Study of Solder Ball Bump Bonded Hybrid Silicon Pixel Detectors at DESY

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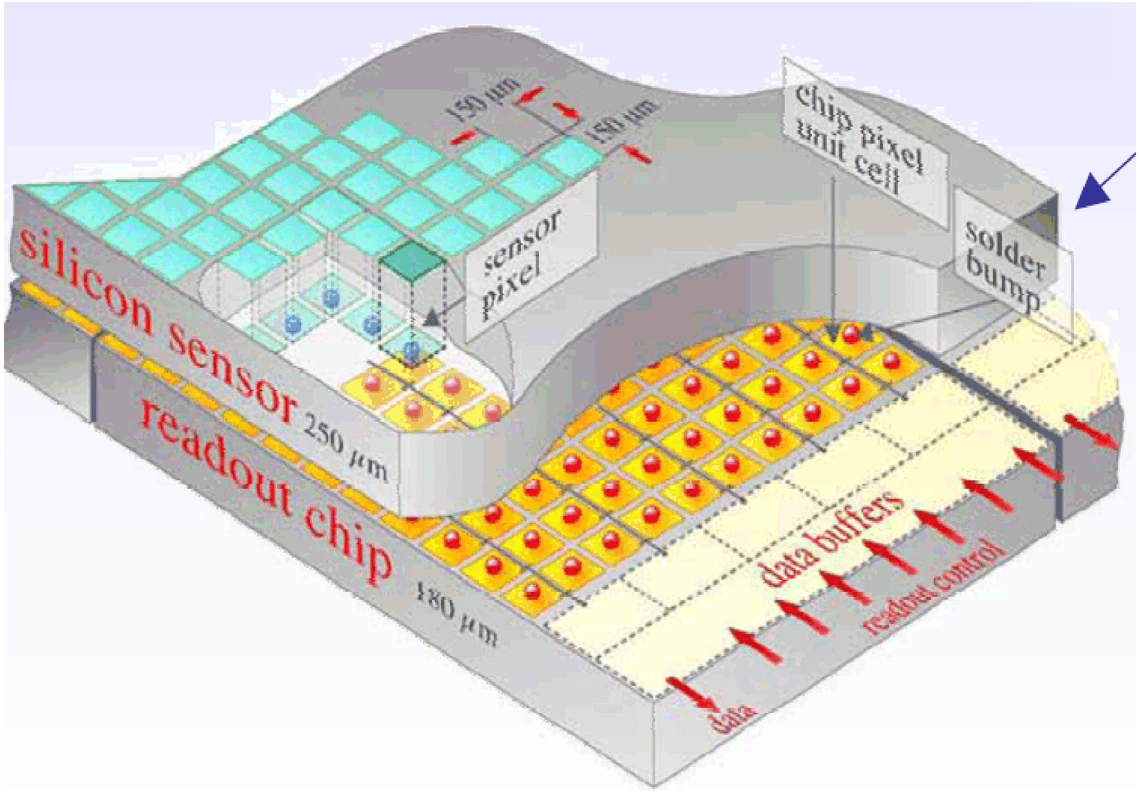
Outline

- Silicon Pixel Detector - Components
- Solder Ball Bump Bonding @ DESY
- Lab Test for Bump Bonding Quality
- Pixel Module @ DESY e^- Test Beam

Hybrid Silicon Pixel Detector

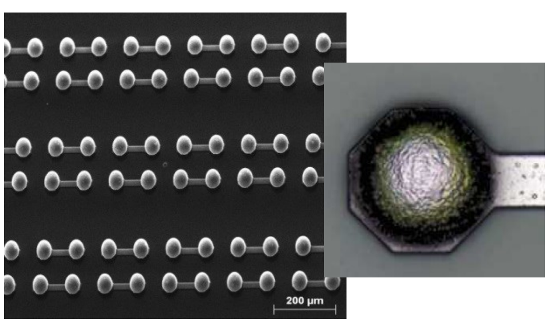


Silicon sensors with 100 × 150 μm^2 pixels, bump bonded to CMOS readout chips for DC connection.

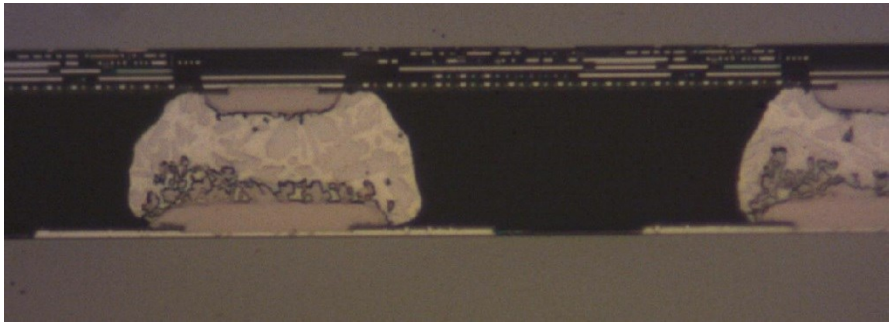
Requires a flip-chip bump bonding technology.

Bump Bonding at DESY uses a solder ball laser jetter and a flip chip bonder

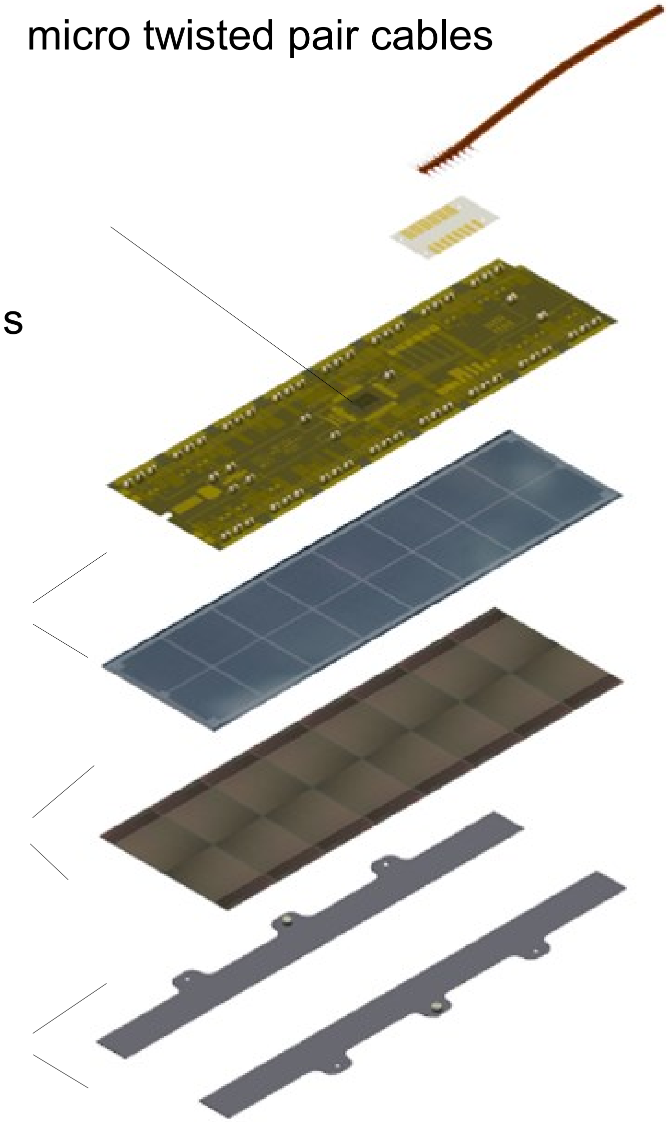
solder ball placement



after flip chip bonding



Module Components



Sensor concept

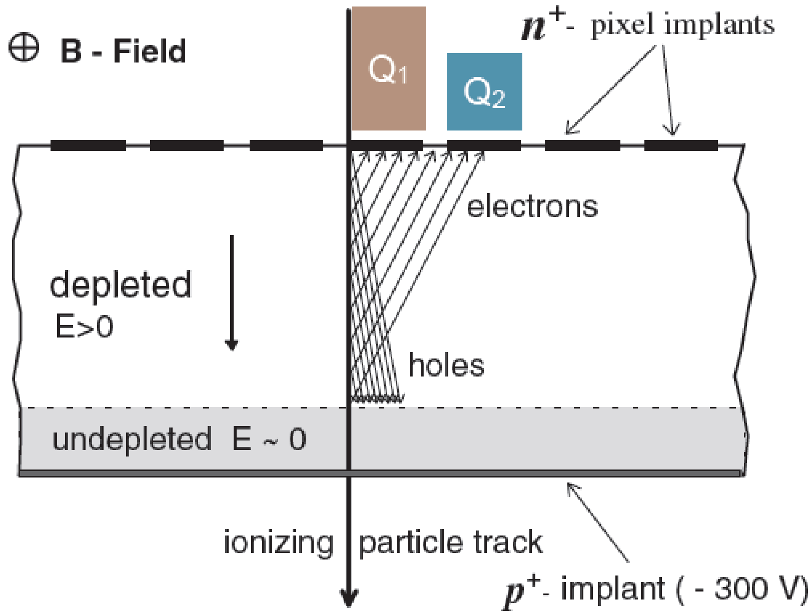
The so called “**n-in-n**” approach
(**n^+ pixel implant in n substrate**)

