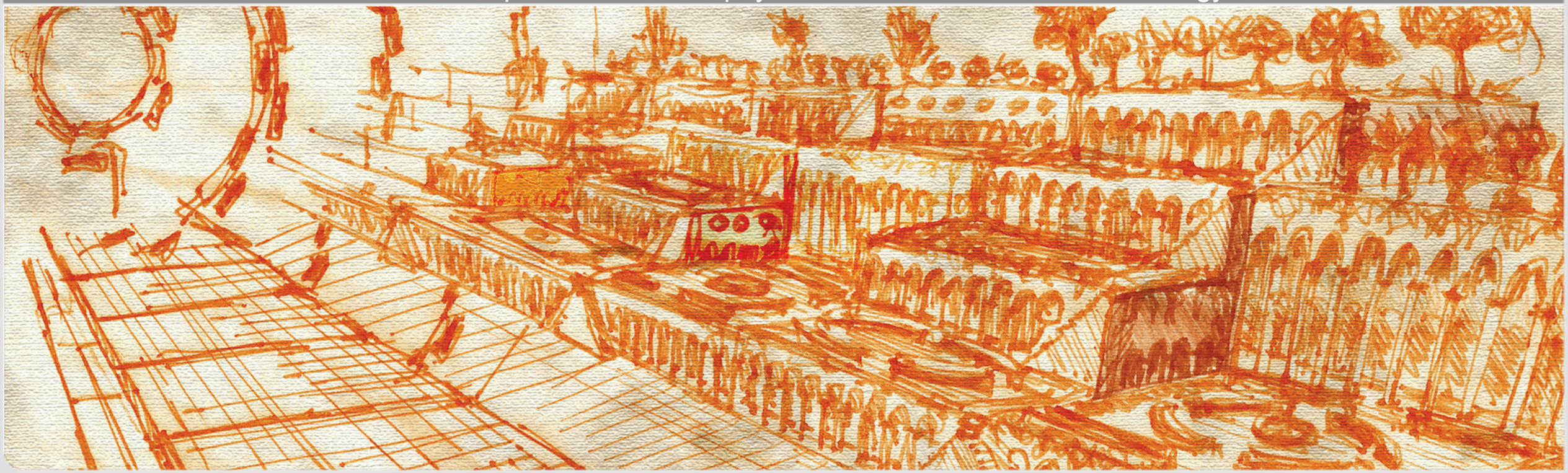
Karlsruhe Institute of Technology

Silicon Pixel Modules for the CMS Phase I Upgrade: Lessons Learned

9th Terascale Detector Workshop
Freiburg, April 6, 2016

Ulrich Husemann
Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology

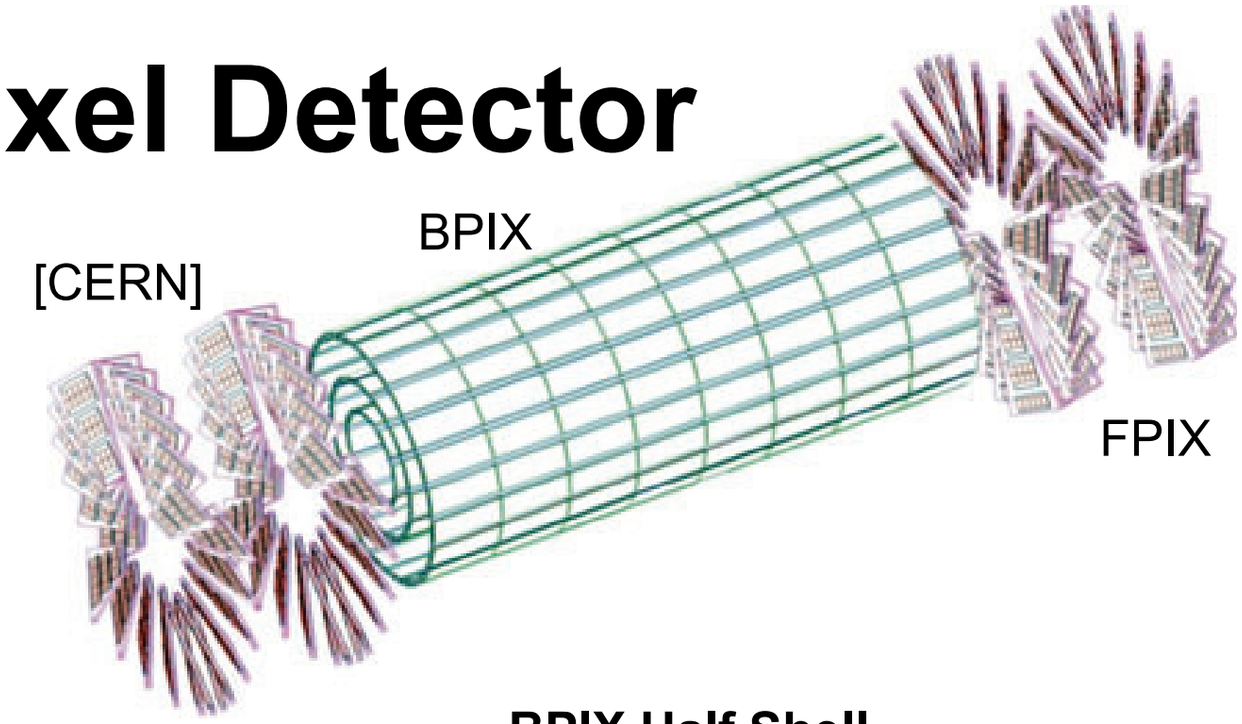


Karlsruhe Institute of Technology

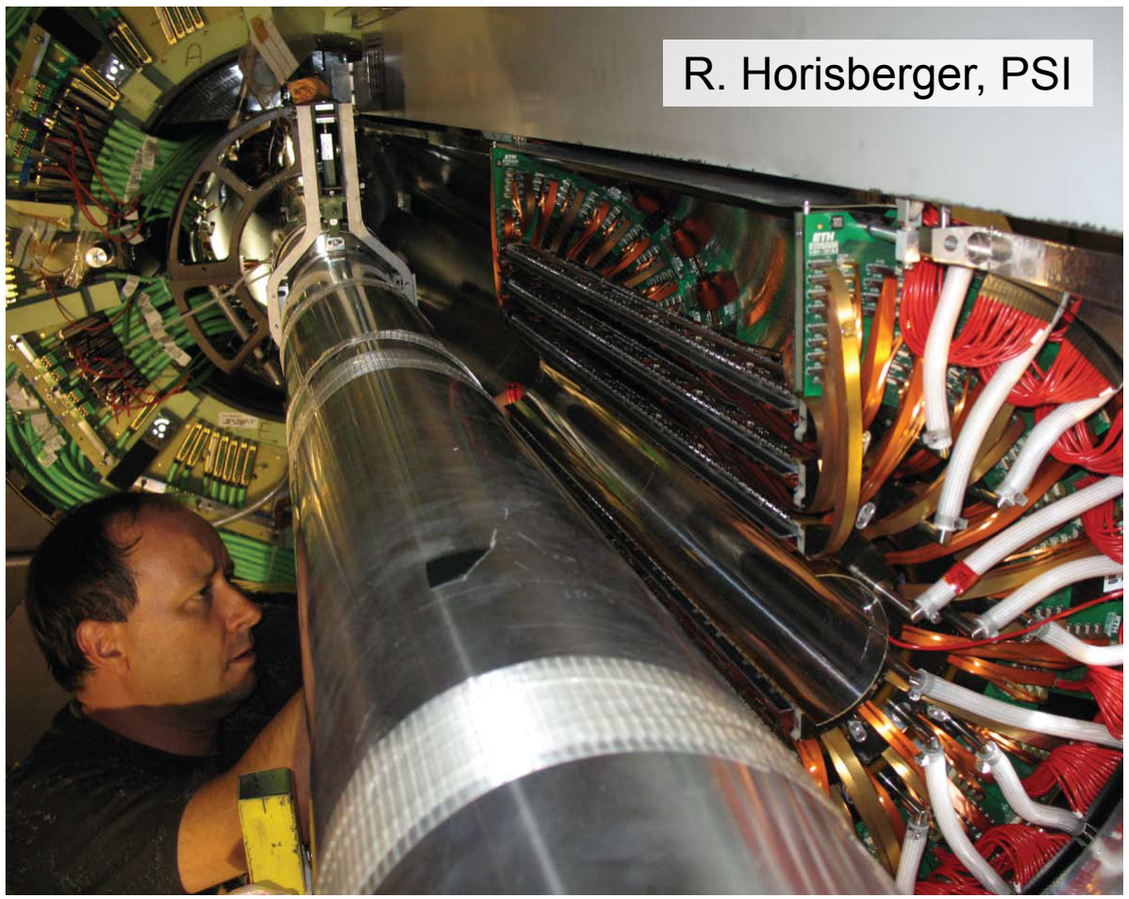
Upgrade of the CMS Pixel Detector

The Current CMS Pixel Detector

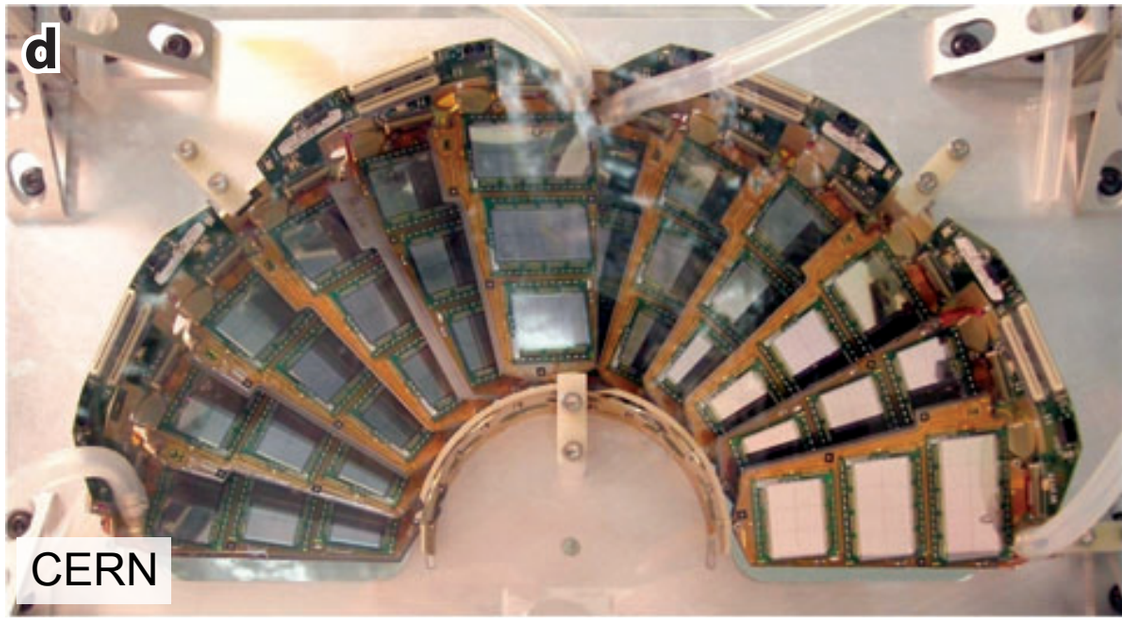
- Geometry: barrel + endcaps
  - BPIX: 3 layers
  - FPIX: 2×2 disks
- Pixel detector modules (BPIX)
  - Sensor: CiS n^+-in-n, 150×100 μm^2
