LHCb UT UPSTREAM TRACKER

– Mechanics & Construction –

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for the LHCb UT Group

Outline

Introduction

LHCb & Its Upgrade

UT Design

Construction

Phase 1. Bare Stave Construction

- Components – Facings, Foams, etc.
- Construction Procedure
- Cooling Tube Assy – Fab, Fittings, Bending

Completed

Phase 2. Flex Attachment Preproduction

- Vacuum Fixtures

Phase 3. Module Construction Ongoing

- Construction, Wirebonding, Sensors, ASICs

Ivan Polyakov

Phase 4. Module Mounting Ongoing

- Attachment and removal

Afters

Stave Production QA

Xuhao Yuan

- Metrology: Smartscope
- Process: Travelers, checklists, database

Shipping: SYR to CERN

- Strongbacks
- Transport boxes

Cooling System

Michael Brodski

- Scheme, related mechanics

Summary and Plans

Overview

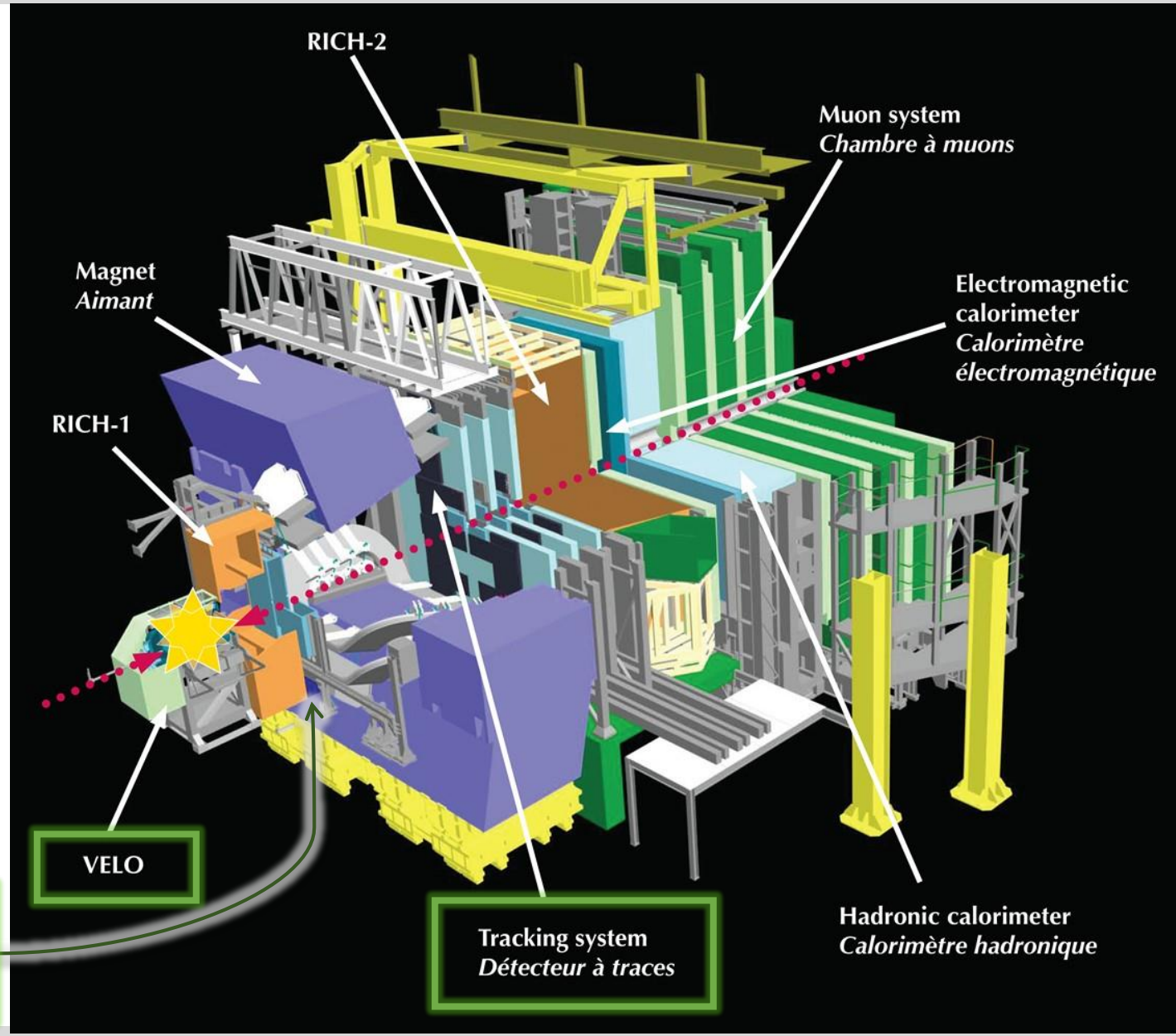
LHCb Detector Upgrade

LHCb Upgrade

- Sub-detector upgrades
- 40 MHz readout
- Trigger upgrade

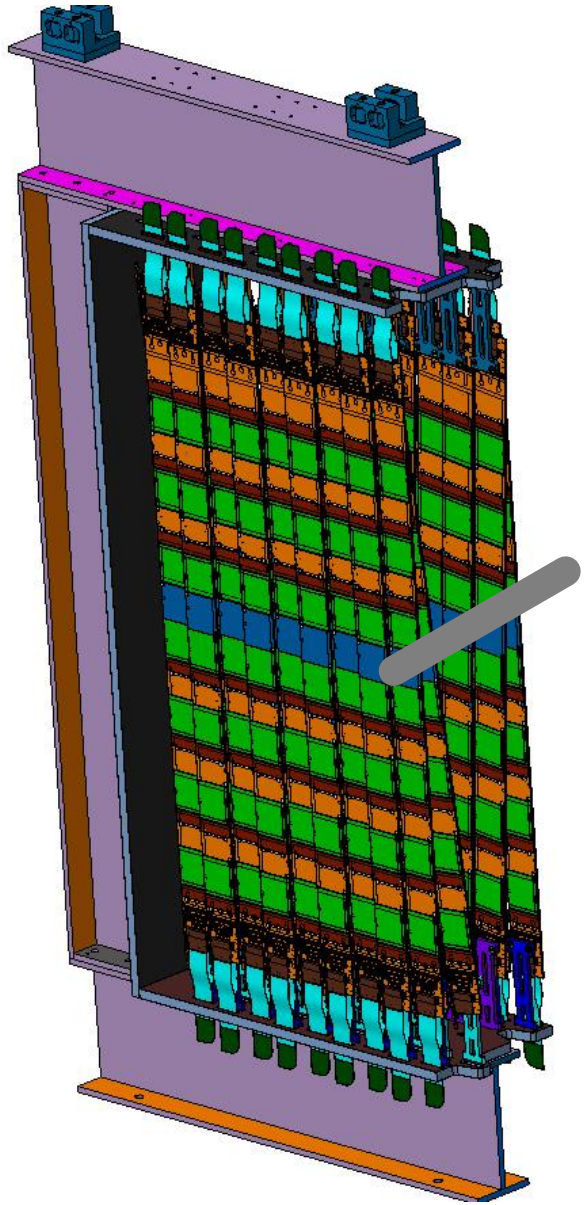
UT Tracker is a silicon strip tracking detector being constructed as part of the LHCb upgrade

UT will provide a fast momentum measurement for the trigger as well as function as part of the overall tracking system where it will severely reduce the presence of "ghost" tracks.



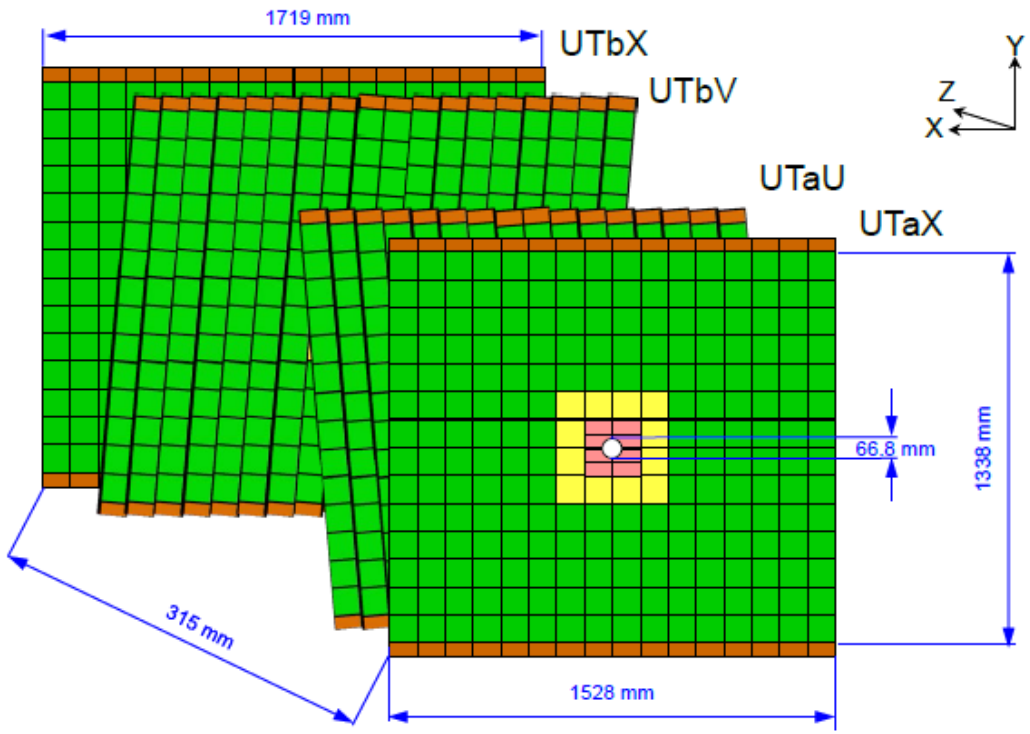
Location of Upstream Tracker

Upstream Tracker (UT)



UT Tracker

- Four planes of ~1000 total ~10x10cm2 silicon strip sensors
- Custom ASIC readout chips (SALT)
- Constructed using stave support structures with silicon on both sides
- Overlaps in X and Y directions to ensure full geometric coverage
- Two planes at stereo angles
- Higher segmentation sensors in the region surrounding the beam pipe
- Innermost sensors have circular cut to approach beampipe and maximize acceptance
- Readout electronics located near sensors to allow segmentation, improved signal/noise



Staves supported in thermal insulating box such that A/C-sides retract from beampipe

Installation scheduled 2019-2020

UT Stave Design (1)

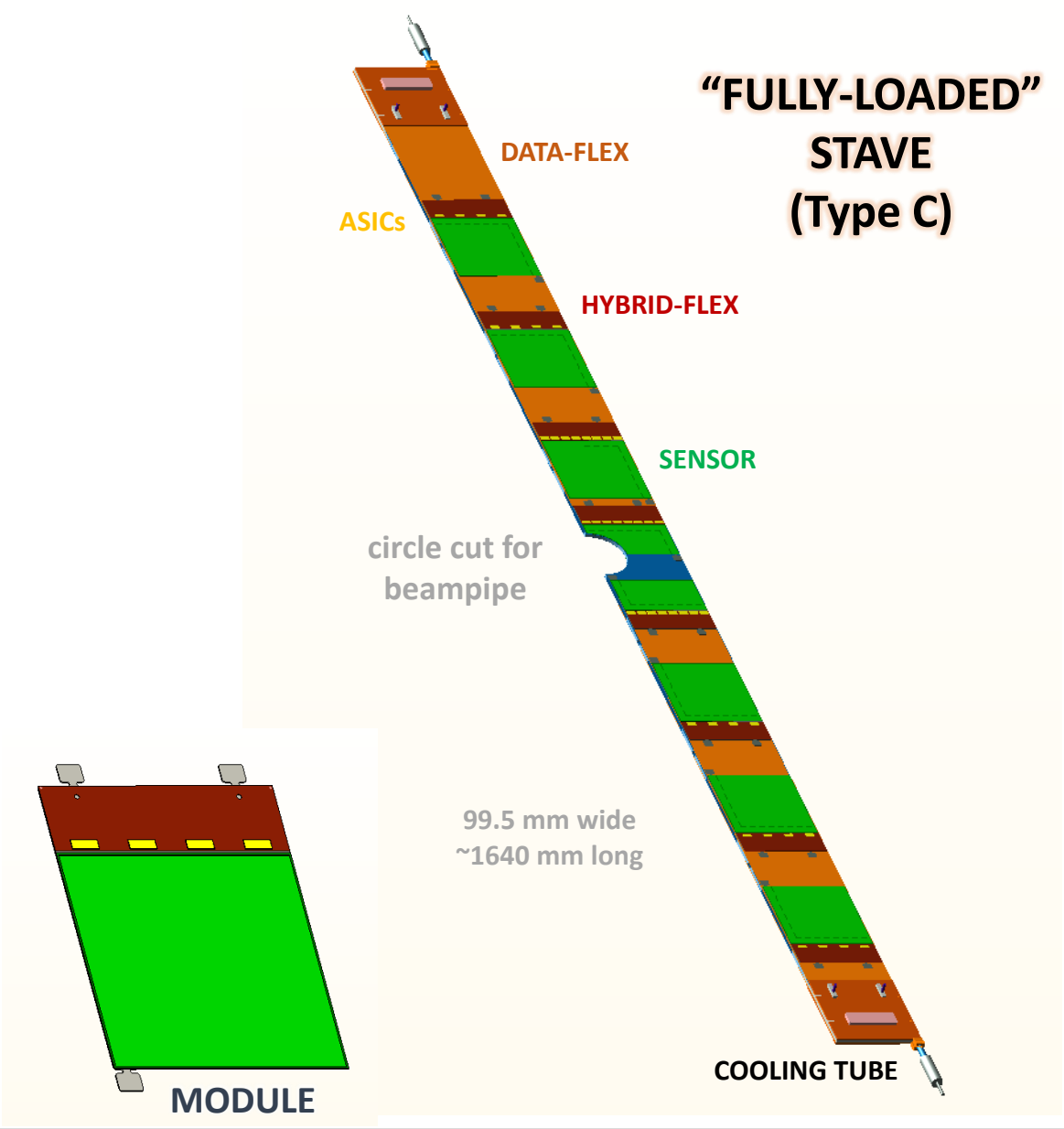
Stave basics

- Main mechanical element of the UT
- Provides for the mounting and precise positioning of the silicon sensors
- Comprised of competing mechanical, thermal and electronic requirements
- Stiff sandwich structure of lightweight CFRP/foam sandwich structure
- Integrated with CO2 cooling system
- Three types based on proximity to beampipe
- Total 68 fully-instrumented staves needed

