The CMS pixel detector in LS1: a surprise with a happy end

Séminaires de physique corpusculaire

DPNC , 21. Sept 2015

R. Horisberger, PSI

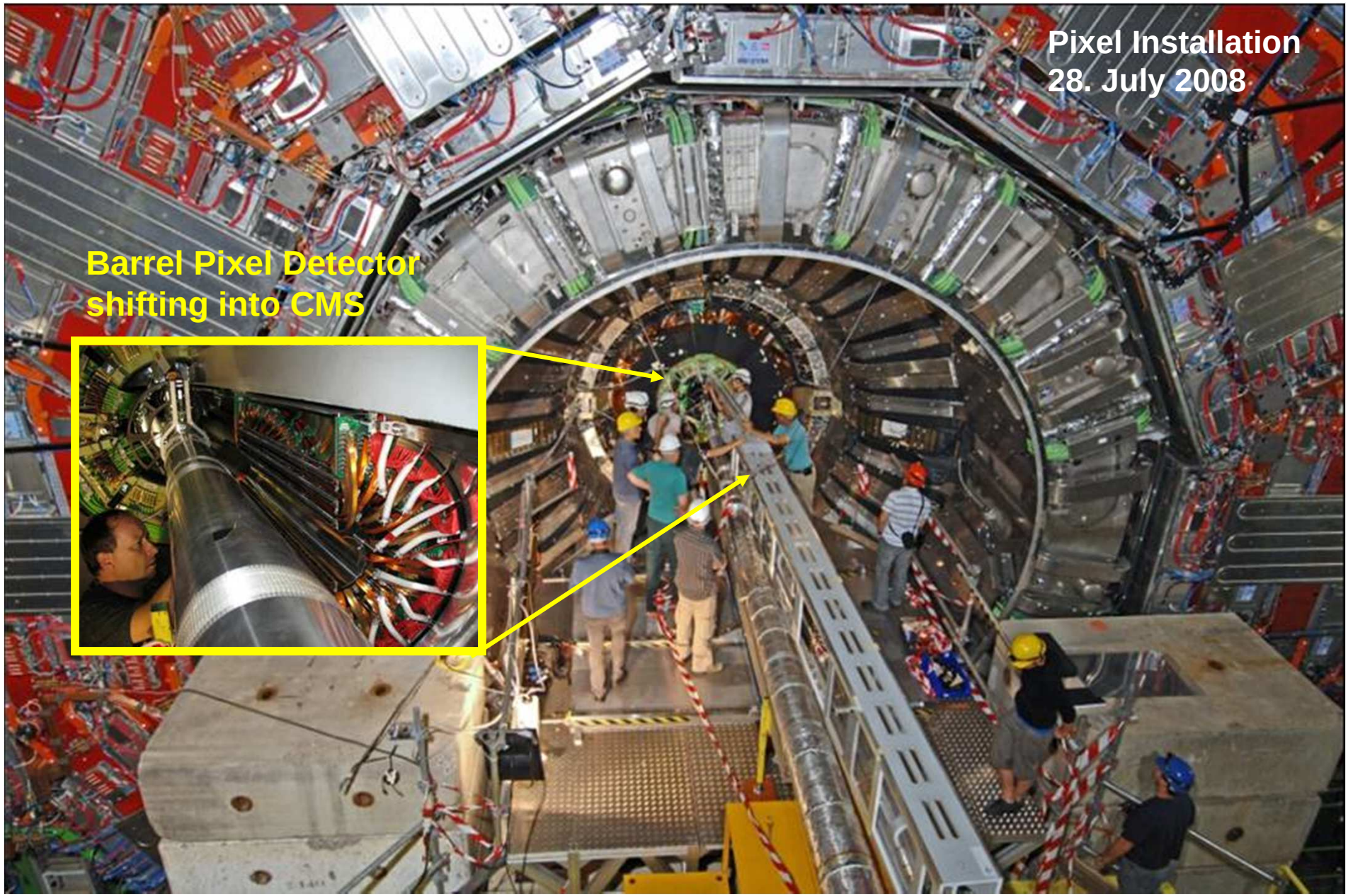
on behalf of BPIX repair groups

PSI *: W. Bertl, W. Erdmann, R.H., H-C. Kästli, D. Kotlinski, B. Meier, T. Rohe, S. Streuli*

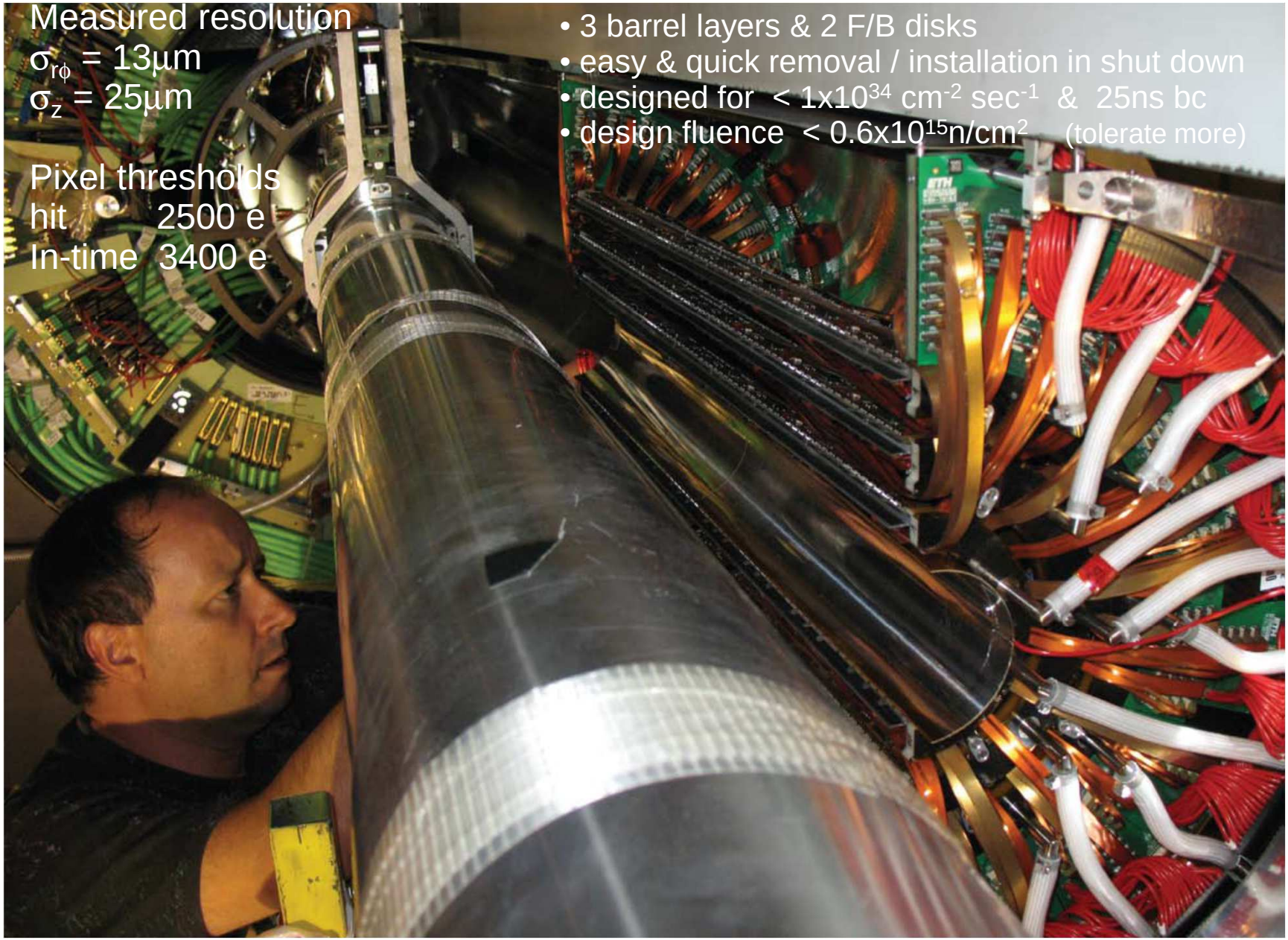
ETHZ *: A. Starodumov, M. Takahashi*

Uni ZH *: L. Caminada, A. De Cosa*

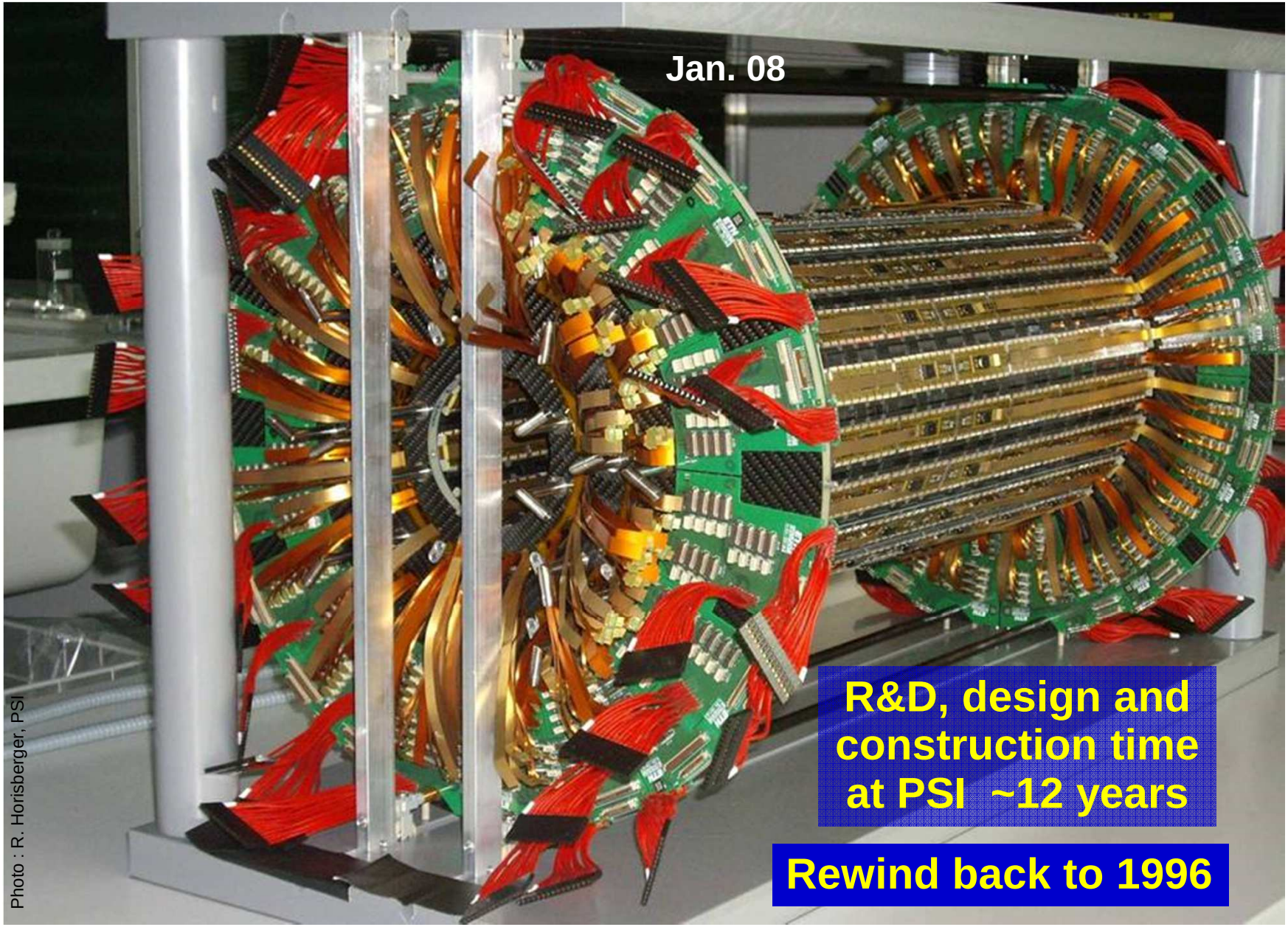
Inserting the Pixel System in 2008



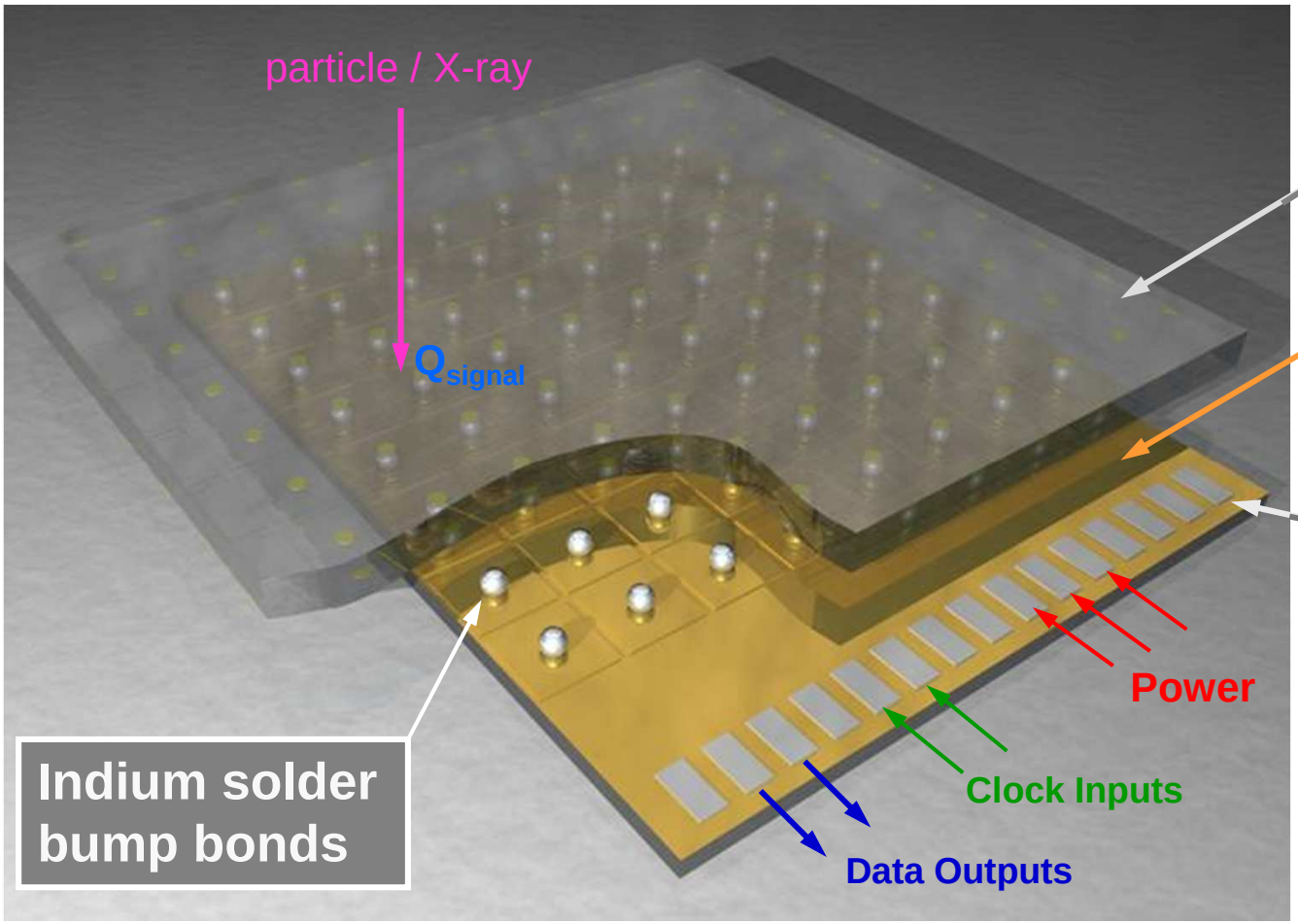
2008 Pixel Detector works very well !



Assembly of Barrel Pixel Detector at PSI



Hybrid Pixel Detectors Basics



pixelated particle sensor

amplifier & readout chip CMOS

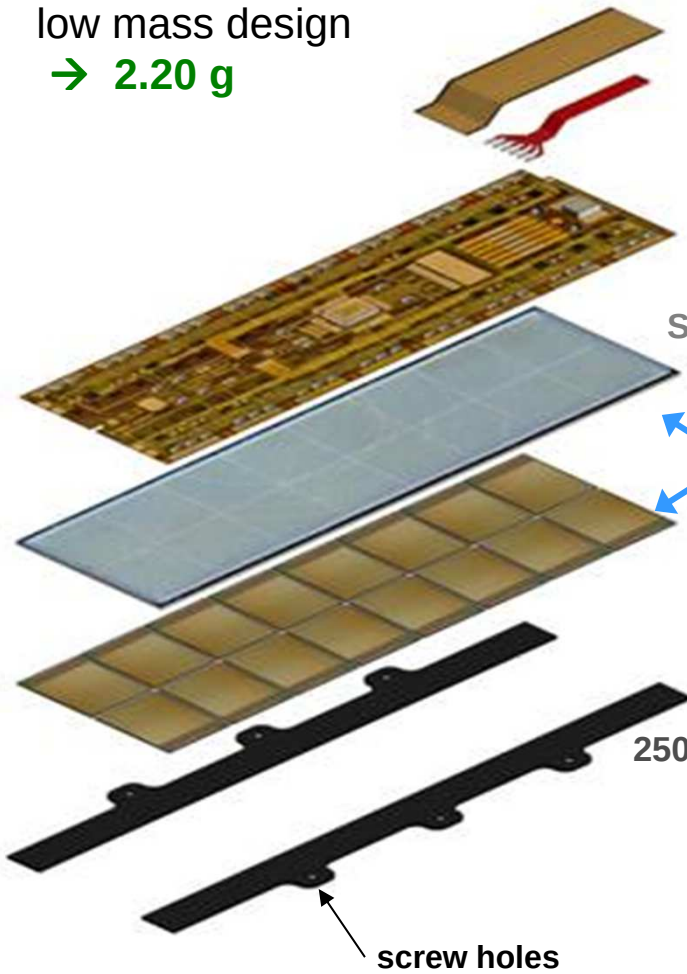
Connection wire pads
power
inputs
outputs

particle / X-ray → signal charge → amplifier → readout → digital data

Hybrid Pixel Module for CMS

Module Construction

low mass design
→ **2.20 g**



In **1996**, completely crazy project:

Major uncertainties about:

1) rad. hard silicon pixel sensors
   for particle fluences to 10^{15} p/cm^2
   - signal charge? trapping ?
   - Lorentz angle ?
   - depletion & type inversion ?
   - HV robustness ?

2) micro-bump bonding
   - feasibility for <20µ bumps ?
   - **costs ?** → budget ?

3) Pixel Read Out Chip (ROC)
   - low power design, speed ?
   - low pixel noise & thresholds ?
   - rad. hardness? (>100KGy) **costs?**

4) Data Rates & Readout
   - 10 Tbit/sec raw data rates
   - ? ? ? ? ? ? ? ? ? ? ?

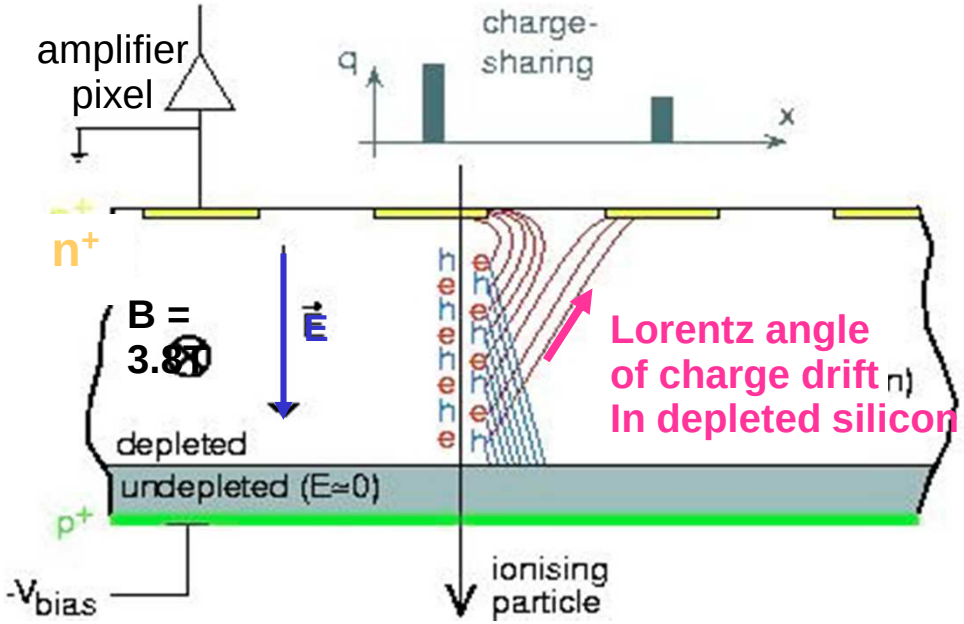
5) 6)…. **Physics performance?**

Pixel Sensor: Precision by Sharing

Sharing of signal charge
by Lorentz angle

ROC with analog pixel readout
→position interpolation (η-algorithm)

Pixel size 100μ x 150μ
→ precision coordinates ~10-20μ

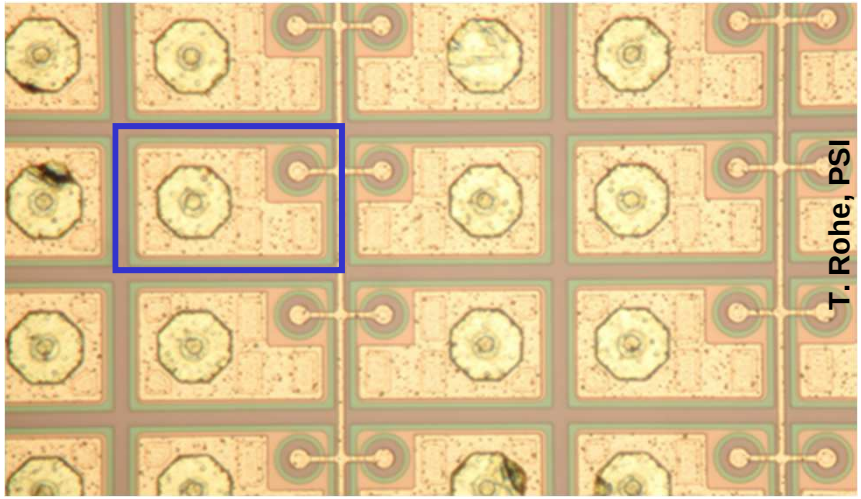


Sensor R&D (PSI)

Design of masks (PSI)

Electrical qualification (PSI)

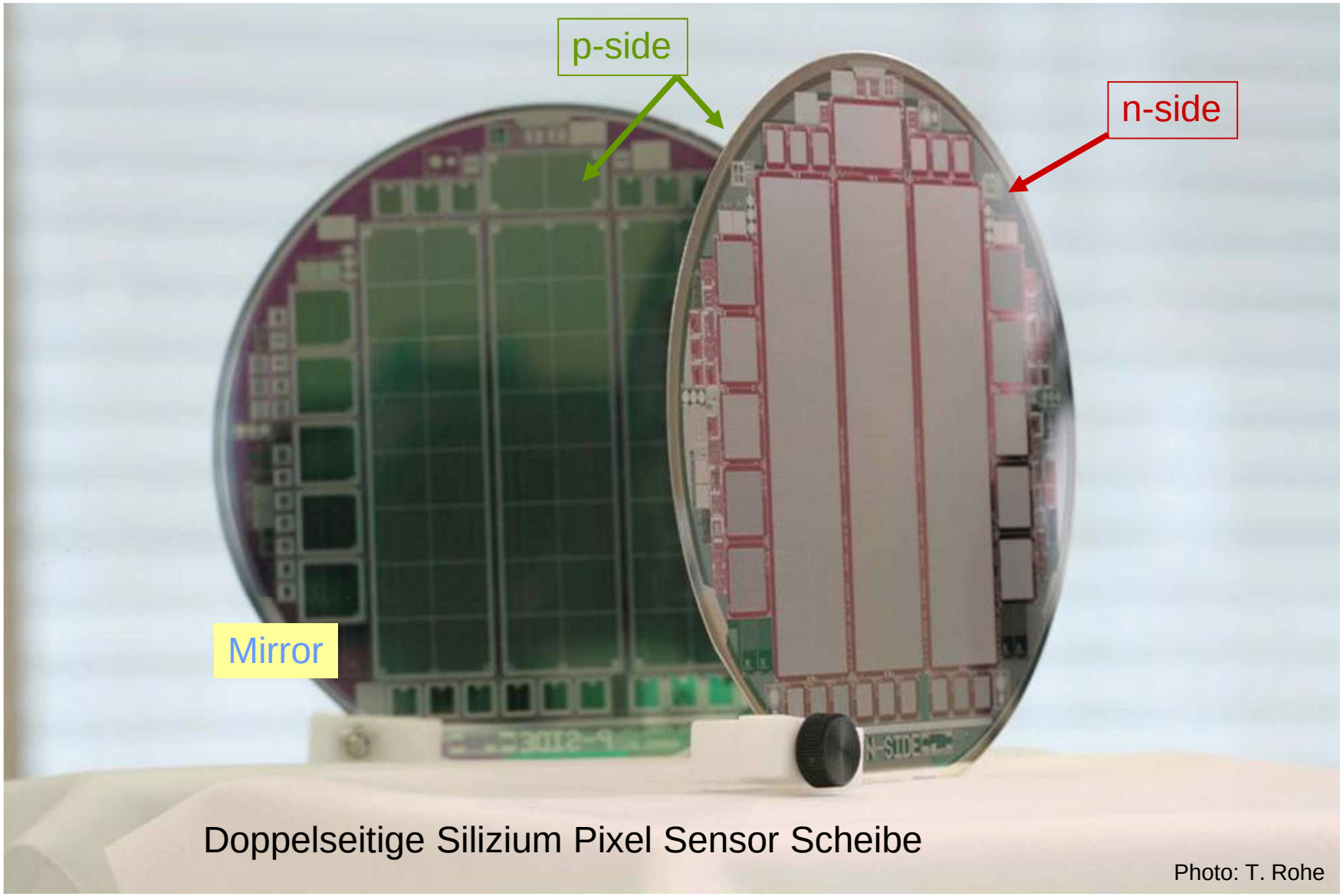
Sensor test beam @ CERN (UZH, PSI)



Silicon sensor production

→ CIS, Erfurt Germany

Silizium Pixel Sensor Scheiben

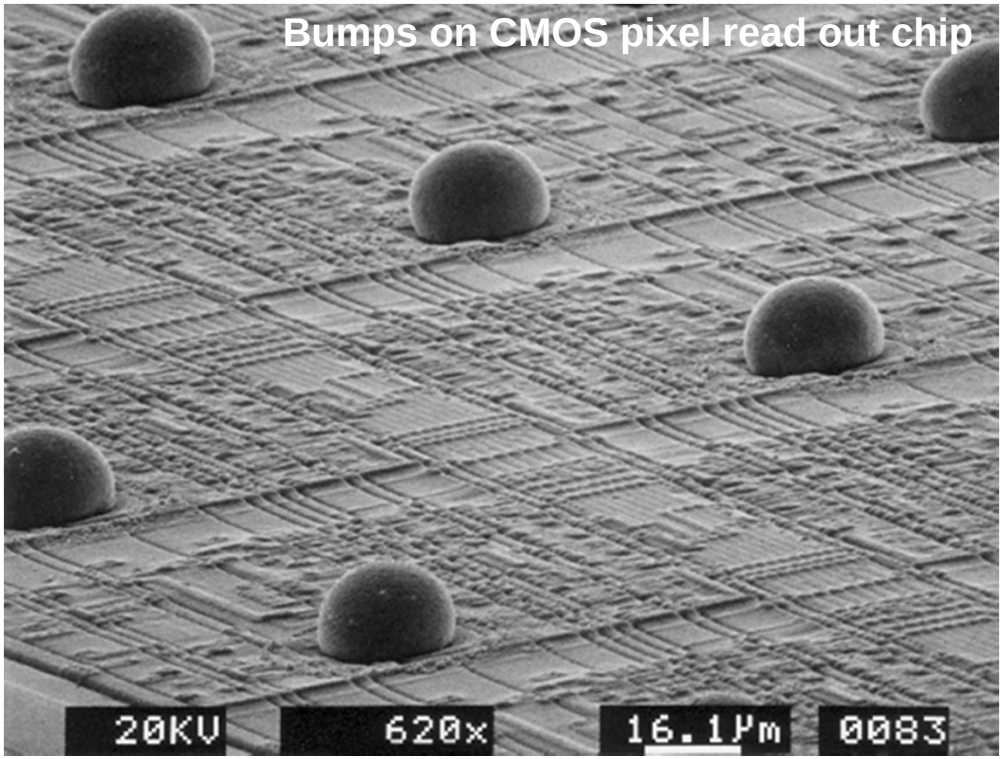


Doppelseitige Silizium Pixel Sensor Scheibe

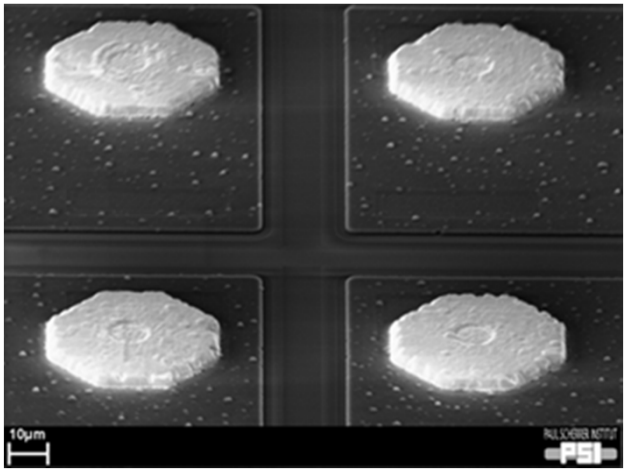
Photo: T. Rohe

Micro–Bumpbonding at PSI

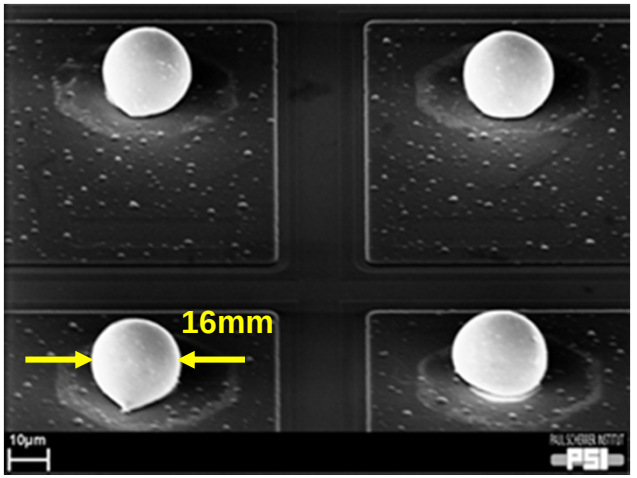
- connecting pixel sensors with ROC electronics
- connection density up to 10'000/cm^2
- technique developed at PSI (LMN)
- licensed to spin-off company DECTRIS



Indium "cakes" before reflow



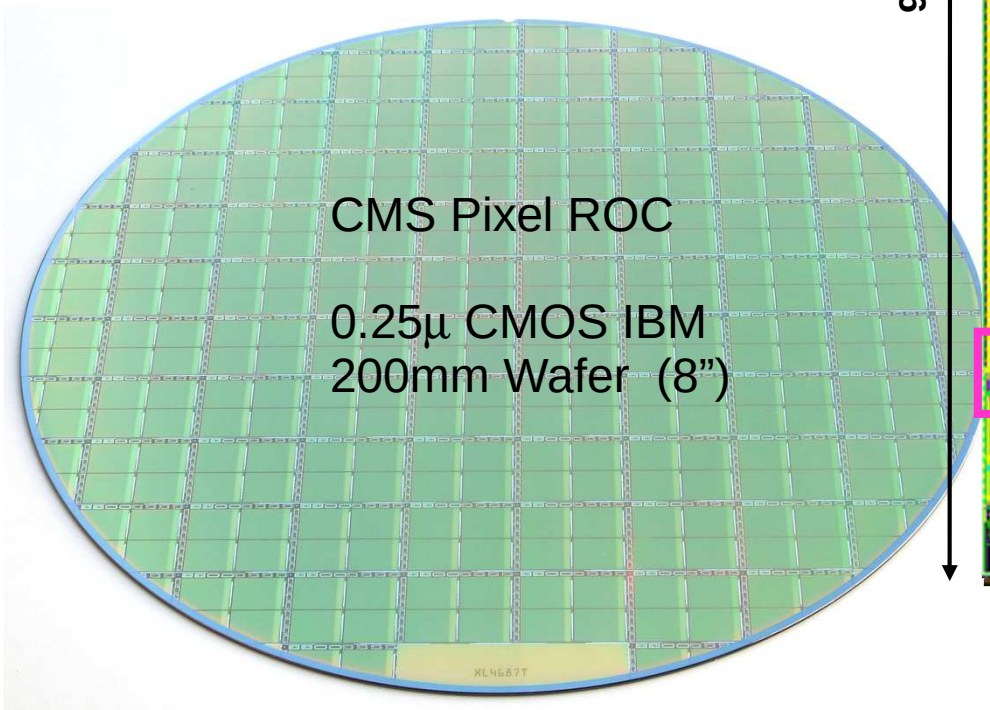
reflow

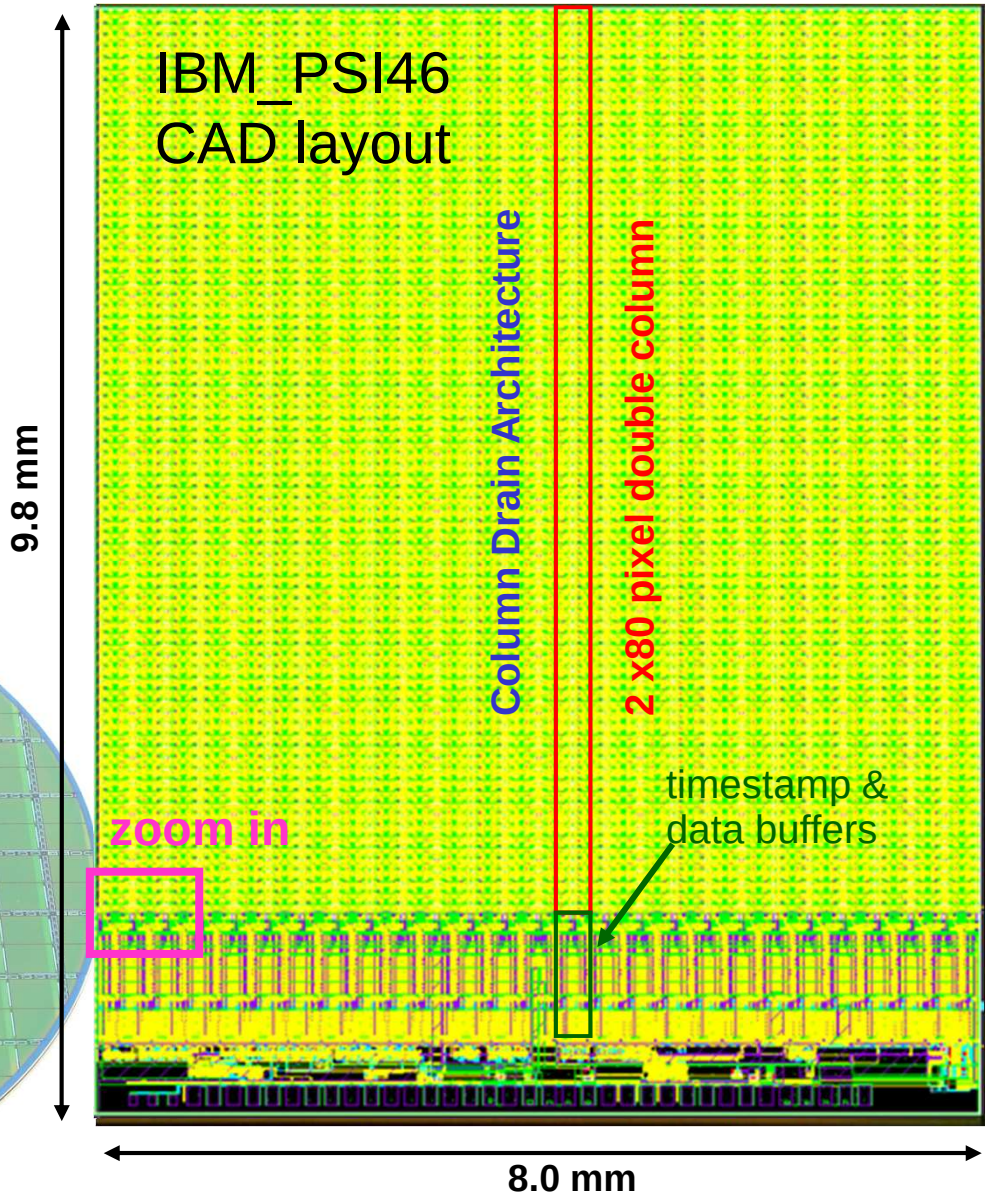


Indium balls after reflow

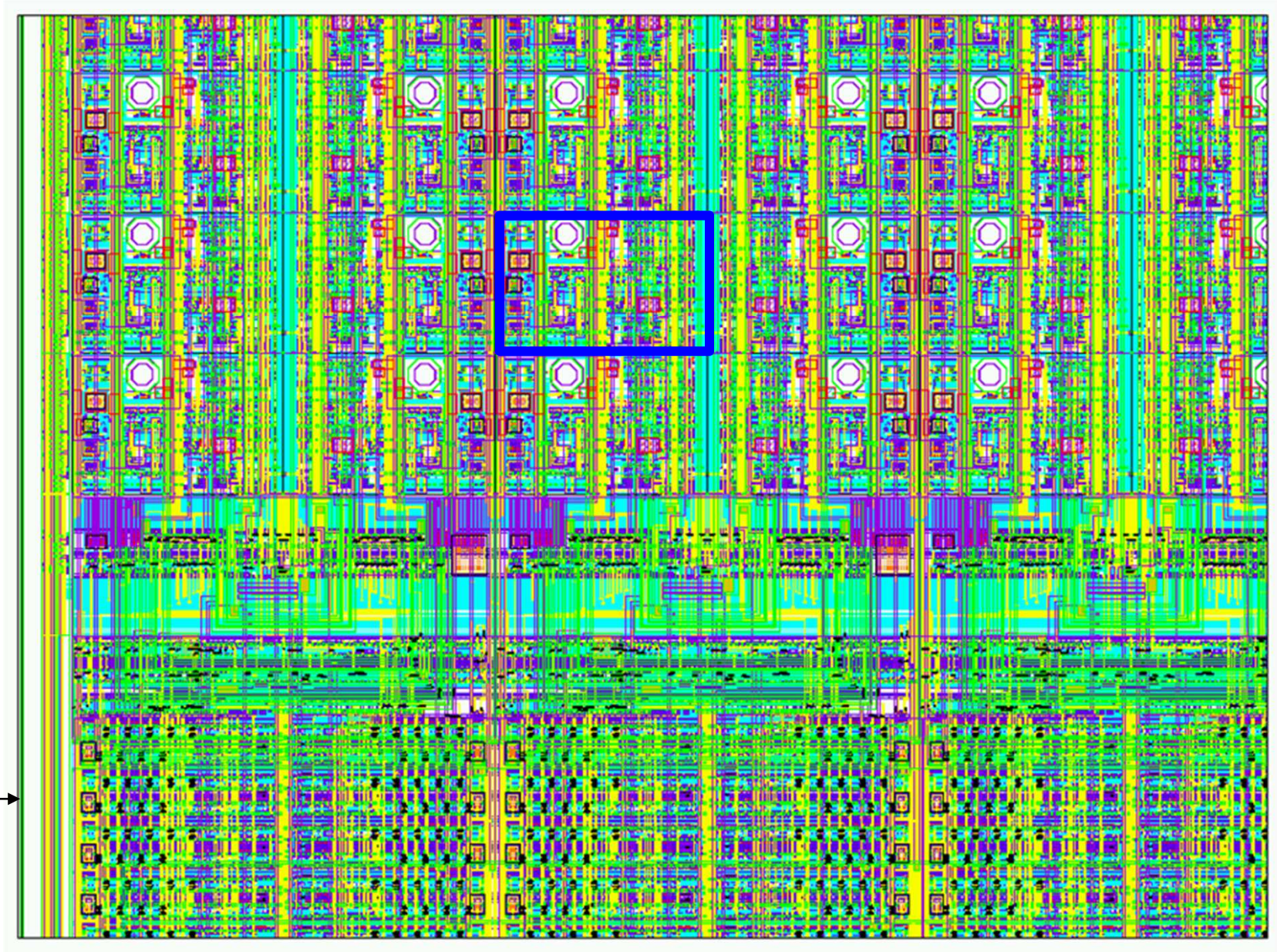
CMS Pixel Read Out Chip

- pixel size **100µm x 150µm**
- **analog pulse height readout**
- **251 transistors /pixel**
- **35µW/pixel (very low power)**
- operating **pixel threshold = 2500 e**
- radiation hard design **(~1MGy)**
- **complete design by PSI group**