  - Analog readout chip: PSI46



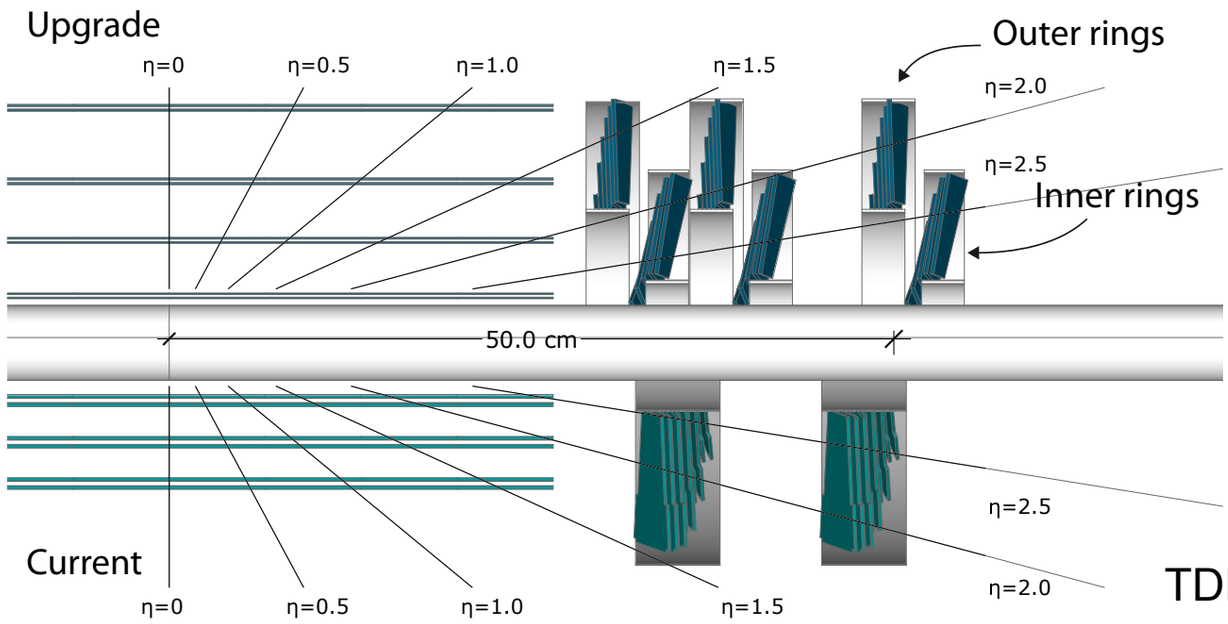
BPIX Half Shell



FPIX Half Disk



General Phase 1 Pixel Upgrade Strategy

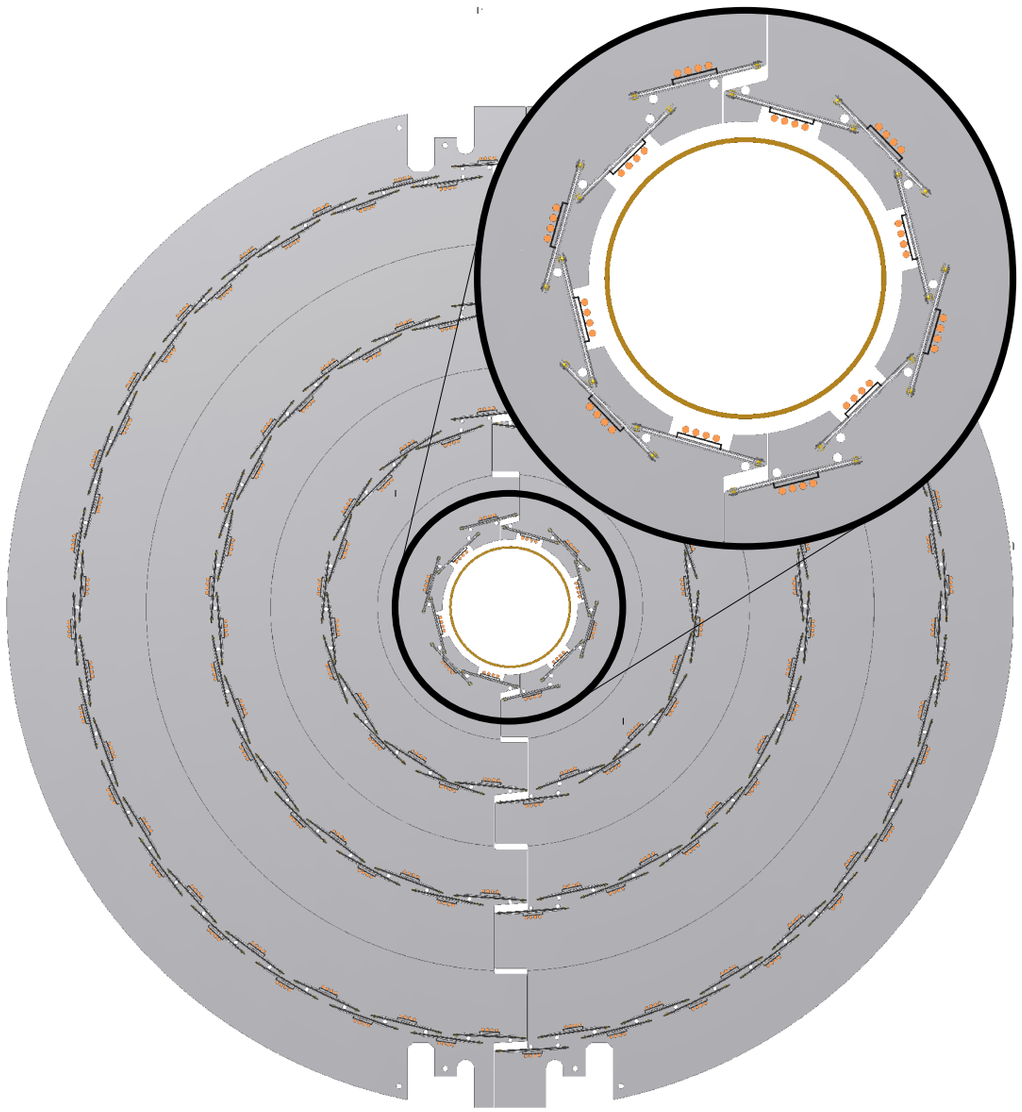


TDR, CERN-LHCC-2012-016

Modification	Impact
More layers: 3 → 4 barrel layers, 2×2 → 2×3 forward disks	More 3D pixel space points, more tracking redundancy
Smaller radius of innermost layer	Improved impact parameter resolution (key to excellent B-tagging at high pileup)
Improved **mechanics**, **cooling**, and **powering**	Reduced material budget: less multiple scattering, fewer photon conversion
New digital **readout chip**	Front-end electronics ready for high rates

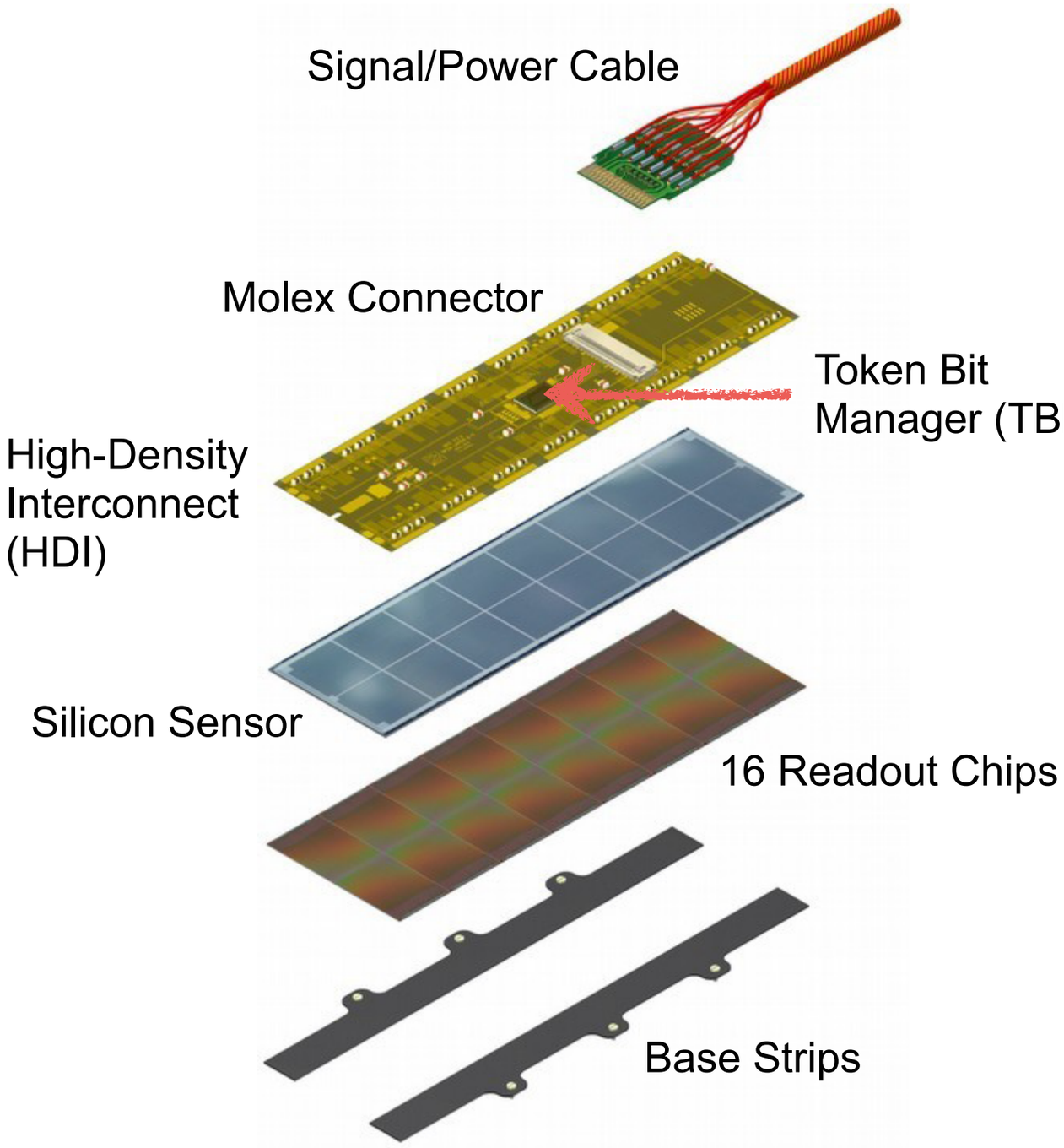
Ulrich Husemann
Institut für Experimentelle Kernphysik

BPIX Production



- Barrel pixel module production: **distributed** effort (reminder: current barrel pixel detector built by Swiss consortium alone)
  - Layers 1 and 2: **Swiss** consortium (PSI, ETH Zürich, U Zürich)
  - Layer 3: **Italy/CERN/Taiwan/Finland**
  - Layer 4: **German** consortium “DPix” (RWTH Aachen, DESY, U Hamburg, KIT)
- **DPix** consortium:
  - Two **parallel production lines** (DESY/UHH, KIT/RWTH)
  - Advantages: exchange of **experience** and **material**, joint **investigation** of problems arising

Updated BPIX Modules



- Step 1: **Bump Bonding**
  - **Electrical** and **mechanical** connection of 16 readout chips with silicon sensor
  - Connection: thermocompression
  - Product: **bare module**
- Step 2: **Gluing**
  - **Mechanical** connection of parts
  - Two steps: base strips → bare module, HDI → bare module
- Step 3: **Wire Bonding**
  - **Electrical** connections: TBM to HDI, readout chips to HDI

Ulrich Husemann
Institut für Experimentelle Kernphysik

Process Flow: Bump Bonding

Sensor wafer production, IV test

Sensor UBM + dicing

ROC production

ROC wafer probe test

Optical inspection UBM + SnPb bumps thinning/dicing

Pipelined process, many dependencies (e.g. external vendors)