Components of fully-instrumented stave

- "Bare" stave – basic structural support, with cooling tube
- Dataflex – signal readout / power distribution / control lines
- Modules – sensor + hybrid + ceramic stiffener, mounted on both sides of stave

Adapting ATLAS-type Integrated Stave concept



UT Stave Design (2)

Bare Stave

- CFRP facings epoxied to foam core in sandwich structure with embedded cooling tube
- Aluminum end-of-stave mounting blocks
- All-epoxy construction

Core Foams

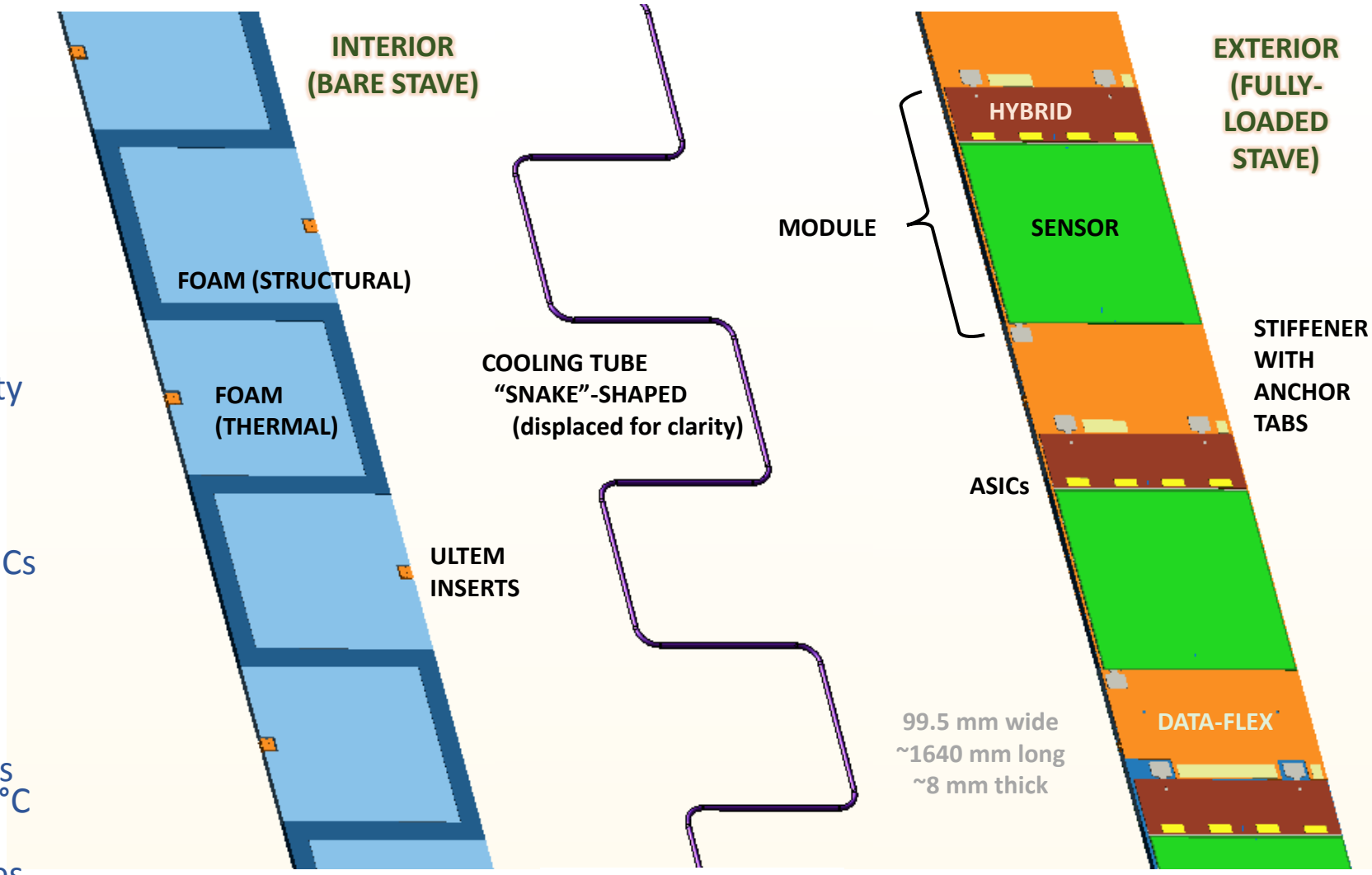
- Thermal foam for heat transfer
- Lightweight structural foam for rigidity of sandwich structure

Cooling Tube

- Ti tube, OD 2.275 mm
- Has "snake" shape, runs under all ASICs and edge of each sensor for efficient cooling

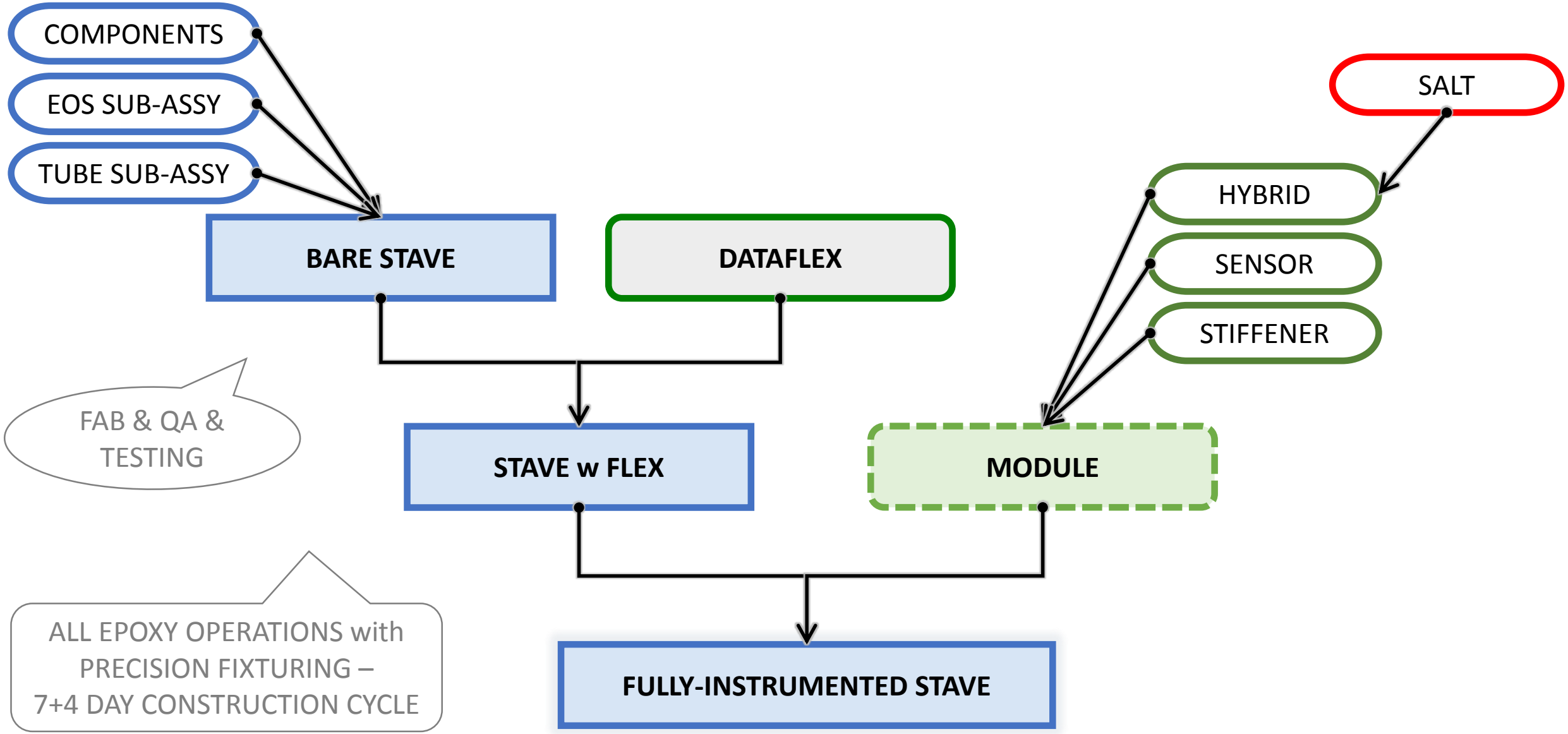
Goals

- Sufficiently stiff
- Sufficiently conductive – keep sensors at ≤–5°C, uniform ΔT=5°C, ASICs < 40°C (~0.8 W/asic)
- Sufficiently non-resonant – few modes below ~200 Hz



Phase 1.
Bare Stave Construction

Stave Construction Overview



Bare Stave Construction: Side-A

Lay down facing on vacuum baseplate fixture

- Hold flat and in position during operations

Dry fit all components before wet run

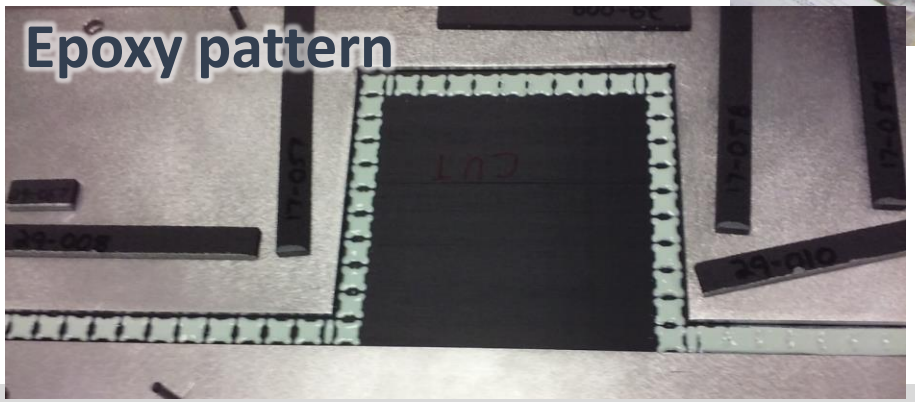
Lay down components (carbon foam, EOS, Rohacell)

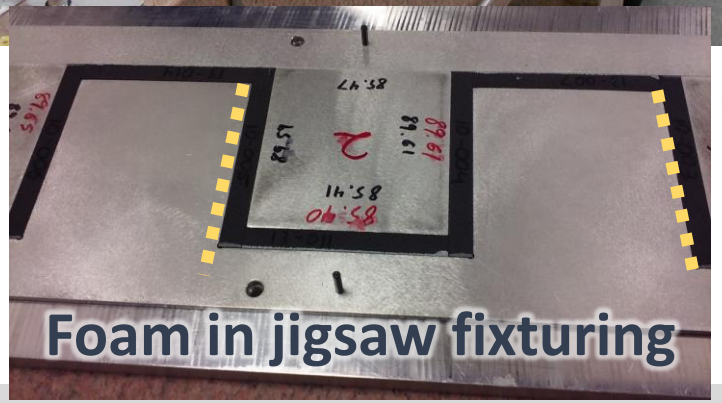
- Positioning guided by precision fixturing, pins, ref edges, etc.

Use stencils for epoxy patterns

- Specialized for proper smearing against foam surface
- Apply epoxy, squeegee excess

Left to cure





ref edges

Components

Facings

- K13C2U high-modulus carbon fibers in EX1515 epoxy matrix, 45gsm
- Layup: prepreg stackup in 0/90/0 orientation
- This emphasizes planar stiffness of the sheet while allowing for thermal conductivity in both in-plane dimensions
- Specs: 120 mm x 1550 mm x 0.21 mm
- Fabrication by University of Washington (Bill Kuykendall, Henry Lubatti) with help from Berkeley (Eric Anderssen)
- Machinability: easily cut and shaped as we need (done by hand)
- Surface texture made by peel-ply, no need for abrading before epoxying

Thermal foam core component

- Allcomp K-9 carbon foam
- High thermal conductivity (~35 W/m.K), low mass density (0.2 g/cm^3)
- Open cell foam
- Machinability is good
- Cut into strips for bare stave core
- The machining of the foam is easy and the resulting surface can be made clean for epoxy

Structural foam core component

- Evonik Rohacell 51 IG, a commercially-available polymethacrylimide (PMI) polymer foam
- Solid, not thermally conducting, very low mass density (0.051 g/cm3)
- Closed-cell foam
- Machinability is good
- Machined surface is left with opened foam cells, so epoxy contact area increased, increasing the adherence.