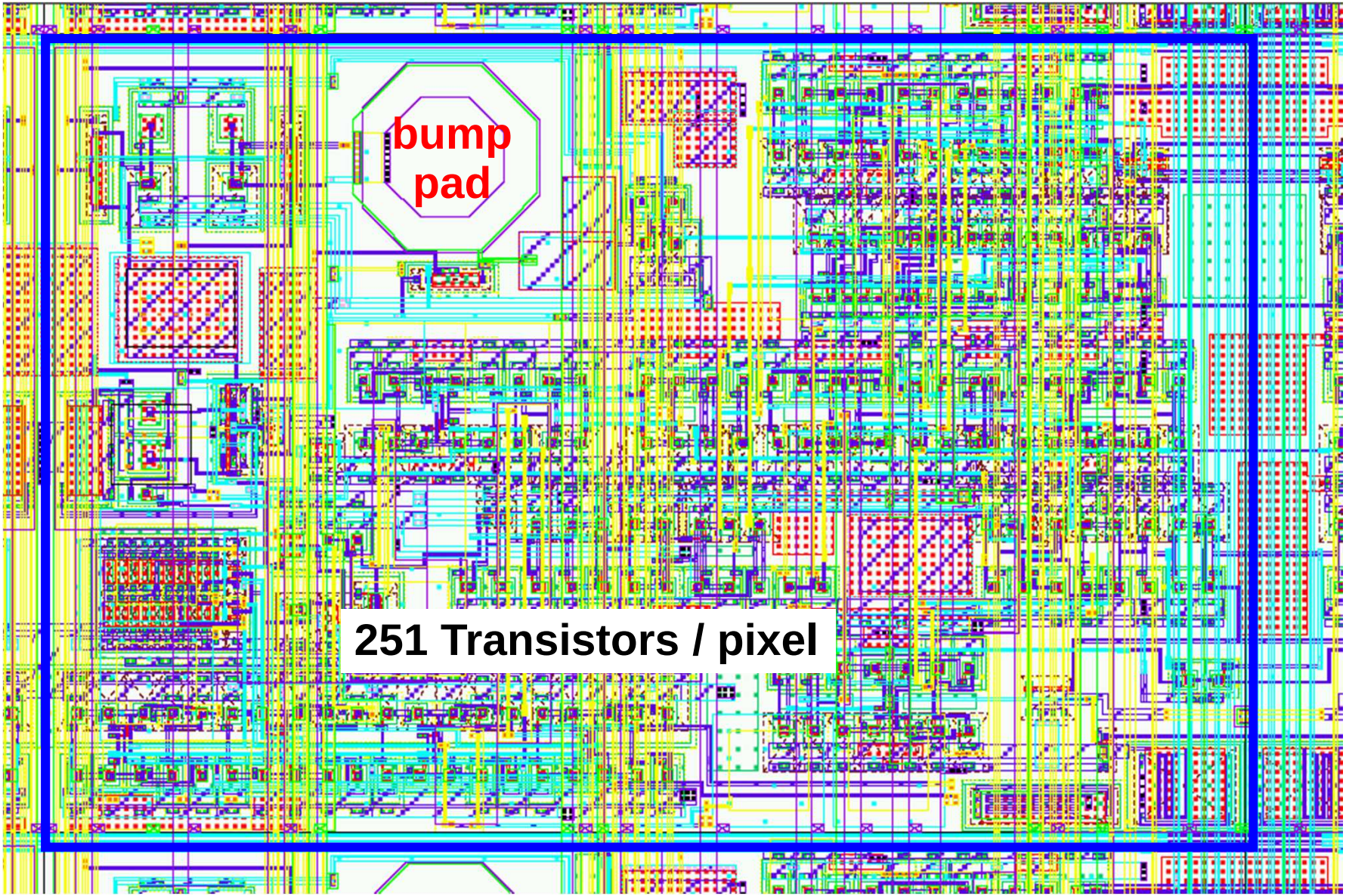




Pixel ROC Zoom (1)

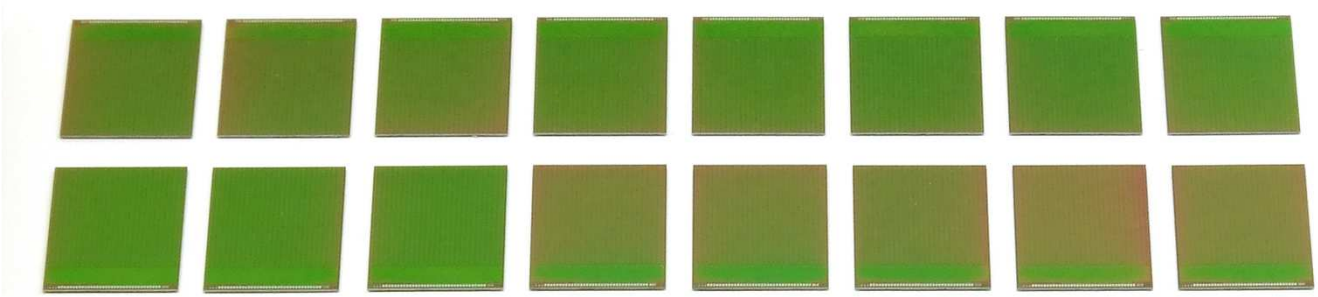


100μ x 150μ Pixel Zoom (3)

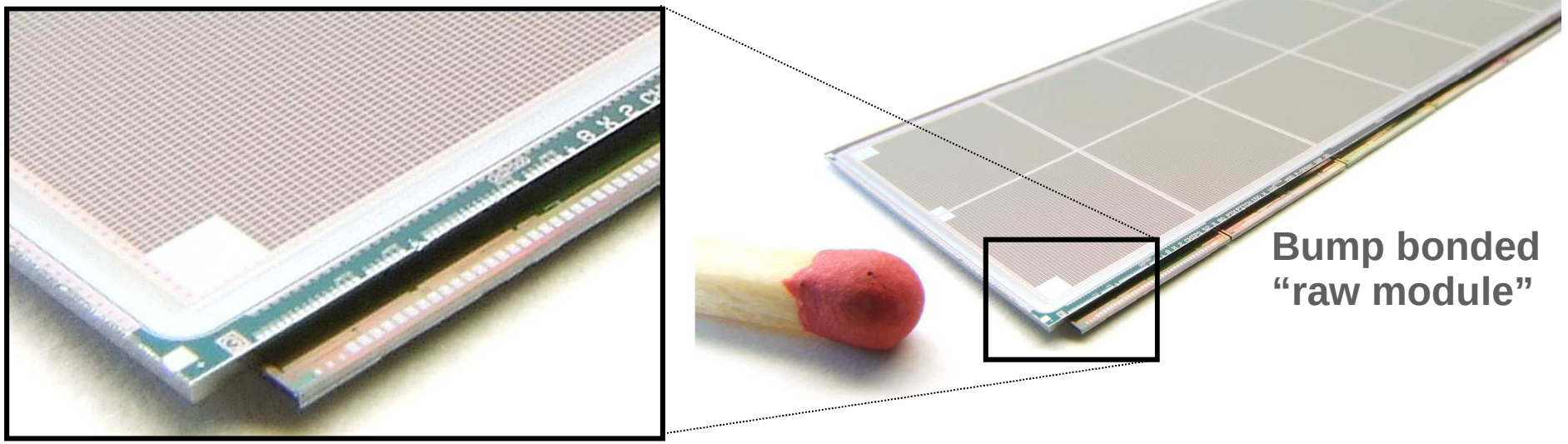


Bump bonding of bare modules

Pixel Sensor with
UBM & Indium balls



16 tested CMOS ROC
chips with UBM & Indium

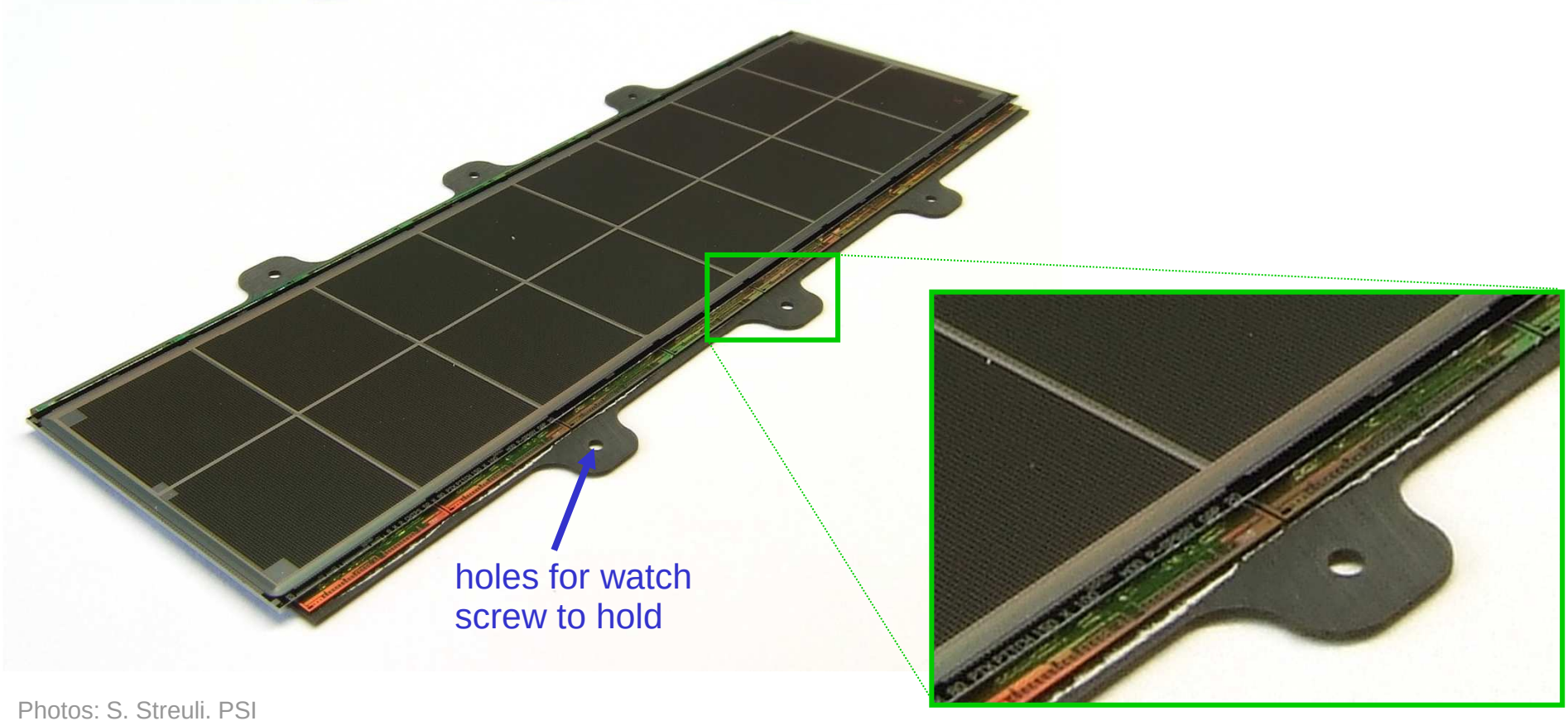


**Bump bonded
“raw module”**

Photos: S. Streuli. PSI

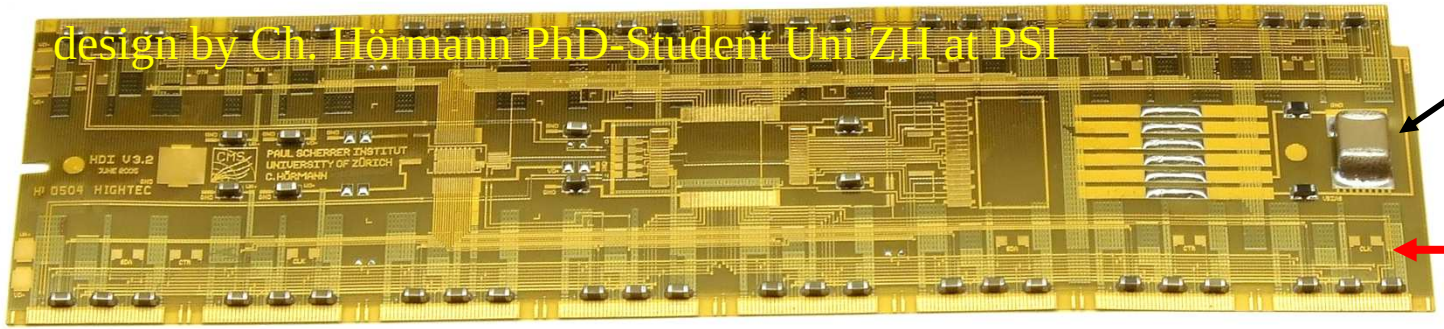
Now glue ceramic base strips under

Si_3N_4 ceramic is almost identical in thermal expansion to silicon crystals



Photos: S. Streuli. PSI

With HDI and Cables finish the module



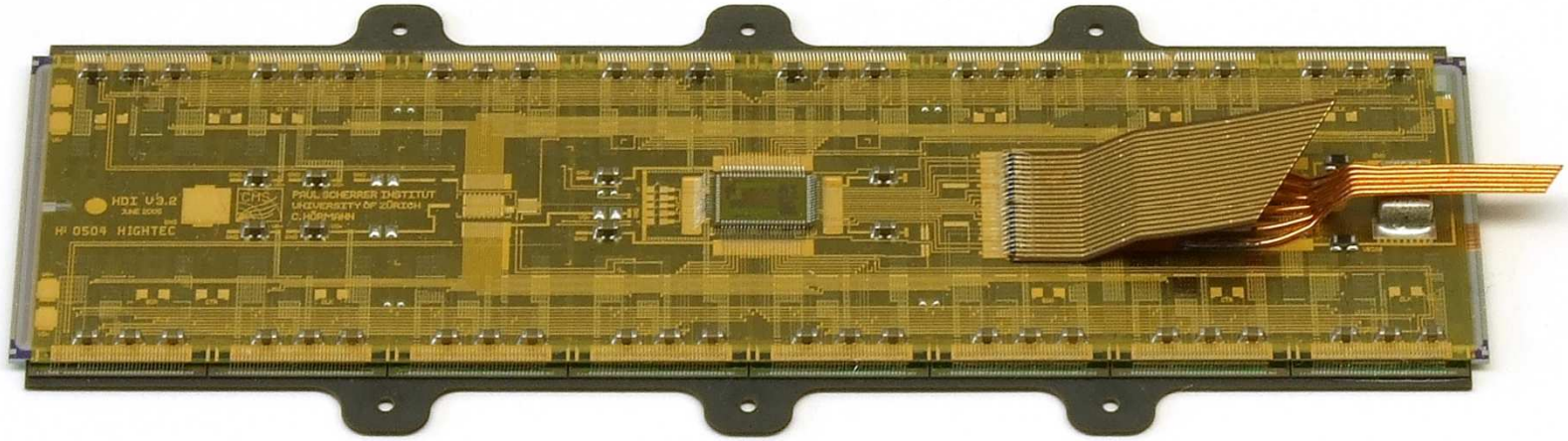
High Density Interconnect (HDI)
3 layers, 48µ thick

DYCONNEX
Bassersdorf

ELECTRISOLA
Eschholzmatt

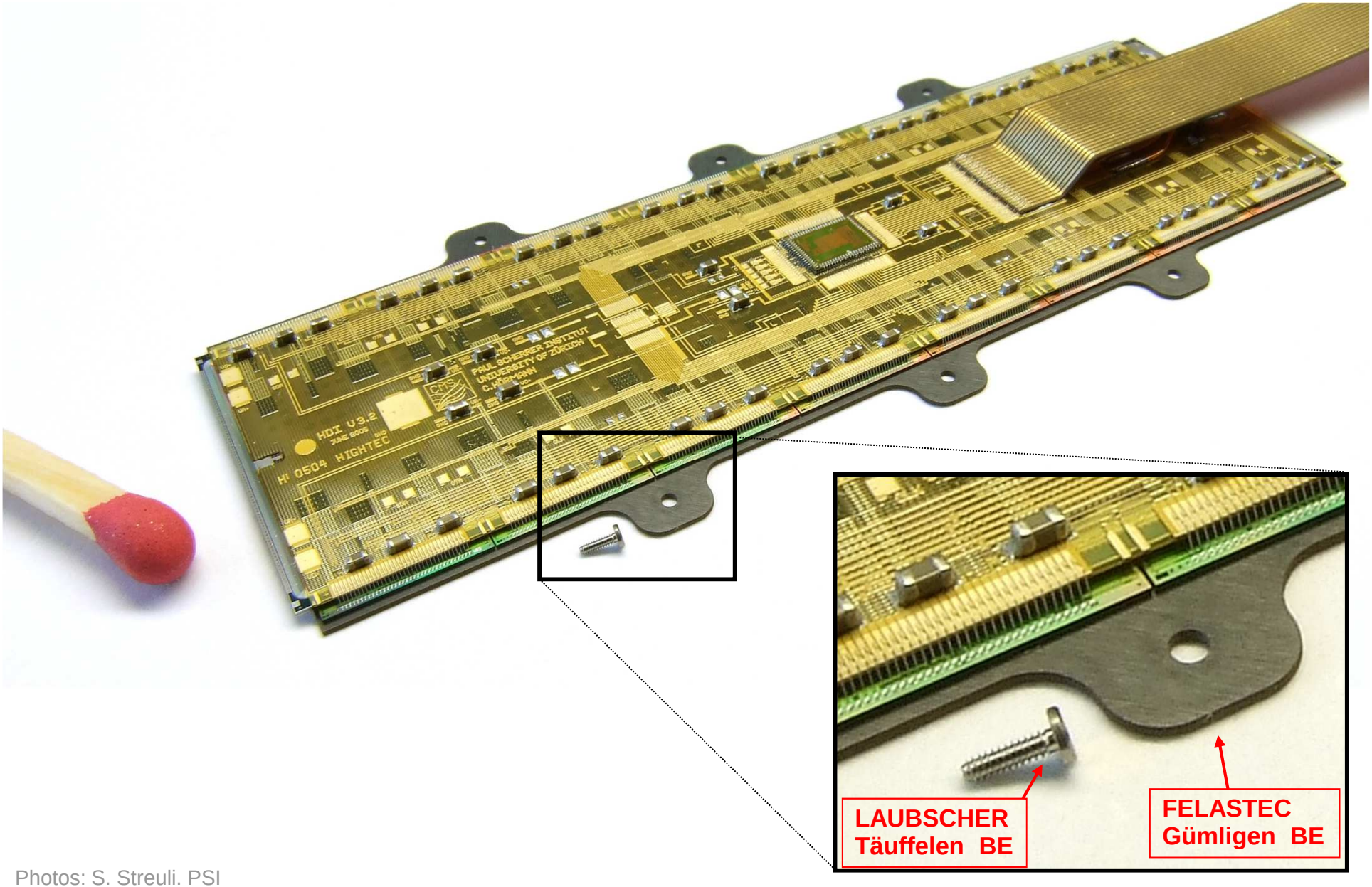
Cu-Claded-Aluminum Power cable (6 wire ribbon) ~1A

KUK
Appenzell



Photos: S. Streuli. PSI

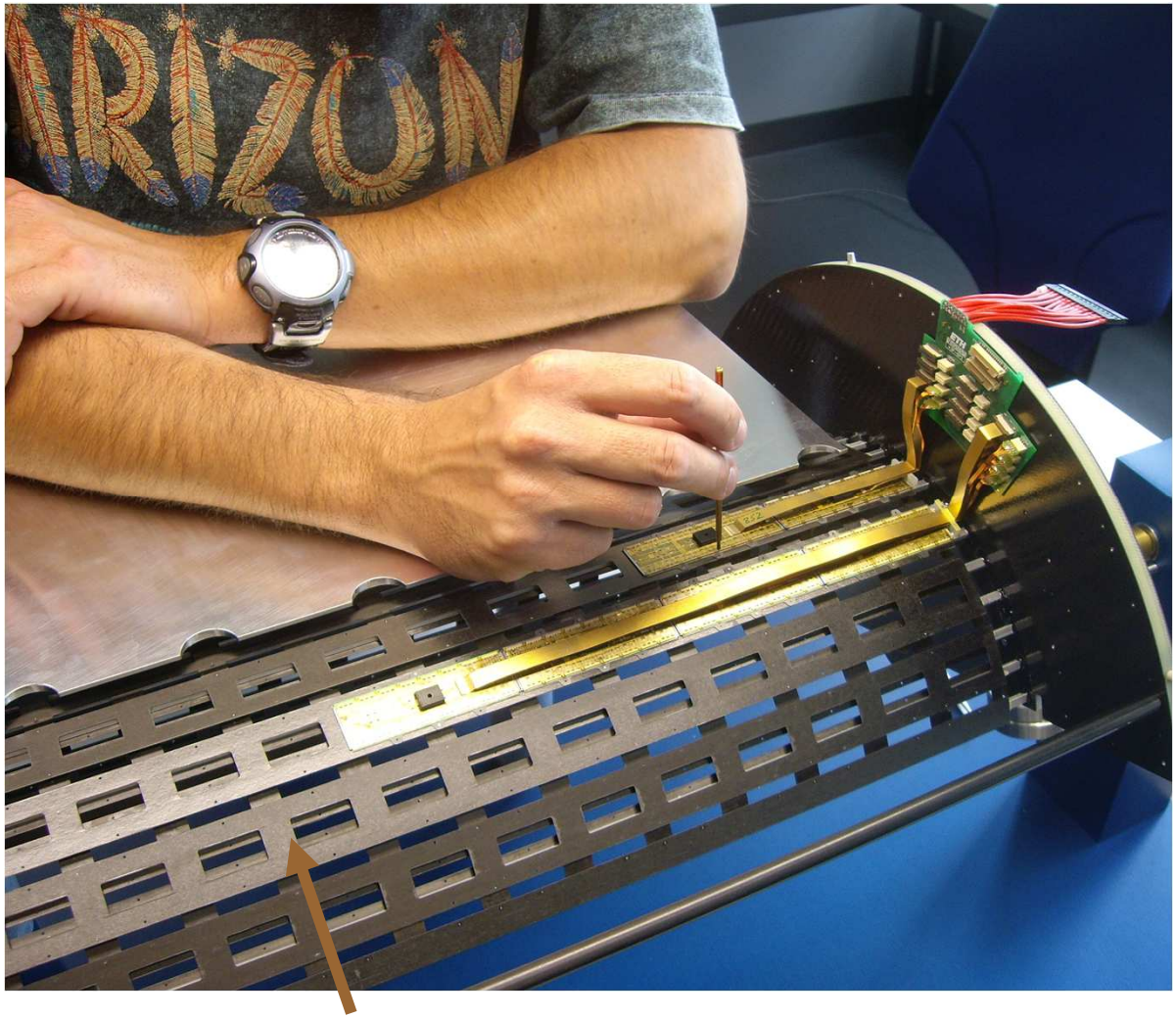
The pixel module will be screwed on

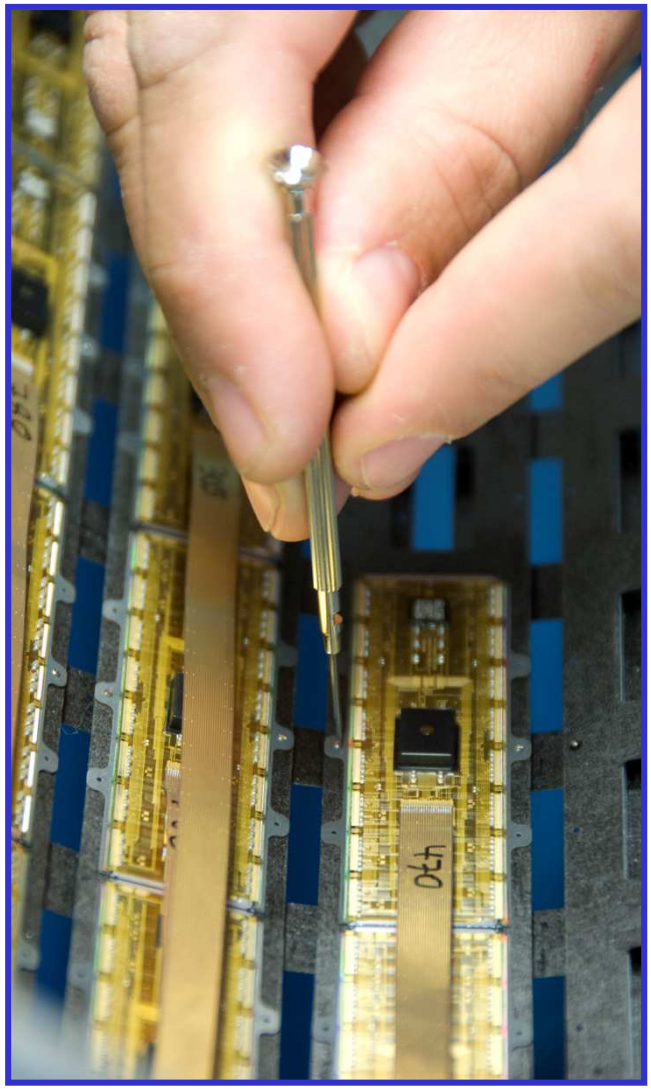


Photos: S. Streuli. PSI

Final Barrel Pixel Assembly

Mounting pixel modules onto C-fibre mechanics with integrated cooling structure





Pixel Barrel mechanics (Carbon-Fibre)
Design & Manufacturing by Uni. ZH

Tightening the Swiss Watch Screw

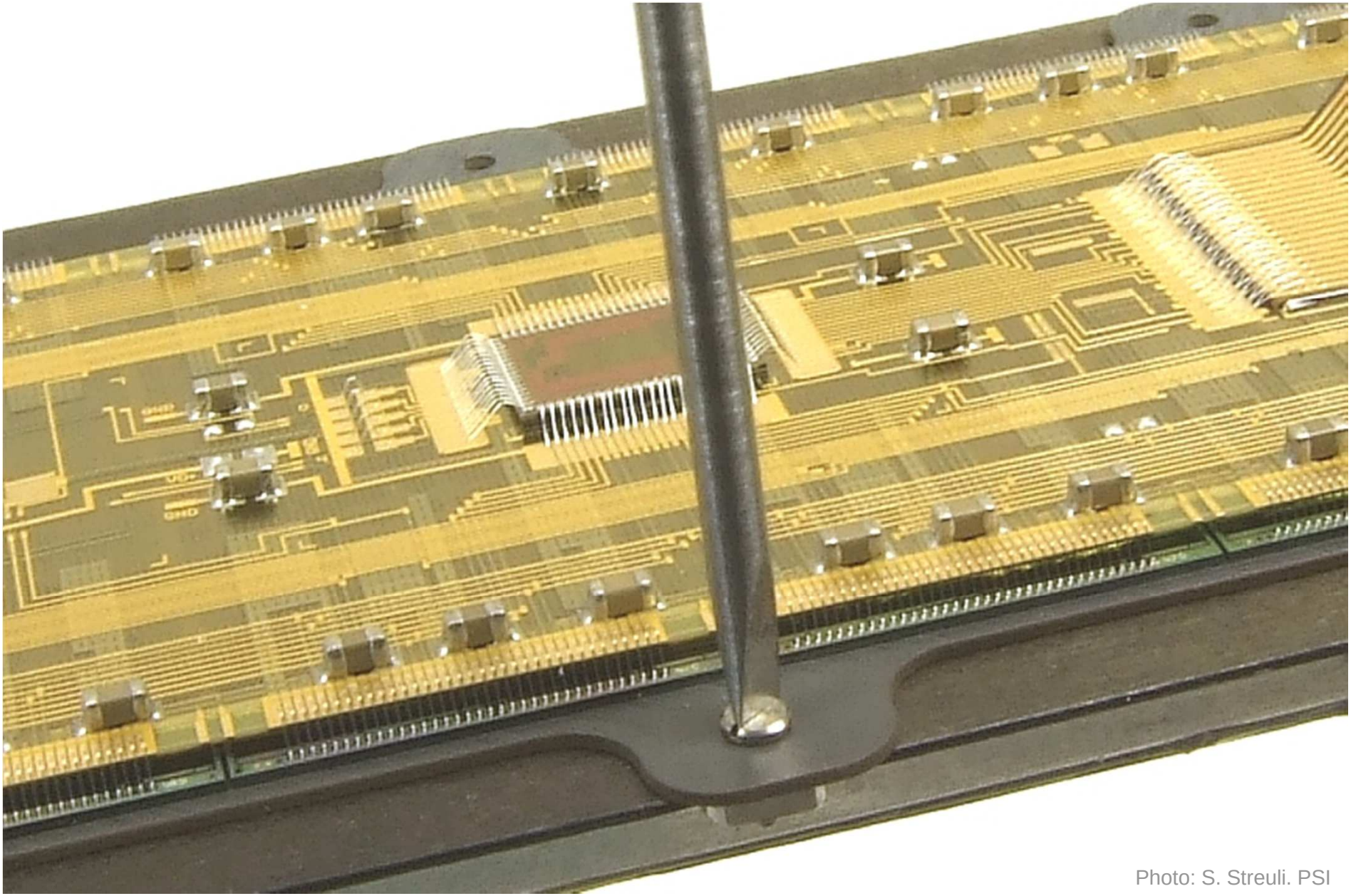
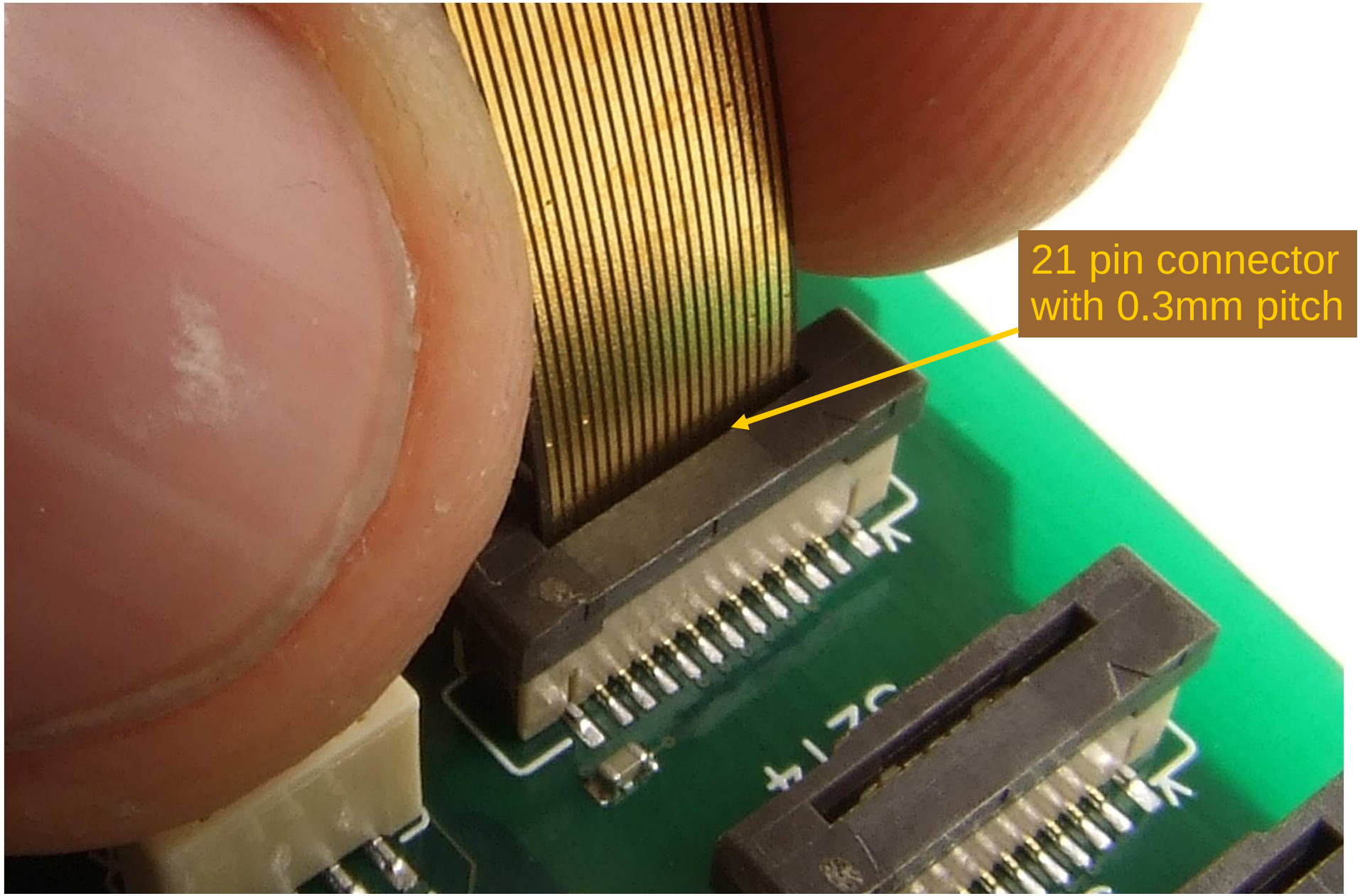


