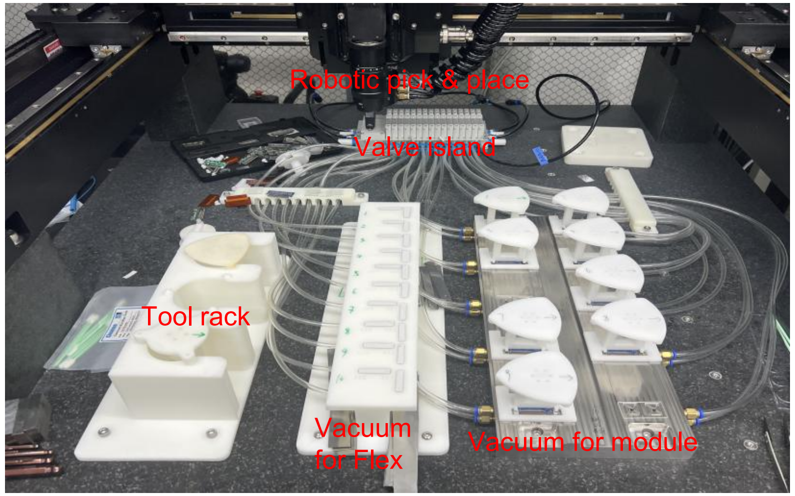
Development of High-precision Detector Unit Loading System

The Gantry System at IHEP

- Basis: gantry system at IHEP
  - Coretech gantry positioning system (repositioning resolution $\sim 1\ \mu m$)
  - Keyence vision system
  - Nordson EFD Glue Dispensing controller
  - Air pressure piping system
  - Custom picking and gluing tools
  - Open-source C++ Qt program with QML GUI to control the system
- Develop new detector unit loading function
  - Design 3D-printed tools for picking up modules
  - Design metal vacuum chuck for placing modules
  - Develop procedures to load detector units
  - Add new GUI for detector unit loading into gantry control software



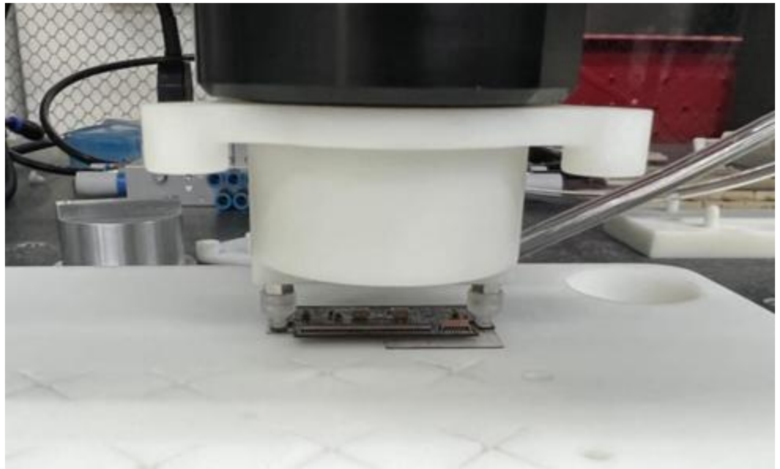
GUI of gantry control software



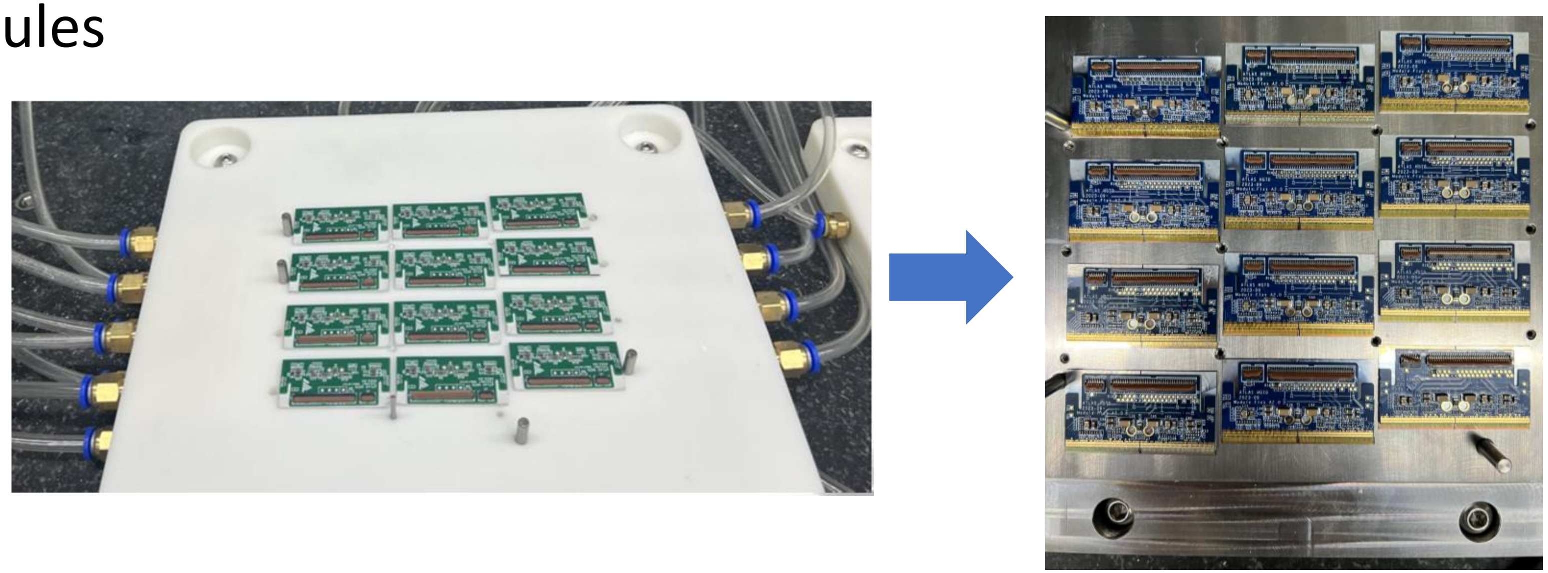
Gantry system for module assembly

Tools for Loading

- Mostly same tools as used for module assembly
- Vacuum chuck for placing modules (3D-printed initially, metal now)
- New tooling for picking up modules