ROC cleaning

Optical inspection

Bonding x 16

Bare Module test/verification

ROC Re-working

Sensor IV test

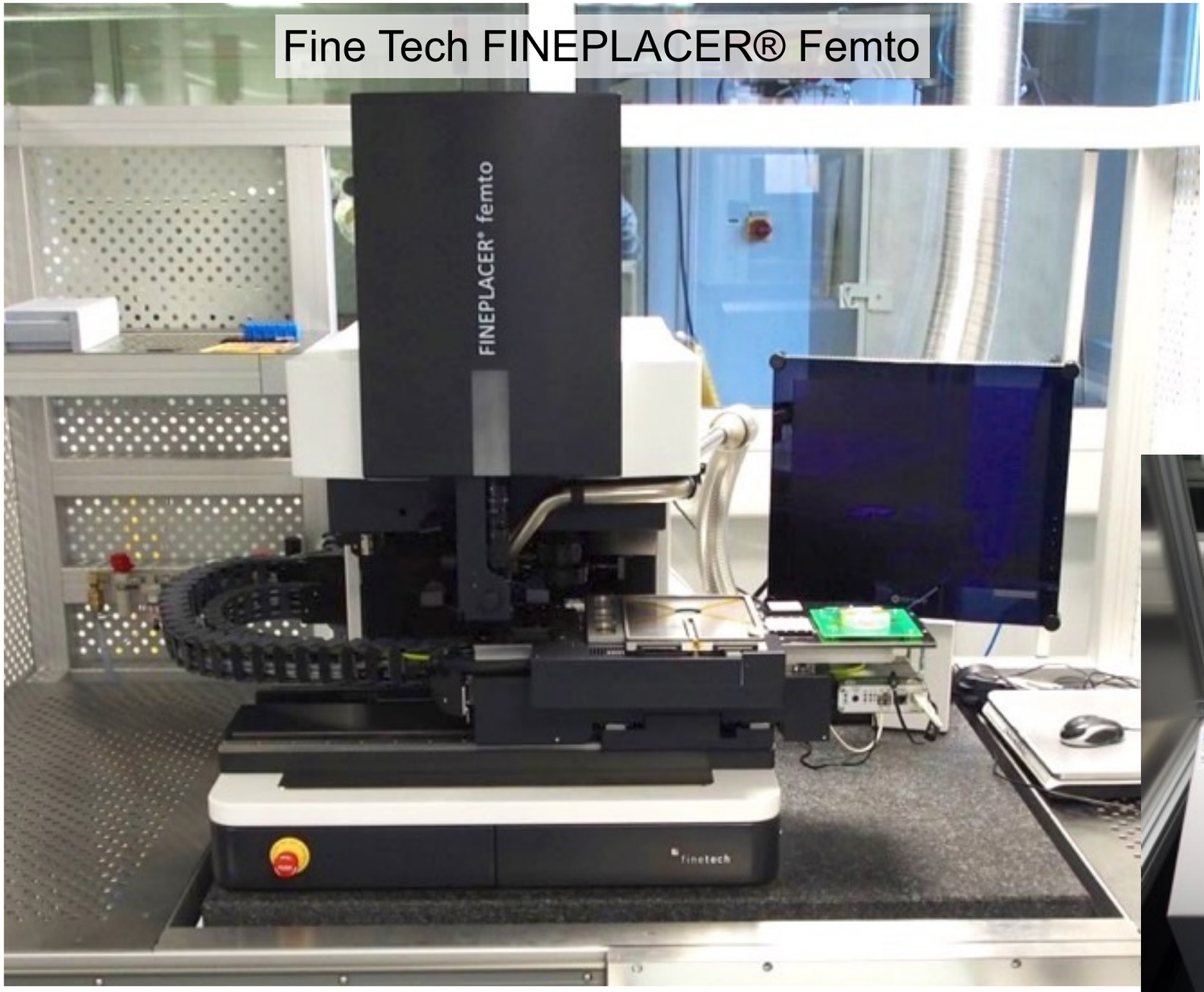
Reflow

Module assembly + test

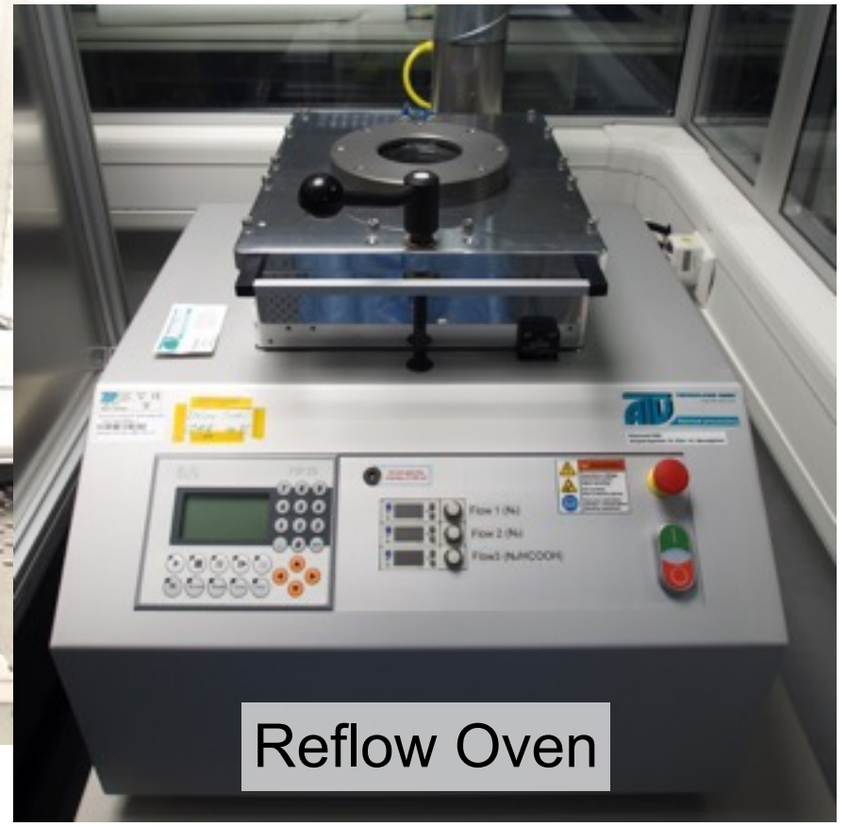
Cold test + calibration

Half-shell integration

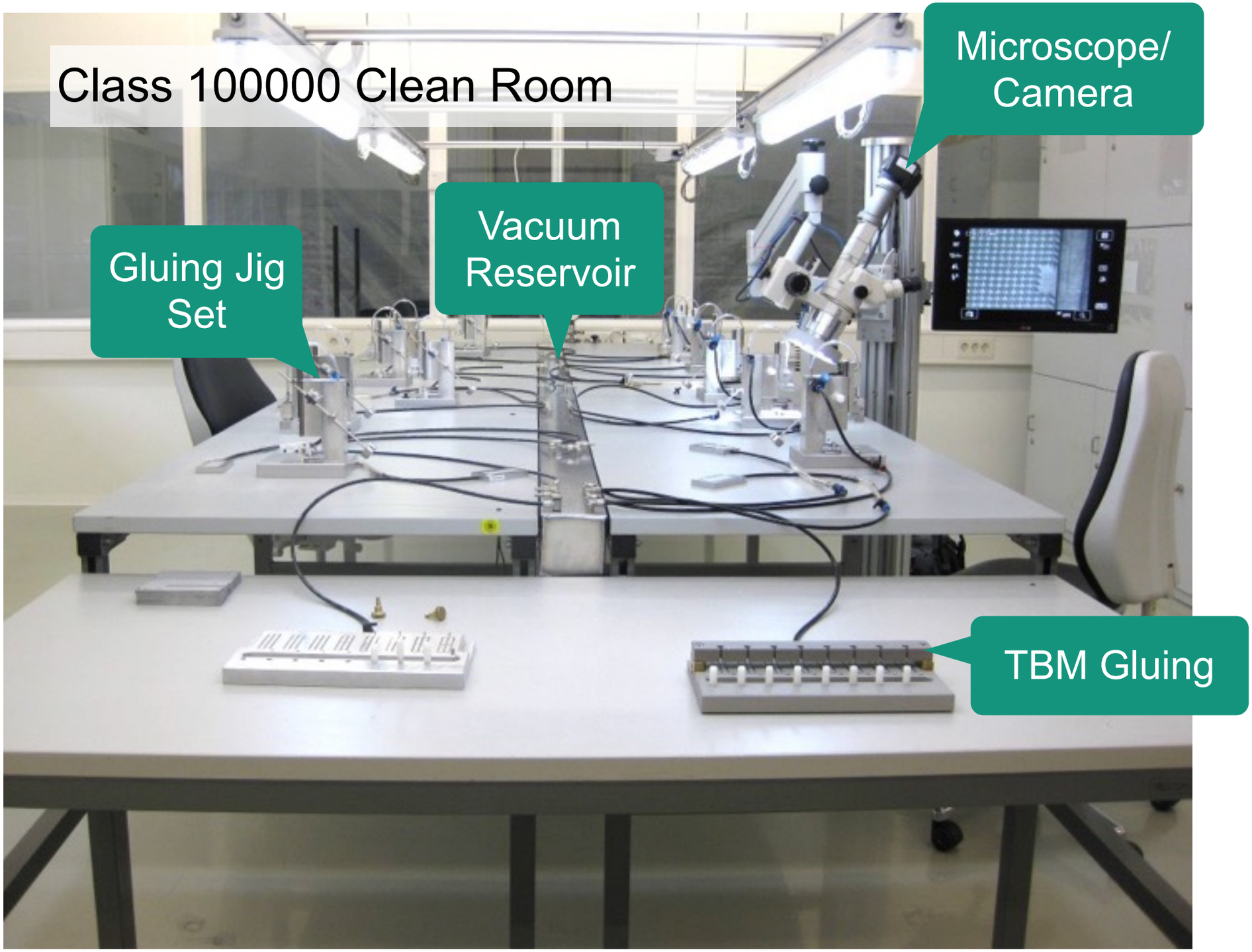
Bump Bonding Equipment



Fine Tech FINEPLACER® Femto

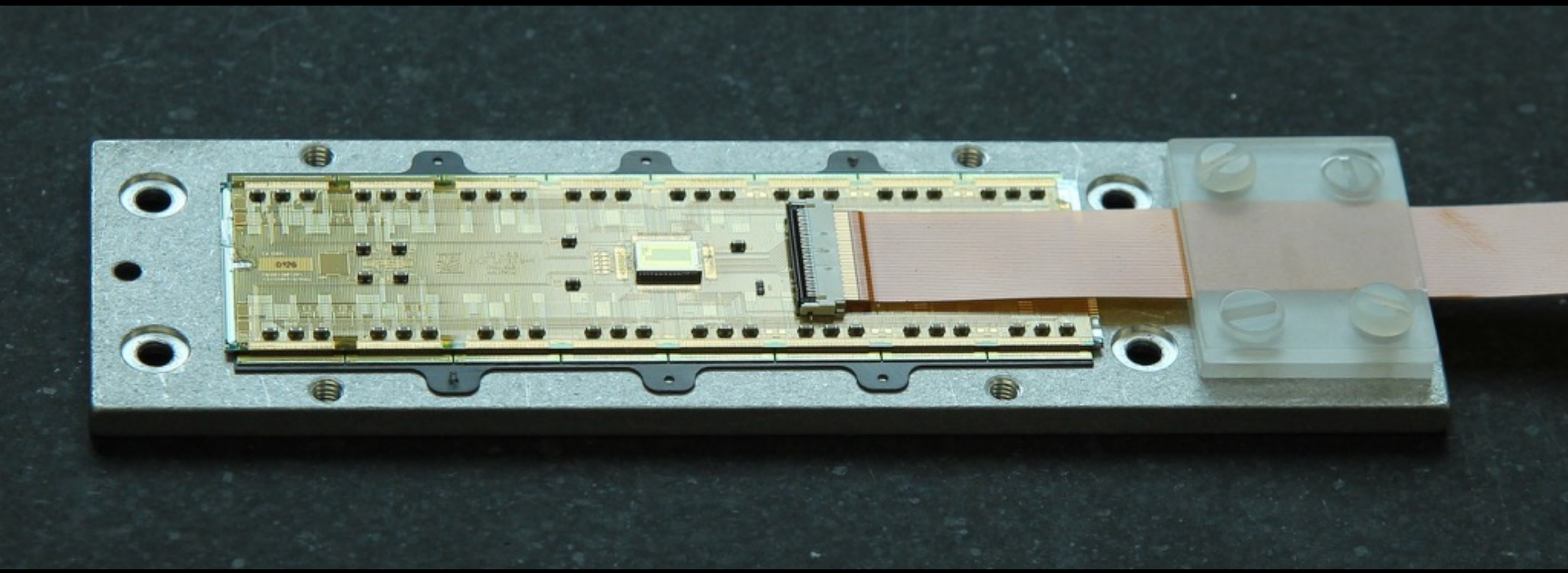

Reflow Oven

Module Assembly Clean Room



Pixel Module Assembled at KIT

Karlsruhe Institute of Technology



"… because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know".