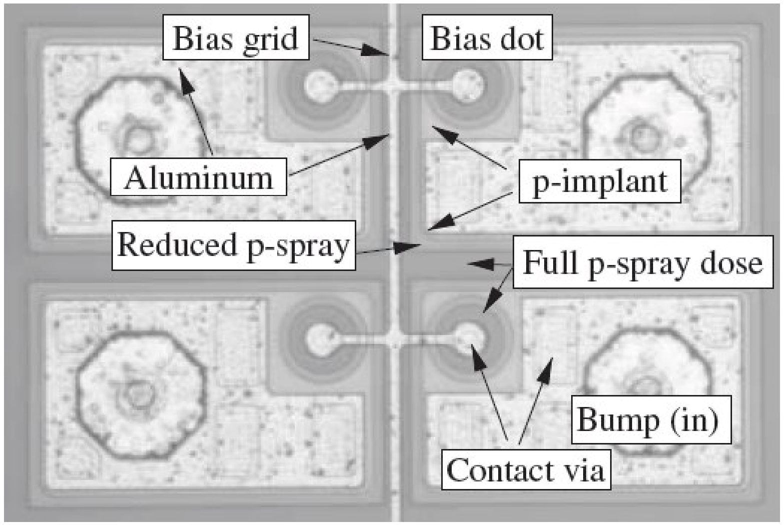
High signal at moderate voltages
- Pixel should respond to small signal (low capacity and noise)

Double sided processing

- All sensor edges on ground
- Inter-pixel isolation (p-spray)
- Punch-through bias dots define the pixel potential in case of missing bump bond connections
- Expensive process

Designed at PSI by T. Rohe et. al. and fabricated by CIS, Erlangen

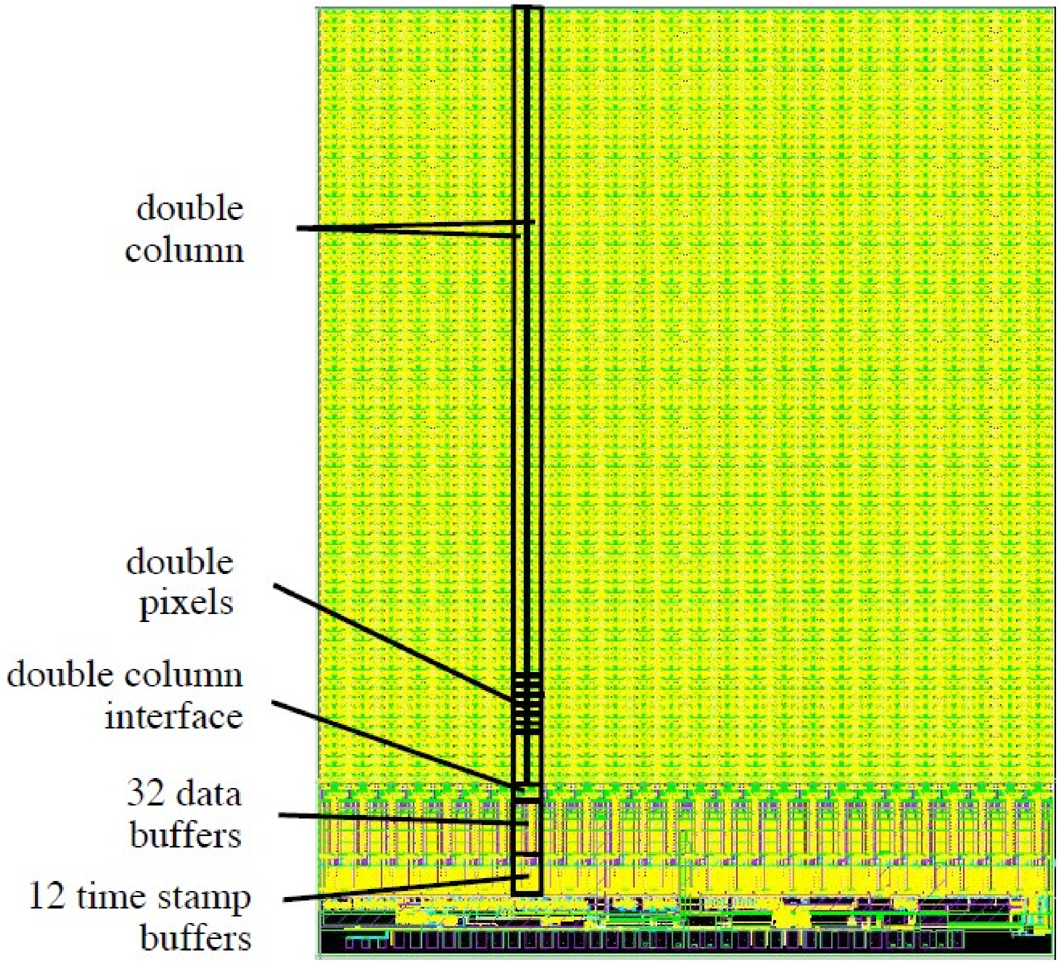




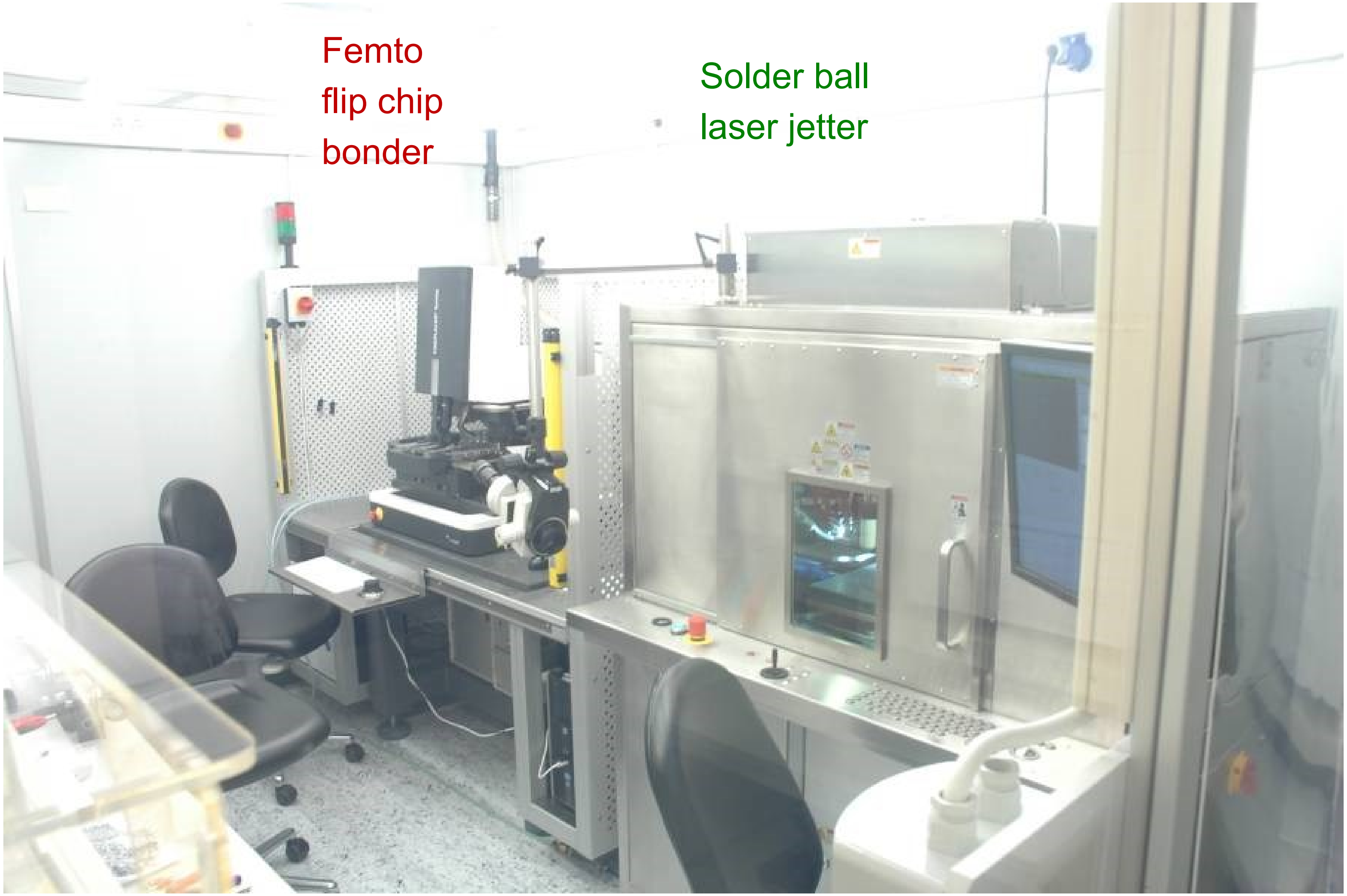
Design at PSI by H-C.Kastli et. al.

Readout Chip PSI46v2

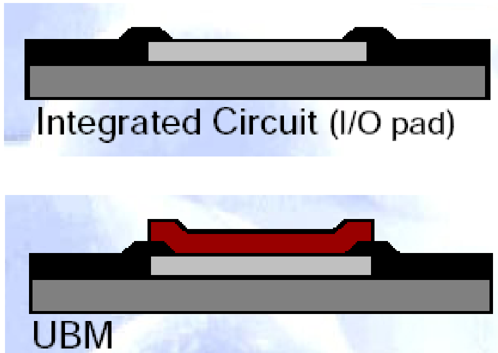
- Process: 0.25 µm, 5 metal layers
- 1.3 M transistors
- number of pixels: 4160 (52x80), organized in double columns
- pixel size: 100 µm x150 µm (rφ x z)
- power supplies: +2.5 V (digital) and +1.75 V (analog), 6 on-chip programmable voltage regulators
- power consumption: ~120 mW = 29 µW / pixel
- Programming interface: modified I^{2}C running at 40 MHz.