Carbon Foam QA Metrics

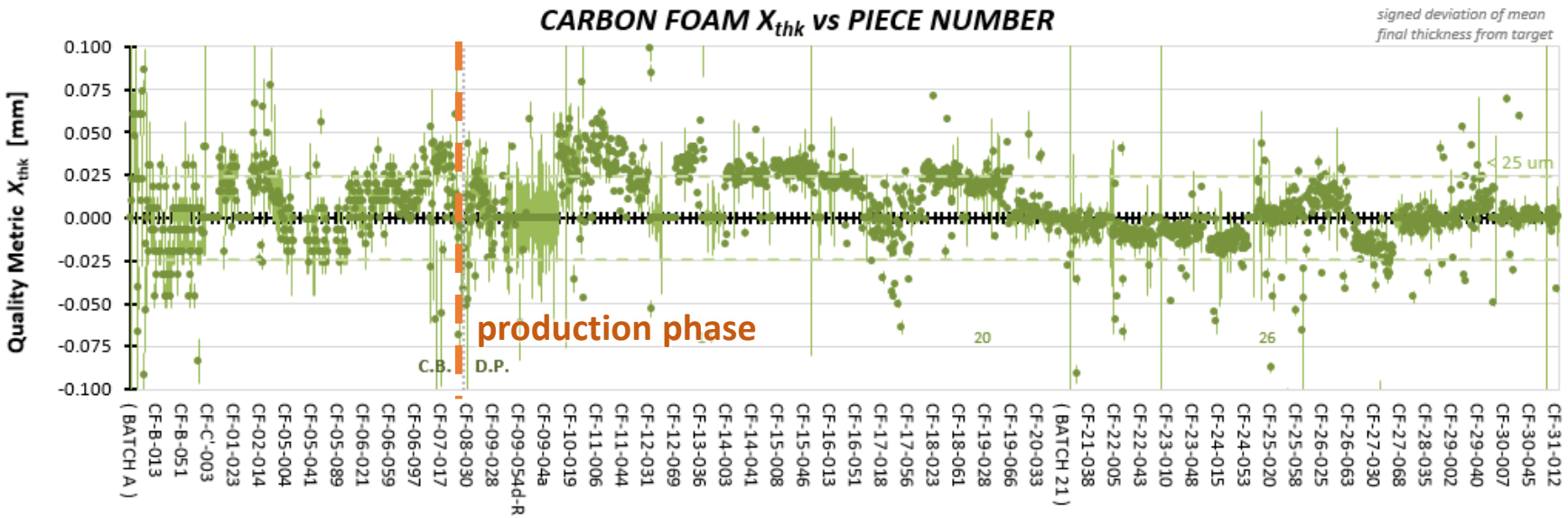
Many internal QA metrics are measured for components and sub-assemblies

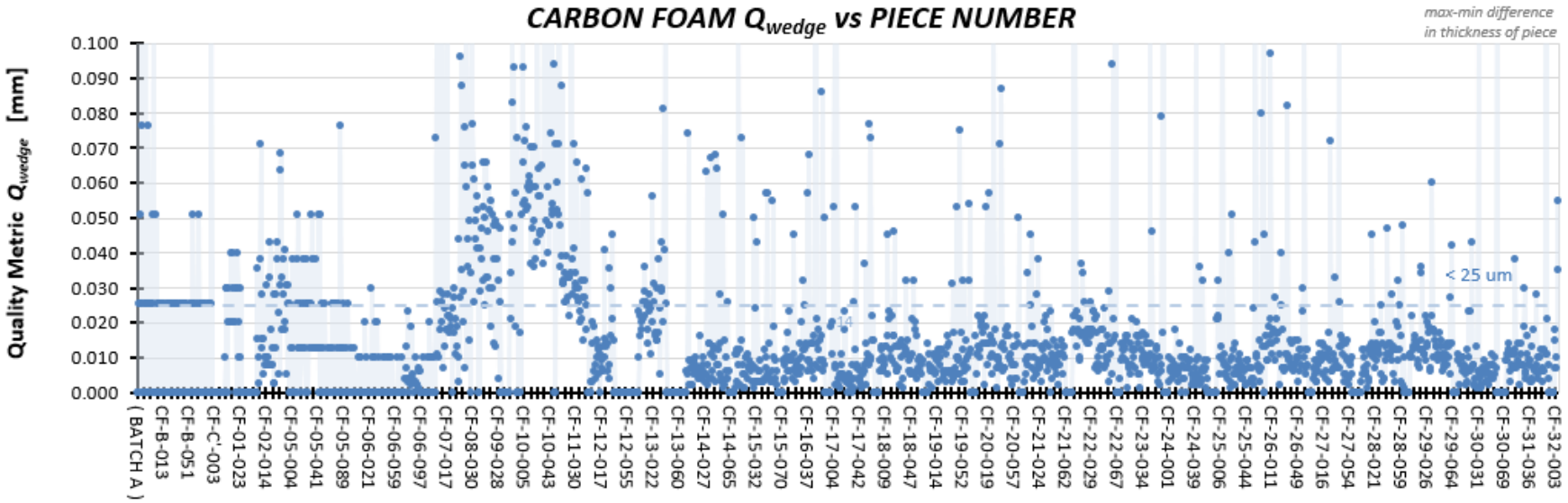
Top plot shows deviation of as-fabricated foam strip thickness from design value

- Shows improvement as process controls implemented for each successive batch
- Most controlled under 25 um
- Shows capabilities of CNC operations

Bottom plot shows wedge in foam strip (max-min thickness)

- Shows reasonably well-controlled process
- Again under 25 um
- Simple piece
- Maintained over lifetime of project





End-of-Stave Mount Sub-Assembly

EOS Mounts have many parts

- Plates, insulator bars, mesa standoffs, epoxy hooks, etc
- Machine shop intensive

Post-fabrication QA

- Dry fitting, dimensional measurements, etc
- Requires dedicated personnel

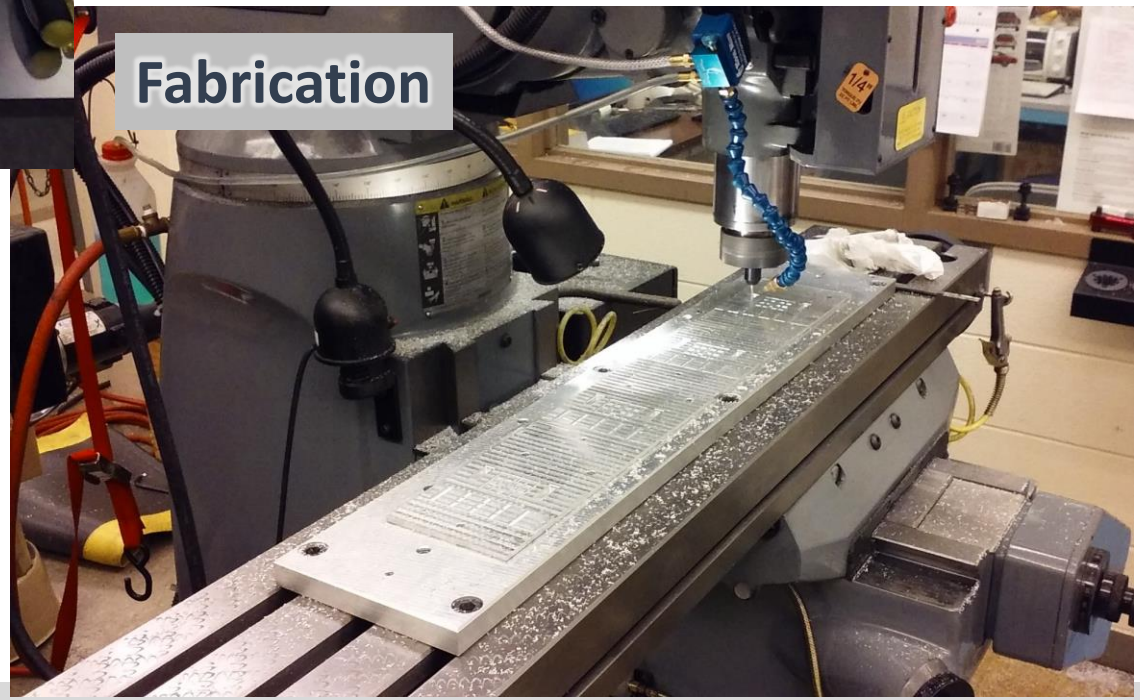


Plate and components epoxied on precision fixture

Held in place while curing

Critical dimensions machined after epoxy construction completed to assure best possible tolerances

- Master reference datum for stave, etc.

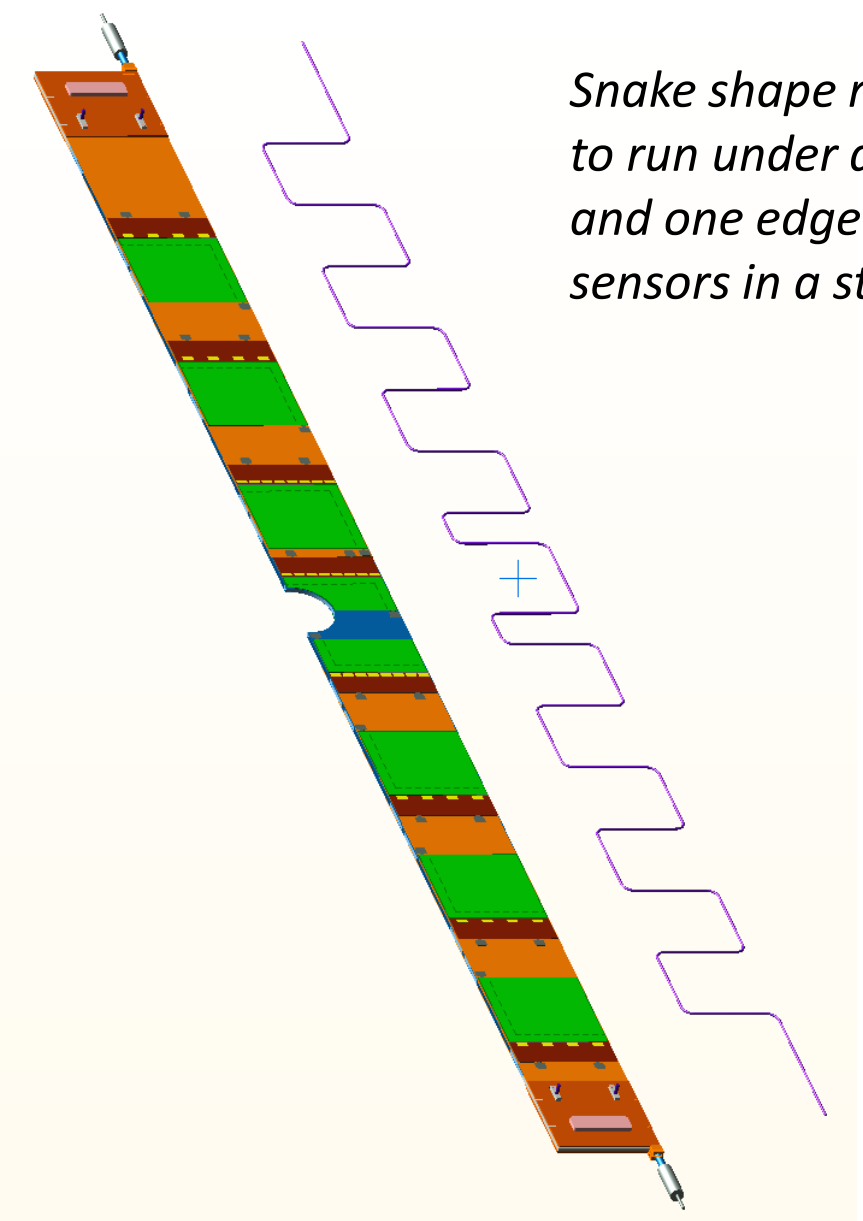
Cooling Tube Sub-Assembly

Raw Tubes

- Titanium CP2 alloy
- Specs: OD 2.275 mm, ID 2.025 mm, 125 um wall thickness, 3.1 m nominal length
- Manufactured by High Tech Tubes Ltd. UK
- Development by ATLAS (Richard French, University of Sheffield) and we have benefitted greatly from their expertise and help

Basic Characterization

- Measured OD, using smartscope
- Measured ID, using a gauge “bullet” test
- Check for obstructions
- Noticed some residual oxidization layer on inner surface of tubes



Snake shape required to run under all ASICs and one edge of all sensors in a stave.

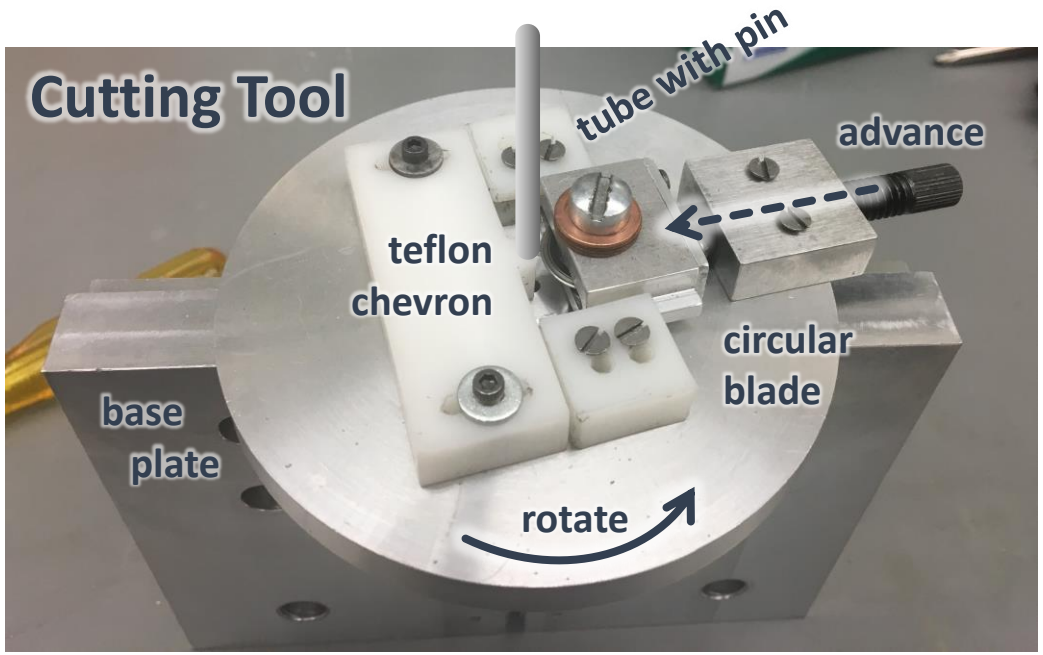
Tube Cutting

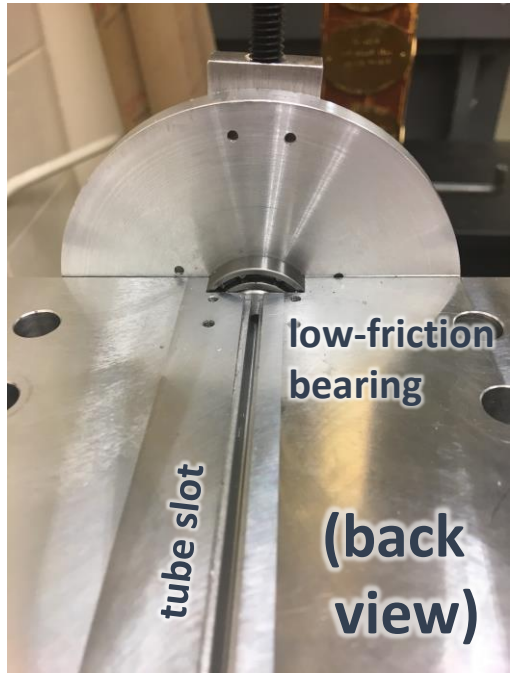
Cutting

- Needed to be cut before brazing (and bending), so length must be correct before bending *
- Developed rotary tooling like pipe cutter with internal pin to support tube and avoid crushing wall
- New blade needed each ~10 tubes
- Measured resulting lengths using form

