LHCb UT UPSTREAM TRACKER
– Mechanics & Construction –

Ray Mountain
Syracuse University
for the LHCb UT Group
Introduction: UT Tracker

Stave

- Stave Design
- Stave Simulations: *Thermal, Thermo-Mechanical, and Dynamic FEA Studies*
- Stave Components: *Cooling Tube*
- Stave Construction: *Stave #01*

Superstructure

- Box Design & Beam-Pipe Interface
- Support Frame & End-of-Stave/Electronics Region

Summary and Plans

Cooling Tests, Cooling System and Manifold Design

→ *see talk by Simone Coelli (Wed)*
UPSTREAM TRACKER: INTRODUCTION
**Upstream Tracker (UT)**

- Four planes of silicon strip sensors
- To be located upstream of magnet, between VELO and Tracking System
- Replaces current TT
- Installation scheduled in 2019
UT has four planes constructed using “staves” with silicon on both sides, with partial overlap in X and Y directions to ensure full geometric coverage.

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.

Supported in box such that A/C sides retract.

Beampipe is captured by detector.

Basic mechanical unit “stave” …
STAVE DESIGN
Stave
• Main mechanical element of the UT
• Provides for the mounting and precise positioning of the silicon sensors
• Comprised of competing mechanical, thermal and electronic elements
• Vertical support
• Stiff sandwich structure
• Integrated with the cooling system
• Three types based on location

Components of fully-loaded stave
• “Bare” stave: basic innermost structural support / cooling tube
• Data-flex: signal readout / power distribution / control lines
• Module: Sensor / hybrid / stiffener, mounted on both sides of stave

Adapting ATLAS-type Integrated Stave concept
**Bare Stave**: CFRP (Carbon Fiber Reinforce Polymer) face sheets epoxied to foam core in sandwich structure with embedded cooling tube, all-epoxy construction.

**Foams**: thermal foam for heat transfer, lightweight structural foam for rigidity of sandwich structure.

**Cooling Tube**: Ti 2.275 mm OD, 135 um wall, “snake” shape, runs under all ASICs and edge of each sensor.

**Goals**: Keep sensors at −5°C or below, uniform ΔT=5°C across sensor, ASICs < 40°C (6 mW/ch, 0.768 W/asic).
Sensor: $-5^\circ C$, $\Delta T=5^\circ C$
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

Design options
- hybrid flex vs hybrid ceramic
- Pyrolytic BN vs AlN
- Electrically insulating, thermally conducting
STAVE SIMULATIONS
THERMAL, THERMO-MECHANICAL, MODAL ANALYSIS
**Thermal Loads for Full Stave**

**Heat loads**
- **ASICs**: 6 mW/ch (0.768 W/asic), 88/stave
- **Dataflex**: ~ 2 W/flex (10% power flow), 4/stave
- **Sensors**: < 1 W/sensor, self-heating in silicon after 50 fb⁻¹ is small, 16/stave

**Stave Type C = 75 W (worst case)**

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**Steady-State Thermal**

**Time**: 1.5
**15/03/2016 15:05**

- **ASICs Internal Heat Generation**: 0.14913 W/mm²
- **Pipe Temperature**: -25 °C
- **SENSORS A1T1 Internal Heat Generation**: 2.9724e-004 W/mm²
- **SENSORS A1T2 Internal Heat Generation**: 1.4137e-004 W/mm²
- **SENSORS A1T3 Internal Heat Generation**: 5.8986e-005 W/mm²
- **SENSORS A1TX Internal Heat Generation**: 5.6886e-005 W/mm²
- **SHORT FLEXBUS Internal Heat Generation**: 7.5155e-005 W/mm²
- **LONG FLEXBUS Internal Heat Generation**: 6.0098e-005 W/mm²

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"Simone Coelli, Mauro Monti (INFN Milano)"
Results show sensors can be kept below $-5^\circ C$, and uniformity $\Delta T=5^\circ C$

Consistent with previous $\frac{1}{4}$-stave models and earlier prototype measurements presented previously

This sets a baseline for the next analyses...
Stave ends are fixed at top, slotted at bottom

Thermal deformations

- Out-of-plane 0.63 mm, buckling
- In-plane 0.27 mm, thermal contraction (prototype: 0.5 mm)
Modal analysis gives resonant frequencies without amplitude information.

