Local supports for the ATLAS ITk Barrel Strip Tracker

Graham Beck (QMUL)
for the ITk Barrel Strips community

ATLAS Tracker Upgrade for Phase II (~2025)

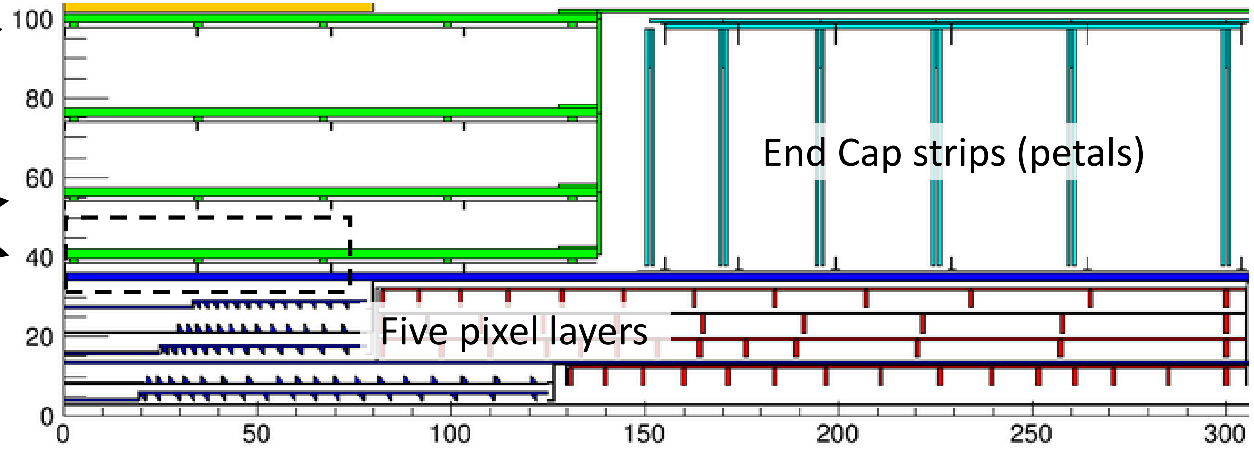
- driven by High Luminosity LHC conditions:
  - ~ 200 events/bunch crossing => need increased sensor granularity
  - ~ 10× integrated luminosity (fluence) => need a more rad.hard detector

=> Completely new, all-silicon tracker (TRT straw tubes replaced).

Major scaling up (similar size to CMS tracker).

4 Double-Sided Strip Barrels (this talk), 2.8m total length

Strips 75.5 μm pitch, +/- 26 mrad stereo



Long (48mm) Strips

R [cm]

Short (24mm) Strips

(dashed: present
barrel strips volume)

End Cap strips (petals)

Five pixel layers

Tracker Quadrant

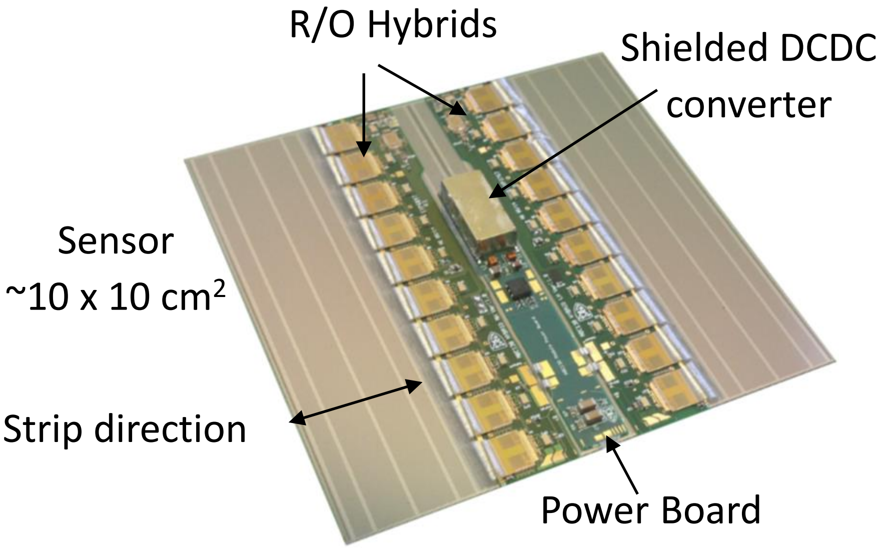
Z [cm]

+ replacing TRT with strips improves momentum precision.

+ aim to reduce tracker material (multiple scattering, X0s before calorimeter..)

Silicon Module: Sensor with Readout and Power pcbs glued directly to it (low mass):

~ 11,000 modules are needed to cover the 4 barrels.

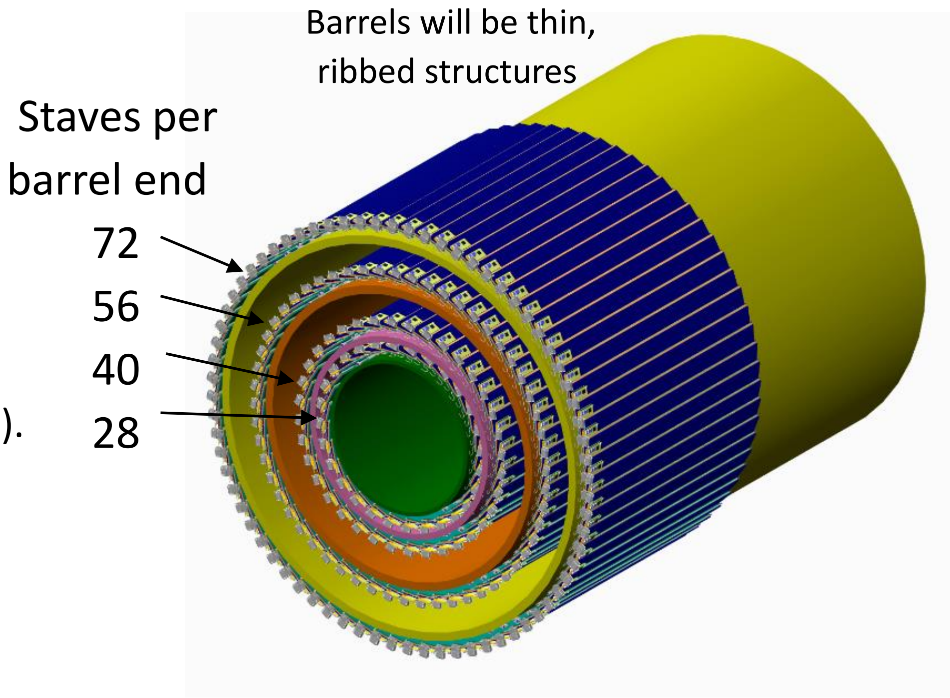


Global (large scale) Support: 4 low mass CFRP barrels.

Local Support is a Stave

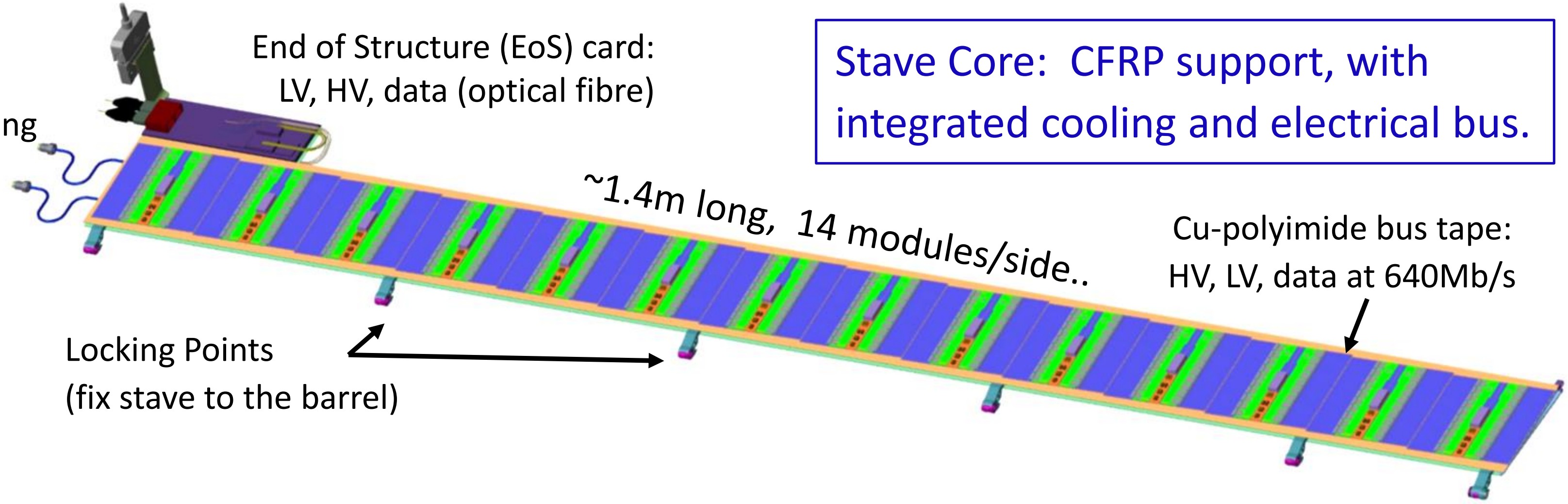
- low mass core, 14 modules on each face.
- half barrel length, end-insertable, fixed to barrel at discrete “locking points” (tilted ~10° to allow overlap in ϕ).
- parallel production+test at several sites (UK, USA).
- integration onto the barrels at CERN.

~400 staves needed.



Total Readout power ≈ 44kW. Cooling by evaporative CO_2 at -30C (nominal).

Stave Core: CFRP support, with integrated cooling and electrical bus.



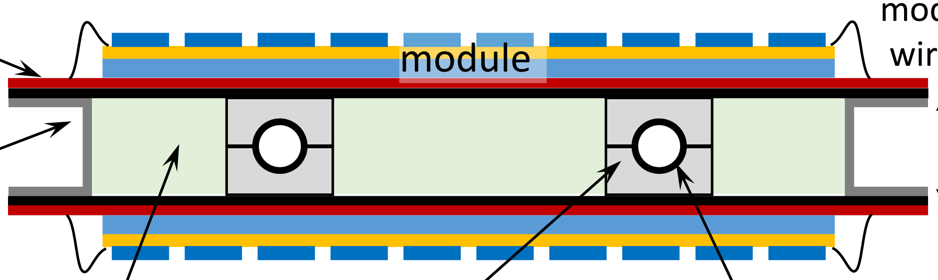
End of Structure (EoS) card:
LV, HV, data (optical fibre)

CO_2 cooling loop

~1.4m long, 14 modules/side..

Cu-polyimide bus tape:
HV, LV, data at 640Mb/s

Locking Points
(fix stave to the barrel)



Bus Tape

CFRP Facesheet

C-channel closeout

module/tape wire-bonds

~5mm

Carbon Fibre Honeycomb

High Thermal K Foam

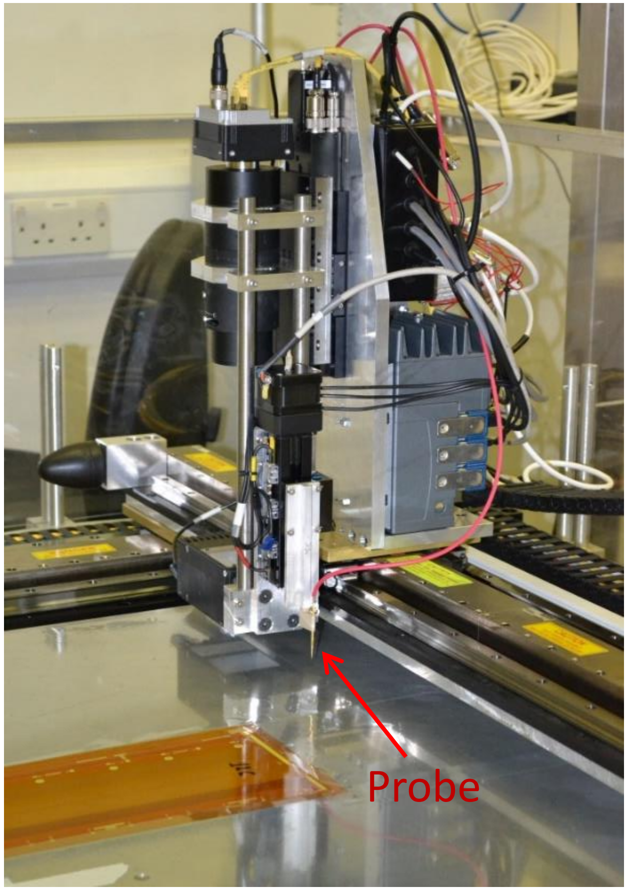
Titanium Cooling Tube
2mm id. (CP3)