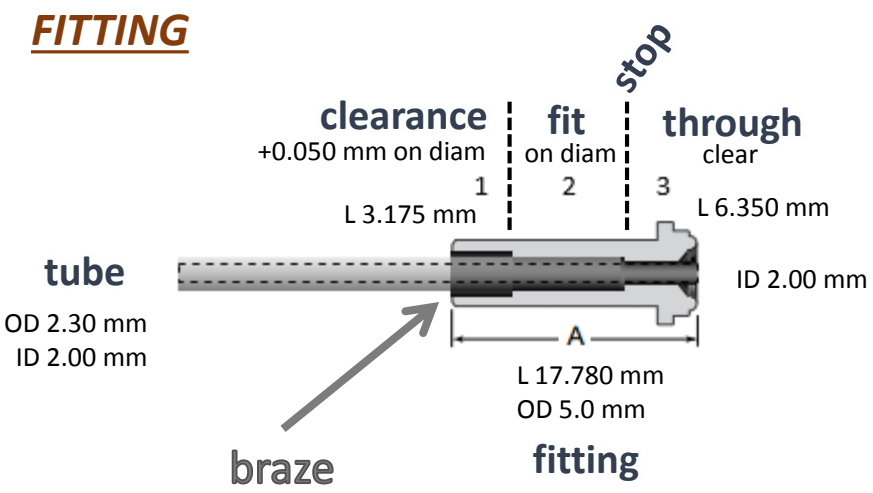
Result

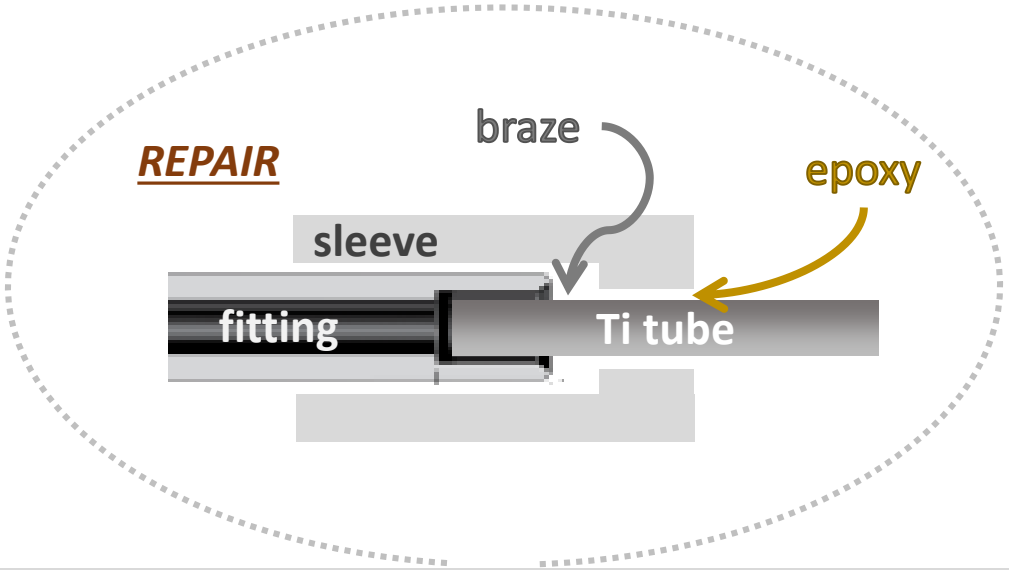
- Cuts made to 0.3 mm of target length (for 3.1 m tubes)





Custom VCR Fittings





VCR Fittings

- Based on Swagelok blank SS-2-VCR-3-BL
- Successive drilling operations, with steps, using mix of starter, high-speed, carbide drills of different diameters
- Allows clearance for brazing preform material intake (segment 1)
- Allows for self-alignment of fitting on tube axis (segment 2)
- Care must be taken to avoid silver bead (sealing surface)
- QA: diameters checked with gauge pins

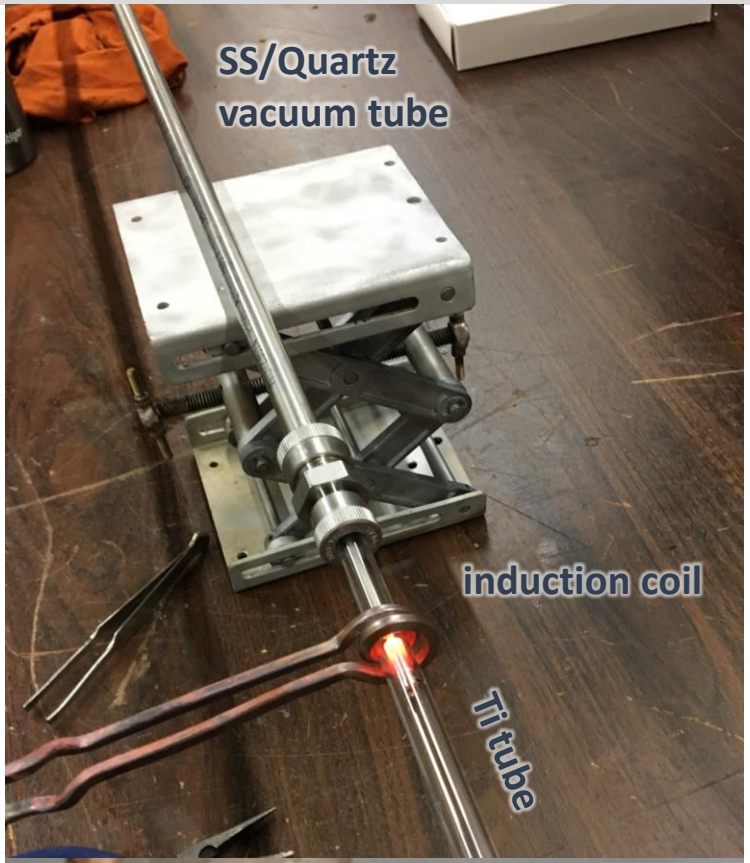
Results

- Machined ~220 fittings at Syracuse
- Cleaned, classified (~20 rejected)

Repair (as needed)

- Second seal using external sleeve epoxied over braze joint

Brazing



Brazing

- Need to attach fittings before bending
- Brazing is the standard option for joining dissimilar metals.
- Must be done in vacuum: in air or argon, must use organic flux, has contaminants
- Special system was set up for us

Technique: heating by induction coil

- One-turn transformer
- Different diameters assure even heating of SS and Ti
- Very localized heating

Brazing material: LM 69-241 braze ring

- Composition: 60% Ag, 24% Cu, 14% In, 2.25% Ti, 0.15% max other
- Thermal properties: 620°C solidus, 720°C liquidus (720–860°C braze range)

Results

- Process variables pinned down to avoid overheating
- Production took place in dedicated setup
- On-site pressure test as quick check, if fail re-braze immediately
- Brazed Aug–Sep 2017, 3 wk prod run for 92 tubes (both ends)

Tube Bending (1)

Bending

- Need 28-32 bends per tube, depending on stave type, approx. 90 tubes
- Single tool to bend entire tube, better repeatability, compensation for neutral axis shift and springback
- Tool based on single-bend design by Ian Mercer (Lancaster)
- Principle: spool and wiper constrain cross-section of tube from being deformed while bend is being made
- Still required some dexterity to hold tube during bending (by hand not by clamp, to prevent any crushing of tube)
- Stops allow controlled amount of overbend (11°) to compensate for springback
- Measured shape after bend with smartscope: angle, location *
- Proved to be a bit difficult, so we used a gauge form for this

Bending Results

- Process went smoothly
- Achieved 90° bends good to within a few degrees
- Planarity not always good, out-of-plane waves in final tube

Testing

- Pressure testing done on final assembly at 186 bar
- If failed can see in first 1-2 hrs

Tube Bending (2)

Keys

- Will sink tube in carbon foam, so its shape will be constrained
- Alloy is soft so its shape can be adjusted a bit
- Alloy is soft, so will stretch
- Not all tubes are the same – annealing process gives some tube-to-tube variation expressed as different plasticity therefore different bending behavior, some of which is localized

Bending Issues

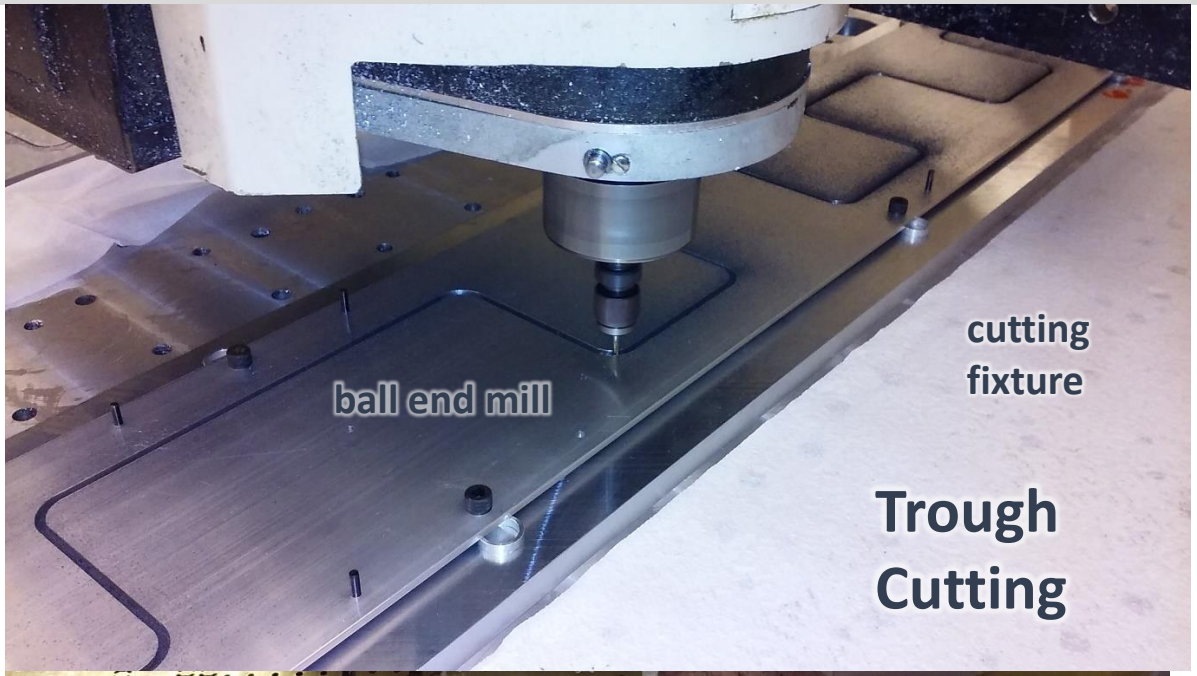
- Material variation precludes high spatial precision in bending shape – don't kill yourself over this
- We worked backwards
- First, establish tube shape in CAD
- Generate CNC code from CAD to cut physical path in carbon foam
- Use same CNC code to cut a gauge form (go-gauge)
- Adjust diameter of spools to get desired radius – tends to be larger than expected naturally, and even more so if not careful when making actual bend
- Adjust locations of spools on bending tool to give a tube shape which fits the gauge form (and therefore also the stave)

Length Control Issues

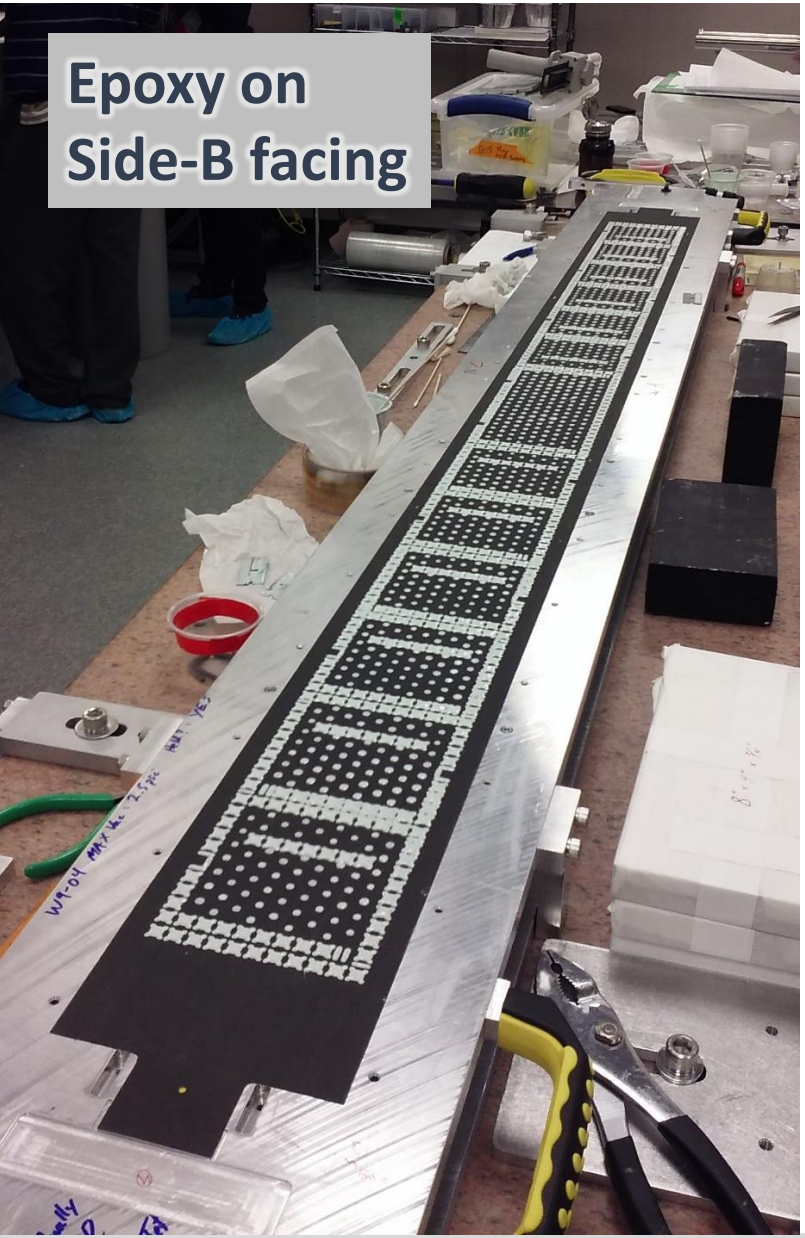
- Had to cut tube to length before brazing, and therefore before bending (we need two different lengths)
- Work by making empirical length correction
- First, bend tube of known length (=CAD length)
- Measure bent tube length over target length (for a few test tubes), typ. 35 mm over
- Reduce length of unbent tube by this amount
- Bend reduced length tube – roughly, see that material stretching and neutral axis effects give ~1-2 mm per bend
- Reached target length within a few mm