Low frequency resonances worrisome for safety of wirebonds.

Investigating ramifications and possible mitigation schemes to increase stiffness and/or add support points.

Plan a series of measurements to assess vibration sources in situ and to measure for real staves.
STAVE COMPONENTS
Face sheets

- K13C2U high-modulus carbon fibers in EX1515 epoxy matrix, 45gsm
- Layup is a three-layer stack of prepreg in 0/90/0 orientation
- This emphasizes stiffness of the sheet while allowing for thermal conductivity in both in-plane dimensions

The facings are easily cut and formed to the sizes we need

We have obtained several batches of facings and have found them to be of good quality and good uniformity

Fabrication by Composite Workshop at University of Liverpool (Tim Jones)
Thermal Foam

Thermal foam core component
• Allcomp K-9 carbon foam
• High thermal conductivity (~35 W/m.K), low mass density (0.2 g/cm³)
• Open cell foam
• Machinability is good

Ideal for spreading the heat transfer from a small tube to the large area required to cool the ASICs and sensors.

The machining of the foam is easy and the resulting surface can be made clean for epoxy.

Epoxy uptake measurements
• Takes epoxy up into carbon foam to a depth about equal to the size of voids, typ. 400-600 um
• Consider it a layer of ~0.5 mm which is a mix of epoxy and carbon foam, 70:30 roughly
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

Typically used in aerospace and industry as core material for a sandwich structure.

It is used as core in this design, and not as a structural element by itself.

Machined surface is left with opened foam bubbles so epoxy contact area increased, increasing the adherence.
Cooling Tube

- Titanium CP2 alloy
- OD 2.275 mm, 135 um wall thickness
- 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

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

Tube Issues:
- Bending
- Fittings
- Brazing
- Welding
Prototype tool: Bend one “wave” (four bends), then index and repeat
Production tool: Bend entire tube with single tool (no indexing), will ensure better repeatability, compensate for neutral axis shift and springback
Baseline fittings scheme

- Orbital weld VCR fittings to stainless stub
- Braze stub to Ti cooling tube, mate mechanically with insertion joint
- Double seal w external sleeve epoxied over braze joint

Issues

- Temperatures: welding before brazing
- In-situ repairs: variation of sleeve/epoxy (clamshell)
- Thermal stress on tubes
Done at local Swagelok facility

Key: Balance Ar pressure inside and outside tube, so avoid bulging of weld inside tube (which would restrict flow)

Made trials with 1/8 OD SS stub + 1/8 VCR fitting

*First results good*

**Ongoing:** Make full-sized Ti tube with these on both ends
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 paste
- 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)

Issues
- Brazing is the standard option for joining dissimilar metals.
- Must be done in vacuum: in air or argon, use organic flux, has contaminants
- Some coat stainless w Cu (highly corrosive environments)
- Process variables need to be pinned down
- Production will take place in dedicated setup
STAVE CONSTRUCTION
BARE STAVE PRE-PRODUCTION
Phase 1 Construction – Bare Stave construction [currently in pre-production]

Scheme: Procedure is an all-epoxy construction in precision fixturing

End-of-stave mounts hold datum serving as master alignment references for all stages in construction. Epoxied to end of facing (Side A)

Epoxy applied via stencil over large areas, volume control is important to assure structural soundness and low mass

Jigsaw hold-downs position foam core pieces after epoxy application. Cure.
Assembly in construction clean room @ SU (~year)

Construction using real materials and real construction techniques, and “finalized” stave design

...although obviously still working through the technique (including fixtures) and will modify as needed

**Stave #01 Construction (1) – Side A**

- **epoxy pattern**
- **facing**
- **vacuum fixture**
- **stencil**
- **surface plate**
- **core components**
- **poly. cover**
- **end-mount**
- **REF edge**
- **Side A closed**
- **Side A epoxy application**
Transport to machine shop. Mill trough in foam core for snake tube. Transport back. (Prototype shown, real Assy will be on a cutting fixture to maintain alignment)

Second facing (Side B) mounted to vacuum fixture 2

Tube already bent and ready.