New tooling used in DU loading for picking up modules, soft contact part for protecting modules



Left: 3D-printed vacuum chuck, cheaper but not flat enough for all modules and vacuum

Right: metal vacuum chuck, better flatness and more expensive

Detector Unit Loading Procedure

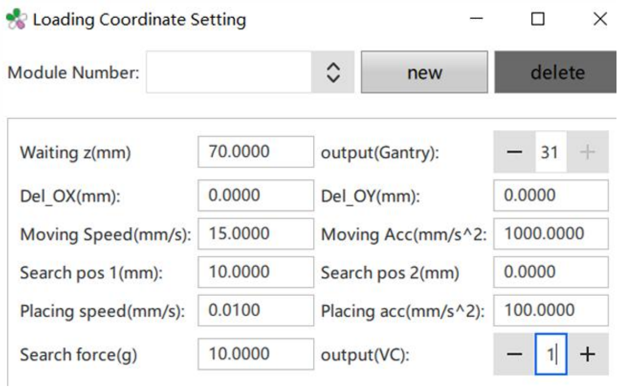
- Follow HGTD loading specification
- Main procedures:

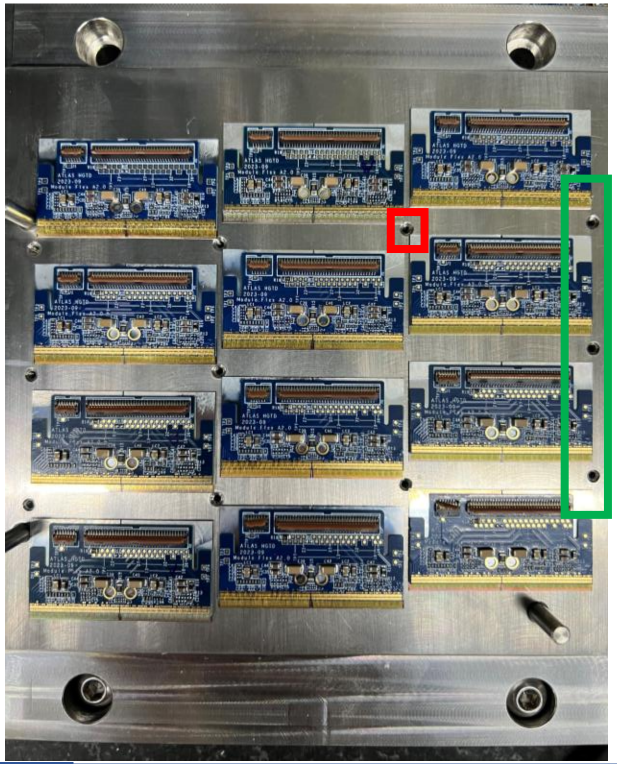
Module placement → Glue dispensing → Support unit loading

- Preparations: glue Araldite 2011, vacuum chuck, support unit, modules, different types of screws, position pins, handle, travel packaging, torque wrench

Module Placement

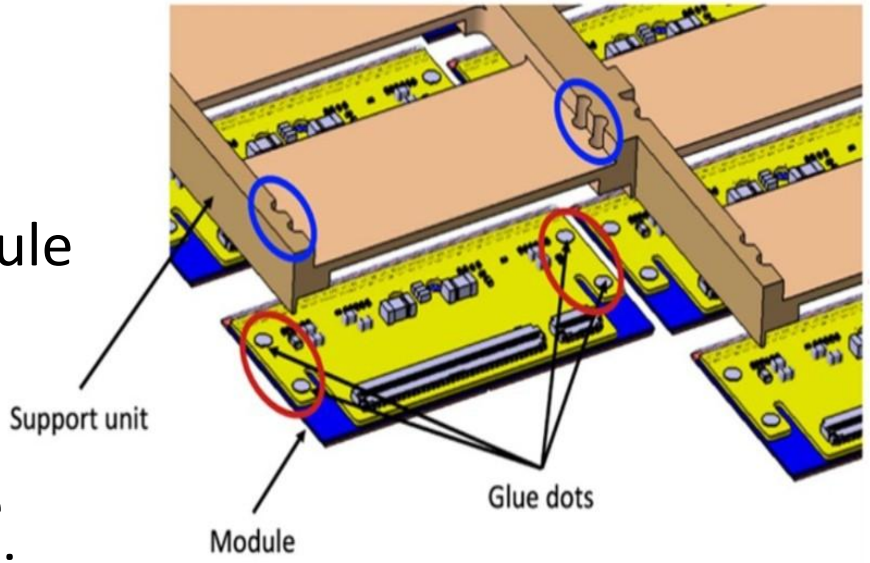
- Calculate module positions with CAD file of SU and modules
- Input module position information into gantry control software
- Fix vacuum chuck with screws and recognize its position:
  - Recognize origin point for reference position of modules
  - Recognize 3 benchmark points for calibration of vacuum chuck position (through calculating rotation of the vacuum chuck)
- Place modules:
  - Take modules out of protection boxes and put on vacuum chuck
  - Turn on vacuums to fix modules
  - Recognize module position with two high voltages
- Move modules to their correct positions:
  - Pick up tooling for picking up modules
  - Other work can be done by clicking on the buttons on control GUI





Glue Dispensing

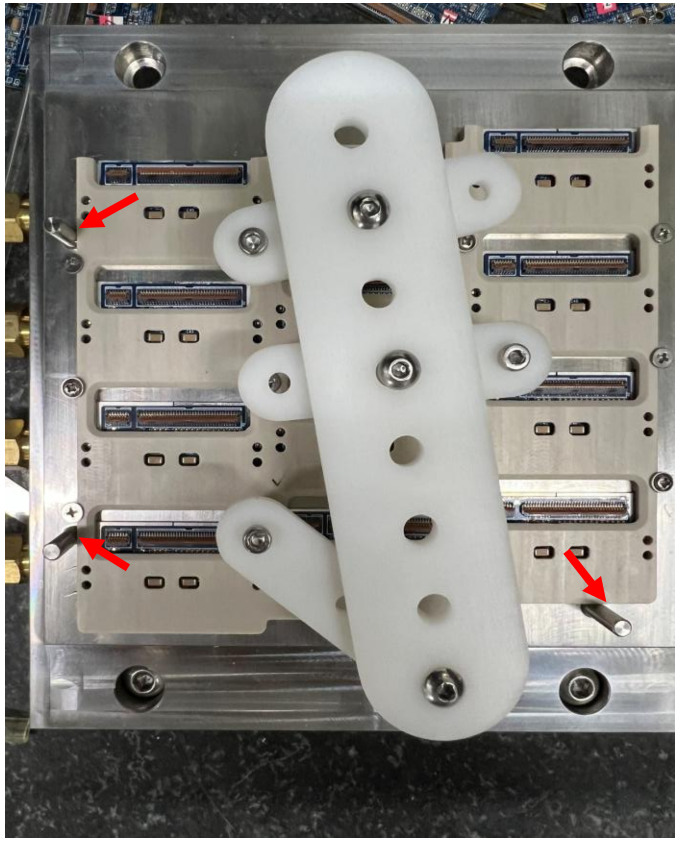
- Prepare the glue
- Get the gluing height:
  - Run the “touchdown” function in gantry control software
  - The program will return a height of needle contacting module
  - Calculate glue dispensing height
- Calibration for needle position:
  - Dispense glue at a known position and input the difference between the real glue position and the expected glue position into the panel
  - The glue position will be automatically corrected afterwards
- Dispense glue:
  - Dispense 4 glue dots in red circles
  - Glue dots allow reliable fixture and feasibility to remove modules

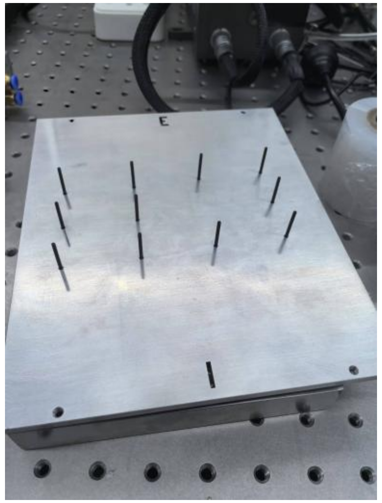


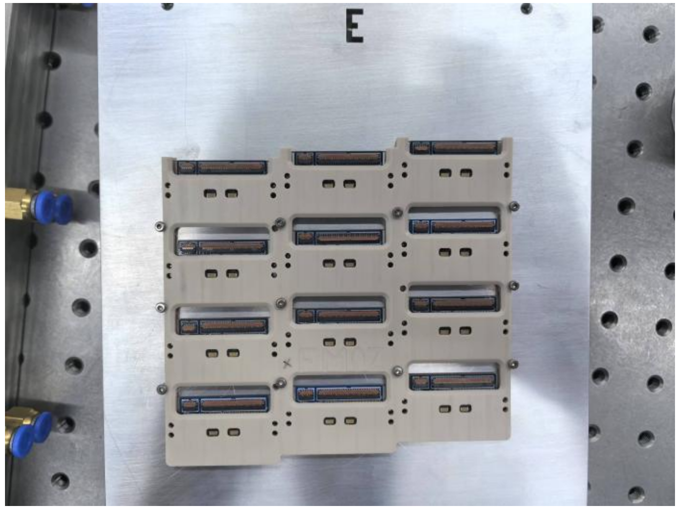
Support Unit Loading

- Put on screws for handle fixture
- Align support unit to the 3 position pins from top
- Move support unit down carefully until contacting
- Fix support unit onto the vacuum chuck with screws
- Wait for glue dry
- Remove screws and pins, turn off the vacuum and pick up the DU
- Fix DU to travelling package and remove handle