D. Rumsfeld

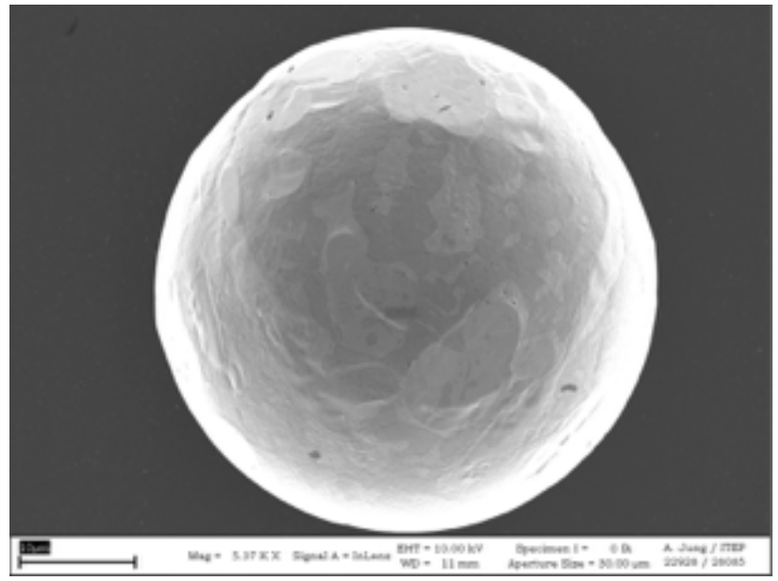
Lessons Learned:

A Subjective Selection

Material Supply

- Example from CMS pixel production: choice of **bumping vendors**

SEM Picture of RTI SnPb Bump

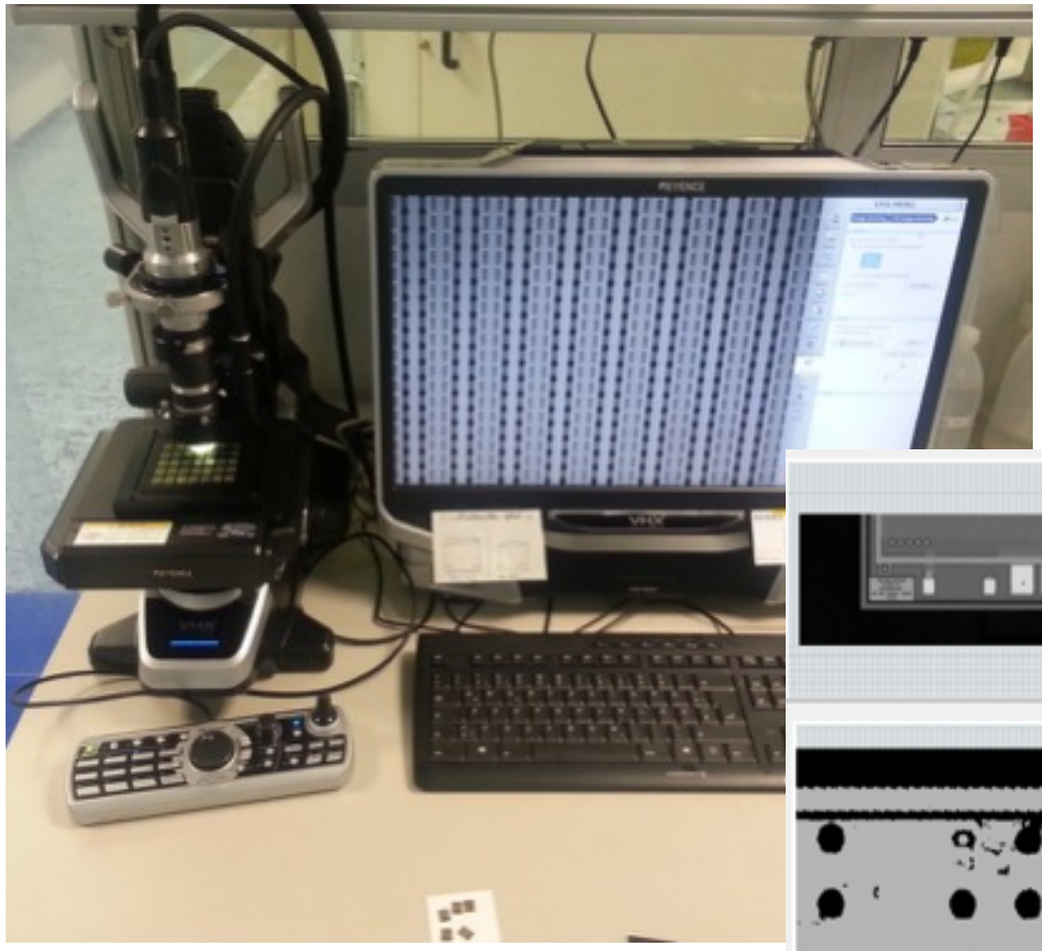


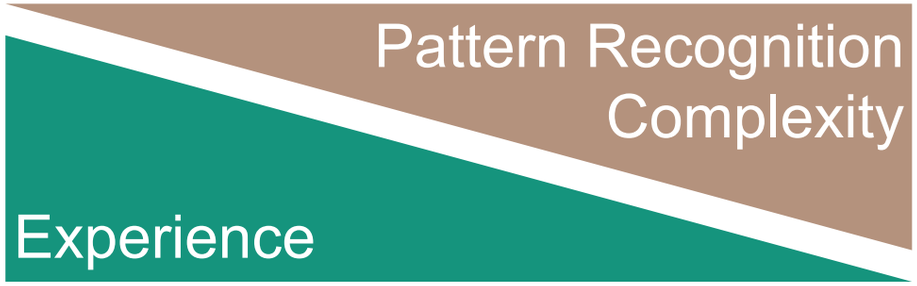
- Step 1: **Find** vendors
  - Check material **specifications** and **availability**
  - **Lesson**: vendor may not be interested in doing business with you at all (too small scale, other priorities)
- Step 2: **Qualify** vendors
  - Check product quality of different vendors with prototypes → best product
  - **Lesson**: production quality may vary from prototype to pre-series to series
- Step 3: Issue **purchase order**
  - **Lesson**: be prepared for delays due to legal problems, customs, …