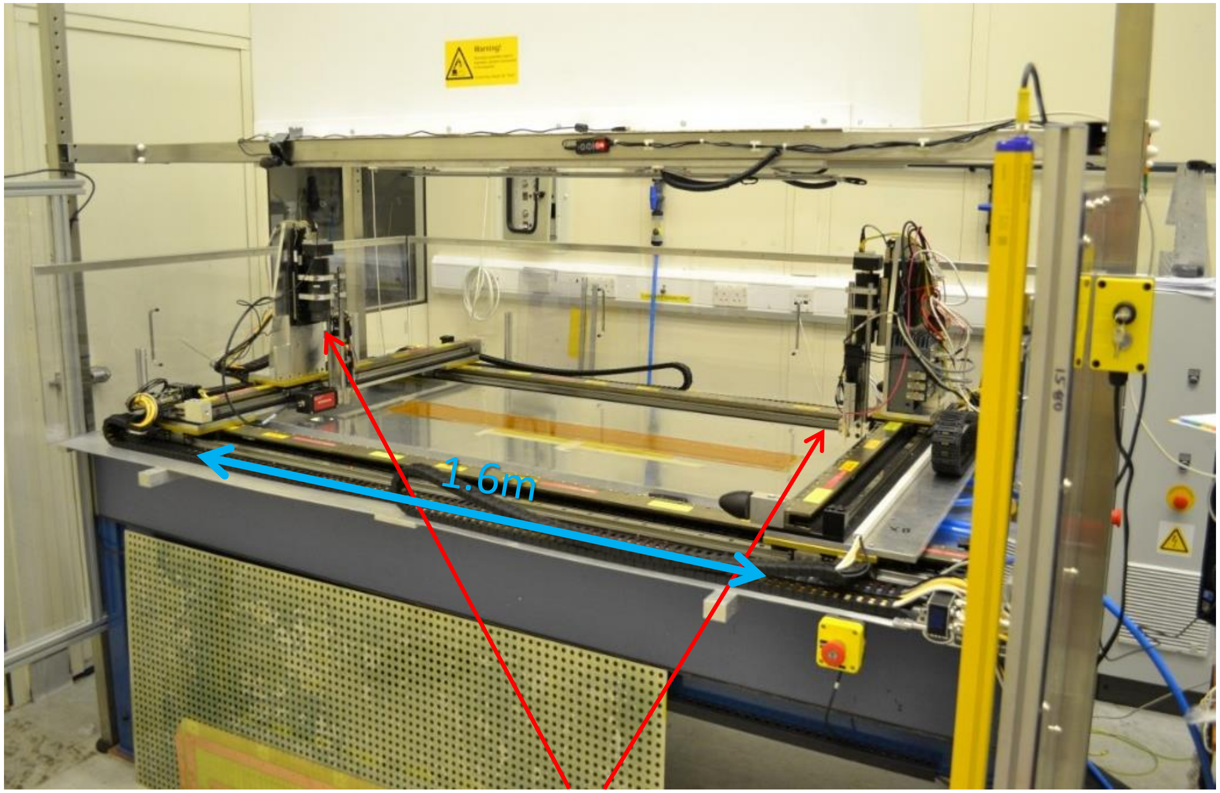
- Vertically symmetric structure minimises thermal deformations.
- Cooling pipes located at ± 1/4 module width to minimise ΔT
- CFRP (mechanical stiffness): Facesheet - 0/90/0 K13C2U, 45g/m^2 + EX1515 cyanate ester Resin.
  Honeycomb - Ultracore Carbon UCF-126-3/8-2.0
- High Thermal K Foam: Allcomp K9 (Graphitised RVC, ~ 0.2g/cm^2, ≥ 30W/mK)
- All-glue assembly using precision jigs (minimal precision parts). Hysol 9396 with graphite powder as filler - aids electrical grounding. *(see e.g. Eric Anderssen talk at 2015 Forum).*

Stave Core Assembly: sub-assemblies.

(More details in 2014 Tracker Forum talks by Peter Sutcliffe and Roy Wastie https://indico.cern.ch/event/287285)

Copper-Polyimide Bus Tape: provides all electrical connections between the EoS and modules. Oxford “Tape Robot” measures trace conductance - checks for shorts - measures HV isolation resistance:





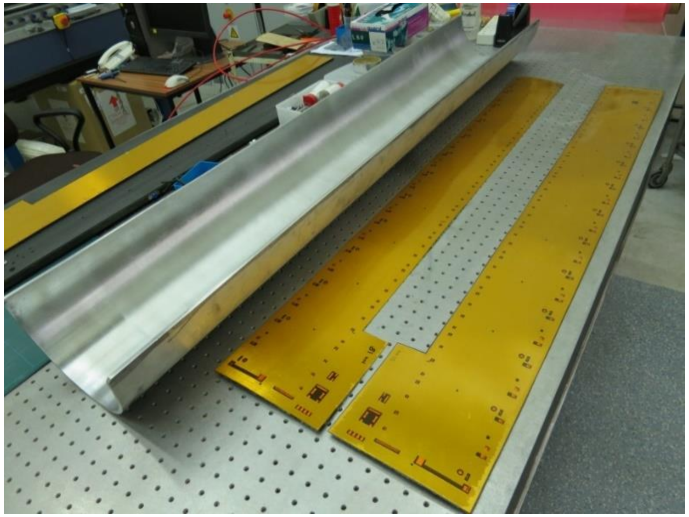
Two independent probe heads + alignment cameras. Many 100s of measurements per tape, <1 hour.

Tapes tested before + after facesheet curing and at end of core assembly….

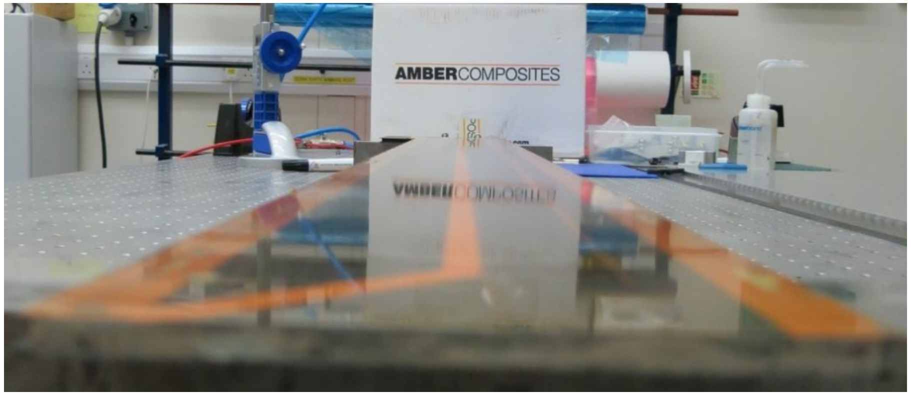
Facesheets:

- formed from CFRP pre-preg (0/90/0) , co-cured with the bus tape (7bar, 120C).
- the tape design allows for a ~0.5mm elongation during this step.

Curved mould compensates for differential CTE
=> tape is flat when cooled to RT.



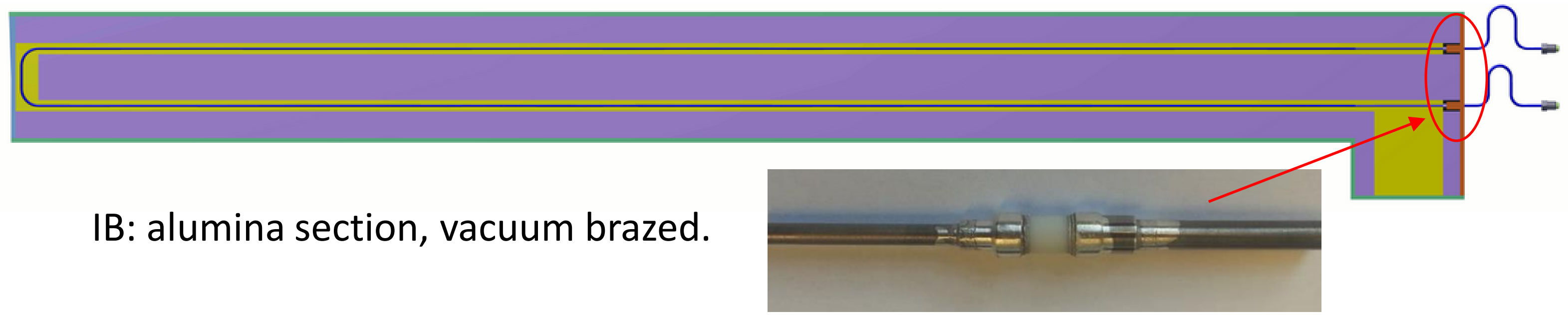
=> Mirror finish (during co-curing and assembly the tape surface is protected by a plastic film)



Cooling Tube: Major length bent to form the "U-bend" (geometry better than 0.3mm on radii)

- must make good thermal contact with the surrounding foam (yellow).

Ends (orbital welded): Insulating Breaks (IB) + stress relief wiggle + temporary connector for testing.



IB: alumina section, vacuum brazed.

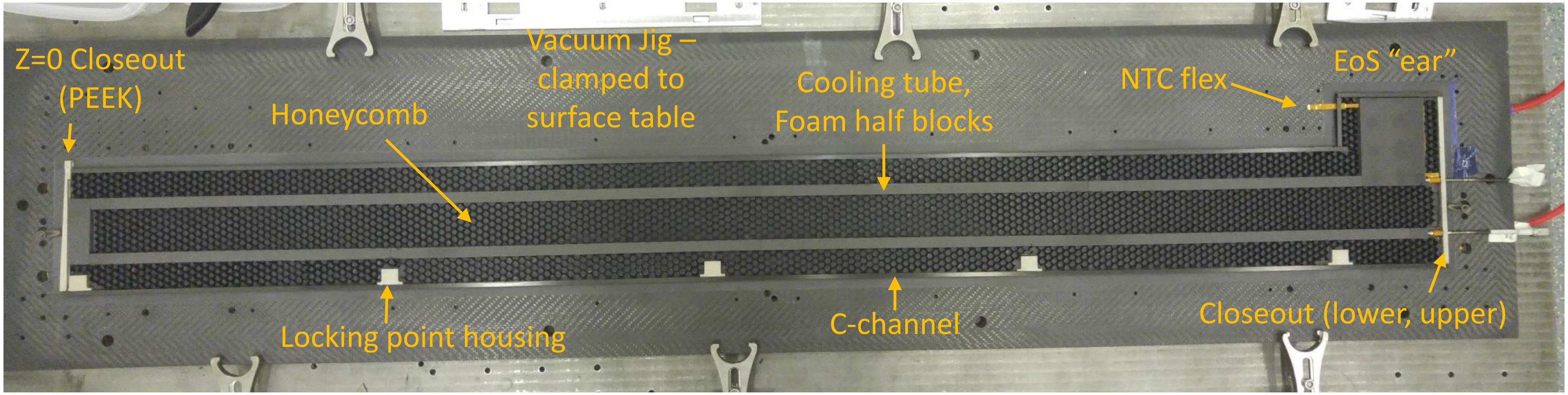
Core Assembly: needs only ~ 100 micron precision, to enable later assembly steps.

(cf track reconstruction achieved by track-based alignment + stable geometry).

Starting with a Facesheet (initially oversize, with dowel holes at ends) the core is built up using positioning jigs and Hysol 9396 epoxy.

Glue Steps (followed by overnight curing):

1. *Lower half foam blocks (channel for tube), end closeouts.*
2. *Cooling tube (+ NTCs), upper half foam, end closeout*

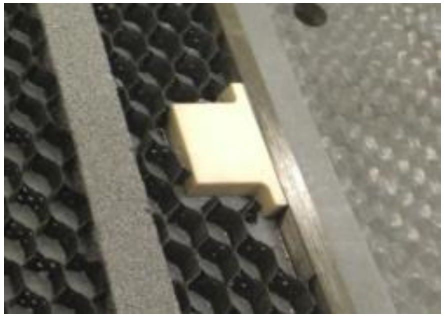


3. *C-channel side close-outs*
4. *Honeycomb core in-fill, locking point housings, Z=0 support*

   Assembly (as in photo) is now milled to design thickness.
5. *Upper facesheet added. Long edges trimmed.*
6. *Locking points glued into housings. Final trim of face sheet.*

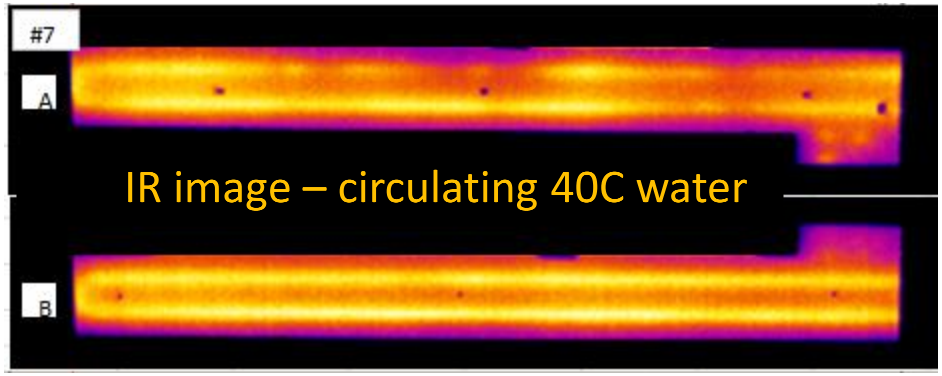
Overall, assembly time is ~ two weeks. Envisage two builds in parallel (per institute).

Design, tooling and assembly procedure have evolved. Two examples:



Locking point housings added, to reinforce the core at support locations.

An early mod. to the jig for the first set of foam blocks was needed - evident here from the IR image of side A.