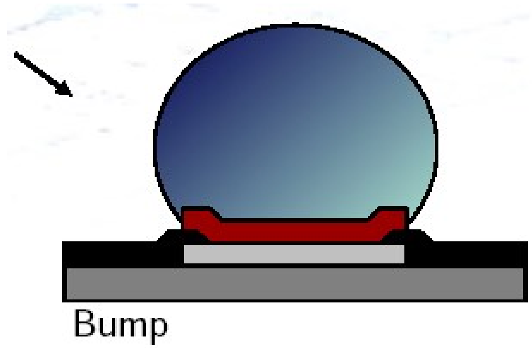


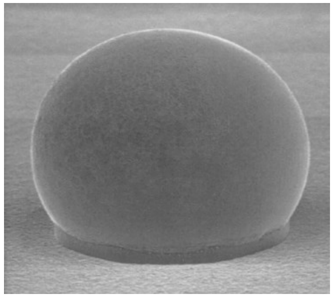
Bump Bonding @ DESY

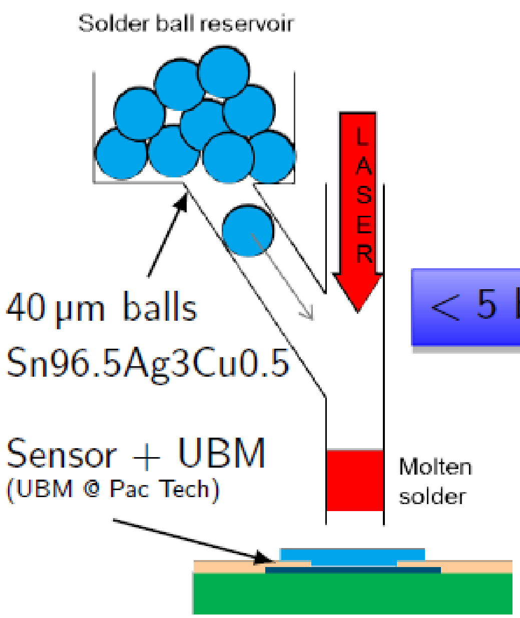


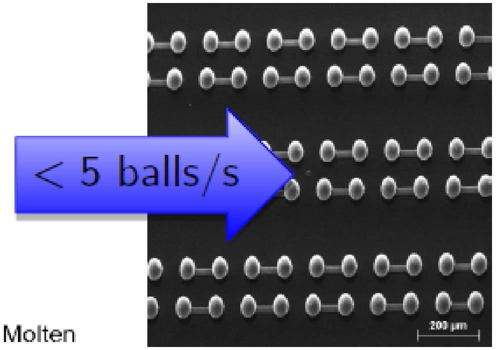
Solder Ball Jetting









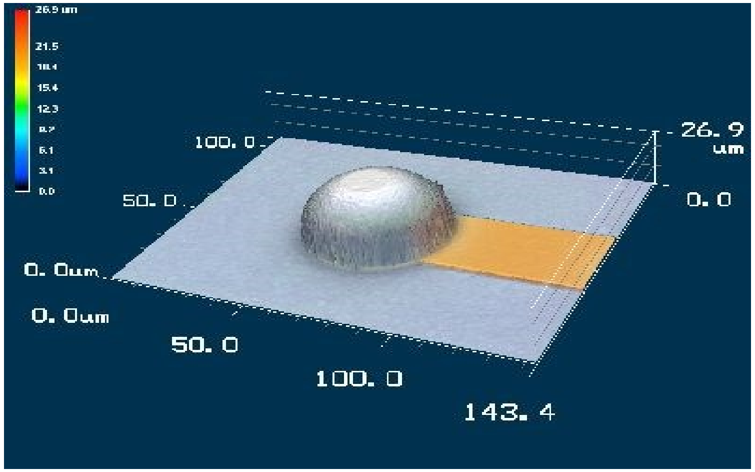


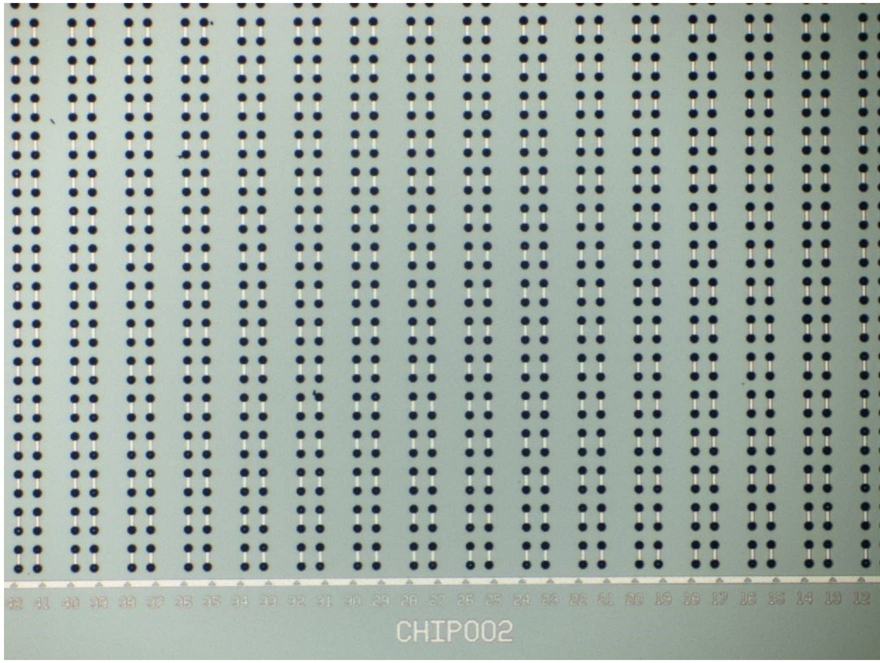
- Start with high-precision solder balls 40 µm diameter
- Singulate and drop through capillary towards pad
- Melt by laser pulse during fall, solidify on pad
- Step-motor controlled: 5 balls/s implies 4h/module

SnAg Solder Balls

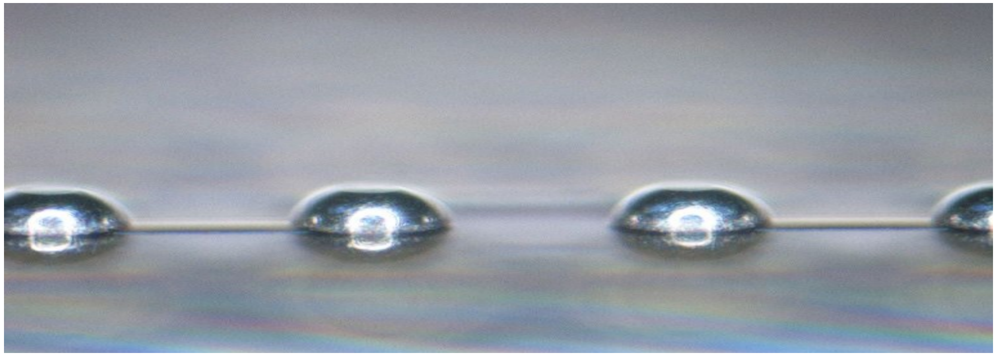
Pad bumped with
40 μm solder ball,
after 240°C re-flow

Composition
96.5% Sn
3% Ag
0.5% Cu





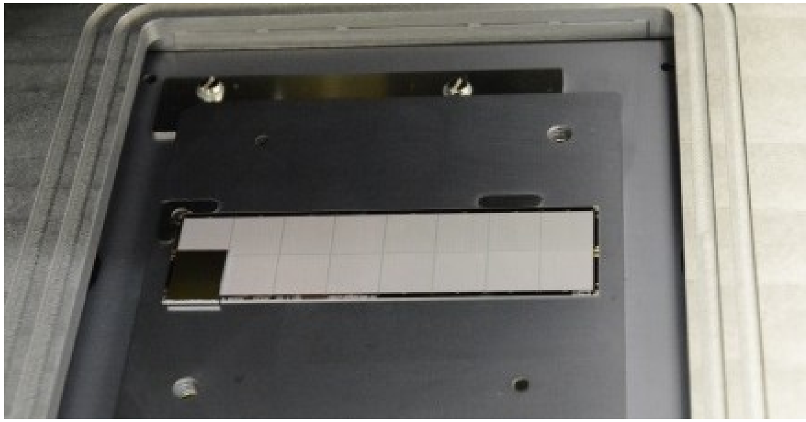
missing balls re-worked automatically



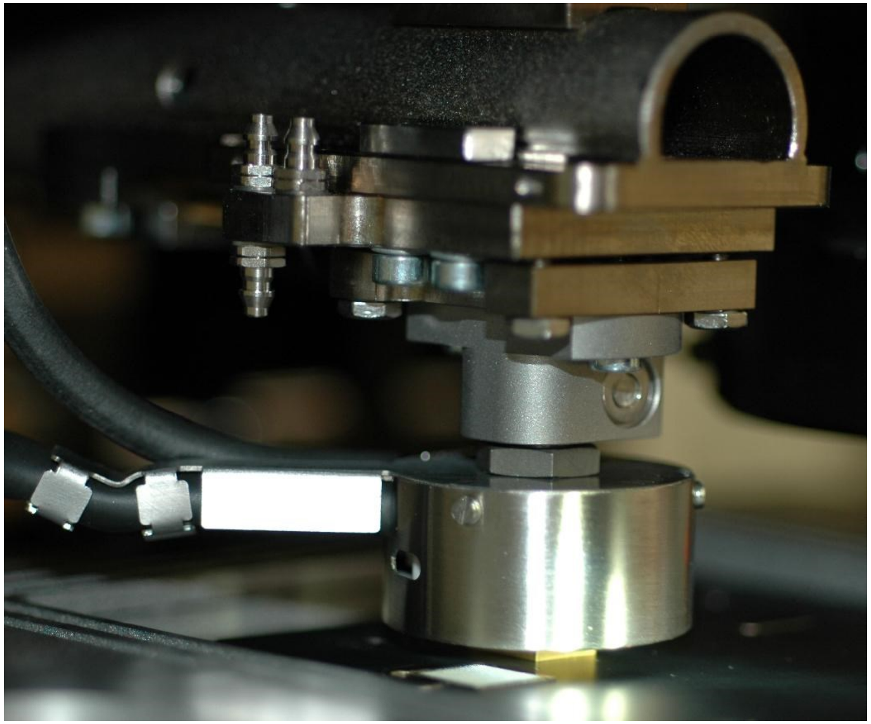
Side view of chain structure with
the 40 μm solder balls