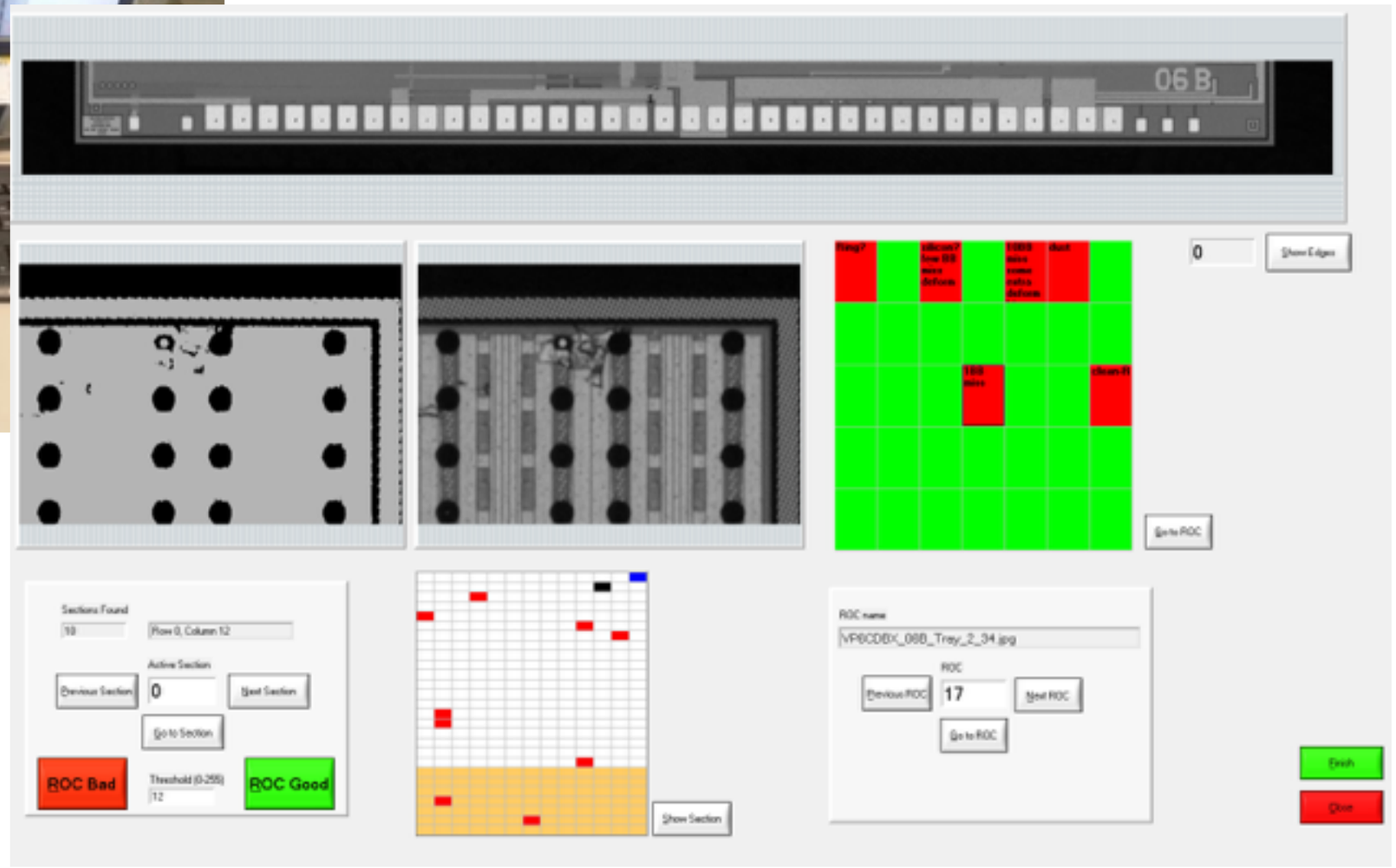
Quality Control

- **Quality** of pixel detector modules depends on
  - Quality of incoming **materials** (sensors, readout chips, HDIs, …)
  - Quality of internal **processes** (bump bonding, gluing, …)
- Incoming **materials**: production quality may vary
  → detailed **acceptance tests**
  - **Lesson:** Acceptance tests take time → **automate** tedious tasks
- Example from CMS pixel production: acceptance tests for chips and sensors
  - Optical inspection: all bumps, sensor UBM, guard rings, …
  - Partial **automation** via pattern recognition → takes time to develop (keep “human factor” involved → save development time)

Semi-Automated Chip Inspection







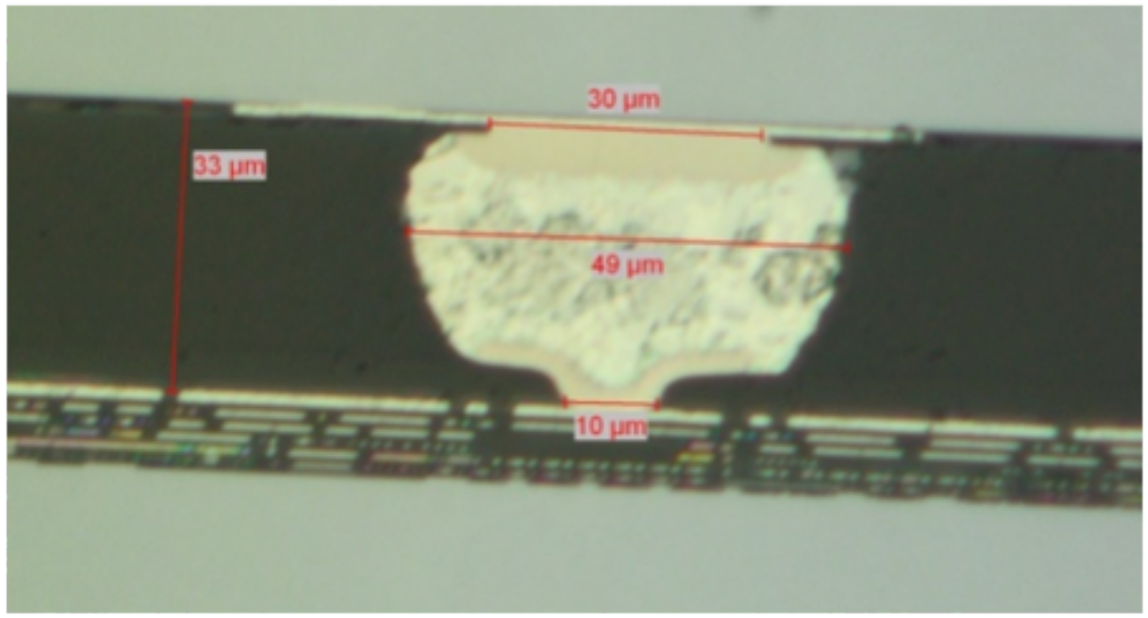
Quality Control: Processes

- Planning: think of **reasonable** quality criteria **before** production
  - “Le mieux est l’ennemi du bien”: how good is good enough?
  - Criteria may be revised based on production experience
- During production: **monitor** and **document** quality of each production step, examples from CMS pixel module production:
  - **Optical inspection**: mechanical precision, any obvious flaws (glue spilled, dirt on wire bonding pad, …)?
  - **Pull tests**: mechanical strength of connections (bump bonds, wire bonds)?
  - **Electrical tests**: intended readout chip functionality?
  - **Long-term trends**: drifts of key quality criteria? (e.g. assembly tools worn or misaligned, varying material quality, people getting sloppy)

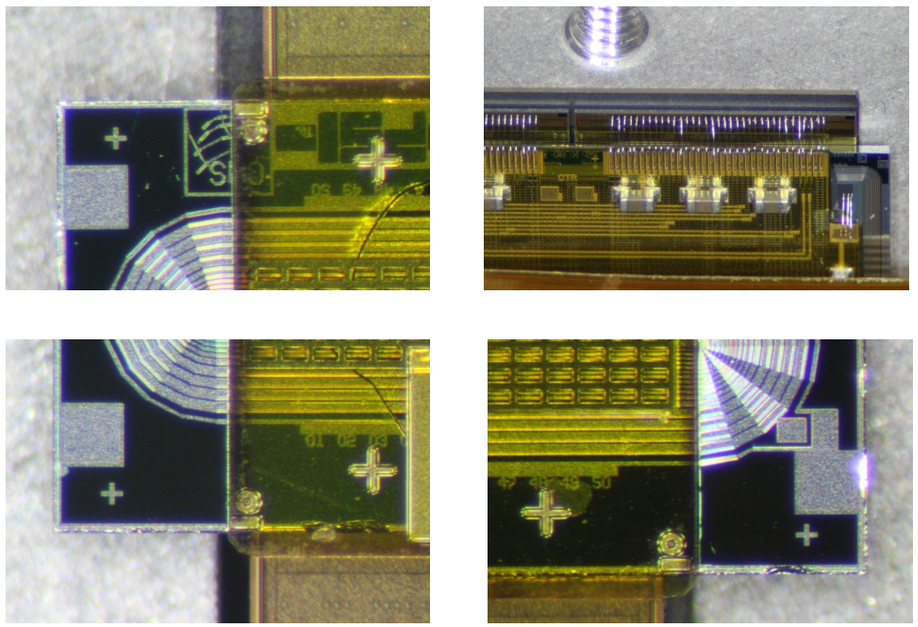
Quality Control: Processes

- Various **diagnostic tools** required for quality control (in-house and external) → check availability, cost, …
- Examples from CMS pixel module production:
  - Electrical tests: custom test boards + firmware + software, …
  - Bump bonding: cross section pictures, SEM, micro X-ray tomography, …
  - Gluing: optical microscope and camera, precision metrology, …