Epoxy applied to tube via stencil. Tube laid into trough.


Open. Finishing operations. Inserts. Metrology. Bare stave is now done.

VACUUM FIXTURE 2 (Facing Side B)

VACUUM FIXTURE 1 (Facing Side A)

Demonstrator #1

Prototype snake tube
Stave #01 Construction (2)

- Side A trough cut
- Tube w brazed ends bent
- Vacuum fixture
- Cooling tube w fitting
- Full epoxy pattern
- Sides A, B mated, Stave #01 closed

→ Last op: trimming, Metrology/QA to come
Single reference edge insufficient

- Component dimensional uniformity will not be better than 1 mm over time, so they cannot be used to mutually self-align core components
- Want to maintain (few) 100 um precision in location, in order to maintain design performance for heat xfer elements, such as the cooling tube
- Fixturing needs to be modified to include locators for all core components

Stave edges should be sealed

- Avoid carbon dust (conducting)
- Apply epoxy to foam edge as component is made slightly oversized
- Cut into foam edge as make final trim to width

Tube bending is a tricky job

- Bending on a R=10 mm spool does not produce R=10 mm tube
- Length between spools is not maintained in the resulting tube (both due to effect of neutral axis)
- Indexing may be the most important part
- These all must be well-controlled if tube is to fit into a trough made by a CNC machine, and need to do so to make optimal tube/foam contact

Use “finalized” stave design

- Intended to lessen the effects on stave of design changes due to (ongoing) development in other parts of detector
- Range the tolerances imposed by reasonable variation of these external factors
SUPERSTRUCTURE:
BOX, BEAMPIPE INTERFACE, SUPPORT FRAME
Two halves of UT will retract from beam pipe
Box Design

Box surrounds the UT planes, and thermally insulates, maintains environment, provide EM shielding, etc. whilst having low XO

Current design

- Composite sandwich panels, all sides, with Airex foam core and CFRP skins
- Thinner versions for front/back panels
- Copper mesh as Faraday shield
- O-ring sealing between panels
- Beam plug has Airex disk and panel with foam seals
- About 1% XO
- Good stiffness as mechanical structure
Prototype box constructed @CERN

• Panels have good planarity: ~130 um ave

Will study

• Technical details of the joints in order to insure tightness,
• Integration of the copper net to ensure Faraday cage behavior
• Test the beam-pipe interface
• Test of thermal properties underway

Autoclave @CERN for panel preparation

1m x 2.5 m capacity

Box Prototype

860 x 500 x 400 mm³
Mounting stave to frame

- Mount w standoffs and custom studs
- Interleaved due to stagger/overlap
- Need access to be able to remove stave if fails

Difficult region, space limited
Route electronics readout, cooling tubes, etc.
SUMMARY & PLANS
LHCb Upstream Tracker is comprised of four planes of silicon sensors which are supported by integrated stave structures.

The UT stave has been designed using FEA model techniques, prototypes, component testing, etc.

Many components have been tested and qualified, some work still remains to be done.

Construction of (bare) Stave #01 finished, although it needs metrology and analysis. Refinements will follow.

Box and Frame design is progressing, with prototype. The end-of-stave region is dense and challenging.

**Phase 1 construction** (bare stave) in pre-production now.
After PRR in June, plan to start bare stave construction
- Soon will have all mechanical parameters and design choices necessary to begin construction
- This will allow us to construct all bare staves, which frees manpower and resources for subsequent phases

**Phase 2 construction** will start when data-flex cables become available
**Phase 3 construction** will begin when modules (sensors, hybrids) are available

Assemble at CERN in 2018-2019
Install in IP8 in 2019
Lots of work in progress on clean room...
(Stave) Construction Clean Room

Room Construction — *all finished*

- **Superstructure**
  - Wall supports
  - Trusses (like old RR bridges)
  - Cross Braces
  - Threaded rods with turnbuckles

- **Ceiling Grid**
  - HEPA fan units
  - Ceiling lights
  - Translucent panels
  - Power plugmolds

- **Walls**
  - PVC softwalls and curtains
  - Sealed outer walls
  - Inside supports for shelving, etc.

