Development and evaluation of prototypes for the ATLAS ITk pixel detector

Quentin Buat (CERN) on behalf of the ATLAS ITk collaboration
HL-LHC and the ATLAS detector upgrade

- Upgrades of the CERN accelerator complex in 2025-2027: HL-LHC
  - Instantaneous luminosity 5-7x nominal LHC
  - Integrated luminosity 10x nominal LHC
  - Up to 200 interactions per bunch crossing
- Major upgrade of the ATLAS detector required
A new tracking system for ATLAS: ITk

- Current ATLAS tracker can not cope with the HL-LHC running conditions:
  - Replace with an all-silicon detector
  - Pixels: 13 m² of silicon, ~5 billions channels
  - Strips: 160 m² of silicon: ~50 millions channels
  - Extreme radiation tolerance, high granularity and acceptance, low material budget
The ITk pixel detector

- 3D sensors in the innermost layer, planar sensors in other layers

- Pixel size: 100x25 μm² for the flat section of the innermost layer
  50x50 μm² everywhere else

- Coverage up to |η|=4

- Fast data transmission with up to 4x1.28 = 5.12 Gbit/s per FE chip

- Minimisation of material budget:
  - CO₂ cooling, serial powering, lightweight carbon structure

- 5 pixel layers:
  - ~10k modules,
  ~35k readout chips
Serial Powering

- Modules connected in series and powered by a constant current source (fast switching behaviour to react to load changes)
- All FES on a module powered in parallel
- Two Shunt LDO regulators on each FE chip to generate constant operating voltage for digital and analog parts
- Hardwired interlock system for protecting the detector
- Additional monitoring by regular FE diagnostics
- Less material, more efficient power distribution but more risk to lose large number of modules
- ~1000 SP chains with 3 to 13 modules in series

Serial powering:
T. Stockmanns et al., NIM A511 (2003) 174-179
D. Bao Ta et al., NIM A557 (2006) 445-459
L. Gonella et al., JINST 5 (2010) C12002
System Tests

- System test programs for all subsystems:
  - Mechanical, thermal, electrical and readout tests
  - Validate / amend the original design, exercise the production chain (QA/QC), prepare the setup for the assembly and integration
- Multi-chip modules with RD53 frontend not available yet
  - Study integration and system aspects on other prototypes
  - Modules based on the FE-I4 chip (used in the ATLAS IBL detector)
Module assembly for outer barrel prototypes

- Multiple-step process up to fully assembled module
- Performed as distributed effort over several institutes in France, Germany, Japan, Switzerland and CERN
- Continuous quality control (QC) and qualification of the modules
- ~80 built and qualified to date
- Exercise for the full production
- More details on modules in Jörn Lange’s talk
Small electrical prototype for outer barrel

- Electrical 7-quad module structure as first step before full-size prototype
- HV power supply used had high-ohmic off mode inducing a forward bias in the last sensor
  
<table>
<thead>
<tr>
<th>Module ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor current (μA)</td>
<td>-4.8</td>
<td>-3.7</td>
<td>-*</td>
<td>-*</td>
<td>-19.9</td>
<td>-2.3</td>
<td>30.3</td>
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</tbody>
</table>

- Lead to adjustment of the HV PSU requirement
- Continuous Quality Control (QC) allows comparison of module performance (e.g. noise) at different stages
- no influence of joint operation on local support observed

Typical continuous QC test
Outer Barrel Demonstrator

- Full size local support: 1.6m long
- CO$_2$ cooling
- Environment-controlled and monitored box
- 32 Duals and 14 Quads modules: 120 FE-I4 (currently under test 54)
- 6 Serial Powering Lines (currently under test: 3)
- Realistic FE-I4 services, cables, PSUs, DCS, interlock, etc…
Half-cooling line setup

**C0₂ cooling pipes**

**Bent pigtail flex**

<table>
<thead>
<tr>
<th>ITk OB design</th>
<th>Half cooling line setup</th>
<th>Module type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demonstrator</td>
<td>Inclined modules (FE)</td>
<td>Flat modules (FE)</td>
</tr>
<tr>
<td></td>
<td>13 (26)</td>
<td>7 (28)</td>
</tr>
<tr>
<td>Layer 2</td>
<td>6 (24)</td>
<td>9 (36)</td>
</tr>
<tr>
<td>Layer 3</td>
<td>8 (32)</td>
<td>9 (36)</td>
</tr>
<tr>
<td>Layer 4</td>
<td>9 (36)</td>
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</table>
Versatile system for electrical studies

<table>
<thead>
<tr>
<th>Powering options</th>
<th>Duals 2</th>
<th>Duals 1</th>
<th>Quads</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV</td>
<td><img src="image" alt="Default" /></td>
<td><img src="image" alt="Default" /></td>
<td><img src="image" alt="N/A" /></td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Merged" /></td>
<td><img src="image" alt="Merged" /></td>
<td></td>
</tr>
<tr>
<td>HV</td>
<td><img src="image" alt="Default" /></td>
<td><img src="image" alt="Default" /></td>
<td><img src="image" alt="BM1-BM7" /></td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Merge" /></td>
<td><img src="image" alt="Merge" /></td>
<td></td>
</tr>
</tbody>
</table>

Module names:
- Duals 2: IM9-IM13
- Duals 1: IM1-IM8
- Quads: BM1-BM7

C0₂ cooling pipes
- Duals
- Bent pigtail flex
- Quads
Operations at low temperature ($T(CO_2) = -25C$)

- Three serial powering lines connected on a single cable saver board
  - BM1-BM7 (quads), IM1-IM8 (duals), IM9-IM13 (duals)
- **Successful operations of three serial powering lines on a single local support!**
  - Lost communication with some modules due to finicky connection between pigtail and flex
  - Exercise switching off each line individually and test compatibility of threshold and noise scans
- Enable a series of electrical and readout tests: some examples in the following slides
1 versus 2 HV lines for the flat section

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<tr>
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</tr>
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The image shows a table with the following entries:

- **Powering options**:
  - LV Default
  - LV Merged
  - HV Default
  - HV Merge

- **Duals**
- **Bent pigtail flex**
- **Quads**

The table compares different powering options and module names for CO2 cooling pipes.
1 versus 2 HV lines for the flat section

- Tune and operate modules with no high voltage, 1 HV or 2 HV line
- $T(CO_2) = 17^\circ C$
- Observe an increase of the noise without HV (expected)
- Similar noise level with 1 or 2 HV line
- Valuable input for the HV powering scheme of the final detector
1 SP lines instead of 2 for the inclined section

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**CO₂ cooling pipes**

- Duals
- Bent pigtail flex
- Quads
2 SP chain versus 1 for the dual modules

- Tune modules in both setups at $T(\text{CO}_2) = 17\text{C}$
- Module LV after tuning is similar
- Run threshold and noise scans on each FE:
  - Overall very similar, some noisier frontends at the end of the line for the 1 SP scenario
System tests for the endcaps

First prototype (‘Ring-0’) with realistic local supports
- L3 ring with one quadrant fully populated with 12 electrical quad modules (2 serial powering lines)

Second prototype (‘Ring-1’) planning
- L3 half ring, 2 SP chains, 11 quad module / side
- RD53 FE chips
Conclusion and outlook

- Outer Barrel demonstrator built confidence in the serial powering scheme
  - Commissioning of a second half-cooling line ongoing (with more functional modules)
  - Could operate 6 SP chains in parallel (useful for readout studies)
- First generation of endcap prototypes used to establish many mechanical and electrical aspects of the detector
  - Valuable input for the design and specifications of the final detector (e.g., services)
  - Lots of experience gained toward production
    - Next generation of demonstrator with (close to final) front-end chip
      - Will allow to verify services design with real local supports, services and modules.
    - Data transmission tests
    - Include prototypes for the inner system with 3D sensors
Additional material
Endcap FEI4 prototype

- Prototype AI stave with SP chain of 6 quads -> upgraded to double side CF stave with 12 quads
  - Materials: CFRP, Rohacell & Al comp (carbon foam), boron loaded adhesive
  - Water cooling: titanium pipe (2.275mm diameter)
  - Low-mass structure ~100g / 55g (with / without tapes)
  - Modules qualified on test card before mounting

- Tapes allow mounting of 6 quads / side -> Serial powering for 12 quad modules -> 48 FEs total
  - 2 x SP chains of 6 or 1 SP chain of 12
  - SP chain extended to 13 using module on test jig -> 13 is SP chain max length for EC
Endcap FEI4 prototype

- No additional noise seen when modules are tested in isolation compared with tests in SP chain

- Different voltage drops seen on quads before configuring chip -> requires specific power on sequence -> issue with FE-I4

- Tuning down to IBL QA levels is possible with SP chain, 1500e- threshold, < 200e noise, < 270 pixels masked
Endcap FEI4 prototype

Double sided stave with 8/12 quads in SP chain - testing with external trigger

- Test beam at CERN SPS 120 GeV $\pi^-$
  - Large scale test of RCE DAQ -> 12 quads -> 18 data links -> 48 FE's in SP chain
  - Clustering and efficiency measurements on quad in the beam
  - First test beam with FE-I4 quad flex
  - Analysis ongoing

Tests of SP chain with external trigger and cosmics in the lab
- Long term stability of DAQ -> 2 weeks data taking -> 8 quads (4 each side)
Table 5: Parameters for the ITk outer pixel inclined section. The number of rows of sensors is the same per-layer as in Table 6. The radii refer to the innermost point of the sensors. The total length in $z$ of the outer barrel sections (flat and inclined) is 104.7 cm.

| Barrel Layer | Radius [mm] | $|z|$ [mm] | Sensors per Row | Module Type | Angle [deg] |
|--------------|-------------|-----------|----------------|-------------|-------------|
| 2            | 150         | 372-1047  | 6              | quads       | 67          |
| 3            | 218         | 372-1047  | 8              | quads       | 58          |
| 4            | 281         | 372-1047  | 9              | quads       | 55          |

Table 6: Parameters for the ITk pixel flat barrel. The number of sensors per row refers to a half-row ($z > 0$ mm) in the central, flat part of the barrel where sensors are placed parallel to the beam line.

| Barrel Layer | Radius [mm] | $|z|$ [mm] | Rows of Sensors | Sensors per Row | Module Type |
|--------------|-------------|-----------|-----------------|----------------|-------------|
| 0            | 39          | 0-245     | 16              | 12             | singles     |
| 1            | 99          | 0-245     | 20              | 6              | quads       |
| 2            | 160         | 0-372     | 32              | 9              | quads       |
| 3            | 228         | 0-372     | 44              | 9              | quads       |
| 4            | 291         | 0-372     | 56              | 9              | quads       |
Radiation Lengths: Run2/ITk comparison
Shunt LDO