Carbon fiber composites and structures in the framework of the ATLAS ITk strips tracker

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Detector R&D retreat@DESY, 19.01.2024

HELMHOLTZ

ATLAS ITk

DESY.

Why CF composites?

Carbon fiber for beginners

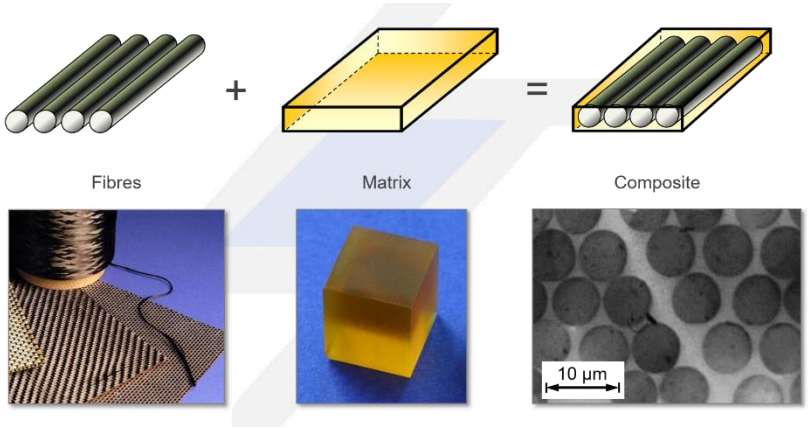
Carbon fiber composites are extremely versatile materials with excellent mechanical and thermal properties

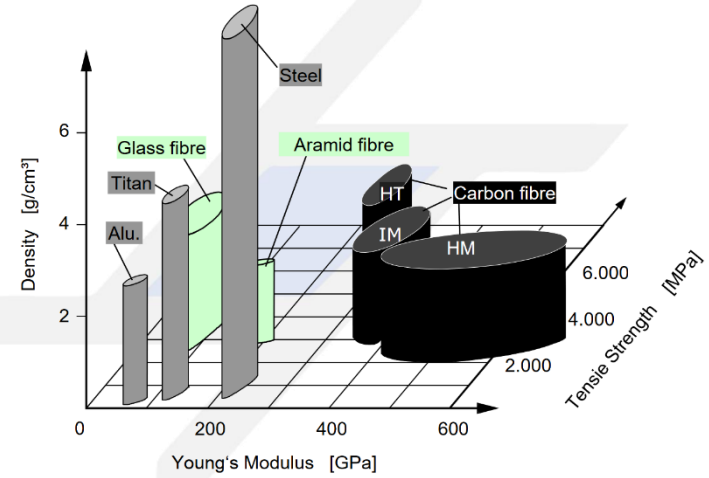
Many different combinations are possible by combining different fibers and matrixes, laminate layers, mixing ratios, manufacturing processes, etc.

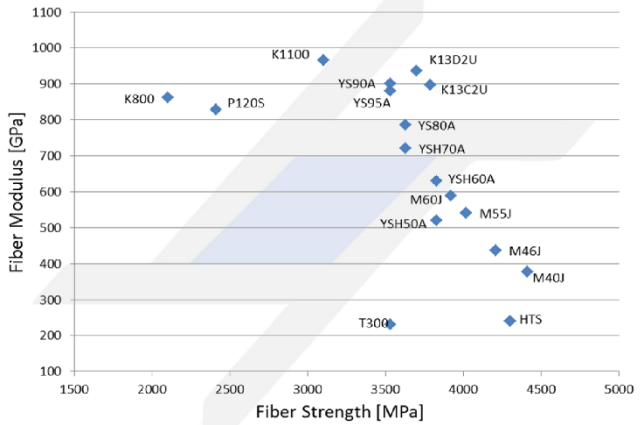
Some of the most interesting properties **that can be obtained** are:

- Low density (~1.4-2 g/cm^3)
- Extremely high strength
- High thermal conductivity (~600-800 W/mK), twice as copper with <25% the density
- Almost negligible CTE ($\alpha < 0.08 \times 10^{-6}$/K) for certain pre-pregs
- Electrically conductive
- Extremely high radiation tolerance

All this makes them an ideal choice for High Energy Physics applications



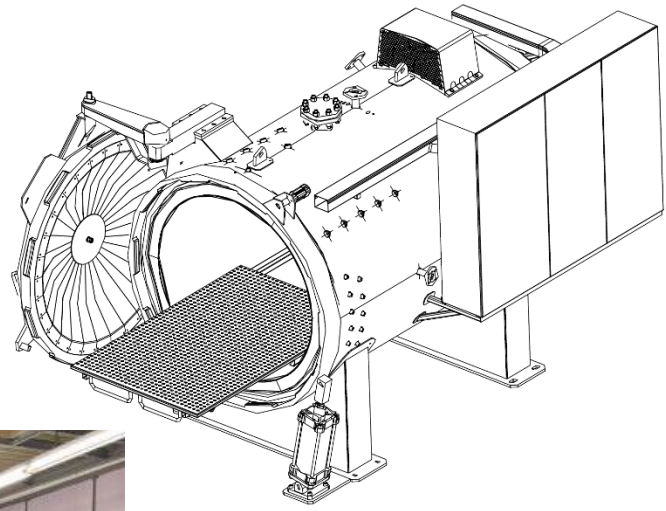




The carbon fiber lab at DESY

An essential infrastructure for the ATLAS group and FH

The carbon fiber laboratory was put in place (with great effort from Volker, Andreas, Ingrid, Darío, Sören, myself and many others) between 2016-2018 in building 43a



It has become a key infrastructure since

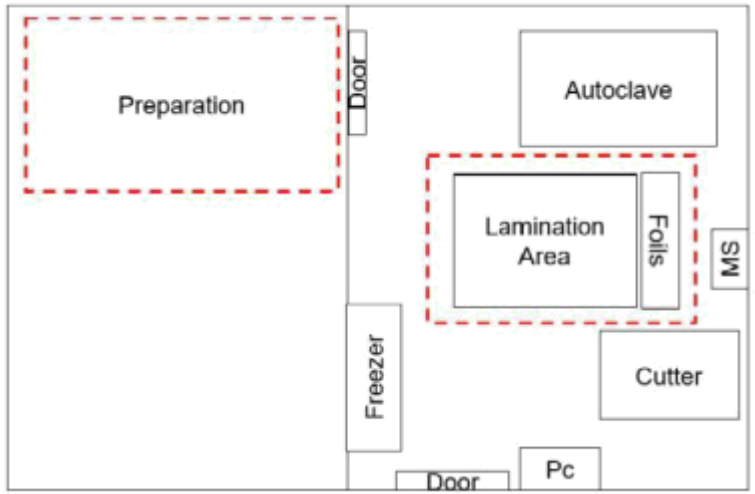
- Big in-house expertise built by our engineers/technicians

The main setup in the lab is an **Autoclave** from Maroso

- 1.5 m long, 1.2 m diameter chamber
- Able to perform curing cycles up to 7 bars and 200 deg C
- 10 internal vacuum lines

Also in the lab: 1.4 x 1.4 m^2 vibrating knife **pattern cutter** from Aristomat

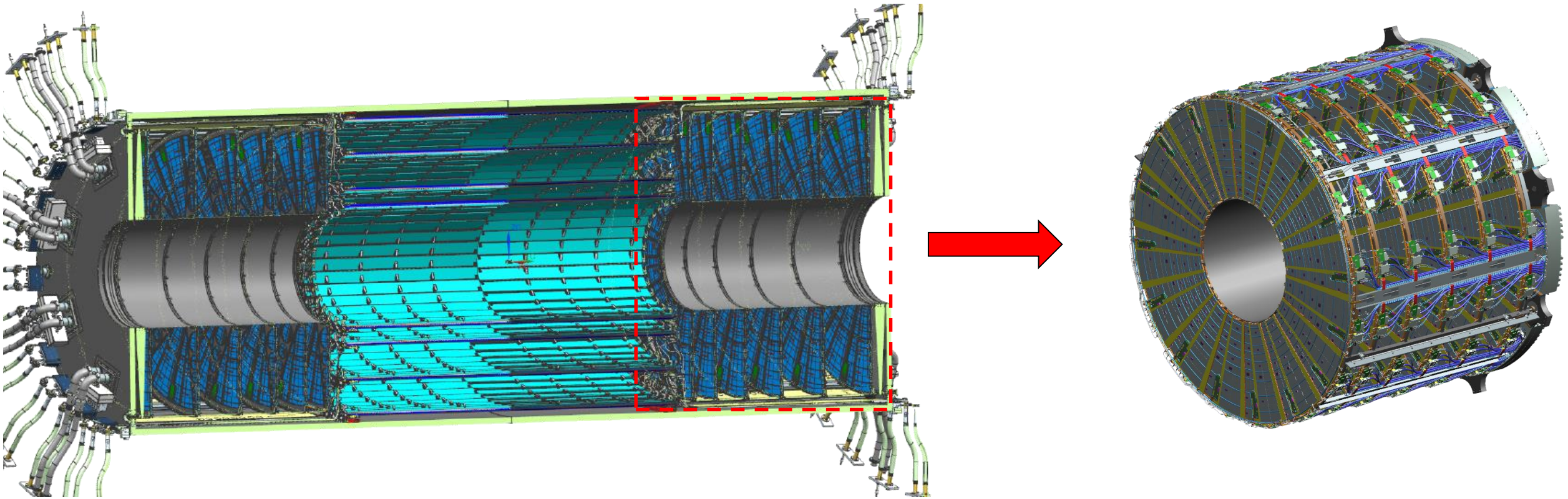
In preparation: 1.4 x 1.4 m^2 automated **pre-preg roller**



The ITk is a carbon fiber-based detector

Forget about silicon. Silicon is boring

Global support structures are mostly made out of carbon fiber



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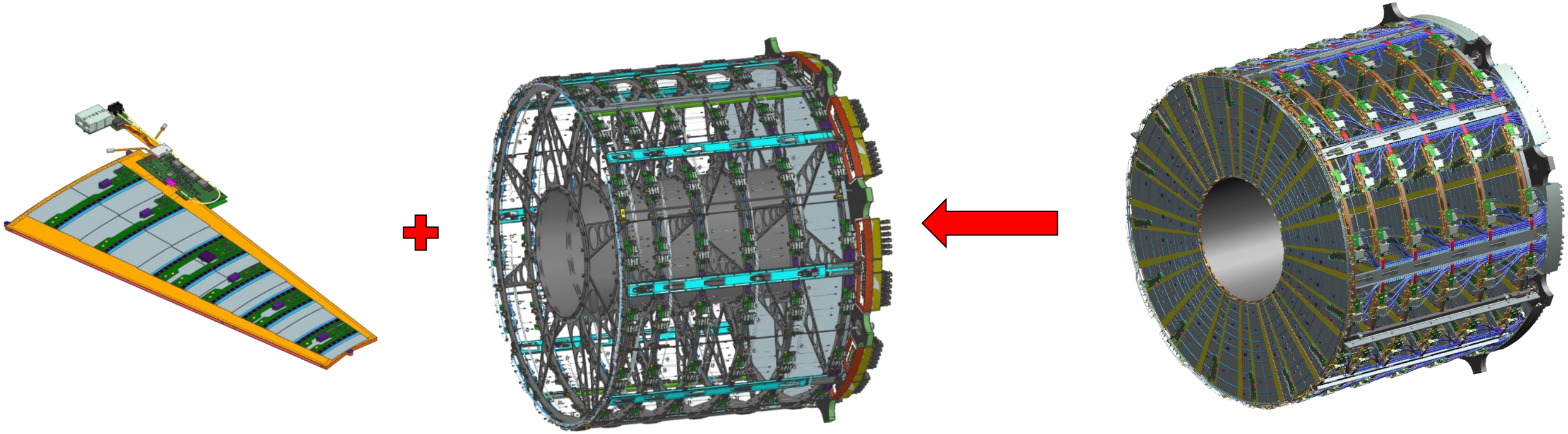

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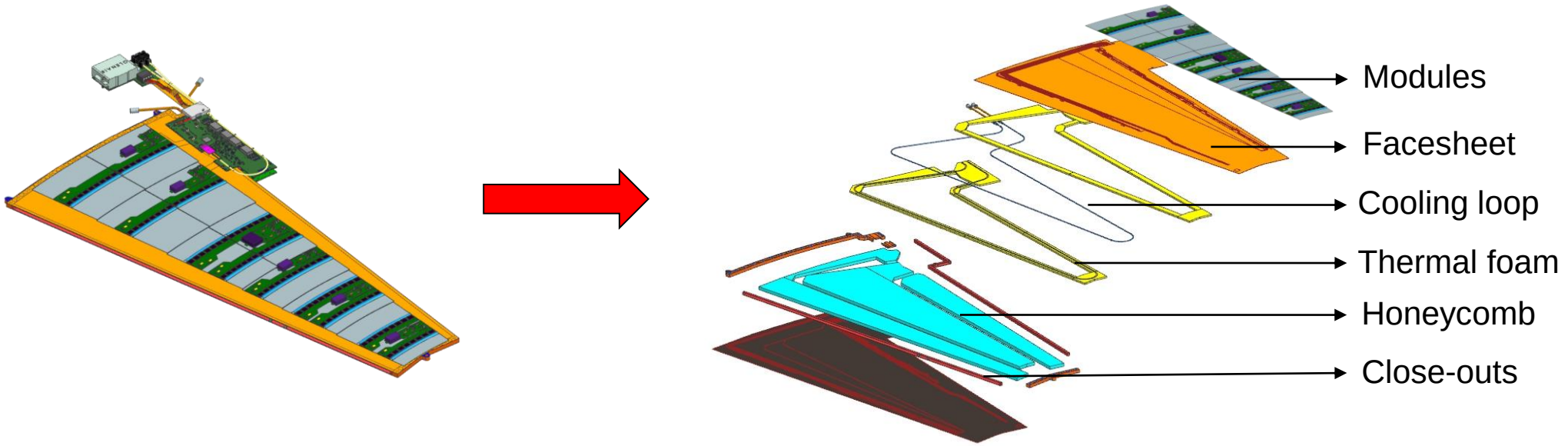
Local support structures are mostly made out of carbon fiber