*Use torque wrench to control the torque applied to screws=0.05N·m

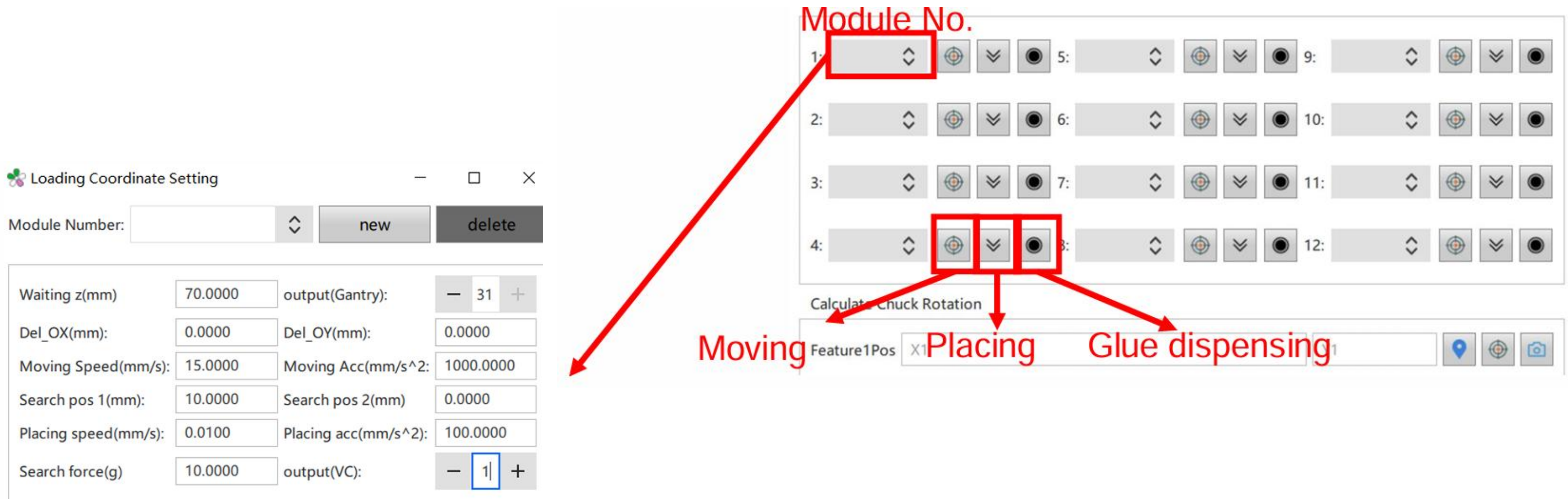






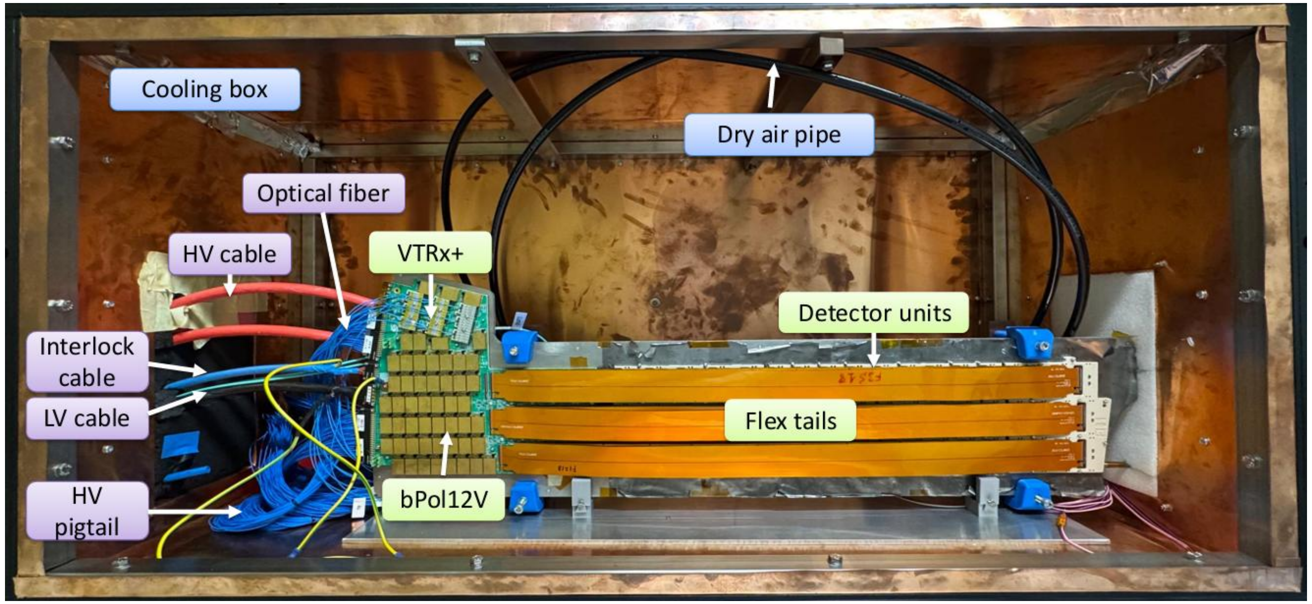
Loading Different Types of Detector Units

- Corresponding vacuum chucks and handles are designed
- Module position array is calculated according to the DU CAD file
- Gantry control software allows a maximum size of module numbers for recording position data and operation



Summary for Detector Unit Loading

- Developed Detector Unit loading at IHEP using gantry system based on the experience of module assembly with the same system
- The developed system was tested on loading 2 different types of DU successfully: FM02DU and FO01DU
- These Detector Units were sent to CERN to work for a demonstrator program to verify the feasibility of HGTD and identify potential issues



Summary and Outlook

- Achievements
  - Proposed improved module designs to survive entire HGTD operation span
  - Developed and tested Detector Unit loading with gantry system
- Outlook
  - Module Optimization:
    - Batch test the production version modules and investigate the wire bonding problems
    - Expand the model to include radiation damage effects
  - Automation Upgrade:
    - Introduce machine learning vision algorithms to improve positioning efficiency
    - Further improve automation and mitigate personal operation
  - Technology Application:
    - Apply to future collider detectors (e.g., FCC, CEPC)
    - Extend to designs of precision electronic equipment

Answers to the Comments

- **盲审老师1**

（1）实验规模局限：热循环样本仅20+模块，建议补充批量生产数据

大规模生产尚未开始，计划于2026年中启动。不过，预生产阶段刚刚启动，首批模块已于最近几周交付。我们对前四个模块进行了热循环测试。相关数据和统计分析已纳入论文最新版本，并已在答辩中进行展示。

这些包含本论文所提全部改进的新型模块，正如先前模拟所预测的那样，展现出更高的稳健性。它们承受的热循环次数至少增加了50%。基于这些数据，预计HGTD模块的使用寿命将较之前显著延长，且在HGTD项目寿命周期内不会出现模块故障。