Photo: S. Streuli. PSI

Now testing the Pixel Halfshell

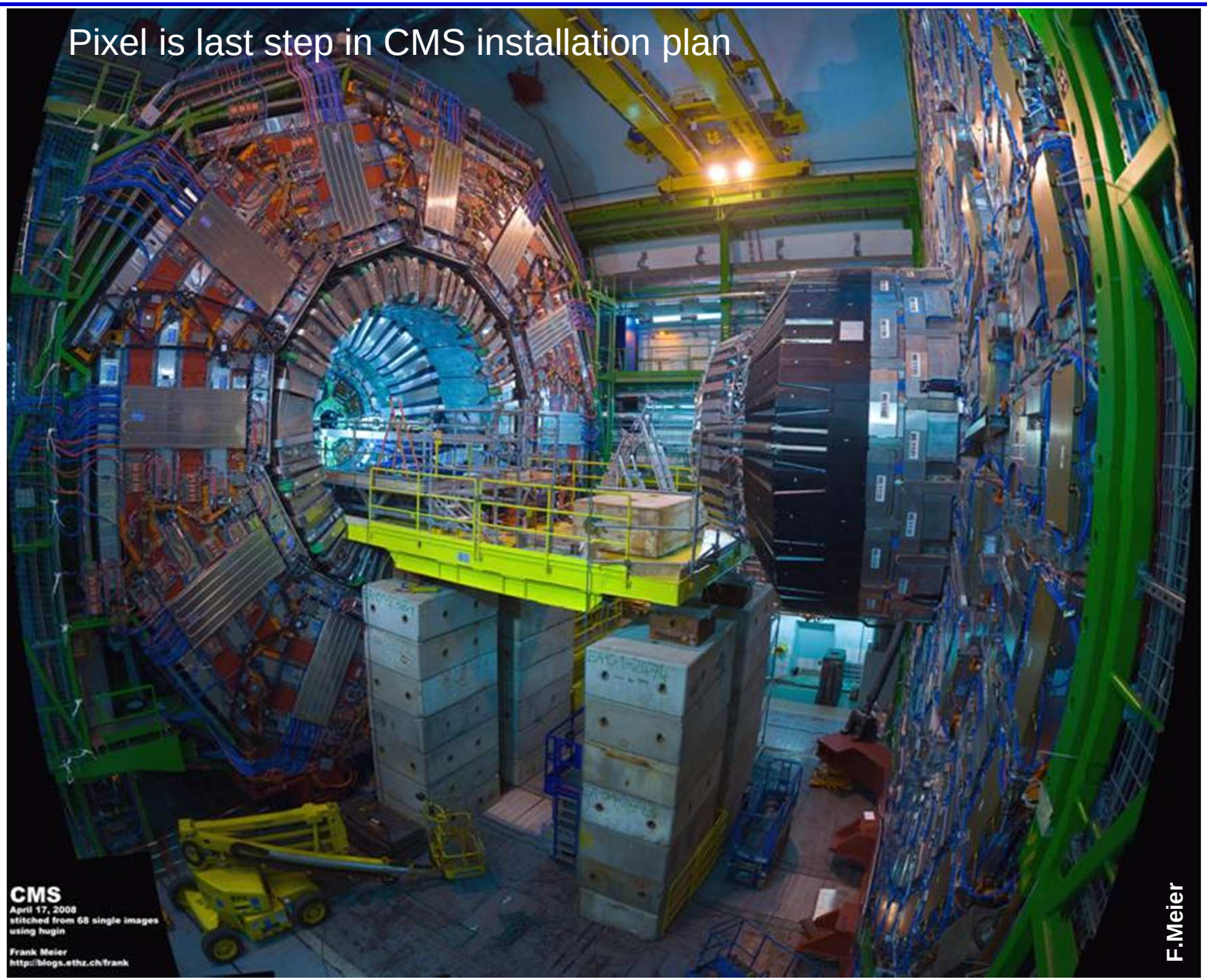
16128 Contacts must be right



Pixel Barrel & Supply Tube together

–x side of CMS Pixel Barrel ready !

CMS is ready to install the Pixel System



From PSI to Point 5, Cessy

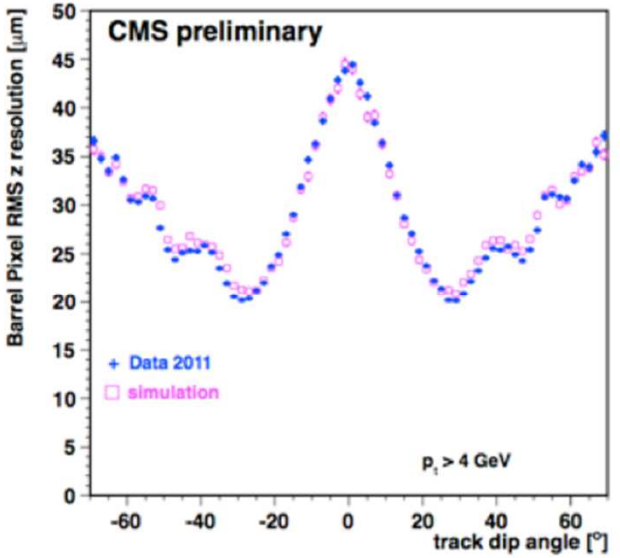
Our party tent “clean room” at Point 5

It’s a big shaft !

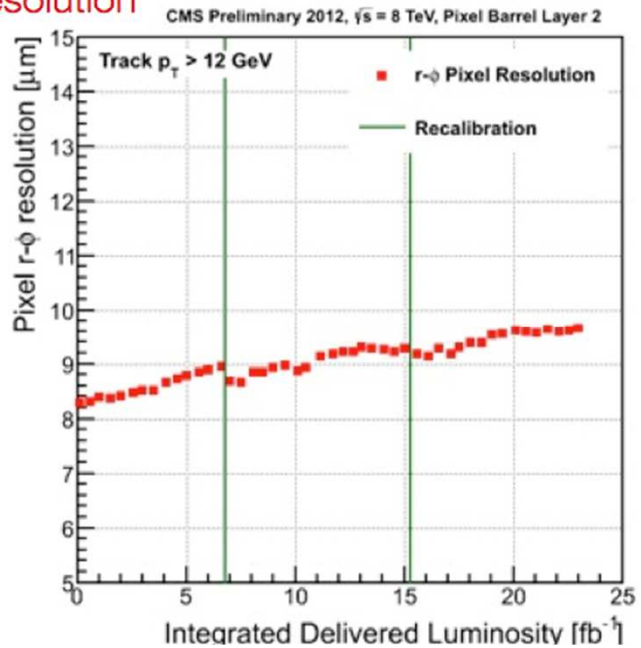
BPIX Insertion in 2008

Pixel Performance in Run 1

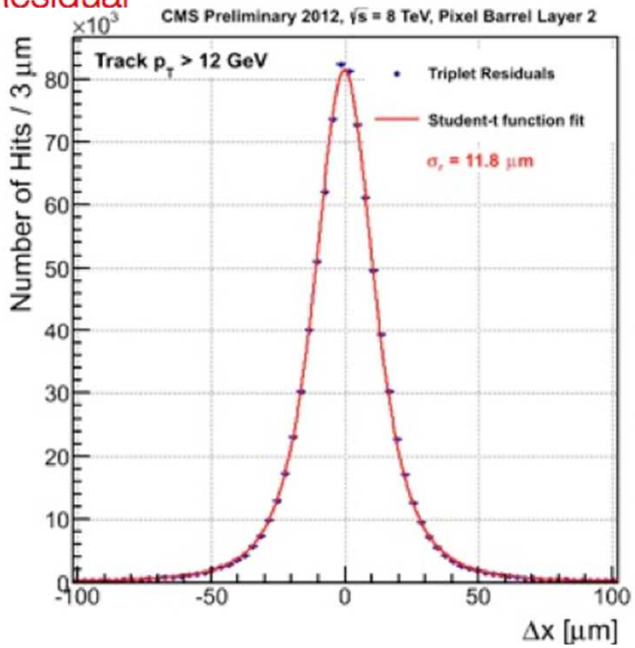
- Spatial resolution measured with the triplet method
- Degradation observed with integrated luminosity
  - Partially recovered after re-calibrations
- Measured resolution better than 10 um at the end of Run 1
  - Consistent with design goals



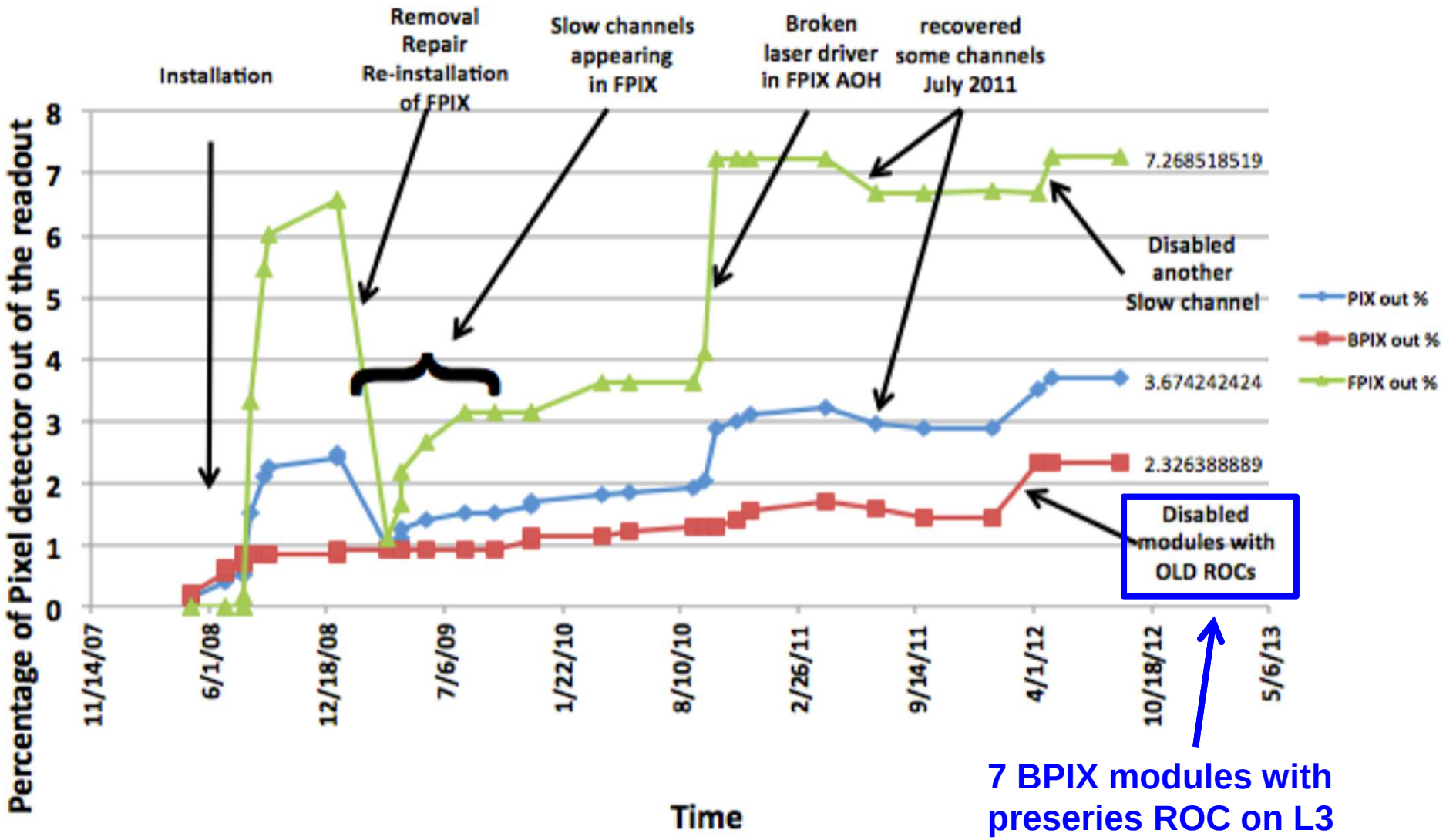
Pixel Resolution



Example of Residual Distribution



Detector status: timeline



7 BPIX modules with preseries ROC on L3 disabled, replace in LS1

BPIX Extraction in LS1 for new beam pipe

BPIX low temperature calibrations at -16°C in Pixel Lab during LS1

- test 32 sectors one by one
- open thermal box & swap cables
- testing done over 12 month
- thermal boxes opened many times
- each time re-sealing required

BPIX damage apparent in last check-out

Monday, 11. Aug 2014: Danek & Lea replace pre-series modules in layer 3.

→ Tests of BPI-quadrant shows serious damage → ~1/4 modules (55) do not work

Wednesday, 13. Aug 2014: Inform BPIX team and tracker community on the situation

Friday, 15. Aug 2014: production of new pixel module HDI launched at HighTec

→ launch production of new modules

Friday, 22. Aug 2014: transport inner BPIX half-shell (+x) from CERN to PSI

Thursday 28. Aug 2014: complete half-shell tested with sector testboard electronics

→ confirm damage map from P5 pixel lab.

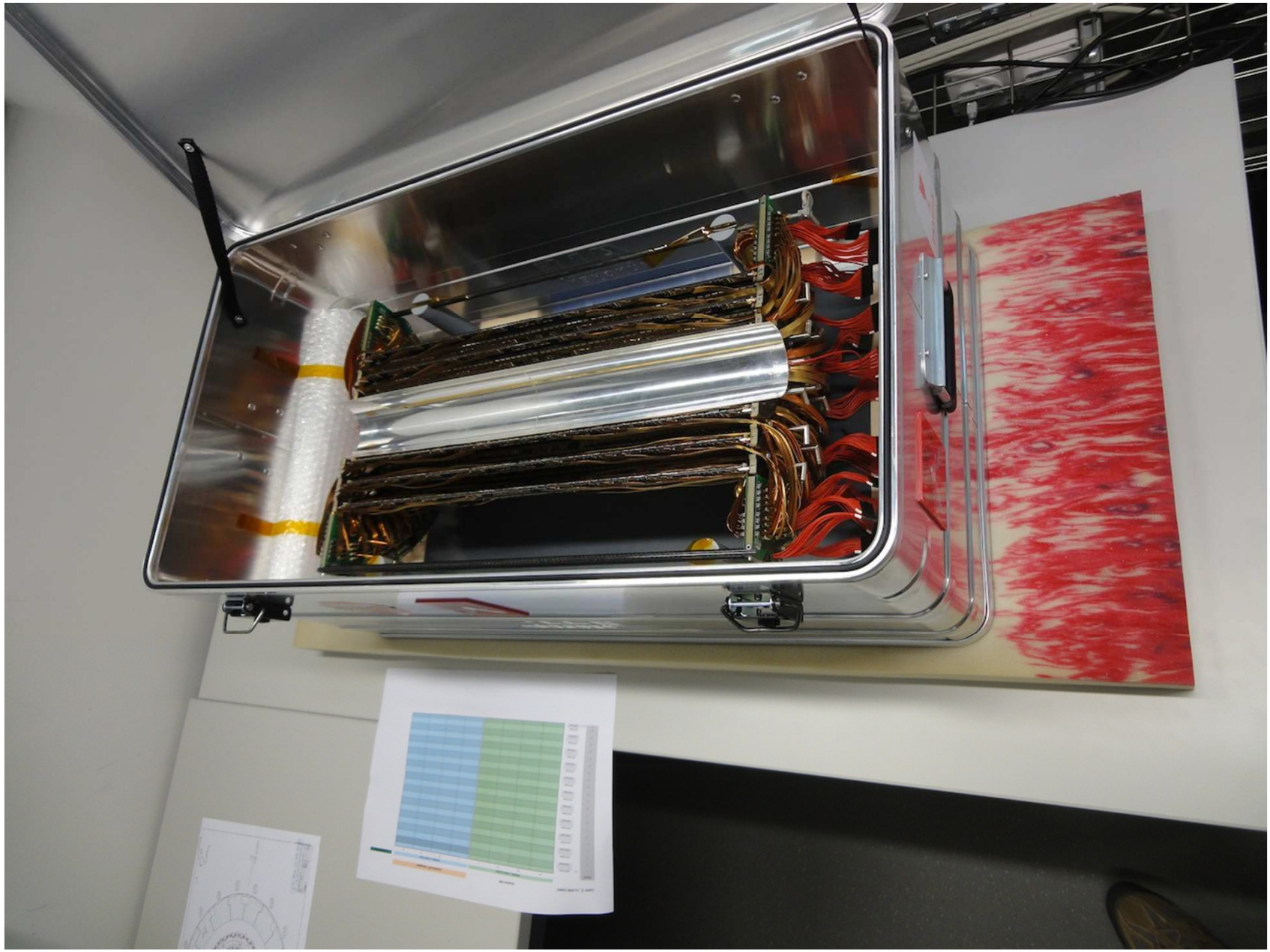
Friday , 5. Sept 2014: express production of new BPIX HDI by HighTec is finished

Monday, 8. Sept. 2014:
- start production of pixel modules at PSI
- bump-bonding of new pixel modules at DECTRIS
- module qualification at PSI by ETHZ (Andrei & Maiko)

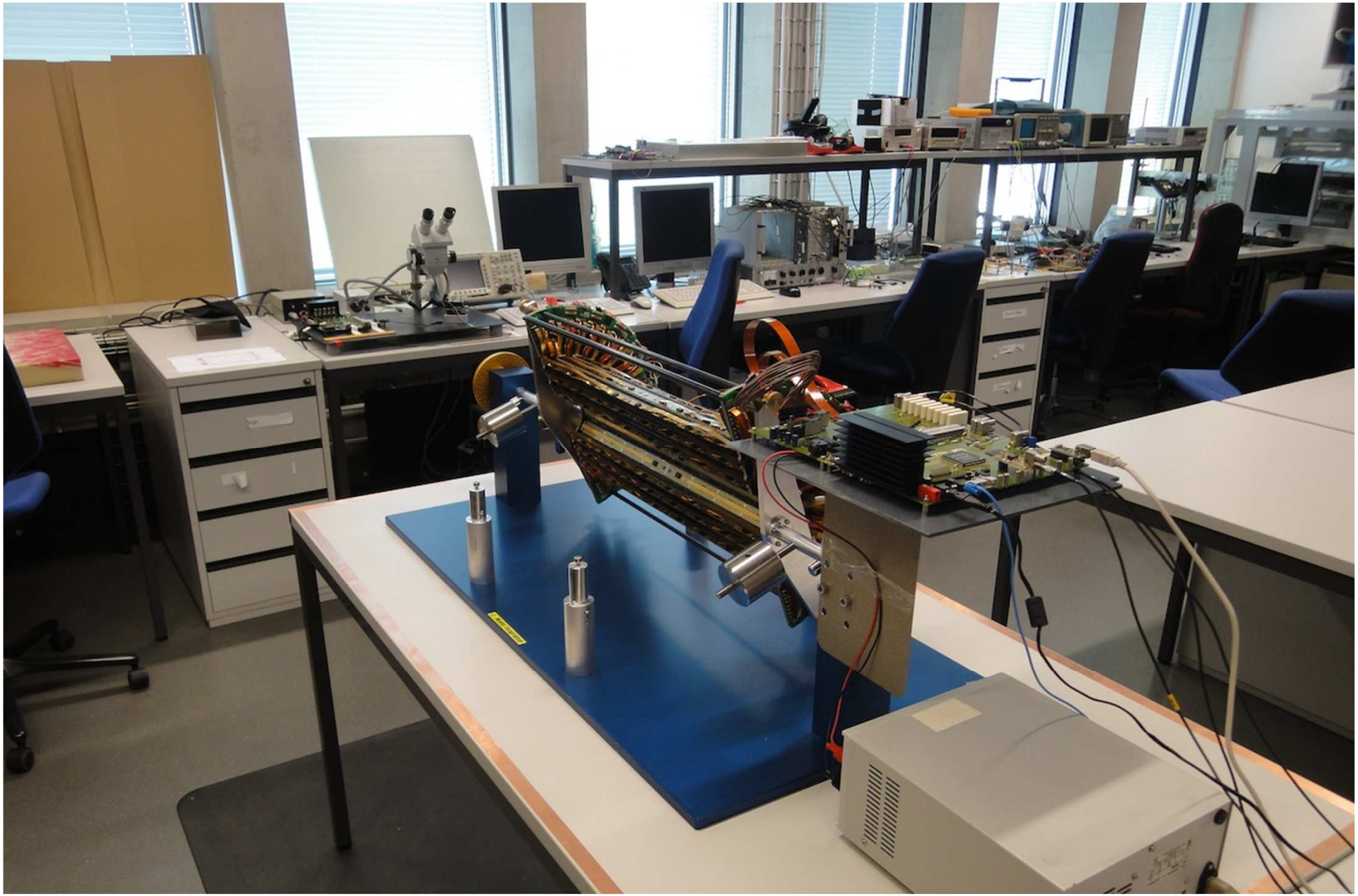
BPIX Activation Measurement at CERN

BPIX Transport from CERN to PSI

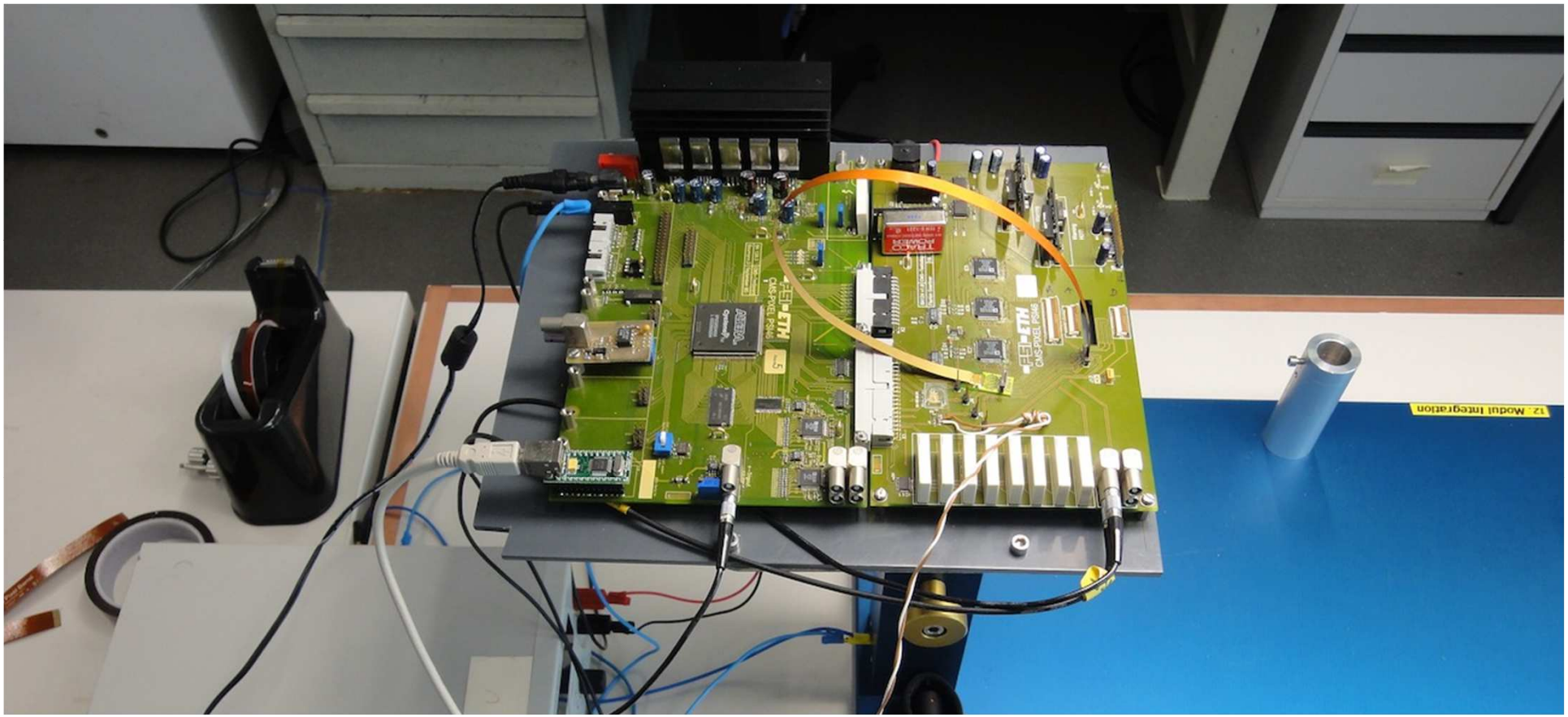
BPIX Transport Box reopened in PSI Lab



Measure Damage Map with Sector Testboard

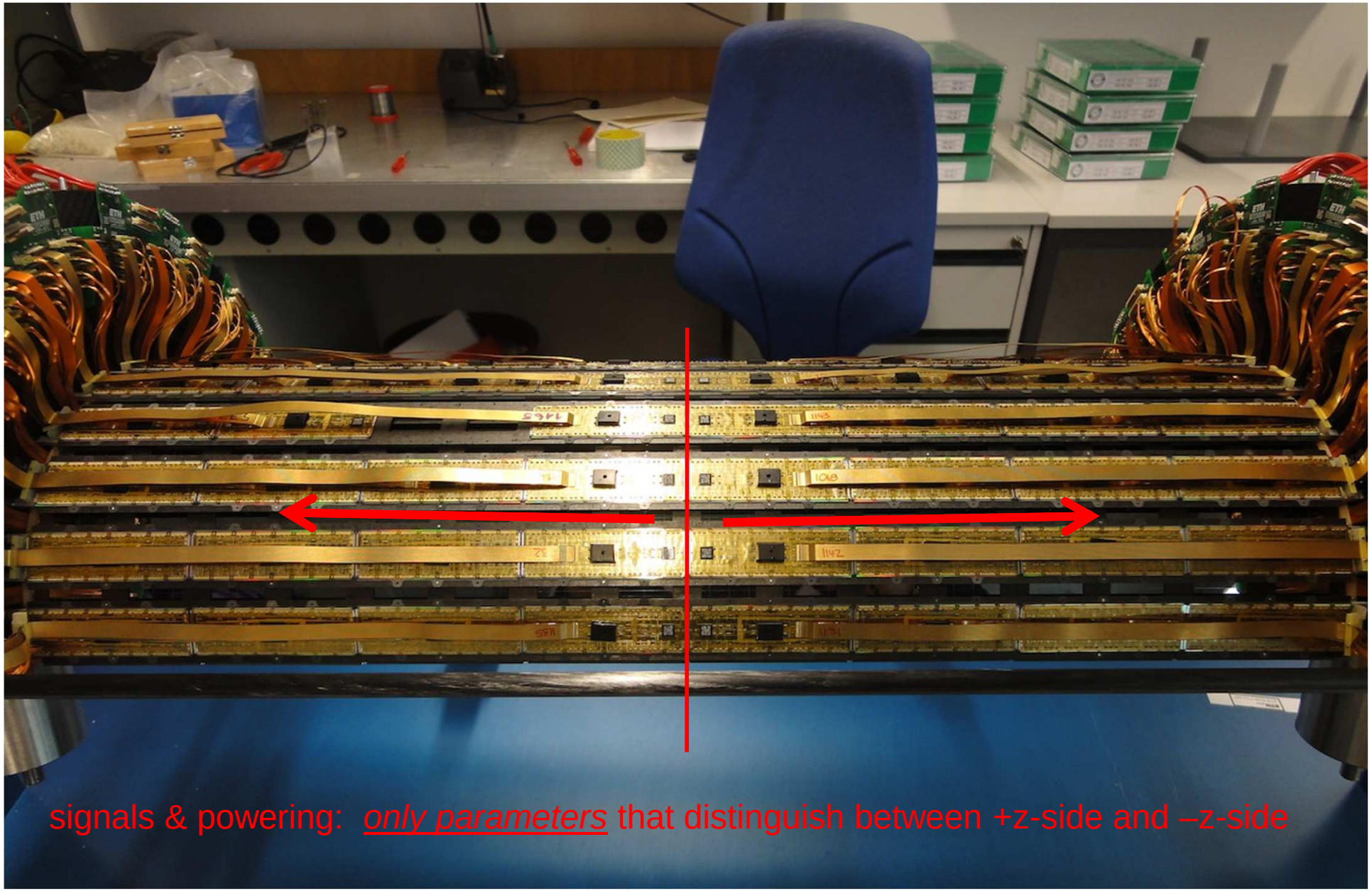


Sector Test-Board with Diagnostic Signaling



- special test board for testing modules & groups of modules (sectors)
- performs functionality of FEC & FEC with parameter scanning software
- diagnostic signaling allows measurement of resulting signal levels by DUT

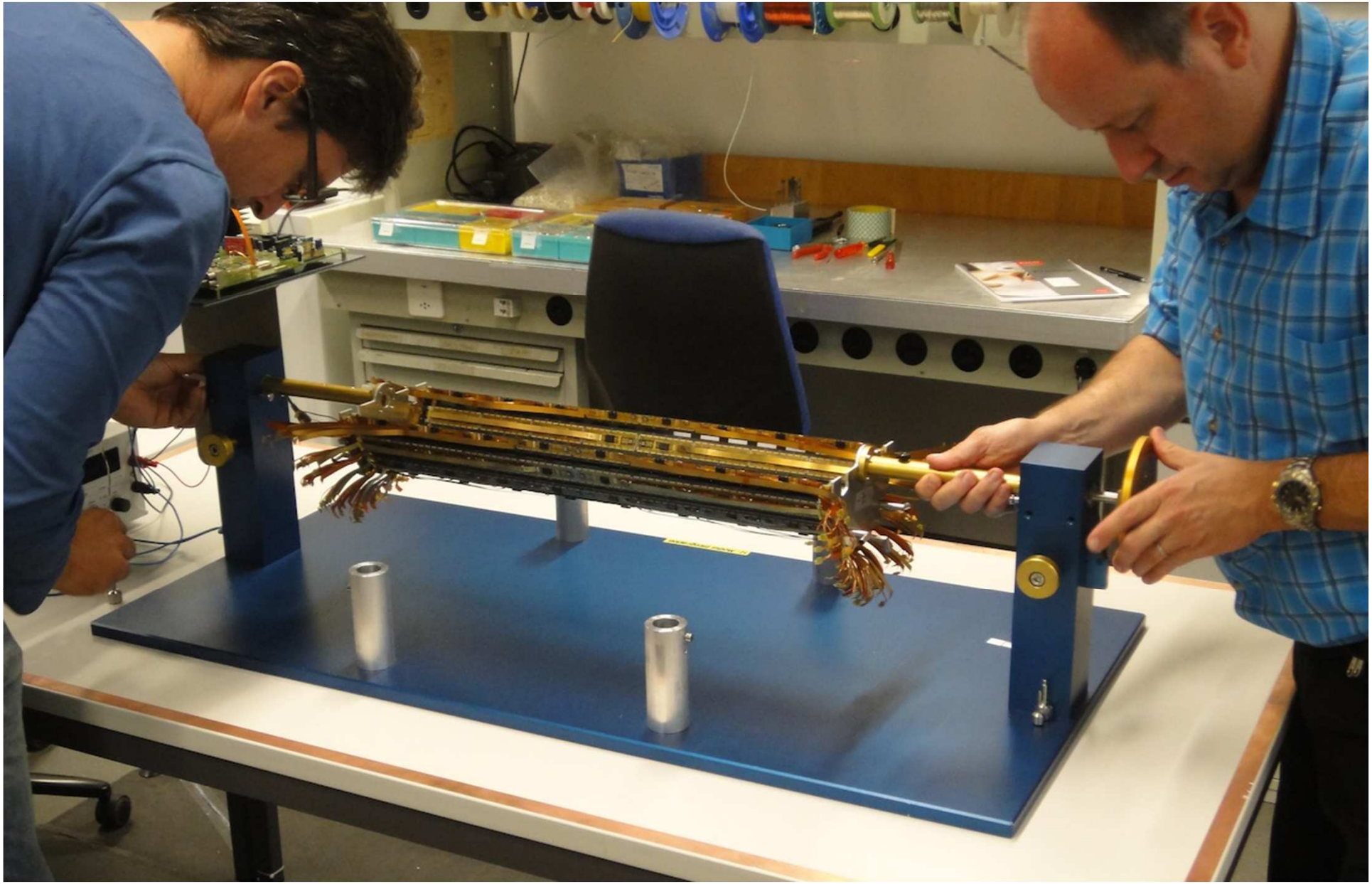
BPIX: +/-z-side differ by signal & powering



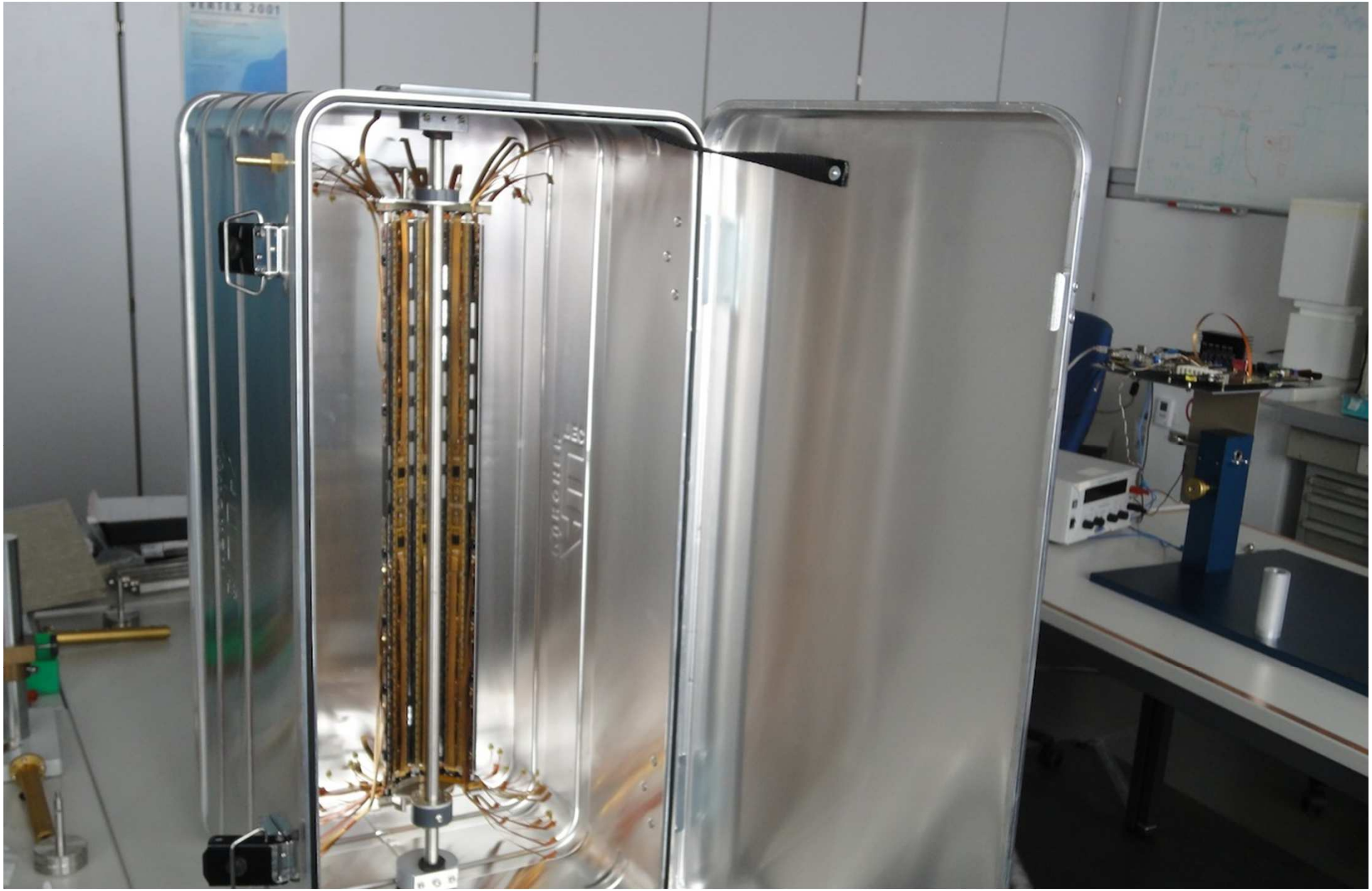
signals & powering: *only parameters* that distinguish between +z-side and –z-side

