Overview of the ATLAS Insertable B-Layer (IBL) Project

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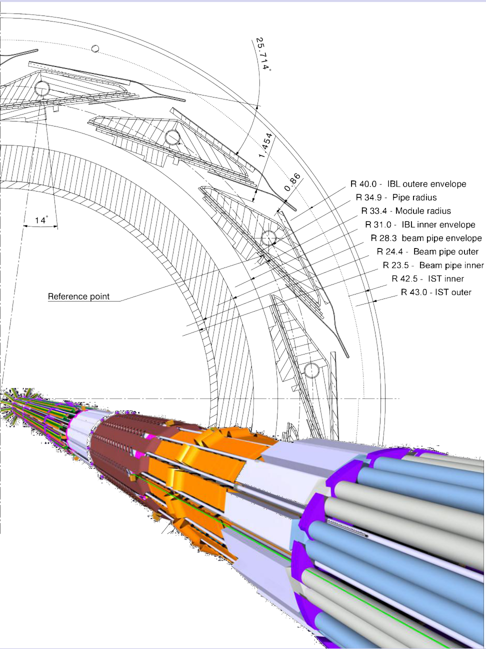
Outline

1. Experimental background and detector layout
2. Electronics, sensors, and modules
3. Local support and detector services
4. Assembly, integration and installation
5. Conclusion and outlook
6. Backup slides

The ATLAS Insertable B-layer



Another ATLAS B-layer

Key parameters

layout:	14 staves (turbine topology)
module radius:	R33.4 mm
active length:	64 cm
channels:	12 M pixels
envelope:	9 mm cylindrical shell

To be installed during the long LHC shutdown (2013-14)

Insertable detector system

The active staves will be fitted with service extensions and integrated on the new R23.5 mm beam pipe. The 7 m long IBL package will be inserted through the aperture of the existing Pixel system.

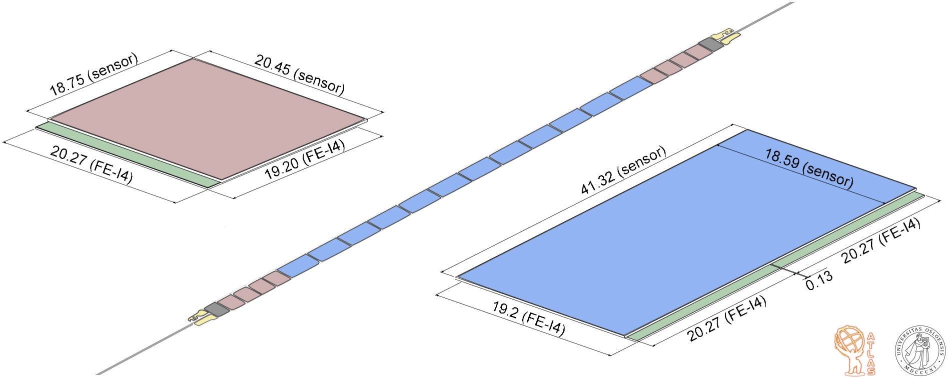
Detector modules on local support

25% single-chip modules:

- Double-sided 3D sensors
- Single front-end ASIC per module
- Four modules in one HV/LV service group
- Deployed at the high-η ends of the staves

75% double-chip modules:

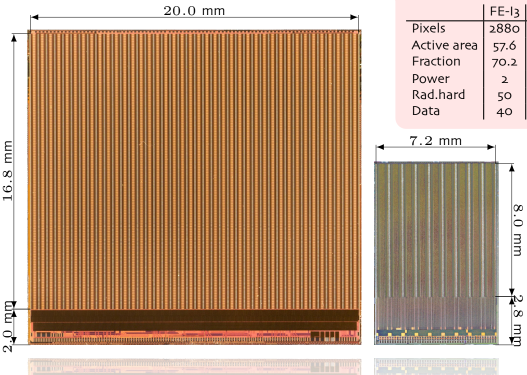
- Slim-edge n+-in-n planar sensors
- Two front-end ASICs per module
- Two modules in one HV/LV service group
- Covers the central part of the detector



Frontend electronics: the FE-I4 135 nm CMOS ASIC

Requirements:

Pixel size:	$50 \times 250\ \mu m^2$
Organization:	336×80 (rows $\times$ cols)
Threshold:	$4000\ e^-$ (in-time)
Dispersion:	$100\ e^-$ (tuned)
Noise:	$< 300\ e^-$ (400 FF)
Pixel capacitance:	$0 - 500$ fF
Charge resolution:	4 bits (TOT)



Comparison:

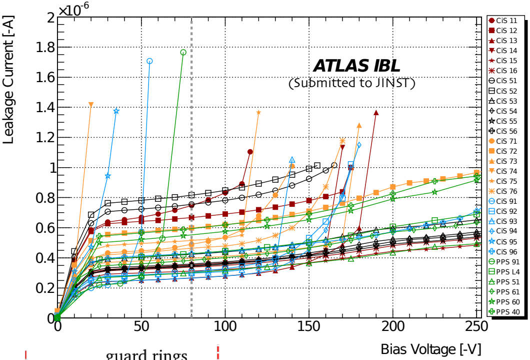
	FE-I3	FE-I4	
Pixels	2880	26880	
Active area	57.6	336	mm^2
Fraction	70.2	88.5	%
Power	2	2	mW/mm^2
Rad.hard	50	250	MRad
Data	40	160	Mbs

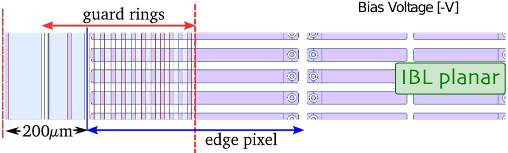
FE-I4 - features and innovations:

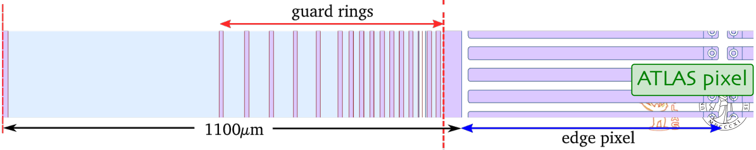
- Four-Pixel Digital Readout (4PDR) hit processing unit
- Distributed memory trigger latency buffering
- Single-chip module stand-alone operation
- Built-in low drop-out (LDO) regulators and references
- High-speed 8bit/10bit encoded data output

Slim-edge n+-in-n planar sensors

- Slim-edge design, guard rings overlap opposing edge-pixels
- Processed on 200 μm oxygenated high-resistivity FZ wafers
- Fabrication with CiS (Germany)
- Single-chip sensors for prototype tests
- Double-chip sensors for production modules
- Production yield: $\simeq$ 90% (includes UBM/dicing)







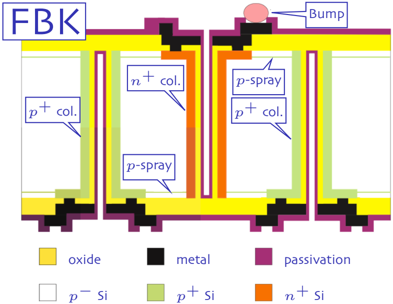
Double-sided double-type columns 3D sensors

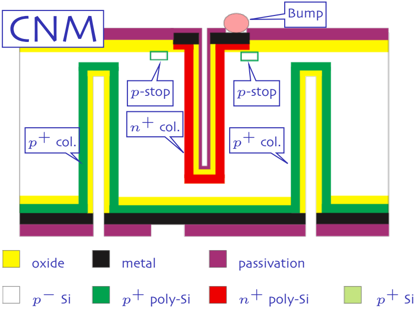
The 3D-sensors have been developed in cooperation with two vendors:

FBK: Fondazione Bruno Kessler (Trento, Italy)

CNM: Centro Nacional de Microelectronica (Barcelona, Spain)

There are small variations in the processes, both vendors fabricate their sensors on identical 4" FZ p-type high resistivity wafers





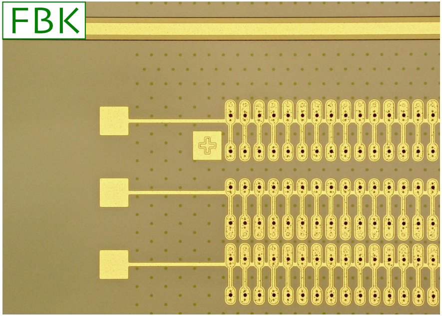
FBK Process:

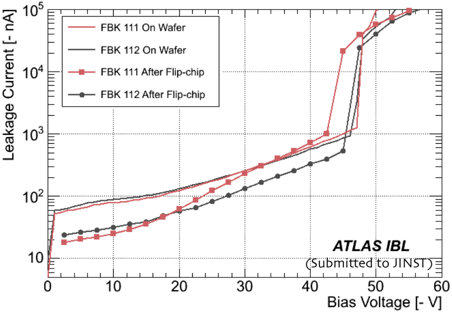
- p-spray insulation, both sides
- Full-depth electrodes
- Unfilled columns

CNM Process:

- Top-side p-stop insulation
- Electrodes don't reach full depth
- Partially filled columns

FBK edge design





Edge design

At the edge are *guard fence posts*; rows of ohmic columns that protects the depleted bulk from edge effects.

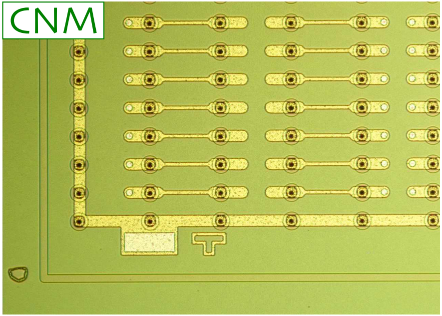
Triage and acceptance

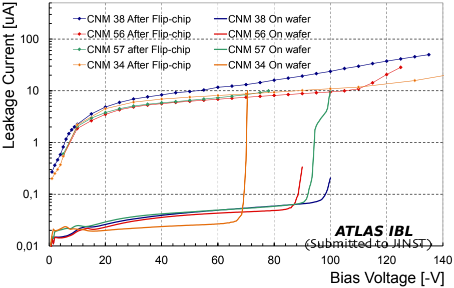
Wafer-level IV measurements important for selecting good sensor tiles for hybridization:

- Temporary metal layer shorts columns of read-out electrodes
- Full bulk current available summing across 80 columns

Method correlates well with final module IV measurements.

CNM edge design





Edge design

The sensor bulk is protected from edge effects by a $n+$ 3D guard ring at ground potential and opposing ohmic columns at bias voltage.

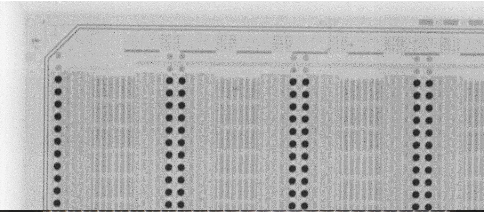
Triage and acceptance

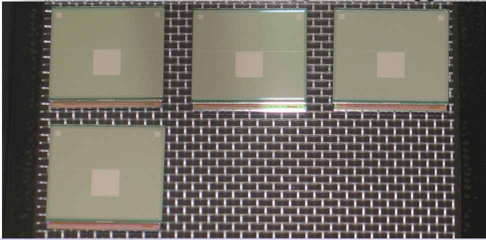
No temp. metal, wafer-level IV measurements considers only the leakage current collected by the guard ring, which turns out to be sufficiently correlated with bulk IV measurements on hybrid modules

Bump-bonding of very large, thinned FE chips:

- FE-I4 wafer thinned to $150\ \mu$m
- Attached to glass support wafer
- Fine-pitch SnAg micro-bump deposition
- Sensor wafer electroplating under-bump metalization (UBM)
- Dicing and flip-chip soldering
- Back-side laser removal of glass support
- X-ray and optical inspection

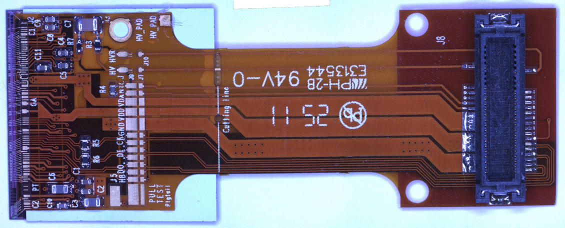
Thinning to $100\ \mu$m results in some ASIC breakage during laser removal; $150\ \mu$m thickness is a conservative yield/material compromise.

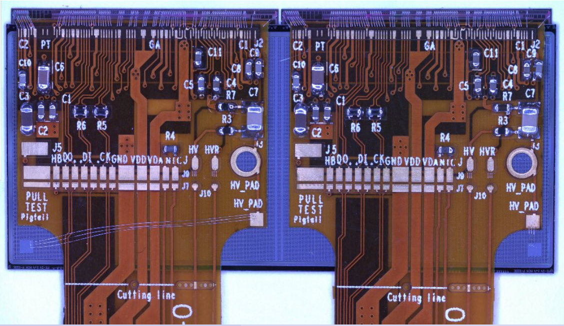




Testable modules, *dressed* with the module flex

Module flex carries discrete passives; notably the low-profile HV capacitor and LVDS termination resistors.
The FE-I4 signal and power lines are temporarily wire bonded to the disposable pigtail, allowing full read-out testing during QA. The *USBPix* PC-based read-out system is designed for this purpose.
As the module is prepared for loading on stave the pigtail is cut and the bridging wire-bonds are removed.





Radiation qualification

Projected radiation load

Toward end-of-service ($550\ \mathrm{fb}^{-1}$) the IBL radiation load is expected to reach:

NIEL: $6 \times 10^{15}\mathrm{n/cm}^2$ ($1\ \mathrm{MeV}$ n eq.)

TID: $250\ \mathrm{MRad}$

FE-I4 total ionizing dose (TID)

Tested to $200\ \mathrm{MRad}$ at the Los Alamos Laboratory ($800\ \mathrm{MeV}$ protons); minimal change to threshold dispersion and $15 - 25\%$ increase in noise.
Incidentally exposed to $750\ \mathrm{MRad}$ during module irradiation at KIT; dead/noisy pixels mostly recovered by FE reconfiguration

Single event upset (SEU)

Tests performed at CERN PS ($24\ \mathrm{GeV}$ protons). **DICE** hardened registers have SEU cross-sections of order $1 \times 10^{-15}\ \mathrm{cm}^2$.

Module irradiation

Detector modules are irradiated up to $5 \times 10^{15}\mathrm{n/cm}^2$:

KIT: $25\ \mathrm{MeV}$ protons (Karlsruhe, Germany)

TRIGA: fast reactor neutrons (Ljubljana, Slovenia).

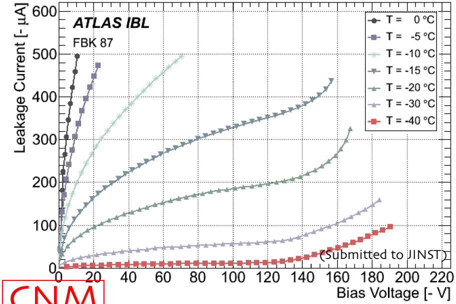
Following irradiation modules were annealed $60\ \mathrm{C}/2\ \mathrm{h}$ then stored cold

IV-measurements after irradiation

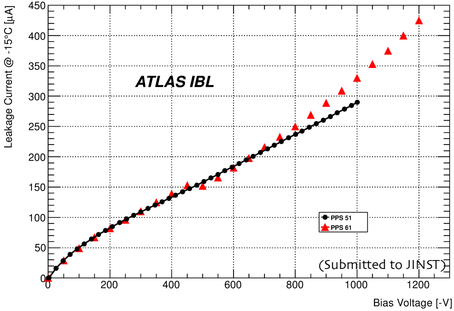
Dominantly ohmic behavior; as expected after irradiation.

- **CiS:** Well within sensor power dissipation limits (200 mW/cm² thermal runaway safety)
- **FBK/CNM:** No signs of breakdown or thermal runaway.

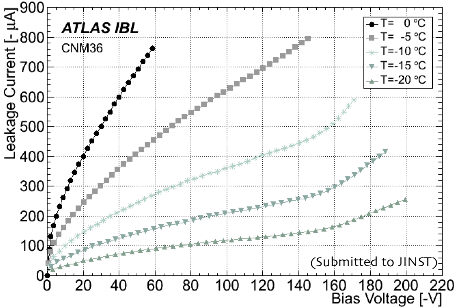
FBK



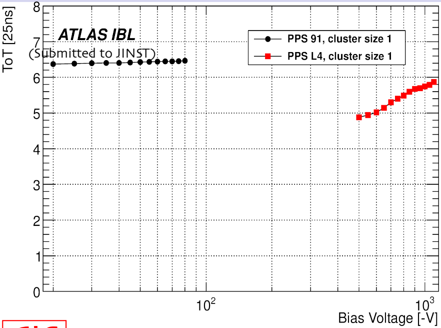
CiS

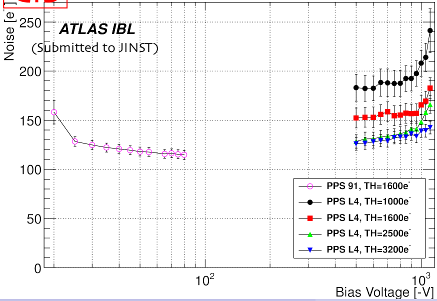


CNM



Planar sensors: signal and noise before/after irradiation

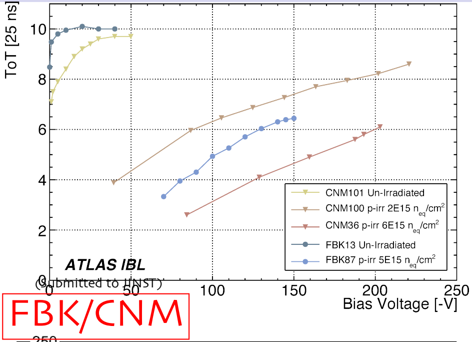


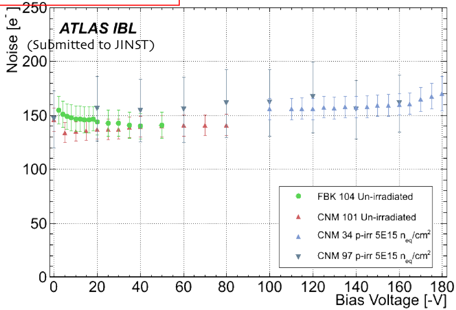


Note: pre/post irradiation are different samples

- Signal is most probable value (MPV) of ^{90}Sr
- Charge in uncalibrated units of time-over-threshold (ToT)
- Indications of charge multiplication toward 1 kV
- Noise is well under control also after irradiation

3D sensors: signal and noise before/after irradiation





Note: pre/post irradiation are different samples

- Regulated cooling to fix sensor temperature at -15 C
- Signal is most probable value (MPV) of ^{90}Sr quasi-MIPs (1-pixel hits).
- Charge in uncalibrated units of time-over-threshold (ToT)
- Satisfactory signal efficiency at/above 160 V
- Noise sensitive to thresholds, but well under control for realistic operating points

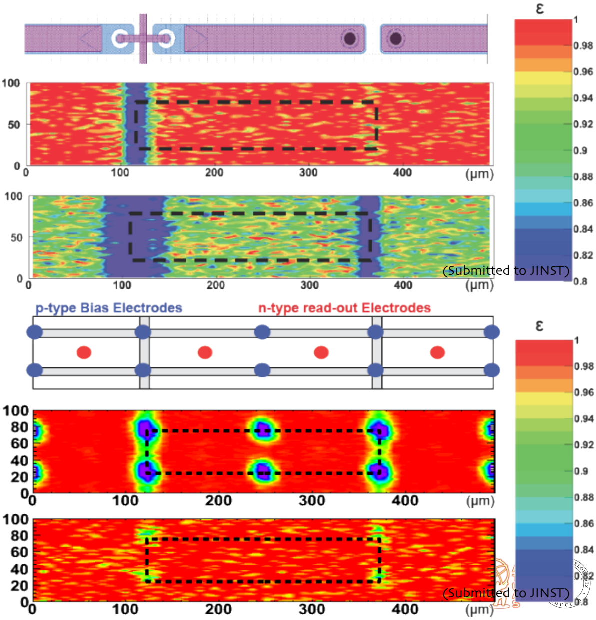
Irradiated sensor efficiency maps

PPS 61 (15°, -1000 V): 96.9%

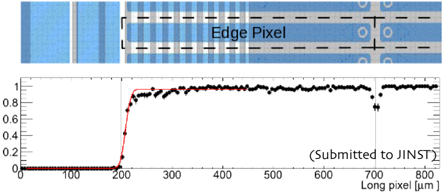
PPS 61 (15°, -600 V): 86.4%

CNM 81 (0°, -160 V): 97.5%

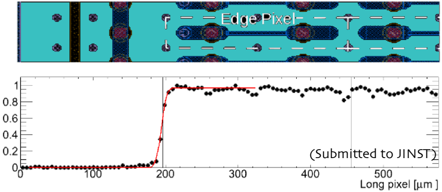
CNM 34 (15°, -160 V): 99.0%



Irradiated sensor edge efficiency



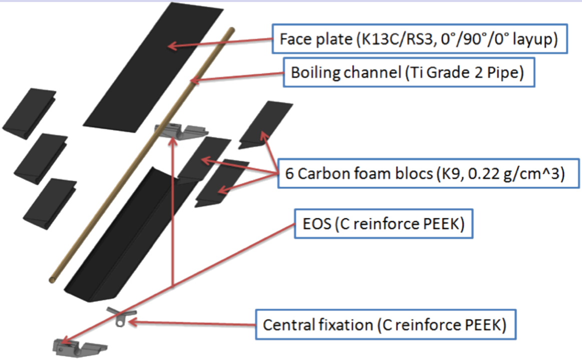
CNM 34: $V_b = -140$ V

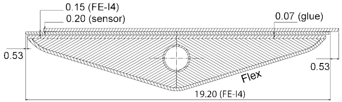


PPS L2: $V_b = -1000$ V

Both planar and 3D sensors reach 50% efficiency approximately 200 μm from the physical dicing edge.

Local support, electrical services





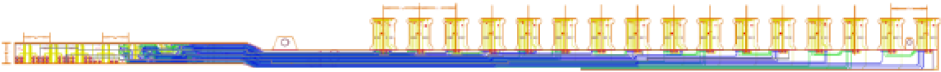
Bare stave

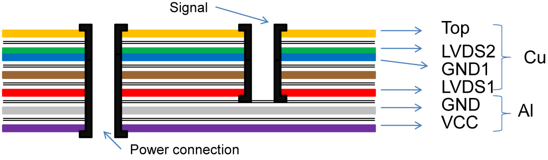
Skinned, low density carbon foam construction - embedded 1.5 mm Ti boiling channel.

Pressure: $150\ bar$ (max test)

TFoM: $< 15\ \mathrm{Kcm^2/W}$

X/X_0: 0.6%





Flex bus

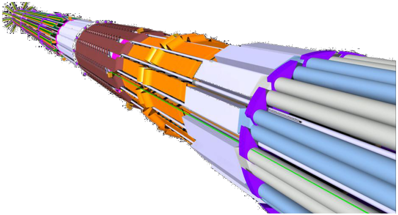
Runs along back of stave, lateral *wings* fold around the edge to connect to modules

Cooling system

Requirements:

The two most demanding operational requirements come from **beampipe bake-out** and safety against **thermal runaway** for deeply radiation-damaged sensors.

Max. power	1.5 kW
Max. test pressure	150 bar
Range of operation	-40 C . . . $+20$ C
Thermal stability	< 0.5 C

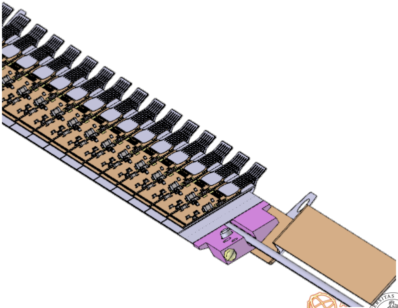


2PACL - two-phase accumulator-controlled loop

The IBL cooling is a CO_2-based evaporative system, essentially derived from the LHCb/Velo-system. Benefits of 2PACL-operation:

- No compressor inside the active detector loop
- No back-pressure regulators
- No exhaust vapor heaters
- Accumulator volume provides regulation inertia

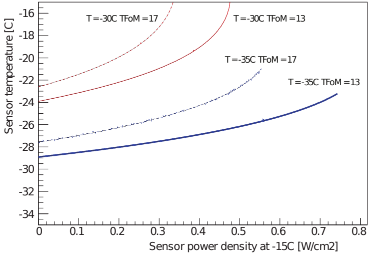
The small-diameter pipes and corresponding volume contributes to minimizing the material budget.

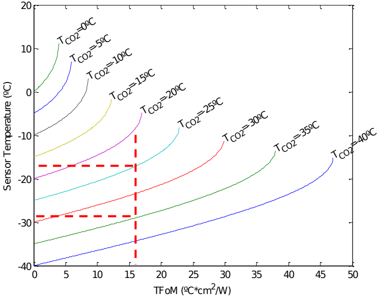


Cooling simulations - thermal runaway safety

Detector operation at end-of-life (planar sensors)

Accumulated fluence	$5 \times 10^{15}\ n_{eq}/cm^2$	(safety factors)
Chip power density	$290\ mW/cm^2$	
Sensor bias voltage	$1000\ V$	
Sensor power density	$80\ mW/cm^2$	(annealed)
at $T_0 = -15$ C	$160\ mW/cm^2$	(not annealed)
	$200\ mW/cm^2$	(design max.)





Self-coupling runaway model:

Leakage current scaling law:

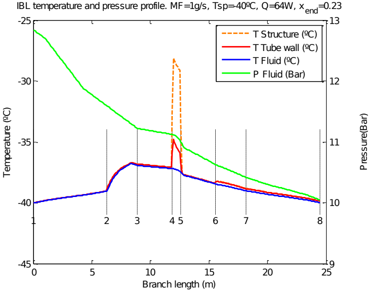
$$I = I_0 \left(\frac{T}{T_0}\right)^2 \exp\left(\frac{E_g}{2\,k_B}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right)$$

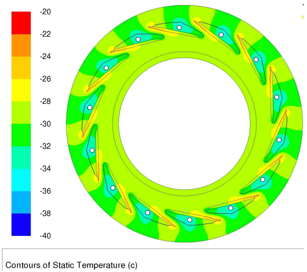
Linear heat-conduction model:

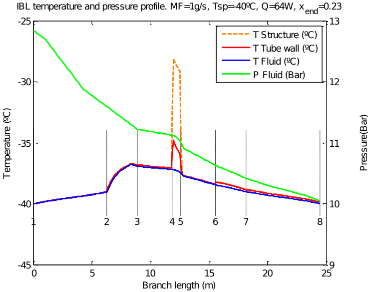
$$T = T_{\text{coolant}} + \frac{\Gamma}{A_{\text{sensor}}}\left(P_{\text{sensor}} + P_{\text{fe}}\right)$$

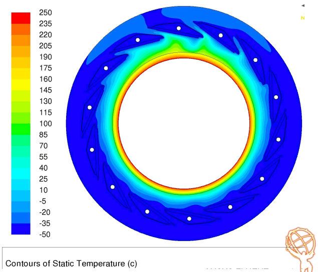
Measured thermal figure of (dis-) merit: $\Gamma = 13\ \mathrm{Kcm^2/W}$

Cooling simulations - nominal and beam-pipe bake-out

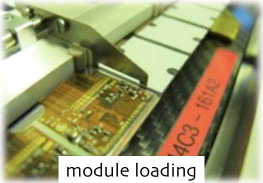


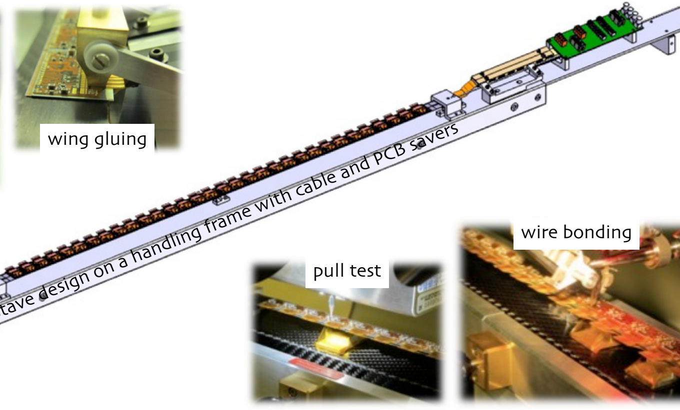






Stave assembly - tooling





ATLAS/IBL References

- ATLAS Insertable B-Layer Technical Design Report. CERN-LHCC-2010-013/ATLAS-TDR-019
- ATLAS Insertable B-Layer Technical Design Report Addendum. CERN-LHCC-2012-009/ATLAS-TDR-019-ADD-1
- Prototype ATLAS IBL Modules using the FE-I4A Front-End Readout Chip. Submitted to JINST (2012)

Conclusions

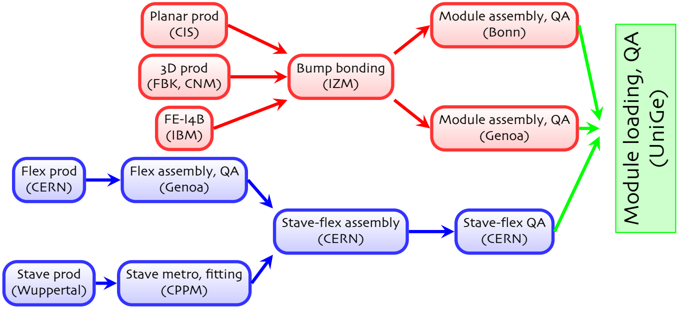
- The FE-I4 ASIC is qualified and in delivery
- Slim-edge planar and 3D sensors are qualified and manufactured
- Module hybridization is in production
- Mechanics and services are qualified and in production
- Evaluation of pre-production staves is ongoing
- The final decision about the installation strategy is pending

Backup slides

Installation scenarios

- Underground insertion into ATLAS
- On surface pre-integration with Pixels
- Final decision subject to the fate of the nSQP-project

Stave assembly - Production flow



Module loading (UniGe)

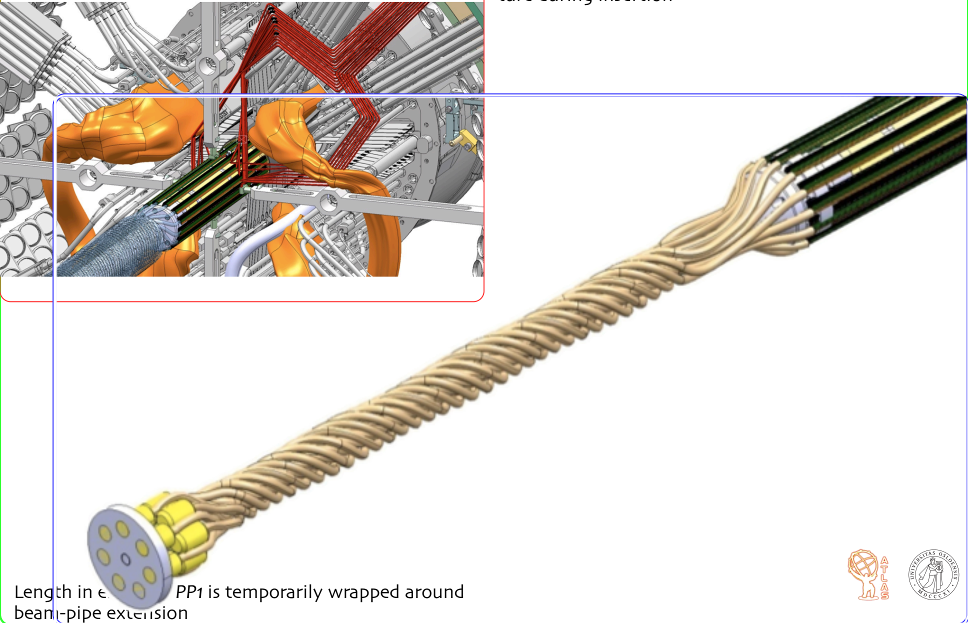
- Reception QA
- Load modules
- Wing gluing
- Wire bonding, QA
- *Thermal cycling (preseries)*
- Metrology, envelope QA
- Readout tests

Staves integration (SR1)

- Stave burn-in, QA
- