The industrial production of Micro Pattern Gaseous Detector: experience from the ATLAS Micromegas

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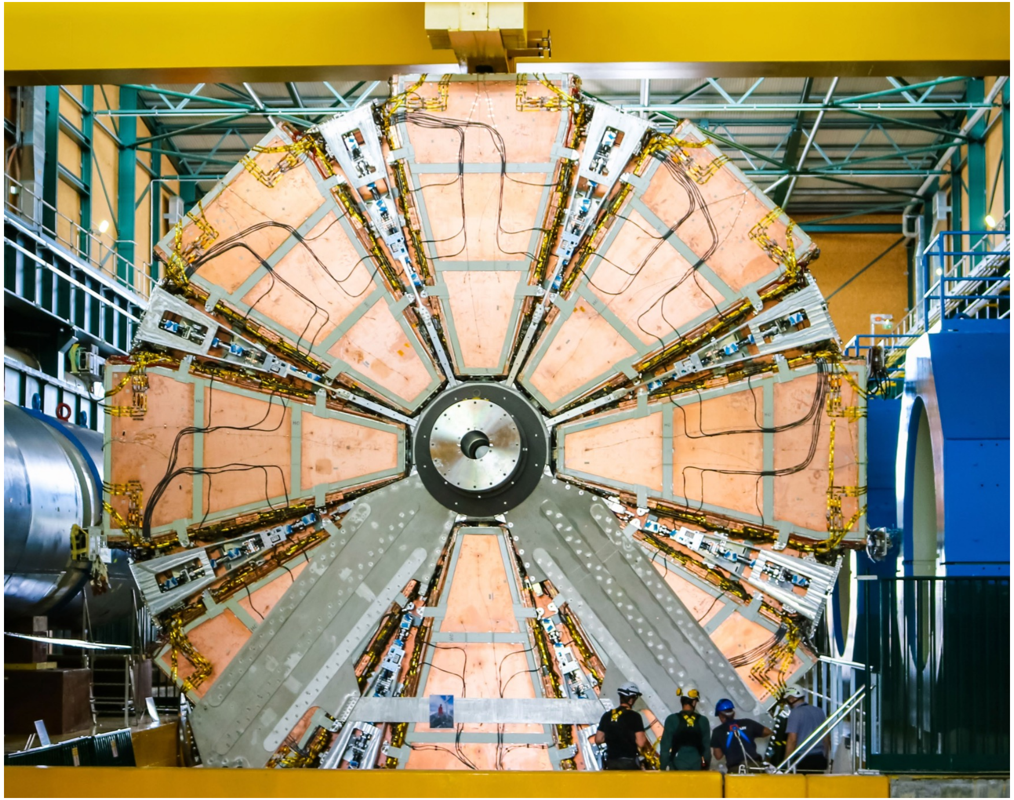
On behalf of the ATLAS Muon Spectrometer System

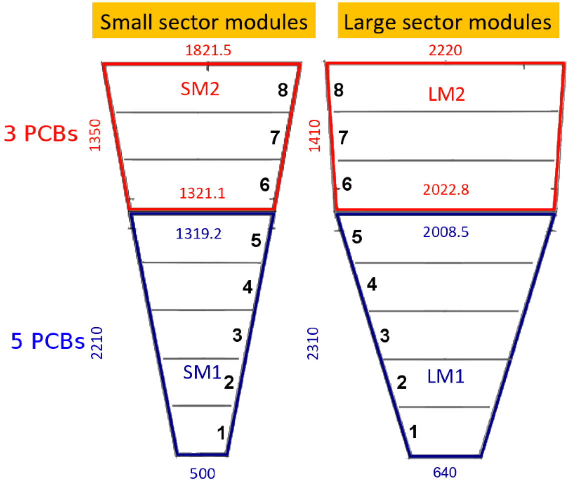
Introduction

- ATLAS Micromegas is the largest MPGD-based system ever conceived and built
- 1280 m^2 active surface
- 2.1 M readout channels
- 128 detectors / 4 types
  - 4 layers
  - 2 to 3 m^2 area
  - Mechanically floating mesh (no bulk)

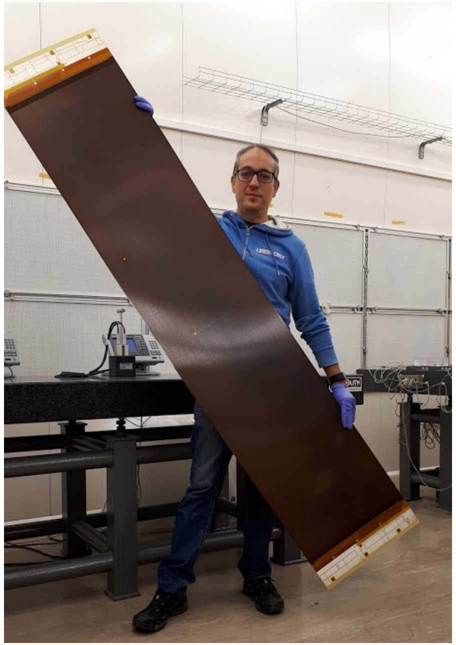
More about ATLAS Micromegas in G. Mancini's talk on Mon. 12^{th}



The production challenge

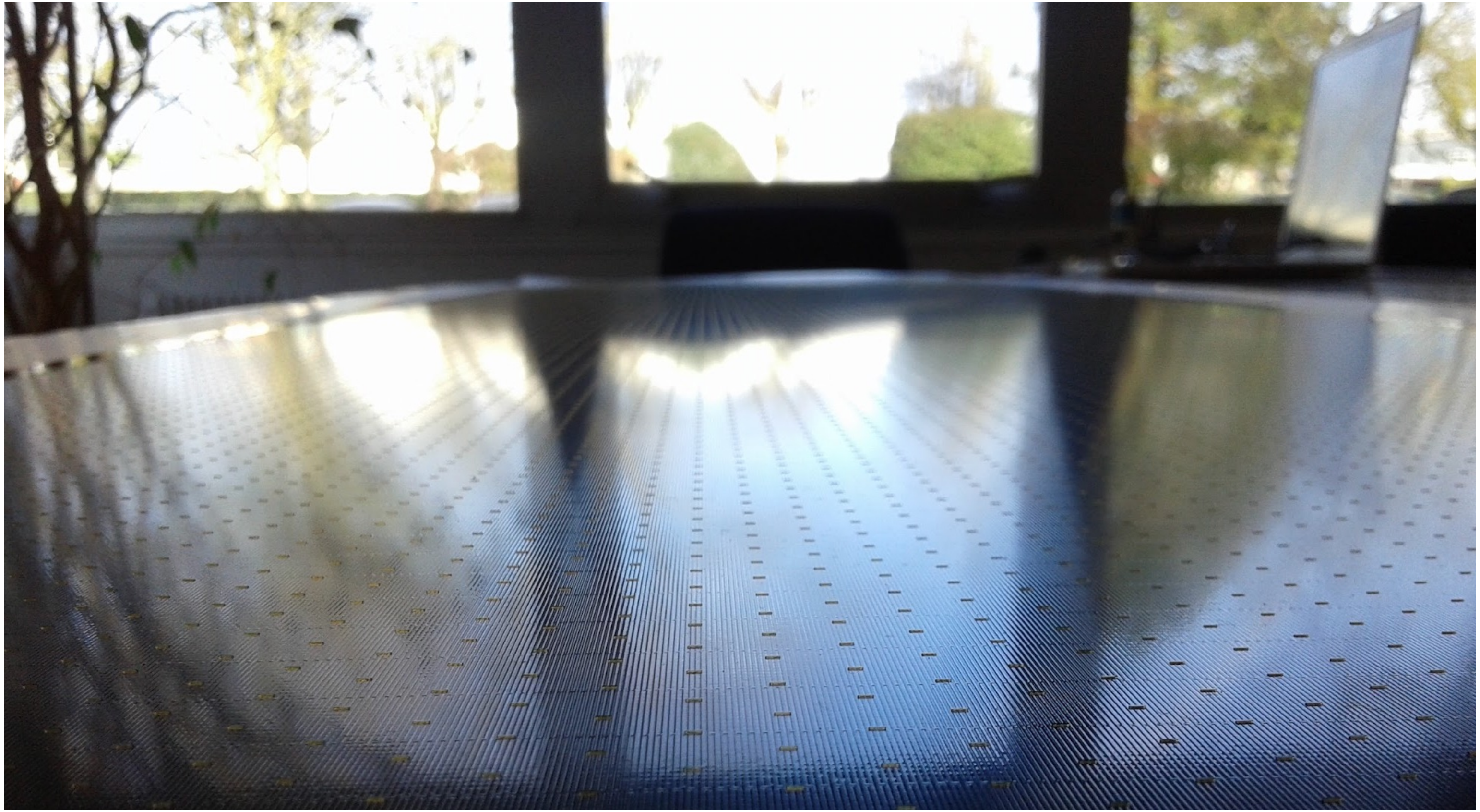


- Mass production: 2800 boards / 32 different types
- Unprecedented size: up to 45 x 220 cm^2
- Full production in industry