（2）辐射效应缺失：未评估辐照损伤对热机械性能的影响（HGTD面临$5.6\times10^{15} n_{eq}/cm^2$注量）

论文前一版本中的最大注量数值存在误导性，因其未考虑HGTD运行期间模块更换的因素。修正后，HGTD模块仅需承受$2.5\times10^{15} n_{eq}/cm^2$的注量。对辐照性能的评估在仿真层面较难进行，在强辐照环境下所有材料都将不能简单当作线性弹性材料对待，这会带来巨大的计算成本，且其相关机械属性数据需要由实验给出，现有条件下很难获得。一般来说，在强辐照下材料的缺陷带来的空洞会增加其对温度的响应从而增加CTE，刚度变化与材料有关，杨氏模量变化一般较小，但材料屈服强度会降低，且韧性和塑性也会变差，即辐照硬化和脆化。对此的解决措施是尽可能在现有条件下提高模块的寿命，以留出足够的安全边际应对辐照损伤带来的影响。为通过实验评估辐射效应，需在热循环测试前将模块置于反应堆中进行辐照。此类测试将极为耗时，因为模块中的金属含量需要长达六个月以上的冷却周期。这意味着在达到等效热循环次数的辐照后进行渐进式测试不具备可行性。虽可在完成最大剂量辐照后实施测试，但其所需时间仍远超过本论文研究周期，且仅能针对少量模块进行。目前确已计划在后续阶段开展此类小规模测试。

（3）成本分析不足：钨合金模块基板可使寿命提升但成本增10倍，需补充性价比论证

本论文提出的解决方案，尤其是更新的新测试结果证明了已能够完全满足HGTD探测器在整个运行周期内对模块稳定性和耐久性的要求。

钨合金方案带来的使用寿命提升远超实际所需的耐用性标准，导致出现超规格设计，而其实际效益有限。此外，该方案因厚度增加需要占用更多空间，且成本更高。因此，该方案不被视为优选解决方案。

Answers to the Comments

- 盲审老师2

（1）建议适当精简摘要部分的内容；

国科大对用英文写作的学位论文摘要中文字数有要求（5000字），所以不能精简摘要部分。

（2）论文中所有引用的图片和数值结果应标明具体出处；

已标明图片和表格的出处。

（3）建议在第二章和第三章末尾也加上一节Summary.

已在第二章末加了的summary，第三章由于和第四章是同一研究的两个相关部分，所以其总结与第四章写在一起。

Answers to the Comments

- 史欣老师

（1） ATLAS 内追踪器 -> ATLAS 内径迹探测器，CMS 硅追踪器 -> CMS 硅径迹探测器

已修改。

（2）It is a preliminary attempt for the LGAD -> It is the first attempt …

已修改。

（3）guiding both gantry-based and jig-assisted assembly methodologies. -> how to guide the jig-assisted assembly method is not evident, please elucidate with one or more sentences.

新增一句相关描述：Gantry-based loading can be done with similar procedures, while the potential problems during loading done with jigs are also comparable.

Answers to the Comments

- 梁志均老师

（1）论文对该工作的创新性，与意义和影响力描述偏少。建议进一步提炼创新性。

在总结章节补充了部分关于工作影响力，意义和创新性的描述。

(1). Through the combined numerical simulation and experimental testing, the module quality witnessed a significant improvement from not reaching HGTD project requirement to meeting the requirement with several times of safety margin. The implemented design optimizations effectively mitigated the bump bonding thermal reliability issue before starting production, thereby preventing potential project delays and financial waste.

(2). This is the first attempt in the HGTD project to load the detector units with gantry system, which provides valuable experience for future production.

（2）论文把HGTD探测器的封装与BGA封装进行对比。鉴于两者在互连层级、几何尺度、材料与热-机械边界条件及失效机理上存在显著差异，直接类比参考意义有限，建议弱化 BGA 对比。

进行对比主要是基于二者都是倒装焊封装，BGA是其中最常见也最成熟的技术之一，而HGTD使用的是较为先进的技术，能够实现不常用的芯片对芯片互联且保证较好的性能。焊球在几何尺度及排布方式上的区别也是论文讨论研究的核心挑战之一。在论文描述中明确了BGA和HGTD使用的技术同属于倒装焊的范畴，是并列关系，HGTD使用的技术能够实现芯片对芯片互联。

Answers to the Comments

- 张华桥老师

1: Have multiple connection for one HGTD pad could enlarge both the strength and reliability. Even it is not feasible for current sensor design, but it should be considered in your study to figure out which way is best for future.

提到的使用多个凸点连接单个pad的方案在HGTD项目中已被提出和讨论，最终没有被采纳，因而没有被作为论文正文讨论。虽然增加凸点数量可以提高热稳定性，但会由于并联电容造成电容激增而影响时间测量分辨。若减小单个凸点的电容以减少该影响，则需要显著减小凸点尺寸，但这会大大增加放电的出现。因此该方案并不适合HGTD，不能作为优化方案。

2: What thermal reliability changes if you change the thickness of polyimide or Cu layer for the module Flex?

使用更厚的任一材料均会带来更高的结构刚度从而放大其热胀冷缩下应力对其他结构的影响，从而缩短模块的寿命。实际上当前所制造的module flex已经做到了工艺能实现的最薄厚度，因而通过改变module flex厚度来优化设计的方案不可行。

3: Fig 4-6: it is really worrying that thermal cycling ~50 times will damage up to 10% of HGTD module, could you explain the strategy of ensuring the success of the HGTD running?