Flip Chip Bonding

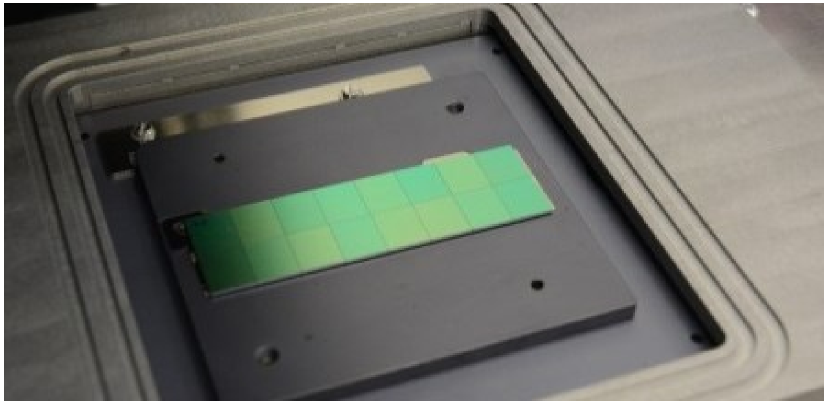
1st ROC placed on sensor (with solder balls)



readout chip bonded onto the Si sensor with 160 N force @ 240°C

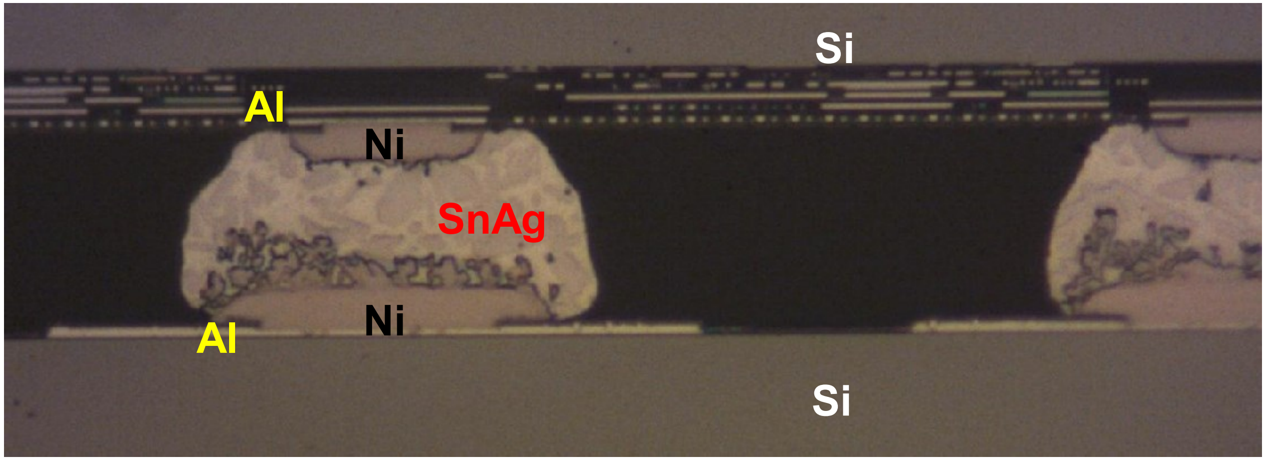


All 16 ROCs: flip-chip bonded



In-situ solder reflow performed in formic acid atmosphere

24 μm

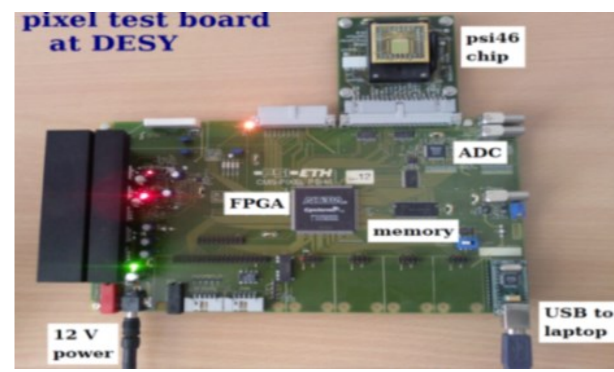


Destructive testing: cut and polish, microscope inspection

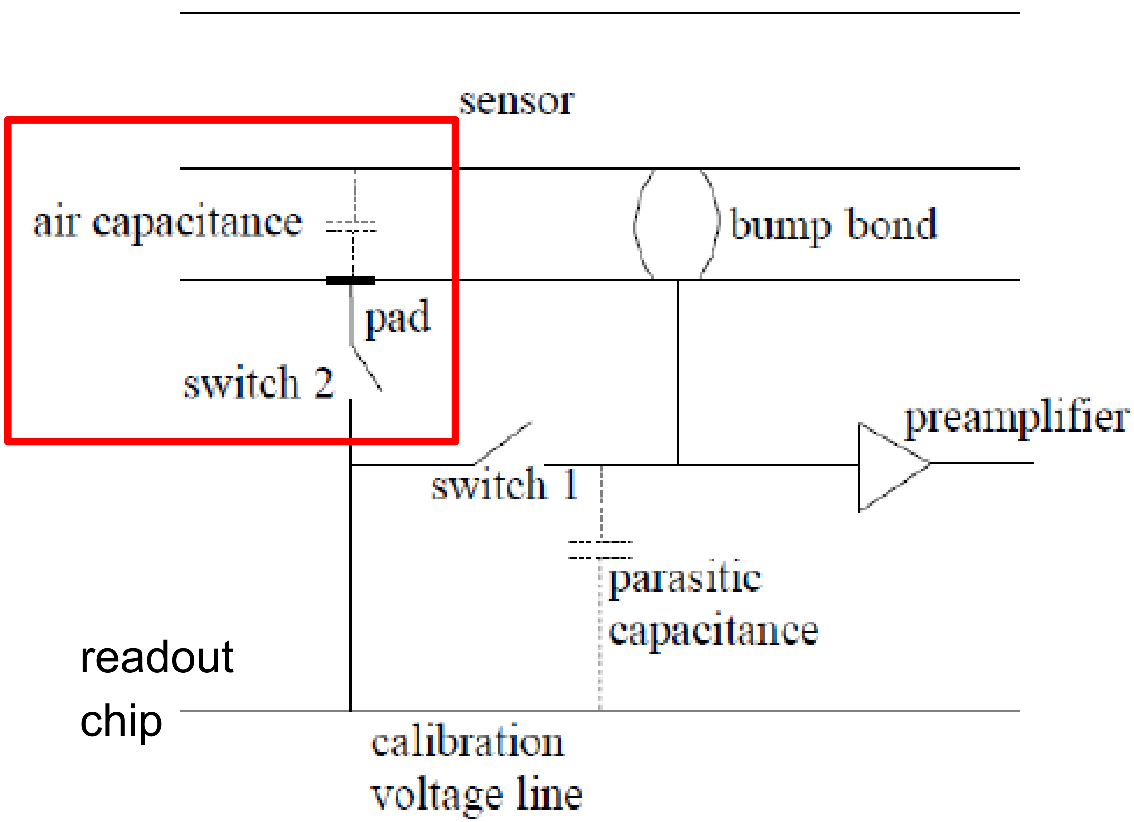
Non-destructive electrical test on a probe station