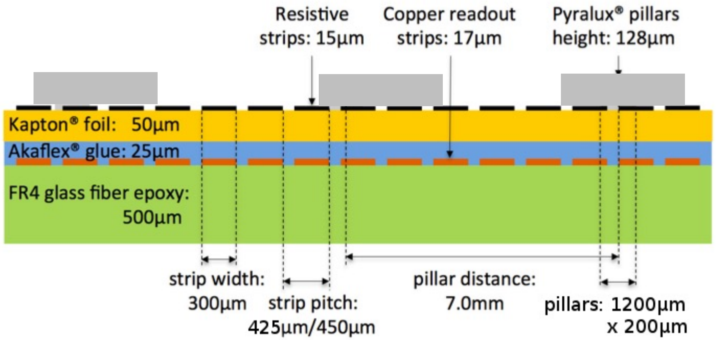


- Technology breakthrough
  → Direct move from R&D to mass production
- Two companies selected after tendering process and negotiations: ELVIA (FR), ELTOS (IT)

Generalities



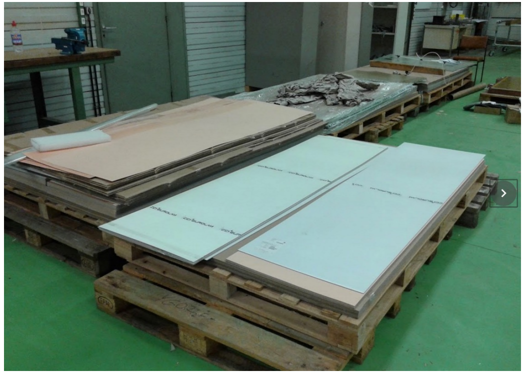
Anode Board Design



- 1022 strips/board
- Readout strips: 300 µm width, 425 or 450µm pitch
- Screen-printed resistive strip pattern with same pitch
- Resistive strips interconnected; pattern interrupted in the center → two HV sections per board
- HV supply via silver line from the side
- Elongated pillars: 1200µm x 200µm
- Readout strips routed to pads for elastomeric connectors (Zebra)

Material Procurement

- Board components are procured centrally and delivered to manufacturers
  - keep control of the procurement (avoid delays)
  - save money



- Base Cu-clad FR4 sheets, halogen free (0.5 mm thick, 2000x600 mm^2)
  - QC (thickness, uniformity, defects) and stabilisation (thermal treatment) at CERN
  - Full quantity procured at at the beginning, delivered to companies in batches
- Kapton (EN type) for resistive foils

- Coverlay (Dupont Pyralux PC1025, 600 mm wide, 128 μm thick)
- Resistive paste (RS12115 100 KΩ/square polymer resistor) for printing
- Ag paste for electrical contact

} Limited shelf-life

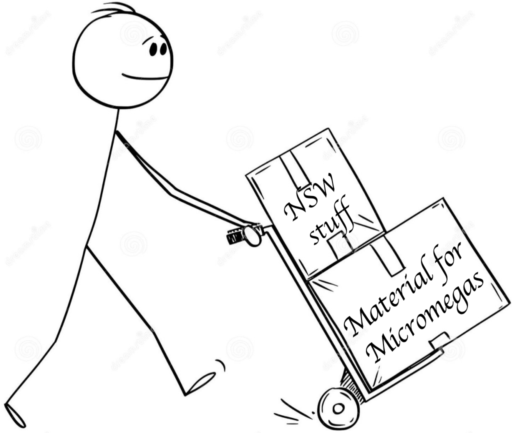
Pyralux PC Standard Product Constructions

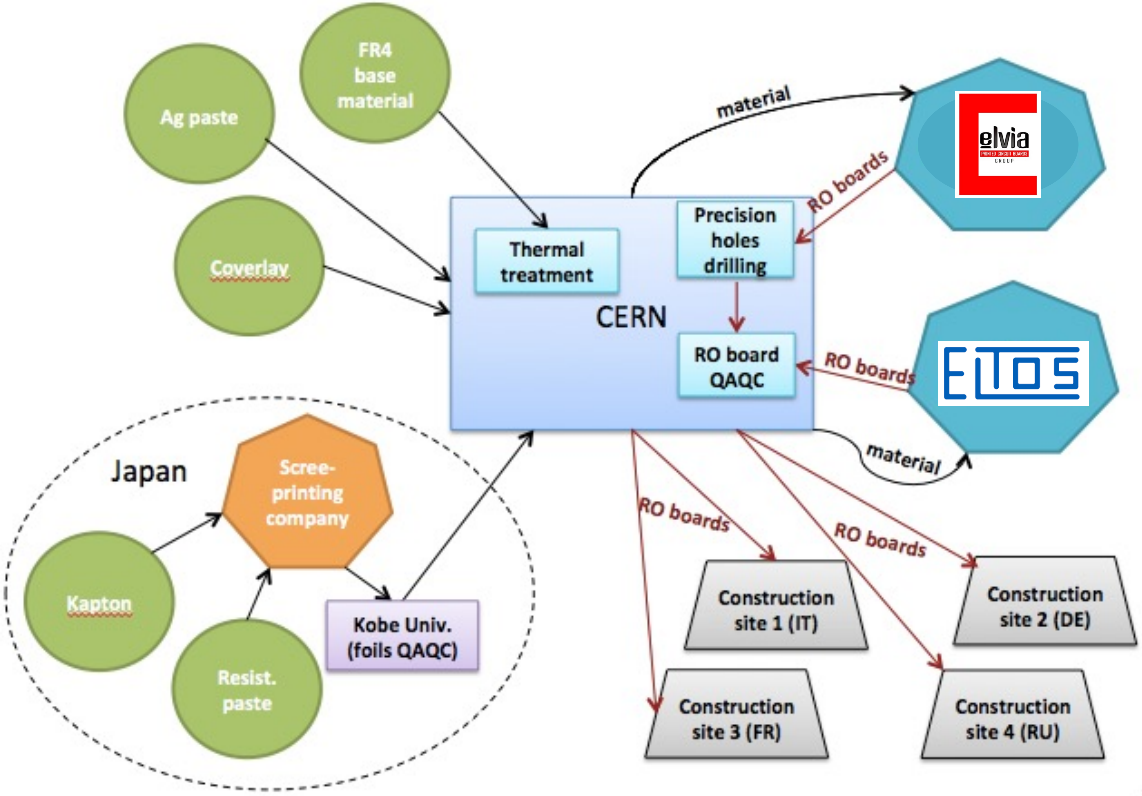
Product Code	PC Thickness, µm	(mils)
PC1010	25	(1.0)
PC1015	38	(1.5)
PC1020	51	(2.0)
PC1025	64	(2.5)

RS121XX SERIES POLYMER RESISTOR TYPICAL PROPERTIES

PRODUCT	RESISTANCE	RESISTANCE TOLERANCE
RS12111	10 Ω/sq.	±25%
RS12112	100 Ω/sq.	±25%
RS12113	1 kΩ/sq.	±25%
RS12114	10 kΩ/sq.	±25%
RS12115	100 kΩ/sq.	±25%
RS12116	1 MΩ/sq.	±25%

Logistic & organization





Board Production

I. Photolithographic creation of copper pattern
standard process.
complex due to: size of board, required precision & board elongation (humidity).

II. Cutting of Kapton foil with resistive pattern
non-standard but simple & required accuracy only ±1mm

III. Stacking and gluing at high P&T of Kapton foil, glue foil and board
standard process for small boards
complex due to: size of board & required cleanliness.