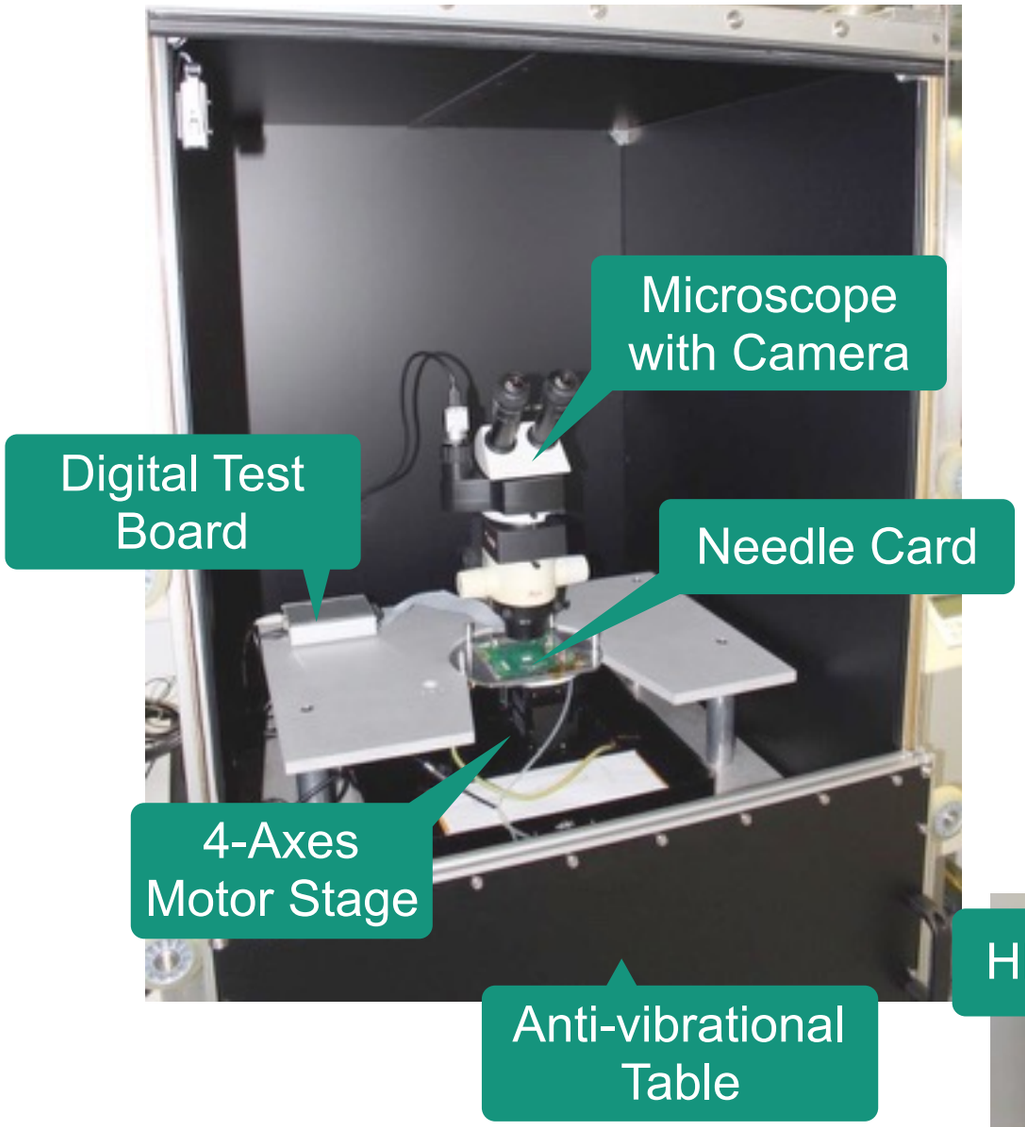
Bump Bond Cross Section



Microscope Picture of Module Edges



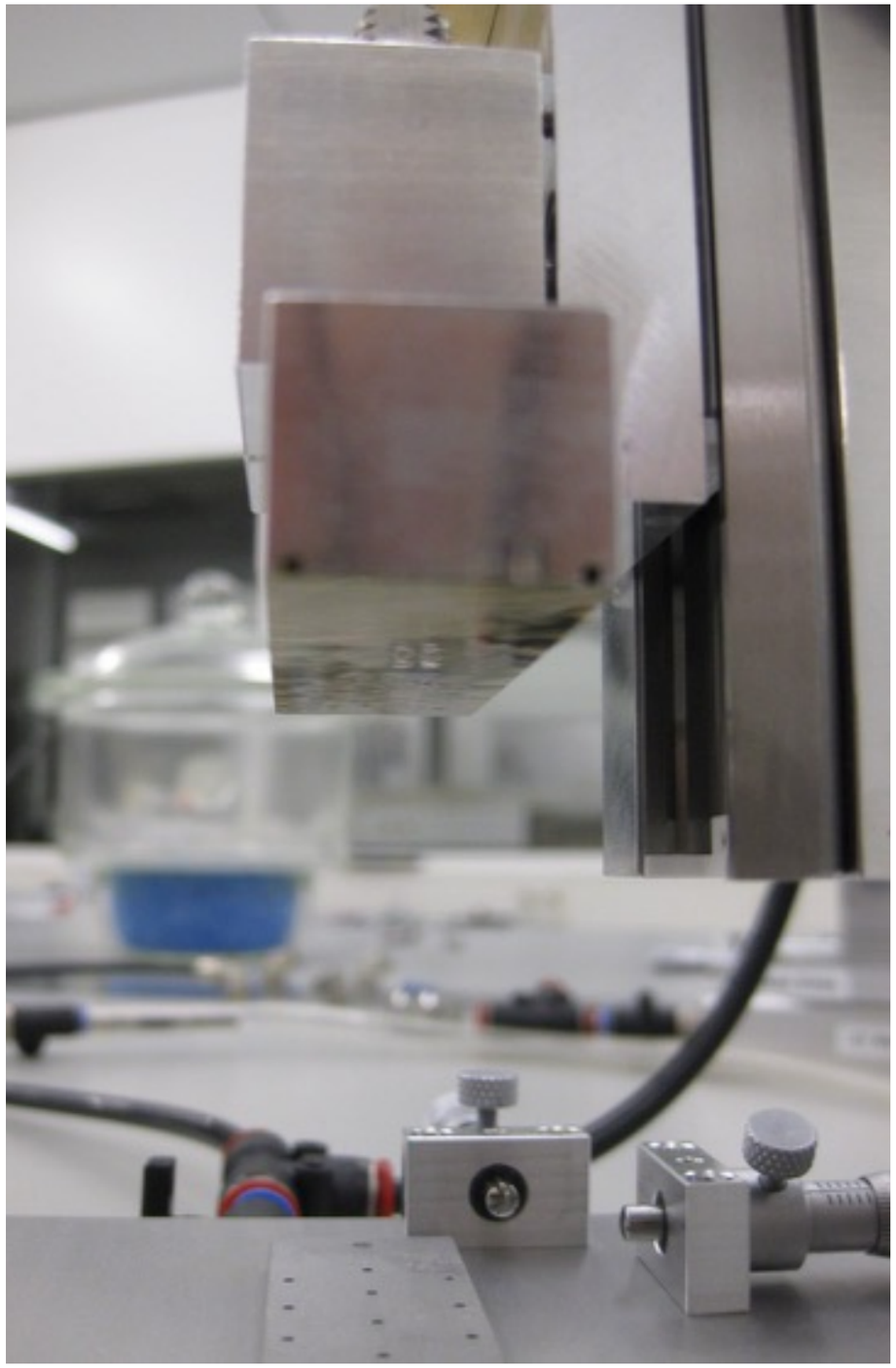
Quality Control: Feedback Loops



- Important: **quick feedback** on production quality
- Examples from CMS pixel production:
  - **Bare module probing** within 1–2 days after bump bonding → quick detection of bump bonding problems
  - **HDI probing** only shortly before assembly → significant delays in case of problems with production quality

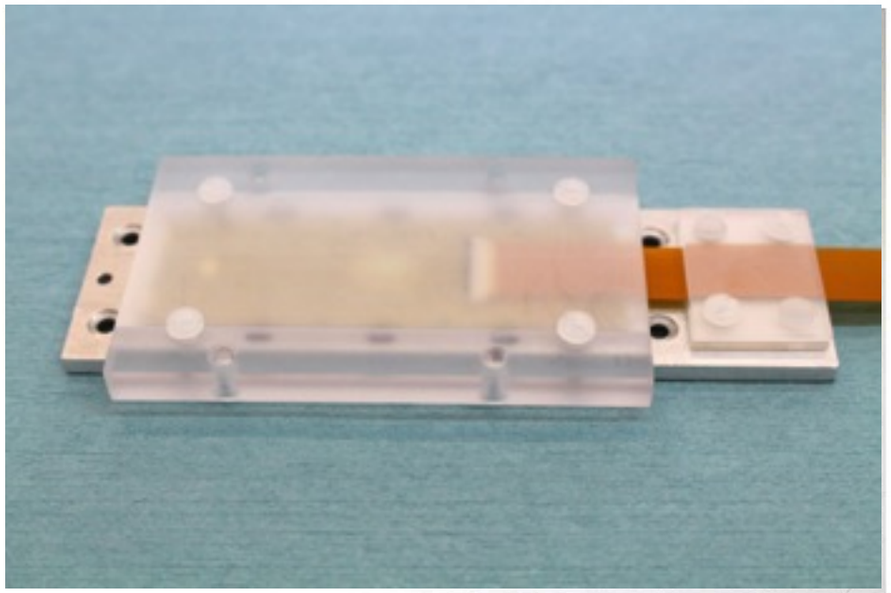
Mechanical Precision

- Recall your undergraduate studies
  - Physics 101: every measurement has an **uncertainty**
  - But did you attend Mechanical Engineering 101? Physical properties (e.g. dimensions) of all materials vary → **tolerances**
- Key question: which mechanical precision is **really required**?
  - Overestimation → over-design of tools (difficult, expensive, …)
  - Underestimation → alignment difficult or impossible
- Example from CMS pixel production: **assembly jigs**



Low-Tech Woes: Module Handles

- Full pixel modules mounted on aluminum “module handles”
  - Flat piece of aluminum, laser-cut, precision holes
  - Protective cap for module, strain relief for cable