Probe Station

Probe Card



Test Board

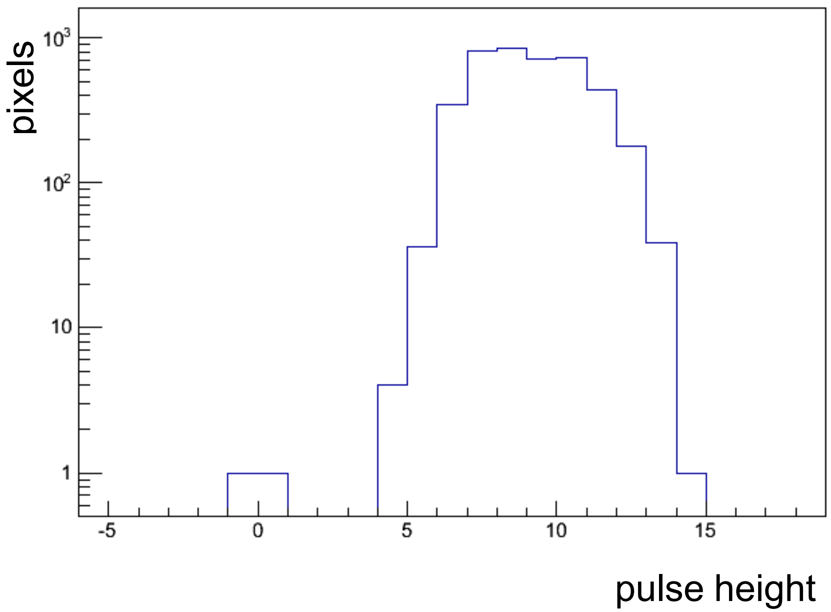


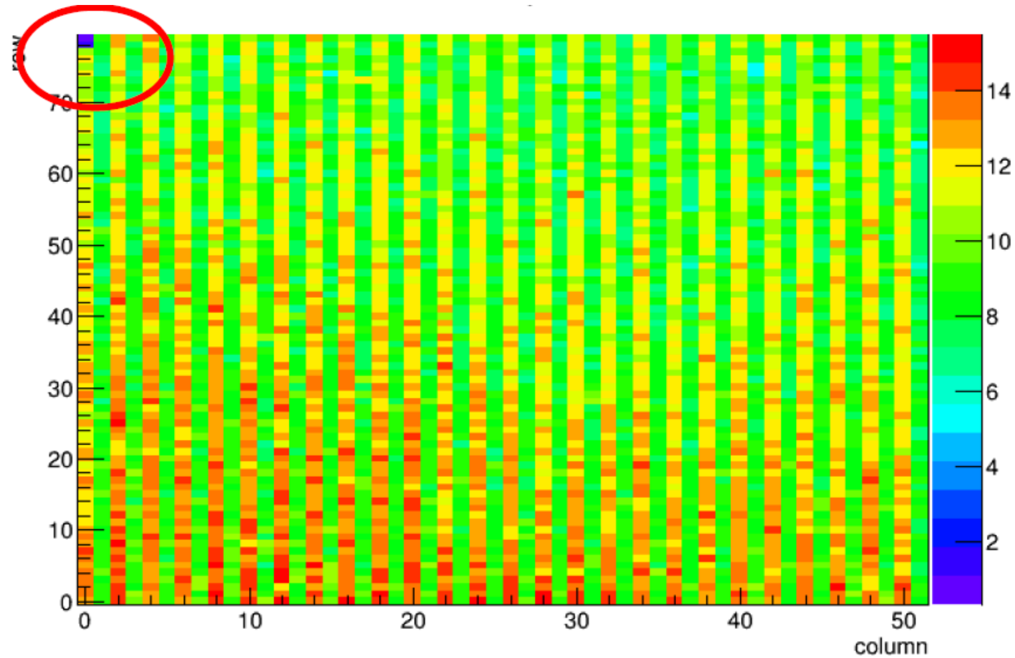
Bump Bonding Test Strategy

Test pulse via sensor pad and air capacitance

- read out analog pulse height (through sensor)
- Missing bump bonds at zero

Test Results

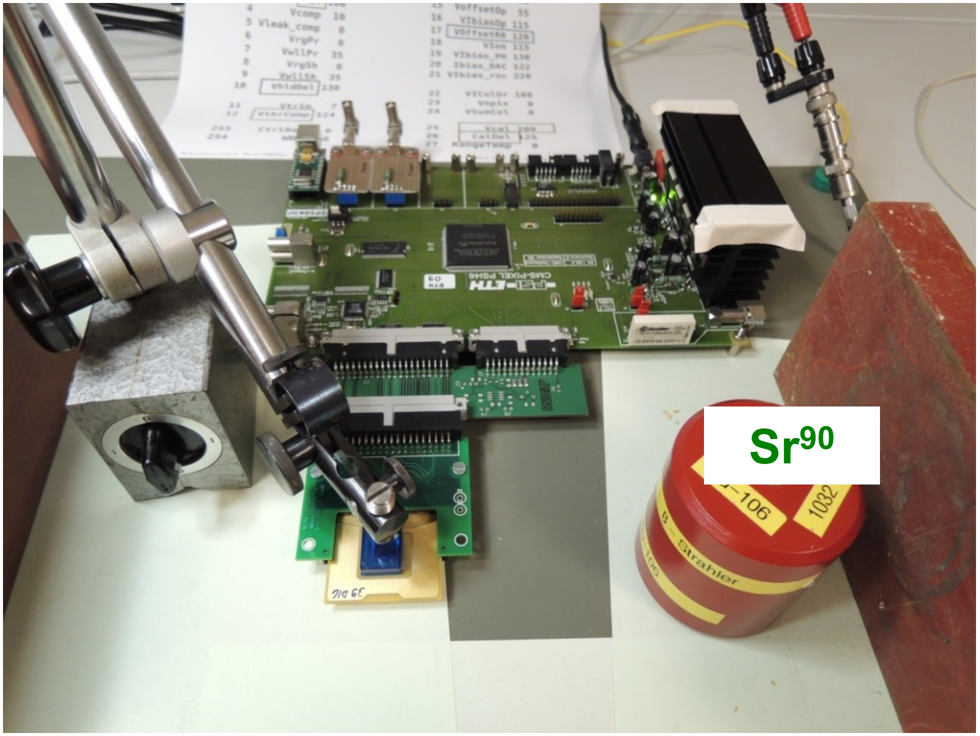


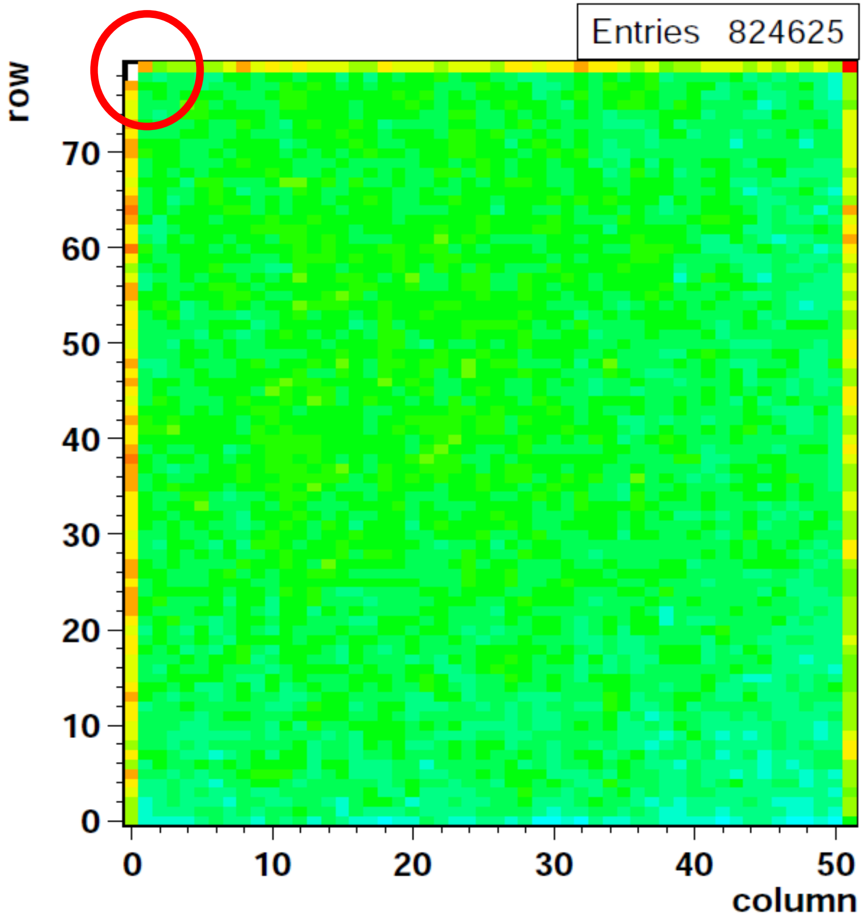


All pixels respond to test pulses – zero pulse height indicate missing bump
Clear separation between missing bump bonds and the good connections

2 Missing Bumps from pulse height test at the top left corner

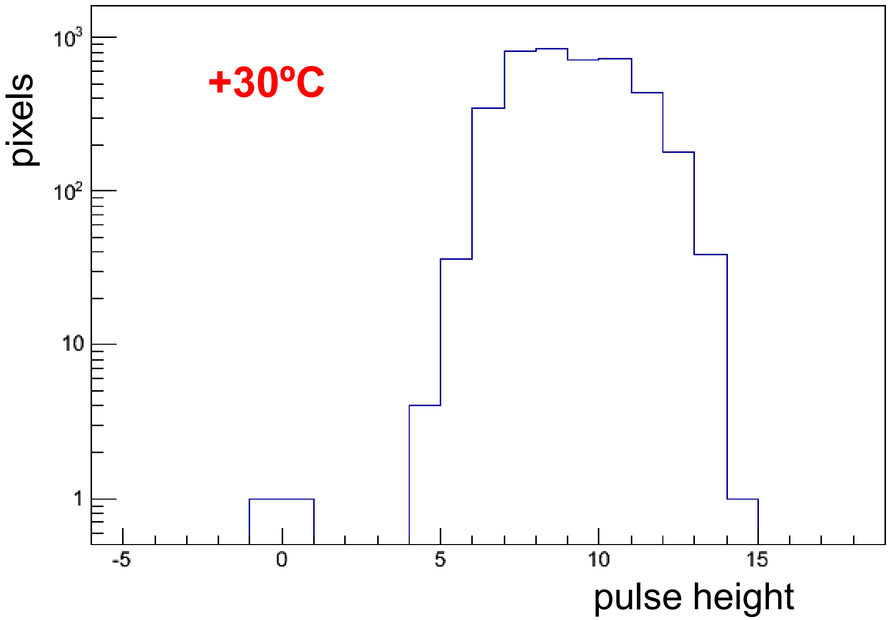
2 Missing bumps at the top left corner confirmed with **Sr^{90} (radioactive β-ray source) hit map**

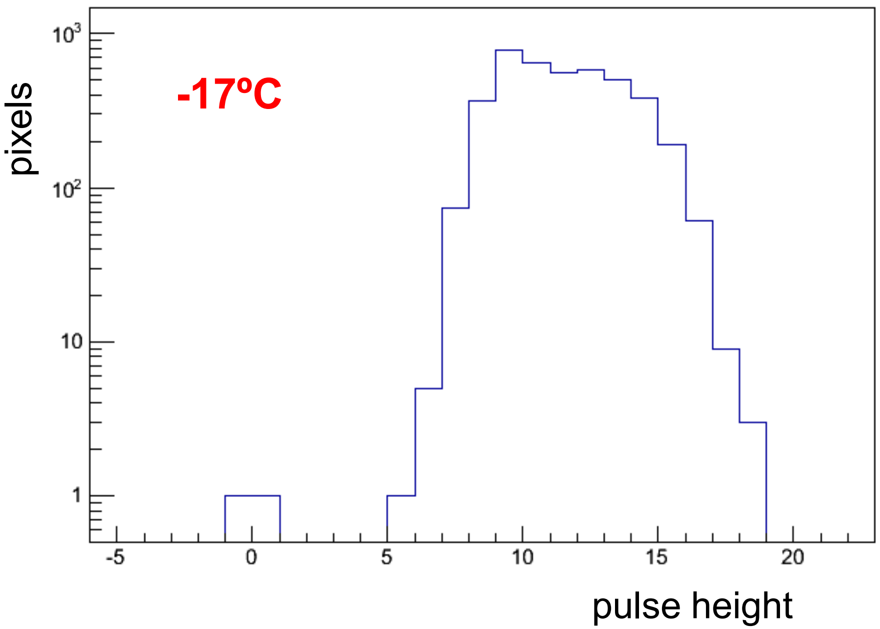




Thermal Cycling

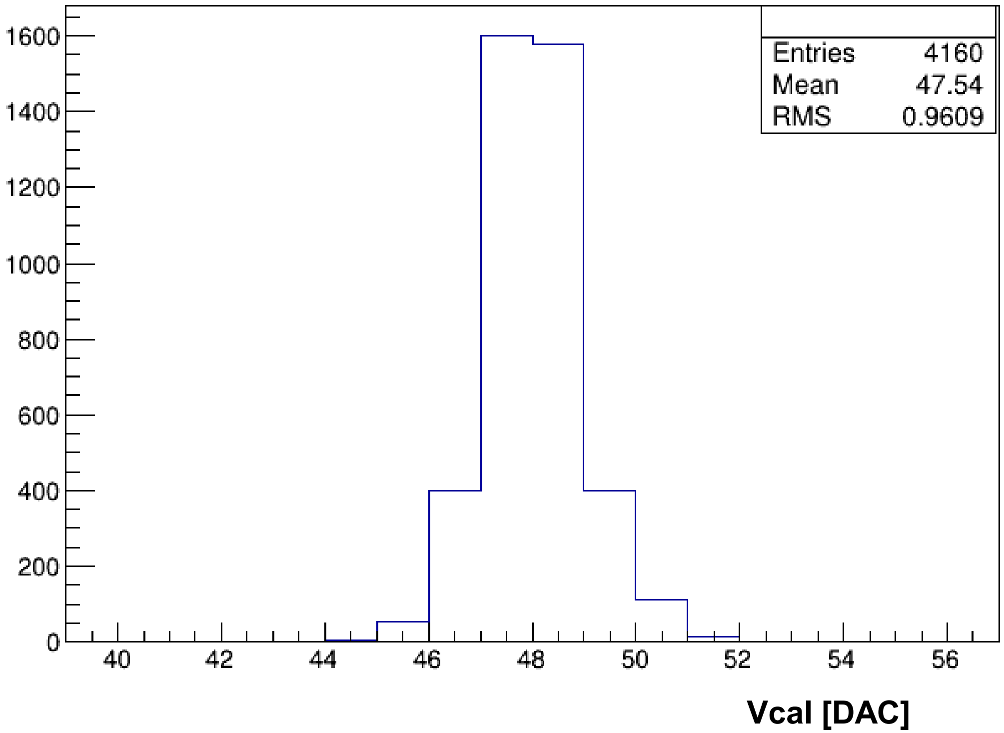
- Temperature variations from **-17ºC to +30ºC**
- Several cycles performed back and forth
- Study performed for a week (1-7 h / cycle)

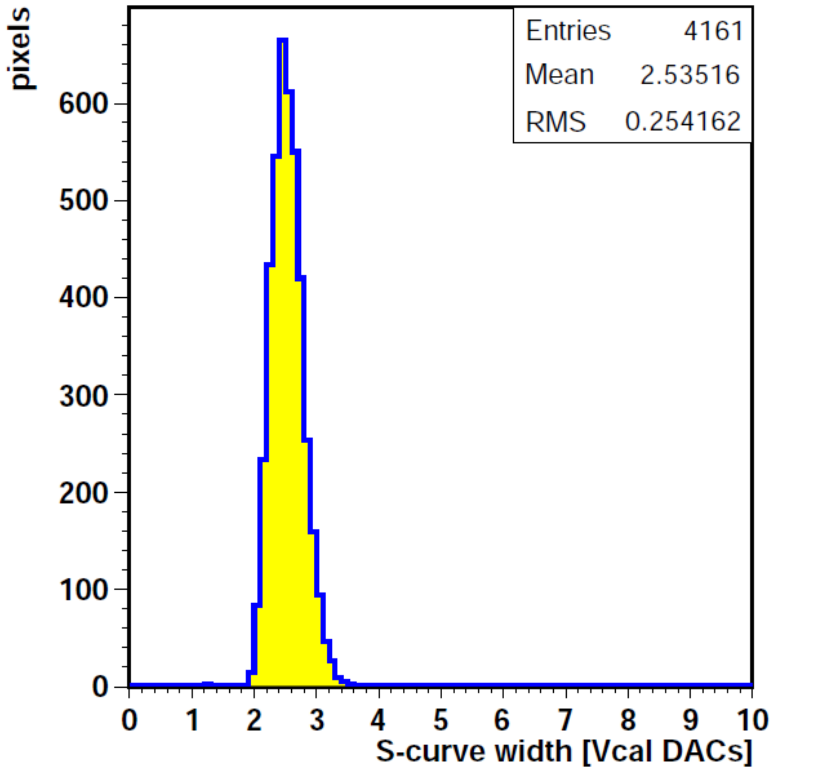




Bump bonding tests show consistency on all days at high and low temperatures
Bumps are in place, 2 bad bonds as expected

Threshold and Noise

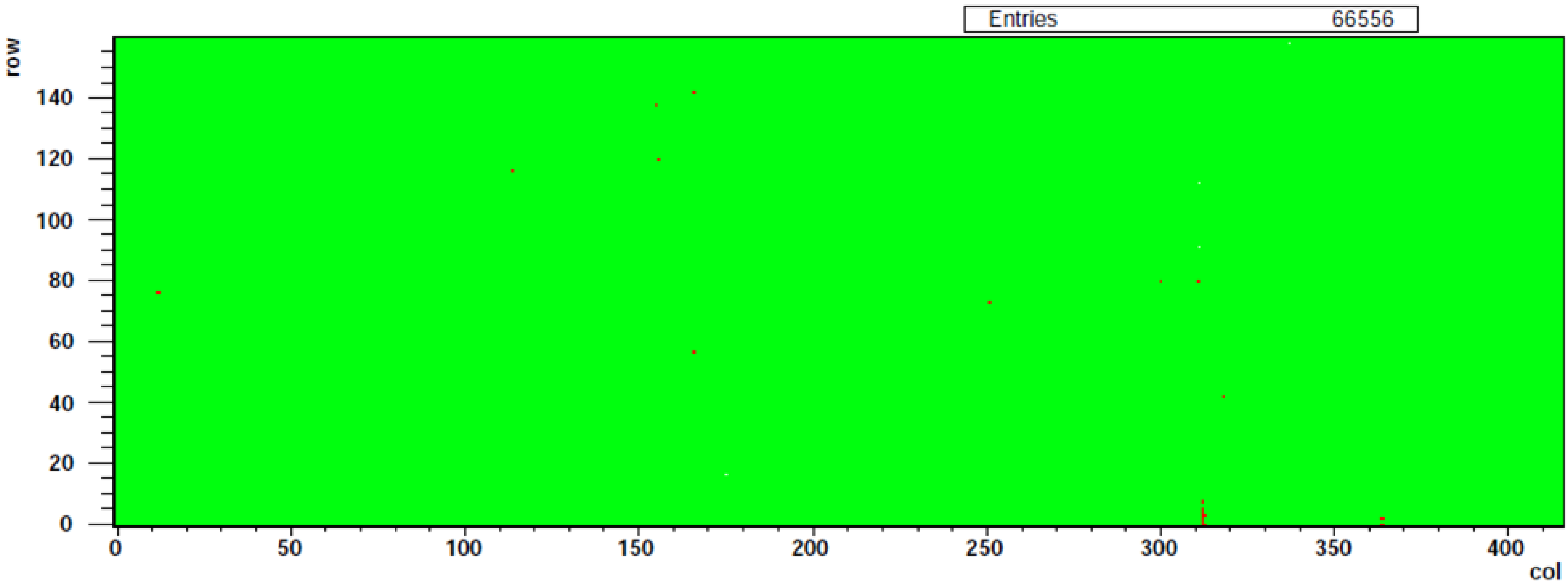




Charge threshold @ **3100 e**, important for charge sharing
Influences position resolution and efficiency after irradiation

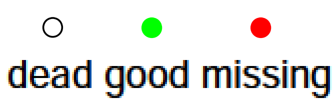
Noise from width of threshold curve **~ 160 e**
Similar to PSI Indium bump bonded pixel modules with the same ROC.