Un-cabling and taking shells apart

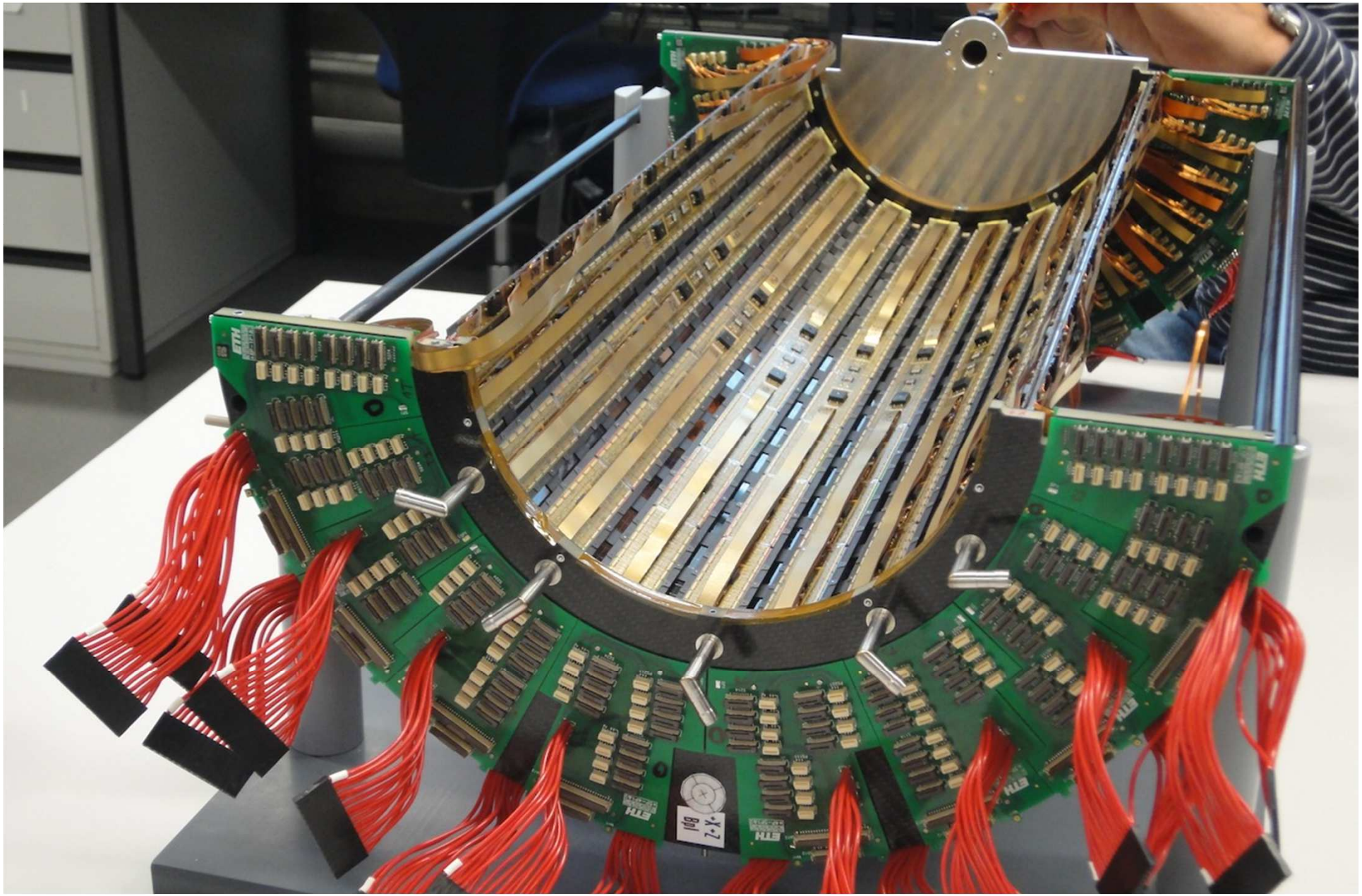
Mounting layer for module removal & testing



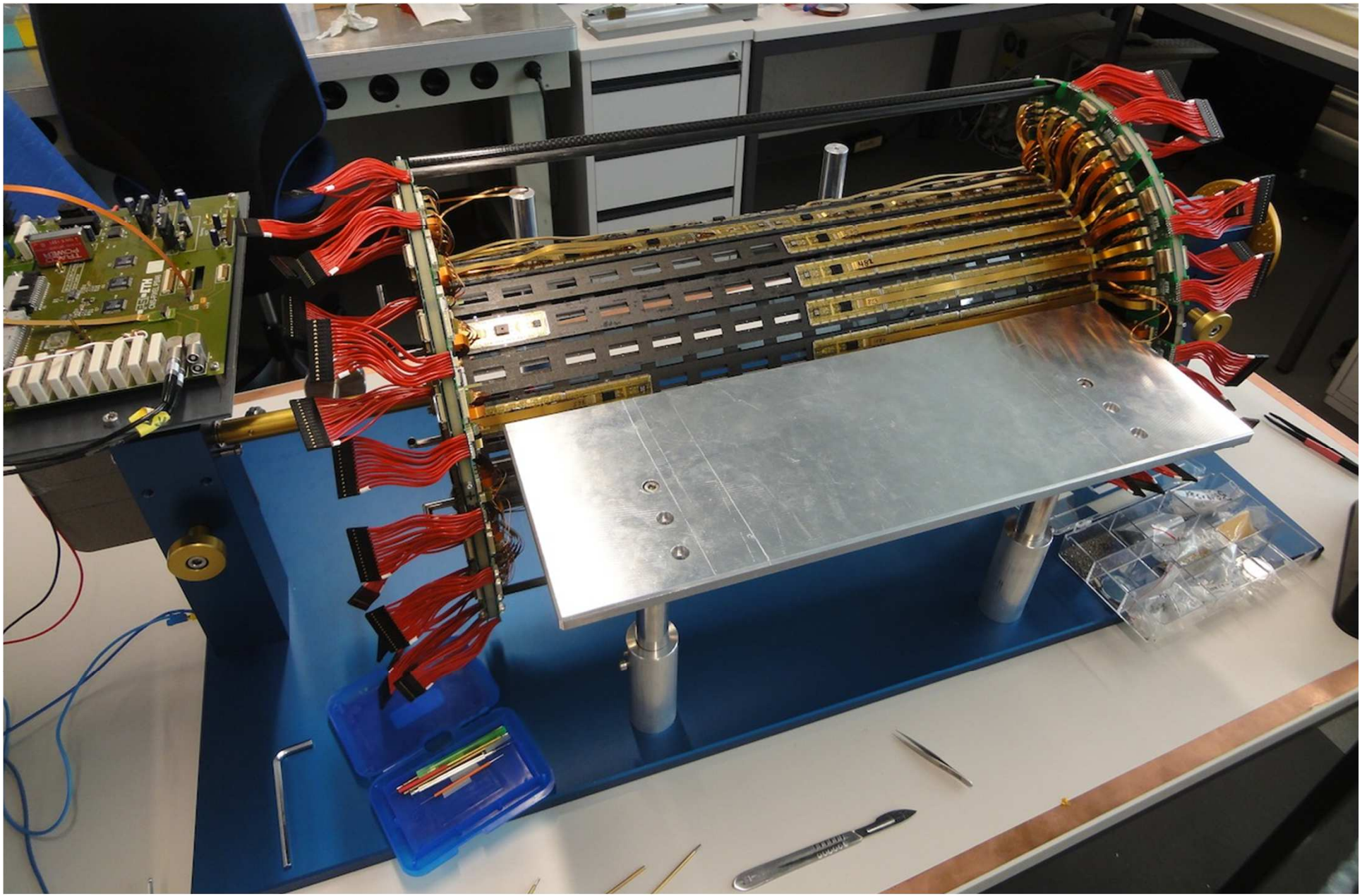
Layer 1 done: preparing for storing in cold



Layer 1&2 done and cold , now do Layer 3

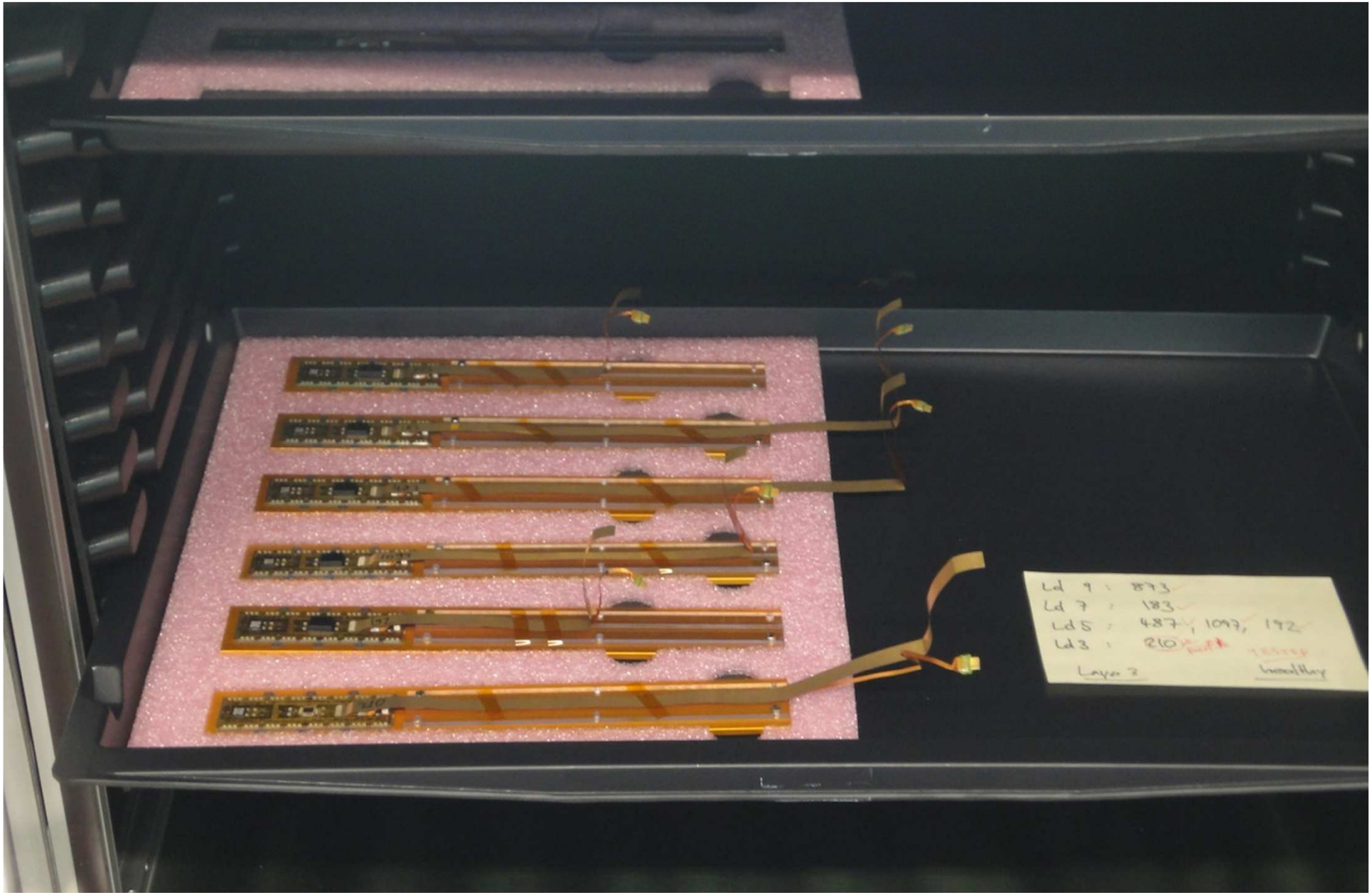


Dismount modules of Layer 3



3 Layers in their own fridges (DP -40º C)

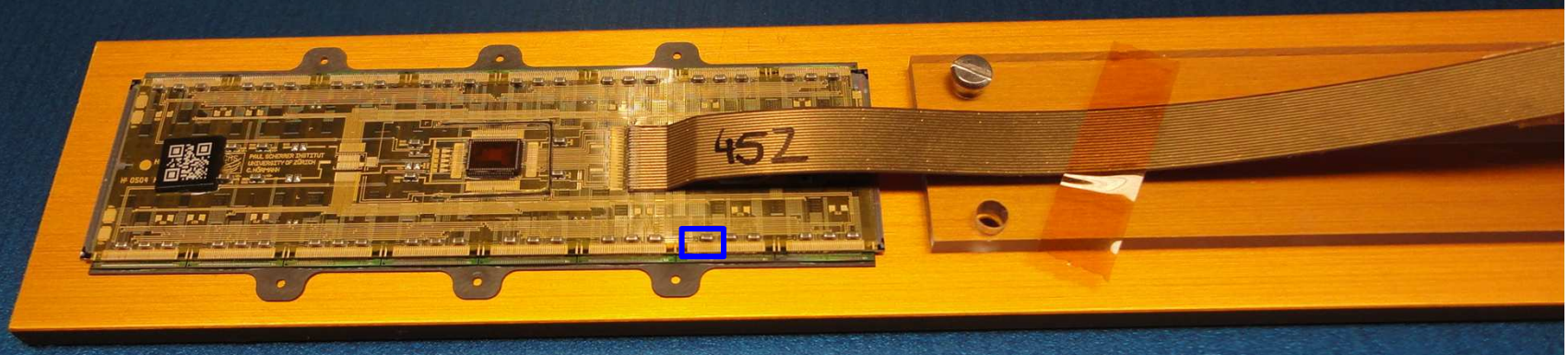
Diagnose & Repair Layer 1,2 & 3 modules



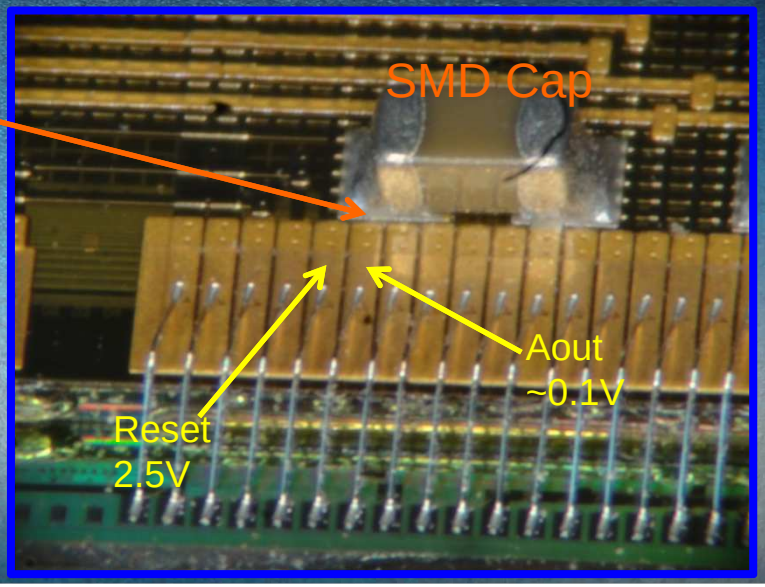
A clear picture of shorts typology emerges

modules of low serial numbers almost always shorts at ROCs between Reset-pin & Aout-pin

serious damaged modules → multiple shorted modules e.g. also at **TBM-pads** & **cable pads** (very dirty too)



solder footprint
rosin based flux



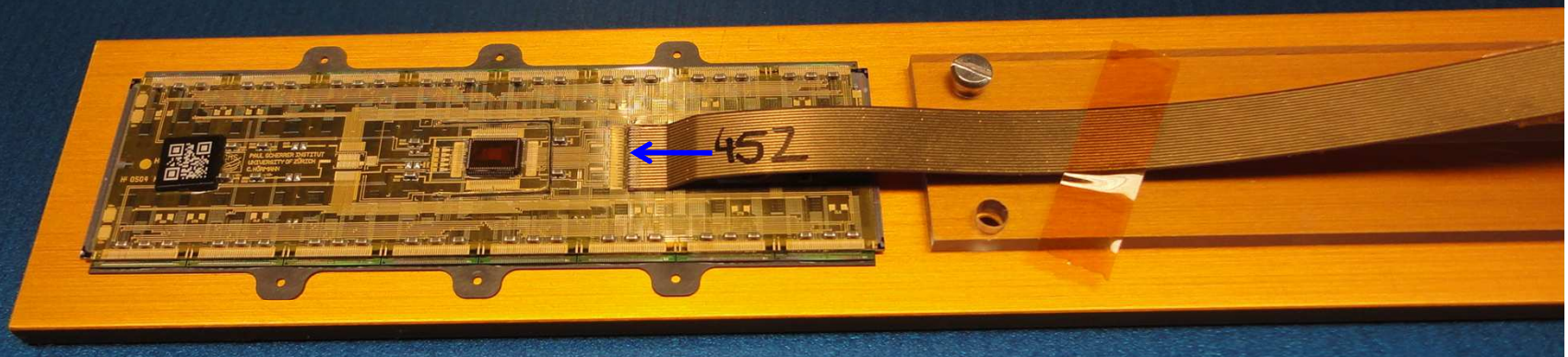
observe typically shorts between pads with 2-2.5V adjacent voltage differences and proximity to SMD components

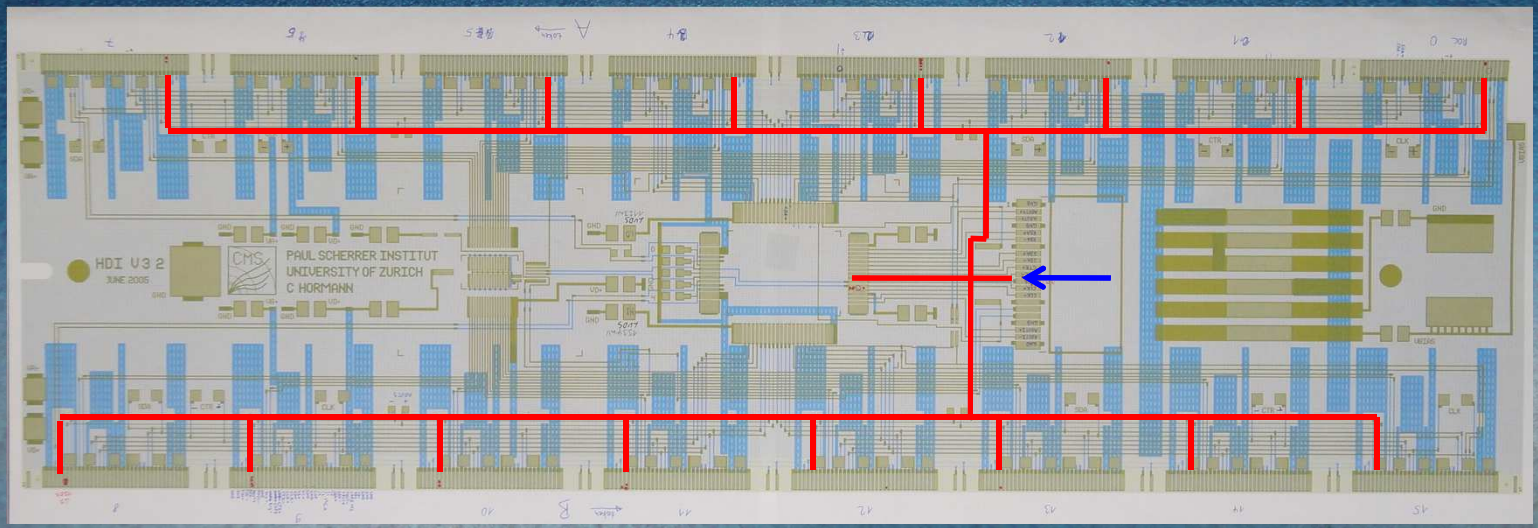
→ observe shorts to disappear when raising current above ~ 20mA

How to locate shots on HDI

Reset line pulled down by ~5mA by short to ground → module reset

resistive path of reset line ~2Ω → locate shorts by precise voltage measurement



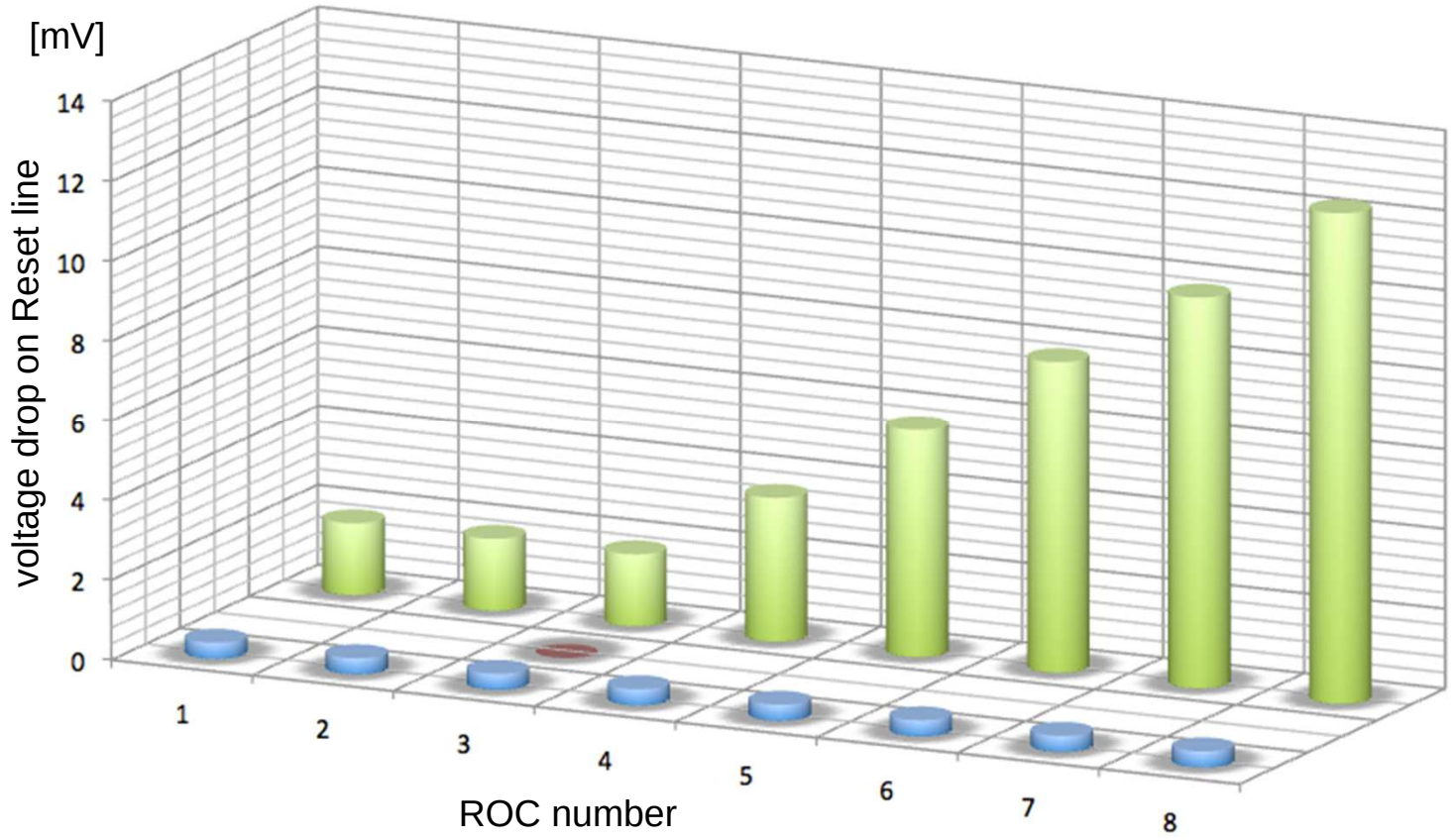


BPIX HDI shorts on defect modules

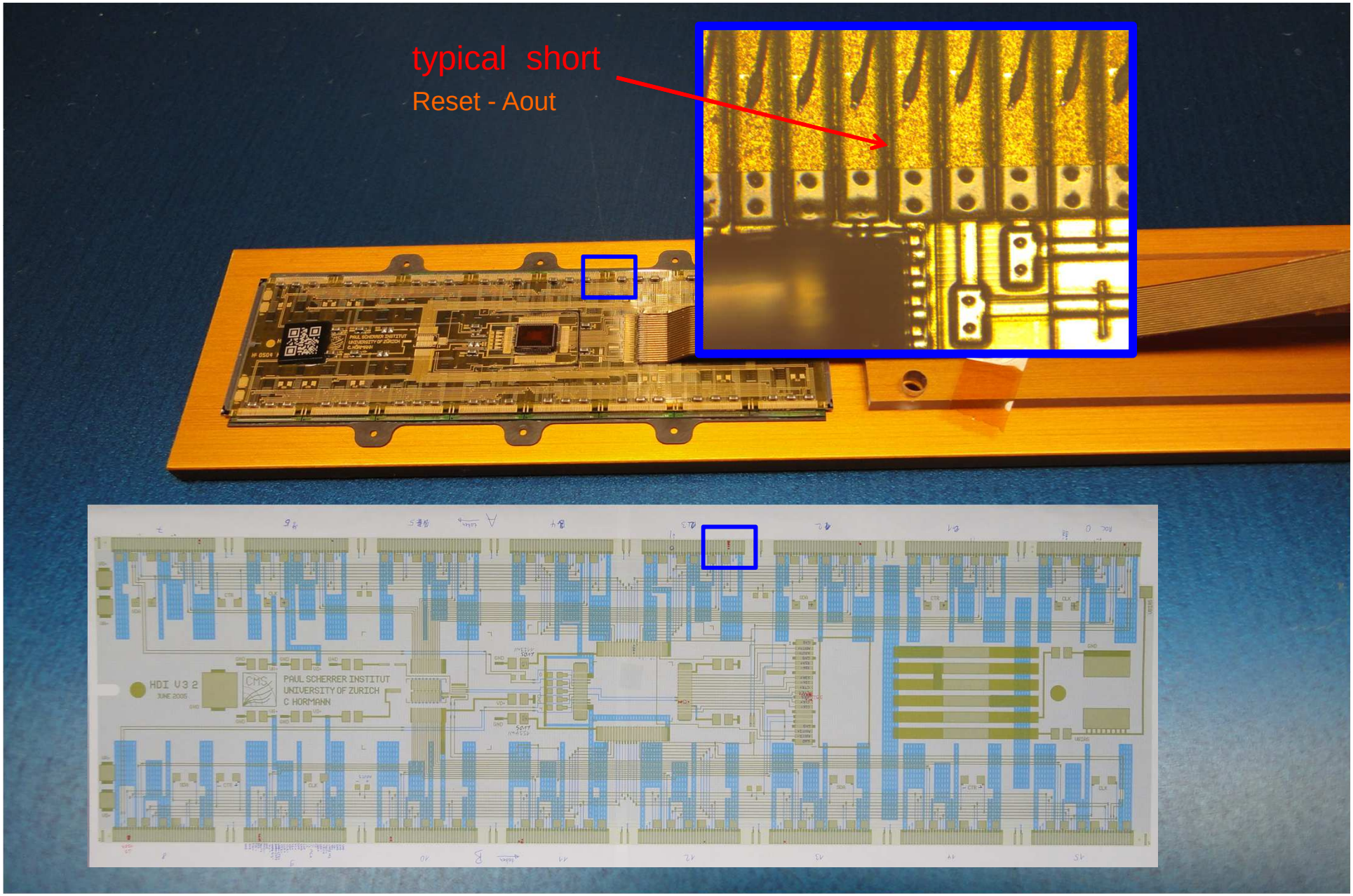
Module #69: (Layer 1, Ladder 7, Position +2) Hub ID=30

Symptom: Reset line pulled down by ~5mA current to A_{out} pad

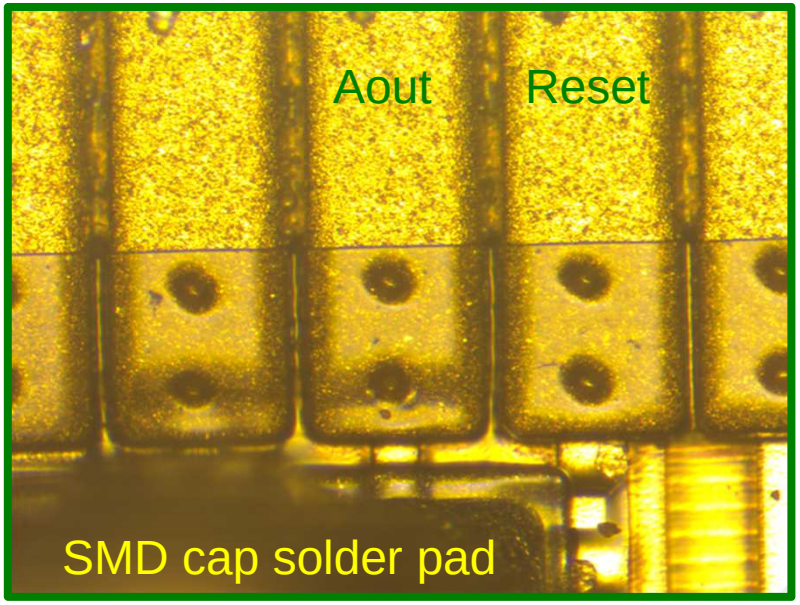
→ Precise measurement of voltage drop on Reset line shows short at ROC 9

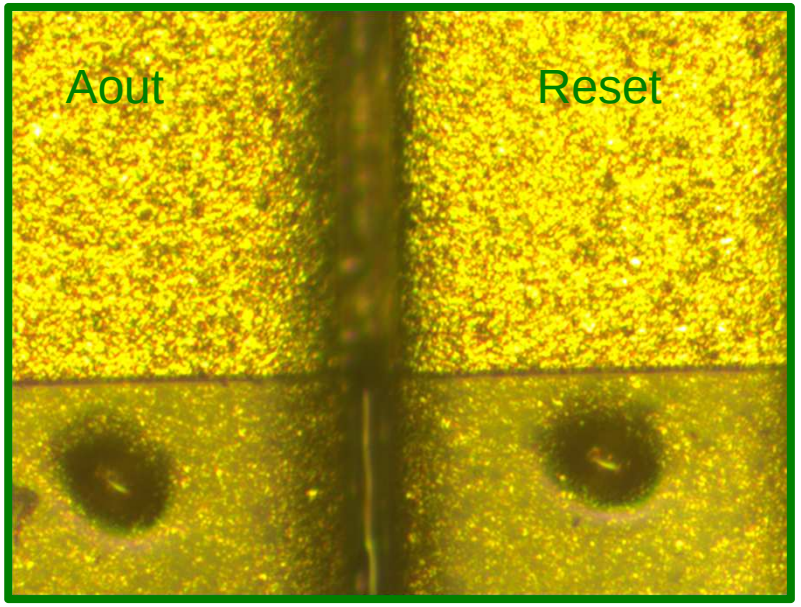


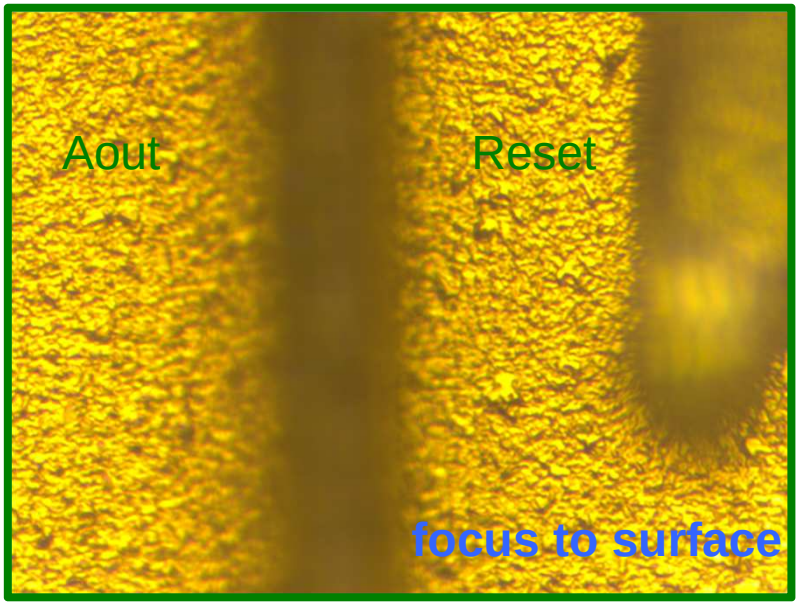
HDI shorts “always” happen at Reset / Aout

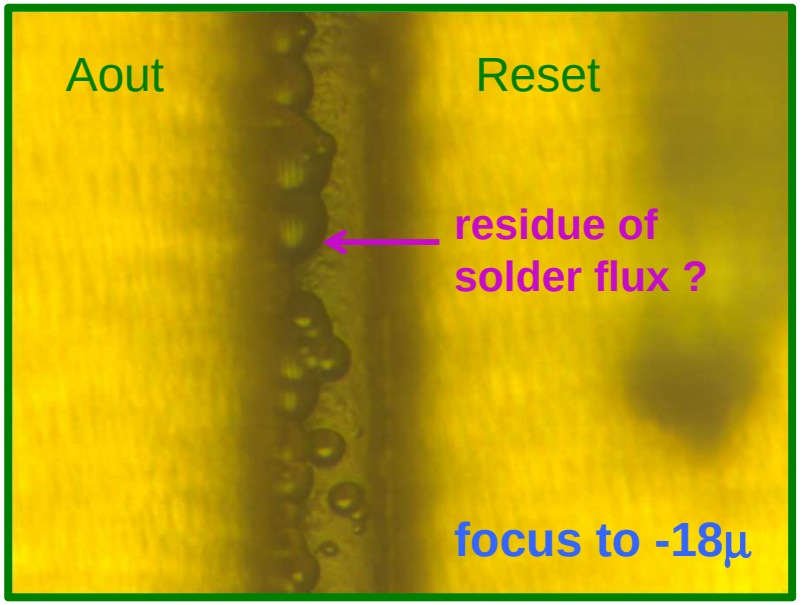


Zoom into cracks between pads





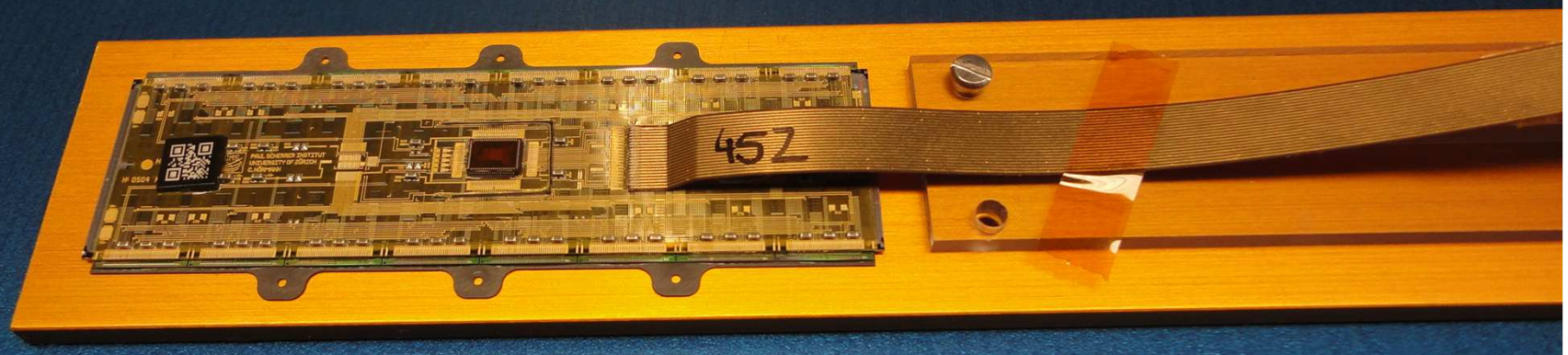


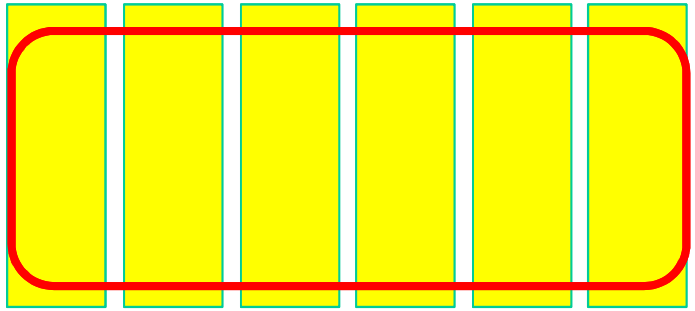


A Story of Cracks and Windows

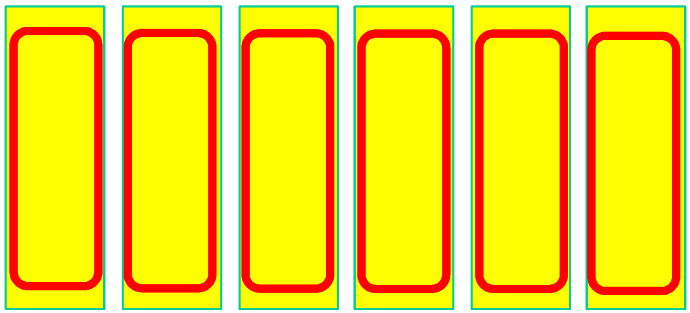
Passivation openings (windows) for ROC, TBM and Cable-pads

- TBM & Cable-pads with common windows for all HDI produced Dec. 2005 – Aug. 2007
- ROC pads with individual passivation windows for HDI produced Dec. 2006 – Aug. 2007



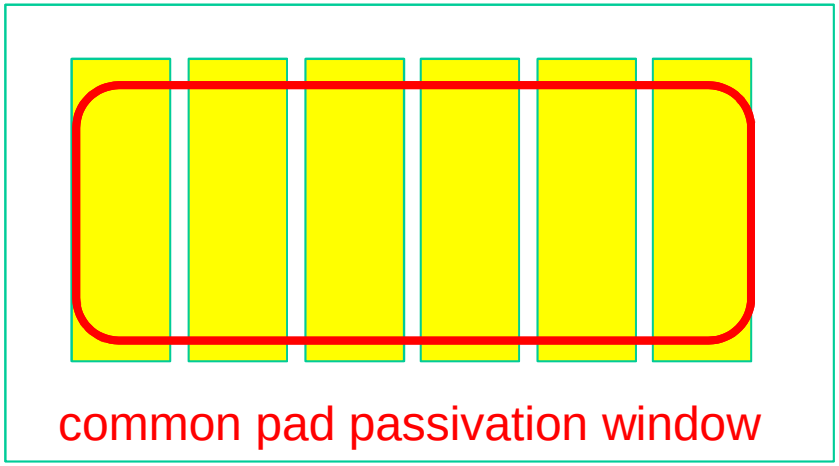


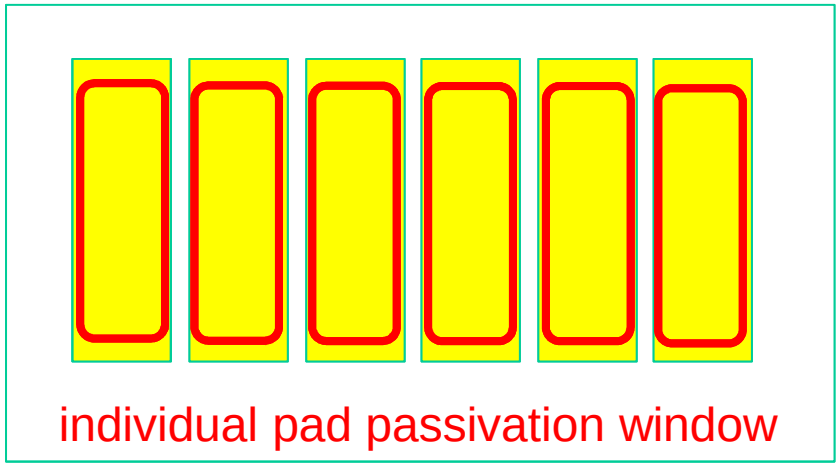
common pad passivation window

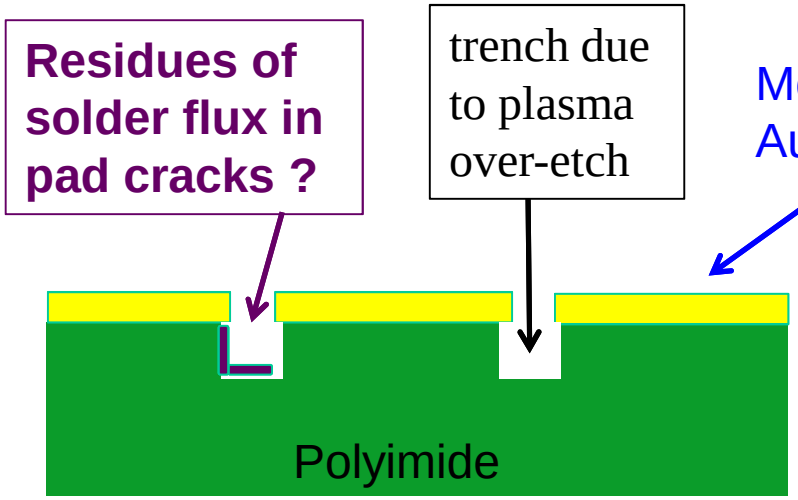


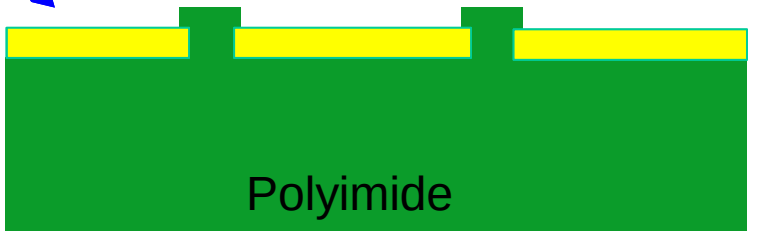
individual pad passivation window

Common & Individual Pad Windows





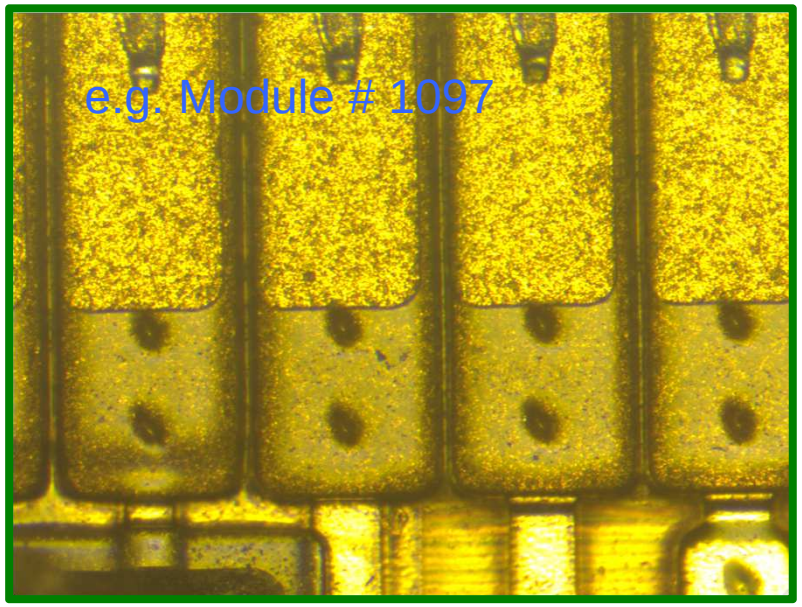


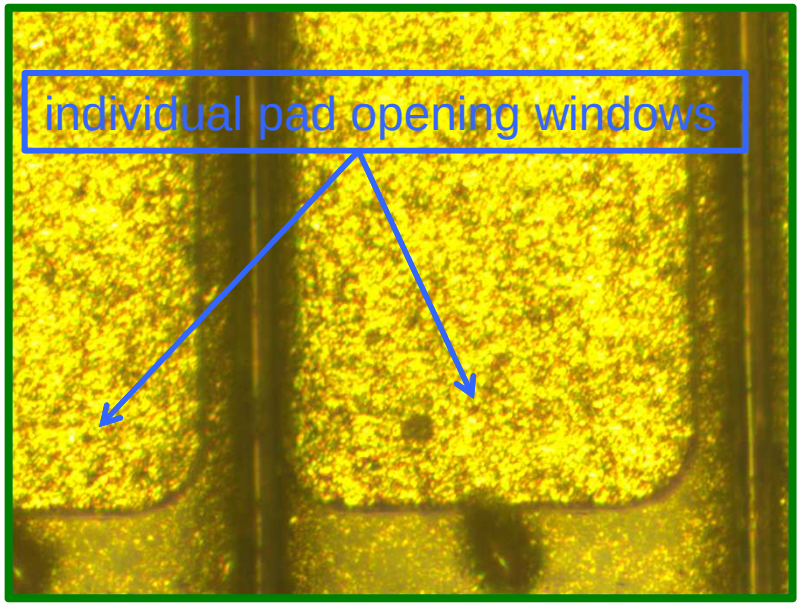


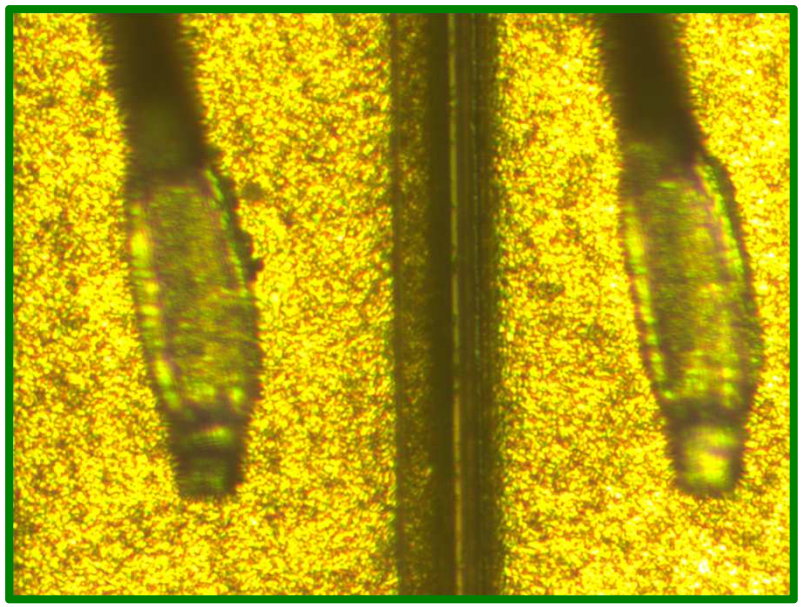
ROC pads of HDI from 2005-2006
→ used till module # ~ 700

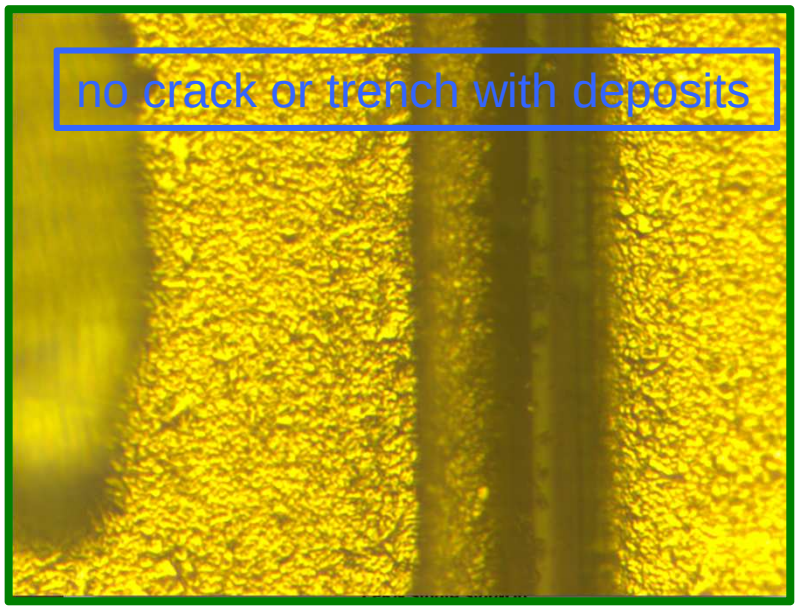
ROC pads of HDI from 2006-2007
→ used in module # ~ 700- 1200

HDI with individual ROC pad windows

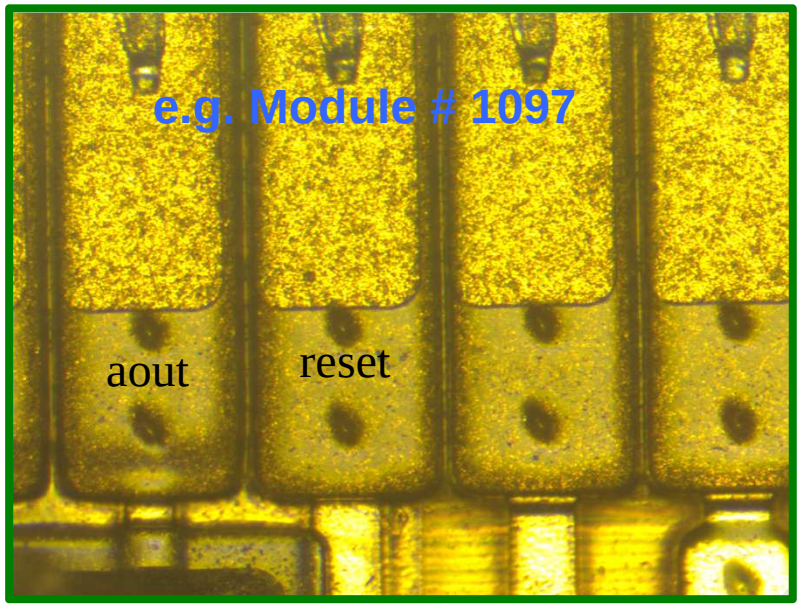


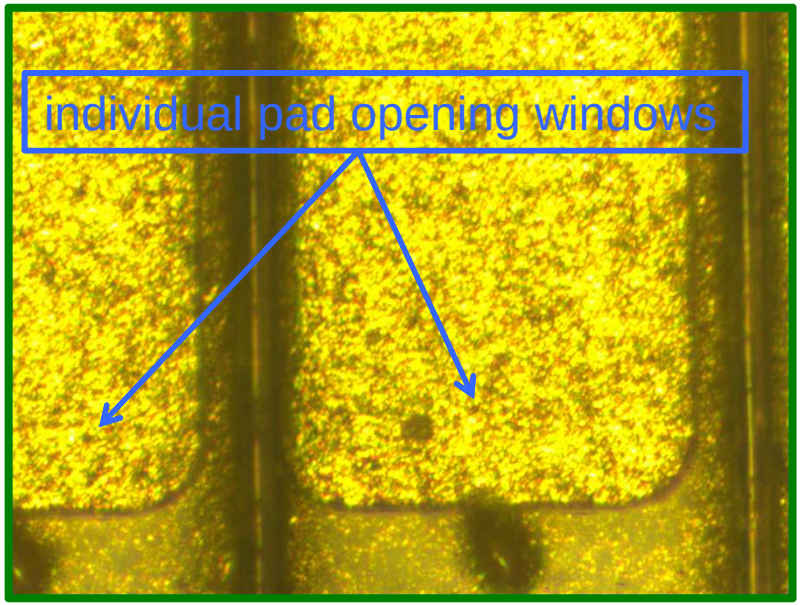






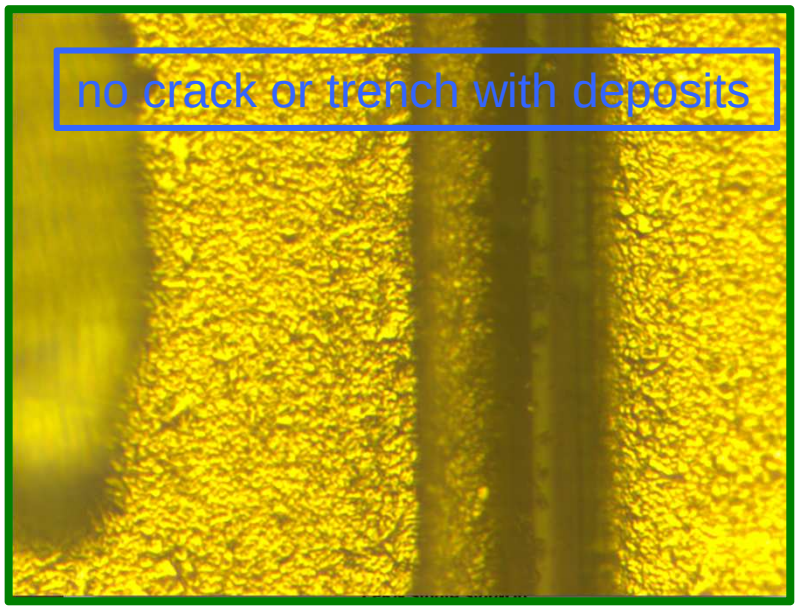
HDI with individual ROC pad windows





From all the ~50 defect modules (some with multiple shorts) have **not seen a single short** between pads with individual pad openings.

HighTec does not manufacture their HDI like PCBs are done. Process based on build up on substrate, very much like chip manufacturing.



Damage Map of Layer 1

Layer 1 , +x-side (near)				Quadrant BMI				Quadrant BPI (damaged)			
				Modules -z-side (Leman)				Modules +z-side (Jura)			
Face #			Ladder	-4	-3	-2	-1	1	2	3	4
1	Top	Half Outer	1				331	418	373		
2		Full Inner	2					757	571	452	1167
3		Full Outer	3				853	759	1197		
4		Full Inner	4								
5		Full Outer	5				818	771	1161	812	1155
6		Full Inner	6								
7		Full Outer	7				1050	130	69	1206	
8		Full Inner	8								
9		Full Outer	9				721	126	284	992	987
10	Bottom	Half Inner	10					376	473	425	387

can be ignored

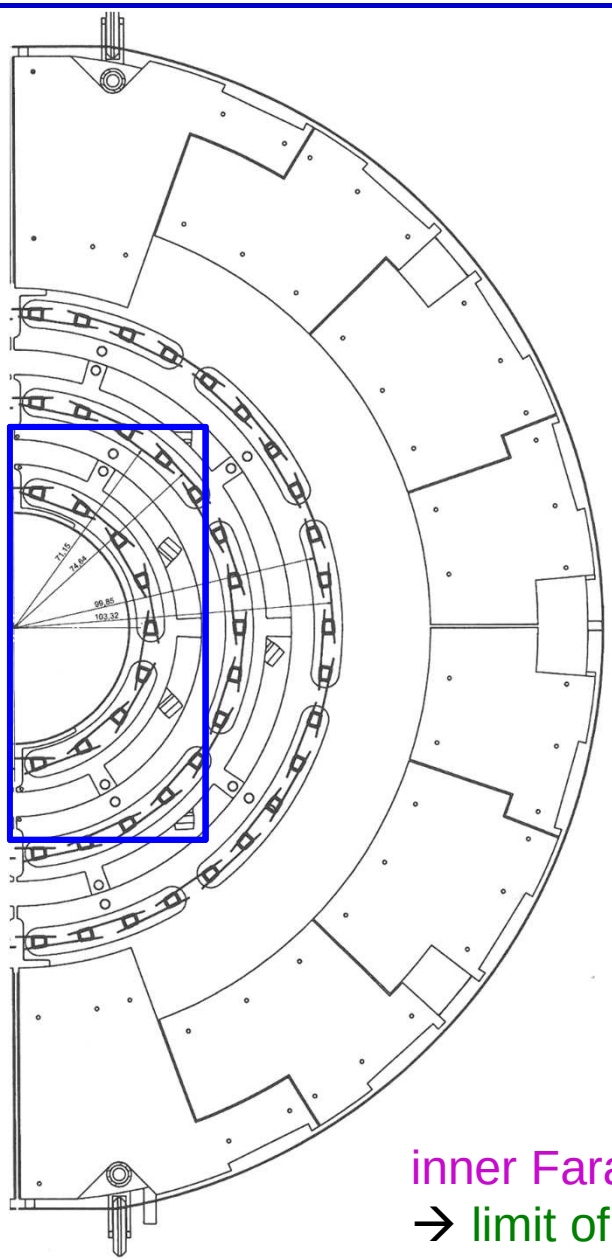
A striking pattern of damaged modules on the same mechanical half-shell !

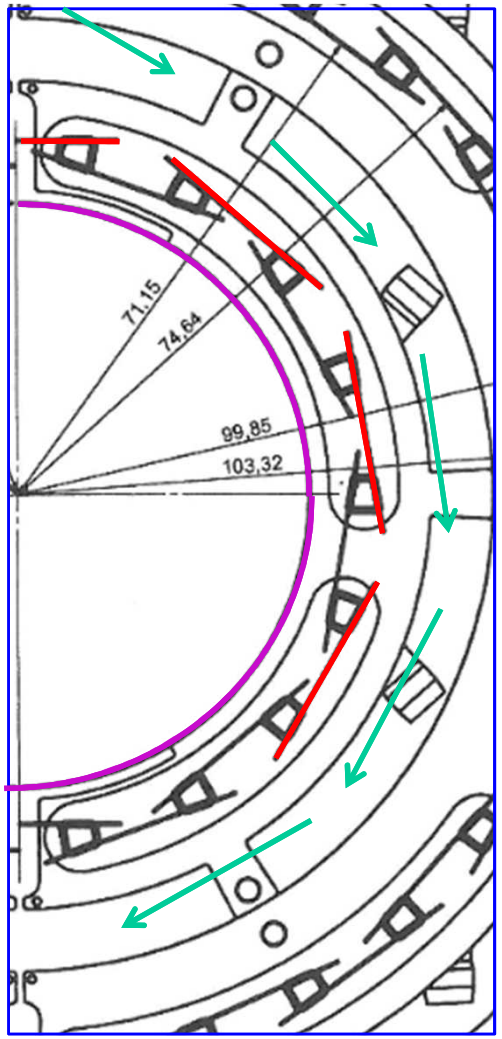
Module number are scattered through randomly on both sides

Only difference is cabling of power and signals +z-side and –z-side

Damaged modules in Layer 1 & Position 1

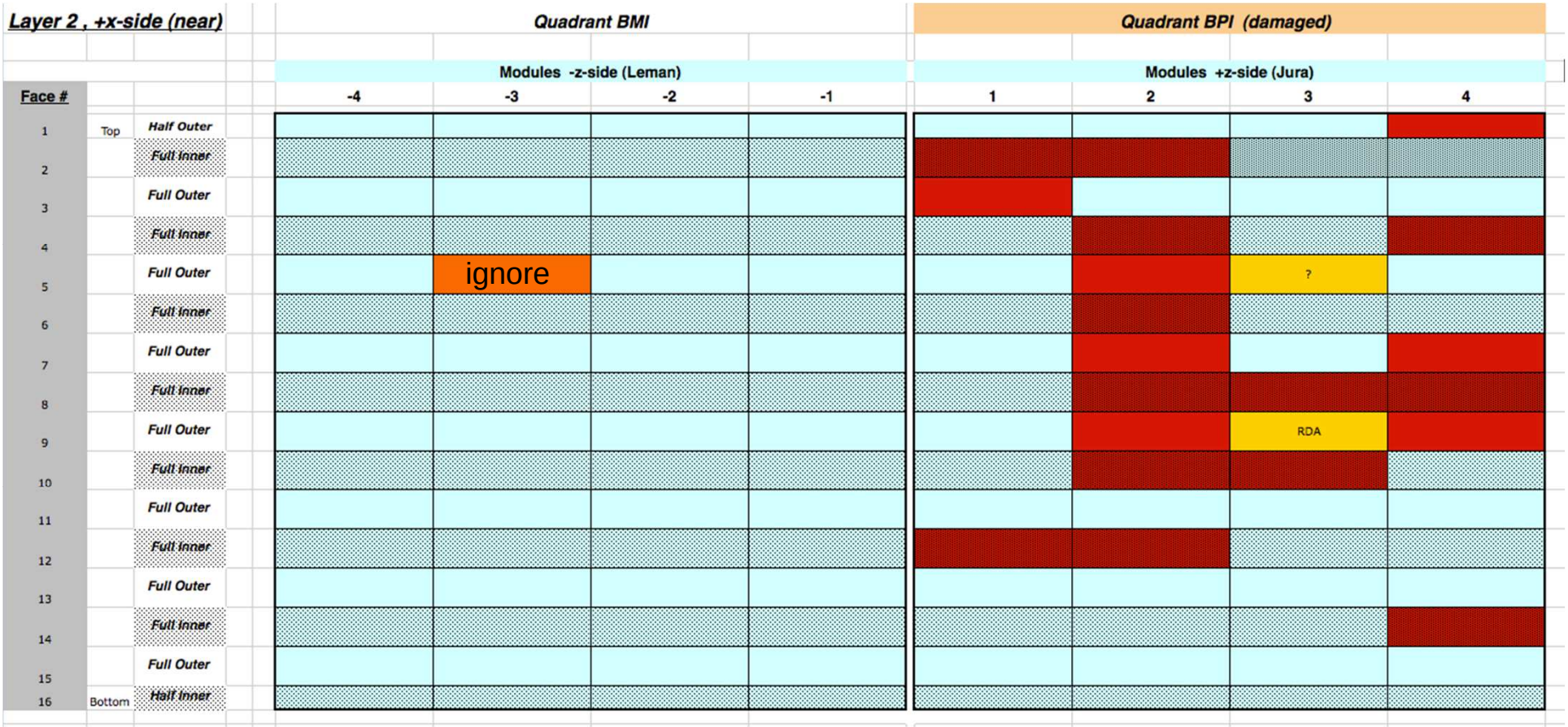
ventilators underneath create vertically airflow down



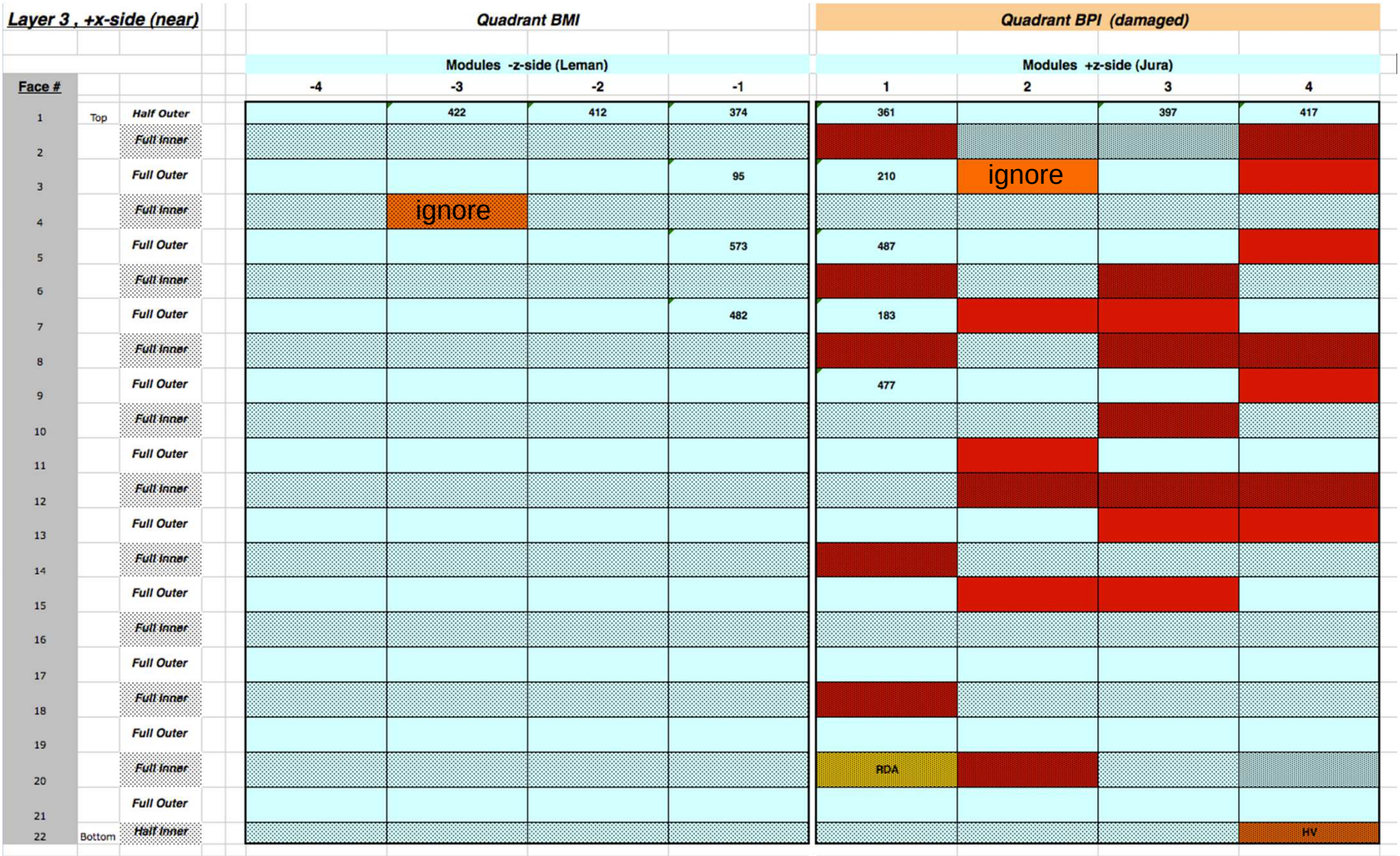


inner Faraday shield very close to 1st Layer modules
→ limit of airflow for innermost oriented modules?

Damage Map of Layer 2



Damage Map of Layer 3



How could this have happened ? A few facts

- power & signaling is **only** parameter in BPIX barrel that distinguishes +z-side (damaged) from –z-side (undamaged)

- 3 other quadrants ok and no damage. Same distribution of module#, HDI-batches, ROC #, TBM #, etc. etc. etc.

- all symptoms of damage indicate a defect mechanism that implies voltage applied in a crucial (bad) moment

- shorts happen with strong preference between pads of **2V** difference or more.

- observe “burning away” of shorts for larger currents → no VDD shorts to GND

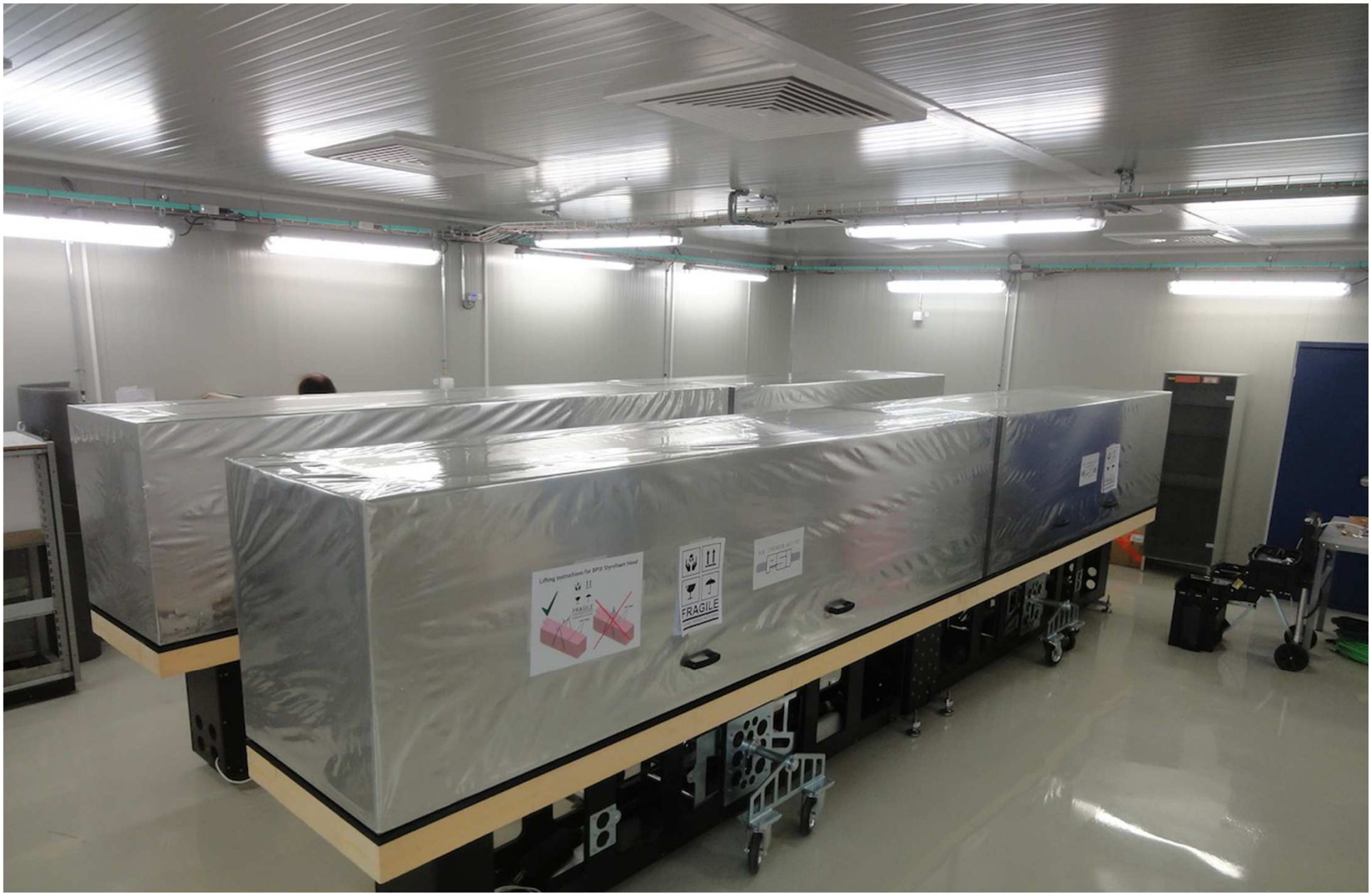
- HDI **shorts only** at pads with ***common passivation windows*** *(trenches)*

- shorts only in close proximity of SMD soldering pads → flux residues (acids)

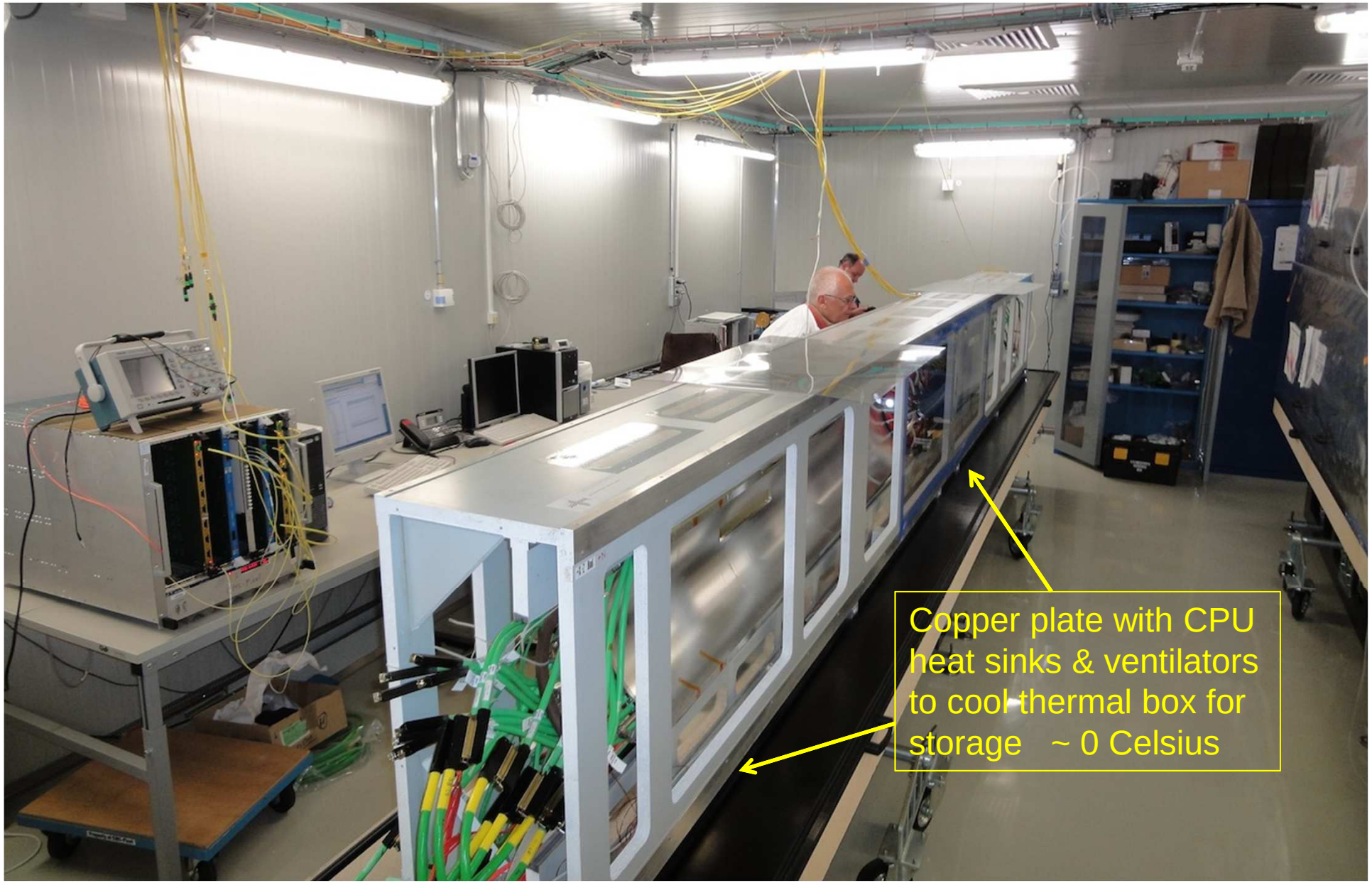
- Need 3 ingredients for shorts: humidity (condense), acid (electrolyte) & voltage !

- Condensation accident in -16^{o}C calibration runs in cooling box at P5 is most likely hypothesis and consistent with all observed symptoms.

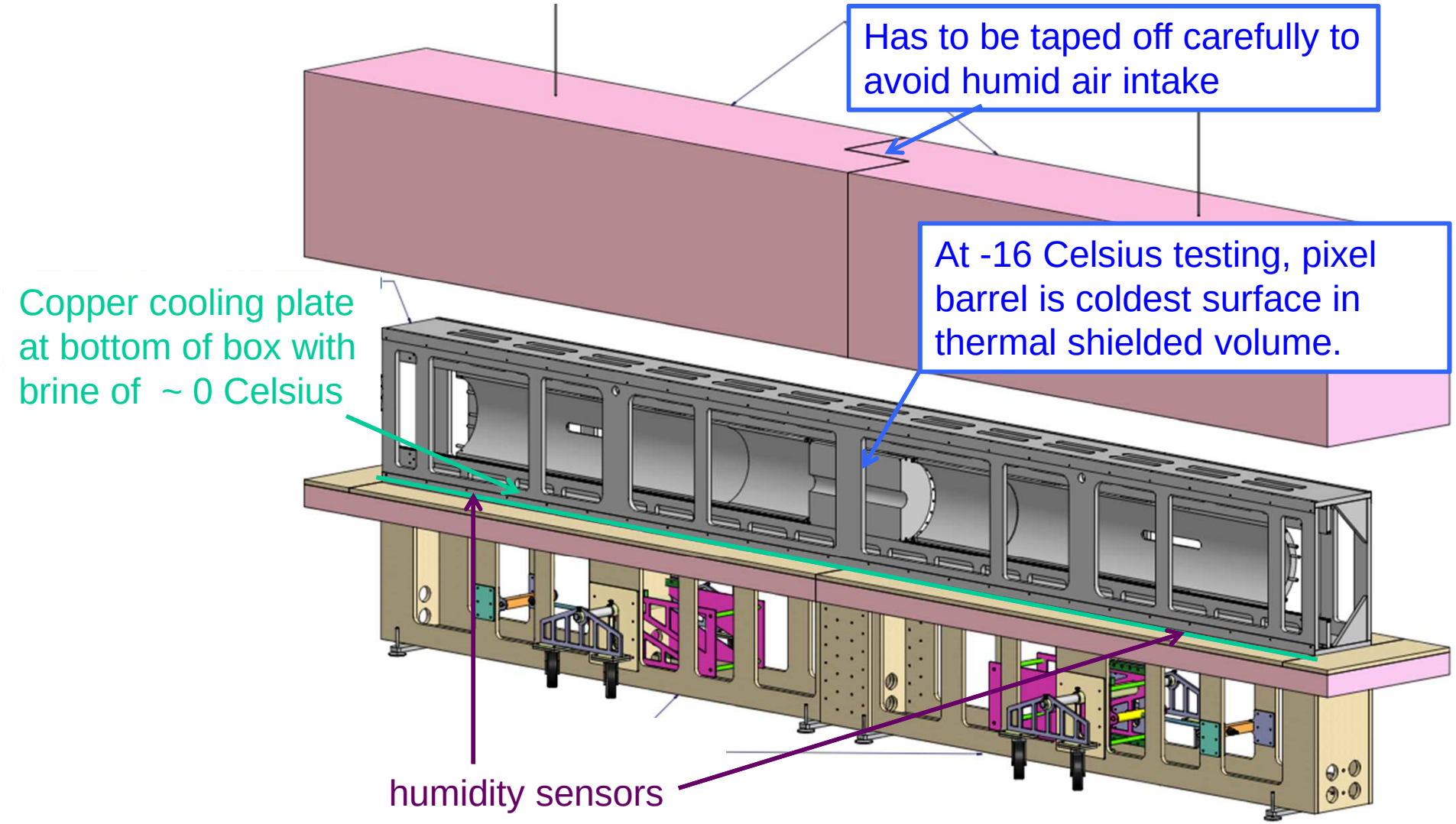
Cooling Tables of BPIX in P5 Pixel Lab



Cooling Tables of BPIX in P5 Pixel Lab



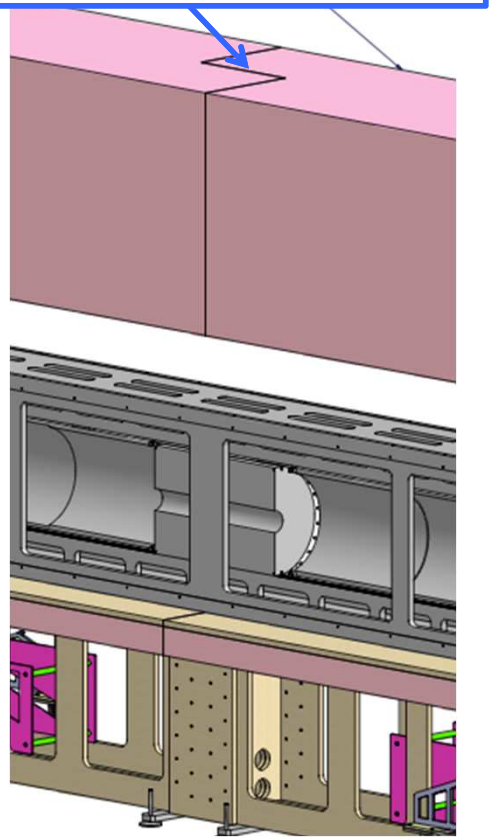
Cooling Tables of BPIX in P5 Pixel Lab



CSI–Pixel Case in BPIX-testing 2013-14

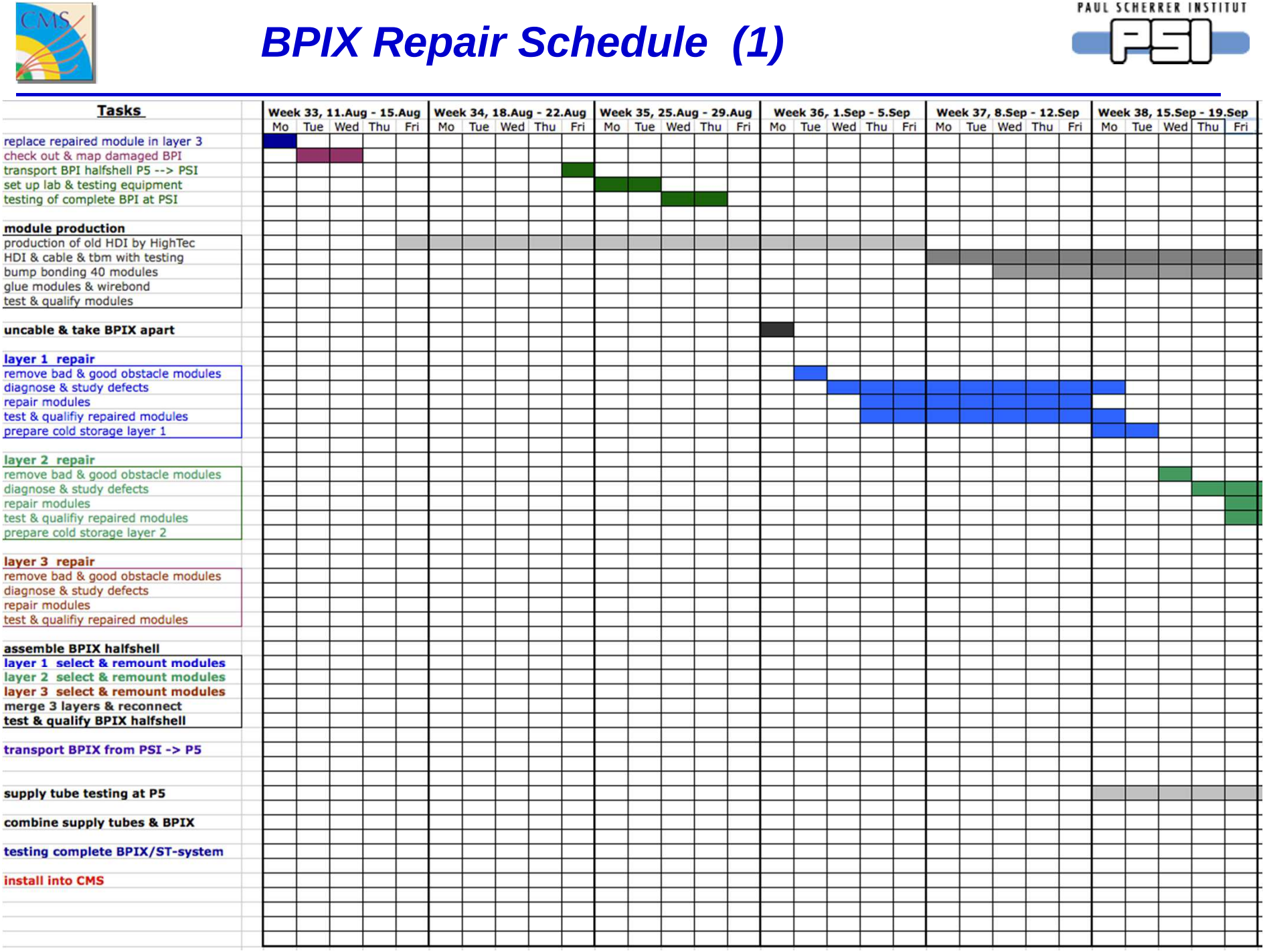
Most likely scenario of events:

- thermal covers opened / closed many times 2013/14
- sealing in Nov/Dec 2013 tests probably left small leak at z~0
- small plumes of humid air (~liters/min) leak inside volume
- copper cooling plate at ~0°C with air temperature ~ +8°C
- ventilators pull down air flow from gap of thermal covers
- local humidity cloud deposits micron thick ice film on coldest surfaces → pixel modules & cooling pipes (-16°C)
- modules under power melt the ice, since HDI on top of sensor has poor thermal contact to cooling pipes.
- sectors under test with power gets damaged by electro-chemical migration with metalorganic-complexes from flux residues in very narrow, deep HDI cracks of early serial #'s.
- modules without power have inert ice film that will later sublimate away again. (no power = no damage)
- humidity sensors at z ~ +/-200cm will not see anything !

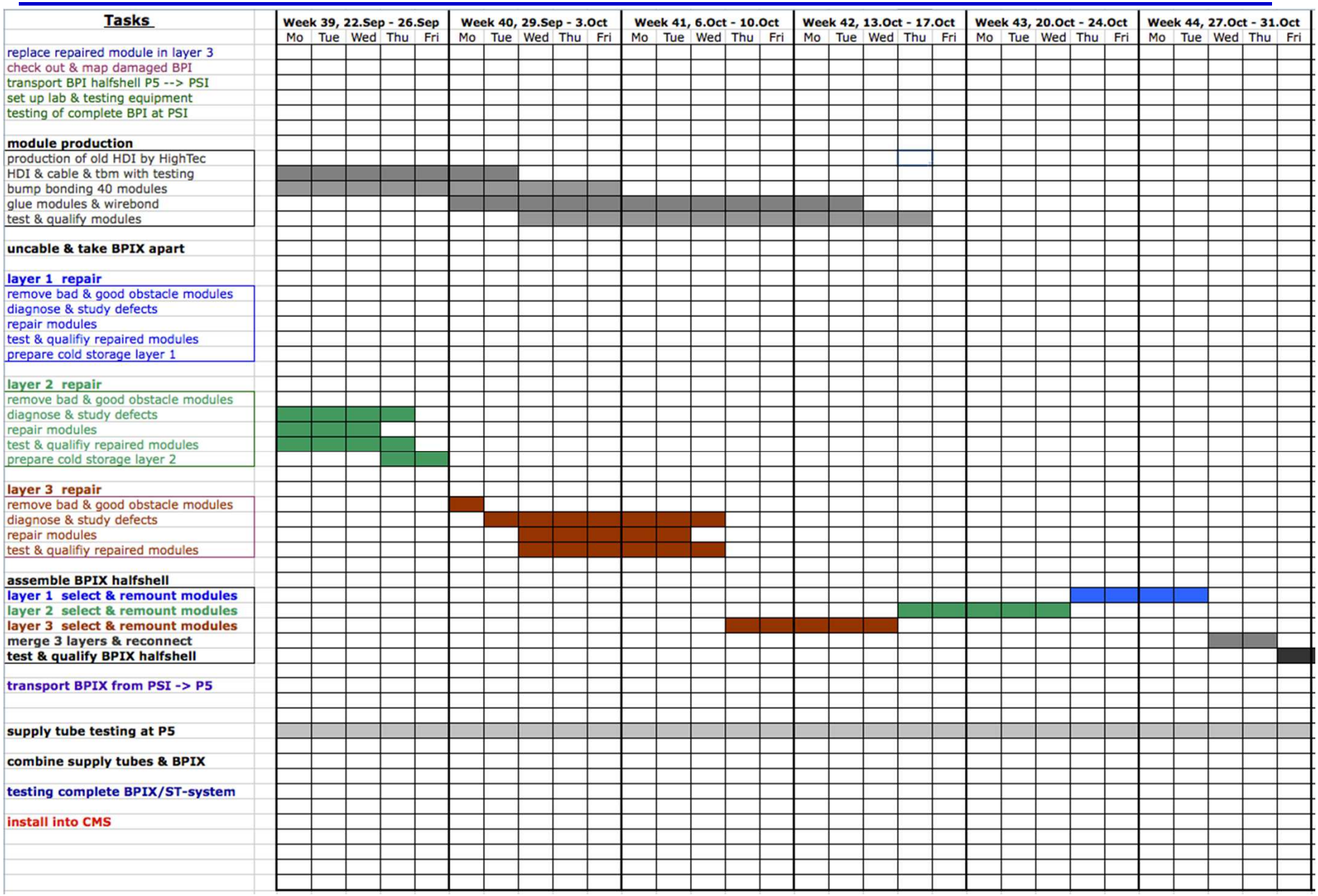


(CSI = Crime Scene Investigation)

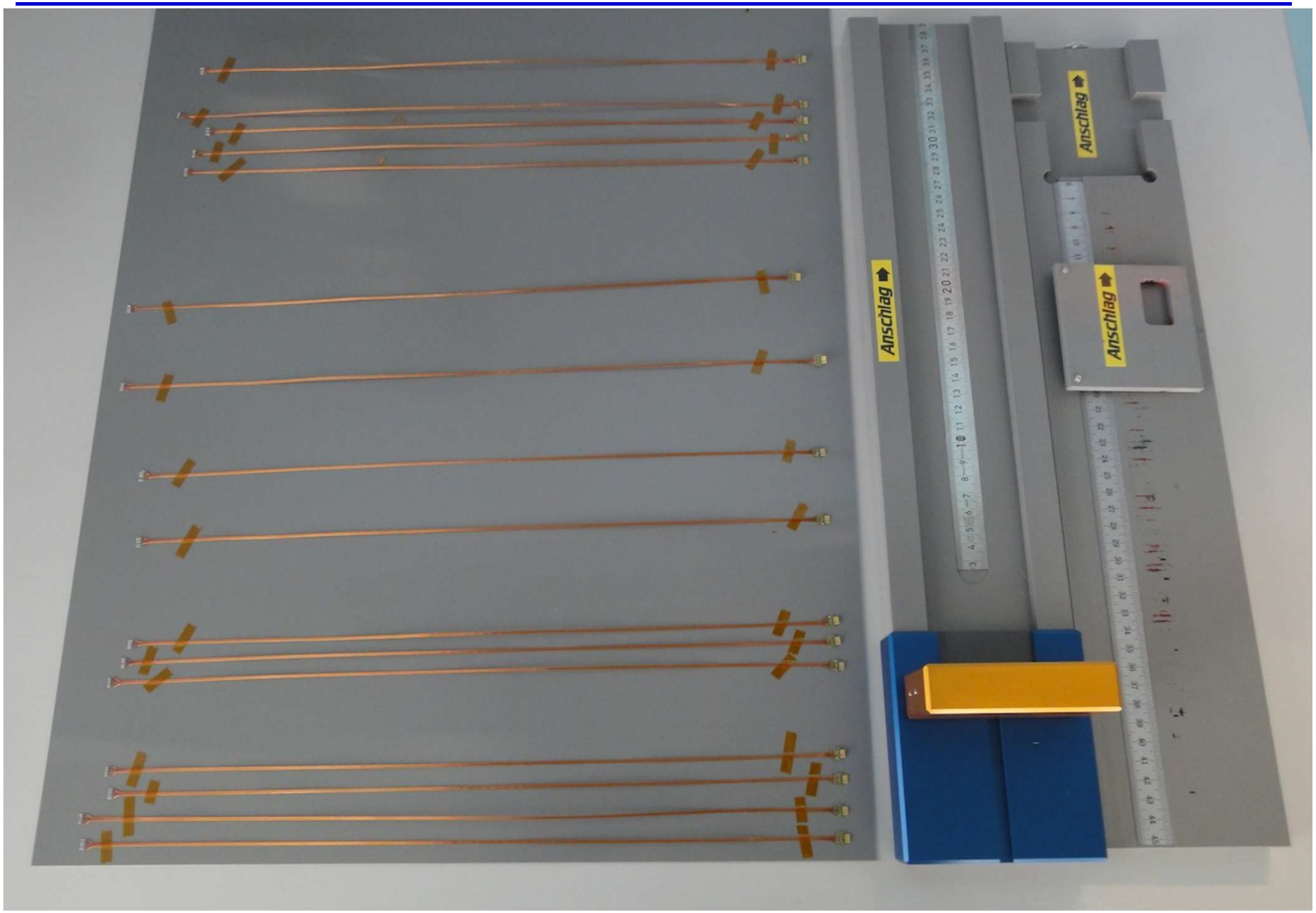
BPIX Repair Schedule (1)



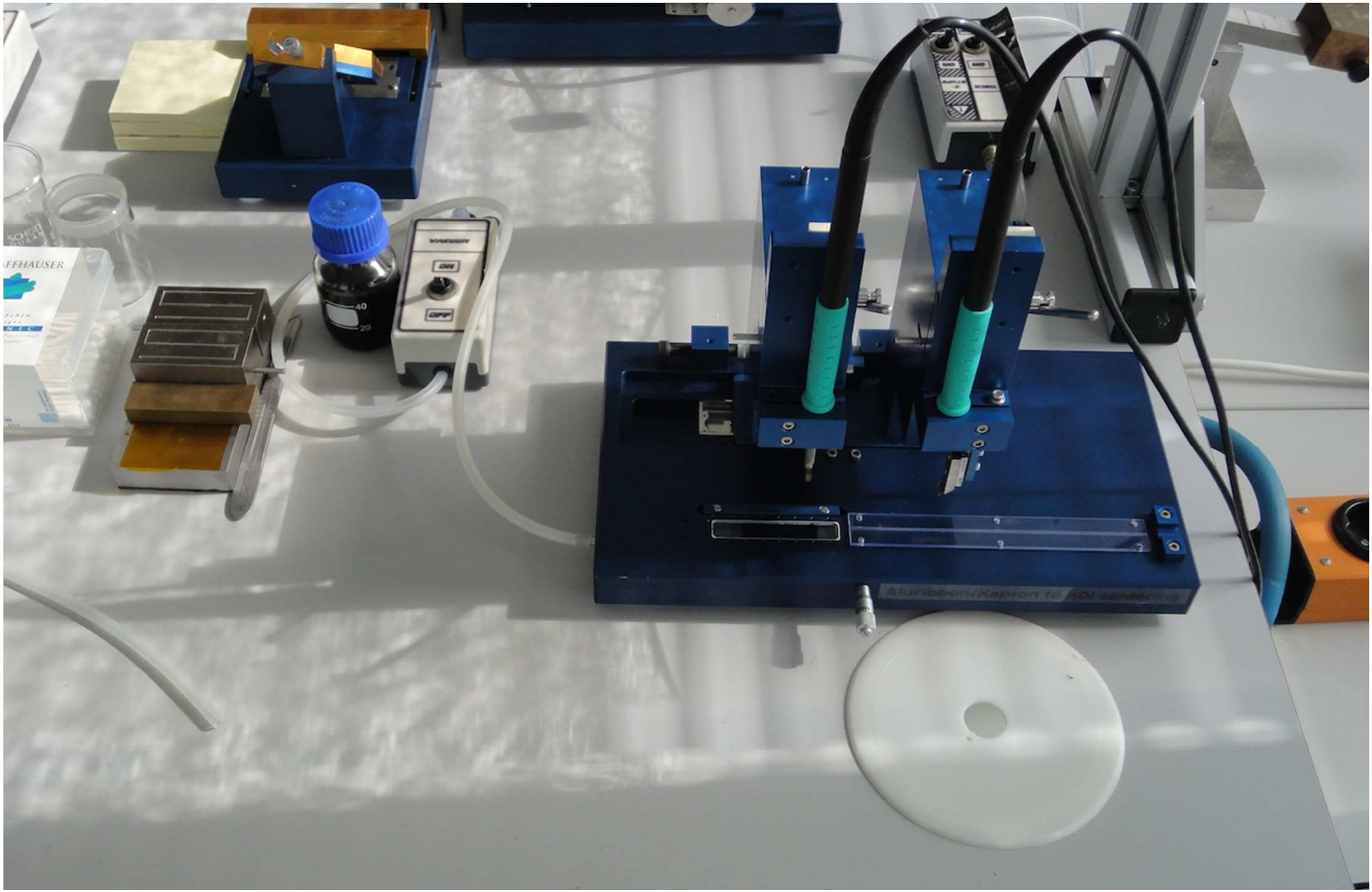
BPIX Repair Schedule (2)



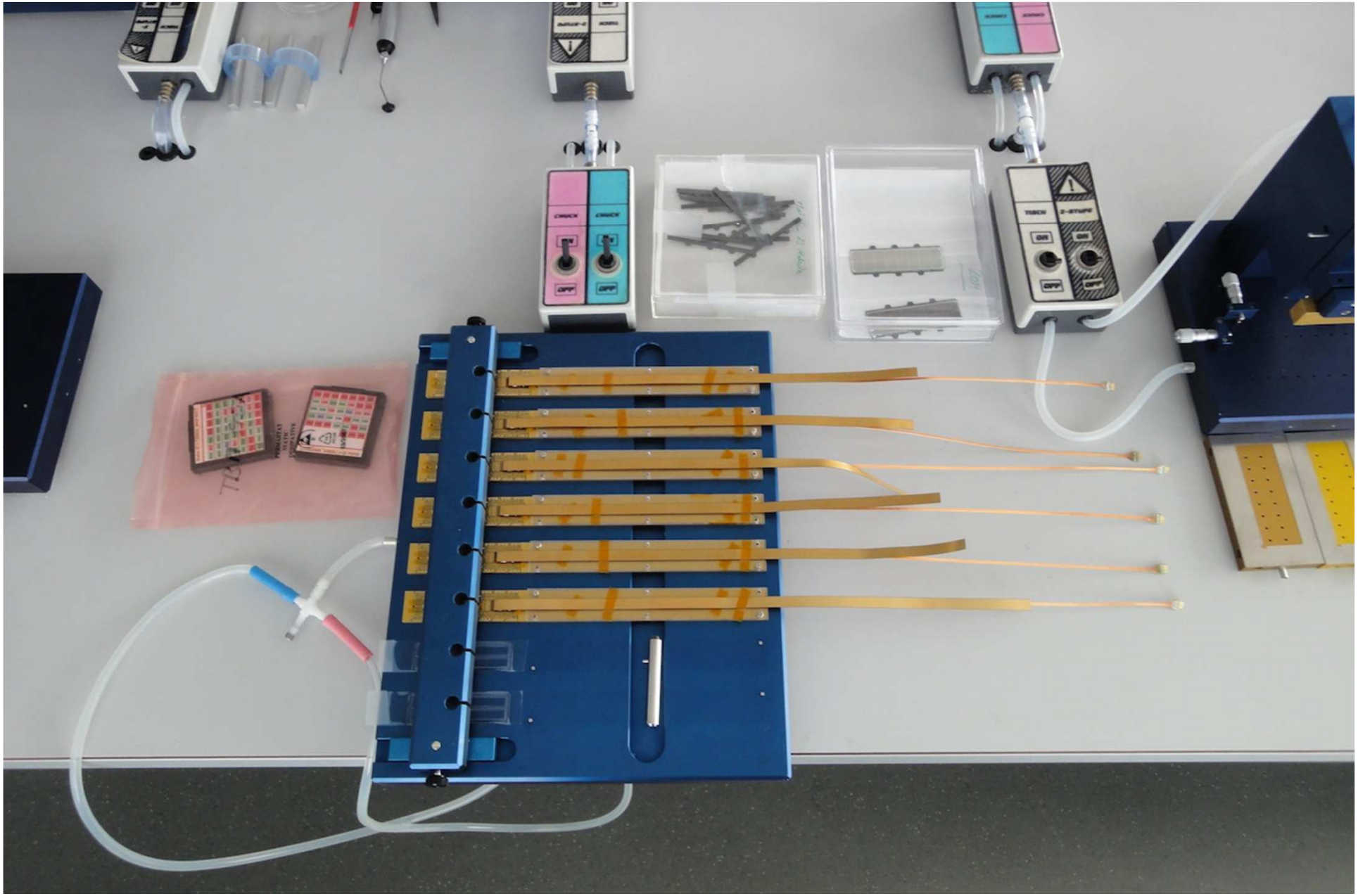
Preparing Cables for Module Production



Solder Station for Module Production

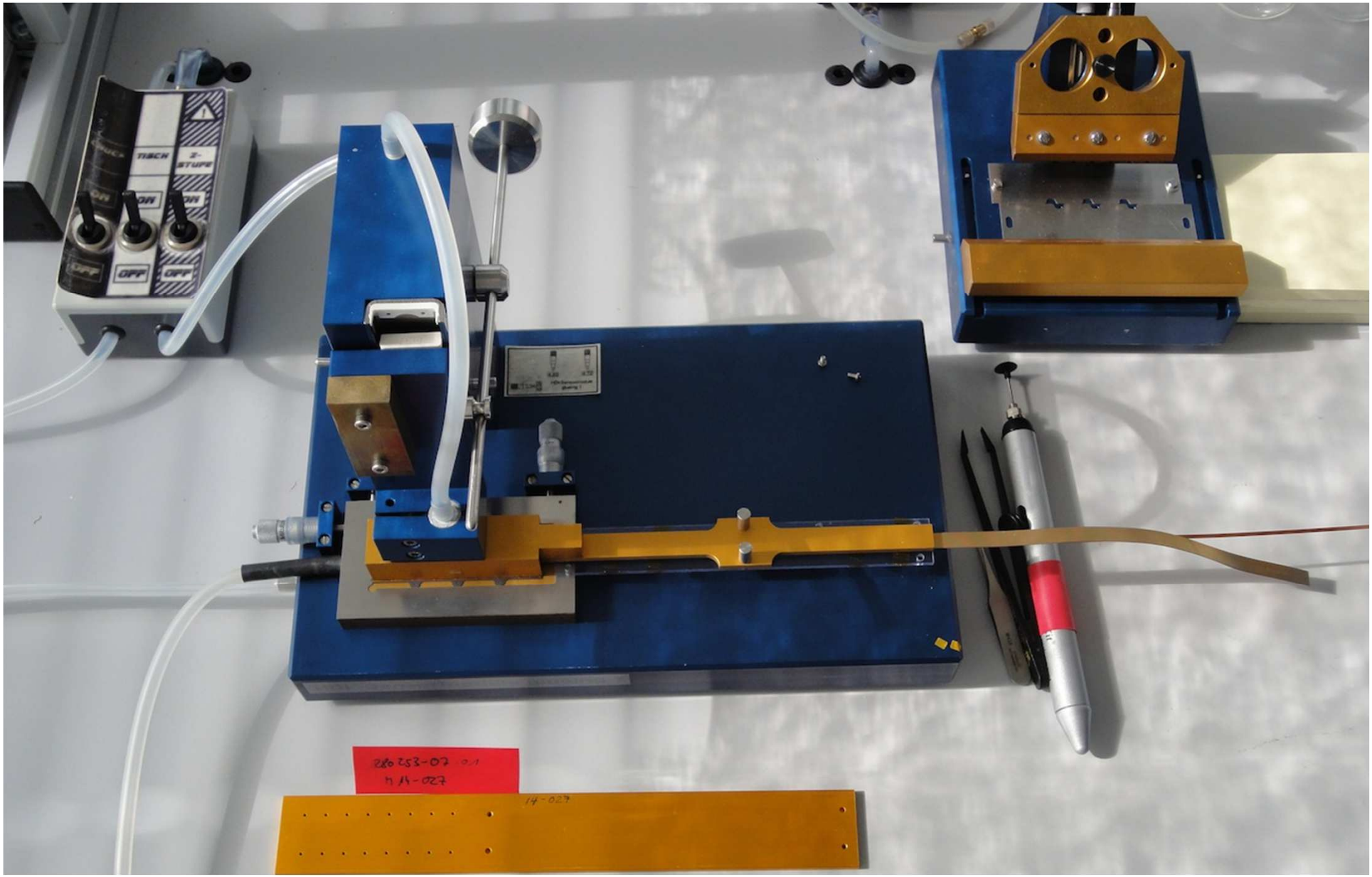


Glueing TBM to HDI

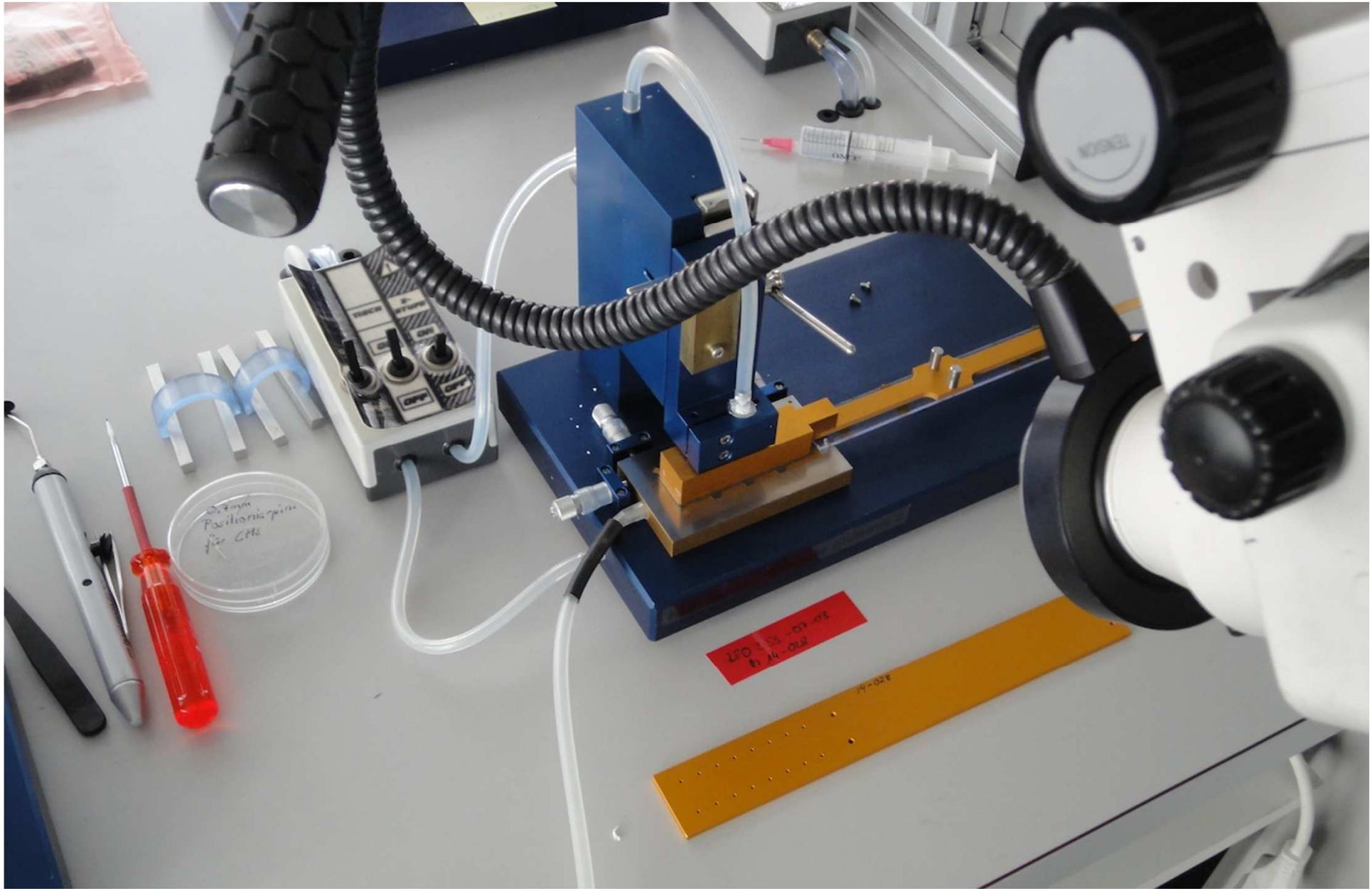


Bump bond ~40 new modules at DECTRIS

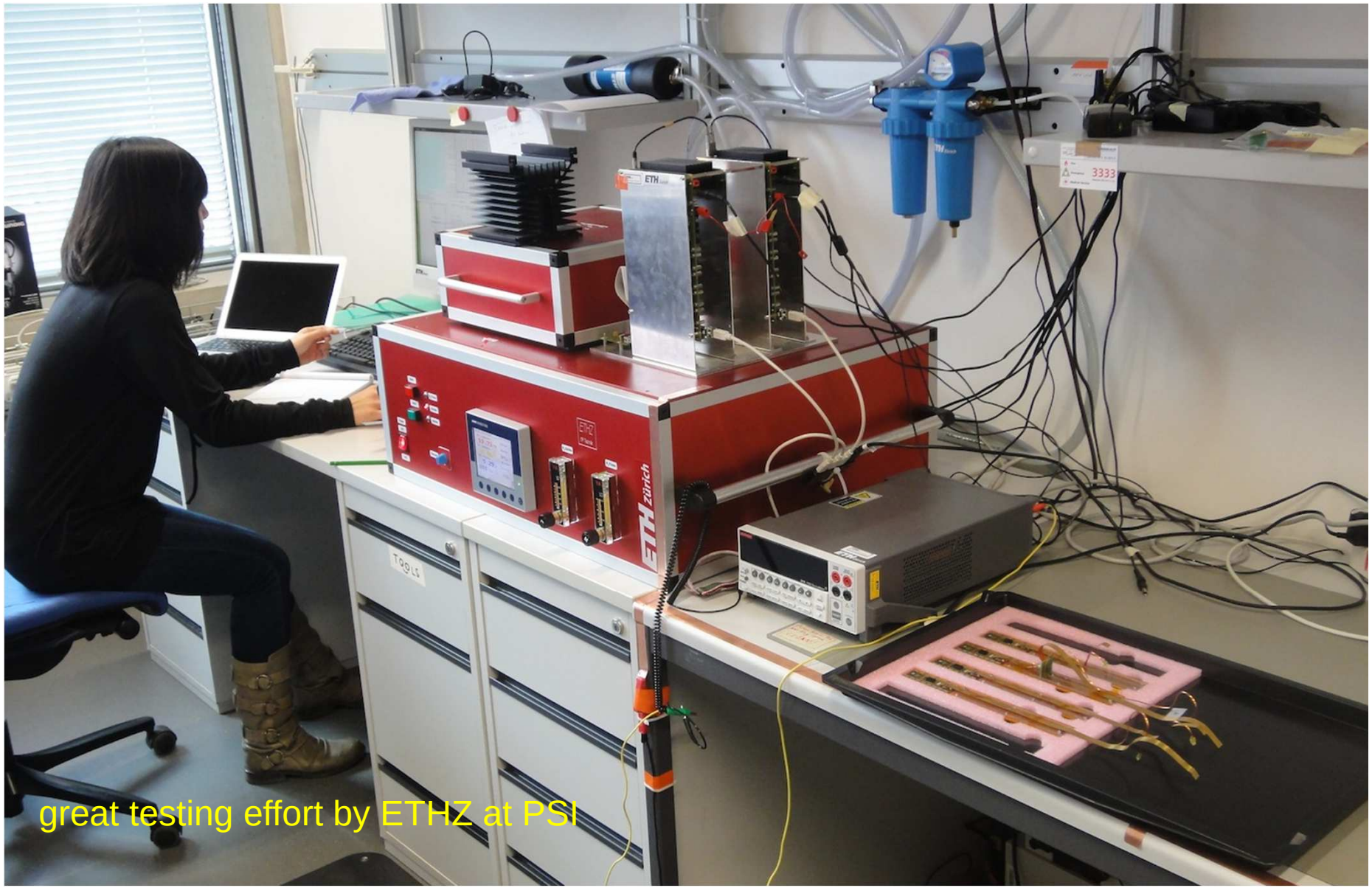
HDI to Bare Module glueing (Station 1)