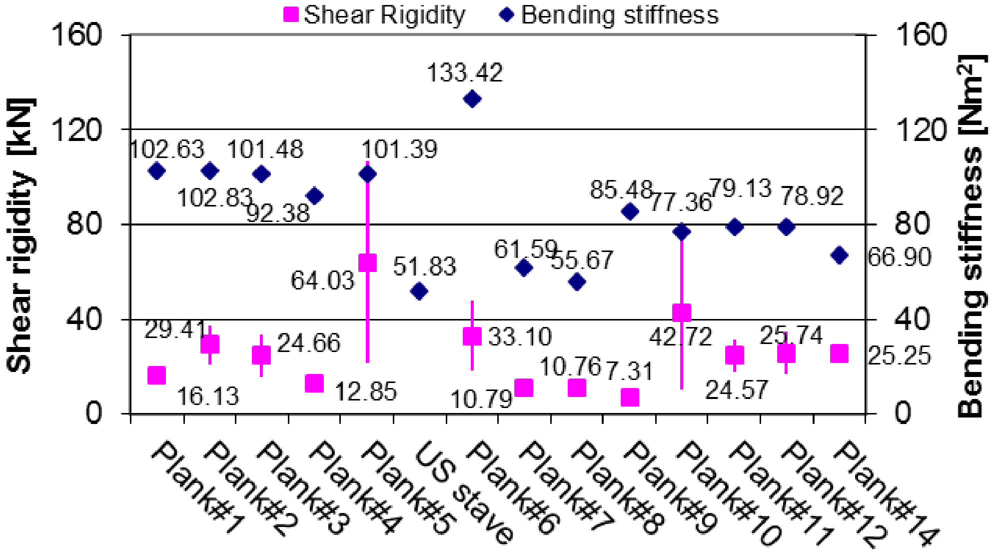


IR image – circulating 40C water

Routine Quality tests include:

- *Measuring Core Weight at assembly stages, to monitor glue usage.*
- *IR imaging*
- *Thermal cycling to -40C.*
- *CMM survey to check flatness*
- *Three point bend test of stiffness.*

QC/QA is currently being developed – need to converge on this!



A qualified Stave Core is loaded into a precision aluminium frame for module mounting – at RAL (UK), BNL (USA).

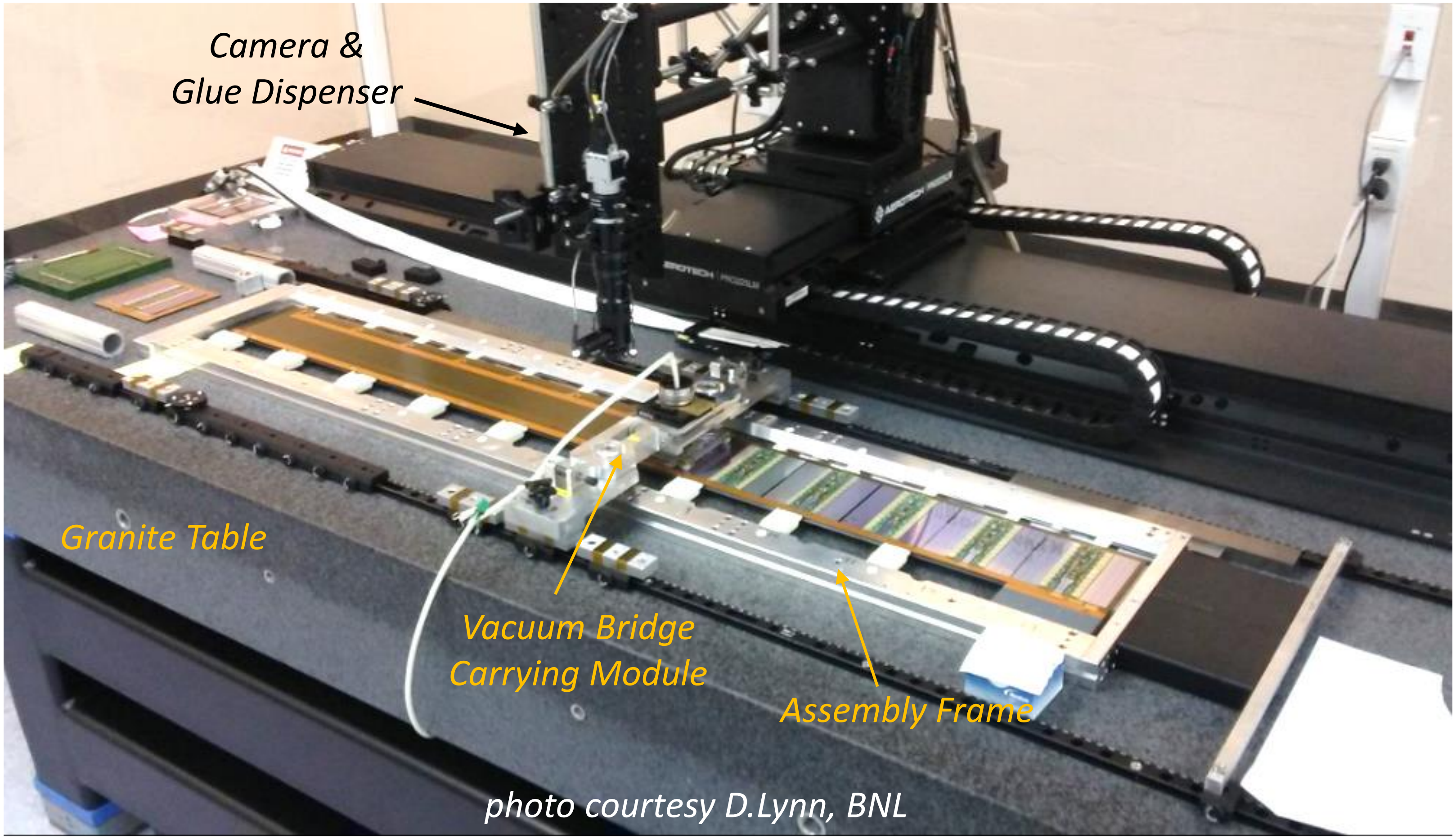
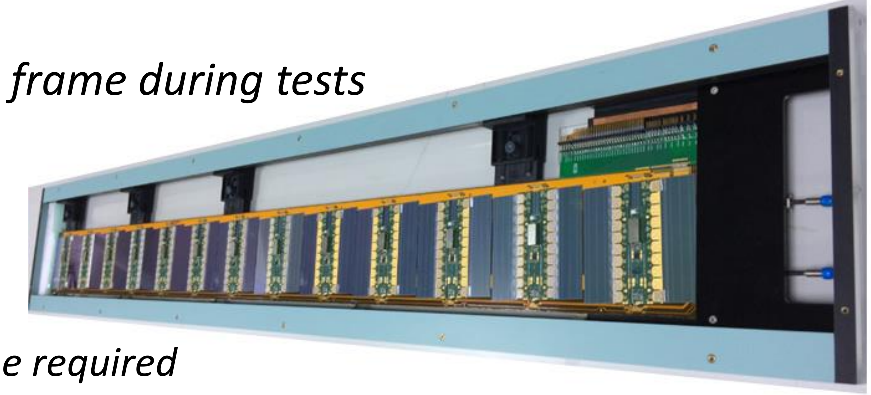


photo courtesy D.Lynn, BNL

Module on bridge is dry-aligned => parked at end while glue (Dow Corning SE4445) dispensed.
Bridge + module replaced and finely aligned (on sensor marks) – allowed to cure.
(BNL) 32 mins /module => expect production rate 2.5 staves/week.
Full geometry survey (input to tracking alignment) …. modules wire-bonded to bus tape.

After completion, the stave stays in a transport frame during tests and shipping, up to insertion into the barrel.

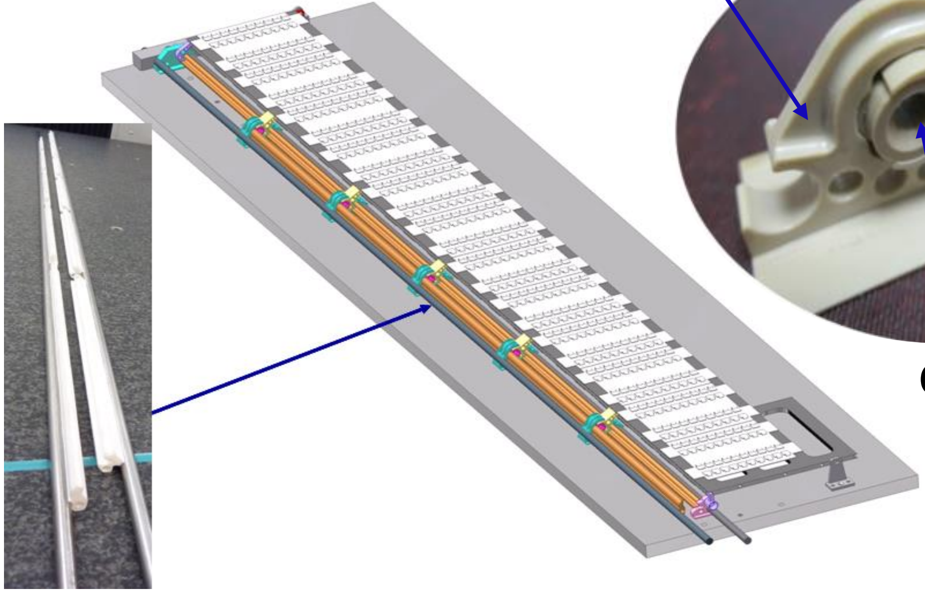
(photo shows UK TM prototype)



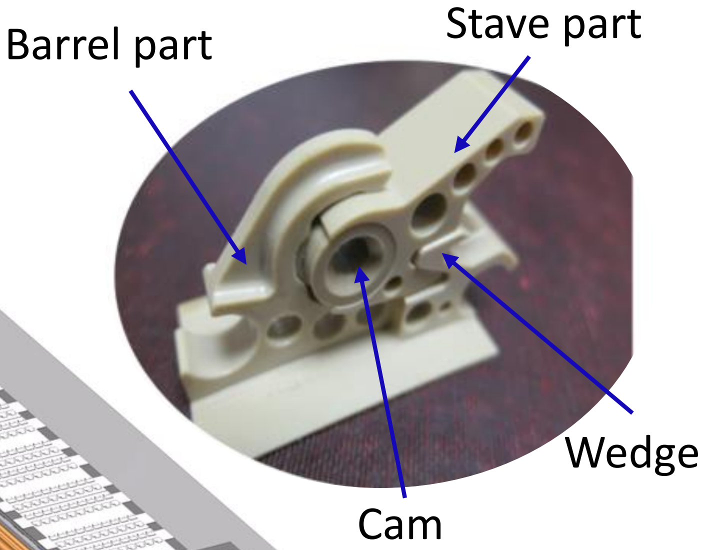
Stave Insertion onto Barrel:

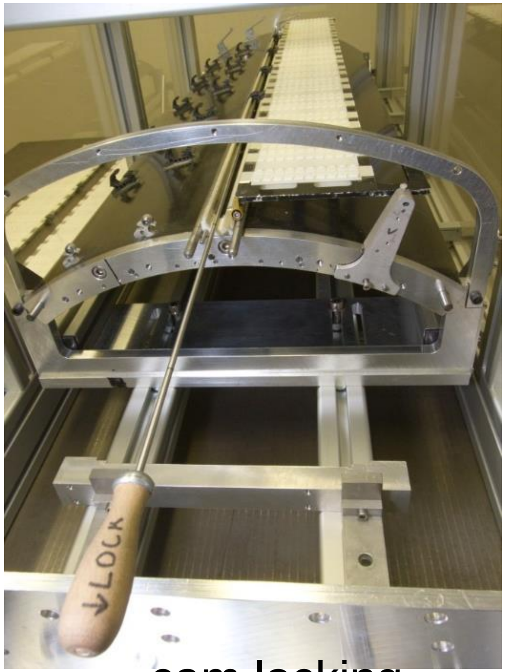
An insertion frame is attached to the barrel end at the required azimuthal position, to support and align the transport frame.

Rails are inserted through the barrel part of the locking fixtures, to form a continuous guide:



The stave is slid into position and the cam rotated to mate the wedge-shaped surfaces:

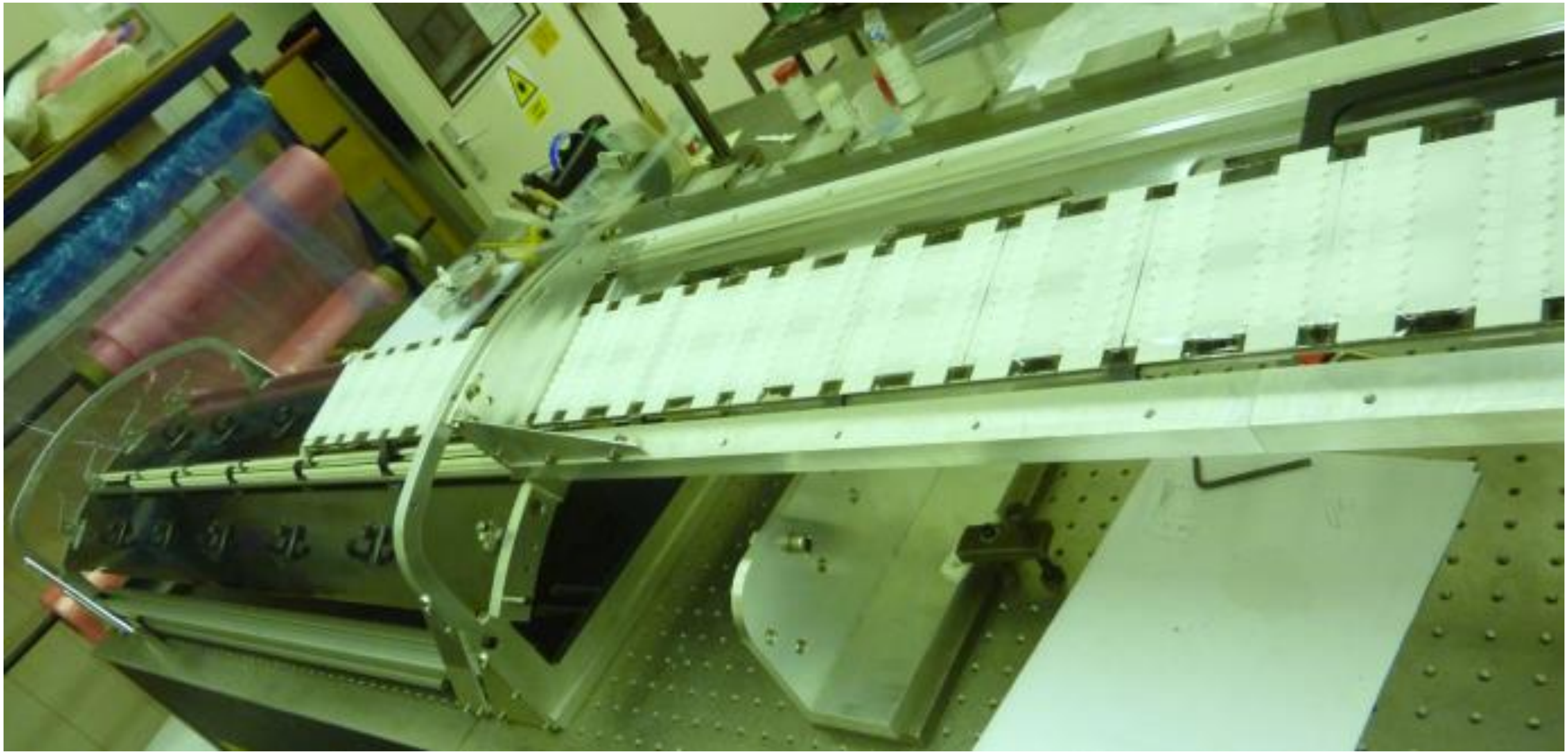




cam locking

** All of the rail structure is then removed **

Prototype insertion frame



- procedure has been demonstrated to work at all angles!