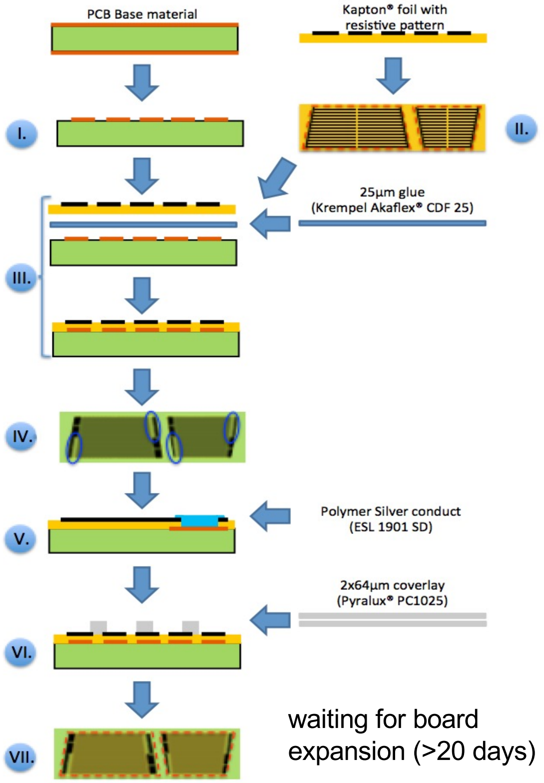
IV. Chemical silver plating of copper pads
standard process

V. Screen-printing of silver paste
non-standard but rather simple & required accuracy only ± 1mm

VI. Lamination of coverlay & pillar creation
standard process for small boards.
complex due to: size of boards, highly non-standard pattern, required flatness

VII. Cutting of boards and drilling of non-precision holes
standard process on CNC machine.
complex due to size of boards, required cutting precision & board elongation (humidity).

Try to make all production steps as close as possible to standard processes in industry

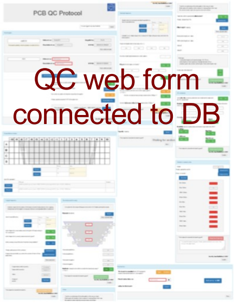


waiting for board expansion (>20 days)

Quality Assurance / Quality Control

- QA/QC lab for foils at Kobe
- First QC at the manufacturer premises
- Dedicated lab set-up at CERN
  - 7 test stations
  - Each board tested according to QC protocol
  - Online form interfaced with QC DB to guide through QC
- Repair facility in a separate room

Online QC form



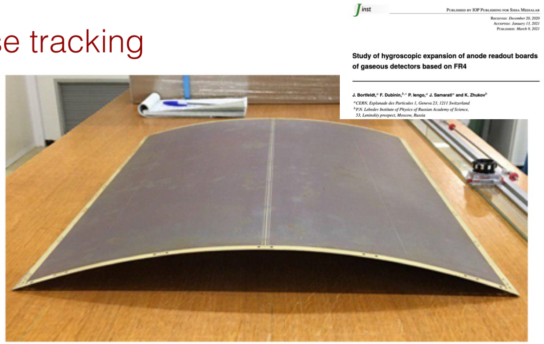
Selected list of production issues

Focus on some of the main issues encountered during the production, actions taken and adopted solutions

Board material expansion

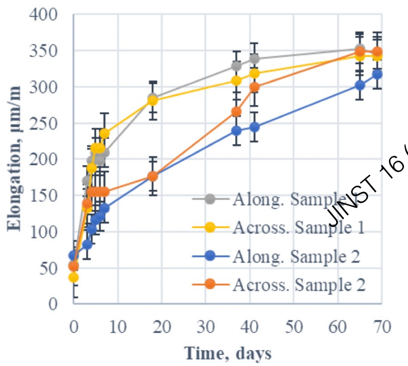
- Knowledge of the board dimension (strip position and deformation) crucial for precise tracking
    - Copper pattern precision <±30 μm
    - Cutting and drilling precision <±200 μm
- FR4 subject to moisture uptake → expansion
    - Described by Fick's laws
    - Made our own study

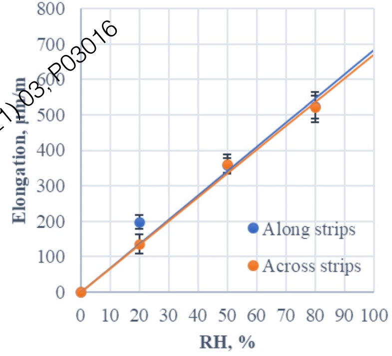
$$\frac{L(t)}{L_\infty} = 1 - \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{D'(2n+1)^2\pi^2}{4l^2}t\right]$$

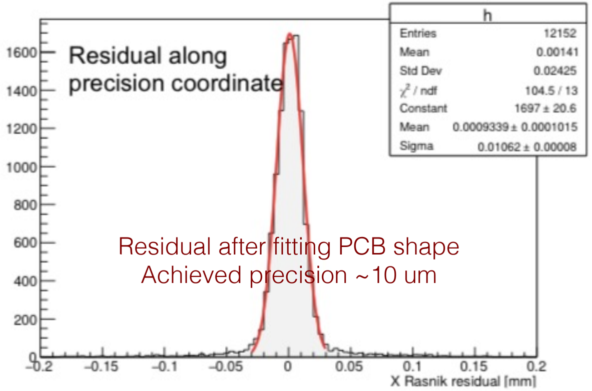


Panel deformation due to moisture absorption

- Expansion: ~400 μm/m at 21° and 50% RH to be accounted during production
    - Cu pattern (masks) scaled accordingly to have the final desired dimensions
        - Scale factors optimised for each company after dedicated studies
    - After the production, the boards are stored for 4 weeks in RH controlled room before being cut/drilled → relaxation time to reach the final size







Residual after fitting PCB shape
Achieved precision ~10 um

Resistive paste

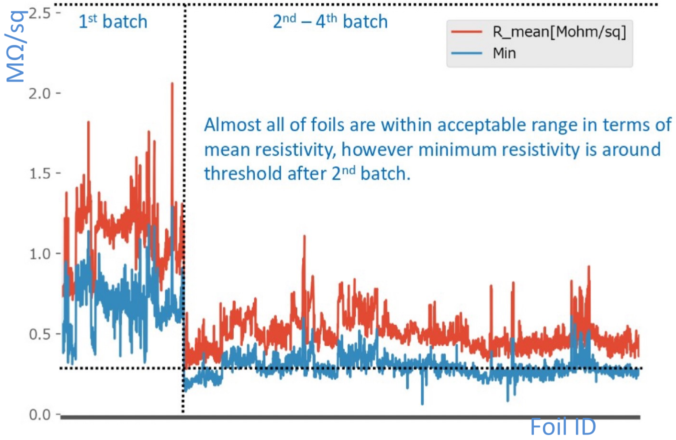
- Single provider: ESL(D), then Ferro (UK)
- Final foil resistance driven by paste resistivity; curing conditions after printing; pressing conditions during board production

3 crisis related to resistive paste:

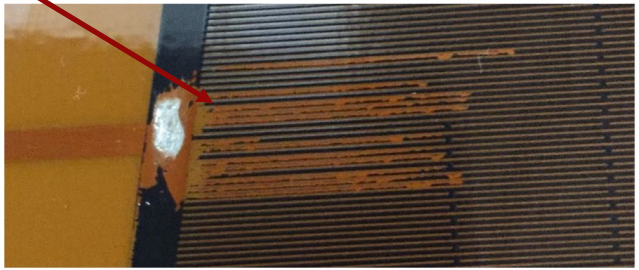
1. 2016: Resistivity 10x higher then expected, finally understood in a change of solvent.

2. 2016: Reported from PCB company low adhesion of resistive strips during PCB manufacturing. Reason found in insufficient curing at foil printing company (Matsuda, JP).
   No information propagated to us →it took time to reconstruct the full story

3. 2019: Paste production was moved from Germany to UK (after Ferro acquired ESL). Delivery of the last batch postponed for months.
   Not able to produce usable paste.
   Strong push from CERN to find a solution. Finally, the German expert was sent to UK to supervise the production. Costed months of delay and required tuning of the pressing condition at the PCB companies



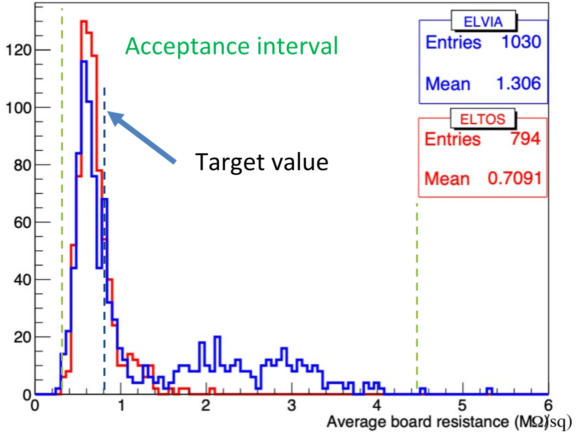
Surface resistivity vs foil ID. Reduced resistivity correlated with the change of batch of resistive paste

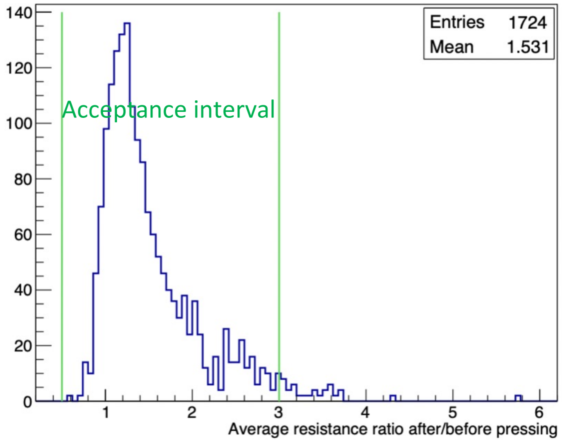


Foil with resistive pattern partially removed

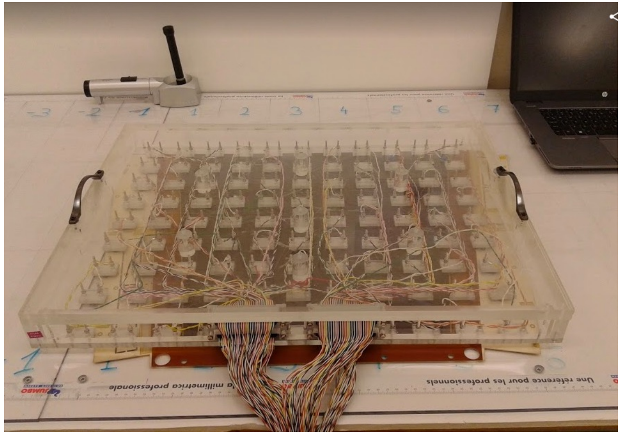
Surface resistance measurement

- Resistivity foils measured at Kobe after production
- Final resistivity of the boards measured at CERN
- Resistivity map measured for each board
- Comparison after/before board production
- Dedicated tool developed and used in both sites

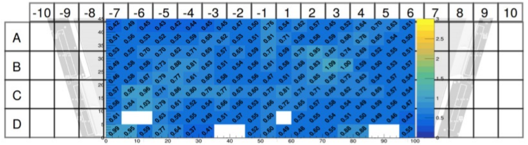




Surface resistivity measurement tool



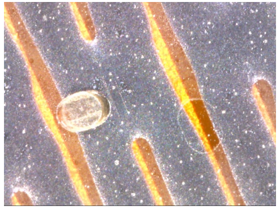
Surface resistivity map of a board



>98% of the foils used for production satisfy the acceptance criteria on resistivity
We now know that the lower limit (set on prototype detectors) was set too low, contributing to the detector HV instability

Pillar adhesion

Detached pillars (oval)

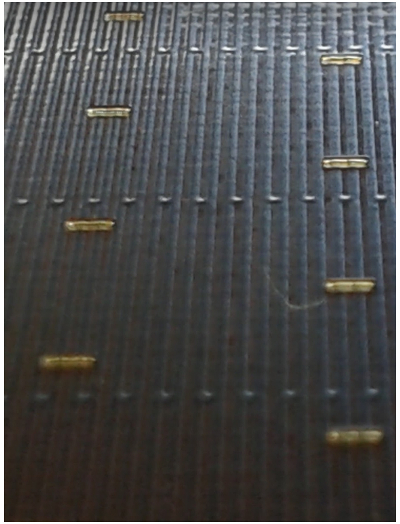


Module0 boards: 2015

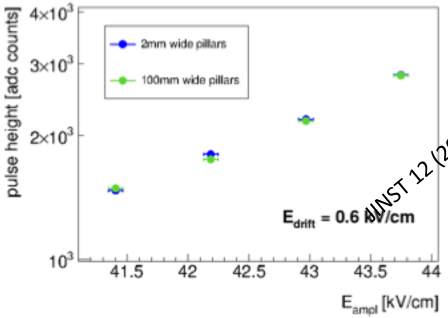
First step forward:
Correct surface polishing
& process optimization
round pillars well attached
(process improvement)

Pre-series board: 2016

Second step forward:
long pillars well attached
(design improvement)



- Long pillars (1.2 mm x 0.2 mm) running parallel to the readout strips do not affect the detector performance, while ensuring larger attachment surface
- Tested on 10x10 cm^2 bulk-MM built at CERN



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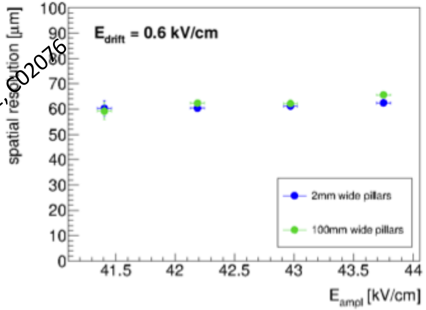
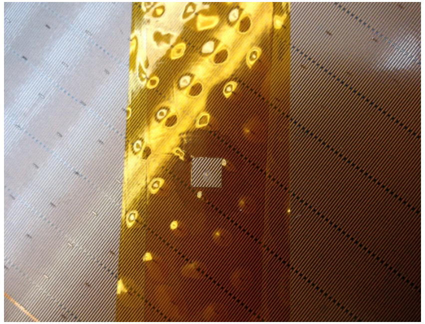


- Mesh sagitta from simulation:
  - between pillars: 2μm @ 600V & 10 N/cm
  - if single pillar missing: 8μm @ 600V & 10 N/cm

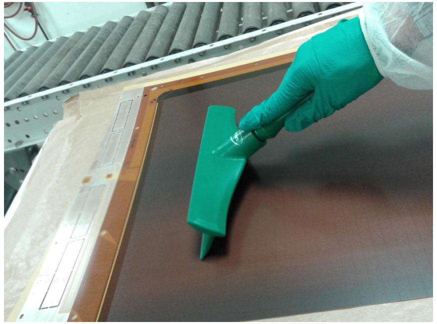
→ individual missing pillars still tolerable

Pillar QC and repairs

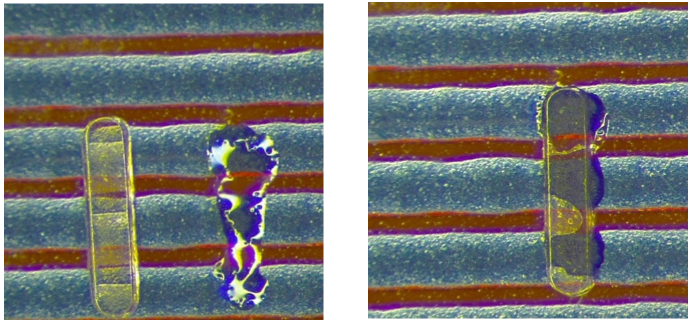
- New adhesion checks implemented
  - ISO: removal with tape → only on limited area
  - Use of window-cleaning tool (hard test)
- Acceptance criteria
  - single missing pillars < 8-10 (3.3k to 20k pillars on PCB)
  - ≥ 2 neighbouring pillars missing
- Reparation procedures developed to recover boards with few missing or badly attached pillars (out of specs):
  - At CERN: manual single pillar gluing with Araldite 2011
  - At companies: local cleaning, re-lamination, development (UV tool developed), curing



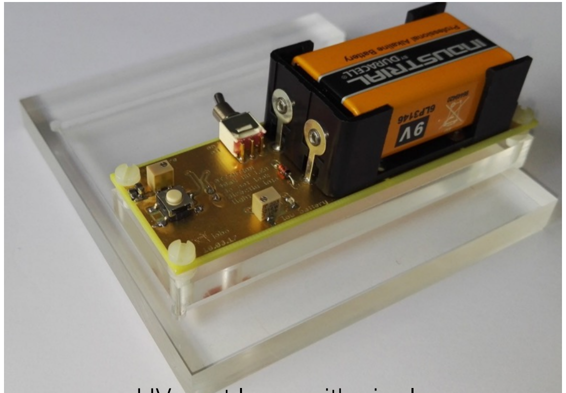
ISO9000 protocol: tape test



Windows squeegee cleaning (raclette) test



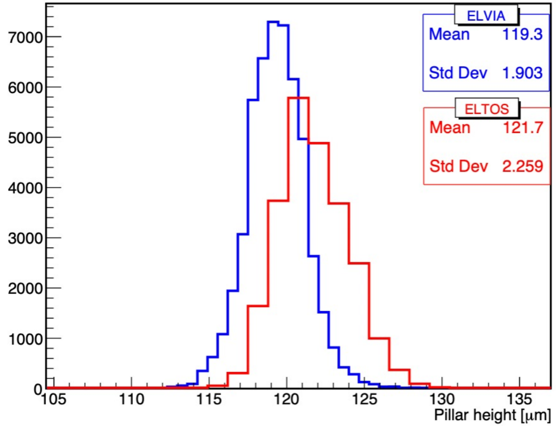
Single pillar gluing (manual)



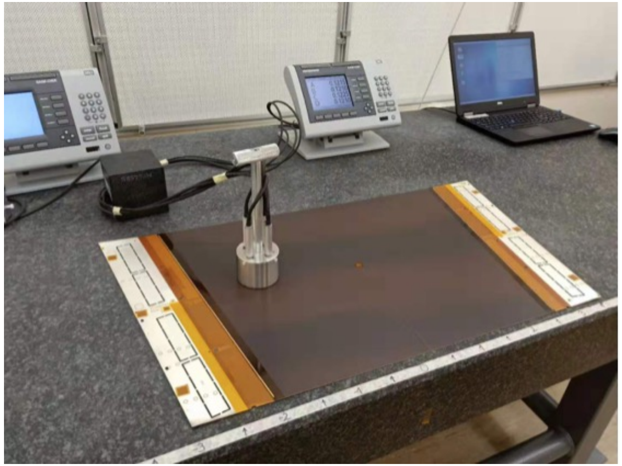
UV spot lamp with single pillar mask (J. Bortfeldt)

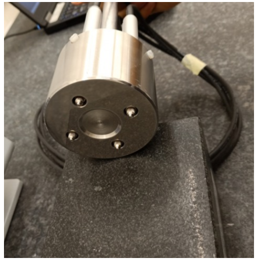
Pillar height measurement

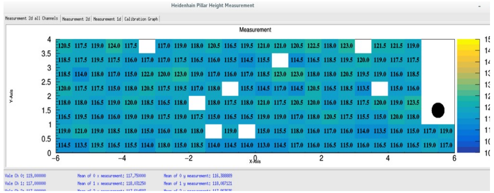
- Pillar height map measured for each board
- Precision of the tool: ±0.5 μm
- Systematic difference (2 μm) between the two companies
- RMS~ 2 μm; L/R asymmetry ~ 2 μm
- Average value: 120 μm (expected 128 μm)

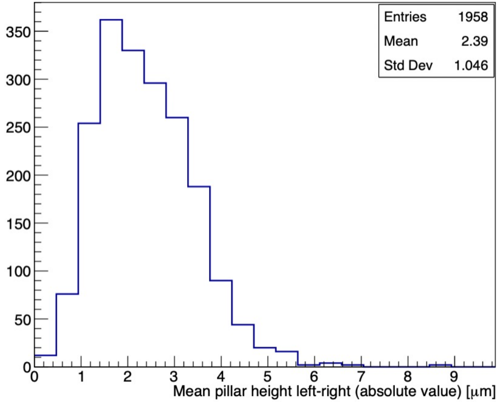


Pillar height measurement tool



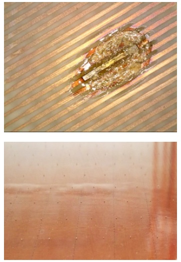


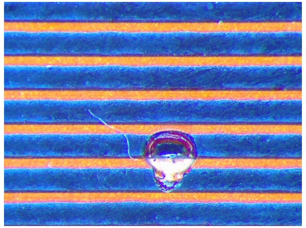




Bumps & enclosures

Module0 boards: 2015

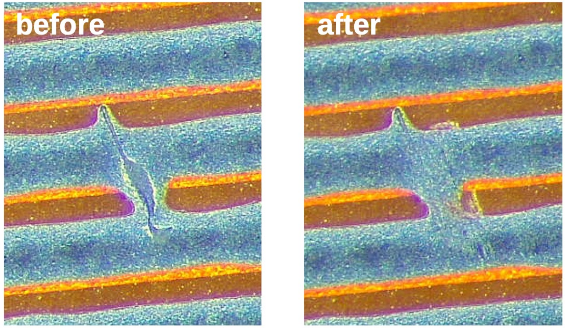




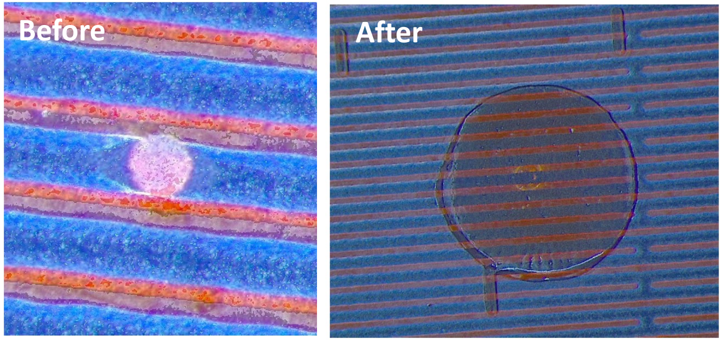
First production batch: 2016

Great improvement thanks to:
- Technology transfer
- Procedure and work-flow optimization
- Cleanliness during gluing

- Repair techniques & dedicate tools developed

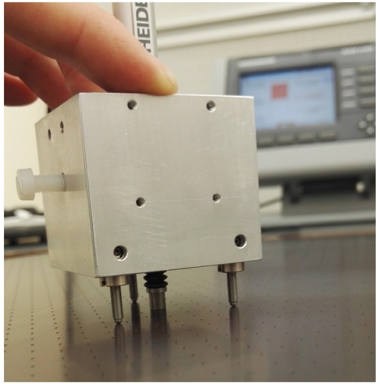


Polishing of resistive surface



Passivation of bumps with coverlay disk

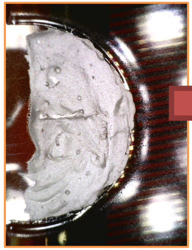
Tool to measure height of bumps & enclosures



HV connection & edge cutting

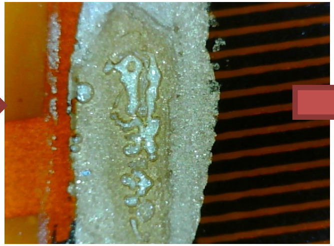
Silver line HV connection

Non-standard manual procedure
Needed iterative TT



Unusable

First step improvement

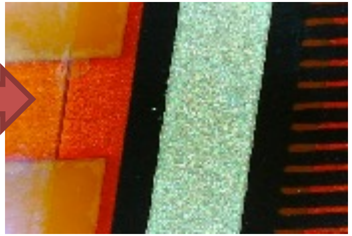


Usable after repair

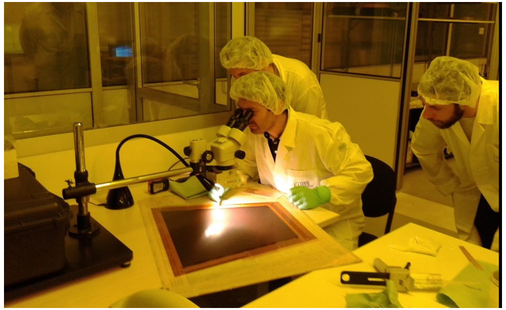
Second step improvement

OK

Third step improvement

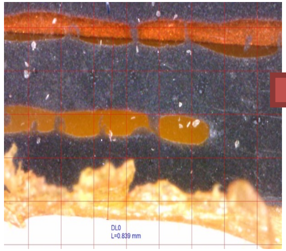


Perfect!



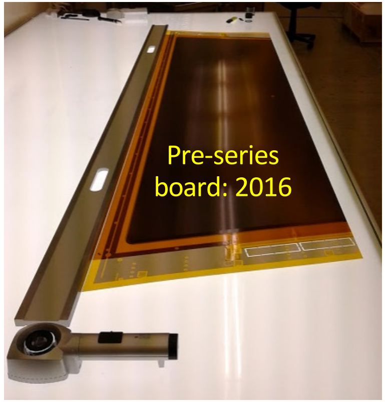
CERN expert showing the HV connection technique to techs from production company

Edge cutting

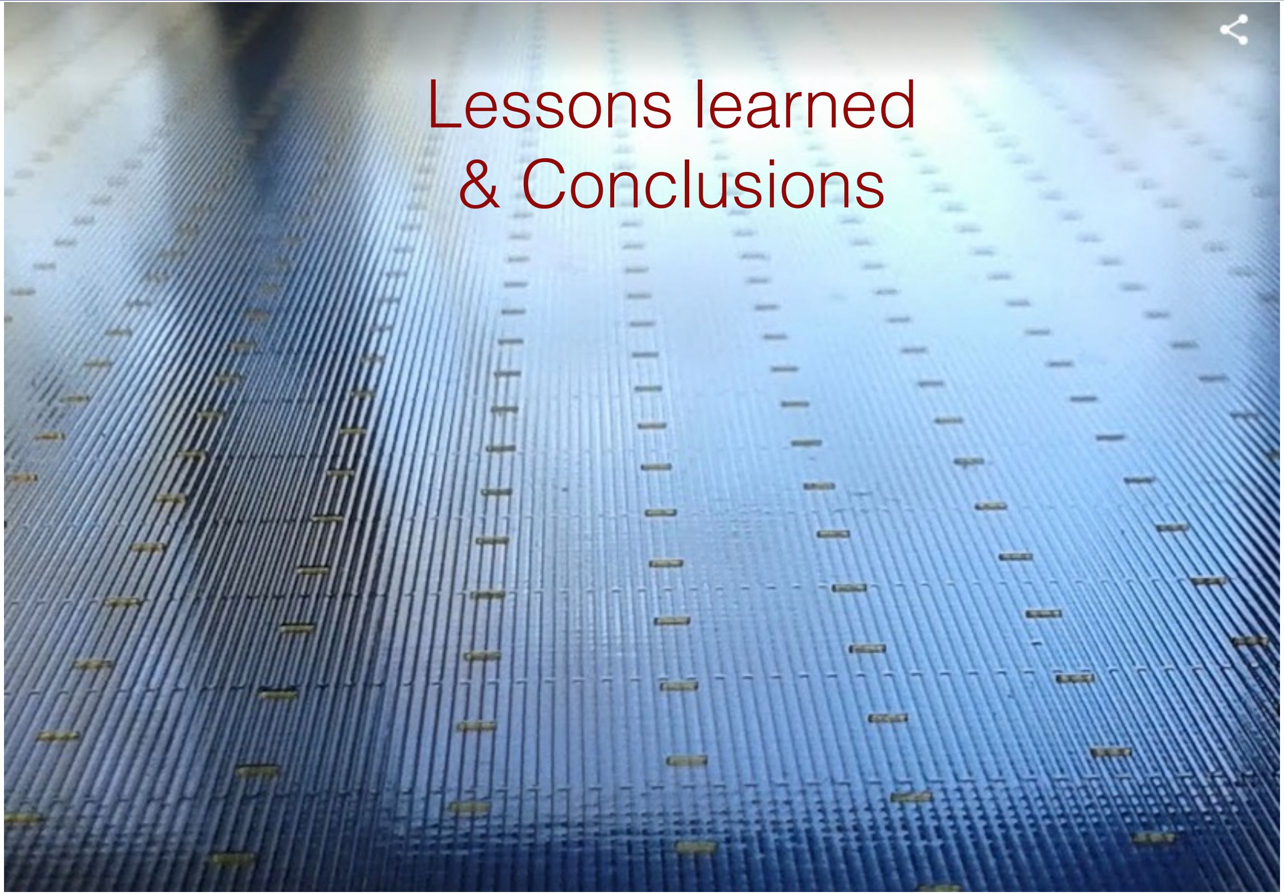


Module0 boards: 2015

Great improvement:
- Procedure and work-flow optimization
- Design improvement: removed 1 strip to allow for larger safety margin

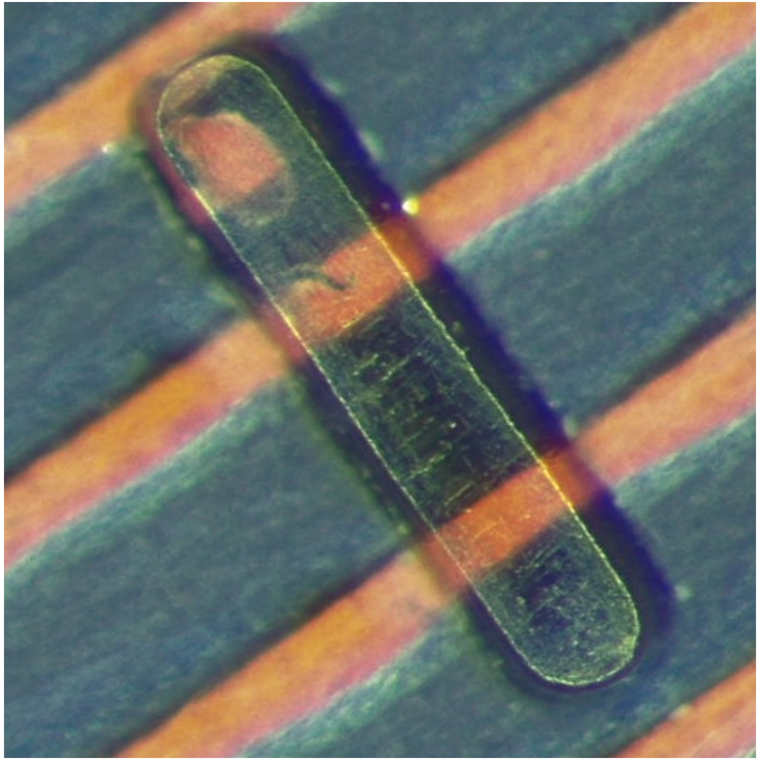


Lessons learned & Conclusions



Lessons learned - 1

- Main criticalities
  - Move from R&D to mass production. No time for real TT to the companies BEFORE the production (limitation also from the tendering procedure). Pre-production helped but most of the TT and process optimisation was done during the production
  - Although most of the production steps were ~standard for specialised companies.
    Both manufacturer assumed the ATLAS production as an R&D expecting a yield <80%
  - Time pressure and long production (>3 years): hard to keep expert manpower at CERN and at the companies
    - Both companies replaced their production supervisor between the Mod0 and the series production
  - Some unforeseen technical issues emerged during the production (e.g., strip etching, see backup slides)
  - Problems in material procurement from single supplier (reproducibility among batches)



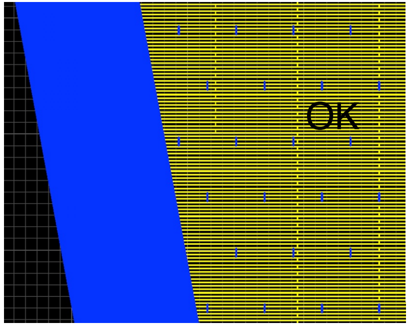
Lessons learned - 2

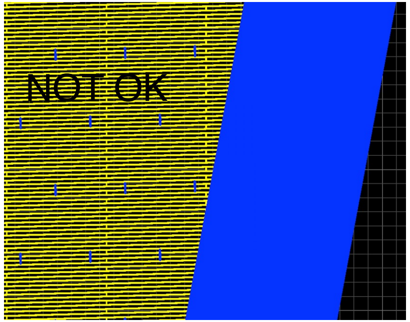
- Main strong points
  - Good choice to go to 2 companies: split production + continuous feedback from independent sources
  - Establish good communication with both companies, especially with the technical personnel doing the work
  - Good choice procure the material centrally by the collaboration. Some problem would have been spotted too late otherwise
  - Huge effort to constantly follow the production at both companies from the same team. Yield went from 64% at the pre-production to >90% for the last batches, demonstrating the feasibility of the project
  - Thorough and complete QA/QC on each single board
  - Set-up of a repair facility to accept board with small, repairable defects

Off topic / Hot topic

- **Design issue**

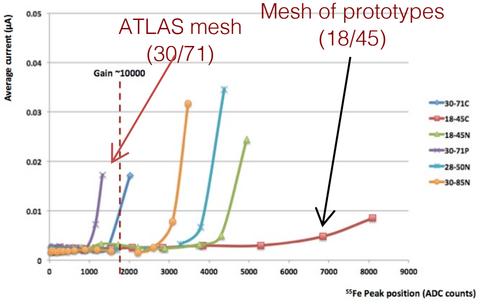
Resistive interconnections extending to the edge: reduce R_{min} → Passivation

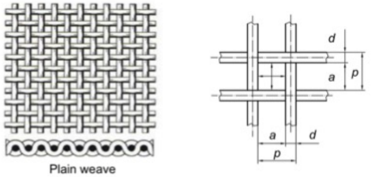


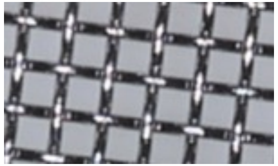


- **Mesh selection**

The mesh used for ATLAS is the less performing for HV stability



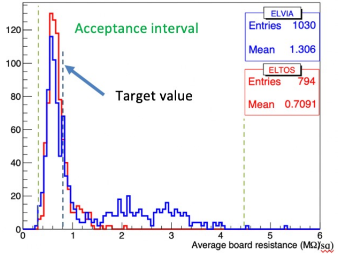


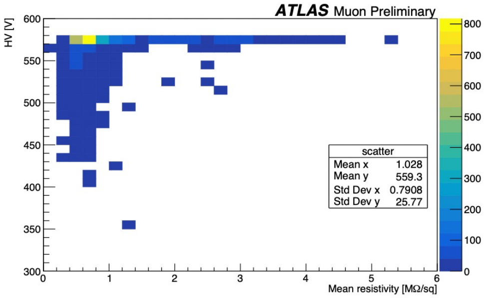


- **Resistivity**

Target value too low (optimised on small bulk prototypes with 18/45 mesh). Min resistance not enough to quench discharged close to the edge

→ Process optimisation (when possible) + passivation



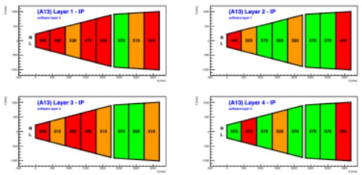


- **Gas mixture**

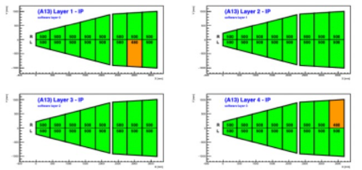
Baseline gas mixture $Ar:CO_2$ 93:7 ok for prototypes not for final detectors. Big improvement by adding 2% of iC_4H_{10}

→ Gas changed

$Ar:CO_2$ 93:7



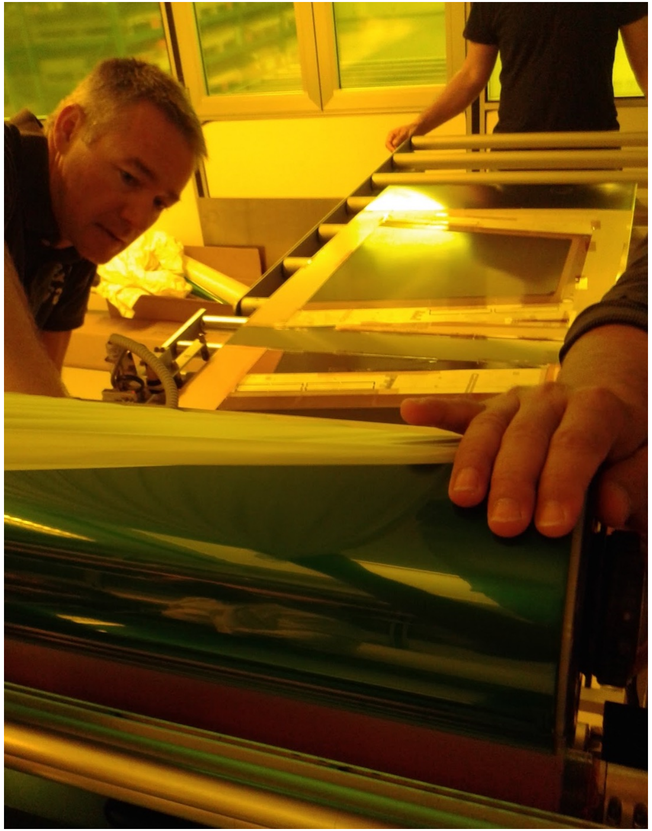
$Ar:CO_2iC_4H_{10}$ 93:5:2



Conclusions

- The industrial production of the first large-scale MPGD system has been successfully completed for ATLAS
- Production span over 3.5 years 2017-2020
- Many issues had to be addressed during the production phase, requiring close and constant follow-up

With the Micromegas for ATLAS the MPGD technology has entered the new era of mass production



Acknowledgements

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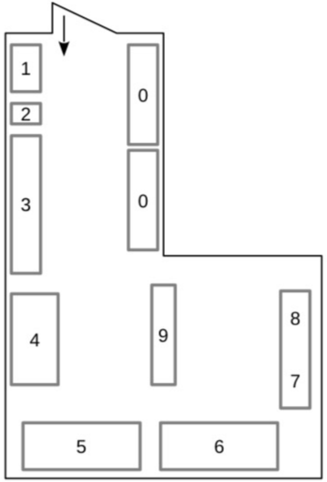
- Previous members of ATLAS Muon System & CERN team:
  - J. Wotshack
  - J. Bortfeldt
  - O. Sidiropoulou
  - F. Kuger
- CERN DT team
- CERN FI Dept. for help in the tendering process
- The many, many colleagues contributing to the construction of the ATLAS Micromegas


Thank you!

Additional Material

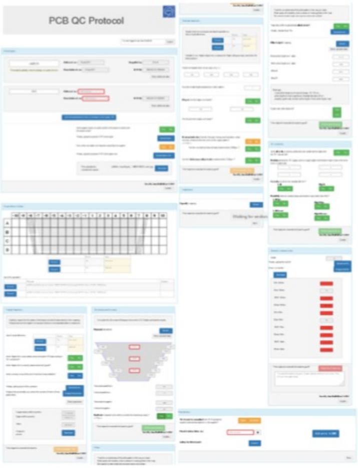
Boards QA/QC

- Dedicated lab set-up in 188
  - 7 test stations
  - Each board tested according to QC protocol
  - Shift work (2 FTE) + experts
  - Online form interfaced with QC DB to guide shifters through QC
  - Repair facility in a separate room



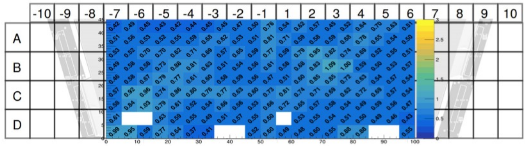
0. shelf & table
   unwrapping
1. computer table
   logistics
2. tool chest
3. top light table
   visual inspection, electrical tests, repairs
4. back light table
   agreement btw. holes & Cu pattern,
   edge precision & straightness, pillar pattern
5. rasmask granite table
   absolute dimensions & shape O(30µm)
6. granite table
   pillar height measurement
7. table
   resistivity mapping
8. table
   strip capacitance measurement
9. self
   storage of boards when QC has finished

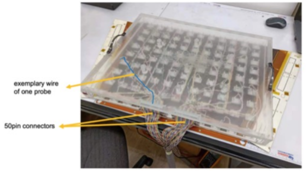
Online QC form

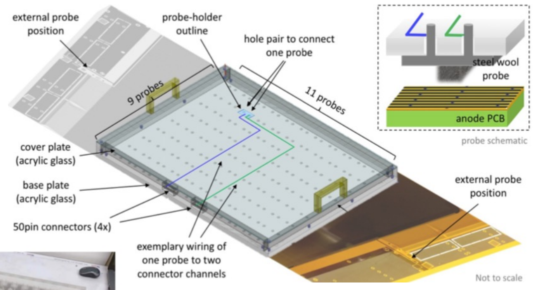


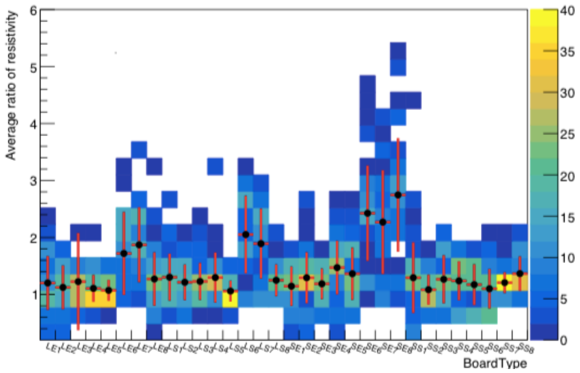
Board QC: resistivity

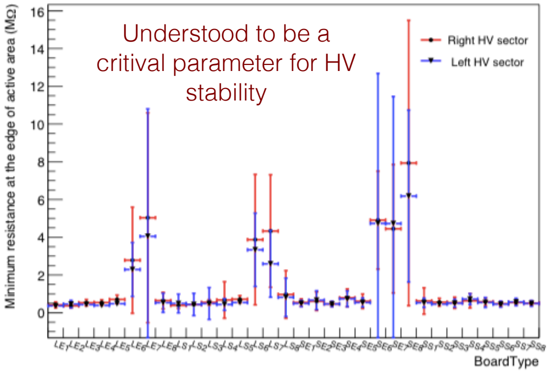
- Resistivity foils measured in Japan after production
- Final resistivity of the boards measured at CERN
- Resistivity map measured for each board
- Comparison after/before board production





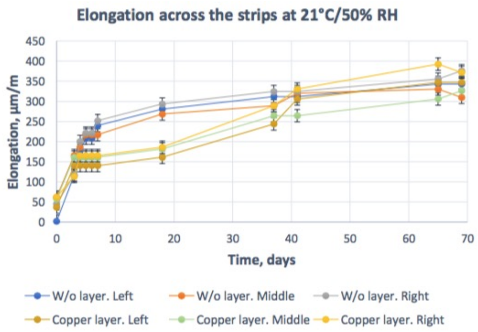


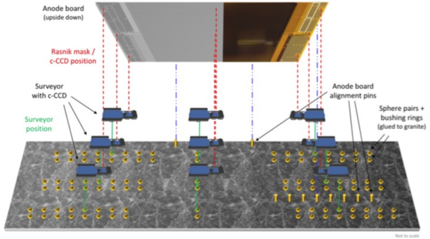


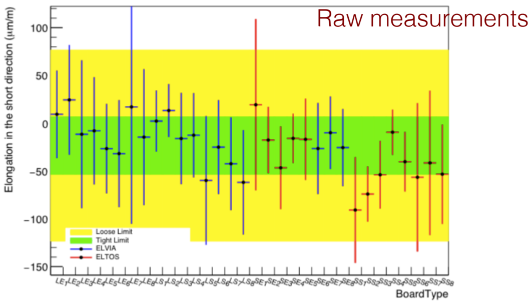


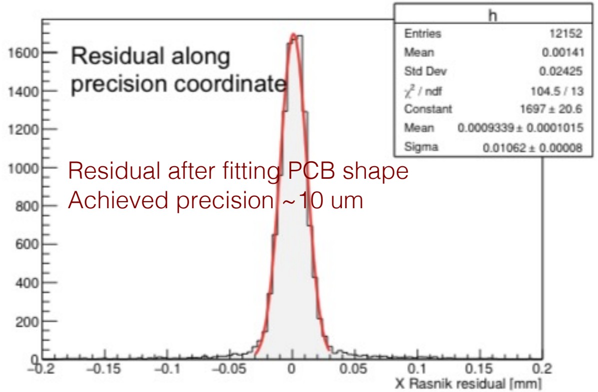
Board QC: dimensions

- Knowledge of the board dimension (i.e. strip position and deformation) crucial for precise tracking
- Boards are subject to expansion for moisture uptake
  - Study of the expansion (result: ~400um/m)
  - Rescaling of the dimension for the board production
  - Waiting period of 4w at the company to let the boards expand before final cutting/drilling
  - Dimension measurement on all the boards (contact CCD tool)









Resistive paste

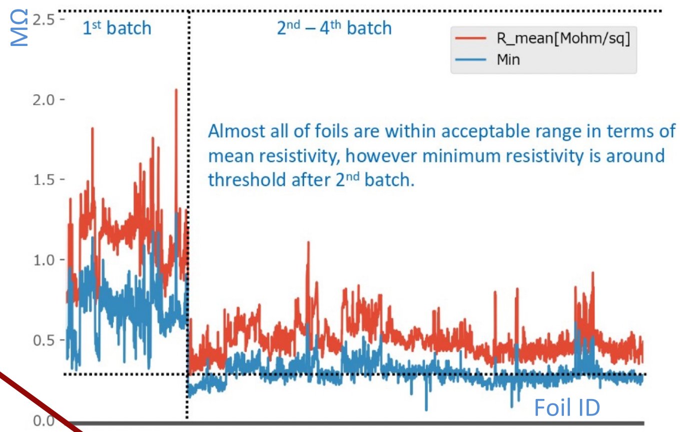
- Single provider: ESL (then Ferro)
- Final foil resistance driven by paste resistivity; curing conditions after printing; pressing conditions during board production

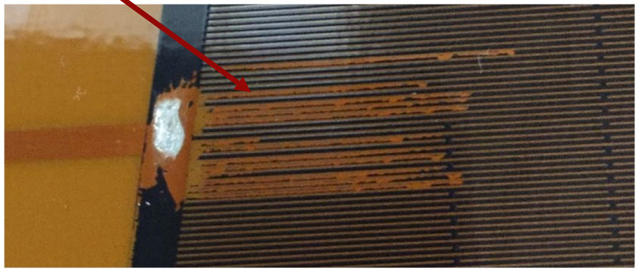
3 crisis related to resistive paste

1. 2016: Resistivity 10x higher then expected, finally understood in a change of solvent. Batch was reproduced

2. 2016: Reported from PCB company low adhesion of resistive strips during PCB manufacturing. Reason found in insufficient curing at foil printing company (Matsuda, JP). Short curing was applied by the company to keep the resistivity to acceptable level after the batch reproduction at 1. Indeed, the re-produced batch of paste had low resistivity and the printing company tried to find a fix by under-curing the foils. No information propagated to us →it took time to reconstruct the full story

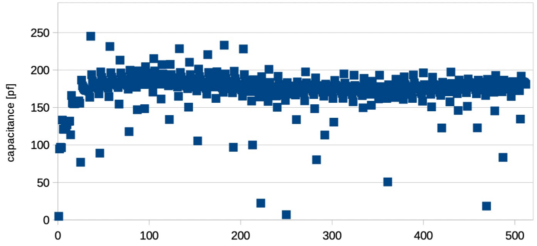
3. 2019: Paste production was moved from Germany to UK (after Ferro acquired ESL). Delivery of the last batch postponed for months. Not able to produce usable paste. Strong push from CERN to find a solution. Finally, the German expert was sent to UK to supervise the production. Costed months of delay and required a quick reaction from us to tune the pressing condition at the PCB companies to get the desired resistance range



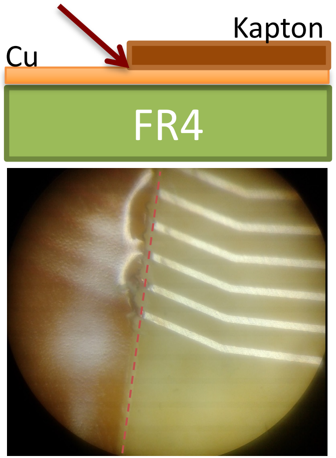


Strip etching

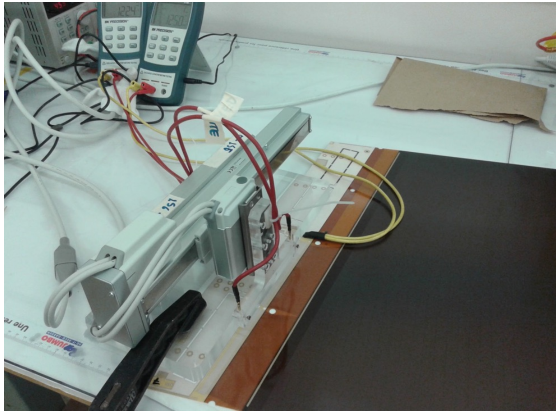
- Unexpected problem observed at the pre-series boards
  Affecting some boards of both companies:
  Cu lines cut at the edge of the kapton foils
  (excess of micro-etching during Ag plating)
  → problem understood and solved
- Capacitance between neighboring strips or strip and HV line is a good indicator for interruptions and cuts
- Automated tool developed for capacitance measurement



Strip capacity vs line number



Cu lines cut at the Kapton edge



Strip capacity automatic measurement setup