HDI to Bare Module glueing (Station 2)



Testing & Qualification of BPIX Modules



great testing effort by ETHZ at PSI

Statistics of Module Repair and Production

- Damaged and removed modules:
  - 39 repaired
  - 7 worked by themselves or various uncontrolled manipulations
  - 10 not repaired

- Used for final replacement were:
  - 40 new or fresh modules
  - 19 repaired modules , selected by grading scheme

- Module remounting was done in following order:
  - Layer 1 with mostly new modules → back to fridge
  - Layer 2 with few repaired modules → back to fridge
  - Layer 3 with ~50% repaired modules → done Friday, 1. Nov. 2014

Remounting scheme of Layer 1

	Quadrant BMI				Quadrant BPI (damaged)			
	Modules -z-side (Leman)				Modules +z-side (Jura)			
Ladder	-4	-3	-2	-1	1	2	3	4
1				331	**418**	373		
2					**757**	**571 ▹ 1413**	**452 ▹ 1417**	1167
3				853	**759 ▹ 1425**	1197		
4								
5				818	**771 ▹ 1434**	**1161**	**812 ▹ 1419**	1155
6								
7				1050	**130 ▹ 1436**	**69 ▹ 1412**	1206	
8								
9				721	**126**	**284 ▹ 1409**	**992**	987
10					**376**	**413**	**425 ▹ 390**	387

	Module replaced
	Module repaired
	Problem before incident
bold and underline	Module was dismounted

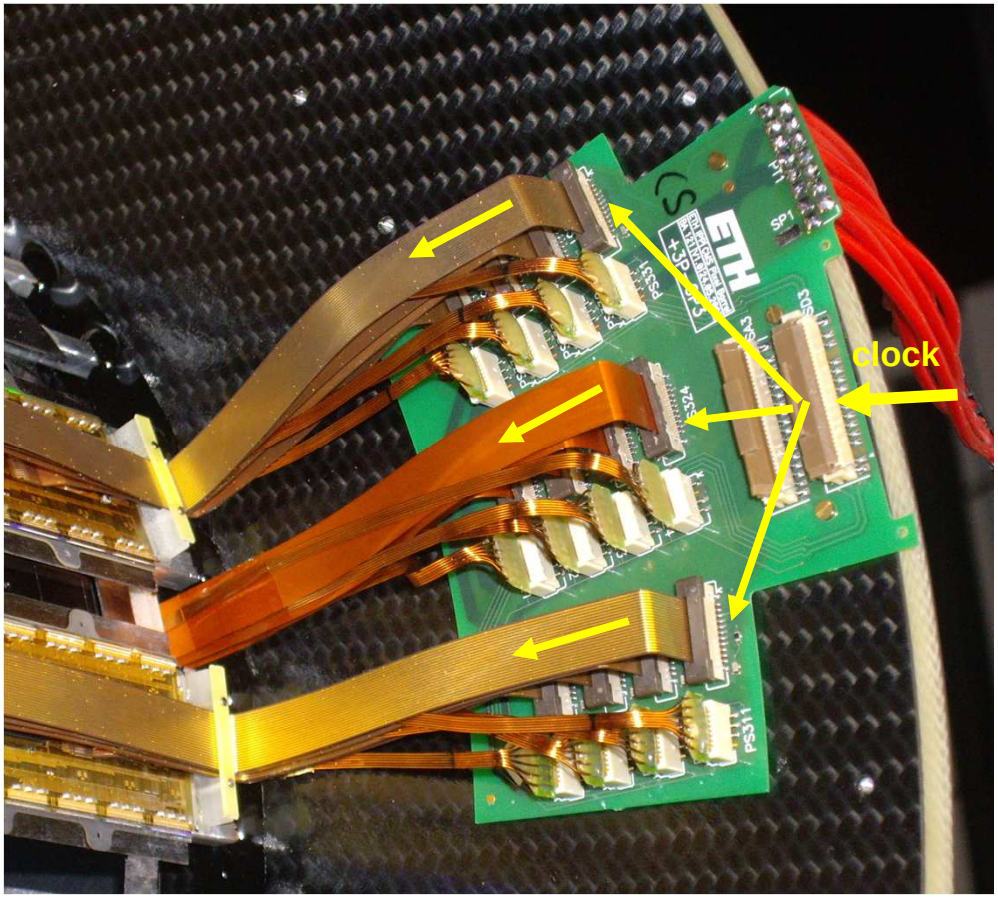
Remounting scheme of Layer 2

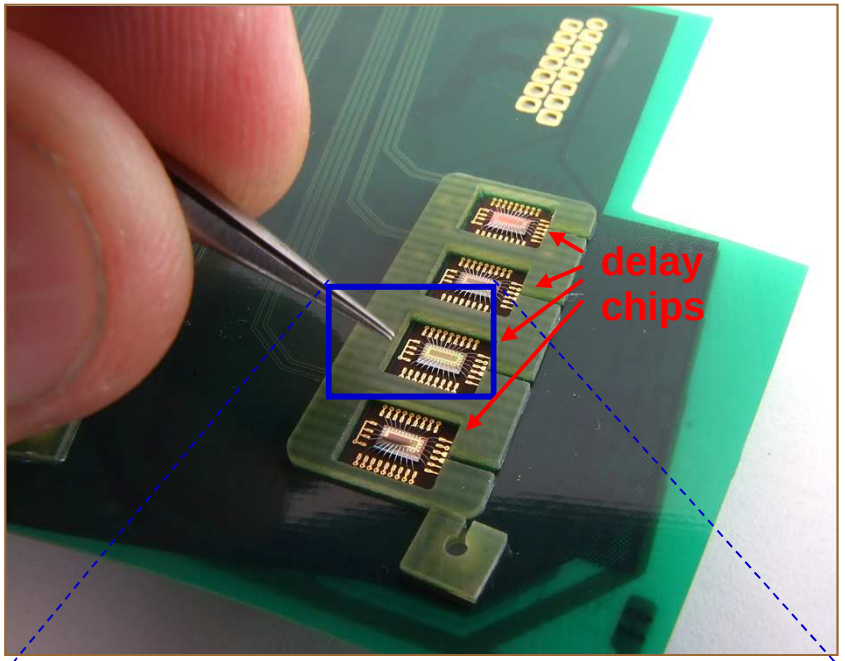
	Quadrant BMI				Quadrant BPI (damaged)			
	Modules -z-side (Leman)				Modules +z-side (Jura)			
Ladder	-4	-3	-2	-1	1	2	3	4
1				1012	379	416	385	383 ▷ 391
2				761	672 ▷ 1428	687 ▷ 1418	939	
3				558	283 ▷ 1403	637		
4				743	138	767 ▷ 1446	579	194 ▷ 1432
5		135 ▷ 844	888	809	246	494 ▷ 1452	598	627
6				43	700	860 ▷ 1450	143	
7				444	456	682 ▷ 1441	800	1103
8				944	787	581 ▷ 1454	615 ▷ 1453	473
9				148	242	254 ▷ 1437	460 ▷ 1424	689 ▷ 110
10				113	1180	281 ▷ 1442	289 ▷ 1448	167
11				593	885			
12				301	286 ▷ 1423	564 ▷ 1445	654	
13				549	83			
14				565	47	185	215	31
15				264	636			
16				965	363			

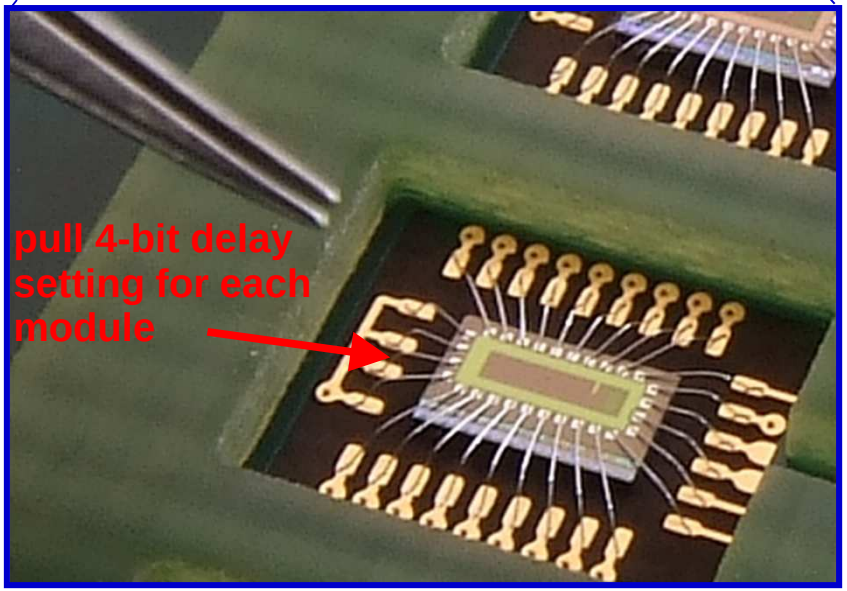
Remounting scheme of Layer 3

	Quadrant BMI				Quadrant BPI (damaged)			
	Modules -z-side (Leman)				Modules +z-side (Jura)			
Ladder	-4	-3	-2	-1	1	2	3	4
1		422	412	374	361		397	417
2				430	**524**	**1117**	**41**	**218 ▹ 1416**
3				95	**210 ▹ 570**	**1178**	**236**	**685 ▹ 273**
4		**128 ▹ 1172**	**448**	**789**	707			
5				573	**487**	**1097**	**192**	**447**
6				776	**705 ▹ 830**	**981**	**706**	747
7				482	**183**	**486**	**623**	911
8				1146	**523**	**752**	**589**	**676 ▹ 1414**
9					**477**	**624**	**873**	**1063**
10				715	**648**	**882**	**241**	521
11					**827**	**70**		
12				788	**713**	**895 ▹ 832**	**155**	**165**
13					**1140**	**497**	**1211 ▹ 490**	**262 ▹ 1415**
14				305	**1101**	1119		
15					**1165**	**1163 ▹ 1205**	**577**	1144
16				463	975			
17					1186			
18				483	**898 ▹ 674**	1067		
19					1132			
20				59	**582 (RDA)**	**712**	890	
21					1135			
22				415	357			**370(HV) ▹ 375**

Test and Replace End Flange Prints

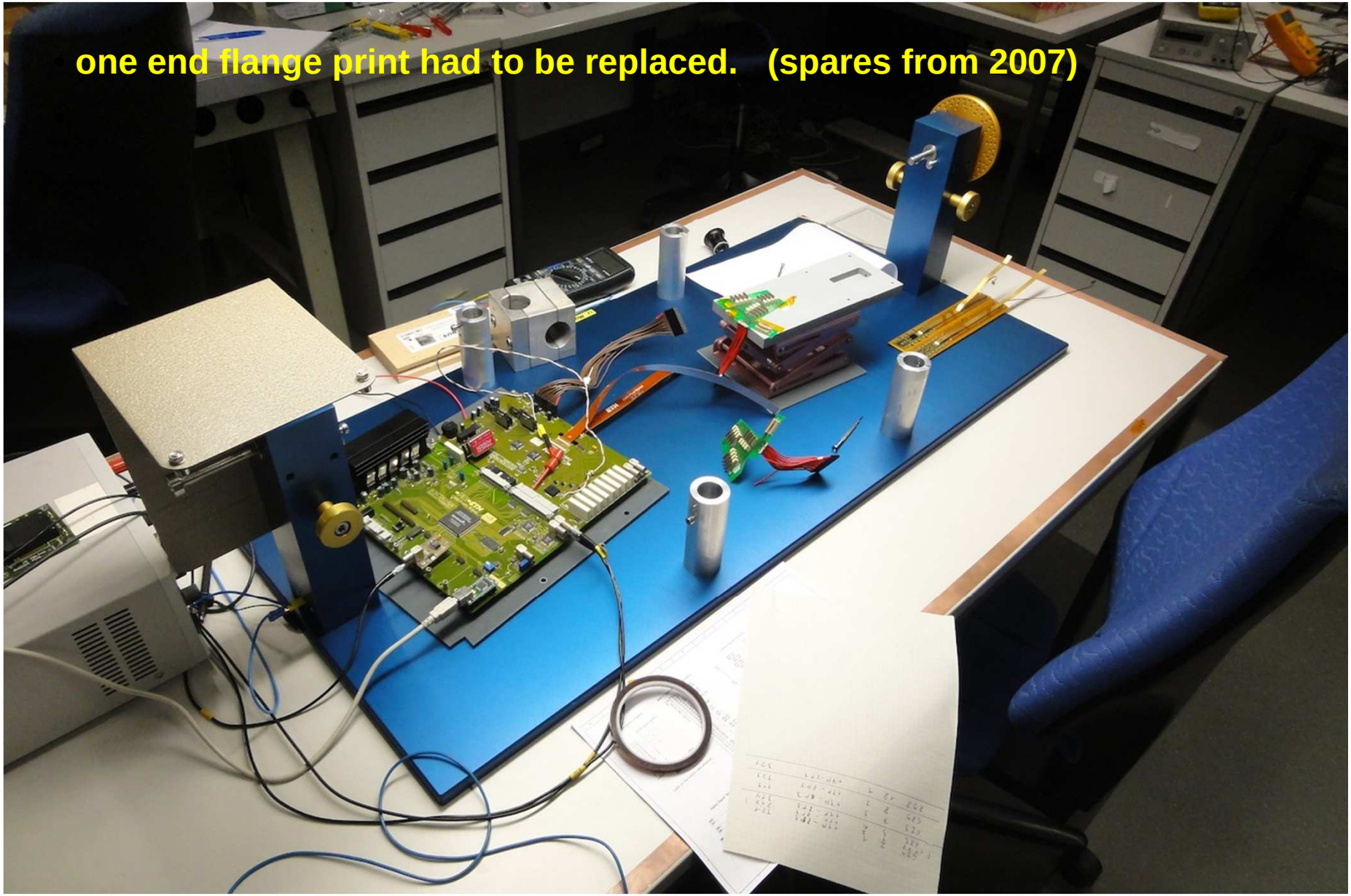




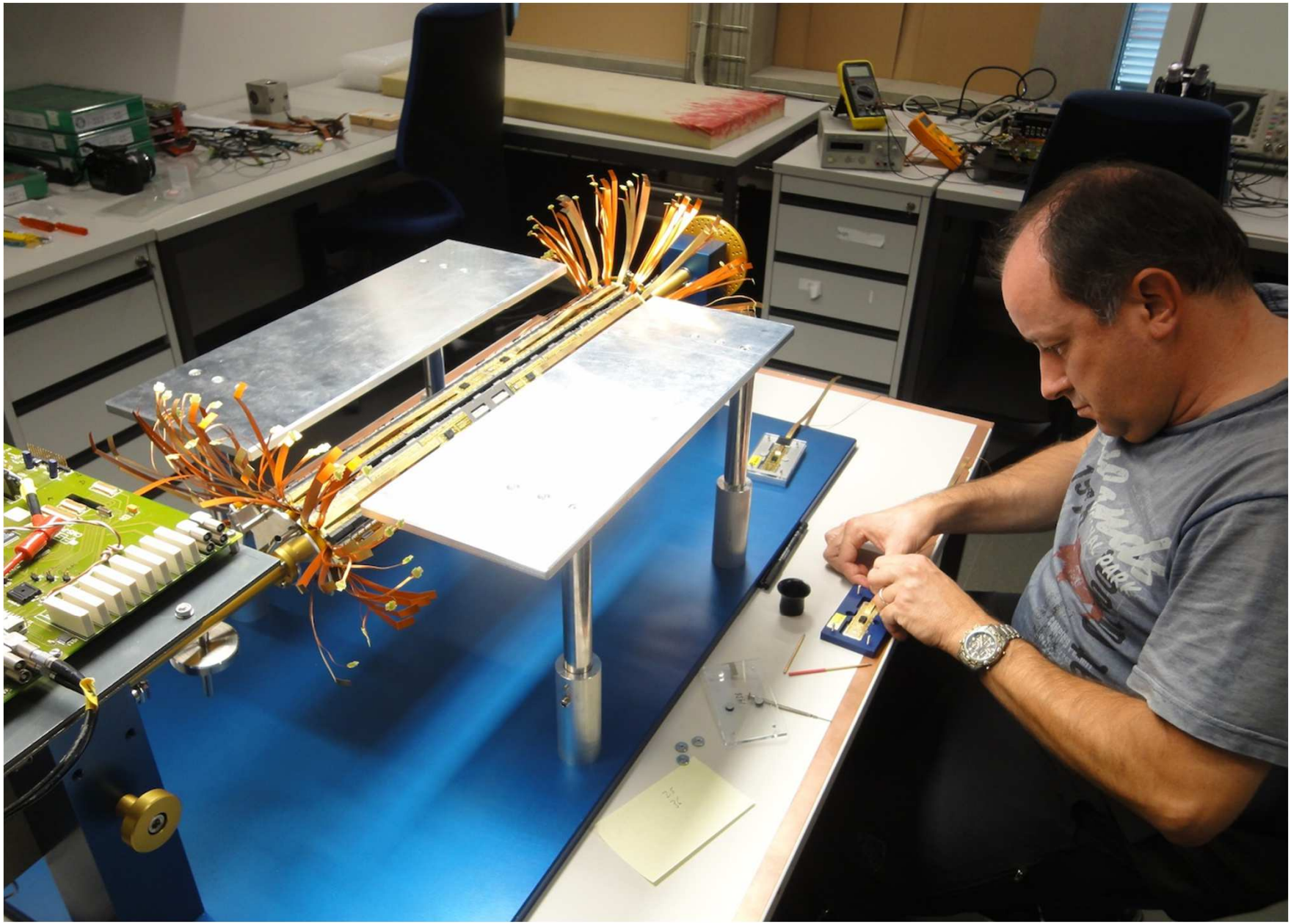


- **delay chips** behind each Kapton cable plug
- delay range 0-3.2nsec, 4-bit → 0.2nsec

Testing and Replacement of End Flange Prints

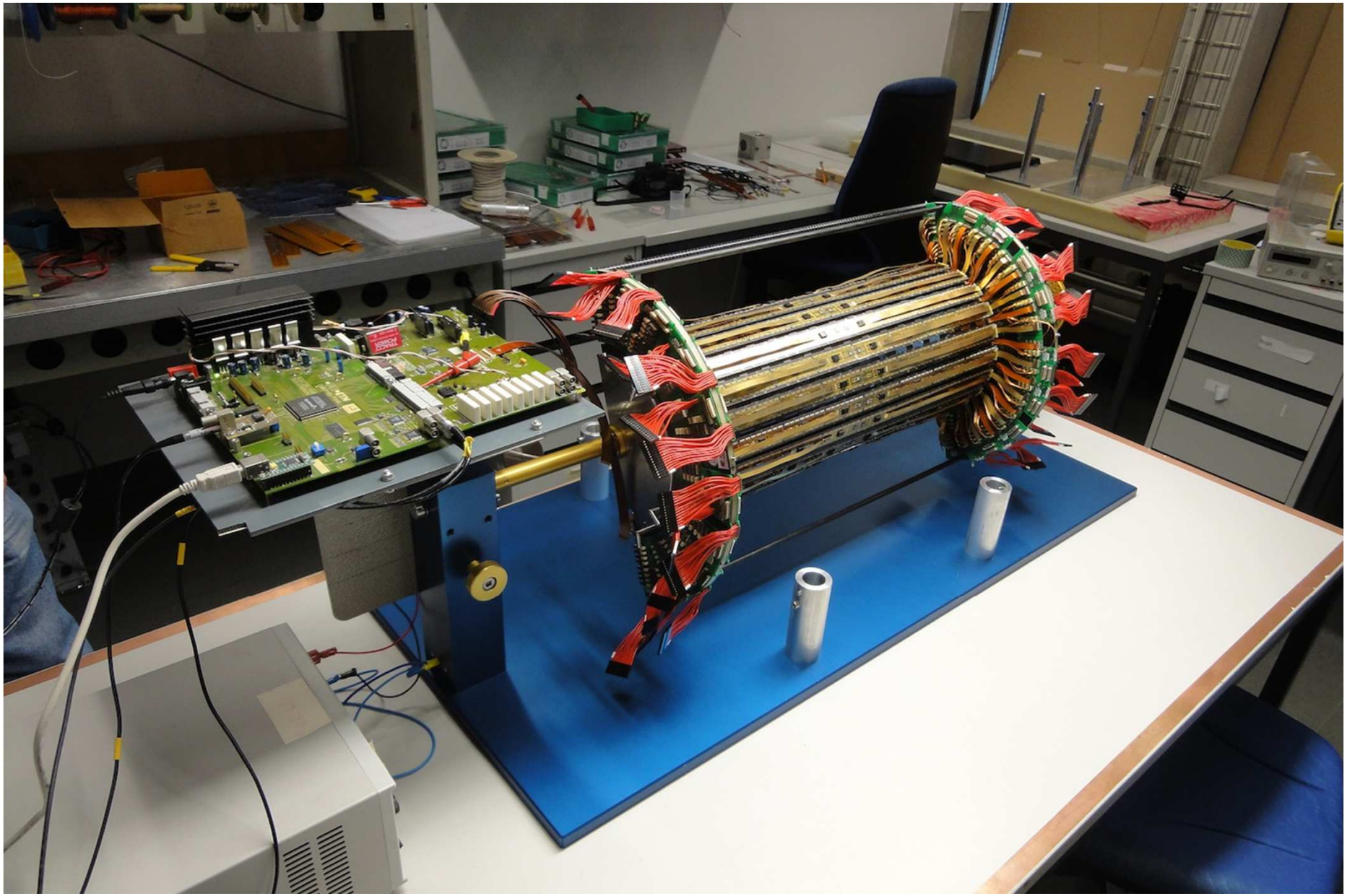


Configure Modules & Remounting Layer 1



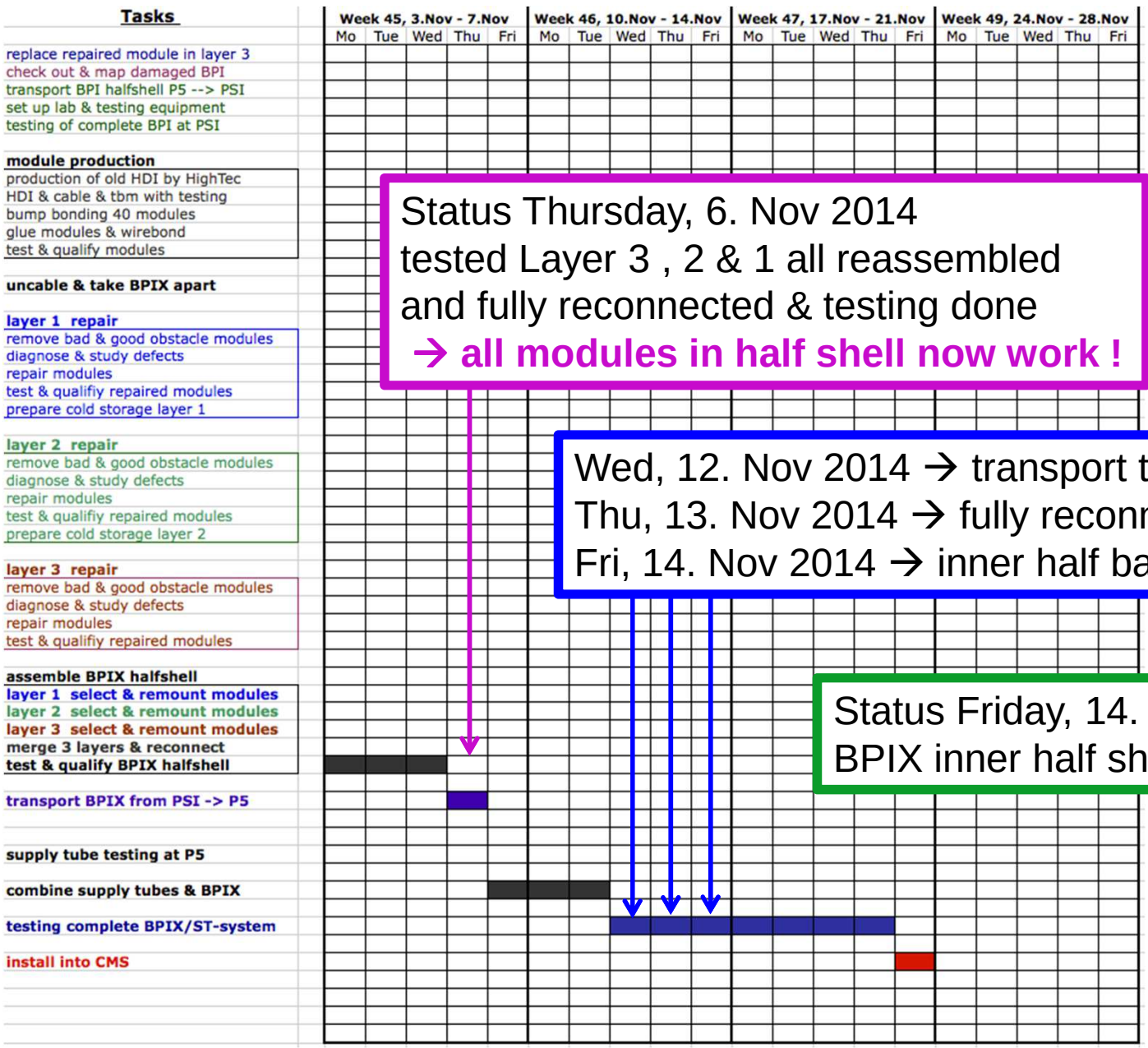
Module testing of remounted Layer 1

Remounting of Layer 3 Modules and Cabling



Testing of complete module groups of Layer 3

BPIX Repair Schedule (3)



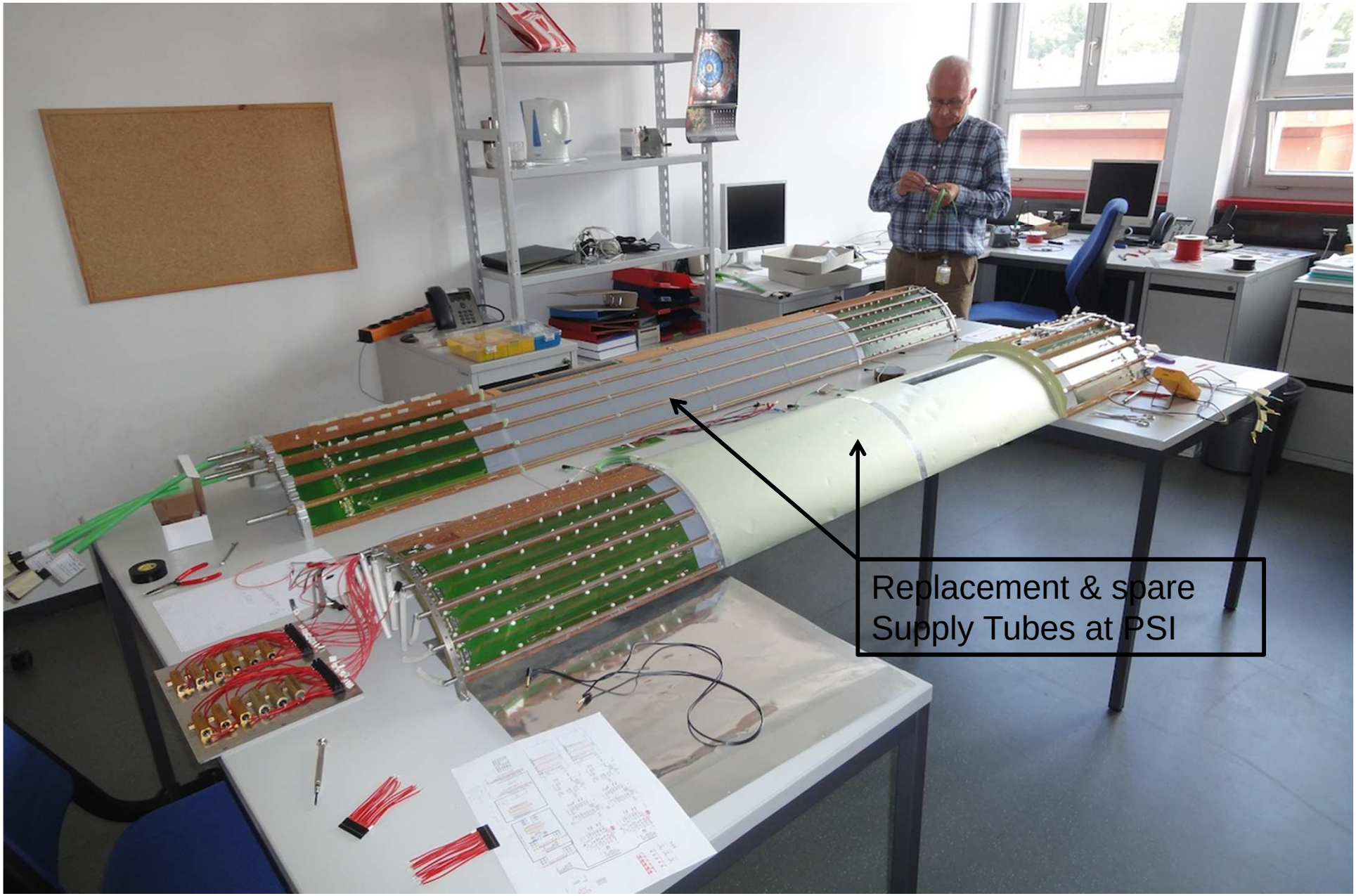
Status Thursday, 6. Nov 2014
tested Layer 3 , 2 & 1 all reassembled
and fully reconnected & testing done
→ **all modules in half shell now work !**

Wed, 12. Nov 2014 → transport to CERN
Thu, 13. Nov 2014 → fully reconnected at Pixel Lab
Fri, 14. Nov 2014 → inner half barrel & ST tested

Status Friday, 14. Nov 2014
BPIX inner half shell fully repaired

this is still the original schedule from begin September

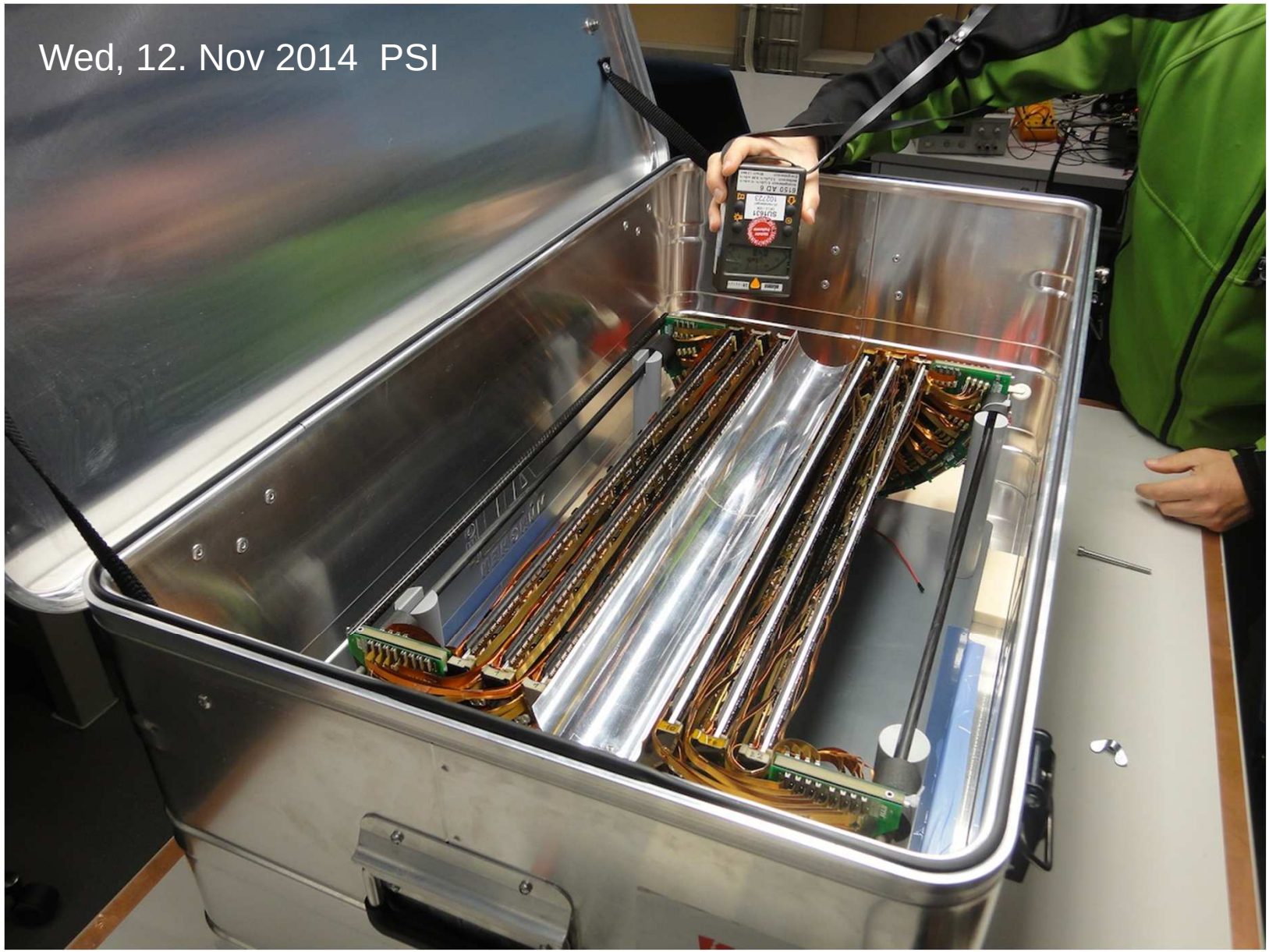
Spare Supply Tube for Power Supply Testing