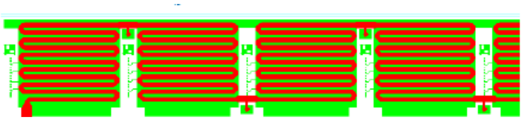
UK Thermo-Mechanical (TM) Stave

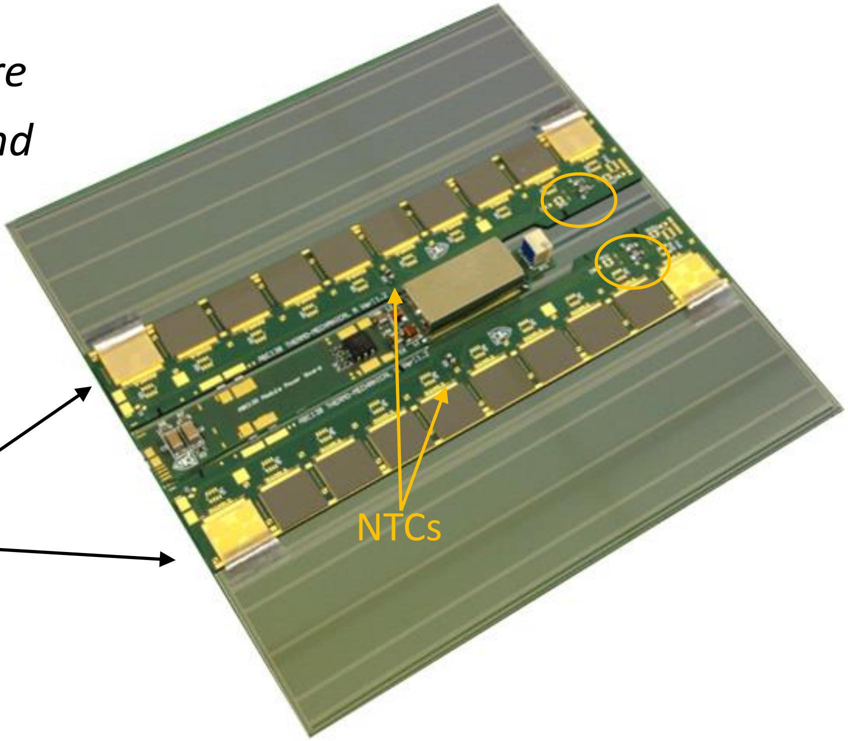
A prototype (2 x 13 modules) that exercises most of the assembly processes (core, modules, module mounting) + QC/QA. Involves many UK institutes:
RAL - Oxford - Liverpool - Glasgow - Warwick - Sheffield - Cambridge – Birmingham – Lancaster – QMUL.
(A similar programme, building on UK experience, is under way in the USA).

Consists of a stave core equipped with a full complement of TM modules:

To avoid wasting valuable wafers/chips these are built from 'mechanical' sensors (no implants) and dummy readout chips . . .

TM hybrids are designed with copper meanders to emulate power dissipated by the chips (SM resistors for HCC chips):

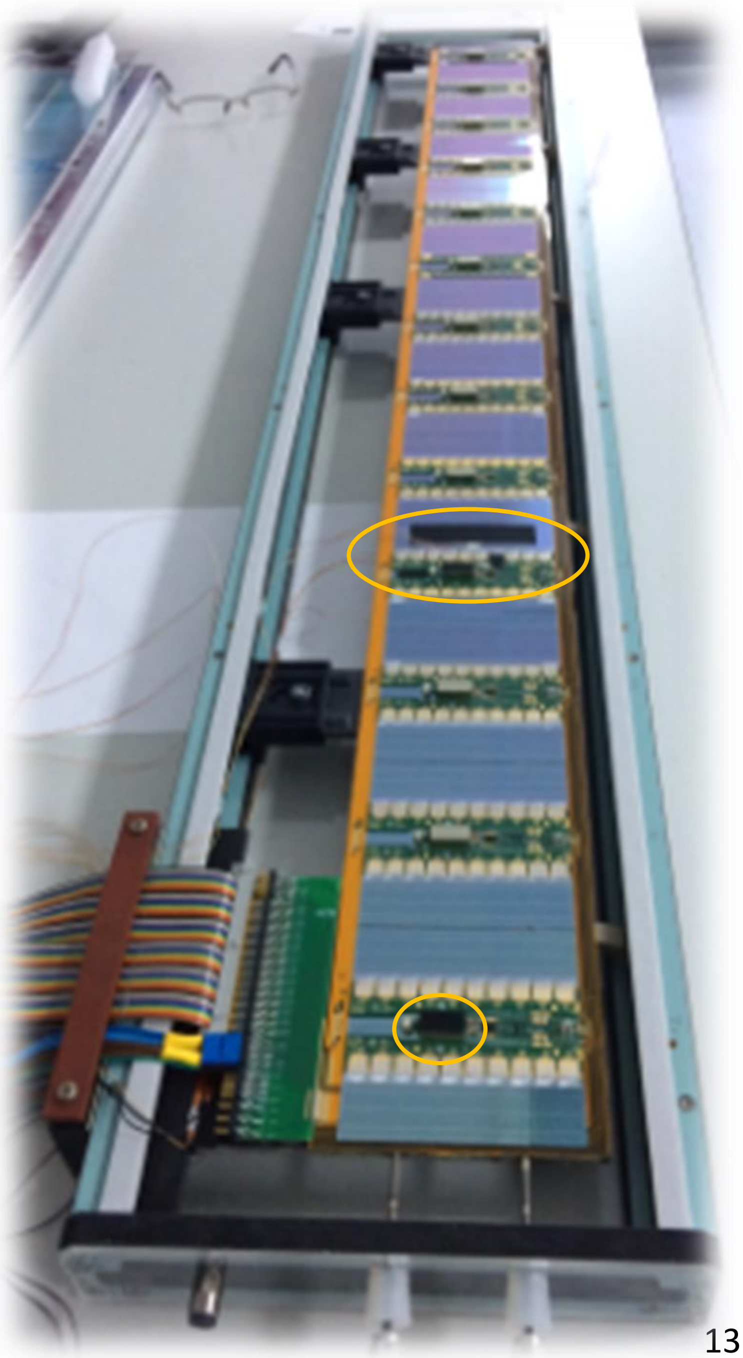




Hybrids are powered by a prototype power pcb, complete with DCDC converter.

TM Stave thermal performance test

- LV power (11V, 6.5A/side) and readout (52 NTCs) routed via pcb attached at EoS.
- Added: EoS heaters, a few thermocouples + patches of black tape for IR emissivity (IR imaging is an increasingly valuable tool…)
- Test Enclosure: uses aluminium mirrors to image full length, both faces simultaneously. (b/u slide)



To date: Test at Room Temperature (least effort × highest accuracy?):

Chilled water pumped round the cooling tube. (high/reliably known fluid htc) …

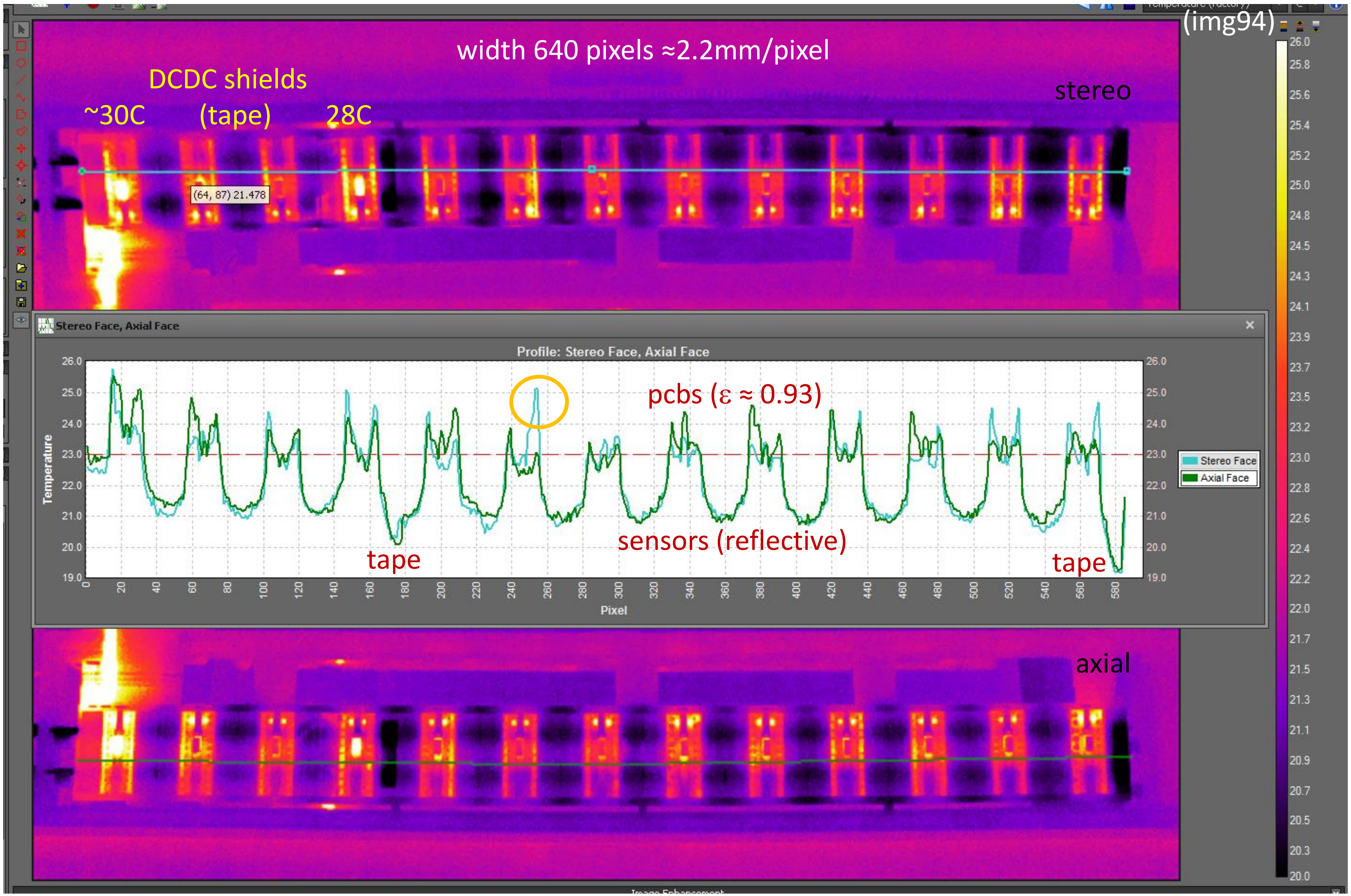
… temperature adjusted to have stave surface close to RT, to minimise ambient heat exchange.

+ stay above dew point (no need to flush dry air)

+ T measurements most reliable near RT.

IR Image A655sc (2mm/pixel)   Stave Power ~140W (EoS heaters off);   Chiller +15C, Ambient 22C.