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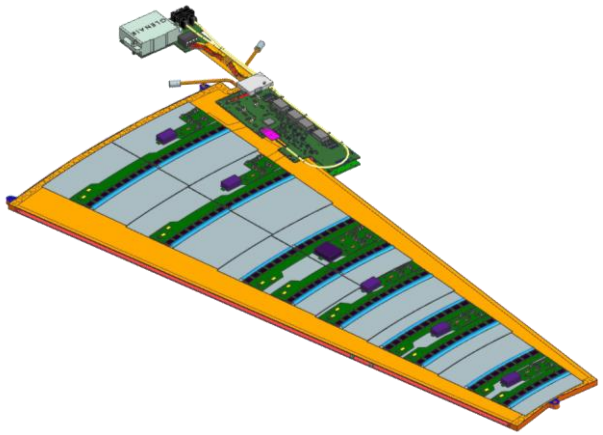

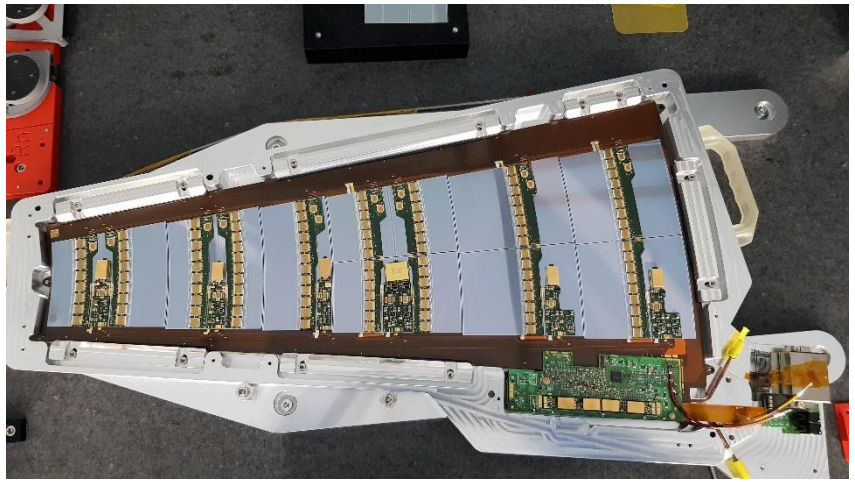

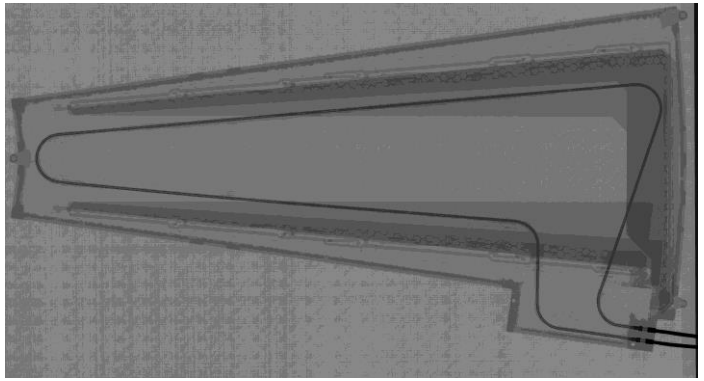

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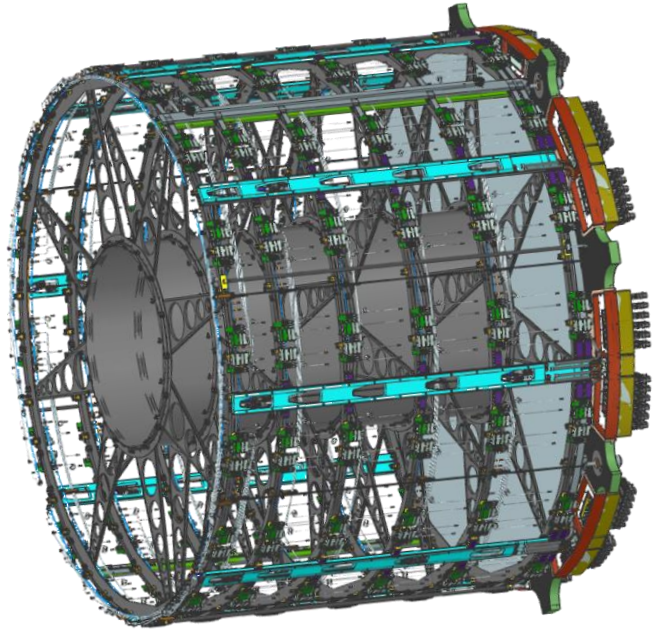
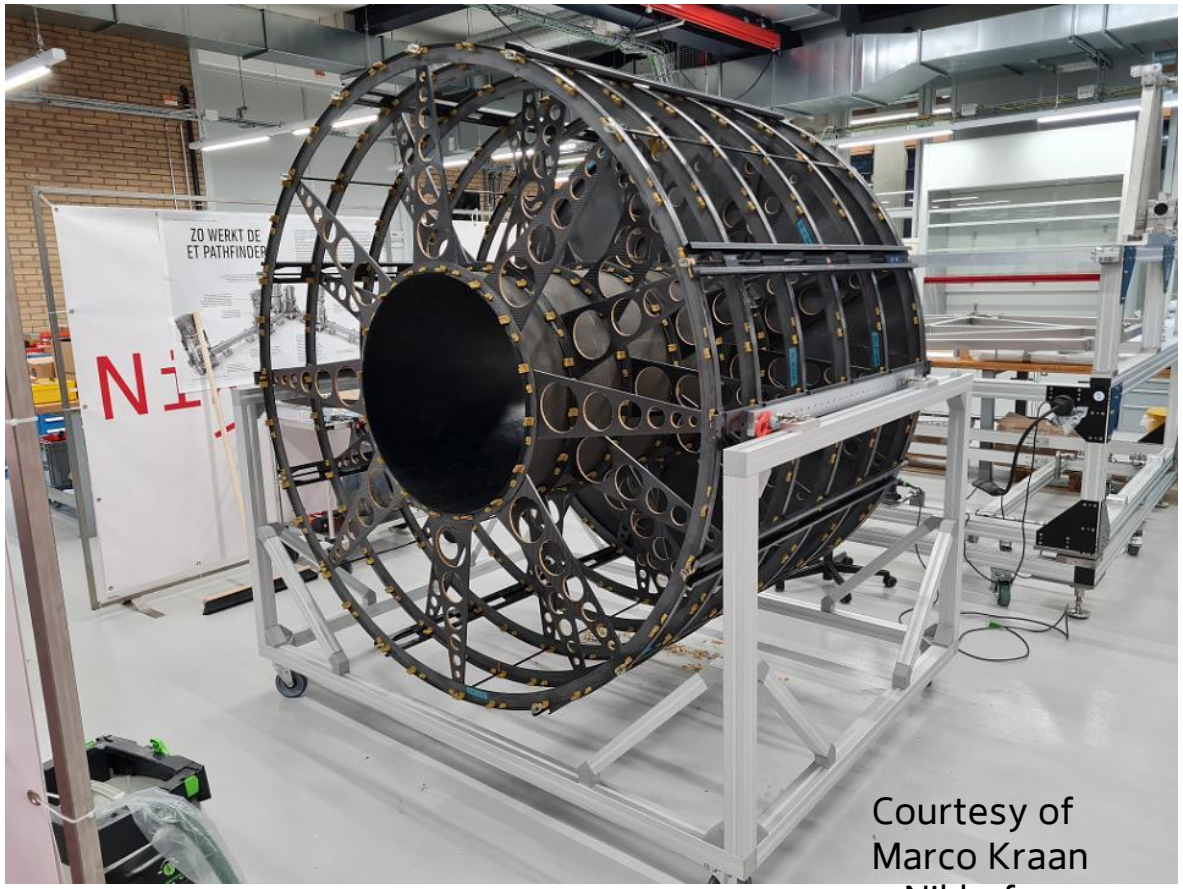


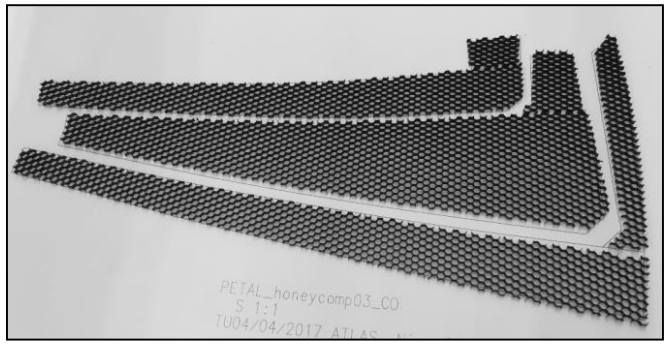


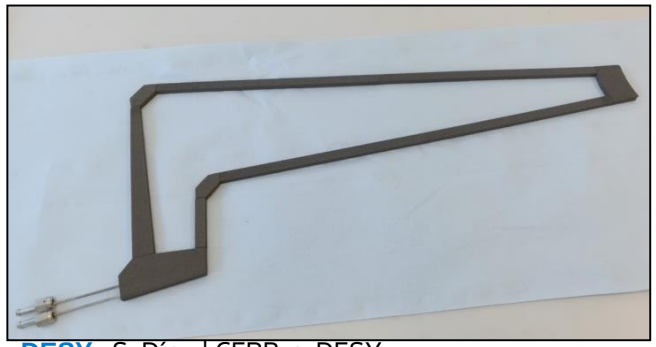
Courtesy of Marco Kraan @Nikhef

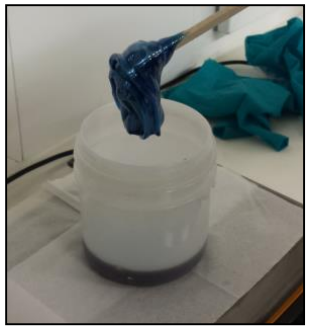
The ITk is a carbon fiber-based detector

Forget about silicon. Silicon is boring

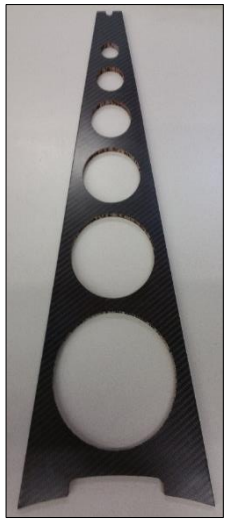
Carbon fiber is really everywhere in the detector

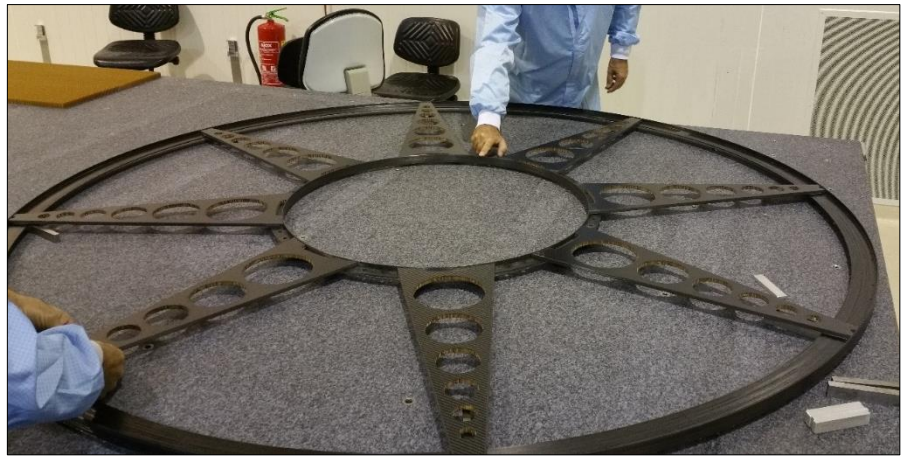






Everywhere in the detector





ITk CFRP components

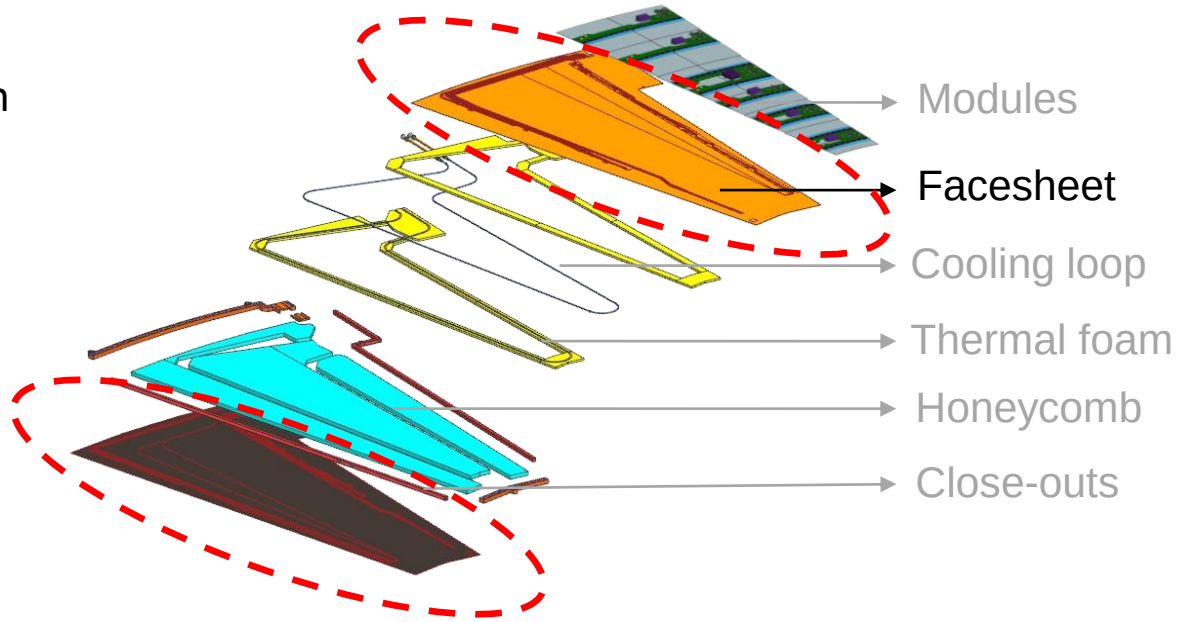
What happens at DESY

The endcap local supports (the petals) are manufactured in industry, but numerous endcap components are produced (and QC'ed) in-house at DESY

- Cooling loops
- Thermal foam sets
- **Co-cured facesheets (the "skins" of the petals)**

DESY is the Endcap site which produces the full amount of co-cured facesheets of the petals

- ~400 pairs ("front" and "back"), 800 tapes in total



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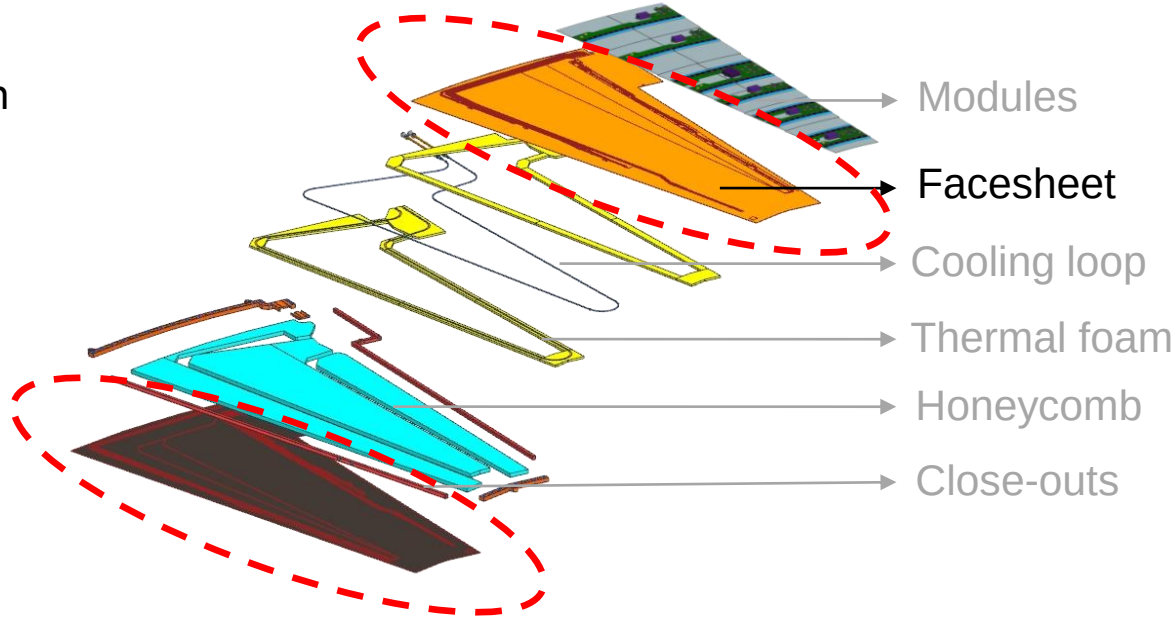
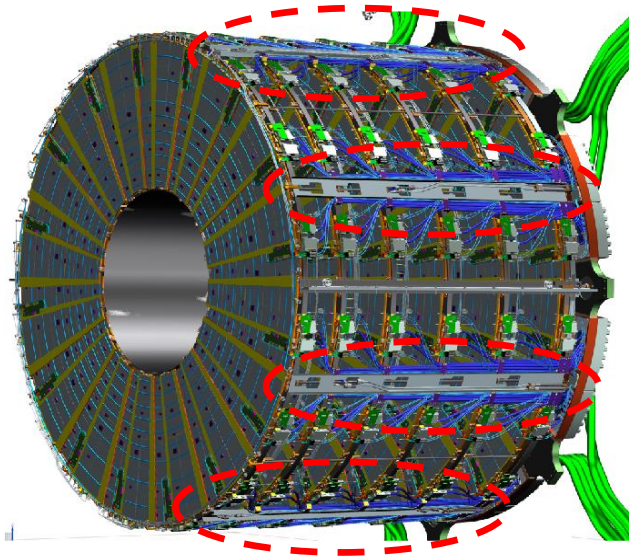
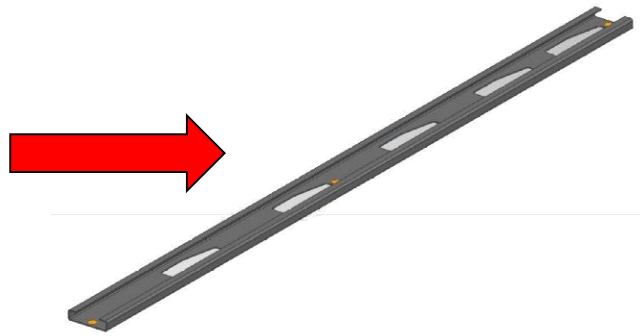
DESY is also responsible for the production of the CF beams on the global structure holding the cooling and electrical services **(the "service trays")**

- 16 service trays in total, 8 per EC







Co-cured facesheets

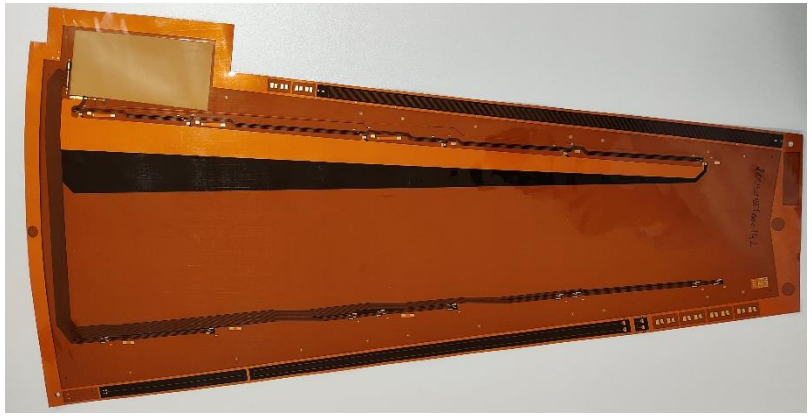
Laminated PCB

The **bus tapes**: flexible polyimide PCB containing the differential data lines, LV and HV lines, and DCS lines

- Optimized for 640MHz differential signaling and high quality wire bonding surfaces

They become "facesheets" once they are co-cured together with 3 layers of carbon fiber pre-preg

- 50 µm thick unidirectional (UD) K13C2U/EX1515, ~ 40% resin content
- 0-90-0 fiber orientation lay-up
  - Optimized for mechanical stiffness on the longitudinal edge and thermal performance on the transversal edge

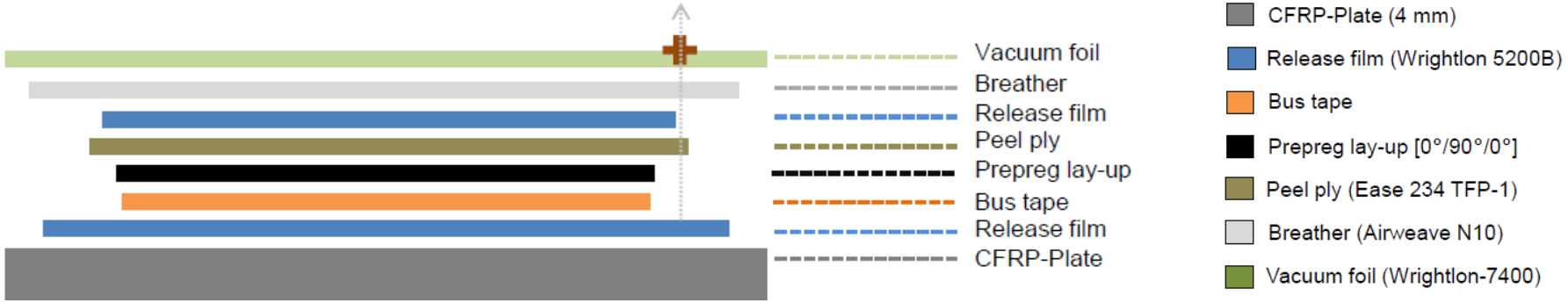


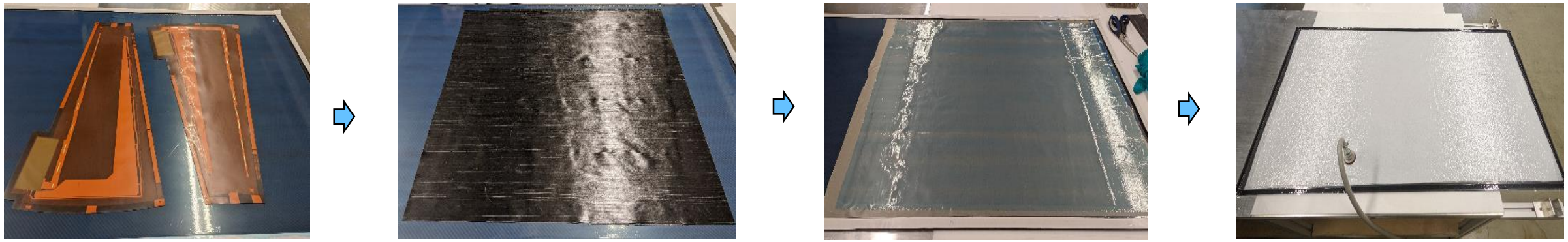
185 µm thick

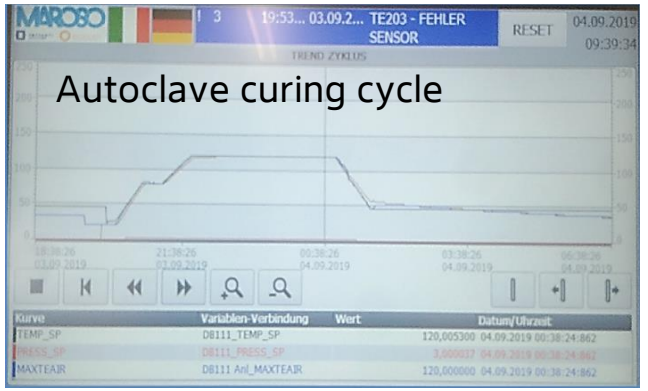
Co-cured facesheets

Co-curing process

"Vacuum-press" moulding







Facesheet production

Mastering the process

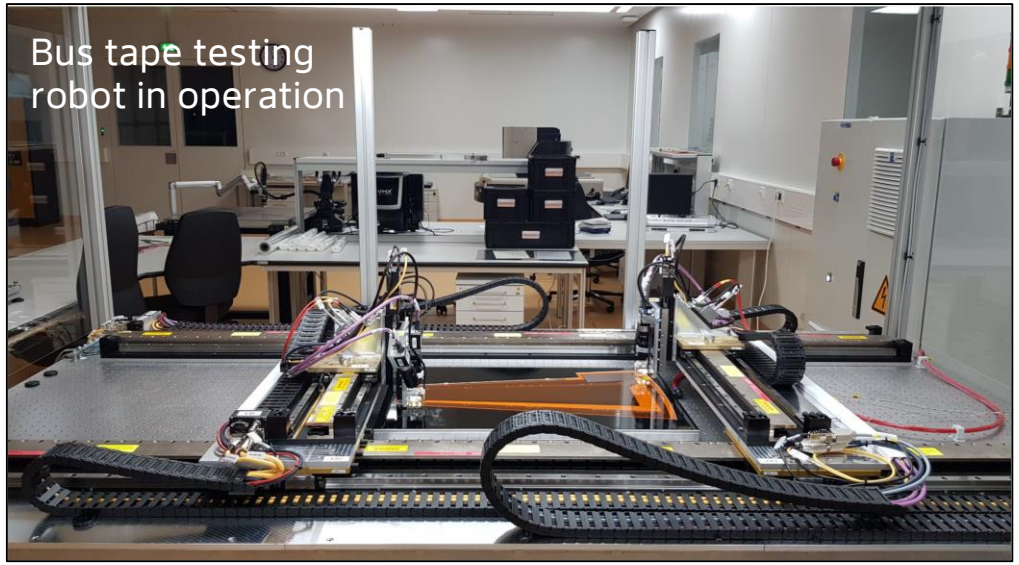
DESY has become a "facesheet" factory:

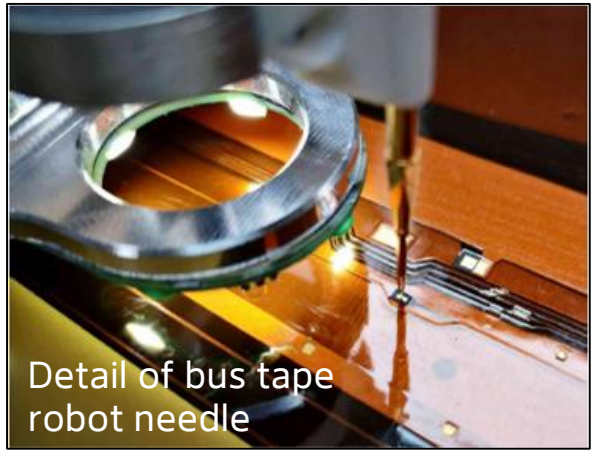
- Able to co-cure up to 20 facesheets per co-curing cycle
- Current record: **72 facesheets in 1 week**

… but that is only part of the process…

Facesheet **Quality Control** checks:

- Visual inspection: contamination, mechanical damage
- Weighing and thickness measurement: Adhesive content, overall uniformity of the process
- Microscope inspection: pad bonding quality
- **Bus tape testing robot**
  - Custom-built, fully automated flying probes robot


Bus tape testing robot in operation


Detail of bus tape robot needle

Bus tape testing robot

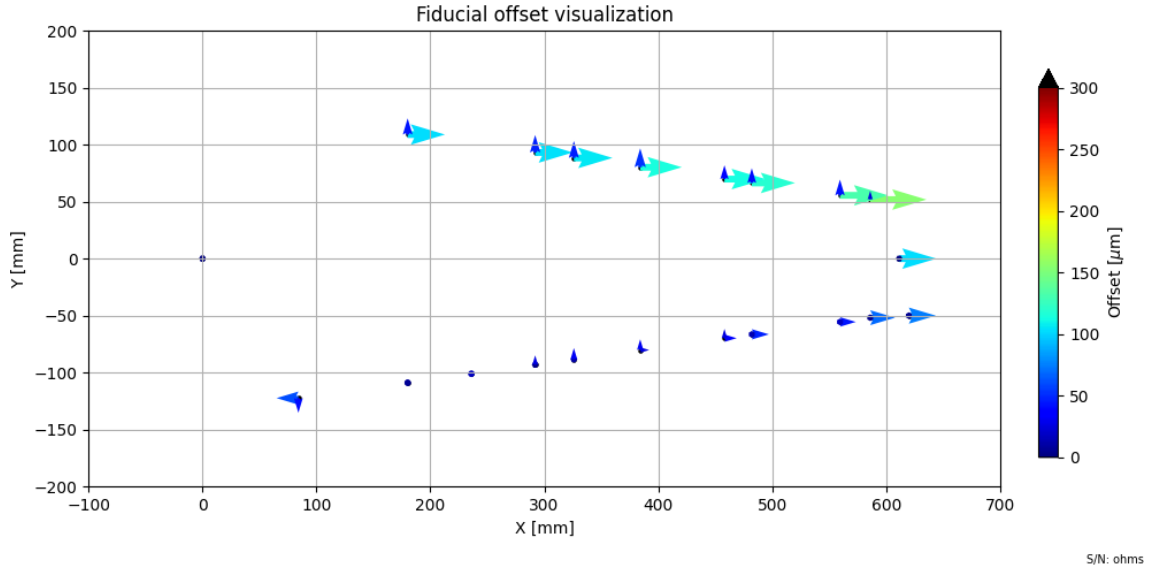
Part of facesheet QC

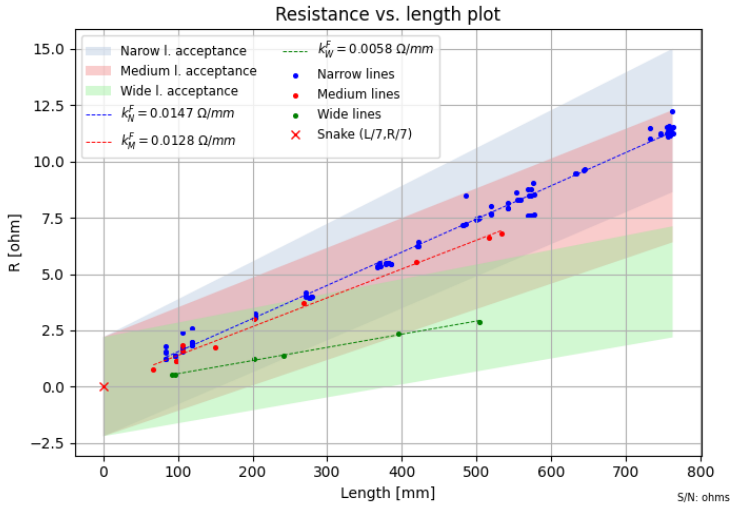
The BTTR performs a fully automated testing routine covering electrical and mechanical checks

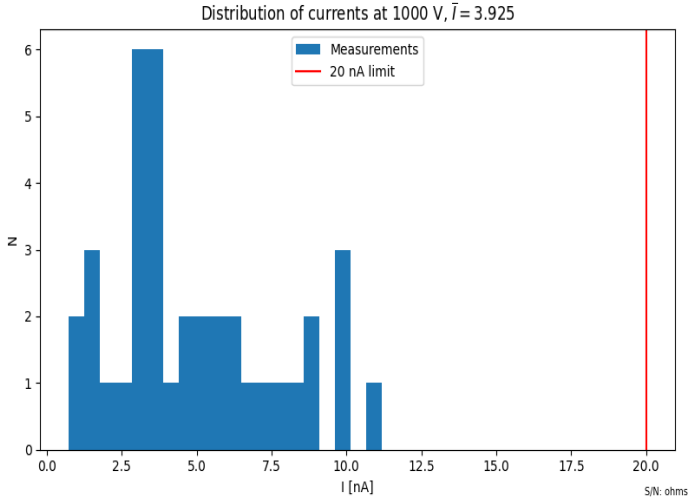
- Stretch tests: deviation of global and local fiducials wrt nominal
- Checks for shorts and open circuits of the bus tape lines
  - Including between GND lines and CF
- Resistance per unit length tests
  - "Narrow" 75 um differential lines
  - "Medium" 80 um DCS lines
  - "Wide" 100 um HV lines
- 1000 V HV isolation tests

Overall, tapes are tested at 3 stages of production

- Bare tapes (JSI, 100%)
- Co-cured tapes (DESY 100%)
- Tapes on cores (DESY 50%, JSI 50%)







Production by the numbers

Overall picture

As of today, we have received 253 bare bus tapes at DESY

- Accounts for **~32% of production**… sort of*

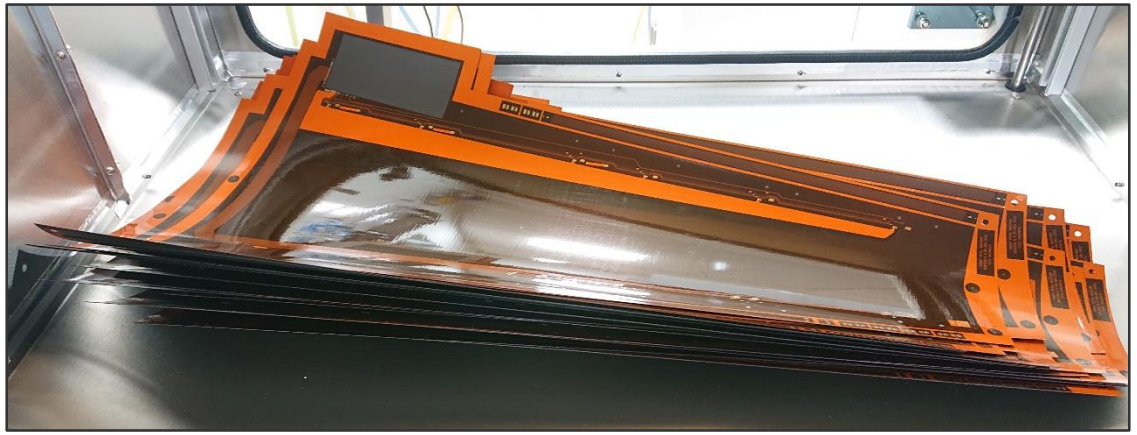
We have **co-cured all of them**… sort of*

As of today, full QC has been exercised on ~ 180 of them, more being tested every day

- 91 backs (52%), 85 fronts (48%)
- Typical QC throughput: 4 tapes/day

Number of "failed" + "under review" tapes so far = 6

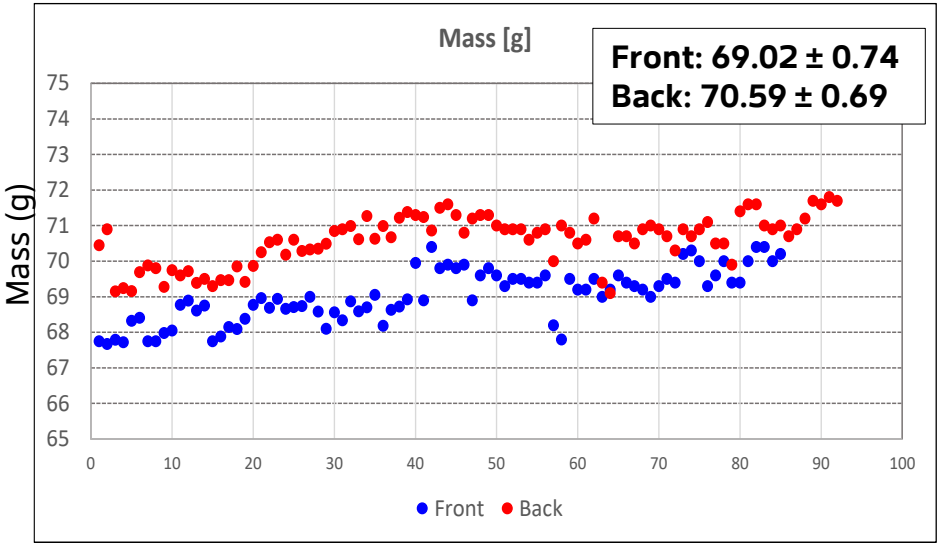
- **Actual "pessimistic" yield post co-curing ~ 96.5%**
  - Only 2 tapes are "definitive" failures: broken lines



* *First batch of tapes (approx. 20 tapes, smaller bottom metal pads) is considered "class B" and only a subset of them were co-cured*

Results (I)

Weight, resistivity, HV insulation



Back tape mass higher than front due to longer LV(ret) copper lines

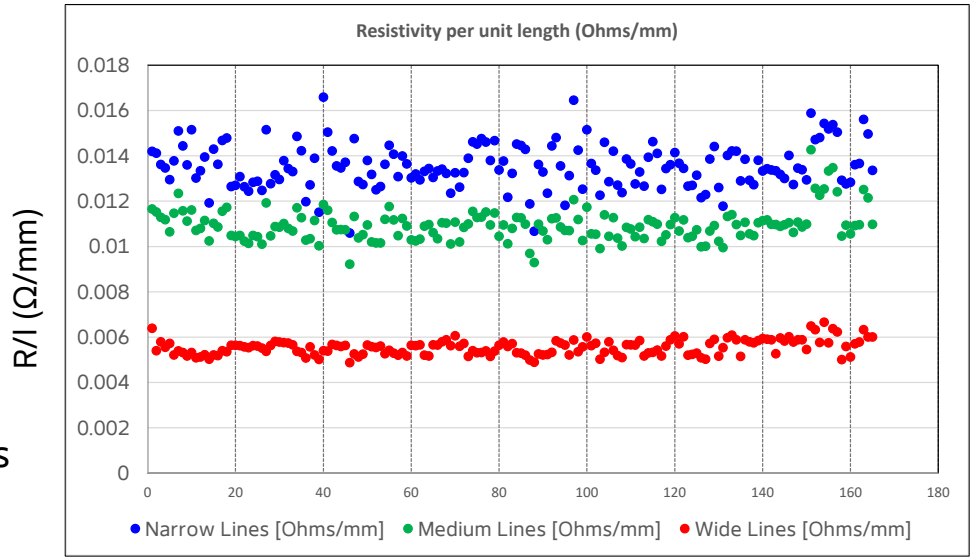
Excellent reproducibility

Mass variations follow pre-preg roll variations (5 rolls used in total)

Very homogeneous results among tapes

Some false "fails" due to bad contact or slightly misaligned probes

- ❖ Retesting is sometimes necessary



Well within specs

0 failures

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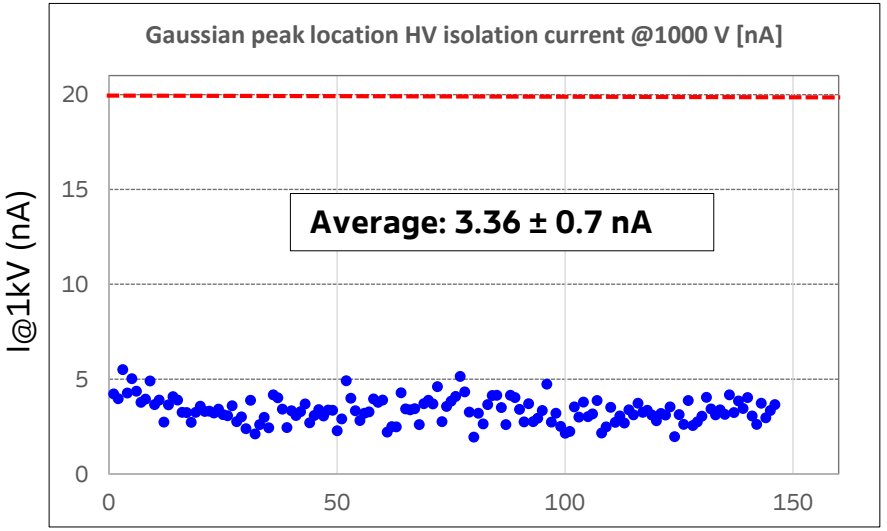
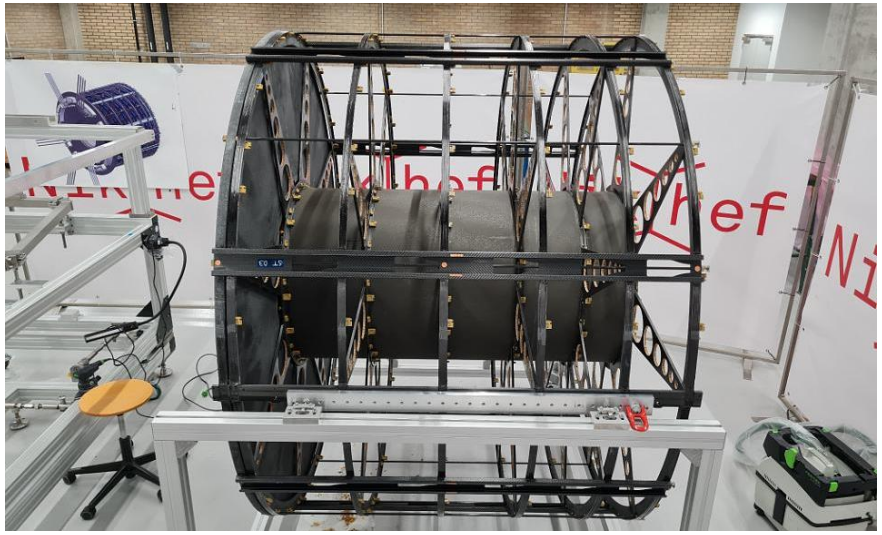


Service trays production

First ITk production at DESY

Service trays serve as

- Holders of cooling and electrical services and environmental sensors
- Structural component of the ECs providing stiffness
- Electrical connections of all the CF components of the global structure (<10 Ohms paths to the Faraday cage)



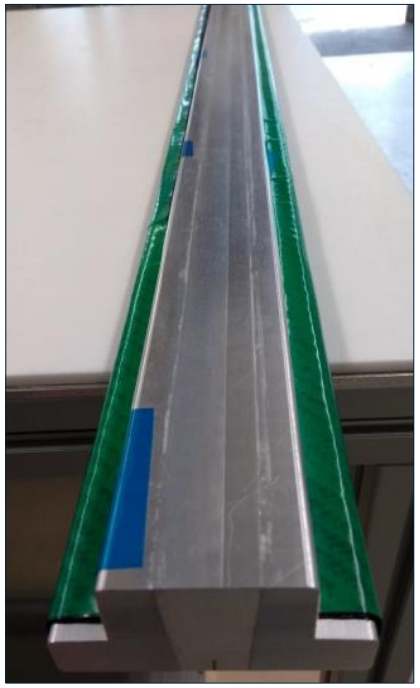
Manufacturing process:

- Vacuum press moulding
  - 6 layers of 200 µm thick 0/90 T300/EX1515 woven pre-preg
  - 18 produced in total, 1400 mm long x 80 mm wide
  - Final machining step required to achieve final precision

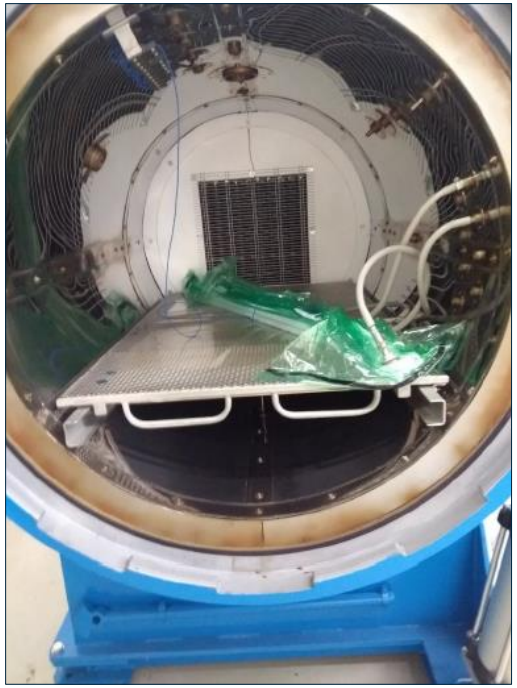
Service trays production

Co-curing process

Lay-up



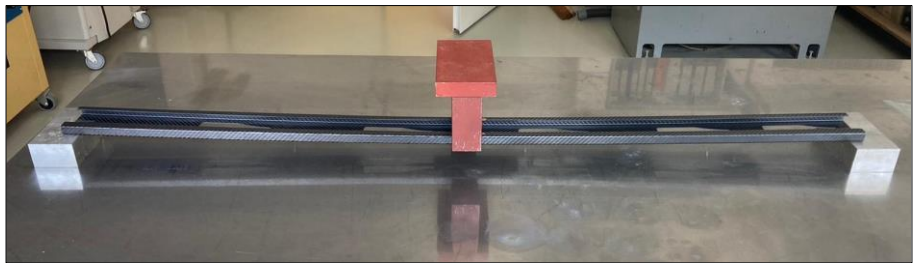
Bagging



De-bagging

Post-processing

Delivery

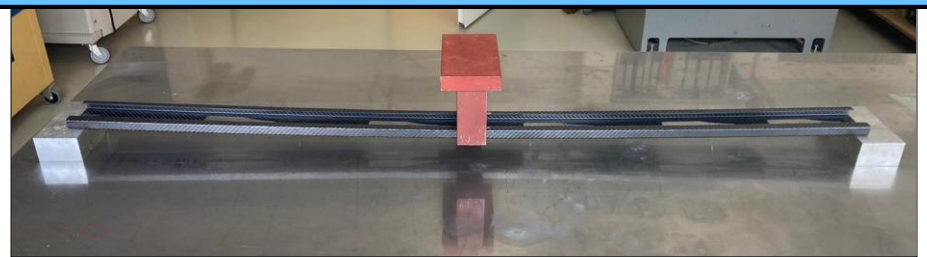


Service trays production

Co-curing process

Lay-up | Bagging | De-bagging | Post-processing | Delivery

Production is completed!



From now into the future

Perspectives of detector mechanics R&D for DESY

MaxRad material database

New collaborative project to prepare for future detector R&D

Project: new small scale project started in December 2023 by a small team

- N. Pacifico (CERN), S. Karmakar, A. Jung (Purdue), JHA (DESY)

Goal: establish a new/extended database of materials used for detector mechanics within HEP following the currently established MaxRad database

- Results of the finished/ongoing/future detector upgrades concerning material characterization should be collected and made available for the whole community
- Examples are Imhotep database (based on CERN Yellow Reports) and MaxRad database (by N. Pacifico at CERN EP-DT)
- Working on standardization of test methods and reporting

Vision: You are in the design phase of your new detector; you go to the database and type in your material specifications (e.g. radiation levels); you get a list of possible materials with attached test reports, use cases and links from other experiments. You are happy!

From DESY side:

- Wish to include our local experience from ATLAS and CMS tracker
- Start looking into the future and explore new materials/assemblies
- Potential for including the material budget measurement and imaging of materials (link)

DESY-FH contribution in DRD8

R&D collaboration on detector mechanics

Starting point: in the ECFA detector R&D roadmap, the topic of integration & detector mechanics was discussed in TF#8

Status quo: apart from the other DRDs already forming, for a potential DRD8 we only had a kickoff discussion in December 2023 at CERN

- Andreas represented DESY-FH in a talk, many other team members were connected

DESY perspective: in case it will be realized, DESY-FH could and should be part of it

- Experience from ongoing CMS and ATLAS tracker phase-2 upgrades
- Extensive infrastructure for developments and detector integration available
  - CF production: CF lab (43b) with Autoclave, pattern cutter, storage, …
  - Metrology: SmartScope, ultrasonic imaging, …
  - Thermal performance: TIM tower, thermal imaging, …

→ Good opportunity now to secure the lessons-learned and use it for future R&D

Interesting fields: detector support structures (CF-based materials), detector integration (tools), cooling (CO_2, microchannel cooling), engineering (CAD, FEA)

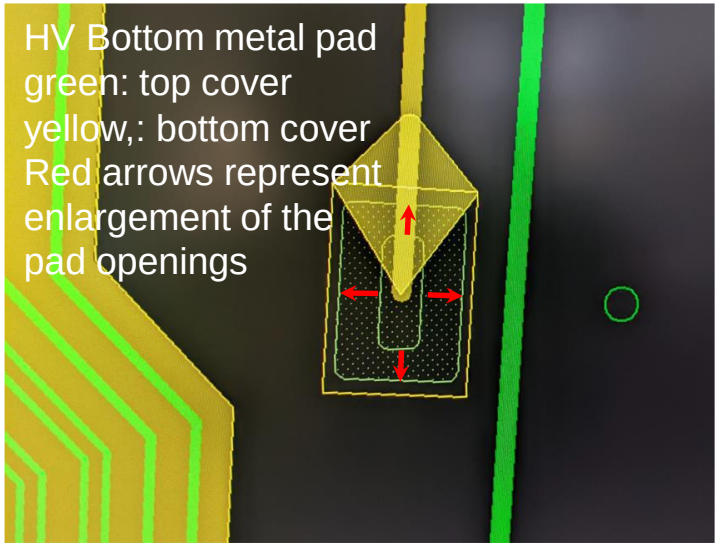
Thanks for the attention

Tape design modifications

Changes during early stages

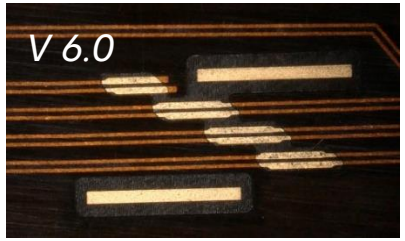
Initial production results forced us to perform minor tweaks in the design

- Increase size of bottom metal pads to avoid "edge bubbles" effects (along with retuning of plating/laser skyving parameters – Dec 2022



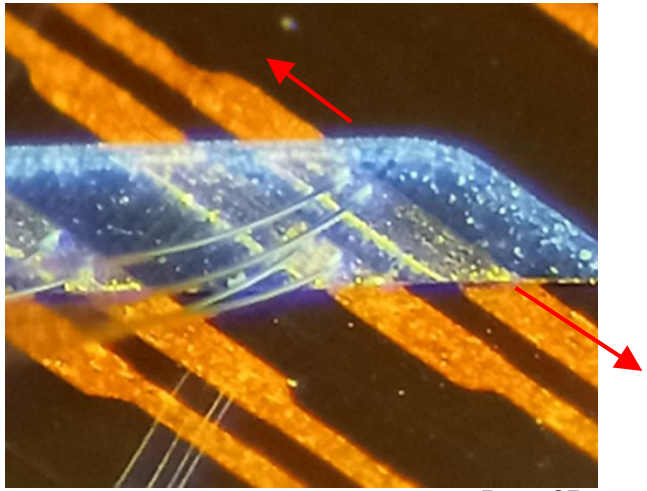
Manufacture and wire bonding of first petals motivated another minor change

- Increase opening of DCS wire bond fields at multiple module locations – July 2023



Additional observations motivated discussions with manufacturer which resulted in optimizations of the whole process without modifying the design

- Further retuning of the laser skyving step – June 2023



We have a very stable and reliable process after the first ~100 tapes

Final design (+addendum) can be found on EDMS

Observations

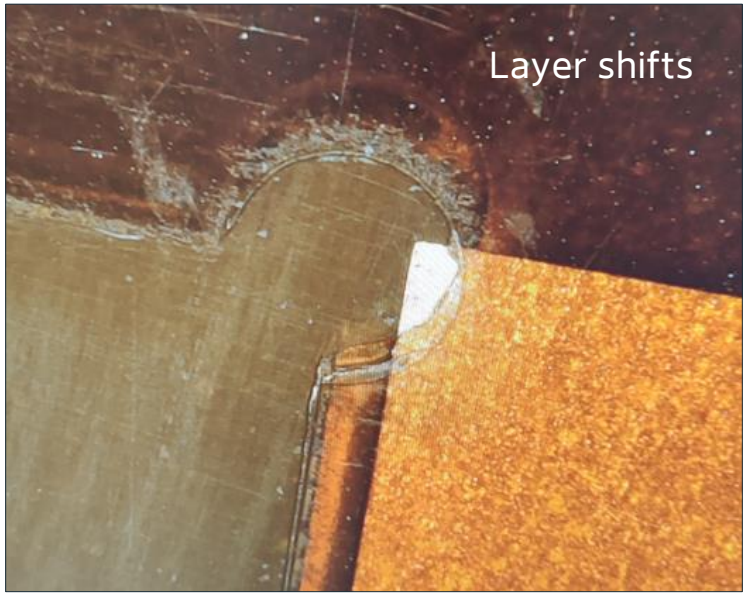
Some minor – and not so minor - defects

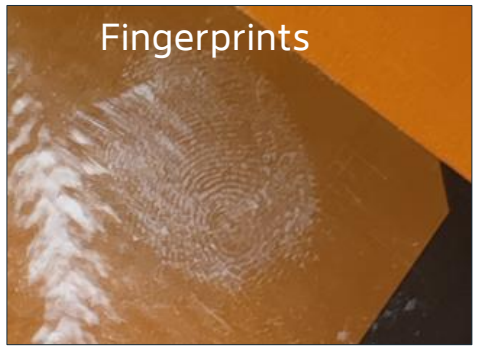
Visual inspection before (JSI) co-curing, during reception testing and after co-curing (DESY) is an integral part of the tapes QC

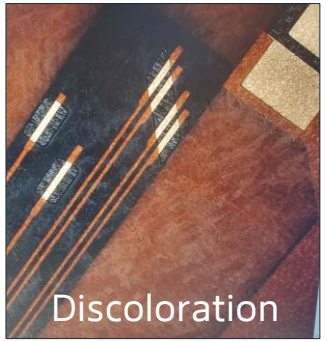
Led to the discovery of multiple defects, most of them minor, which were communicated to elgoline and allowed retuning of the manufacturing process

Communication among Elgoline Inc., JSI and DESY proven to be extremely constructive

- ❖ Elgoline very open to any suggestions for improvement







Results (I)

Visual inspection

Determination of quality of the co-curing surface

Every single bond pad per tape is inspected

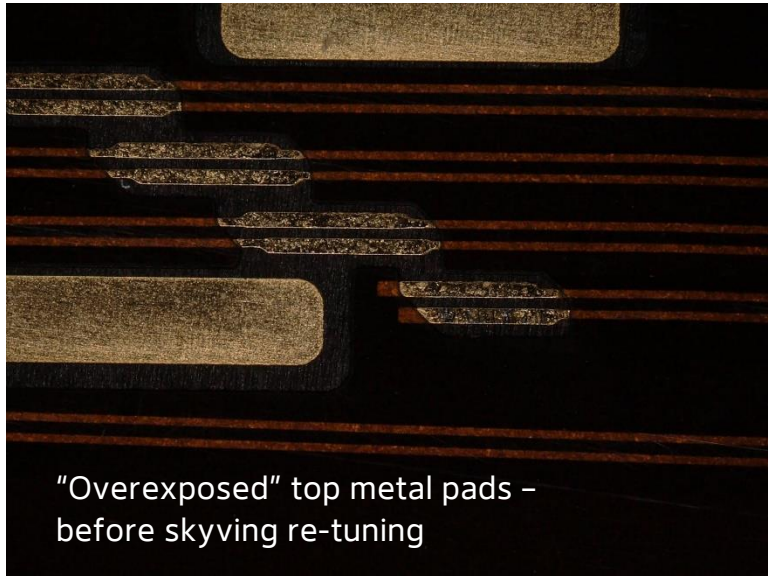
- If there are no problems, the process takes 5 min/tape

A subjective process

- Allowed the observation of "edge bubbles" effect
- Allowed the re-tuning of the skyving parameters after batch 2-3

One tape deemed "failed" due to very bad bond pad quality, passed all BTTR tests

- Tape was cut to pieces for bond pull testing, all pads were bondable within specs

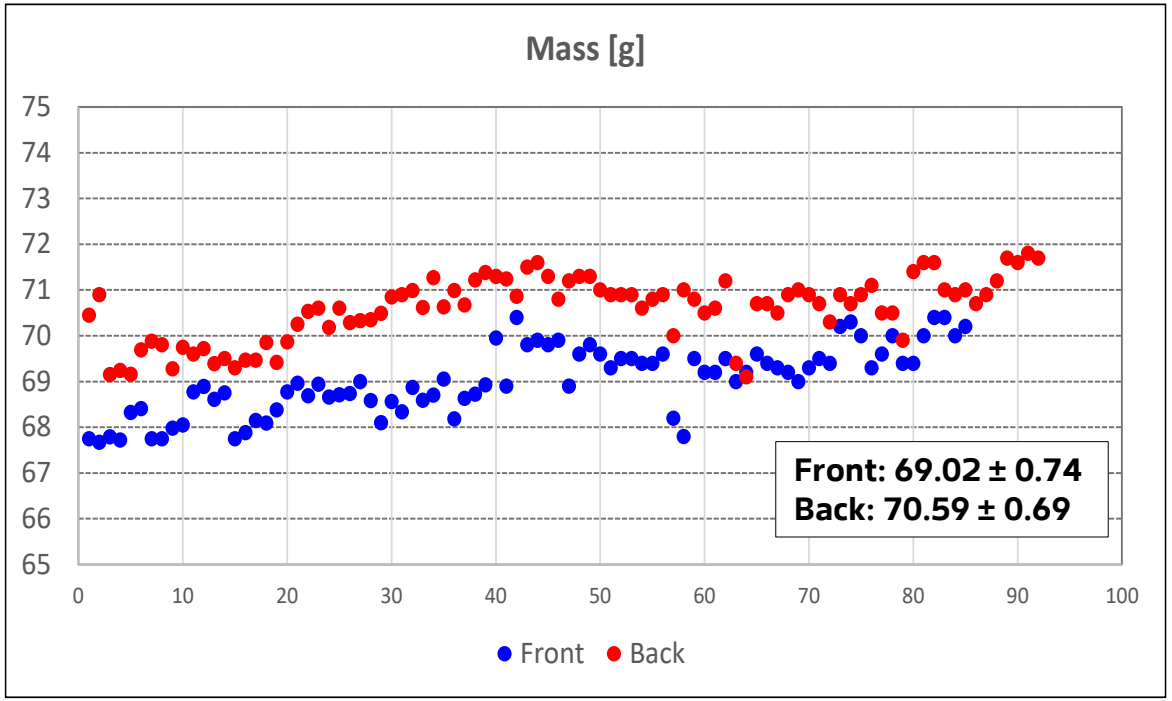


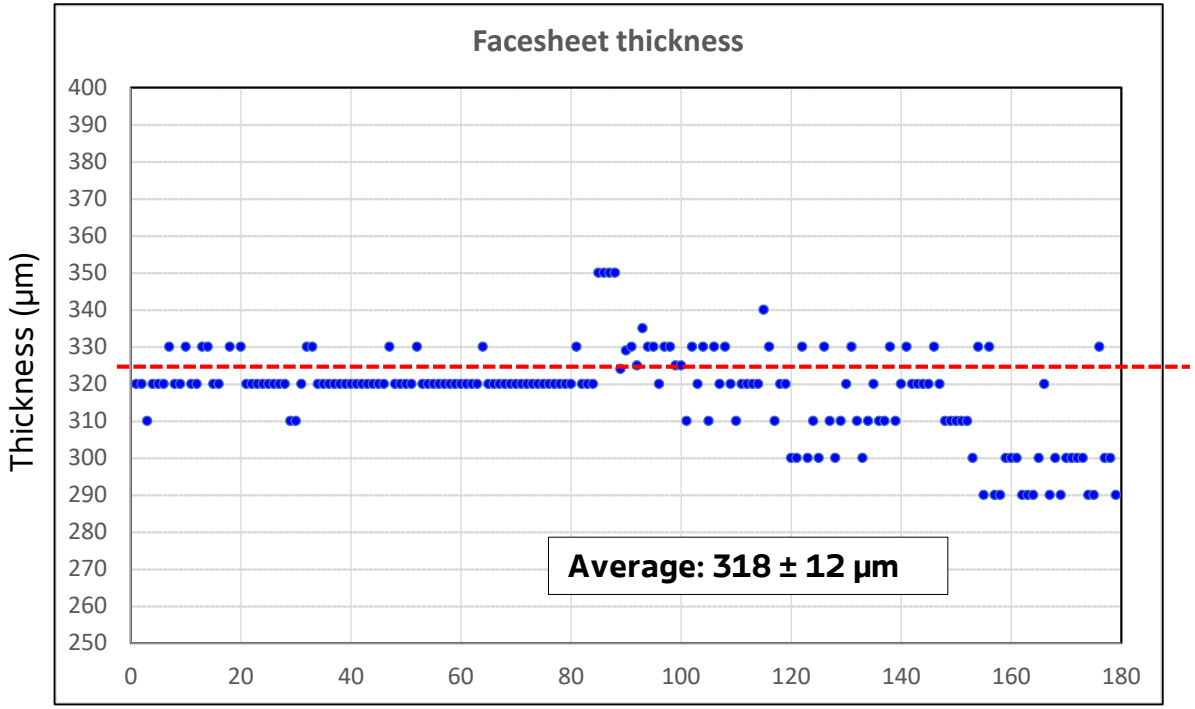
"Overexposed" top metal pads – before skyving re-tuning

top metal pads after skyving re-tuning

Results (I)

Weight and thickness





Back tape mass higher than front due to longer LV(ret) copper lines

Excellent reproducibility

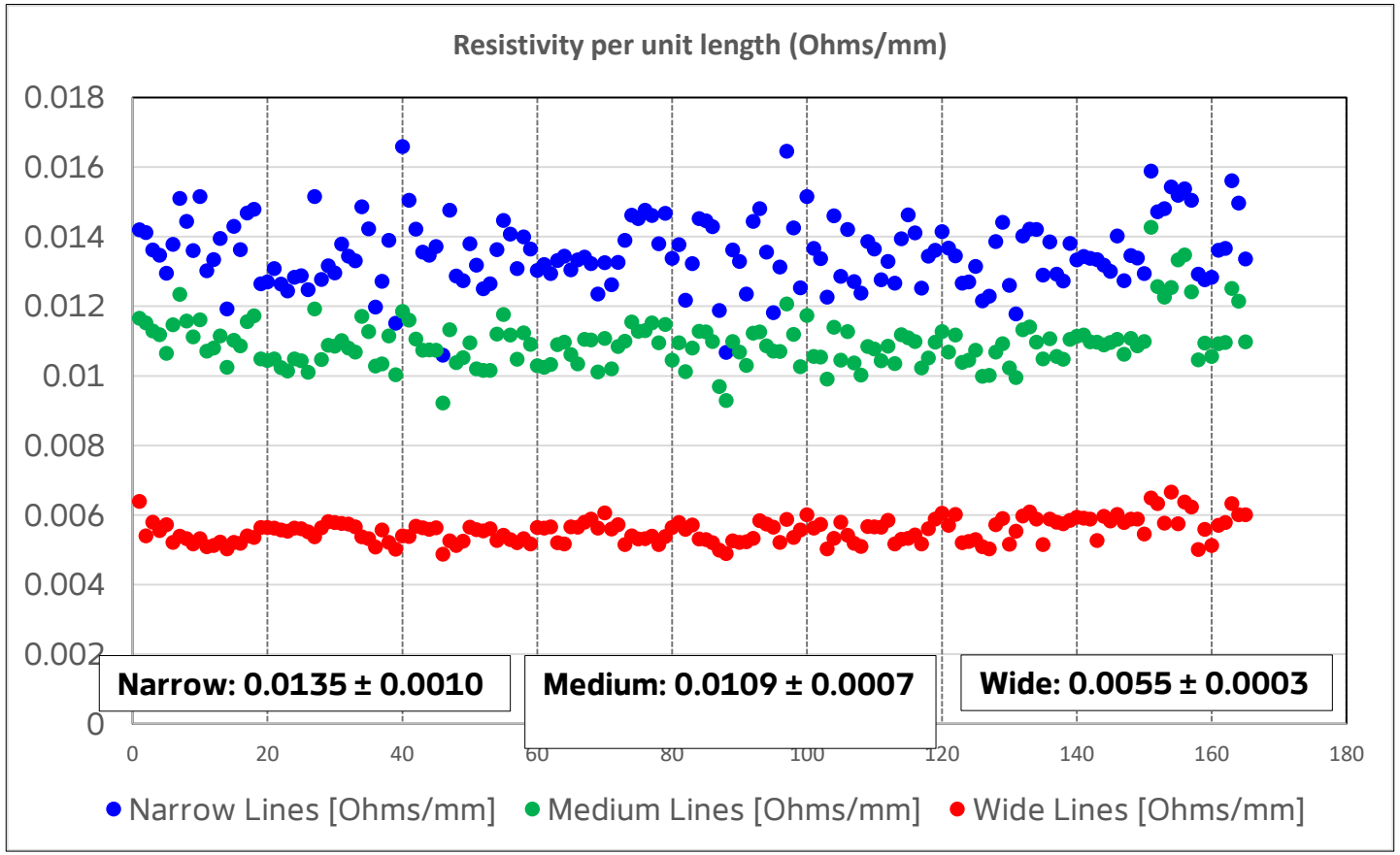
Mass variations follow pre-preg roll variations (5 rolls used in total)

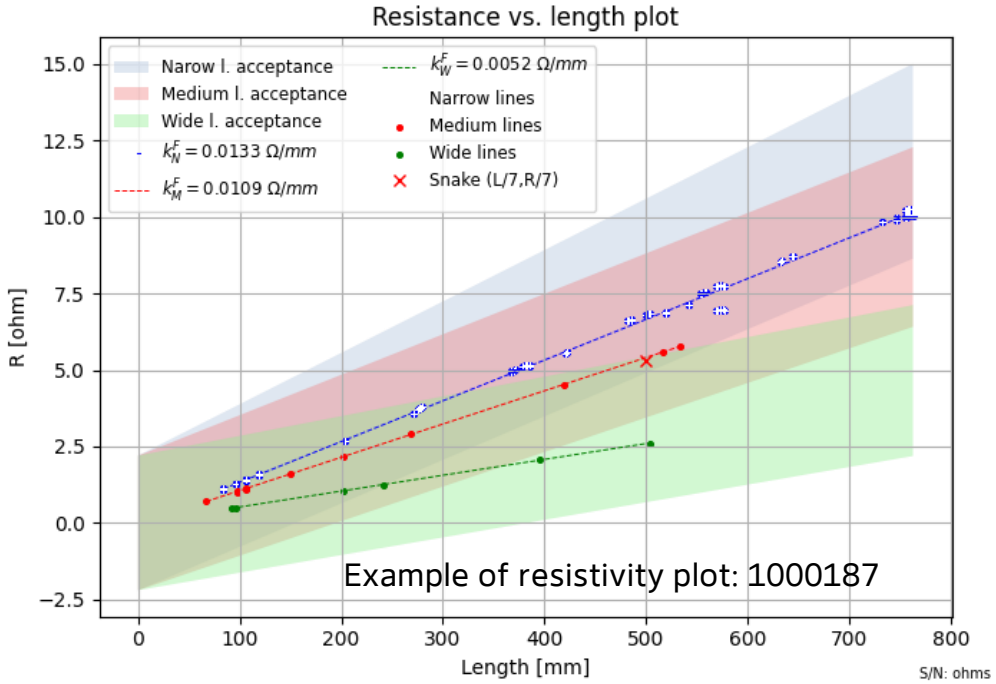
Thickness measurement not very reliable

Highly operator dependent

Results (II)

Resistivity measurements





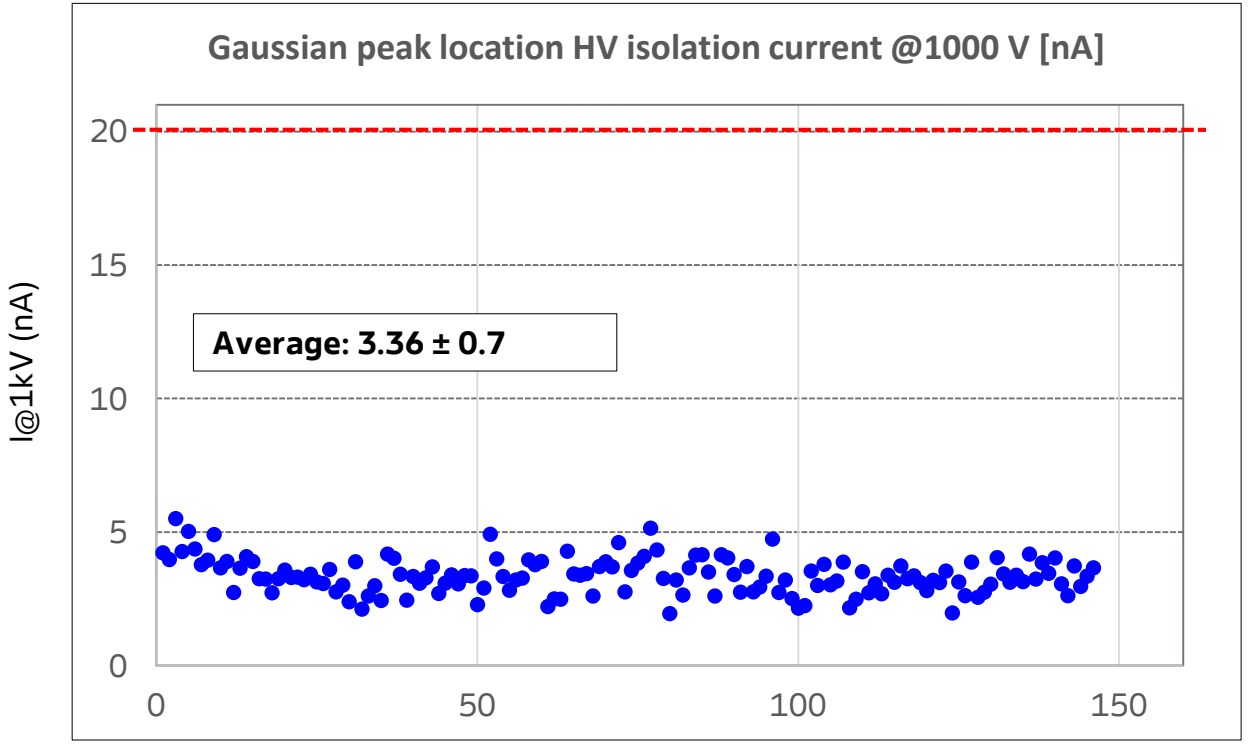
Very homogeneous results among tapes

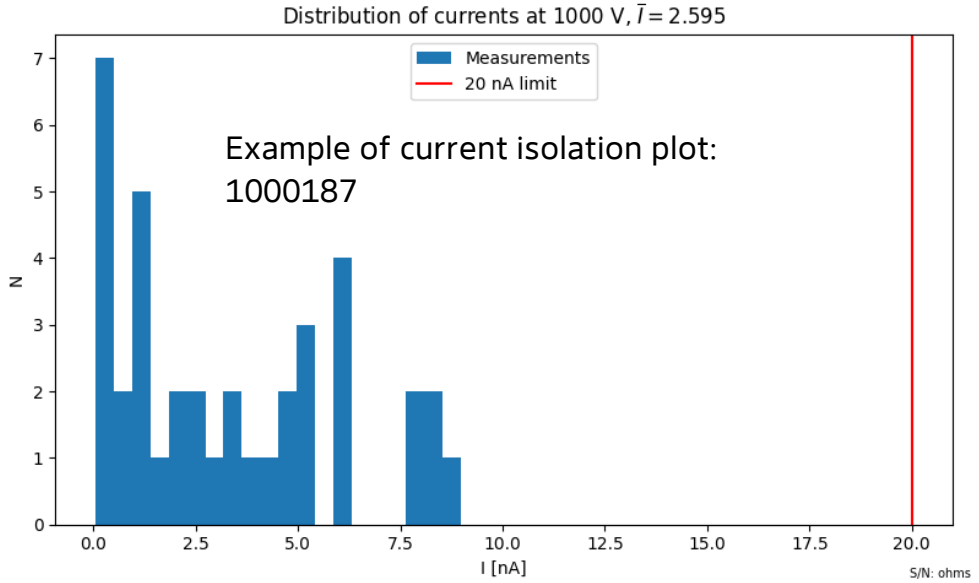
Some false "fails" due to bad contact or slightly misaligned probes

- ❖ Retesting is sometimes necessary

Results (III)

HV isolation at 1000 V





Well within specs

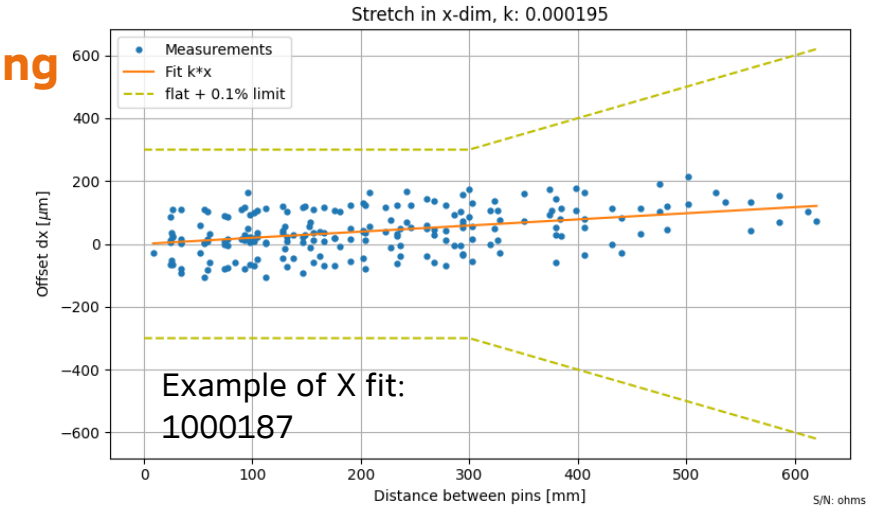
0 failures

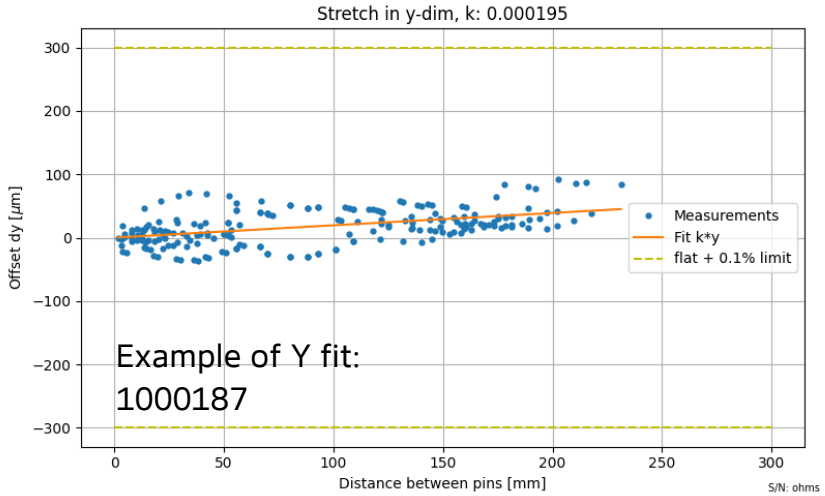
Some false "fails" due to bad contact or slightly misaligned probes

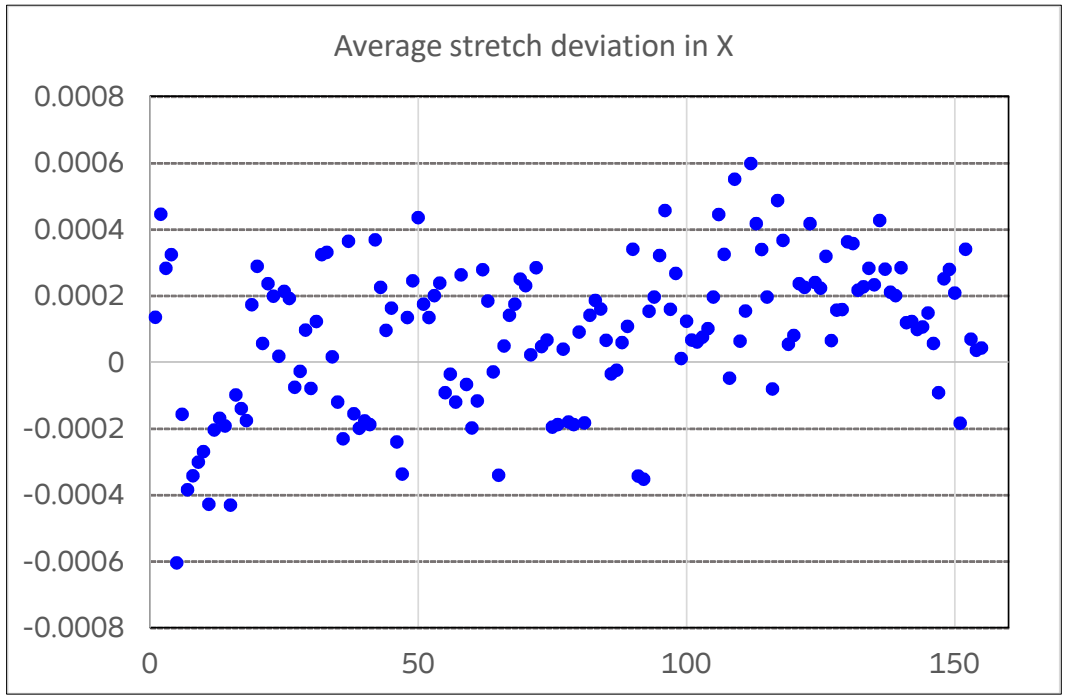
❖ Retesting is sometimes necessary

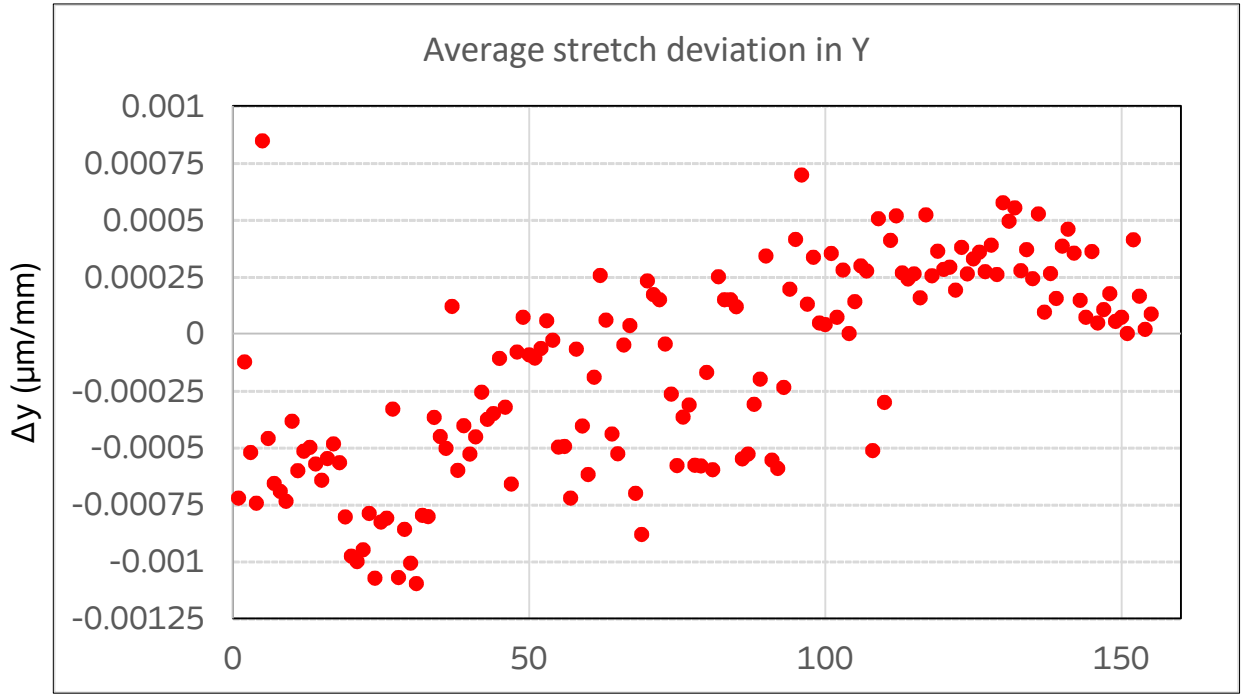
Results (III)

Stretch after co-curing



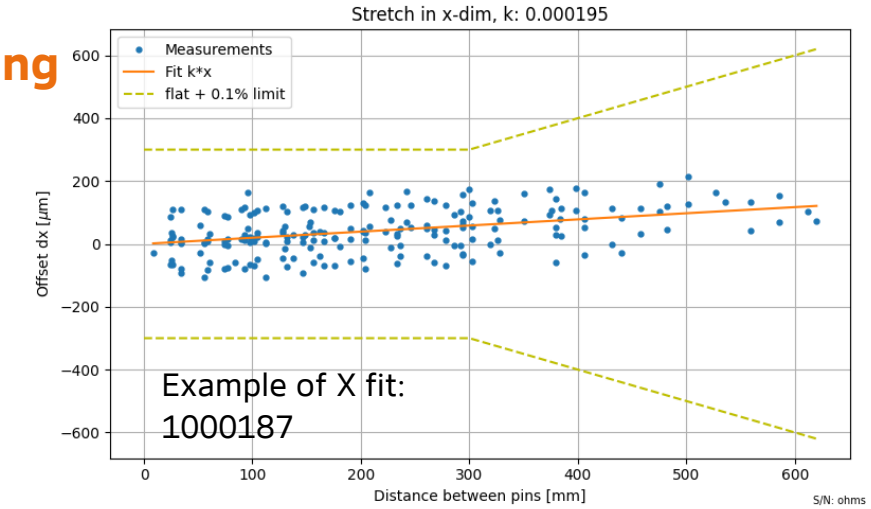


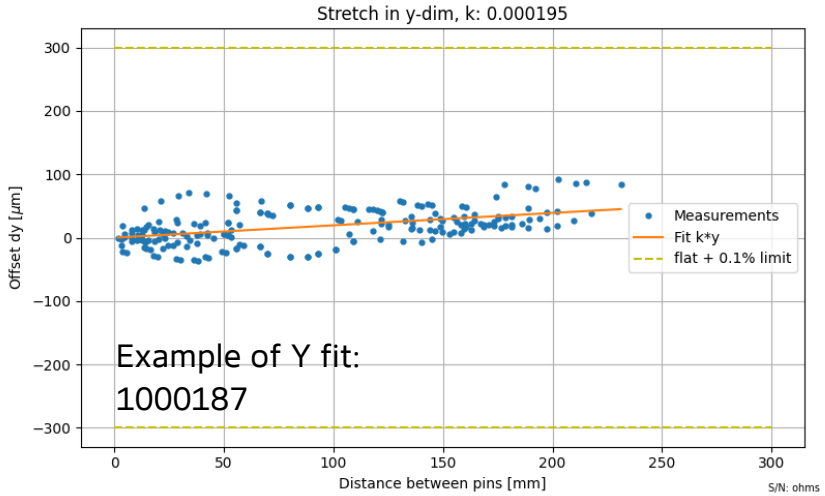


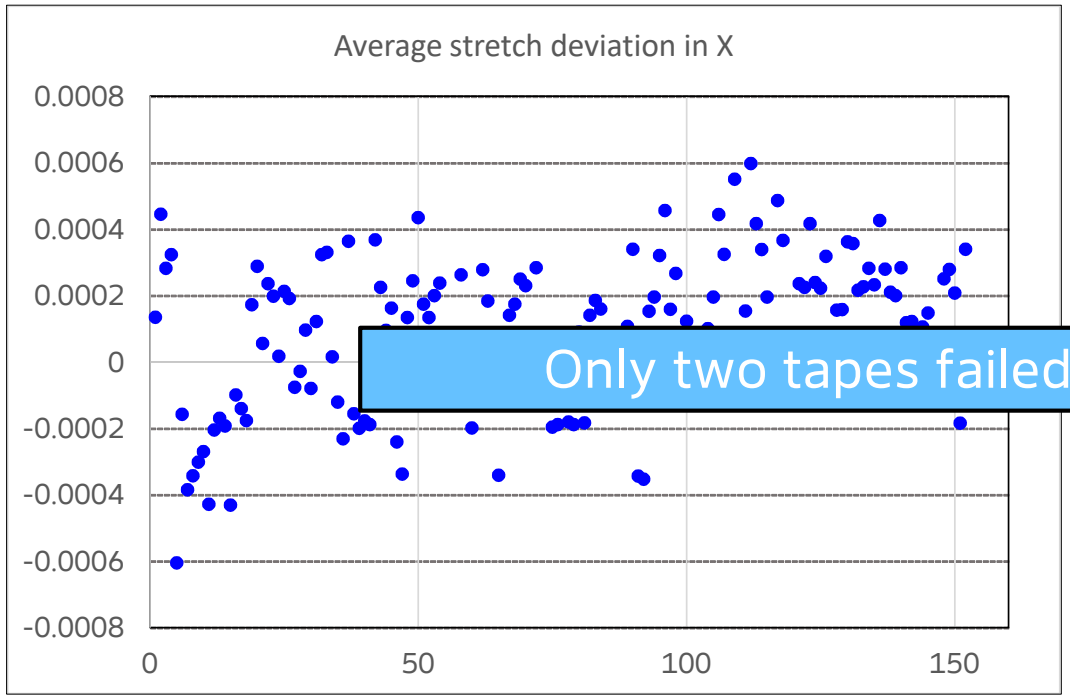


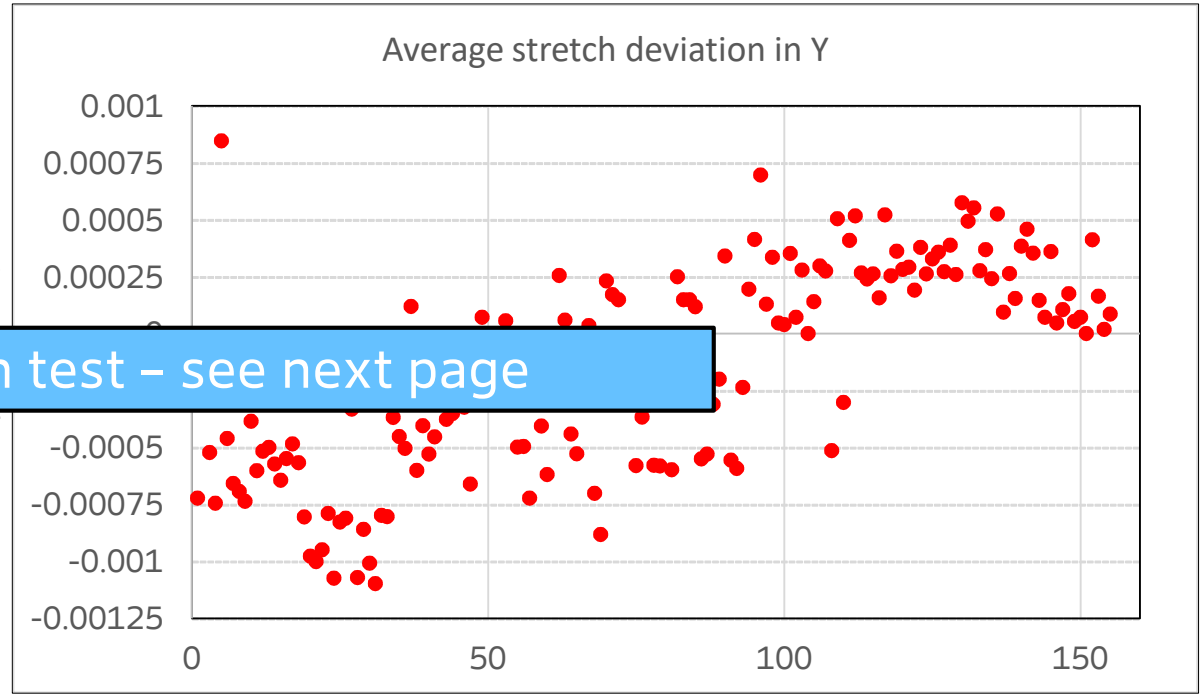
Results (III)

Stretch after co-curing





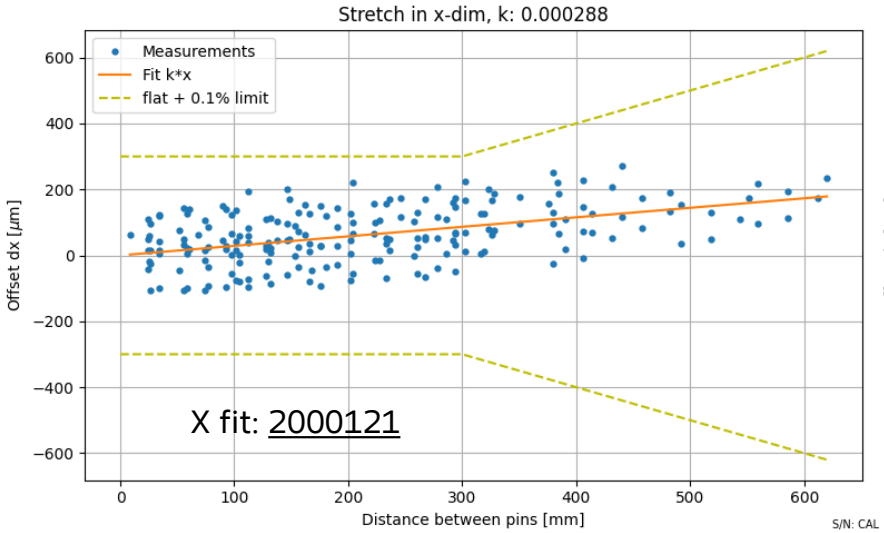


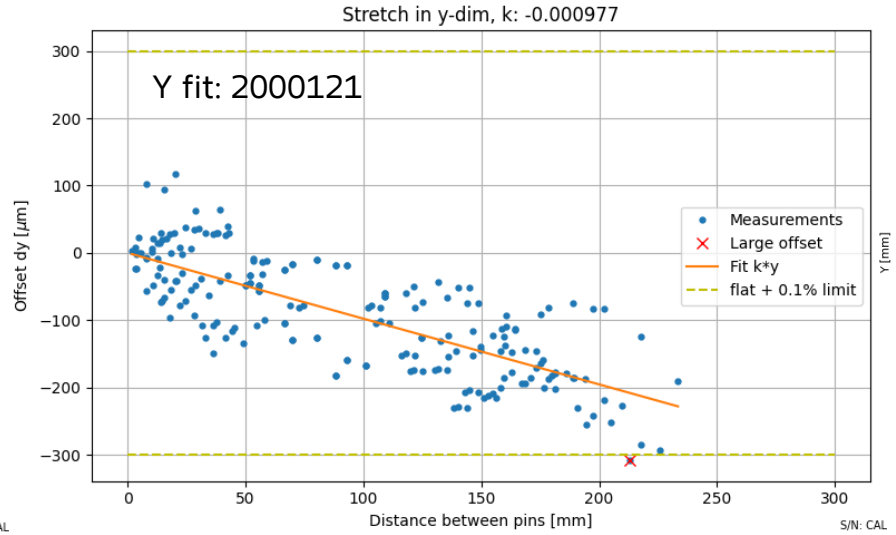


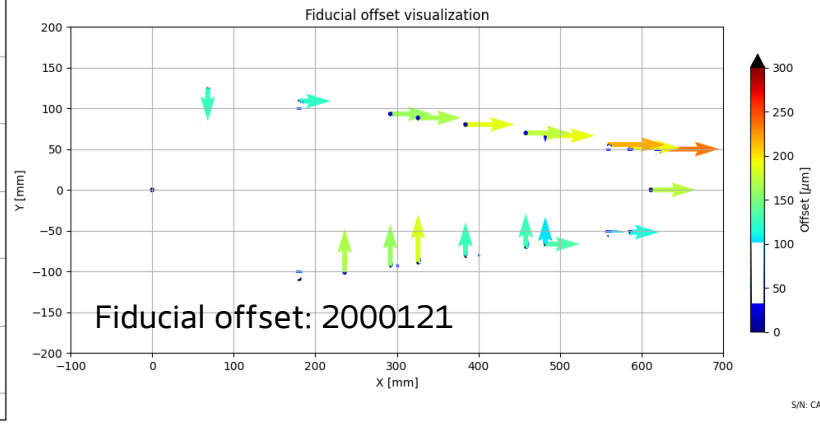
Only two tapes failed stretch test – see next page

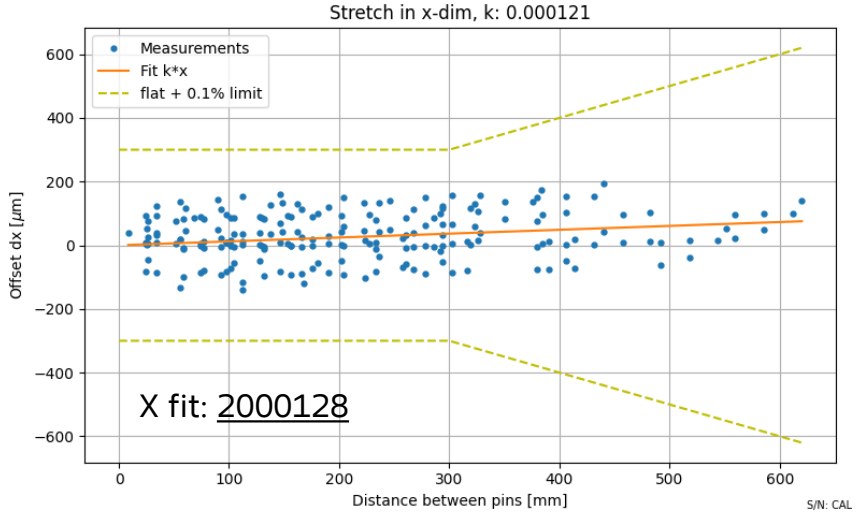
Results (IV)

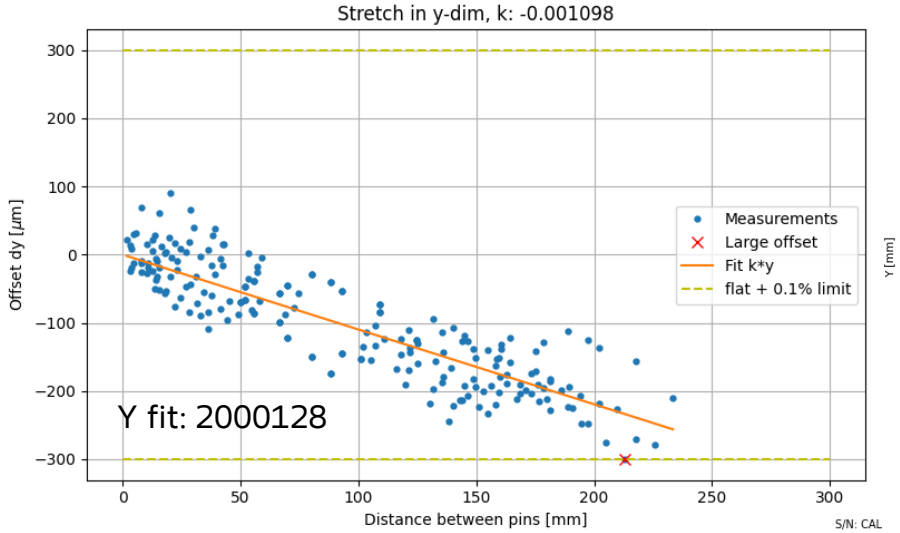
Stretch after co-curing – 2 tapes “failed” stretch tests

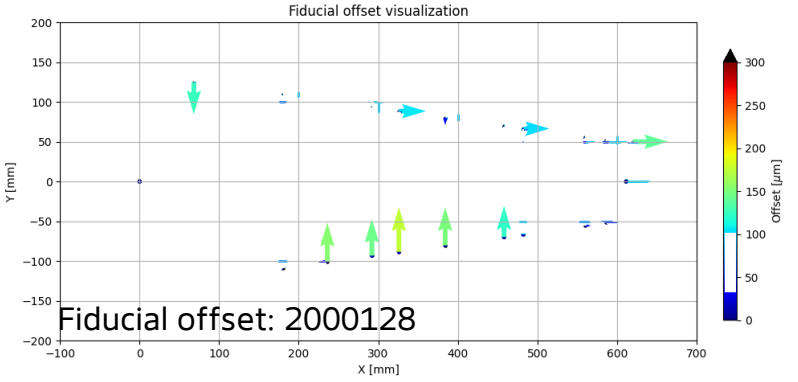












Wire bonding

Testing of coupons

AVS requested **to NOT cut the bonding coupons** from the sacrificial region

- They will provide traced cut coupons prior to assembly + post assembly
- The plan is to perform sample bond pull testing "on core" coupons and retain "co-cured" coupons for additional tests if needed
- Expect to inspect all "co-cured" and "on-core" coupons for the first months of core production
- Bond pull testing of the worse case has happened, easily within specs, no problems observed
- NO evidence of bad quality surfaces for bonding on tapes/cores since PPB started (AVS cores)

Database implementation

BTTR and QC results

Three stages for bus tapes: “bare”, “co-cured”, “on-core”

Fully automated scripts for upload of all QC steps

Script for VI, weight, thickness + Script for Bus tape testing robot tests