Cooling Tube Sub-Assembly – Yields (92 total)	
Overall:	82 good, 8 recovered as spares (short or leak-repaired), 2 lost
	2 damaged handling – recovered one
	1 damaged cutting – recovered as short
	4 brazes failed – redone, short
	6 brazes redone – double-ring, recovered
	3 leaks – repaired w epoxy+sleeve
	1 pressure test fail – lost

Stave Side-B Construction (1)



Stave Side-B Construction (2)



Tube now in trough

Side-B facing placed on pick-up tool vacuum fixture

Epoxy applied to facing with stencils

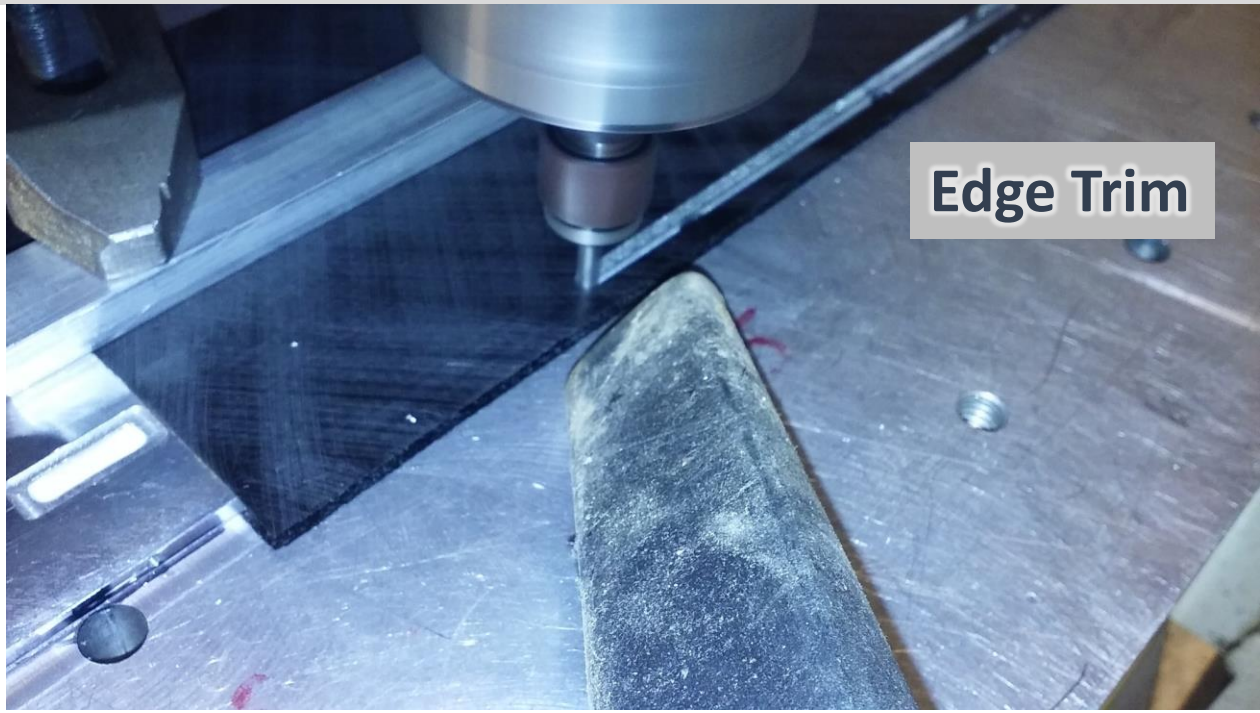
Vacuum pick-up tool flipped over, mating Side-A and Side-B

- Plates precisely located using alignment pins
- Clamp, weigh down, check gap size

Leave epoxy cure

This closes the bare stave

Finishing



Ultem inserts added to each edge (to allow handling when modules are mounted)

Edges (foam) sealed with epoxy

Edges trimmed of excess facing material and excess epoxy

Mass of bare staves ~450 g, RMS 5 g

Then, off to QA and flex attachment

Phase 2.
Flex Attachment to Stave

Flex Attachment (1)

Stave placed on vacuum pull-down baseplate fixture

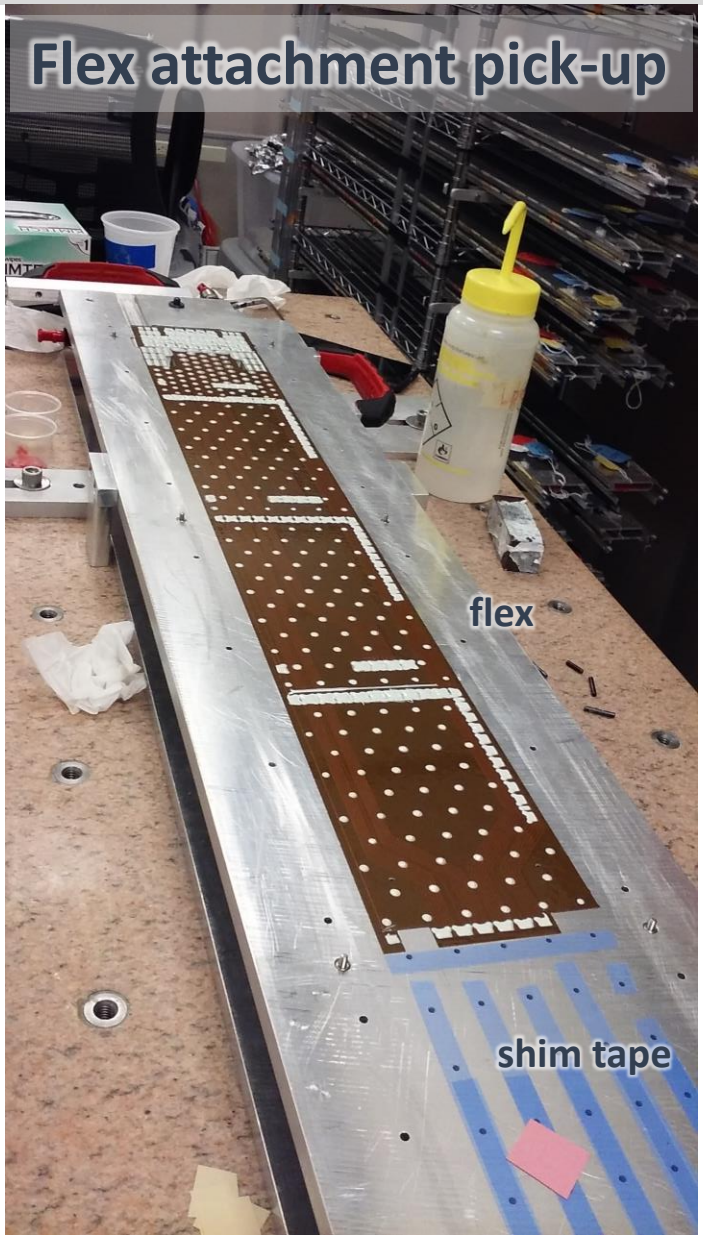
- Fixed by locator pins

Flexes placed on vacuum pick-up plate

- Two flexes per face
- Position fixed by locator pins

Epoxy applied to flex with stencils

- Pattern determined by areas where thermal interface must be good for heat transfer, or mechanical support must be good for wirebonding.
- Otherwise minimized for basic mechanical adhesion
- Reduced from full epoxy layer to ~35% coverage



Flex Attachment (2)

Flex pick-up tool is flipped over by hand so flex w epoxy contacts stave

Alignment pins locate pick-up with respect to base plate

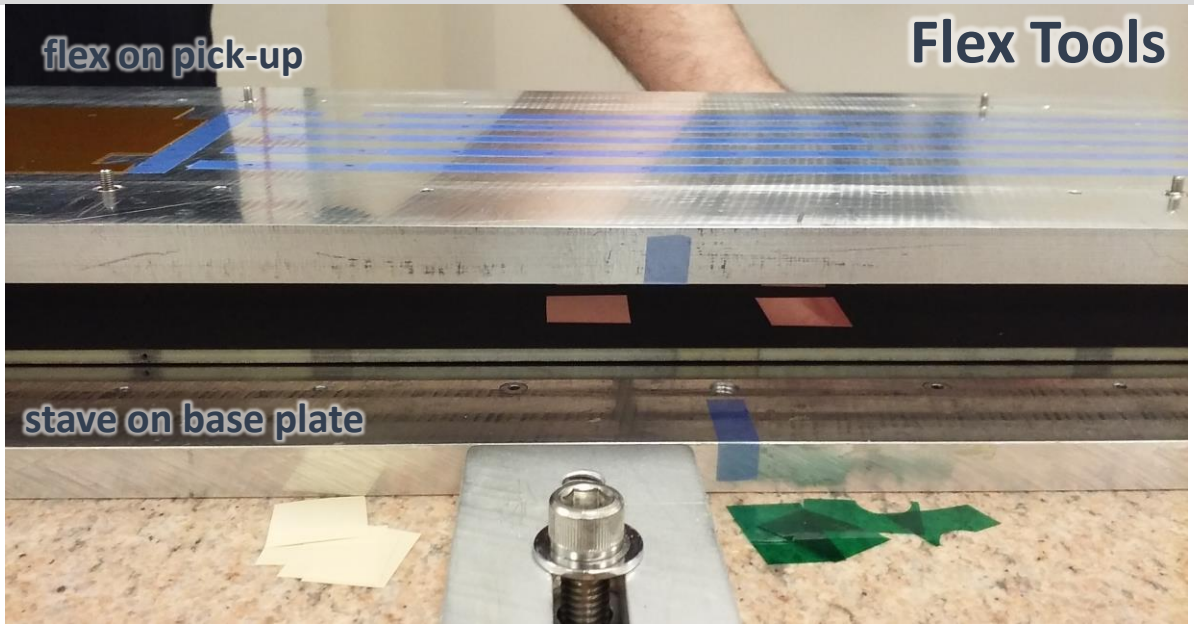
- round and diamond pins

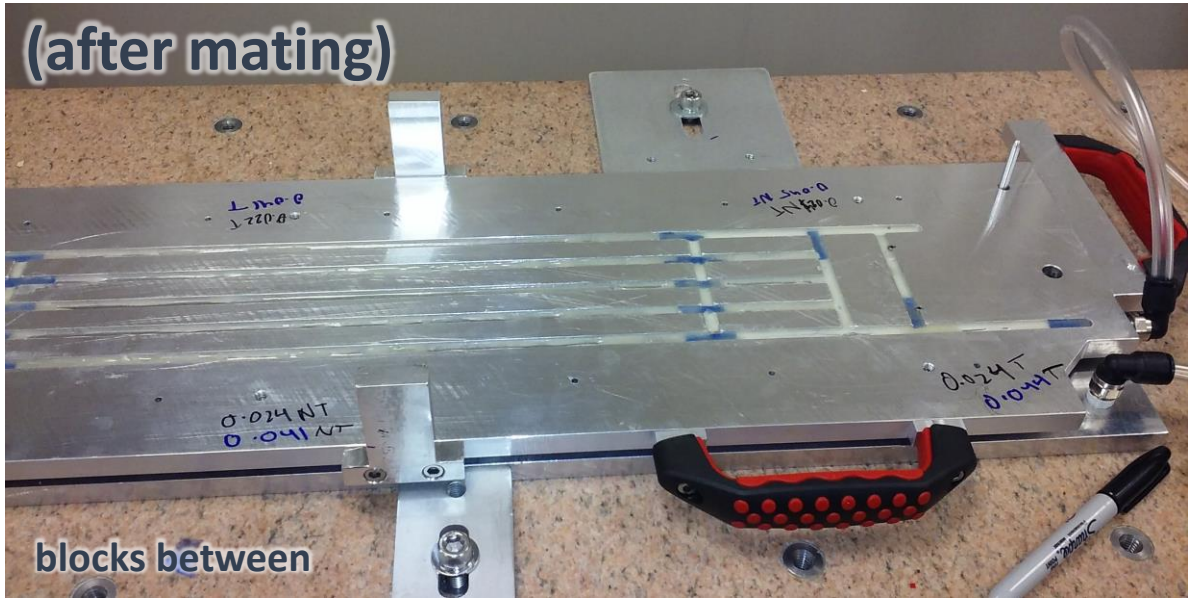
Gap is controlled by set screws and shim blocks

- At several locations along length
- After engagement, pick-up is lowered onto shim blocks as critical mating surfaces
- Set to keep a 0.1 mm gap for epoxy between flex and stave (following Cherwinka's rule)