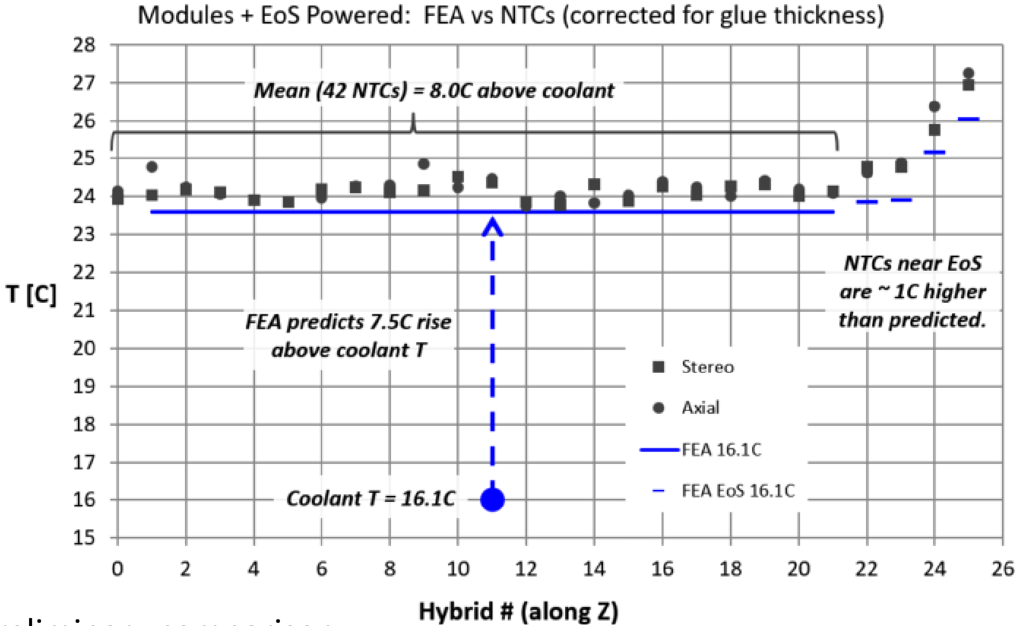
module: 12 11 10 9 8 7 6 5 4 3 2 1 0

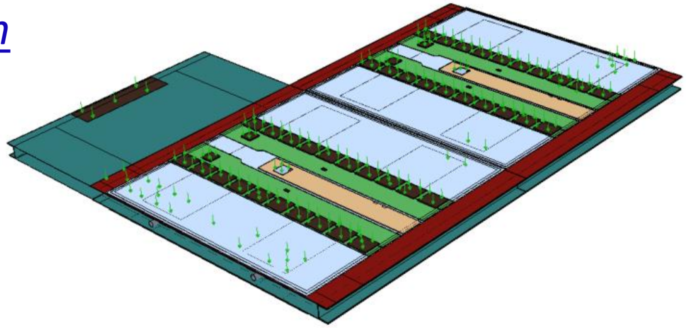


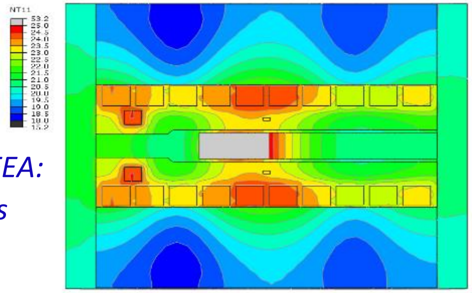
- *~2C hybrid rise at EoS is <u>expected</u> (insulating breaks + LV bus heat).*
- *LV leads / connectors / pcb are warm (inject some heat into EoS?)*
- *Ringed: hybrid with known 80μm out-of-spec glue (electrical module)*

T rise (above coolant) vs FEA prediction

Temperature is uniform over most of stave length, rising towards end (as expected). The two faces are very similar!

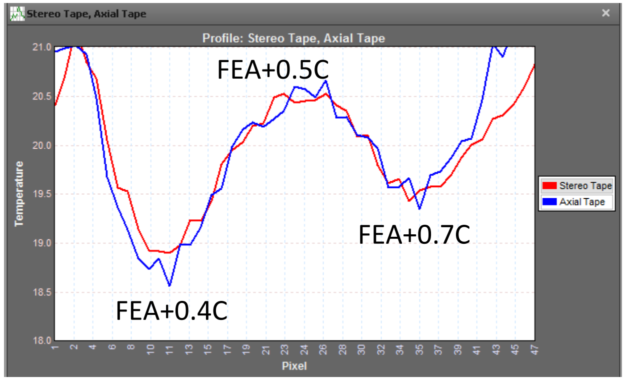






Mid-Z module FEA:
0.5C T bands

Sensor (tape): transverse IR Profile



Preliminary comparison:

(Expect ≤ ±0.5C error in measured T rise).

Over most of stave length hybrid T rise is 7 (±7)% higher than FEA prediction. End of stave appears slightly worse (10%) possibly due to external loading.

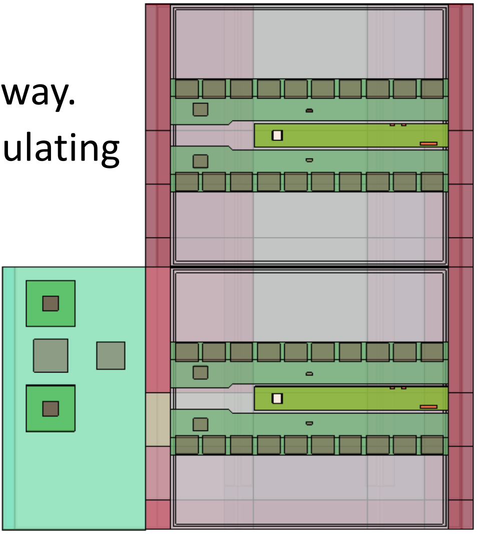
Effect of EoS card heating on EoS and modules is as expected.

(Note that the TM stave cannot emulate Sensor Heating).

If there *is* a discrepancy, is its origin single or cumulative? Thermal joint uncertainties? (foam-pipe still not satisfactorily explained). *How important to detector operation is a 10 or 20% increase in thermal R?*

Intend to measure at -30C with blow-off CO_2 (but expect a much less accurate measurement) … TM stave will then move to Oxford for thermal deformation tests.

Radiation damage and Thermal Performance.



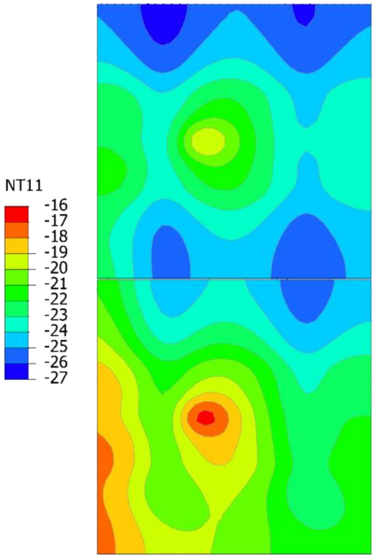
The major driver for thermal performance has been to avoid Thermal Runaway.
- most critical region is the Inner Barrel at End of Stave (highest fluence, insulating breaks, thermal load from EoS cards).

At end of life (here assuming 3000 fb^{-1}, fluence safety factor x1.5, 500V)
FEA predicts runaway if the CO_2 evaporation temperature hits -15C.
=> a comfortable margin if Tevap = -30C.

Using the analytic model* we can predict how this margin changes with increasing thermal resistance:

% R increase wrt nominal FEA	=>	Runaway Margin (C) wrt -30C
0		15.0
+10		13.2 <= cf TM stave, preliminary.
+20		11.6
+50		7.1

Sensor T at end of life (nominal FEA)



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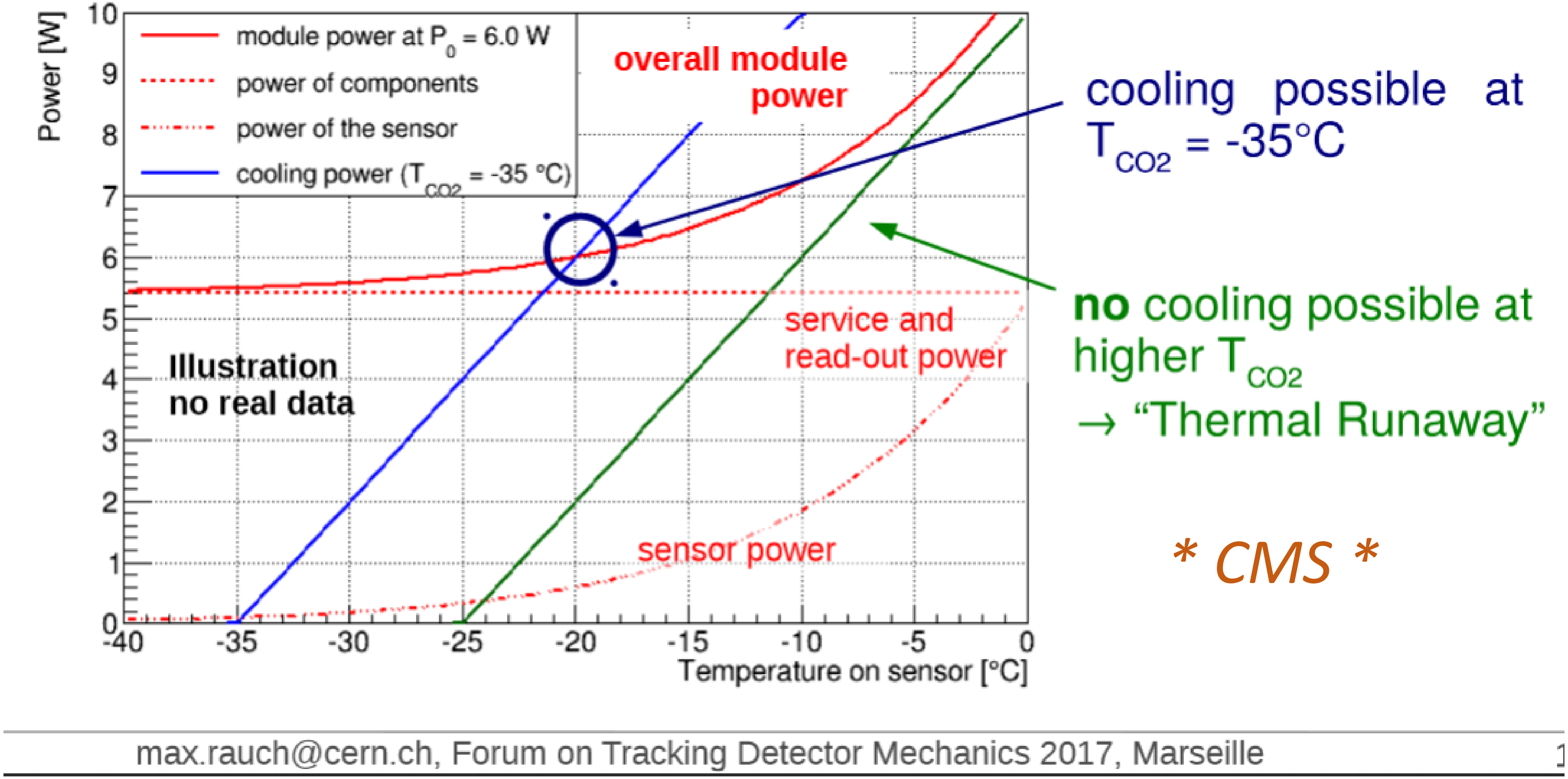
[*] [NIM A 618 (2010) 131–138]. The FEA increase in Sensor temperature can be fitted by TWO thermal parameters describing the effect of electronics and Sensor power, allowing an analytic prediction of runaway.

Very neat description of Thermal Runaway shown yesterday by Max Rauch (CMS).

A couple of (very minor) comments:

- This is a 1-d description (a good approximation to e.g. ATLAS IBL => a single thermal R “TFM”). More generally T0 (the sensor T when sensor power = 0) is a useful second parameter.
- There is a higher intersection of the red curve and blue line: the detector will sit here if it runs away but is current limited by the PSU (and will degrade other sensors on the same PSU).



cooling possible at T_{CO2} = -35°C

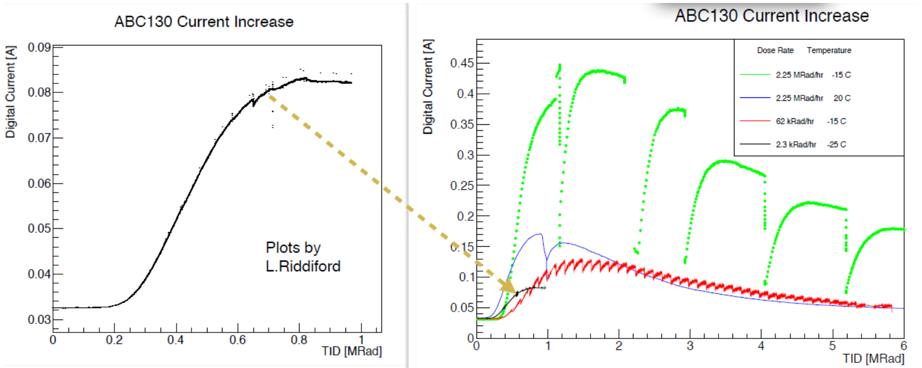
no cooling possible at higher T_{CO2}
→ “Thermal Runaway”

** CMS **

max.rauch@cern.ch, Forum on Tracking Detector Mechanics 2017, Marseille

Radiation Damage: ‘Total Ionising Dose’ (TID).

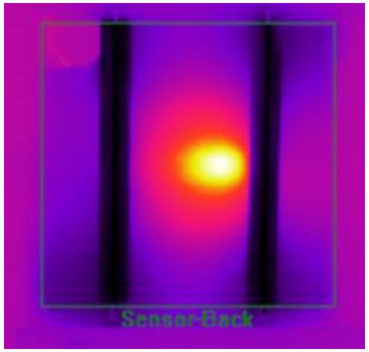
Strip readout chips are designed in 130nm Global Foundries technology: the digital transistor design uses Shallow Trench Isolation (STI).



Studies of T and dose-rate dependence of digital current.

Trench oxide is +ve charged by radiation, opening a parasitic channel => increase in chip digital current.
The +ve charge anneals (current falls) when radiation source is removed.
Interface traps are –ve charged (more slowly; have very long annealing time)
The combination gives a temperature- and dose rate-dependent current bump, peaking at 1-2 Mrad – with worrying consequences! (cite IBL) e.g:

- Increased readout power & module temperatures: peaking at different times according to location in the detector.
- High DCDC current draw × lower efficiency worsens the sensor hot-spot.
- Annealing between beam runs (e.g.) could result in a rapid change in detector alignment.



Sensor hot-spot observed at large hybrid current.

Need:

- *chip irradiation studies (ongoing, many institutes)*
- *a more sophisticated analytic model, to predict the consequences.*

* See e.g. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 52, NO. 6, DECEMBER 2005 2413 Radiation-Induced Edge Effects in Deep Submicron CMOS Transistors, Federico Faccio and Giovanni Cervelli.

Thermo-Electric model of the module (Georg Viehhauser)

Generalisation of analytic model, to include Temperature and Dose dependence of chip power.