论文初始版本的评估指出：当我们进行62次热循环后，最多会有7.5%的混合模块出现1个受损焊盘。考虑到每个混合模块包含225个焊盘，这相当于在HGTD寿命周期结束时仅有0.03%的焊盘受损。该数值远低于硅基器件在寿命末期因所有因素共同作用所预期产生的常规失效概率。

此外，论文中新增的基于预生产模块的最新研究表明（这些模块已包含本论文提出的所有改进措施），热循环导致损坏的可能性已显著降低。目前预计在HGTD整个运行寿命期间不会发生此类损坏事件。

Answers to the Comments

- 张华桥老师

4: adding statistical positioning results of the produced HGCal modules will help a lot to understand the performance of your design.

在此语境下，"统计定位"的具体含义尚不明确。鉴于HGTD焊盘尺寸为1.3毫米，定位并非主要问题，最终模块位置可通过追踪与校准程序进行修正。可在答辩结束后进行进一步修改。

5: explain why positioning accuracy of 5 micron is import in HGTD module assembly (you can always do alignment during the run, and CTE induced effects will be much larger than 5 micron for the system)

模块组装过程中，各部件间的相对定位精度至关重要。针对混合模块之间的布局及其与支撑单元的装配存在多项严格技术要求，以避免发生碰撞。

值得关注的是，模块柔性电路与PEB上的连接器间距为500微米，且可能相距70厘米安装，这就要求其角度对准精度达到0.04度——这相当于混合模块需要实现约13微米的分辨率定位精度。

6: Generally, there is no much uncertainty associated with your studies. could add at least for part of them in the tables etc.

在这类研究中，我们通常会在评估中采取保守方法，而非精细计算不确定度——因为我们的目标是确定一个高度稳健可靠的配置方案，而非仅能在66%的情况下正常工作的方案。若要精确计算这种不确定度，需要耗费不合理的时间来调整模型中的所有参数。例如我们选择评估超过60次循环的故障次数，而实际预估的HGTD寿命周期仅约为36次循环，这样的评估更为保守。另外，有限元仿真进行的是数值计算，本身几乎不产生不确定度（误差）。本工作的不确定度（误差）主要源于模型相关问题：网格划分（空间）/时间步长（时间）（更小的网格/时间步长会降低不确定度，但需要更长的计算时间）；模型简化也是不确定度和误差的重要来源。在本研究中，仿真结果主要用于验证趋势（哪种设计寿命更长），而并非获取非常准确的寿命预测，因为我们将在测试中进行实际验证。

Backup

Material Properties

Material	Thermal conductivity (W/(m·℃))	Specific heat constant pressure (kJ/(kg·℃))	CTE (ppm/℃)	Young's modulus (GPa)	Poisson's ratio
Copper	401	0.385	18	110	0.34
Epoxy resin	0.23	1	70	3.78	0.35
Polyimide	0.8	1.4	20	2.8	0.34
$Sn_{3.5}Ag$	79	0.22	19	Anand model	0.4
Silicon	154.3	0.7	2.578	169/169/130	0.064/0.36/0.36

Anand Model for Bump

- Flow equation:

$$\frac{d\epsilon_p}{dt} = Ae^{-\frac{Q}{RT}}\left[\sinh\left(\xi\frac{\sigma}{S}\right)\right]^{\frac{1}{m}},$$

- Evolution equation:

$$\frac{dS}{dt} = \left\{h_0\left|1-\frac{S}{S*}\right|^a \operatorname{sign}\left(1-\frac{S}{S*}\right)\right\}\frac{d\epsilon_p}{dt},$$

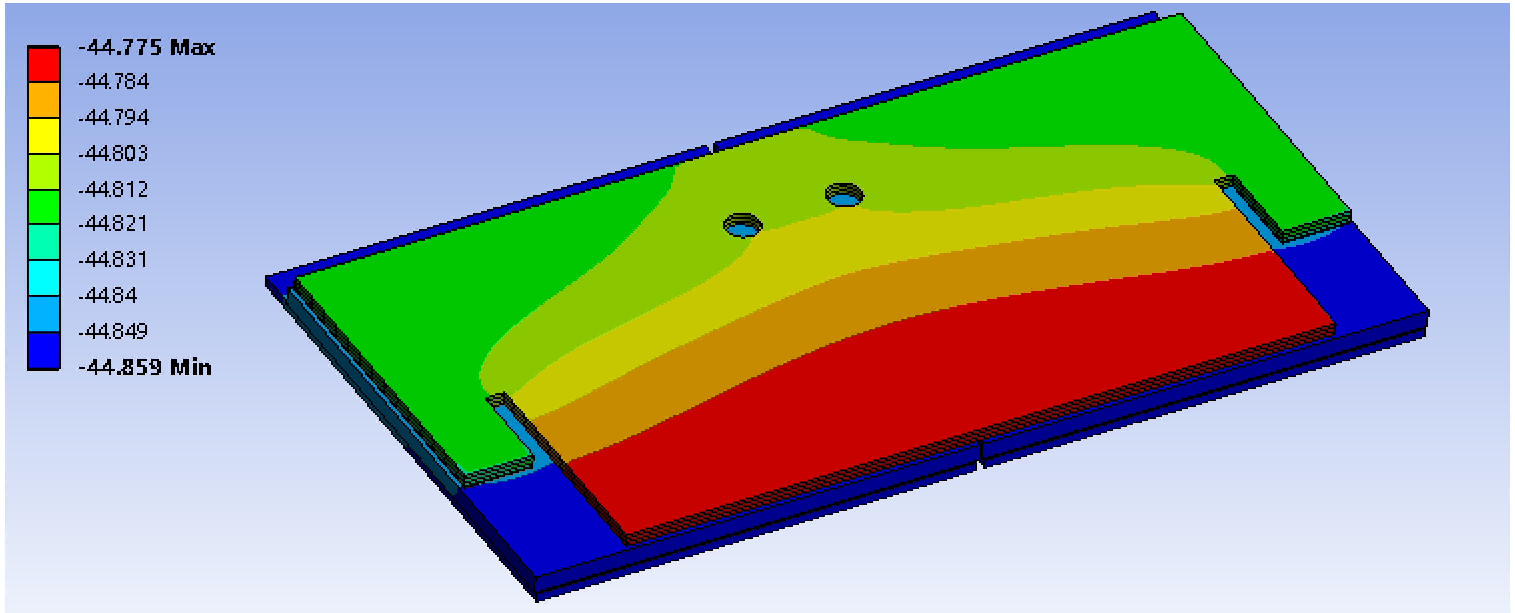
- Saturation value equation:

$$S^* = \hat{S}\left[\frac{\frac{d\epsilon_p}{dt}e^{-\frac{Q}{RT}}}{A}\right]^n.$$

- Solve for three variables as functions of time (t):
  - Plastic strain (ε_p)
  - Stress (σ)
  - Deformation resistance (S)

Parameter	Value
Initial deformation resistance S_0	2.3165 MPa
Activation energy than universal gas constant Q/R	10279 °C
Pre-exponential factor A	1.7702×10^5 s^{-1}
Multiplier of stress ξ	7
Strain rate sensitivity of stress m	0.207
Hardening/Softening constant h_0	27782 MPa
Coefficient for deformation resistance saturation $\hat{S}$	52.4 MPa
Strain rate sensitivity of saturation n	0.0177
Strain rate sensitivity of hardening or softening a	1.6

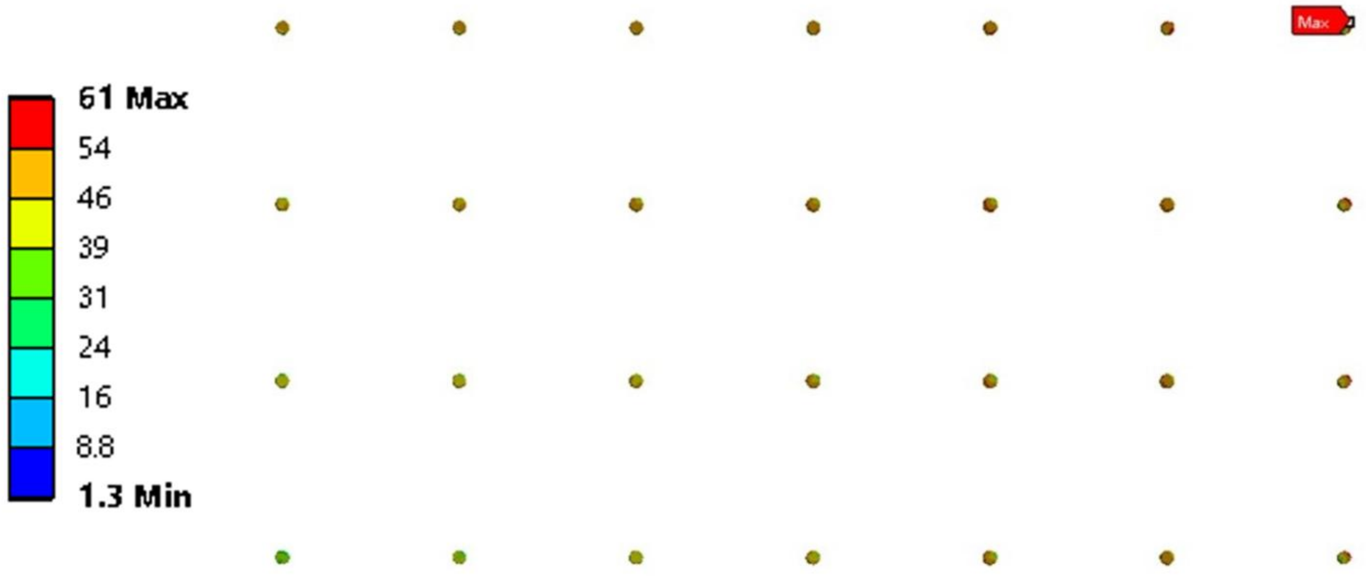
Temperature Distribution

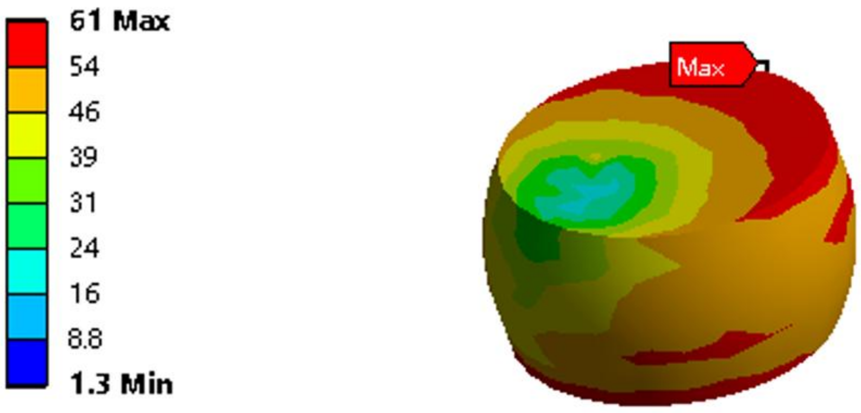


Time (s)	Environment temperature(°C)	Maximum module temperature(°C)	Minimum module temperature(°C)
0	22	22	22
300	14.5	15.17	15.09
600	7	7.72	7.64
900	-0.5	0.23	0.14
1200	-8	-7.28	-7.36
1500	-15.5	-14.78	-14.86
1800	-23	-22.28	-22.36
2100	-30.5	-29.78	-29.86
2400	-38	-37.28	-37.36
2700	-45.5	-44.78	-44.86
3000	-38	-38.54	-38.61
3300	-30.5	-31.13	-31.22
3600	-23	-23.64	-23.72
3900	-15.5	-16.14	-12.23
4200	-8	-8.64	-8.73
4500	-0.5	-1.14	-1.23
4800	7	6.36	6.28
5100	14.5	13.86	13.78
5400	22	21.36	21.28
5700	29.5	28.86	28.78
6000	37	36.36	36.28
6300	44.5	43.86	43.78
6600	37	37.61	37.54
6900	29.5	30.22	30.13
7200	22	22.72	22.64

