Tracking detectors

Light mechanical support structure
Outline

Light mechanical support structure

- **Layout** and **assembly** of the new ITS detector
- **ITS ultralight staves mechanics**
  - Production process
  - Performances
  - Future Development
The Inner Tracking System detector of the ALICE Experiment is being replaced in 2020. It is constituted by 7 layers equipped with ALPIDE chips. It is divided in a Inner Barrel, 3 innermost layers, and an Outer Barrel, 4 outer layers.

- The ITS is constituted by:
  - 7 layers: 3 (IL), 2 (ML), 2 (OL)
  - 192 Staves: 48 (IL), 54 (ML), 90 (OL)

Coolant Single-phase \( \text{H}_2\text{O} \) leak-less (< 1bar)
Pixel operational temperature < 30°C
Pixel max temperature non-uniformity < 5°C
Chip Power dissipation < 40mW/cm²
The basic building block of a stave is the module. The module is an array of 9 chips for the Inner layers and 2x7 chips for the Outer. 1 single module is used for the IB stave, while 4 and 7 modules are used for the OB staves.

Assembly of **ITS Module** (HIC)

CERN (DSF cleanroom) (IB)  
Bari (IT),  
Liverpool (UK),  
Pusan (South Korea),  
Wuhan (China),  
Strasburg (France)

Outer Barrel module (OB) 2x7 chips  
2238, nominal 1692

Inner Barrel module (IB) 1x9 chips  
48+48 for 2 IB produced  
working on spare
The **IB staves** are built at CERN

@ CERN

The **OB staves** are being built in 5 construction centres

@ Berkeley (US), Daresbury (UK), Frascati (IT), NIKHEF (NL), Torino (IT)

Assembly of **ITS Stave**

Flexible Printed Circuit (FPC)

9 sensors

Cold Plate

Connector

**Assembly**

Nominal 48+48 for 2 IB

**Spaceframe & Cold Plates**

> 300 produced

@ CERN

**Power bus**

**FPC**

2x7 sensors

**Cold Plate**

**Spaceframe**

**Connector**

**Fitting**

**module**

**IB stave**

**OB stave**

**Assembly**

Nominal 144
The **IB staves** are built at CERN.

The **OB staves** are being built in 5 construction centres.

Once ready the staves are assembled to form a layer.

@ CERN
Outline

Light mechanical structure

- **Layout** and **assembly** of the new ITS detector
- **ITS ultralight staves mechanics**
  - Production process
  - Performances
  - Future Development
Production process: **layout**

**IB Spaceframe & Cold Plate**

- **Positioning**
  - 0.3 m, 1.7 gr
  - Stave Precise positioning
  - End Pieces

- **Cooling**
  - Light-high thermal conductive
  - Cold Plate

- **Stiffness**
  - Light-stiff mechanical
  - Spaceframe

**OB Spaceframe, OB Cold Plate**

- **Positioning**
  - Stave Precise positioning
  - End Pieces

- **Stiffness**
  - Light-stiff mechanical
  - Spaceframe

- **Cooling**
  - Light-high thermal conductive
  - Cold Plate

Connection between Space Frame and Cold Plate
Satve mechanics production process: **ingredients**

The materials used are carbon rowing, fleece, prepreg and carbon foil for thermal management.

**Polyimide tube:** ultrathin tubes available in different size and with different features.

<table>
<thead>
<tr>
<th></th>
<th>E [GPa]</th>
<th>X_t [MPa]</th>
<th>K [W/mK]</th>
<th>CTE [K^{-1}]</th>
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<tbody>
<tr>
<td>PI</td>
<td>2.5</td>
<td>305</td>
<td>0.205</td>
<td>40</td>
</tr>
</tbody>
</table>

IB  Inner Diameter 1.024 mm  wall thickness 25 µm

OB  Inner Diameter  2.05 mm  wall thickness 32 µm

**Carbon Fleece:** continuous-strand mat finished with a chemical binder to hold fibers in place. Filament diameter= 5µm, th=20 µm, 8g/m2.