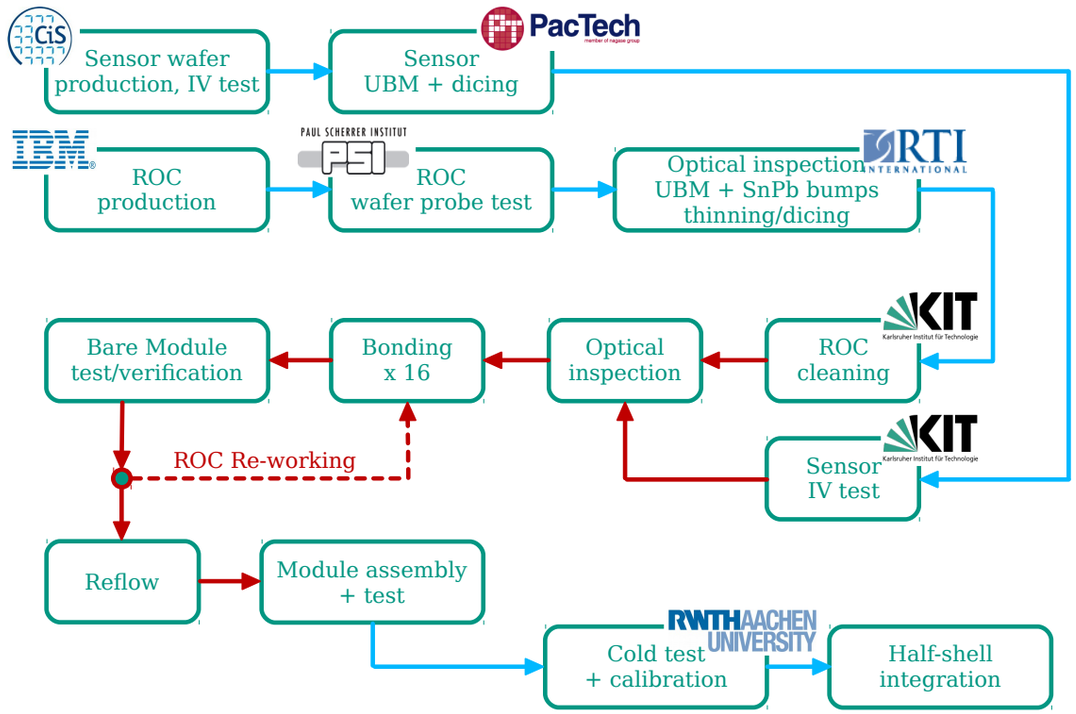
- Challenge: handle = **interface** to many production/testing steps
  - Handle has to fit assembly jigs, transport and storage system, test systems
  - Problem: three different test systems, two of which had been partly designed beforehand (one needs very flat handles to hold vacuum, one has to use alternative protective cap → additional precision holes)

Low-Tech Woes: Gluing

- Delicate interplay of amount of glue and glue viscosity
  - Ideal: **full contact area** wetted → best mechanical and thermal contact
  - Too much glue or glue too liquid → glue may be sucked into vacuum holes, modules glued to assembly jig while curing
  - **Lesson**: control and document glue **preparation** (mixing, pot time) and **environment** (temperature, humidity)

Logistics

- Analyze production **workflow**
  - Production may get **stuck** between steps → define efficient **handshake** (e.g. as part of bookkeeping → next slide)
  - Production **throughput** limited by **slowest** process → check for **bottlenecks** (production steps, supply chain)
  - Production could be interrupted by **single point of failure** → provide **fallback** solutions, **backup** for trained personnel



Bookkeeping

- **Meticulous documentation** of each step is a must!
  - Purpose: tracking of **production problems**
- Bookkeeping **tools**
  - **Many** tools available: paper logbooks, paper travelers, e-logs, Wikis, Google docs, local database, project database, full product lifecycle management
  - Goal 1: avoid information **cluttering** and **duplication** → centralize
  - Goal 2: **keep threshold** to enter information **low** (for physicists and technicians) → simple, easy to use, in local language

Bookkeeping

Laufzettel HDI 549-17-008 Box 5 0,62

KIT Karlsruher Institut für Technologie

1. HDI Operator: Datum/Uhrzeit:
optische Kontrolle: ○ gut ○ auffällig
Bemerkungen:

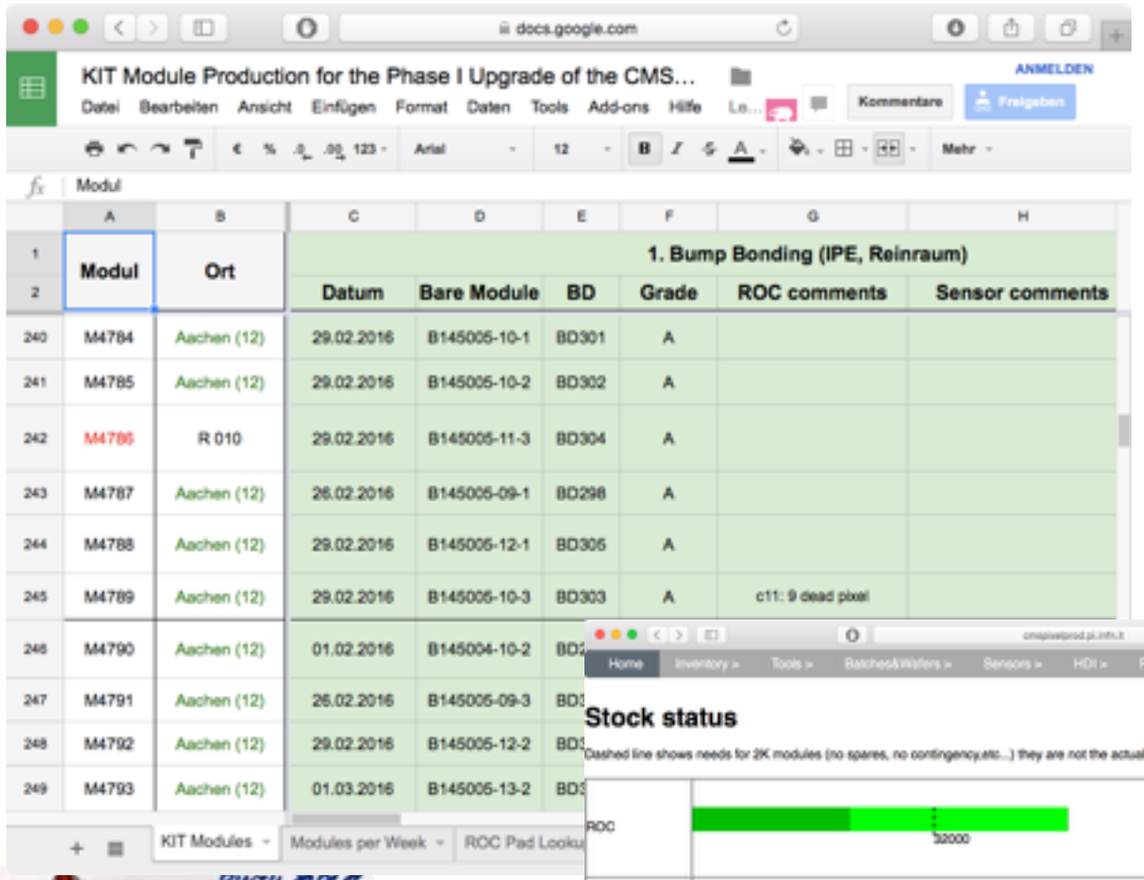
2. TBM kleben Operator: Weiler Datum/Uhrzeit: 29.02.16 / 10:00
Temperatur: 22°C Luftfeuchte: 27%
optische Kontrolle: ○ gut ○ auffällig
Bemerkungen:

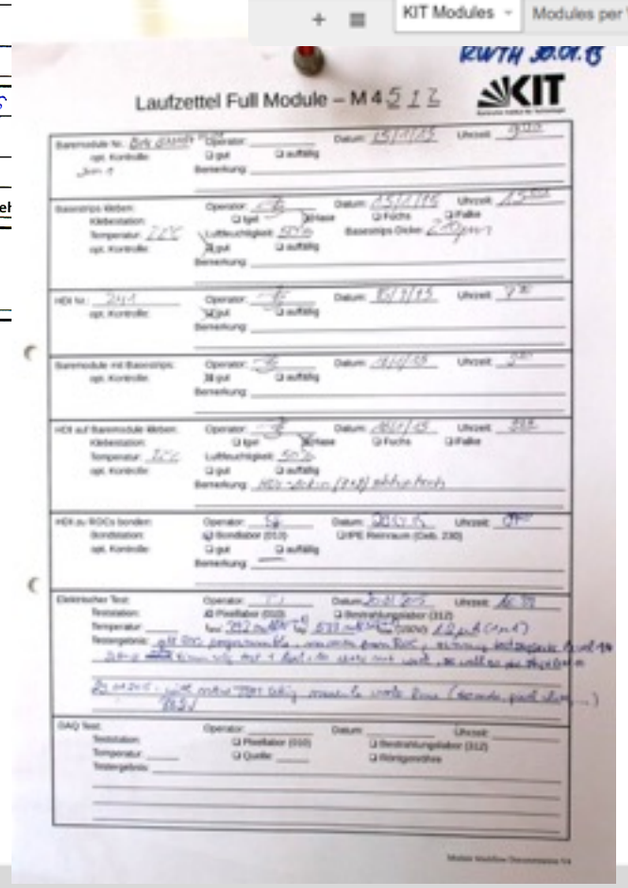
3. TBM bonden Operator: St Datum/Uhrzeit: 03.03.16 11:25
Temperatur: 25.6°C Luftfeuchte: 21.6%
optische Kontrolle: ✓ gut ○ auffällig
Bemerkungen:

4. Pulltest Operator: Datum/Uhrzeit:
Anzahl Testbonds: mittlere Zugfestigkeit:
Bemerkungen:

5. HDI Test Operator: Heindl Datum/Uhrzeit: 03.03.16
Bemerkungen:
siel

→ Testergebnis ✓ HDI OK ○ HDI Ausschuss:





probably not the ideal solution…

Summary & Conclusions

- Detector construction projects: complex process with **many** (known and unknown) **unknowns**
- Example: production of **pixel detector modules** for the CMS Phase I upgrade → many old and some new lessons learned
  - Material supplies: dealing with various vendors, varying quality
  - Quality control: material and processes, feedback loops
  - Mechanical precision and gluing
  - Logistics and bookkeeping
  - …