Full Module Bump Bond Test



module with 16 readout chips:

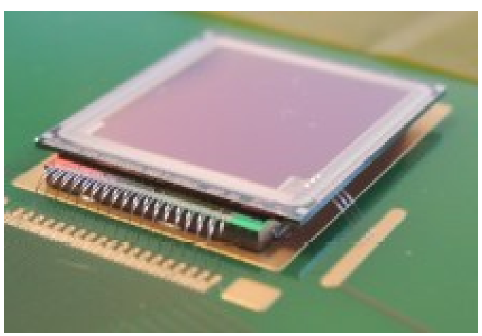
66'560 pixels

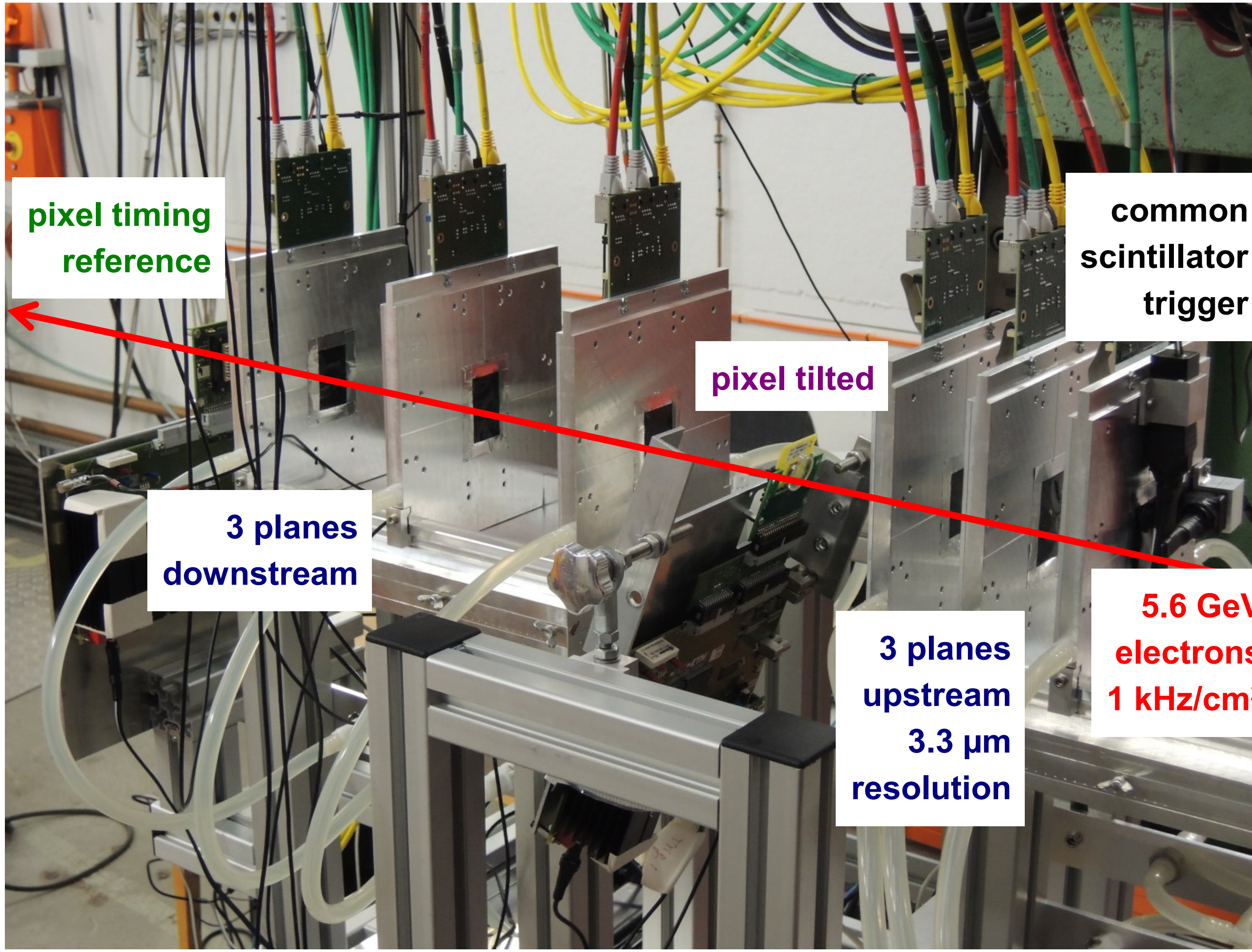


- bump bonding test result:
  - white = dead pixel (4)
  - green = good bump (99.97%)
  - red = missing bump (19)

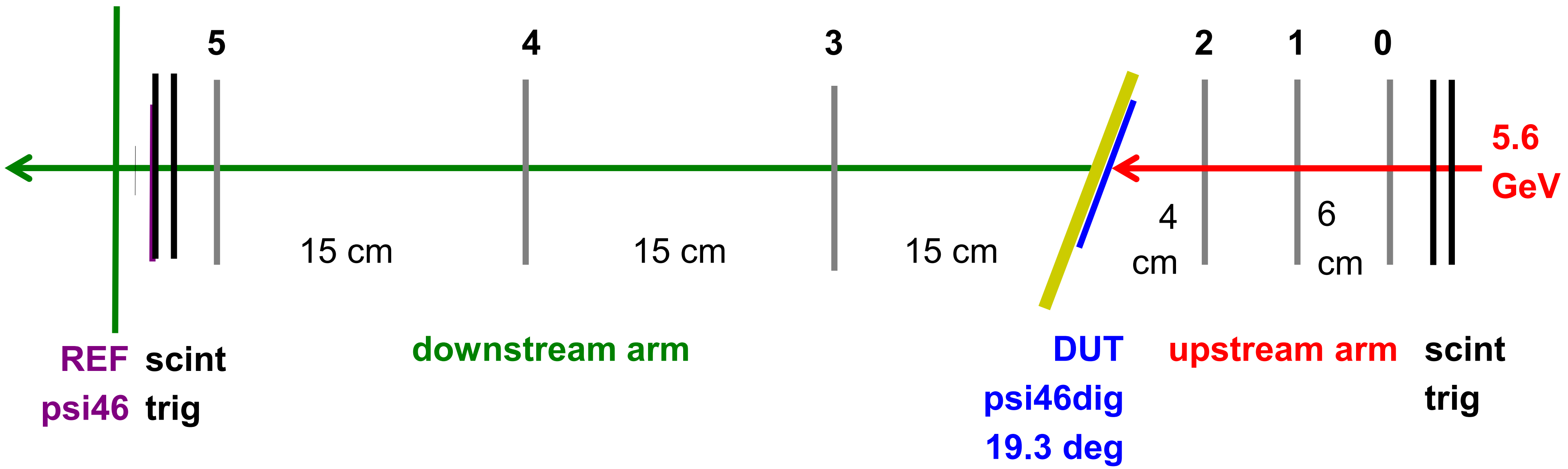
DESY Testbeam
and AIDA Telescope
with Mimosa Sensors

Single chip module as
device under test (DUT)