Vacuum plates maintain flat flex surface

Epoxy is left to cure



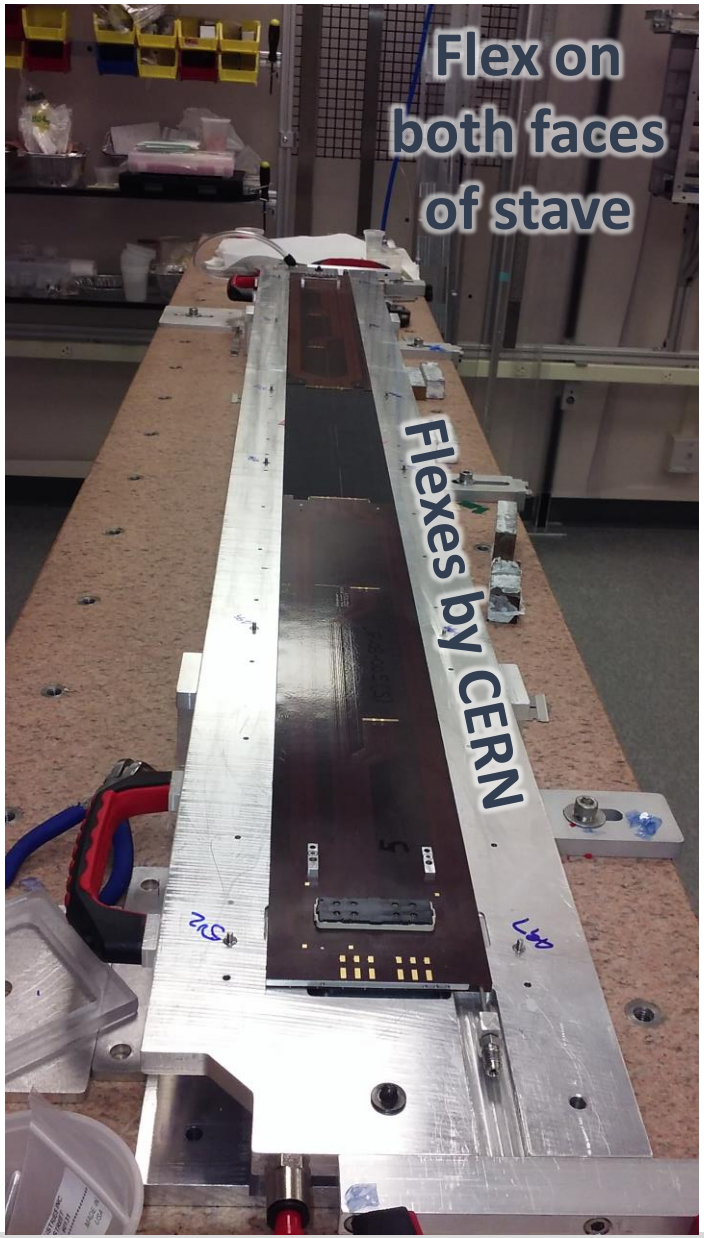


Flex Attachment (3)

First full stave done, both sides (i.e., 4 flexes), as well as several single faces

Flex fabricated by CERN workshop (Rui De Oliveira et al.)

Flexes in production now, awaiting first production batch to begin attachment process en masse



Phase 4.
Module Mounting
(Fully-Instrumented Stave)

Module Mounting on Stave

Precision location of sensors on stave

Modules are mounted individually

Baseplate fixture for module attachment

- Can only contact stave in certain areas, to avoid sensors, use riser blocks for support
- Stave fixed in known location
- Array of alignment pins determine where modules (sensors) are positioned wrt master ref datum

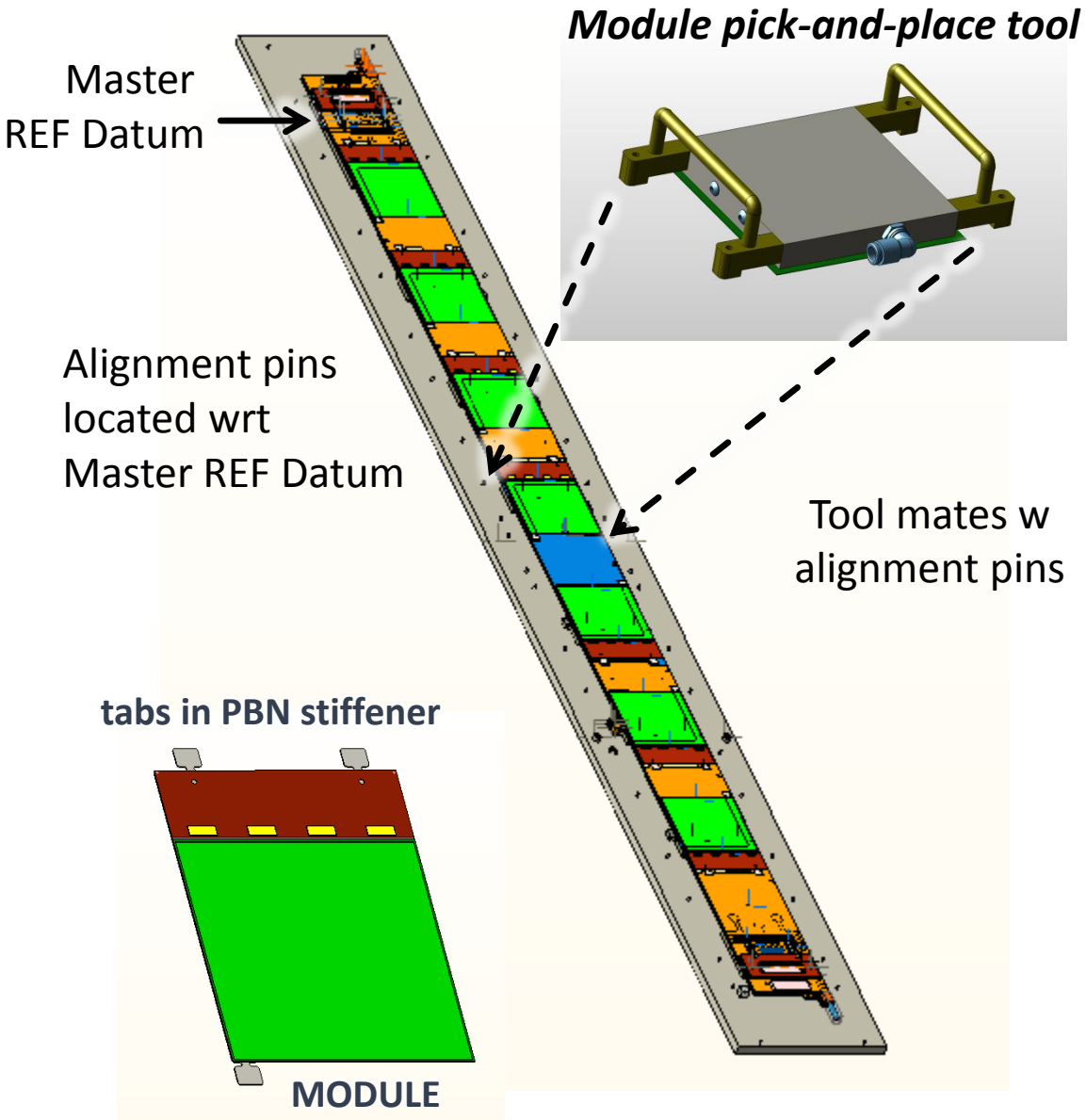
Thermal interface material film applied to stave and heated

- TIM Thermflow T725
- Heat to ~65°C

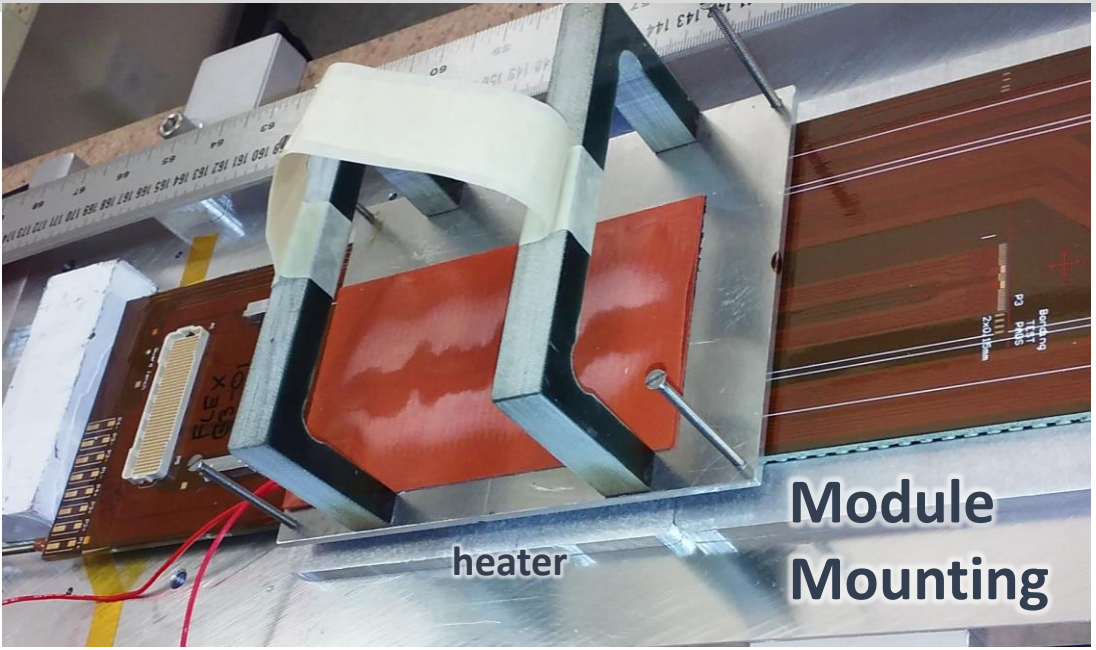
Hard epoxy applied to anchor tabs

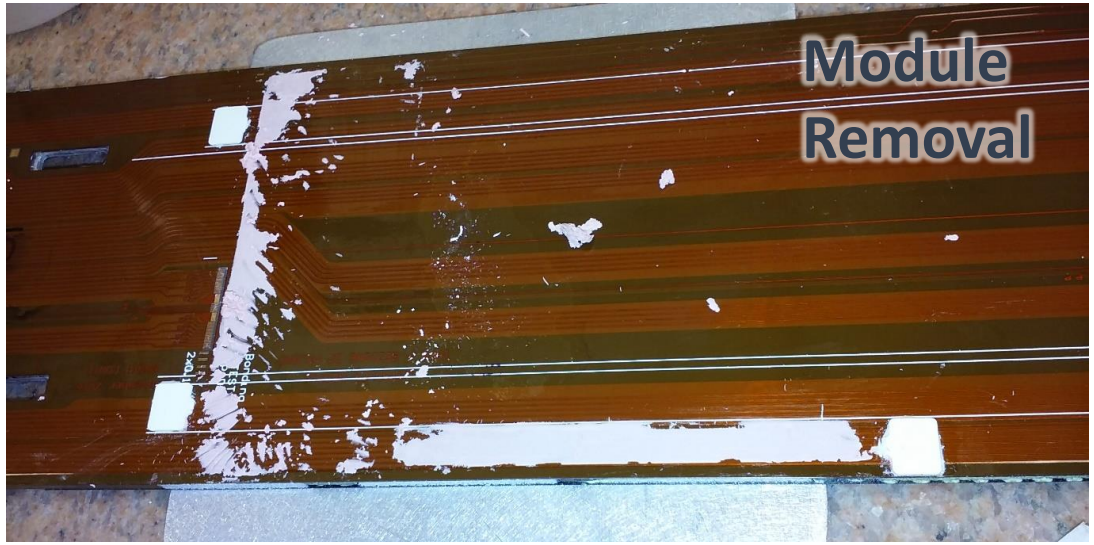
Vacuum pick-and-place tool transfers module to stave

Repeat for all modules on side



Module Mounting and Removal





Have mounted and removed several modules to stave w flex

- Using prototype heater
- Done by hand

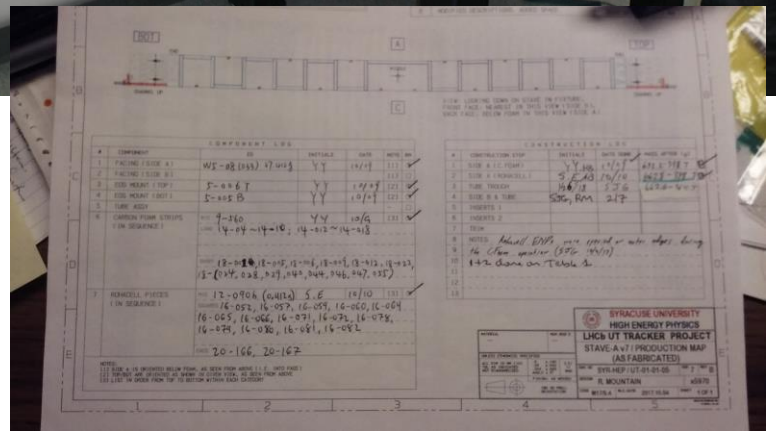
If module is damaged, can remove and replace it

- Effected by cutting tabs (at narrow necks)
- Removing thermal interface material (dissolves by applying acetone)

Awaiting hybrids + ASICs to start module construction

QA

Stave Process QA



Smartscope measurements

- Critical locations
- Construction feedback

Procedures

- Detailed written procedures on all construction processes for shifters
- Standardize and “industrialize” production of components, sub-assemblies, and staves (at least a bit)

Travelers

- Many steps and tasks to perform and check
- Checklist and signoff sheet that follows all staves, sub-assemblies, and batches of components
- Itemization of procedure step-by-step
- Process control to assure uniformity in construction

Training

- Best to train teams specialized in specific tasks

Database

- Repository of details of stave construction, which modules on which stave, where staves mounted in box, etc.
- All components, sub-assemblies, staves are labelled uniquely, and their measurements stored
- Absolutely necessary