- Environment temperature: -45.5°C
- Almost uniformly distributed temperature at any time

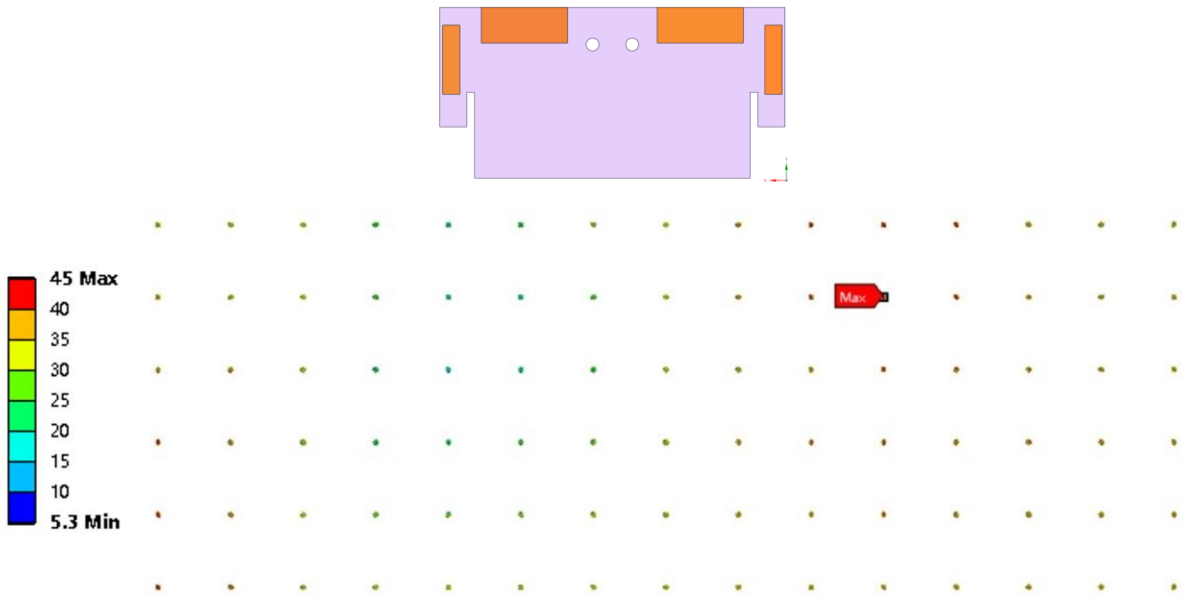
Stress Distribution



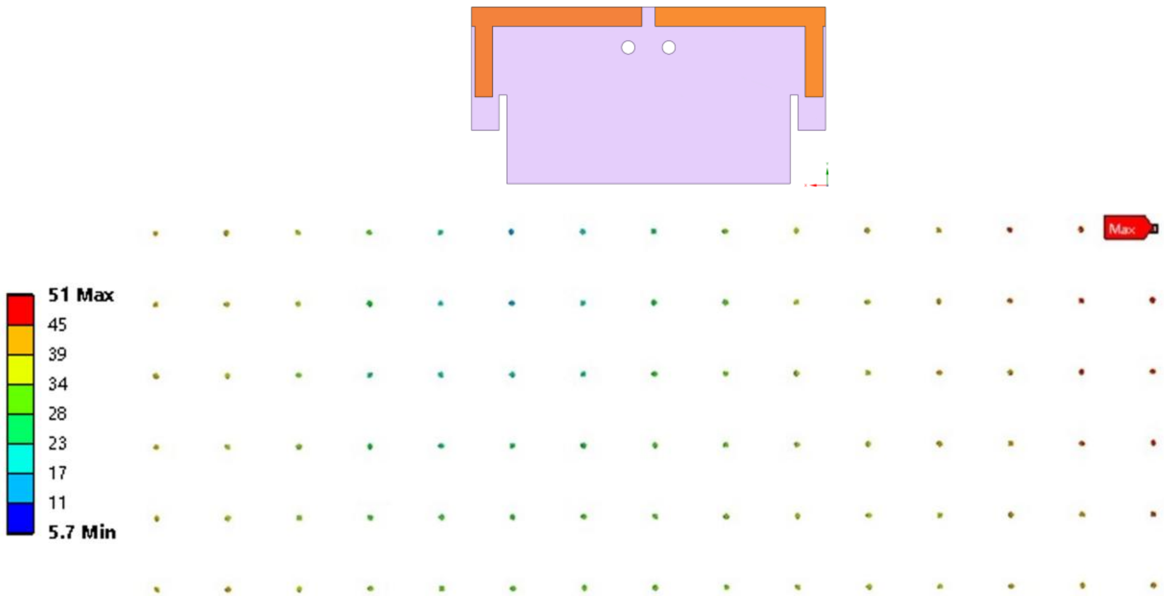


- Maximum stress on surface contacting to sensor (single bump)
- Global maximum stress on the bump at right top corner

Pattern A (3029 cycles)



Pattern B (566 cycles)



- Pattern A redistributes stress to change bump with maximum stress to middle
- Gap between glue parts (Pattern A) allows better stress relief