- **Floor**
  - Special tile with sealant

**Incremental Work — from here on**

- **Services**: vacuum lines, compressed dry air, spot lighting (as needed), internet drops, etc.
- **Storage**: components, intermediate assemblies, bare staves, etc.

**Equipment Installation — in progress**

- Granite tables for stave construction (in place)
- Smart Scope for metrology (next)
- Construction Fixturing (as fab)
Set up for module construction and wire bonding

Features 3 adjustable height ESD cleanroom workstations (2x 60”x30” and 1x 72”x30”) and wire bonder

Recent additions:

• Additional Power conduits installed, being connected to outside 20A circuits
• Internet drops added
• Added adjacent gowning room to separate clean from changing areas (gray)
• Service lines (vacuum, dry air) in progress
For testbeam modules:
- 2x TT hybrids assembled and wire bonded already
- 2 more hybrids are being worked on
Module Work Being Done

Module Construction Tests:
- V2 Assembly Jigs being tested
- Module Carrier PCB + Jig tests

TB Prep:
- Mounting plates and covers being assembled
- Sensor PCB cleaning and assembly

Wire bonding:
- Bonding Hybrids FE + BE
- Bonding Full Modules
**MATERIALS PROPERTIES**

**LHCb UT STAVE - MATERIAL PROPERTIES DATABASE USED FOR FE ANALYSIS**

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* NOTE

FACEPLATE: THE CFRP ORTHOTROPIC PROPERTIES HAVE BEEN CALCULATED WITH ESAComp SOFTWARE STARTING FROM PLY PROPERTIES MEASURED FROM THE UNIVERSITY OF WASHINGTON FOR THE CFRP HAVING THIS STACKING SEQUENCE: THREE PLY LAY-UP [0/90/0], FIBER $K13C + RESYN RS3 VOLUME FIBER 60% TOTAL THICKNESS 200 μm

R. Mountain, Syracuse University FORUM on Tracking Detector Mechanics 5/23/2016
Measure wall thickness

- Bend sections of tube, encase samples in epoxy
- Grind radial and longitudinal cross sections, polish surface
- Image under digital microscope
- Measure points on radii, bin

Wall thickness as a function of bend angle

- Fish-shaped (expected)
- Inner bend thickening, wrinkling
- Outer bend thinning
- Bending bunches material forward into the bend
- Consistent with studies carried out by H. Yang¹, N.C. Tang²

Technique is the same

- Measure points on inner/outer surfaces at even intervals on circumference

Wall thickness as a function of azimuthal angle

- Slight egg-like shape (expected), follows from longitudinal results
Module Materials

Acquiring and Testing component materials for mechanical / adhesive / thermal properties as well as radiation damage testing

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Glue</th>
<th>Thickness [mm]</th>
<th>Thermal conductivity [W/m/K]</th>
<th>phase change / burn in</th>
<th>Density [g/cc]</th>
<th>Operation range</th>
<th>Comment</th>
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<td>1.41</td>
<td>55C</td>
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<td>-55C to +125C</td>
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<td>-55C to +125C</td>
<td>film</td>
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**Pyrolytic BN – Typical Properties (@R.T.)**

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<th>Property</th>
<th>Value</th>
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<td>Apparent Density (gm/cc)</td>
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<tr>
<td>Tensile Strength (MPa)</td>
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<tr>
<td>Flexural Strength (MPa)</td>
<td>80</td>
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<tr>
<td>Thermal Conductivity (W/m.K)</td>
<td>“ab” 60, “c” 2 **</td>
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<tr>
<td>CTE (10^{-6}/°C)</td>
<td>“ab” 2 (@1000°C) 3.0 (-40 to +150°C) **</td>
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<tr>
<td>Resistivity (ohm-cm)</td>
<td>10^{15}</td>
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<td>Dielectric Strength (kV/mm)</td>
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<tr>
<td>Dielectric Constant</td>
<td>“ab” 5.2, “c” 3.4</td>
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<td>Total Metallic Impurities (ppm)</td>
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<td>Outgassing</td>
<td>&gt;Negligible</td>
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<tr>
<td>Maximum Suggested Use (°C)</td>
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* might work as is, but would have to grow thicker and cut slices to get max K
** from Morgan. Other values from Momentive. Compare to 2.3 for Si.
Measured ultimate shear strength (USS) for Thermflow films, using sandwich pull method.