**Carbon Roving:** Bunches of filament parallel to each other. Filament diameter=5 µm

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<td>M60</td>
<td>3K</td>
<td>103</td>
<td>588</td>
<td>3.92</td>
<td>151</td>
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<tr>
<td>M55</td>
<td>6K</td>
<td>218</td>
<td>540</td>
<td>4.02</td>
<td>155</td>
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</table>

**Carom Unidirectional Prepreg:** Ready to mold or cure material in sheet form which contains fiber all aligned in one direction. Filament diameter=11 µm

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</tr>
</thead>
<tbody>
<tr>
<td>K13D2U [0] fibre</td>
<td>2K</td>
<td>935</td>
<td>3688</td>
<td>800</td>
<td>-1,1</td>
</tr>
</tbody>
</table>
| K13D2U [0] prepreg  | 2K       | 563      | 1800/340  | 6        | ~450                | 1.2 / 61
| Ex1515 cyanate resin|           |          |           |          |                     |

**Thermal Pyrolytic Graphite:** Thermal management material with very high thermal conductivity and flexibility.

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</thead>
<tbody>
<tr>
<td>Amec FGS_003</td>
<td>30</td>
<td>1.6</td>
<td>1500</td>
<td>15</td>
</tr>
</tbody>
</table>

**Carbon foil:**

- FAW inner Diameter 1.024 mm  wall thickness 25 µm
- FAW inner Diameter  2.05 mm  wall thickness 32 µm

**Human hair**

Human hair 5-11 µm

**Encompass**

Encompass 5-11 µm
Production process: recipe

IB Spaceframe & Cold Plate

1. Manual lay-up on mould 1: Cfleece/K13D2U 90°
3. Mould 1 and 2 closure
4. Curing at 24°C for 24h
5. Post Curing at 125°C for 3h
6. Remove pipes mandrels
7. Cold Plate Finishing
8. Locate the Cold Plate in the winding moulds
9. Place the three vertex M55J longitudinal threads
10. Wind with M60J
11. Cure at 24°C for 24h
12. Remove inside mandrel
13. Cut wound thread at moulds interfaces
14. Space Frame Finishing
15. Connectors gluing
16. Hydraulic Fitting gluing
17. Cold Plate Coating
18. QA test
19. Store
20.
**OB Spaceframe**

1. Prepare impregnated carbon thread and prepreg
2. Cover external moulds with vaseline/teflon tape 10 micron
3. Place resin with aerosil in the 3 external moulds at ribs extremities
4. Place impregnated thread ribs in the groves of the 3 external moulds
5. Press and cover with teflon (30mm width in the central region of 42mm mould)
6. Prepare the 3 internal 1/3 wedge mandrels with vaseline/teflon
7. Place prepreg strips and thread on the edge of the moulds, apply resin on both sides
8. Insert the 1/3 internal wedge-mandrel
9. Install the tubular enflatable internal mandrel
10. Install the other two 1/3 internal wedge mandrel
11. Install the bottom external mould
12. Thighten the bolts
13. Rump up temp at 100°C and apply 3-4 bar pressure in the enflatable mandrel
14. Cure at 130°C for 3 hours
15. Open mould extremities for enflatable mandrel extraction
16. Rump down the temperature 90°C, wait 30 min
17. Open the mould at 90°C, remove spaceframe
18. Cool to room temperature
19. Finishing, cleaning
20. Connectors gluing
21. Coating
22. QA test
23. Store