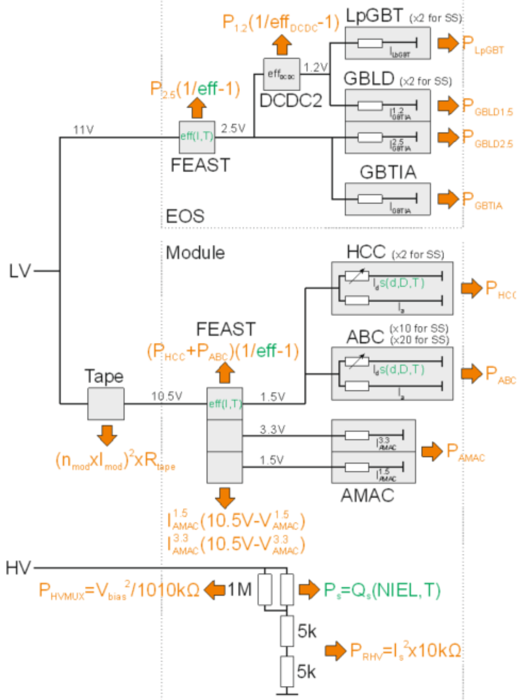
- couples electronic and thermal circuits:

Electronic

Equations for power dissipation, including (green) dependence on temperature, dose and fluence.

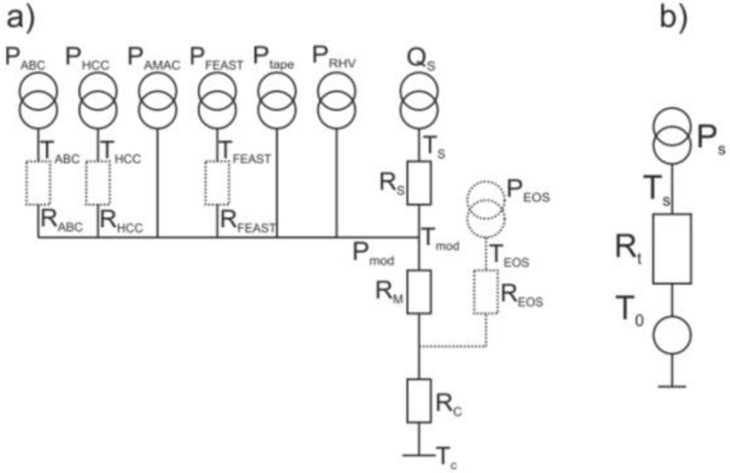
Thermal

Equations for sensor and chip temperature rises. Lumped Thermal Resistance elements (values derived from FEA).



Power Dissipated per Component

Component Temperatures

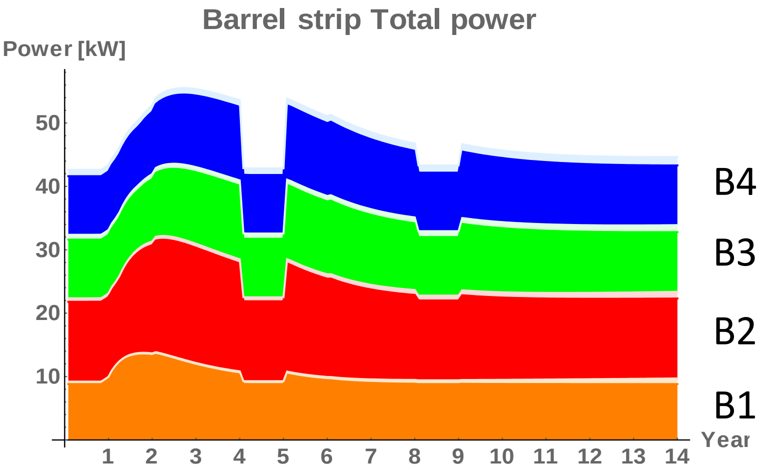


=> tractable solution (using Mathematica) => insight + strategies to suppress TID bump effects.

Example of a Thermo-Electric model Prediction

! Preliminary: needs a better model of TID and FEAST (dcdc) characteristics.

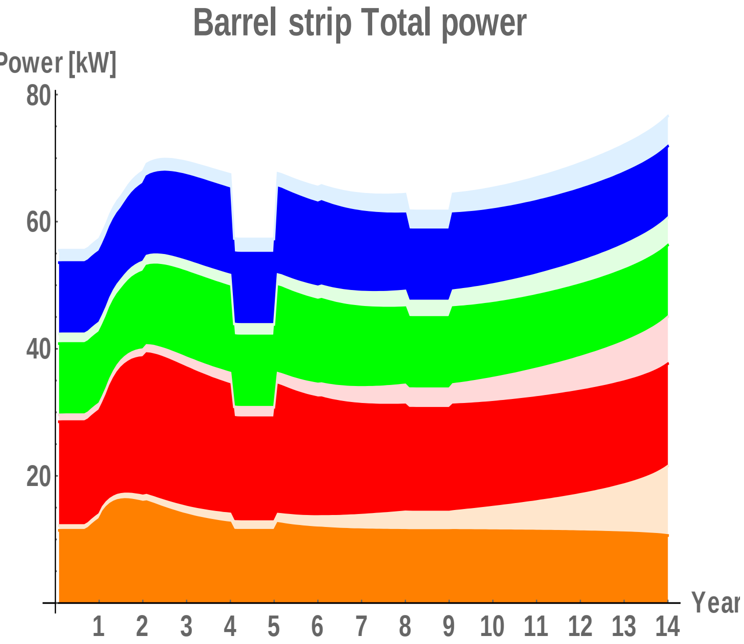
T-E model prediction for Barrel Strip Total Power, by Barrel and by Year



Nominal

Tevap -35C, Vbias 500V

Light bands are HV power contributions



with Safety Factors applied:

Tevap -25C, Vbias 700V

+20% Chip current, +20% Dose and Fluence.

(B1 will exhibit runaway in year 13 if +50% dose/fluence)

We do not have an official version of safety factors to be used, but the above example suggests we can’t afford to be very conservative.

Outlook – A few points.

We have some confidence that we can build the stave cores, and mount modules on to them. We will need a high production yield.

However there is a lot still to be done including basic design of End of Structure region.

We will not have the final readout chipset until 2018, lpGBT later.

We need to develop agreed assembly and QA/QC procedures.

Timeline

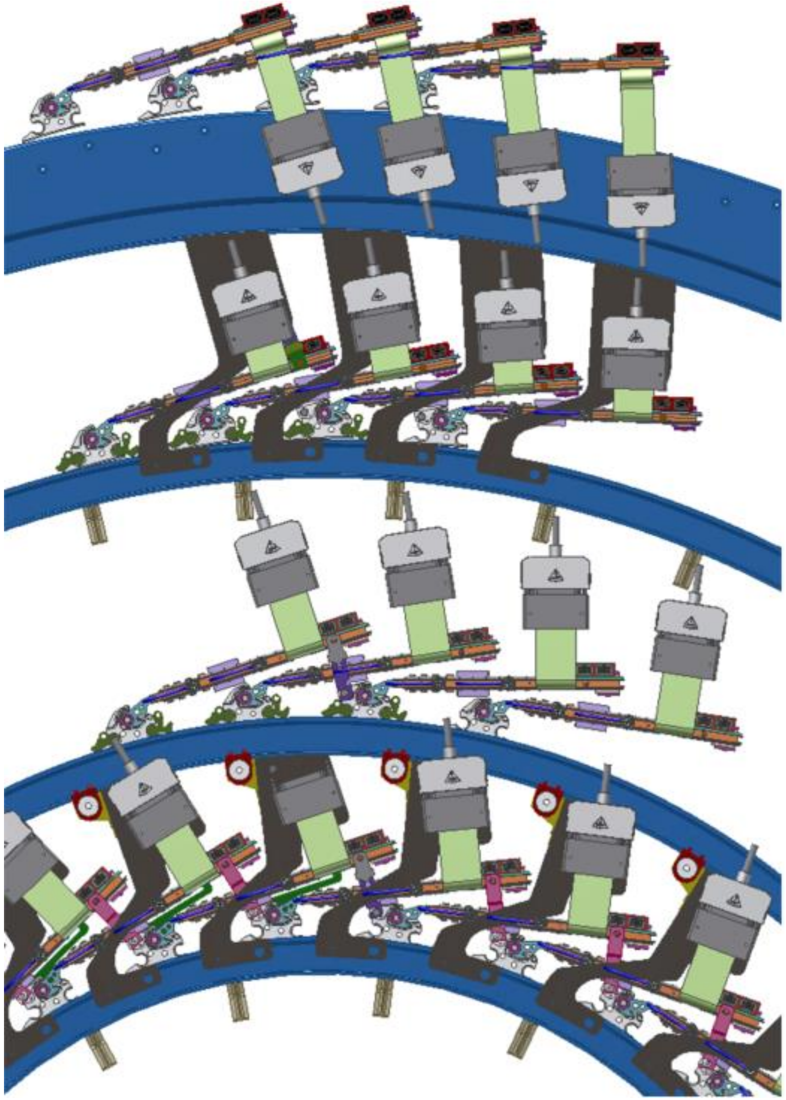
Spring 2017 we published the strips TDR:
Technical Design Report for the ATLAS Inner Tracker Strip Detector , CERN-LHCC-2017-005.

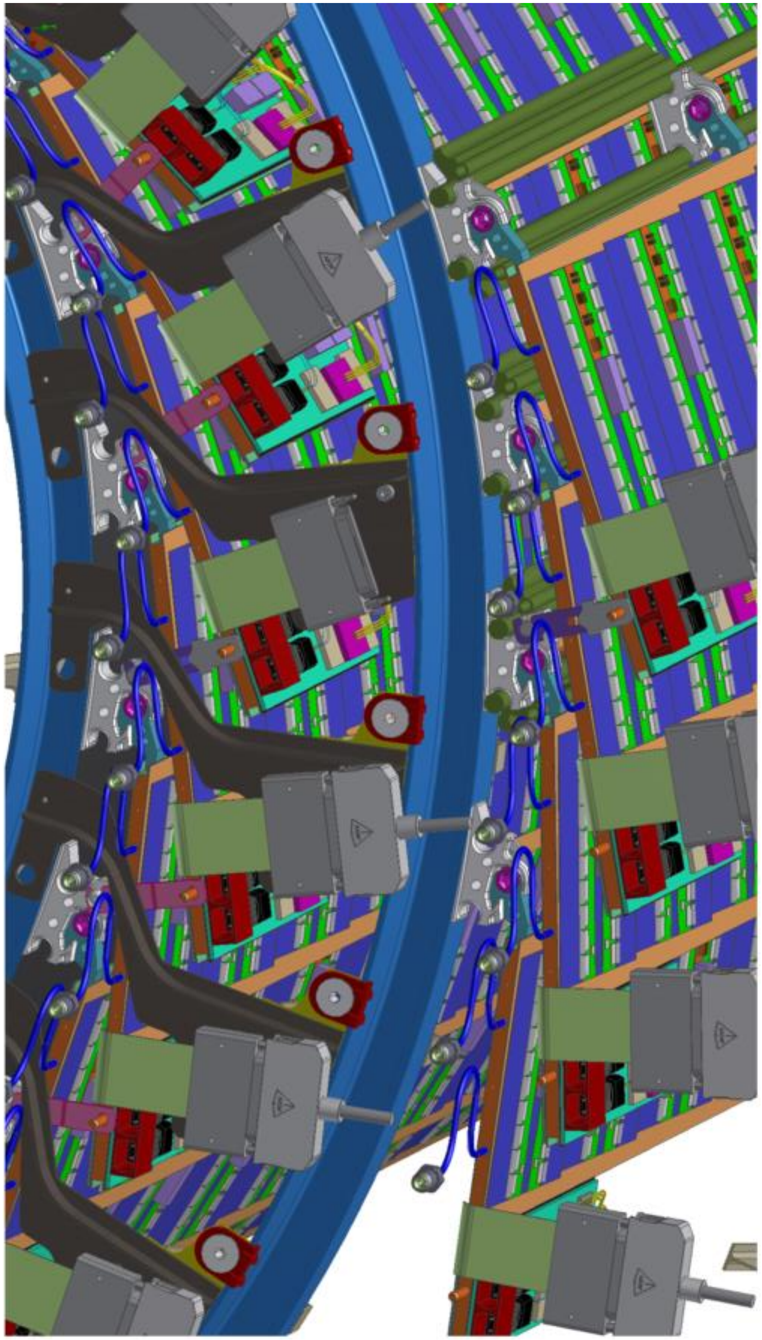
The current timeline is:

- 2019 Pre-production
- 2020 – 2023 Production + Loading
  2021 – 2023 Integration onto Barrels
- 2024 ITk insertion into ATLAS.