Testing of Supply Tube reintegrating BPIX

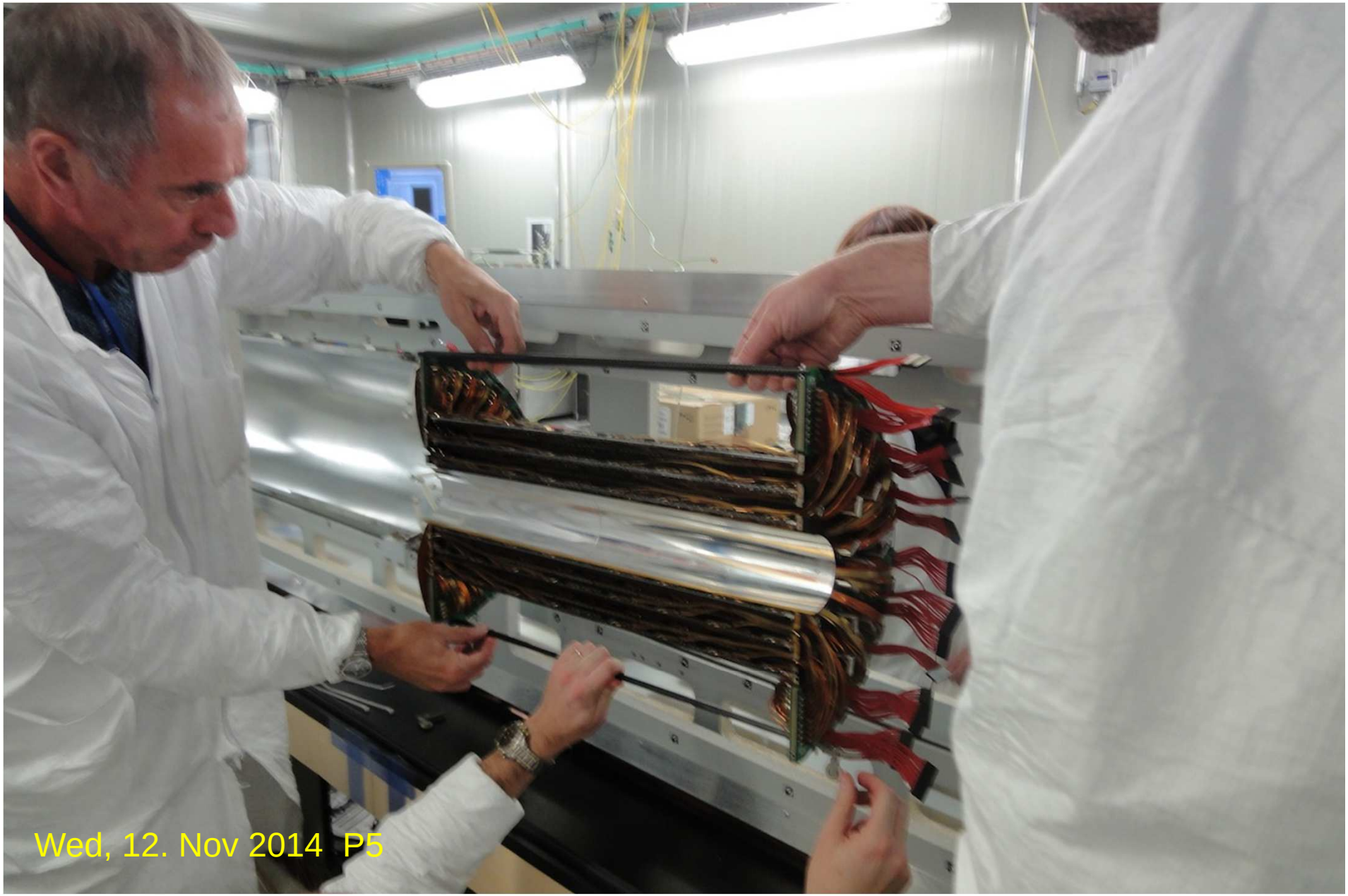
Testing of Supply Tubes at P5 has been done before re-integration ***(Uni ZH)***

Repaired inner half shell ready for transport



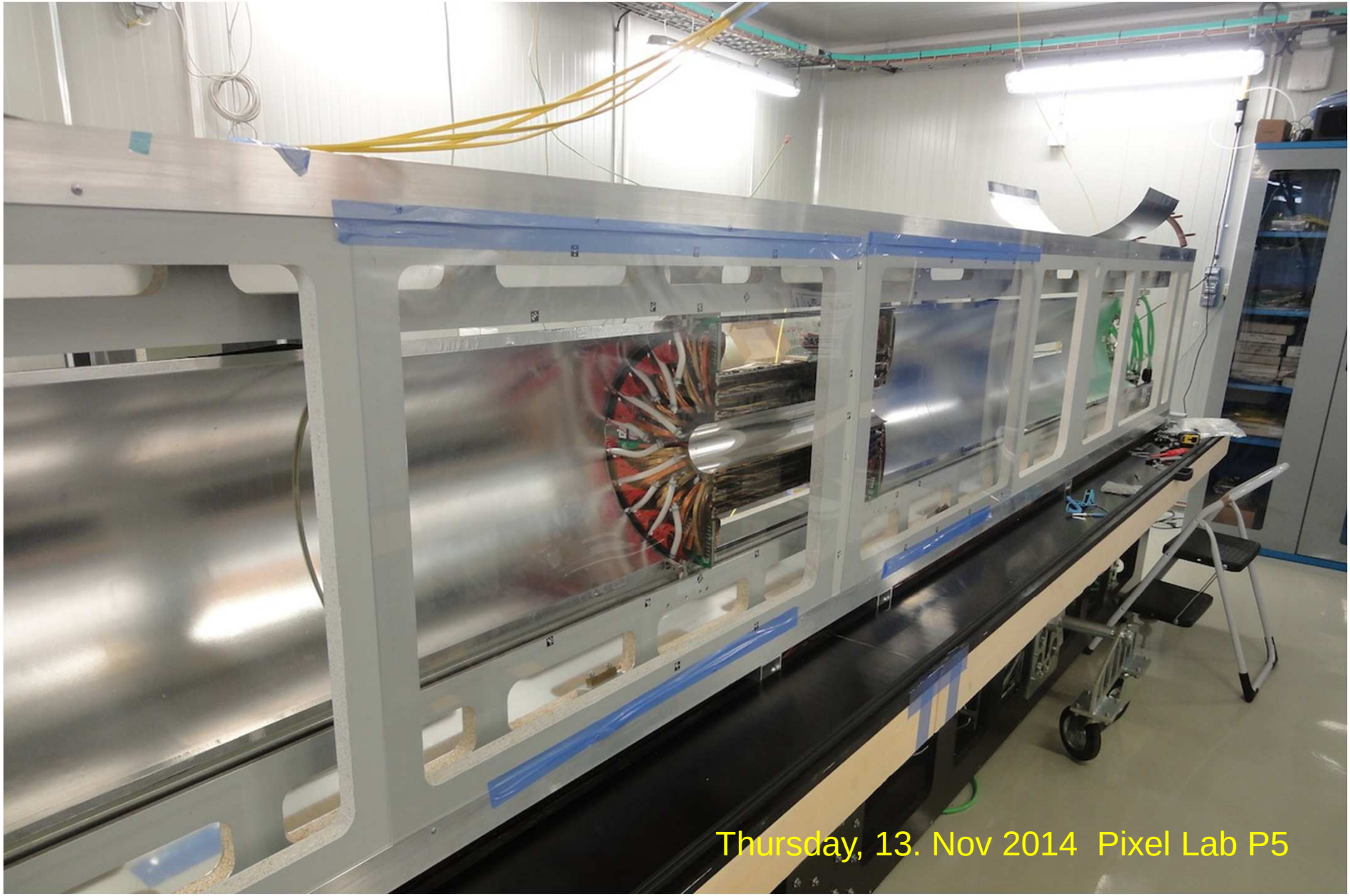
Getting Ready for PSI → P5 Transport

Reinserting Barrel into Rails in Cassette

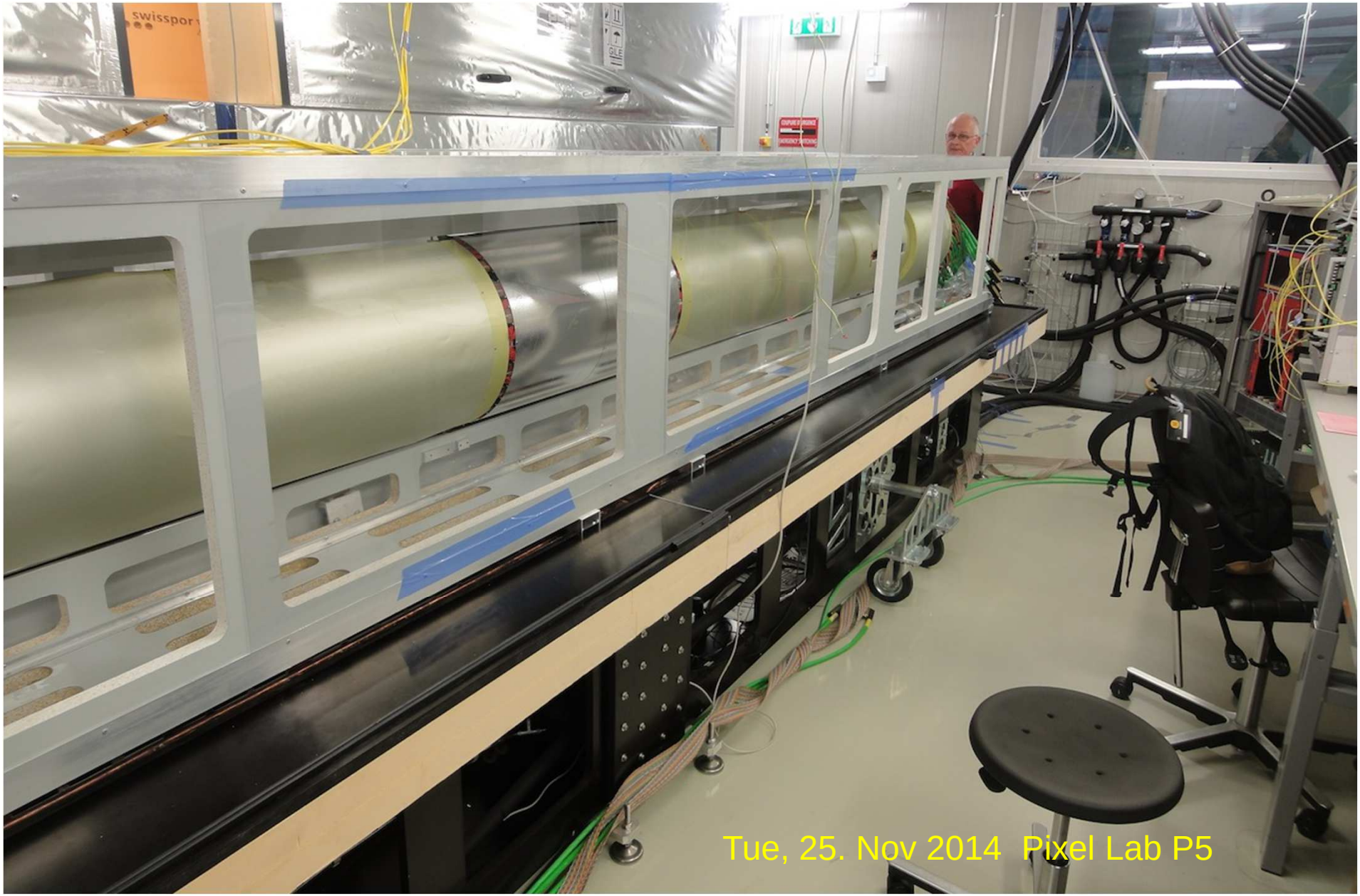


Reconnecting Cooling, Power & Signals

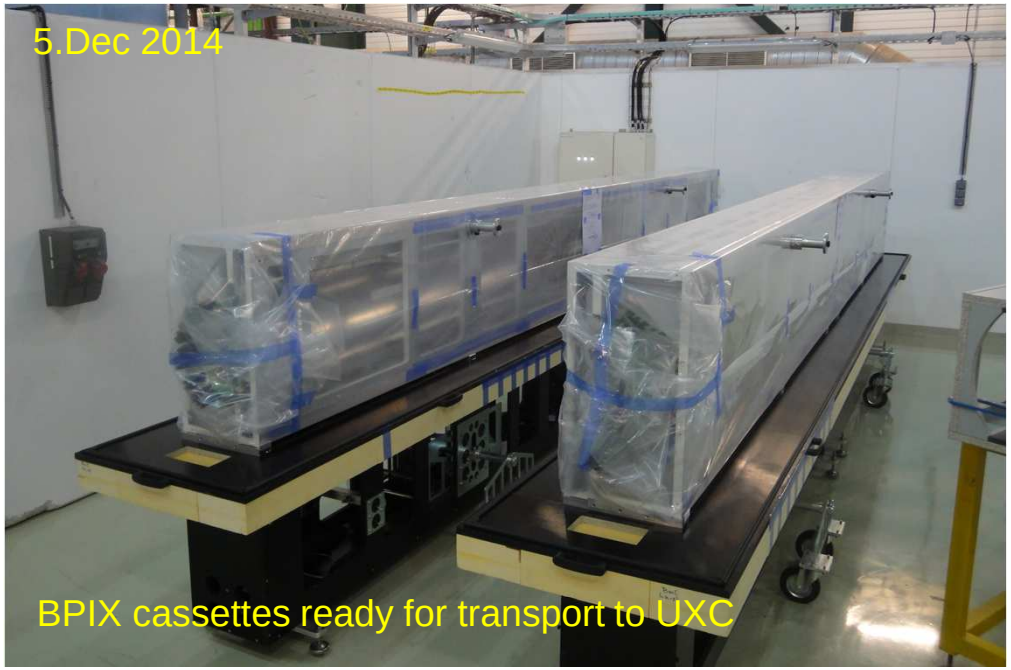
Supply Tubes and inner Barrel reconnected

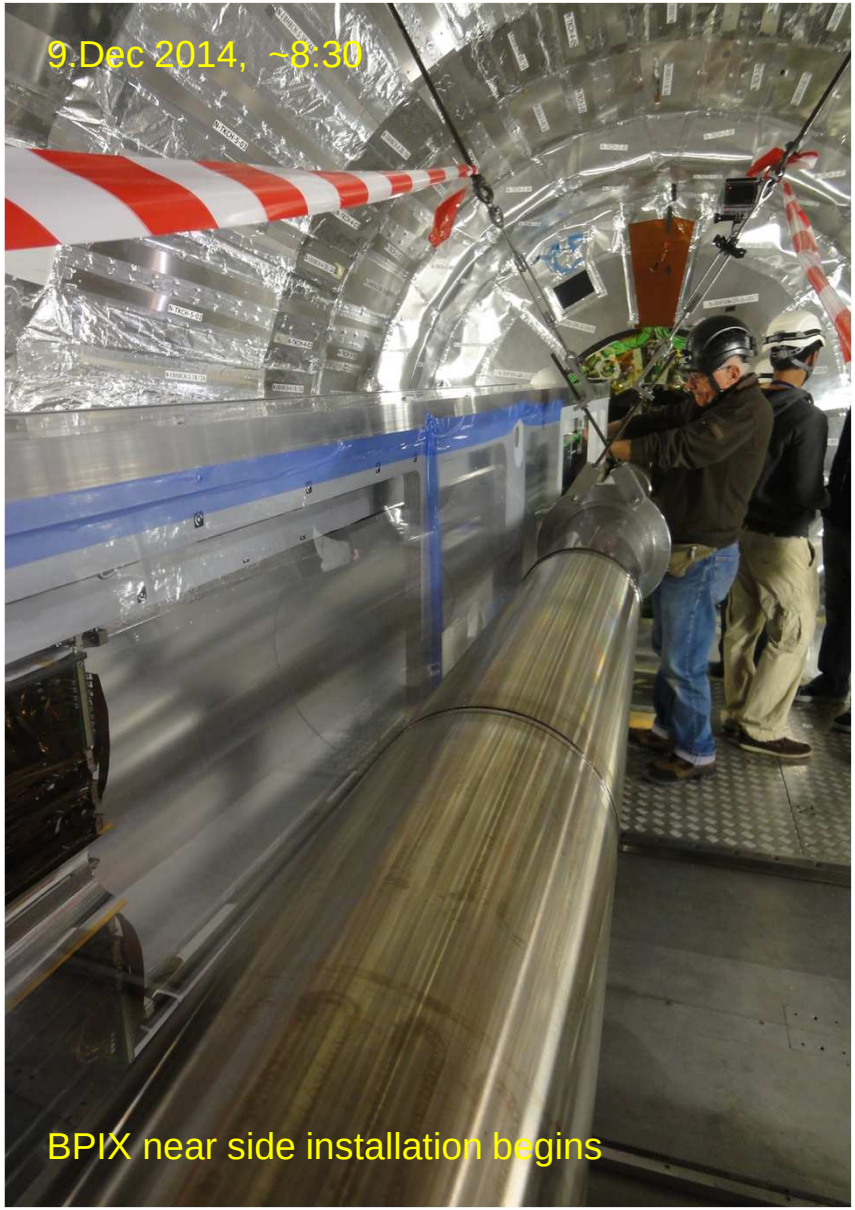


Inner Barrel Half Shell with Shield mounted

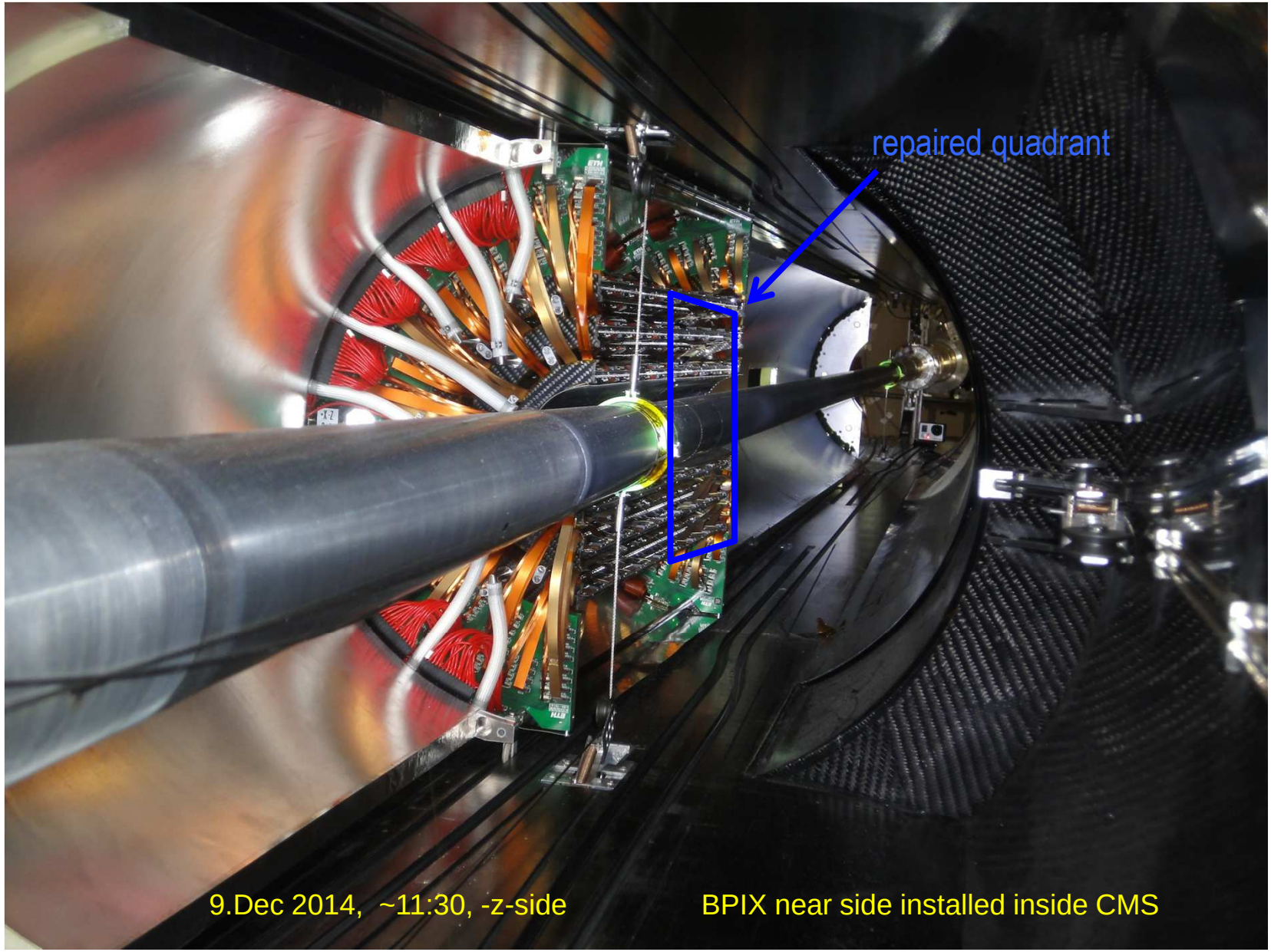


Installation of BPIX System in CMS

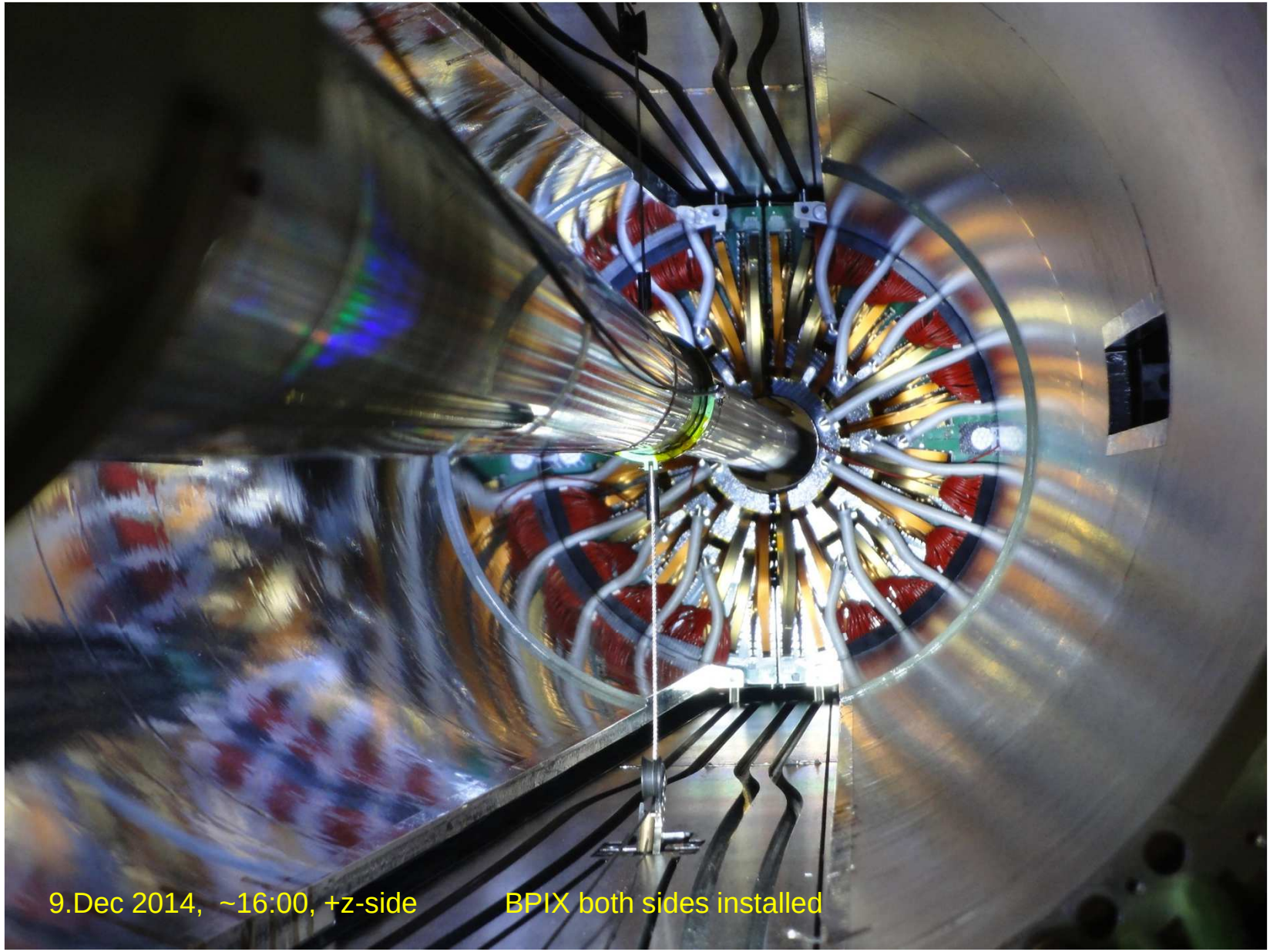




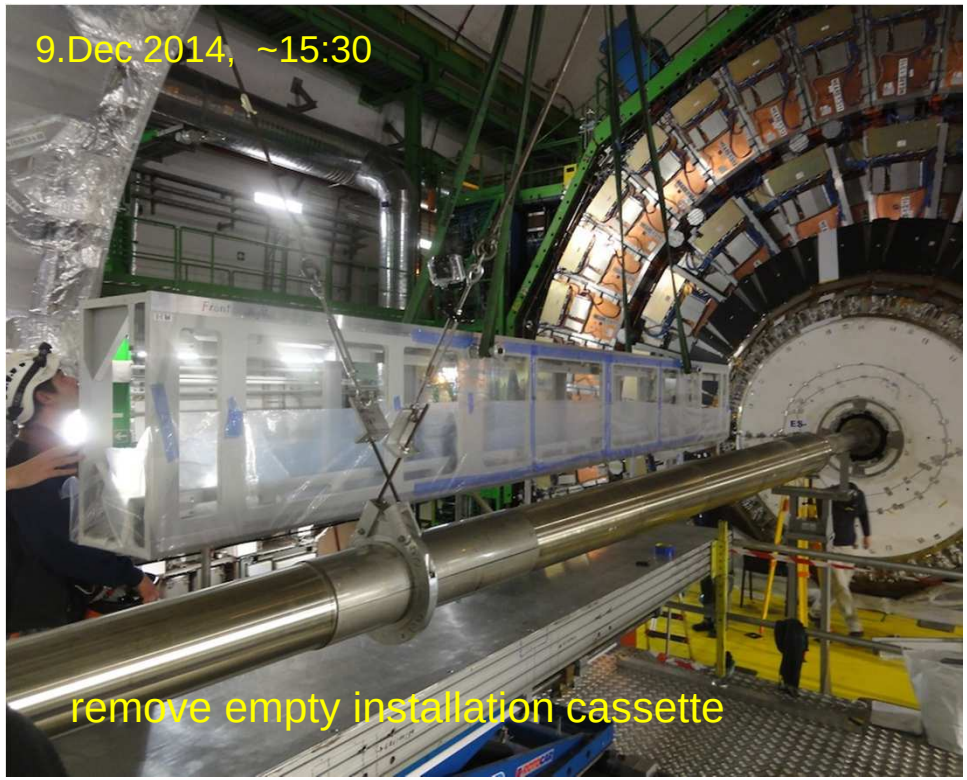
Installation of BPIX System in CMS

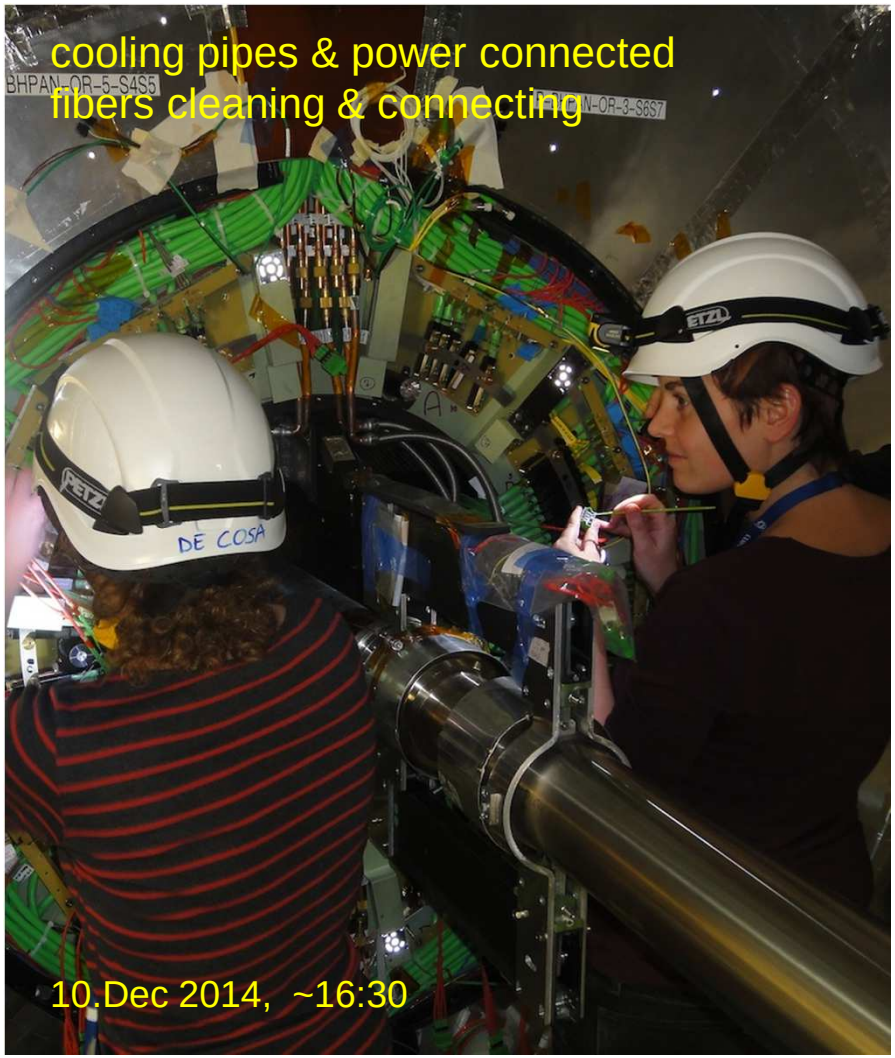


Installation of BPIX System in CMS

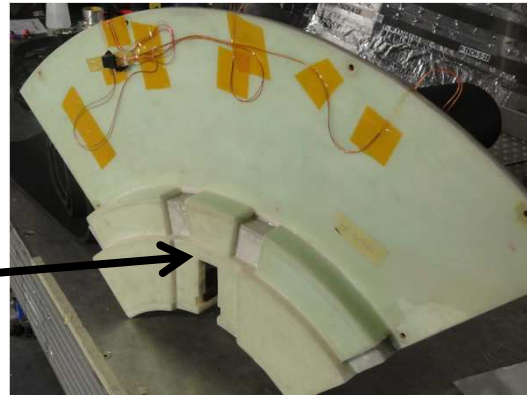


Installation of BPIX System in CMS



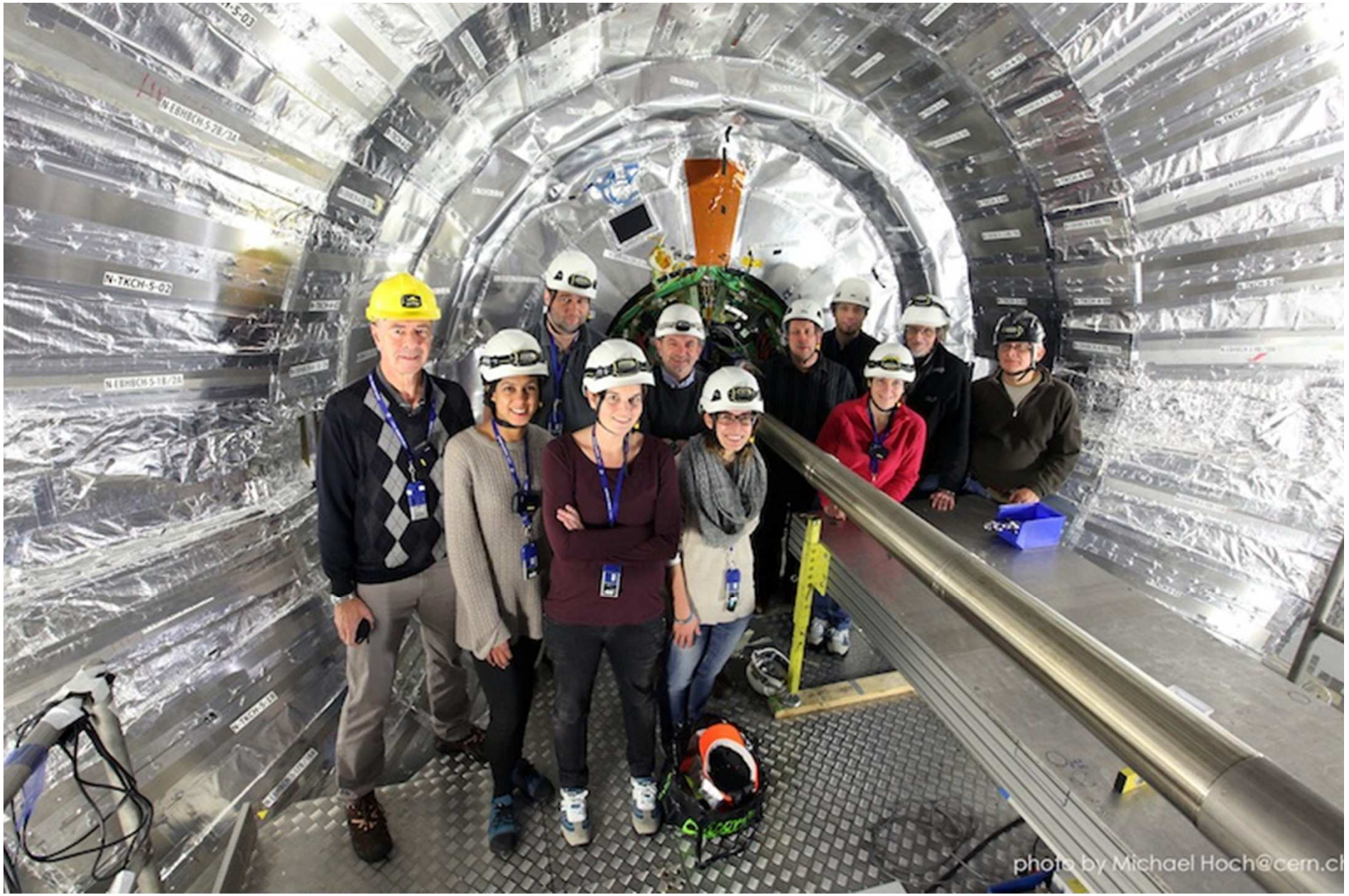


open issue:
thermal shield PP0
has no space for
cooling pipes



10.Dec 2014, ~18h BPIX fully cabled

Crew of BPIX Installation in CMS



Conclusions & Outlook

- repair of damaged BPIX quadrant 100% successfully completed in time
- humidity, power and pockets of electrolyte residues are cause of shorts
- big effort to re-launch the full module production of “old” modules
- repair was a major effort for the original BPIX team (PSI, ETHZ, Uni ZH)
- long term tests with repaired non-installed modules show no negative results
- BPIX is re-installed and works fine
- FPIX (including Pixel Upgrade Pilot Blades) are also re-installed and work fine.
- Pixel back in CMS and excellent shape for Run 2 and will do great physics !
- Success possible thanks to :
  - lasting institutional memory (people, equipment, log-books)
  - enough spares in cabinet
  - dedicated team with focus on vital tasks & procedures