**OB Cold Plate**

1. Prepare carbon paper, prepreg, fleece, pipes and resin
2. Cover mould for substarte with vaseline/teflon tape 10 micron
3. Place plyies of fleece prepreg and fleece inside the bottom mould
4. Close the mould with the top part
5. Cure at 130°C 3h, extract the substrate for next use
6. Prepare polyimide tubes with internal steel wire mandrel
7. Cover the mould (Plate side) vaseline/teflon film
8. Cover the mould (pipe side) with Penta 111 (silicon oil) and teflon
9. Place the impregnated substrate from step 5 in the mould
10. Place fleece on bottom mould/ put resin
11. Place carbon paper on bottom mould/put resin
12. Place tubes with mandrels in the mould
13. Join top and bottom mould, screw together
14. Cure 24h at Room Temperature
15. Finishing clening
16. Connectors + Hydraulic Fitting gluing
17. Cold Plate Coating
18. QA test
19. Store
**Mechanical connectors**

The Stave is positioned on the end wheels reference planes by connectors at both extremities that engage a ruby sphere fixed in the reference plane. The Stave position is then frozen by a bolt.

**Hydraulic connectors**

SSSteel fittings 316L connected to PUR plastic tube, tightness provided by mechanical interference.

**Hydraulic connectors**

Provide spaceframe accurate positioning.
Outline

- **Layout and assembly** of the new ITS detector
- **ITS ultralight staves mechanics**
  - Production process
  - Performances
  - Future Development
Material/layer: ~0.3% $x/X_0$ (IB)

- Single stave, for perpendicular tracks
- Tilted stave with overlap, inclined tracks

Material/layer: ~1% $x/X_0$ (OB)

- Single stave, for perpendicular tracks
- Tilted stave with overlap, inclined tracks

Whole layer overall

- $X/X_0=0.276\%$
- $X/X_0=0.346\%$
- $X/X_0=1.039\%$
- $X/X_0=1.157\%$
Characterization of the stiffness of ultralight weight structures through touchless measurement system

**Static**

- 1.5 kg
- 1.5m, 35 gram
- Bending and torsional test performed

**Dynamic**

- 1.7 grams

**Flexural stiffness**, \( EI = \frac{FL^3}{a \text{sag}} \)

**Type of fixation**

- Both ends free: concentrated load \( a=48 \)
- Both ends fixed: concentrated load \( a=192 \)

**Torsional stiffness**, \( GI_p = \frac{ML}{\phi} \)

**Beam with Concentrated Mass**:

\[
fn = \frac{1}{2\pi} \sqrt{\frac{g}{\text{sag}}}
\]

**Mile’s equation SDOF**:

- Natural frequency, \( fn \)
- Constant PSD input (P value), \( \xi \) damping ratio
- Accel. response, \( X_{GRMS}(fn, \xi) = \frac{\pi fn}{2 \sqrt{2\xi}} P \)

**Touchless deformation measurement**: 3D laser scanning

**Bending test results**

**Frequency [Hz]**

- 1st frequency 108 Hz
- 2nd frequency 146 Hz

- Acceleration response
- Natural frequency
- \( X_{GRMS}(fn, \xi) \)

**Sine Sweep**: Vertical [m/s²/V]

**Before**
Dynamic stability: input Data

Vibration environment acquisition at ALICE Experiment

Acquisition sensors set-up:

- Cavern floor
- Inside ALICE experiment

The Input data of power spectral density (PSD) is taken as much as possible close to the detector interface.
**Dynamic stability:** prediction of sensors stability

Predict sensor stability in operative environment (seismic, cultural noise, cooling, services, ...)

Frequency domain transfer function $H(f)$ coming from dynamic characterisation

$$R_y(f) = |H(f)|^2 R_x(f)$$

Expected short-term displacement X-RMS

$\Rightarrow$ X-RMS < 1 µm @ 3-100 Hz
**Dynamic stability**: prediction of sensor stability

Finite Element Analysis used to predict stability of cantilevered Inner Barrel

\[ R_y(f) = |H(f)|^2 R_x(f) \]

Conservative Damping factor 1%

Cage has been considered rigid

All B.C. have been excited

**Structural analysis and modal analysis of entire barrel**

Based on static and dynamic characterisation of IB stave

- 51 Hz
- 66 Hz
- 79 Hz
- 130 Hz
- 161 Hz

Relative Y-displacement

\( \text{Input: } 0.7 \, \mu\text{m} \rightarrow \text{Output: } \sim 1.0 \, \mu\text{m} \)
**Air-circulation: mechanical stability**

The ITS has a dry air-circulation with a minimum flow <2m/sec for Detector Volume humidity control and temperature uniformity.

Minimum air flow in ITS does not affect stave stability <1um Experimental verification performed using wind tunnel (CLIC)

Measured PSD of the amplitude of out-of-plane vibrations at different locations along the length of the CLIC stave

RMS of the amplitude of out-of-plane vibrations at different locations along the length of the CLIC stave
**Thermo-elastic stability**

**Objective:** Determine the stave thermo-elastic expansion

**Test article:** IB Space Frame 25mm sample

**Test procedure:** temperature increase and sample length change measured by LVDT*

**Test article:** OB Space Frame & Cold Plate

**Test procedure:** temperature increase and sample length change measured by microscope.

*linear variable differential transformer

CTE< 5µm/m/°C

CTE< 4-6µm/m/°C

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<table>
<thead>
<tr>
<th>DIL 402</th>
<th>T. Alpha x10^-1/°K</th>
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<tbody>
<tr>
<td>Atmosphere</td>
<td>Helium at 150 ml/min</td>
</tr>
<tr>
<td>Calibration standard</td>
<td>Graphite</td>
</tr>
<tr>
<td>Temperature program</td>
<td>RT to 150°C at 1°C/min</td>
</tr>
<tr>
<td>Sample length</td>
<td>approx. 25 mm</td>
</tr>
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</table>

@ CERN EN-MME

Δl resolution: 0.125 nm / 1.25 nm

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Graph showing temperature program RT to 150°C at 1°C/min and sample length approximation 25 mm.
Objective: Determine Stave thermal stability and thermal map in operative condition

Test article: IB stave (Spaceframe & Cold Plate + HIC)

Test procedure: operate stave continuous trigger, temperature recorded at time intervals

Objective: Test procedure: operative mode, start-up, alternatives modes

70% of the power dissipated over 10% of the chip surface

100 kHz trigger, 1024 pixels occupancy
Analog: 1.8 V 108 mA,
Digital: 1.8 V 915 mA

Other tests performed...

Determine Stave thermal response during start up
Determine Stave thermal map at different trigger rates (100kHz and 400 kHz), ...
Burst pressure

Beside water leak-less system (p<1bar) the Cold Plates have been characterized up to burst pressure.

**Objective:** Determine the maximum inside pressure that a Stave can withstand before burst

**Test article:** IB Cold Plate

**Test procedure:** increase water pressure up to burst

**Objective:** Determine the maximum inside pressure that a Stave can withstand before burst

**Test article:** OB Cold Plates

**Test procedure:** increase water pressure up to burst

Polyimide Pipe Burst @ ~ 50 bar

Tests repeated before and after irradiation

Dose: \(1.7 \times 10^{13}\) MeV equivalent neutrons

Systematic tests on all staves up to 3bar.

System operative pressure < 1bar
Outline

- Layout and assembly of the new ITS detector
- ITS ultralight staves mechanics
  - Production process
  - Performances
  - R&D and Future Development
R&D performed during ALICE stave development

Upper structure (M60J fibre)
Silicon frame with microchannel
Peripheral cooling

Silicon microchannels

Carbon fleece (20 µm)
K13 D2U (120 µm)

3d printed Accura25

No pipes
In hadron collider vertex detectors stringent cooling requirements, driven by the minimisation of radiation damages, will need the development of new heat exchanger substrates to achieve better performance and lower temperatures.

Cold plate: **silicon microchannel**

- **CMOS-compatible processes**
- Microchannels on the back of the sensor
- Channel
- Parylene coated channel

**See A.Mapelli presentation**

Cold plate: **3D print titanium**

- 3D printed ceramic, ...
- Different materials engineered for CTE compatibility
- Lego concept

See J.Buyaert presentation

Cold plate: **Carbon vascular**

- Carbon Layers
- Polyimide pipes available on the market down to a diameter of 51 micron (burst pressure up to 340 bar)
- Lego concept

See also next slide....

**R&D** future Hadron collider (high rad.) **Vertex** detector, substrates
R&D: Future tracker large surface coverage, ... high pressure

- Future large surface coverage: compromise between minimum material, cooling performance and cost
- Cheap and flexible large substrate such as carbon fibre structures embedding polyimide pipes

Alice ITS R&D study several parallel pipes (4 pipes)

High pressure, minimum bending radius

POLYMIDE PIPES
available on the medical market, used in HEP and tested up to 50 bar, braided pipes allow for larger pressure value, (hoop strength almost double), and smaller bending radius.

Alice ITS OB Stave
1.5 m

ITS OB Stave
1.5 m

Alice MFT (LS2)

DEVELOPED BY
USED IN ALICE
in 2 DETECTORS: ITS and MFT (LS2)
WILL BE ALSO USED BY

ALICE
NICA
SPhENIX
SINE
MPD

needs R&D for full thermal characterization for high pressure and two phase fluid compatibility,...

Needs R&D for full thermal characterization for high pressure and two phase fluid compatibility,...

(already tested with C₄F₁₀)

<table>
<thead>
<tr>
<th>Øi (mm)</th>
<th>Tol +Ø (mm)</th>
<th>Min Th. (mm)</th>
<th>Max Th. (mm)</th>
<th>Pmax [Bar] @th.min</th>
<th>Pmax [Bar] @th.max</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.051</td>
<td>0.0051</td>
<td>0.00635</td>
<td>0.0127</td>
<td>169.8</td>
<td>339.6</td>
</tr>
<tr>
<td>1.024</td>
<td>0.0127</td>
<td>0.0254</td>
<td>0.1778</td>
<td>36.8 (50*)</td>
<td>257.3</td>
</tr>
<tr>
<td>2.052</td>
<td>0.0178</td>
<td>0.032</td>
<td>0.1778</td>
<td>23.2 (25*)</td>
<td>128.9</td>
</tr>
</tbody>
</table>

*used in ALICE ITS – MFT and tested
The design of new vertex detectors in lepton collider will have to cope with unprecedented requirements on minimum material budget and dimensional stability.

- Reduction of material in front of the sensor will be pursued by investigating new sensors technologies and air cooling solutions.
- Air/gas cooling flow to cope not only with thermal but also with structure vibration requirement.
Proposal for a new vertex detector:
- new beam pipe with IR = 16 mm, wall thick = 0.5 mm
- three truly cylindrical Si-pixel layers based on ultra-thin, curved sensors
- material budget: X/X₀ ≈ 0.05%
- inner-most layer: at R = 18 mm

Installation foreseen for LS3:
- replacing Inner Barrel of ITS2 (the upgraded ITS being installed now in LS2)
- Outer Barrel of ITS2 will stay in, Installation foreseen for LS3

Key improvements:
- reduction of material budget (0.35% → 0.05% per layer) and equalisation of its homogeneities
- increase of tracking precision and efficiency at low transverse momenta

- chip size is traditionally limited by CMOS manufacturing ("reticle size")
- new option: stitching, i.e. aligned exposures of given parts of a reticule to produce a larger circuit
- feasible, but needs specific design
- on a with 300 mm wafer (available in 65 nm technology node), a single chip fits a full half-layer

Bending Si wafers + circuits is possible!
Radii much smaller than ALICE needs are obtained
Circuit-specific R&D is needed
R&D contact with IZM (Fraunhofer) has started
Investigating options to start with existing ALPIDE chips + wafers

Courtesy: R. Turchetta, Rutherford Appleton Laboratory
**R&D: ITS2** being installed in **LS2**

- **Glue (90µm)**
- **Pixel Chip (50µm)**
- **Coating Parylene (10µm)**
- **FPC (175µm)**

Dimensions:
- ~ 280mm, 50 bar, 1.7 gr
Si only 1/7 of total material

Non uniformity due to overlaps+ support/cooling

Remove water cooling

Possible by reducing power consumption in fiducial volume to <20mW/cm²

Remove external data lines+ power distribution

Possible to make a single large chip and use that for distribution

Remove mechanical support outside acceptance

Benefits from increased stiffness by rolling Si wafer

ALPIDE already close: ~40 mW/cm² actually largely sufficient if periphery outside fiducial volume
New beam pipe:
“old” radius/thickness: 18.2/0.8 mm
new radius/thickness: 16.0/0.5 mm

Possible layout based on air-cooling/ peripheral cooling
Sensors hold in place with low-density carbon foam
Fixation into the experiment by surrounding support structure, as well as at both ends
Cooling at the extremities (chip peripheries)

Extremely low material budget:
Beam pipe thickness:  500 µm (0.14% X0)
Sensor thickness:    20-40 µm (0.02-0.04% X0)

Convective heat transfer enhancement by bonding a layer of foam to a solid substrate and allowing gas to flow across the foam surface.
For the innermost layers of future lepton collider vertex detectors, the reduction of material budget and the mechanical stability should be pursued by:

- **minimizing active cooling** material through new optimised micro capillary or peripheral cooling design;
- **eliminating active cooling and rely on air or gas cooling**, possible for low dissipated power (<20 mW/cm²) and low rad levels;
- **eliminating on detector electrical substrate**, possible if the sensor covers the full stave length (stitching) and connectivity is provided at sensor edge;
- **eliminating the support structure** providing self-supporting sensors by exploiting the flexible nature of thin silicon (<50 μm).

In hadron collider vertex detectors, stringent cooling requirements, on the removal of dissipated heat and on the limitation of radiation damage, will require the development of new heat exchanger substrates to achieve better performance and lower temperatures. Promising directions to investigate:

- **Silicon microchannel on the back of the sensor**
- **3d printing microchannel substrate**
- **carbon microvascular substrate**
Back-up
Assembly of ITS Half Barrels

Layers are then assembled to form Half-Barrel @ CERN
Installation of **ITS Half Barrels**

Half Barrels are inserted from one side of ALICE, driven by a system of rails provided by an ultralight carbon structure called Cage. The Inner Barrel is cantilevered in the active area to minimize material.
Carbon foam used as radiator in detector GAS cooling application

It is possible to obtain **convective heat transfer enhancement** by bonding a layer of foam to a solid substrate and allowing air to flow across the foam surface. The high effective conductivity ensures that the layer of foam readily entrains heat out of the solid substrate to be swept away by passing fluid. Convective heat transfer enhancement then occurs in two ways: first due to the **roughness of the exposed surface**, and second due to the **additional surface area exposure** to fluid that infiltrates the foam.

**Graphite foam heat sinks**
(a) block, (b) stagger, (c) baffle and (d) zigzag configurations.

**Carbon foam**: high thermal performance, properties are porosity dependent

<table>
<thead>
<tr>
<th></th>
<th>POCO HTC</th>
<th>Density [g/cm³]</th>
<th>K In plane [W/mK]</th>
<th>K Out of plane [W/mK]</th>
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<tbody>
<tr>
<td>0.9</td>
<td></td>
<td>70-245</td>
<td></td>
<td>245</td>
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</table>

The most important problem facing the graphite foam heat exchanger is the **pressure drop**. In order to reduce the pressure drop, it is important to adopt an appropriate configuration of the graphite foams.