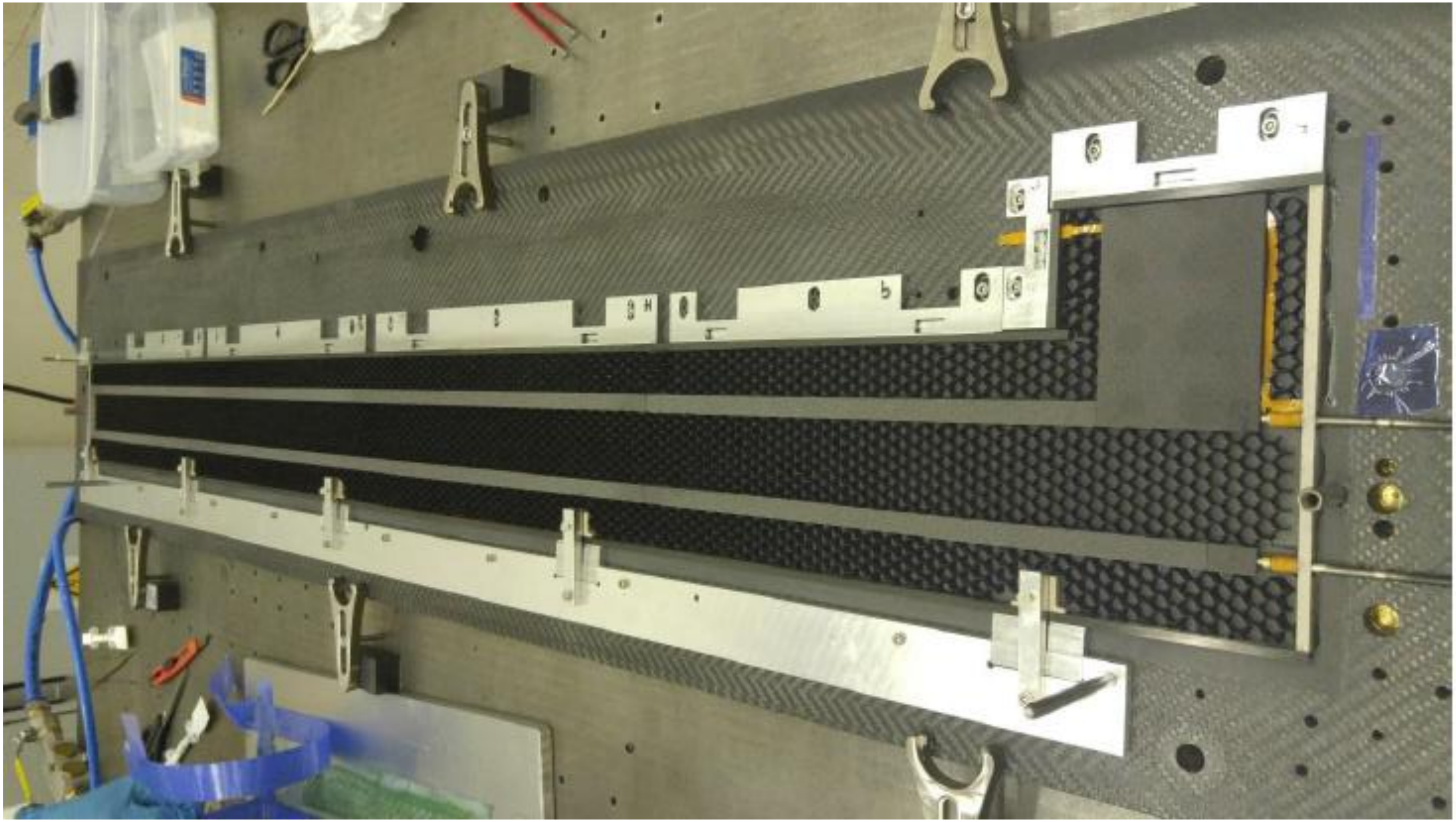
Backup Slides

Stephanie Yang – latest CAD of barrel end.

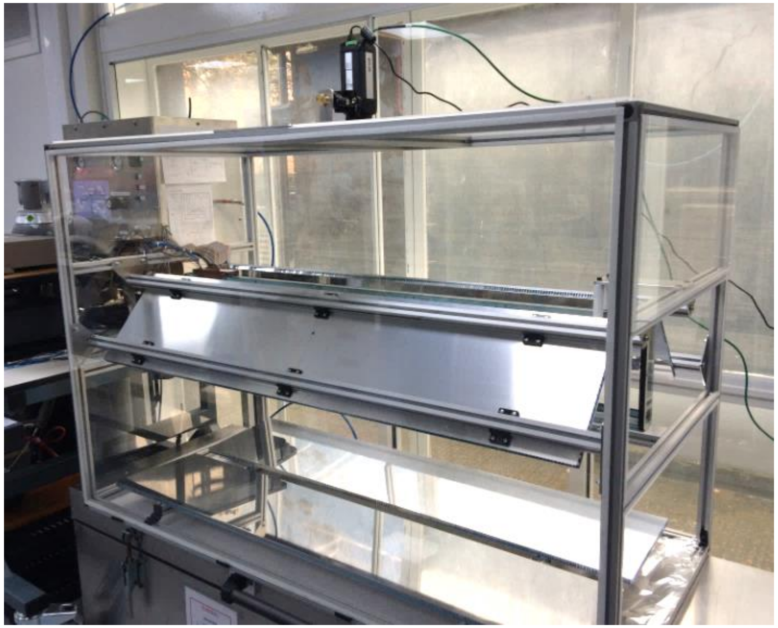




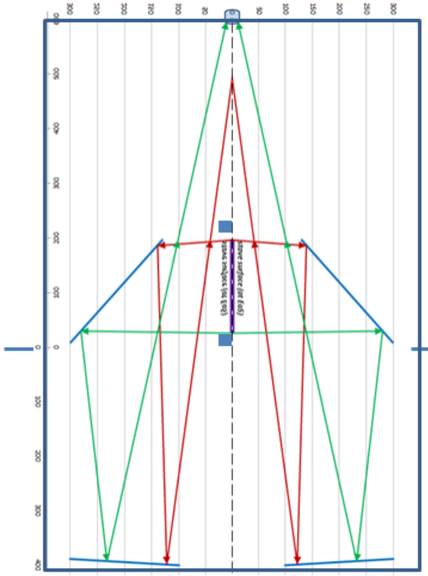
Oxford Core Assembly – LP housings and honeycomb glued.

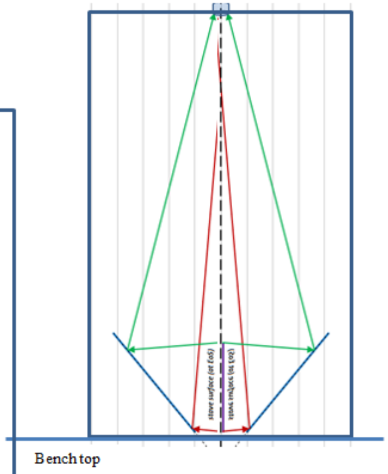


IR test box: - is big.

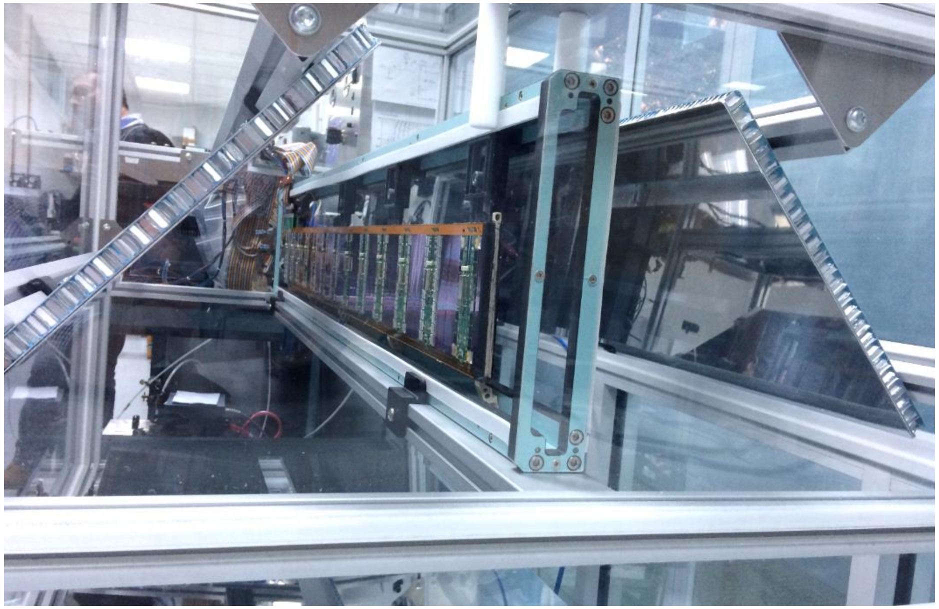


45° fov / w.d. =1.69m.





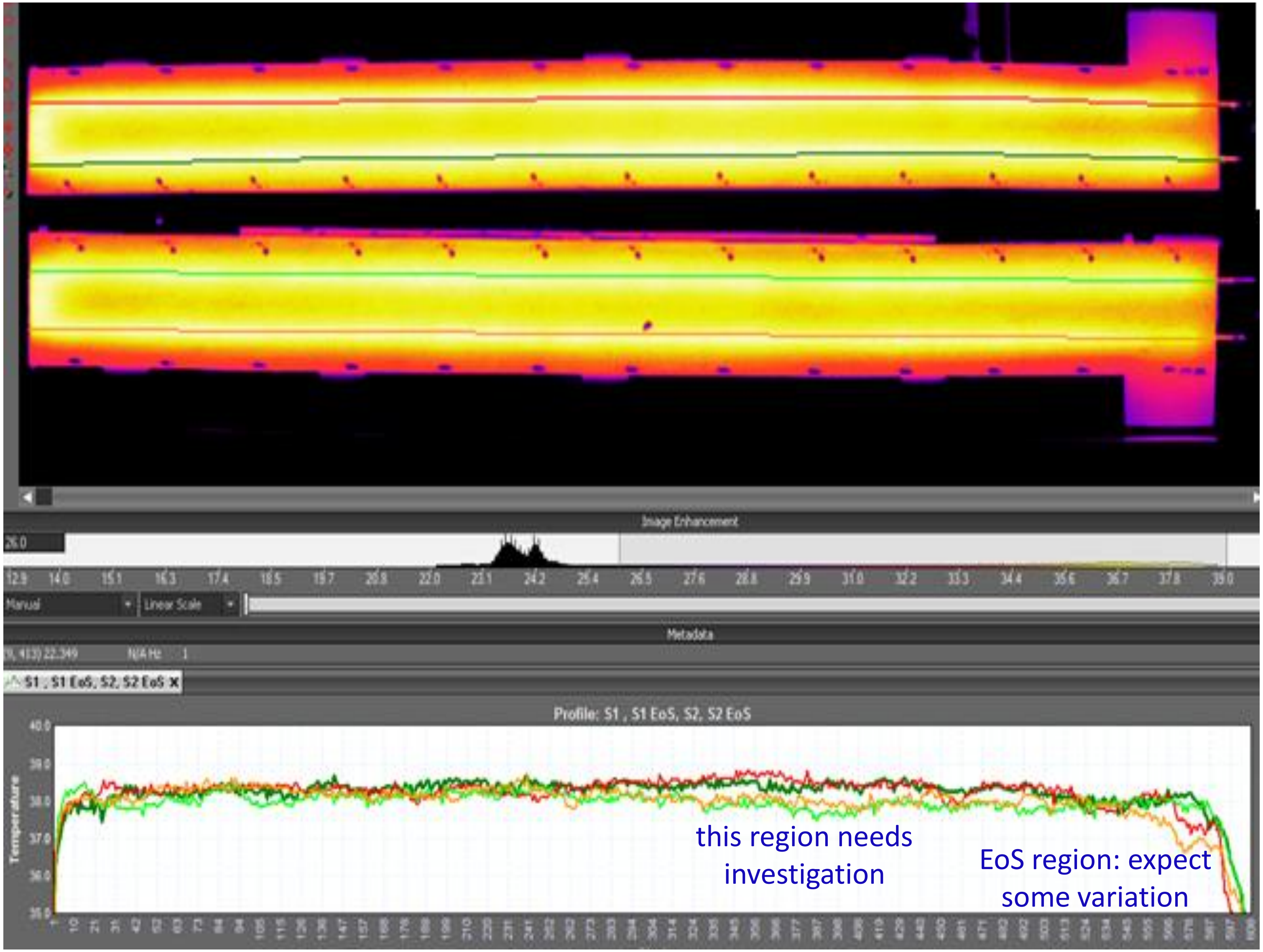
80° fov / w.d.= 0.83m. (will configure like this when confident the 80° lens works at low T)



IR image width: 640 pixels => 2mm/pixel.

Aluminium mirror reflectivity ≈ 98.7%. (spot radiometer + 50C surface, measuring at ~45° directly and via the mirror).

IR image of Bare TM Stave Core (#13). Water at +40C.



this region needs investigation

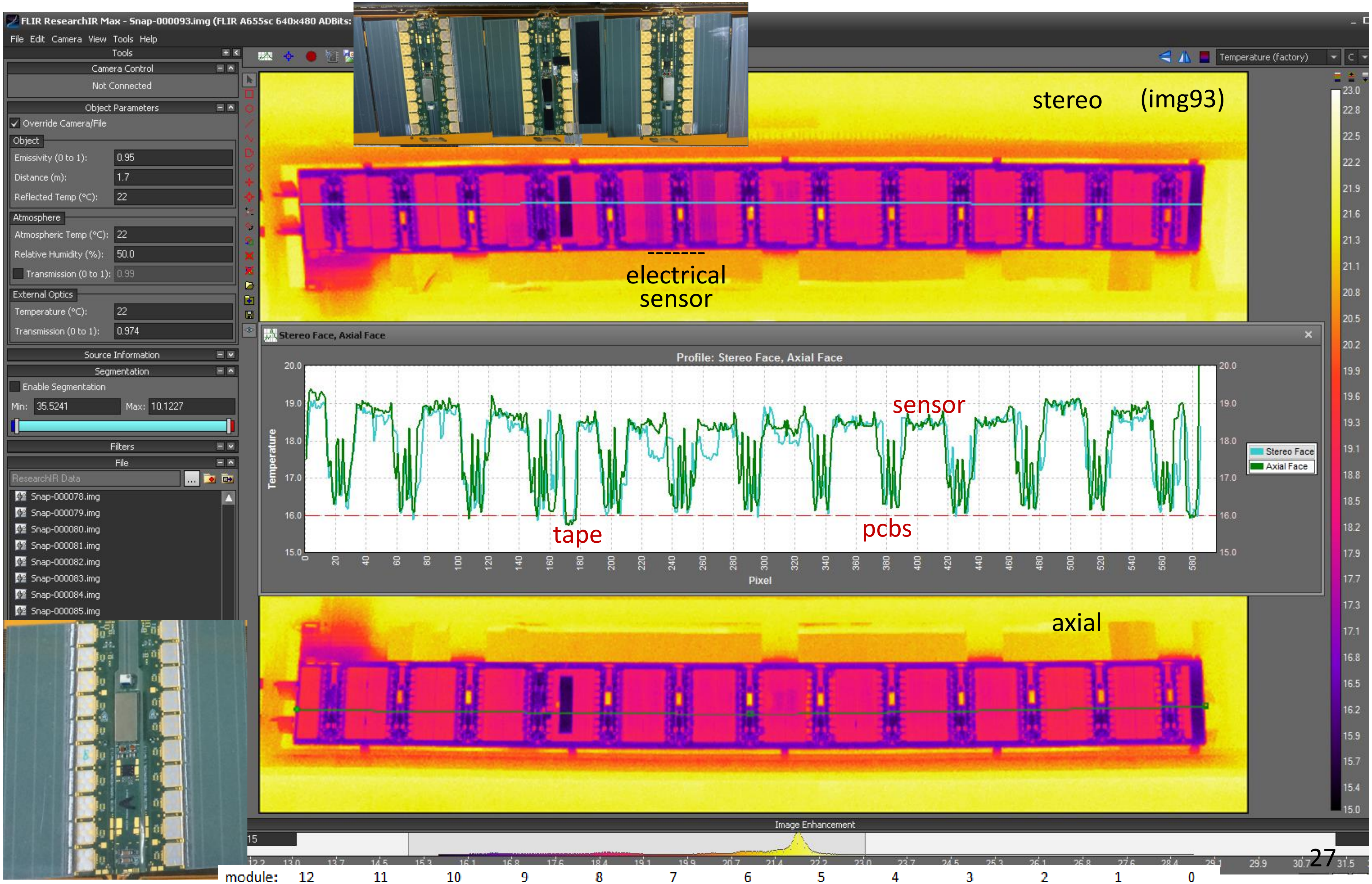
EoS region: expect some variation

Chiller at +15C. Stave not yet powered so ≈ 6C BELOW AMBIENT: expect ≈ 20W thermal load.

Beware: sensors reflect IR around the enclosure like a kaleidoscope.

Hybrid IR temperatures are relatively reliable (emissivity ~ 0.93).

TM Stave



FLIR ResearchIR Max - Snap-000093.img (FLIR A655sc 640x480 ADBits:

Camera Control: Not Connected

Object Parameters

☑ Override Camera/File

Object

Emissivity (0 to 1): 0.95

Distance (m): 1.7

Reflected Temp (°C): 22

Atmosphere

Atmospheric Temp (°C): 22

Relative Humidity (%): 50.0

☐ Transmission (0 to 1): 0.99

External Optics

Temperature (°C): 22

Transmission (0 to 1): 0.974

Segmentation

☐ Enable Segmentation

Min: 35.5241 Max: 10.1227

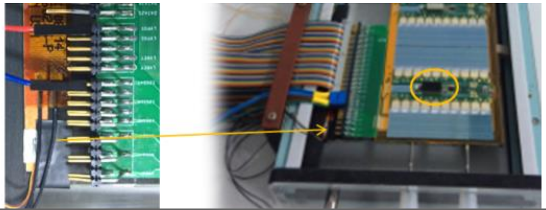
File

ResearchIR Data

Snap-000078.img
Snap-000079.img
Snap-000080.img
Snap-000081.img
Snap-000082.img
Snap-000083.img
Snap-000084.img
Snap-000085.img

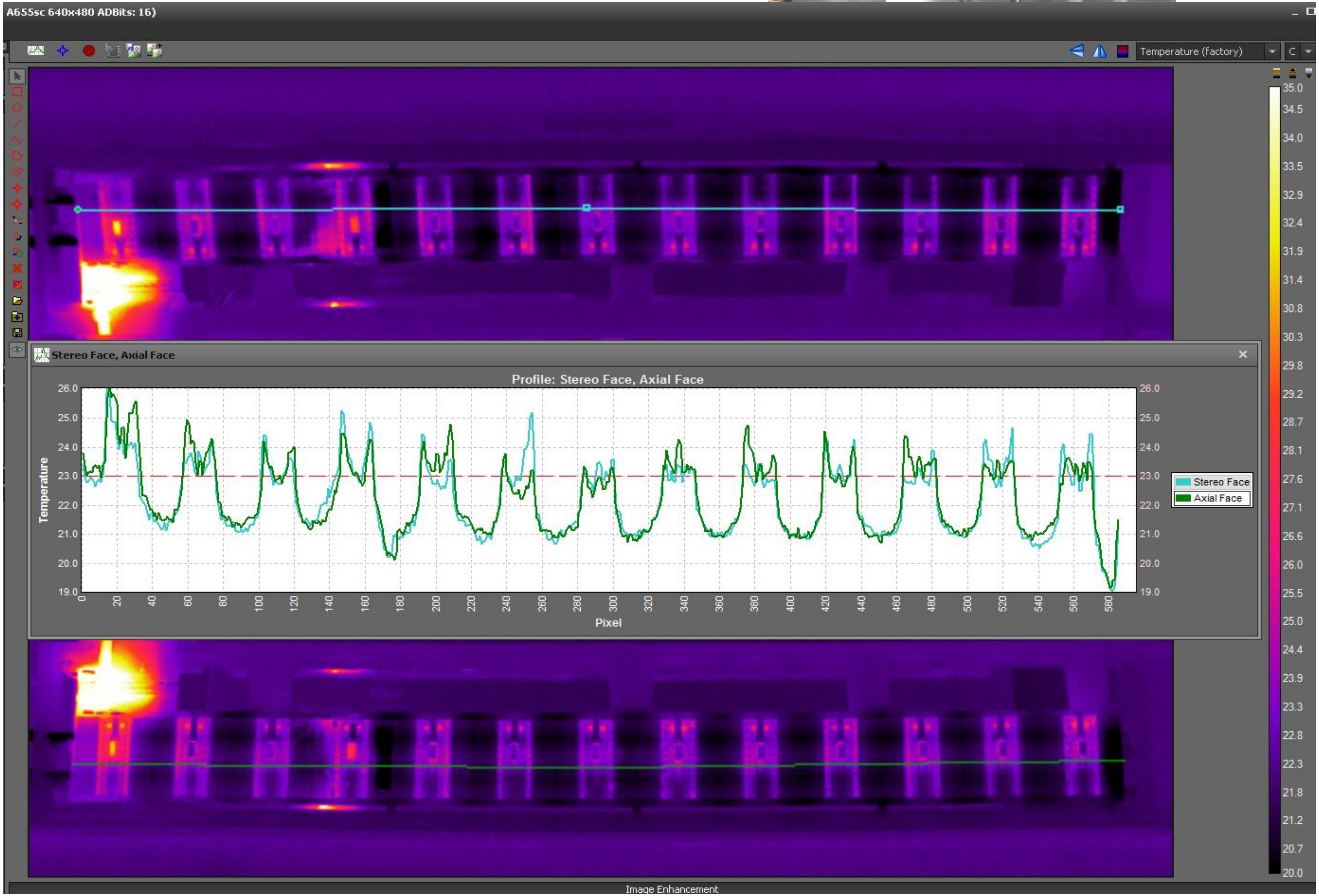
Temperature (factory)

TM Stave



Modules and EoS Heaters Powered Total 145W.

EoS CFRP (corner) IR = T/C ≈ 44C. = T(fluid) + 28C (good!)



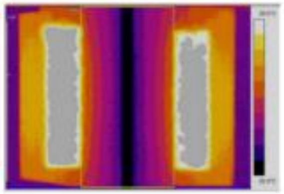
From Eric Anderssen's talk at 2015 Forum (Nikhef)

Foam Interface Verification

Recent Thermal Investigations

G.Beck (QMUL)

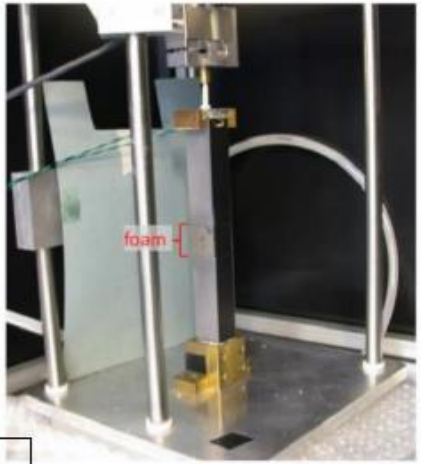
- HTC of foam-pipe joint measured:
  - 2.2875mm OD Ti pipe and
  - Allcomp foam (0.19 g/cc)
  - Glue: Hysol+30% BN
  - Two samples:
    - 2.26mm channel
    - 2.20mm channel
- HTC = 9400 W/m²K (±15%)
  →1 W/mK glue, 106 µm thick)
  - Eric A: 1.1 W/mK, 100µm (htc=11,000)
    - Good agreement
  - Same for both samples



Graham Beck QMUL

Recent Thermal Investigations cont'd

G.Beck (QMUL)



- Measure DRY
  - Allcomp foam – lead
  - No Glue or grease
  - Very smoothly milled surfaces
  - Joint HTC (W/m²K)
    - 0.258 g/cc foam:
      - 4400, 5600 (lower, upper)
    - 0.198 g/cc foam:
      - 4500, 4400 (lower, upper)
- Joint HTC <<10,000 → glue contributes appreciably to the conductance, even for an ideal joint geometry.
  - Will be even more important in the case of a poor fit.

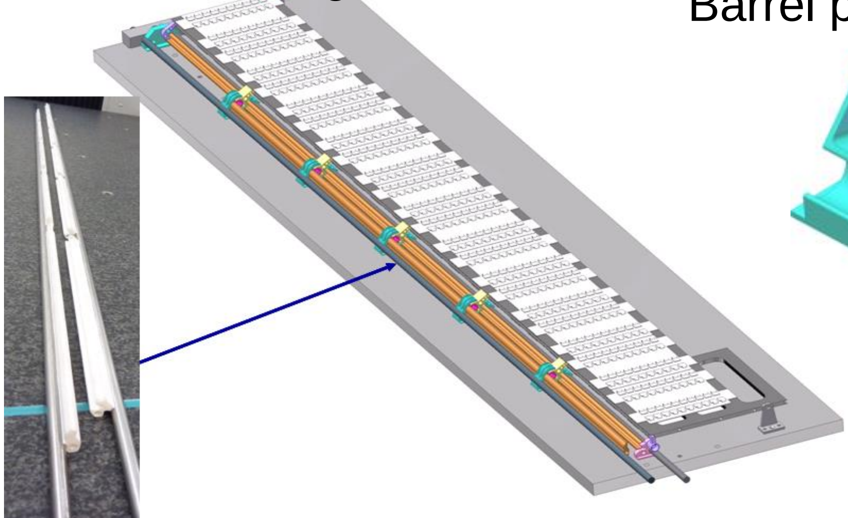
- **Initial studies with CVD foam ~0.35g/cc density or higher; 0.2g/cc developed with BN filled epoxy simultaneously**
- **Reducing mass in foam required increased attention to interface**
- **G Beck documented that ~1/2 of the thermal conductivity is due to physical contact (conversely poor contact or tolerance control is bad)**
- **Filled Adhesive is fully the other half and bridges gaps—perhaps more**

(Georg Viehhauser’s slide)

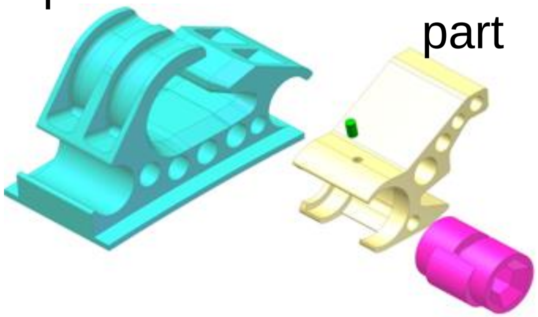
Stave insertion

- Individual modules tend to lead to integration of large structures (barrels), which then need to be mounted into each other
  - Did this for SCT – found this a sequential, complex process
- The introduction of staves as mechanical units allows for direct installation into structure
  - Designed for end insertion: staves are slid in from the barrel end
  - Challenges:
    - Clearances
    - Staves need to be guided during insertion → tooling
    - Locking (need to be able to do this reliable from the end → tooling
    - All tooling must be completely removable (to avoid dead material)

Removable guide rails



Lock point

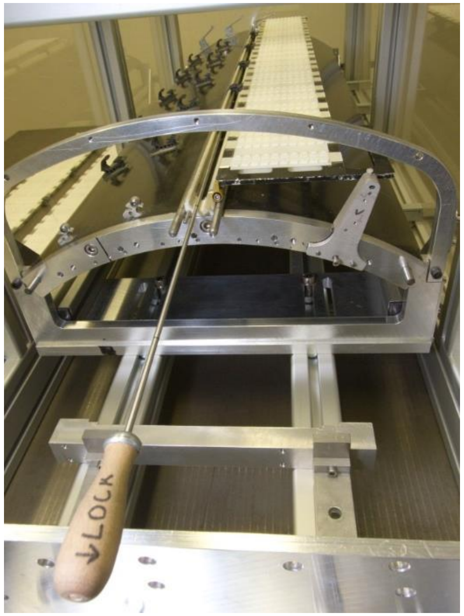


Barrel part

Stave part

Locking cam

Locking of co-axial lock points



Thermal Resistance Stack-up (mid-Z stave module)