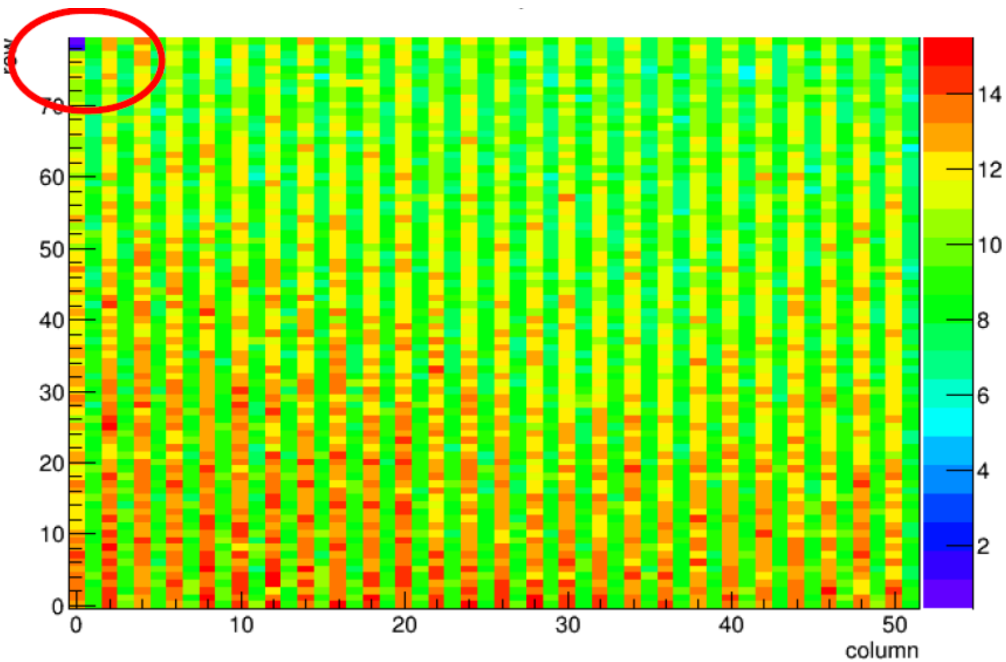


DESY Test Beam Setup

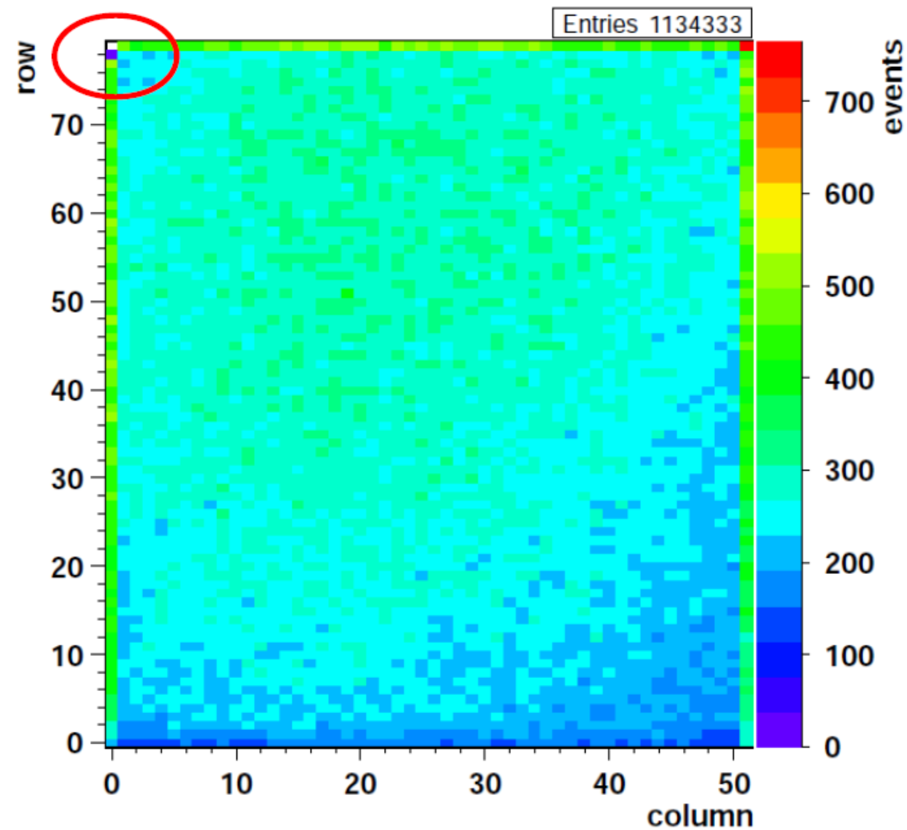


- Upstream telescope arm 0-1-2:
  - as close as possible to DUT, but allow for tilting
- DUT = single chip module, tilted by up to 30 degrees
- Downstream telescope arm 3-4-5:
  - equally spaced between DUT and REF
- REF = single chip module for timing
- Trigger: 4-fold scintillator coincidence, 1×1 cm^2 area

electrical test



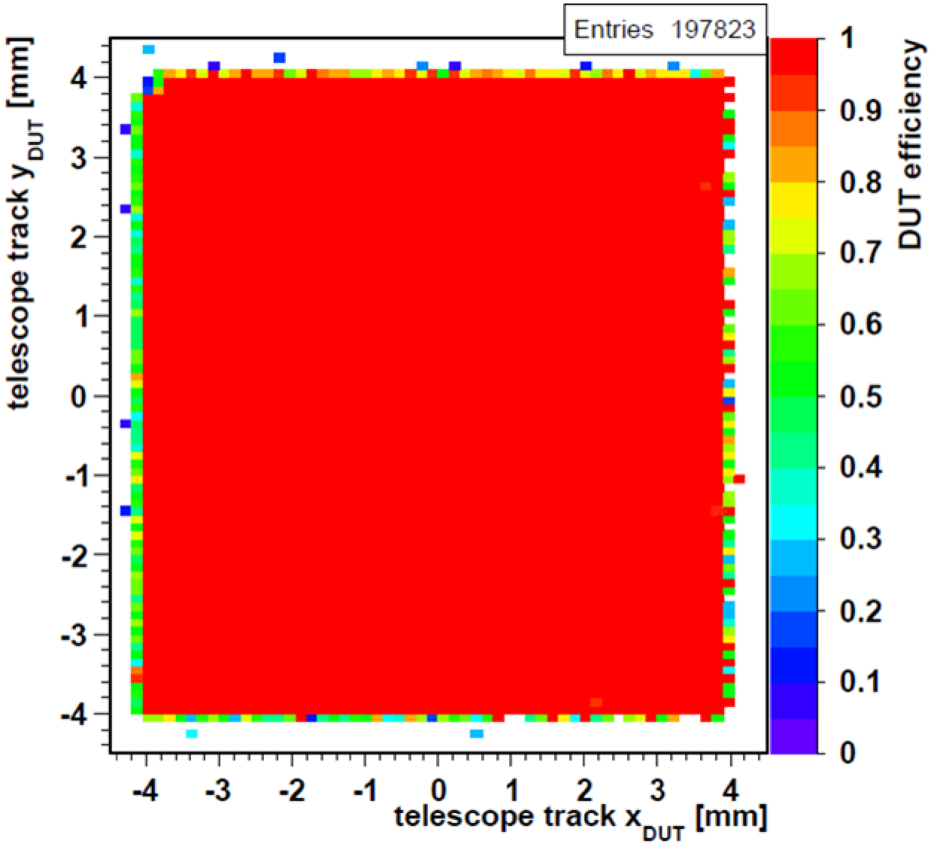
beam profile @ DESY test beam



2 Missing bumps at top left corner (reconfirmed with beam profile in DESY test beam)

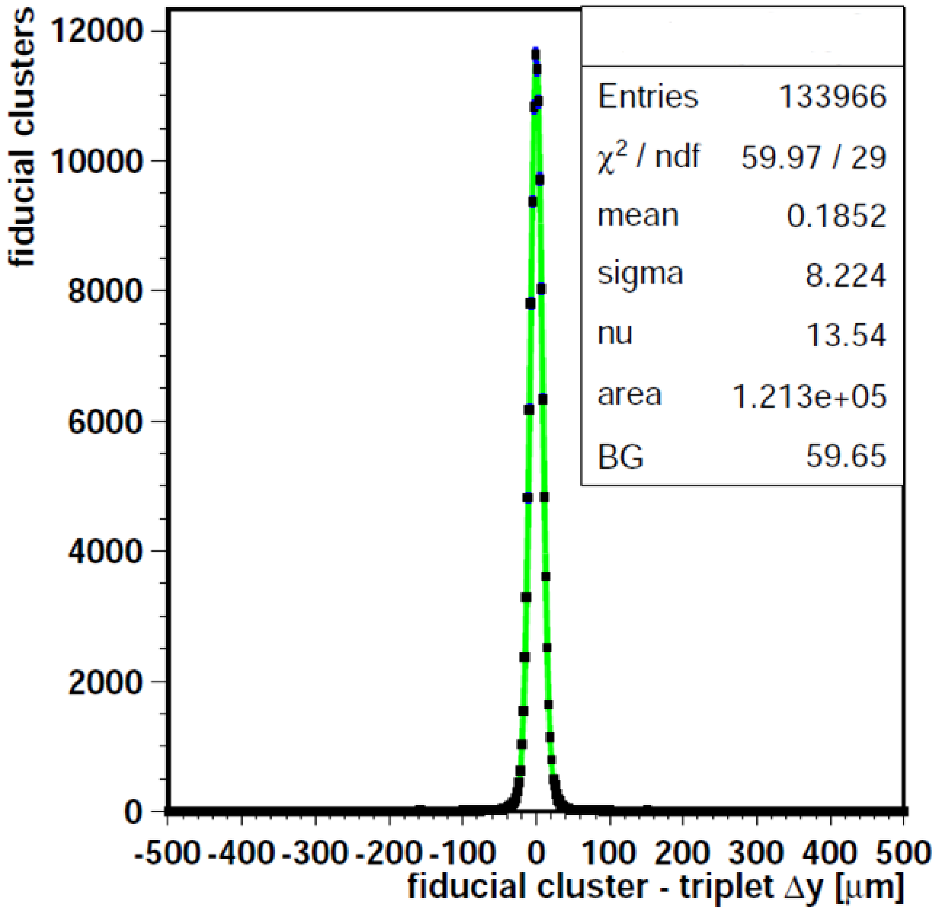
Tracking Efficiency

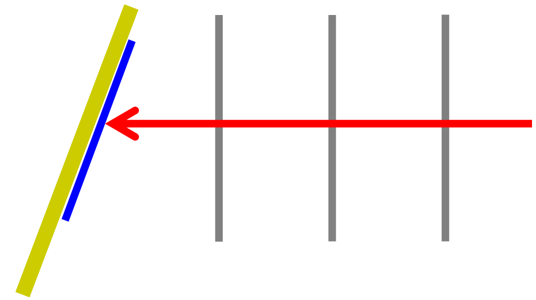
$$\text{Efficiency} = \frac{\text{DUT hit linked to isolated telescope track with link to REF hit}}{\text{isolated telescope track with link to REF hit}}$$



Fiducial Efficiency **99.965%**

Position Resolution





Position resolution calculated by comparing the track position interpolated by the telescope planes and the pixel hit position using **charge sharing** between rows

$$\text{atan}(\text{pixel width in row direction}/\text{sensor thickness}) = \text{atan}(100\,\mu\text{m}/285\,\mu\text{m}) \approx$$ **19.3 degrees**

Tilt 19.3 degrees, **Resolution ~ 7 μm**

Corrected for 4.3 μm telescope resolution

Summary

- Set up in-house flip-chip bump bonding process for hybrid silicon pixel detectors
- Solder ball placement using commercial laser jetter covering the entire sensor
- Electrical testing of the bump connections by sensing a capacitively induced charge
  - high bump bond yield achieved (confirmed by source test)
- Noise in DESY SnAg bump bonded detector similar to PSI In bump bonded detector
- Detector at DESY electron test beam: high tracking efficiency of **99.96%** and an excellent position resolution **7 μm** achieved