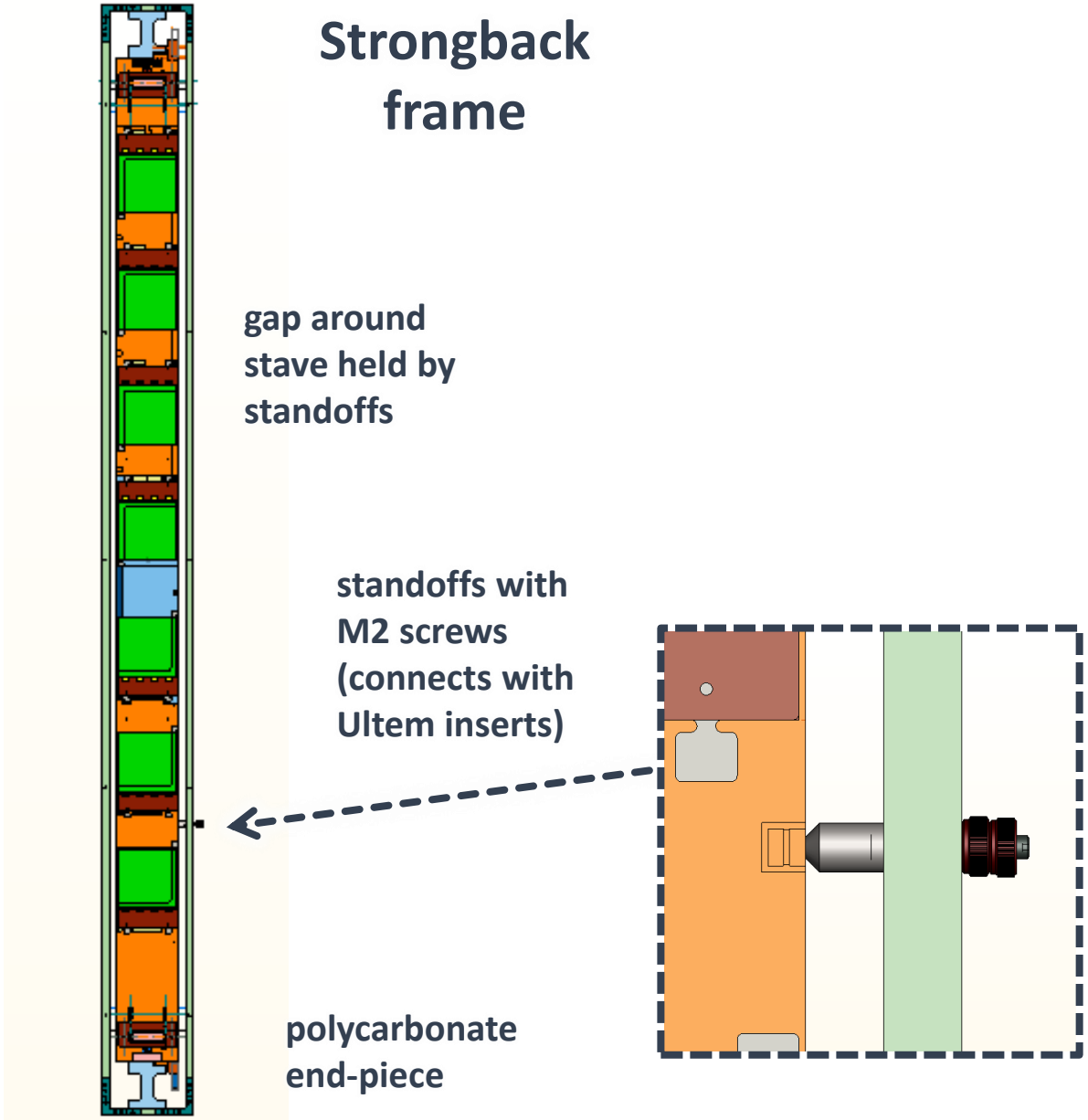
Shipping: SYR to CERN

Strongbacks

Frames designed to allow handling of staves after they are fully instrumented and to use for transport

- Strongbacks attach to stave around entire perimeter to threaded Ultem inserts in edges
- Box channel design provides stiffness when stave is oriented in manner not specifically designed to be

Fabricated by University of Cincinnati (M. Sokoloff, A. Bray)



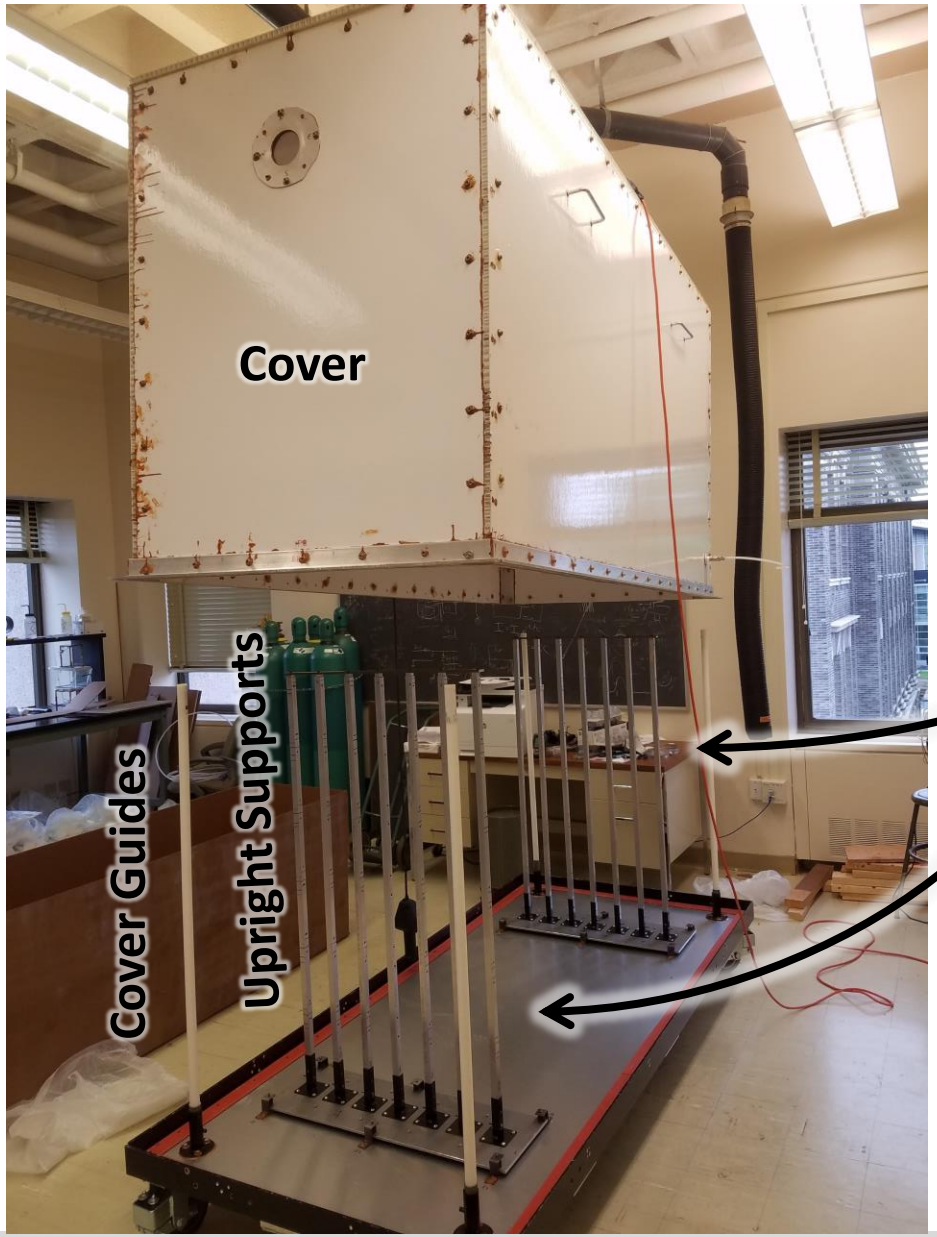
Transport to CERN (1)

Scheme #1: Transport Cart

- Ship 35 staves in strongbacks to CERN
- Three levels of vibration dampening and isolation, over wide absorption bandwidth
- No direct coupling between bottom plate and staves, or bottom plate and cart, use "Sorbothane" isolators
- Pressure relief valves (at +/- 0.1 psi) with air filtering, desiccant
- Vibration, temperature, humidity, and pressure datalogging
- Overall 1.1 m x 2.5 m x 1.5 m

Ship to CERN in outer (wooden) box on palette

Construction in progress at Syracuse (S. Stone, X. Liang, J. Shupperd)



Transport Cart

Staves go here

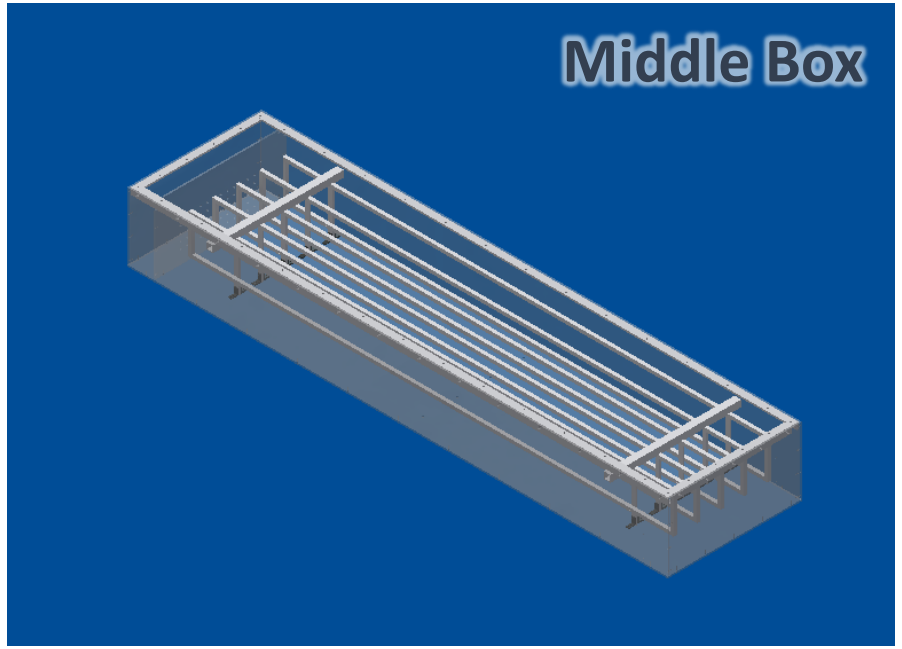
Transport to CERN (2)

Scheme #2: Five-Stave Box

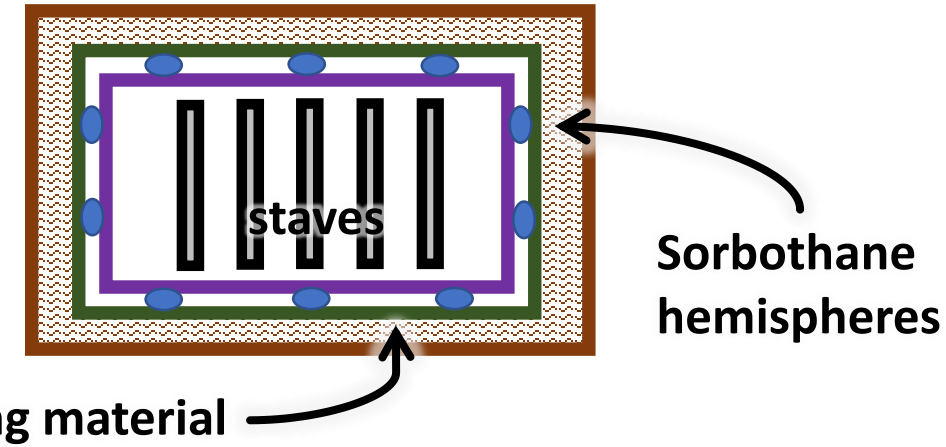
- Three nested boxes
- Inner box – holds 5 staves in strongbacks, polycarbonate, dessicant, pressure relief valves (at +/- 0.1 psi)
- Middle box – T-CORE material, lightweight, strong, impact-resistant
- Outer box – reinforced corrugated cardboard, treated with sealant and "Neverwet" waterproof coating
- Between each box is vibration isolation material: Sorbothane hemispheres, packing material
- Vibration, temperature, humidity, and pressure datalogging

Lighter than 150 lbs, so does not have to ship as "freight" which means more direct shipment and better handling "package service" is available

Plan to ship this box seven time for first half of staves, followed by the remainder of staves in transport cart



Shipping Scheme (cross section)



Summary

Summary and Plans

Bare stave construction completed

Flex attachment starts next week

Module mounting starts later this summer

Delivery of first half of staves throughout fall 2019. Second half early next 2020.

Assembly in box to be done on surface. Installation in LHCb to follow.

BARE STAVES PRODUCED

BARE STAVES	UT	SPARES	EXTRAS/ TEST	TOTAL
Type-A	52	5	3	60
Type-B	8	4	3	15
Type-C	8	4	2	14
	68	13	8	89

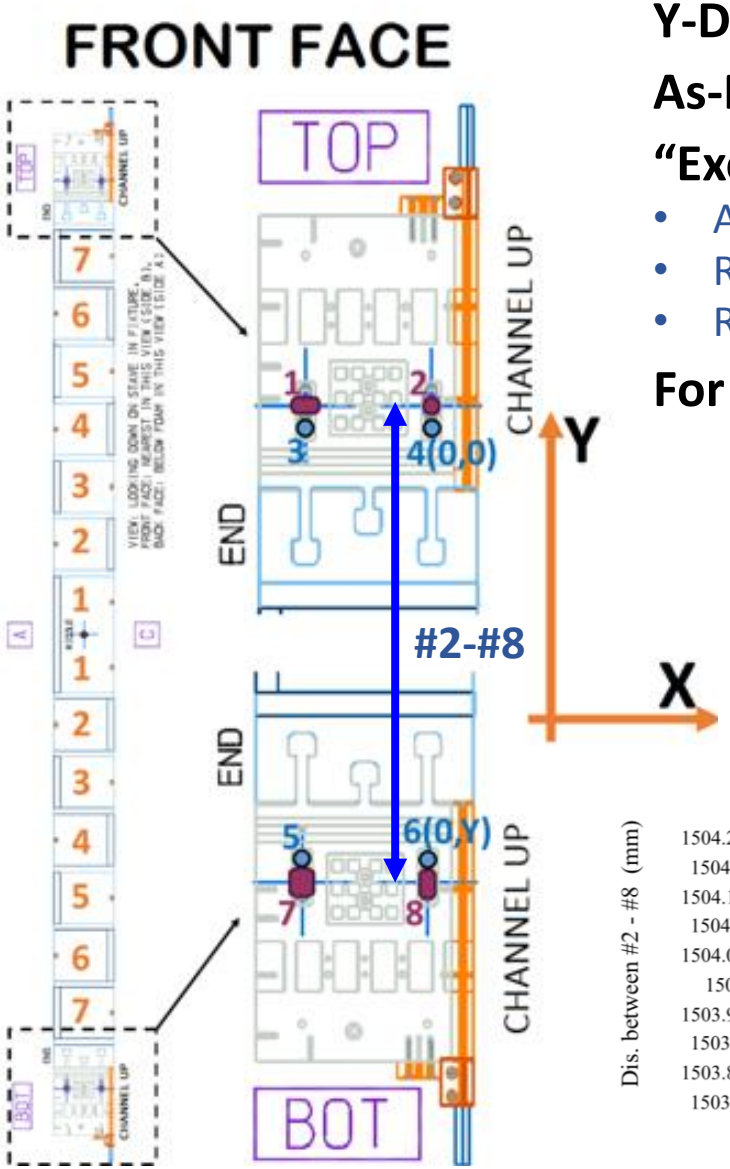
Note: Not all spares will be instrumented. "Extras" are staves used for tests or possibly spares if needed.