Compared USS under irradiation at 30 MRad ($^{60}$Co $\gamma$-rays) for different curing conditions: no significant effect of irradiation for any sample.
Sensor Epoxied to PBN Stiffener

Difference in sensor profile after wrt before epoxy operation: effect of epoxying to PBN

Sensor MSL3092_10
(after–before epoxy, rotated)

Epoxied edges: one less, one more bowed
Free corner rotated down by ~250 um
(approximate size of free-standing sensor bow)
Have several samples of brazed tube in hand
- GH Induction Atmospheres (Rochester NY)
- LM 69-241 Ag-Cu alloy
- Single-joint, double-joint samples

Have several samples of epoxied tubes in hand
- Araldit 2011
- Armstrong A12

Types of samples made
- Single epoxy joint: one simple Ti/SS insertion joint with cap epoxied on end
- Double epoxy joint: one simple Ti/SS insertion joint, other Ti/SS insertion joint with sleeve
Pressure tests (ongoing)
- Raise sample to 150.bar
- Then let leak out, measure leak rate of sample plus system (in dead end line which is valved off from step-down regulator)
- Repeat with irradiated samples – Irradiation to 100 kRad ($^{60}$Co $\gamma$-rays)
- Repeat with thermal cycling (typ. 5 cycles, RT to $-15^\circ$C)
- Repeat with pressure cycling (typ. 5 cycles, 1 bar to 150 bar)

Samples tested
- Braze single joint: @RT
- Braze double joint: @RT
- Armstrong single joint (IRRAD): @RT, TC
- Armstrong double joint (IRRAD): @RT, TC
- Araldit double (IRRAD): @RT

All samples tested reached >150.bar without exhibiting any obvious leak, cracks, or other catastrophic failure modes
Assembly to be done in surface clean lab
  • LUCASZ cooling plant, powerful enough for more than a half-plane (425 W/half-plane)

Fully-instrumented staves shipped to CERN
  • Staves have been tested/QA before shipping

Box half with frame and cooling manifold assembled and ready
  • Has removable cover panels on open sides and dry air flush

Assemble half-detector (C)
Mount staves one-by-one on half-plane (inner first, e.g. UTAU)
  • Start from stave near beampipe, move outward
  • Connect back pigtails, mount stave to frame, connect cooling, connect front pigtails, connect HV cable to stave

After mounting stave, fully test all aspects of stave to qualify it for operation
  • Power up, cool down, read out
  • Mechanics: adjustments, cooling, deformations...
  • Electronics: test-pulses, readout, noise...
  • Need LV/HV power and cooling for each stave

If pass, mount next stave and test it
Repeat until half-plane done

Fully test half-plane
  • Establish level of operation of half-plane
  • Mechanics: deformations...
  • Electronics: half-plane readout, noise...
  • Need power and cooling for entire half-plane

Repeat assembly on next half-plane
  • Order: (AU-AX)-(BV-BX) — A then B
  • Or: (AU-BV)-(AX-BX) — Inner then Outer (Z)
  • Or: another order?

Partially test two adjacent half-planes
  • Mechanics: deformations, collisions...
  • Electronics: cross-talk between neighboring staves...
  • Need power and cooling for different groups of a few staves in-plane and in adjacent planes

Repeat until entire half-detector done
Rig half-detector into pit

Repeat for other half-detector (A)

Readout electronics assumed to be installed and ready prior to mounting staves
Four planes of sensors – Box/Frame retract – beam pipe is captured by UT
Standoffs in EOS mounts prevent crushing data-flex cable when mounting (both sides).

Standoffs on frame allow stagger in Z, which provides overlap in X.

**Custom stud**
- Locates stave in standoffs
- Thermal contraction in slots
- Kinematic movement via spring-loaded nut and spherical washer set

**Kinematic mounts at top and bottom of stave**
- Fixed at top
- Slotted at bottom