First test stave now at CERN: mounted in test box, under electronics testing

– FIN –

Length Metric for Constructed Staves

Xuhao Yuan



Y-Distance from top to bottom mounting holes (MNT-T1 to MNT-B1)

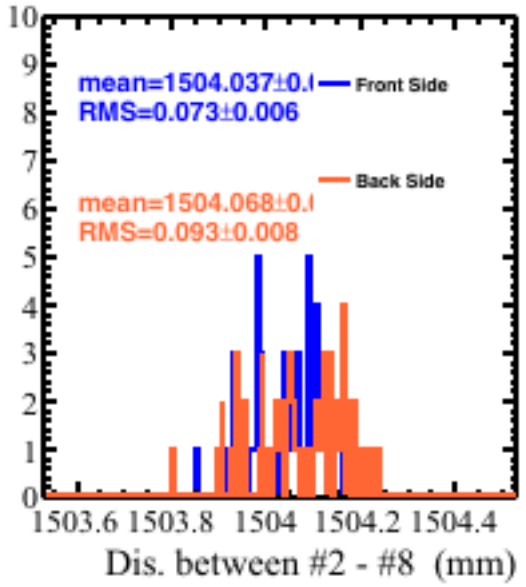
As-Fabricated lengths shown in histogram, all lengths shown in line plot

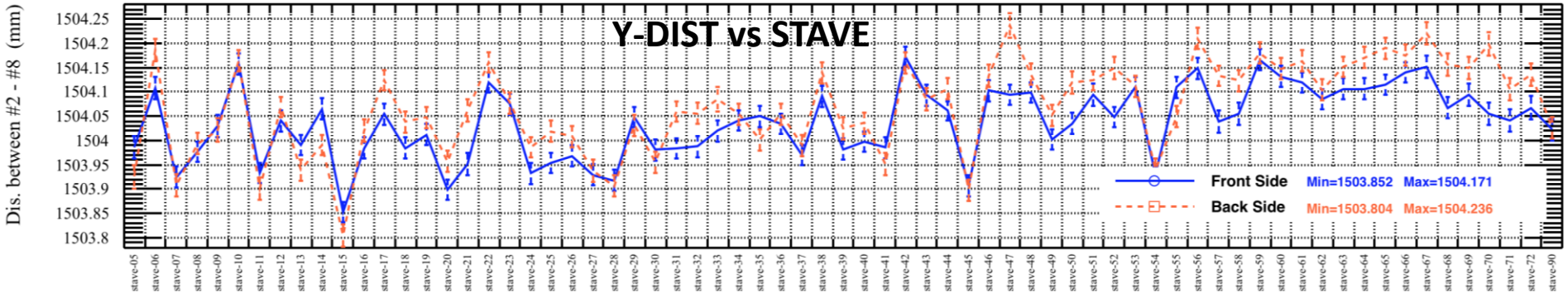
"Excess" metric gives comparison to target (CAD value)

- Average under 50 um (i.e., accuracy)
- RMS within 100 um (i.e., precision)
- Range within +/- ~200 um

For all Type-A and Type-B staves (Type-C in progress)

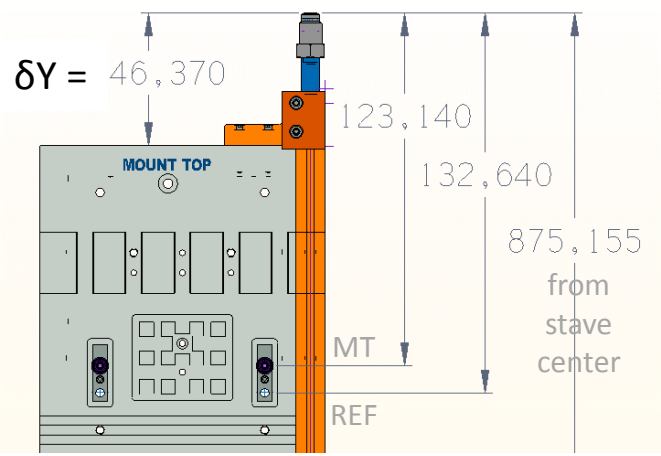
HOLE #	ELEMENT		Y [mm]	Y RMS	Y MIN	Y MAX	"EXCESS" [mm]	"EXCESS" MIN	"EXCESS" MAX
#2 - #8	MNT-T1	FRONT	1504.037	0.073	1503.854	1504.171	0.007	-0.176	0.141
	to MNT-B1	BACK	1504.068	0.093	1503.804	1504.236	0.038	-0.226	0.206
		CAD	1504.030	–					





Tube Extension in Constructed Staves

Harris Bernstein



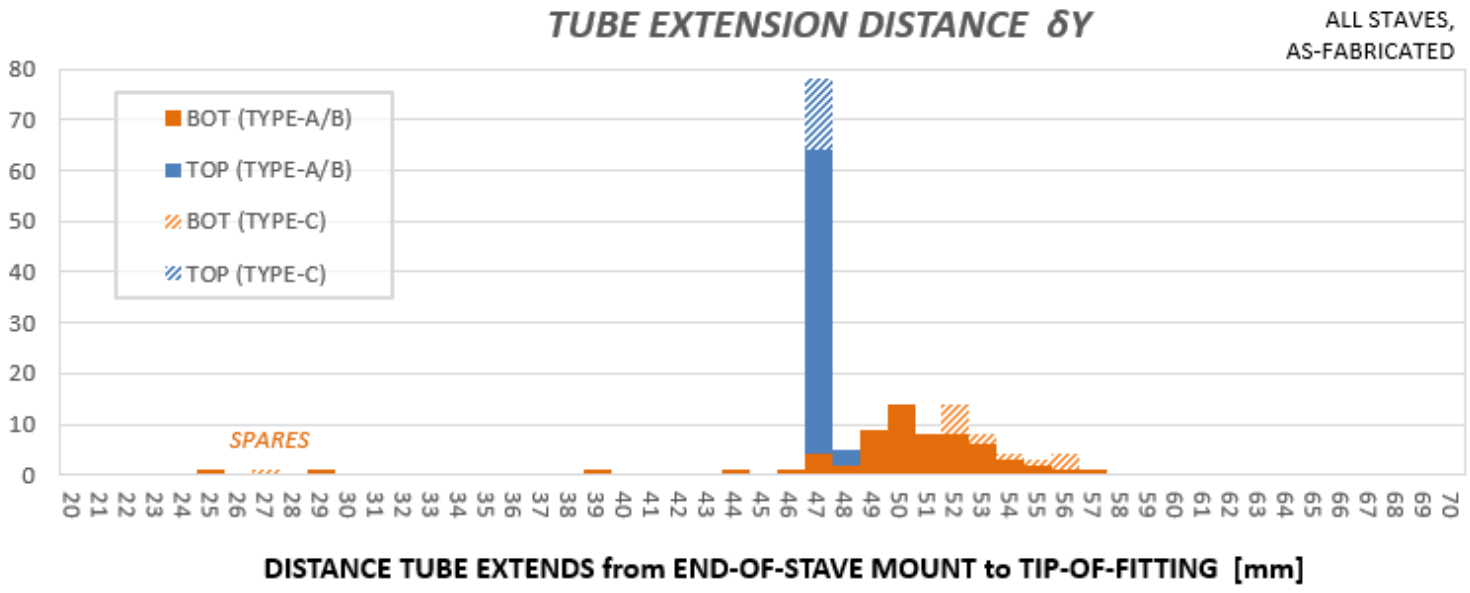
Distance tube sticks out from the end of stave, δY

Target given in drawing

As-Fabricated values given in histogram

- TOP very tight, near target, mean ~1 mm over
- BOT more of a spread, typ. ~10 mm range around mean of ~4 mm over, but a few shorter (can be mounted on TOP or BOT)

All bare staves



	TYPE-A/B		TYPE-C	
	TOP	BOT	TOP	BOT
ENTRIES	63	63	14	14
MEAN	47.4	50.1	47.4	51.9
RMS	0.2	5.0	0.0	7.3
SKEW	4.4	-3.2	1.1	-3.4
KURT	17.5	13.1	-2.4	12.3
UNFL	0	0	0	0
OVFL	0	0	0	0
MIN	47	25	47	27
MAX	48	57	47	56

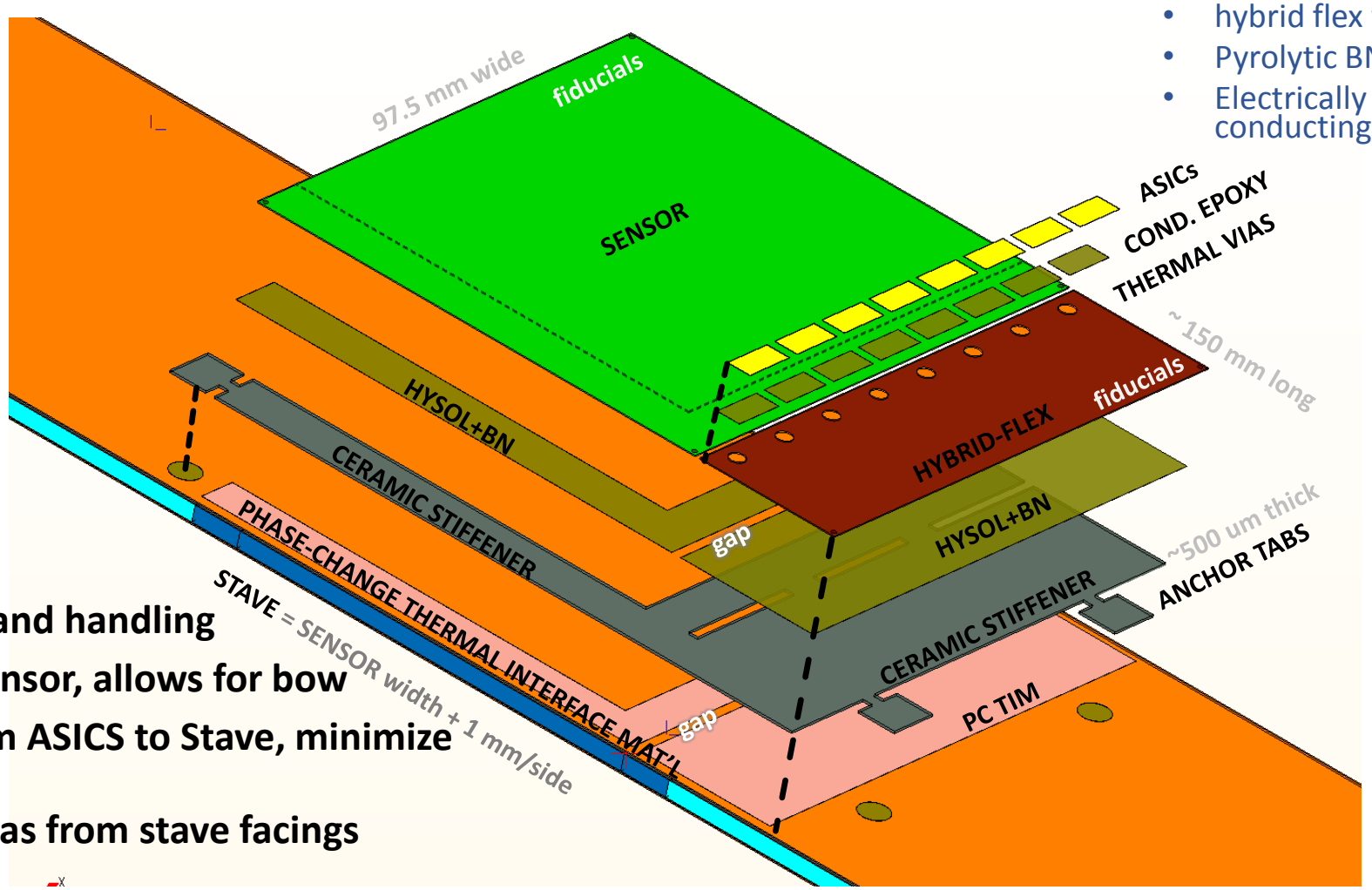
TUBE EXTENSION DISTANCE
TARGET: 46.370 mm

ABSOLUTE LHCB-Y POSITION
TARGET: 875.155 mm
(ADD 828.785 mm)

UT Module (exploded view)

Design options

- hybrid flex vs hybrid ceramic
- Pyrolytic BN vs AlN
- Electrically insulating, thermally conducting



Sensor: –5°C, ΔT=5°C

Stiffener: CTE match to Si

Protect wirebonds, testing and handling

Not mech over-constrain sensor, allows for bow

Maximize heat transfer from ASICS to Stave, minimize from ASICs to sensor

Electrically isolate sensor bias from stave facings (ground)

Reworkable epoxy (TIM): allows module removal if needed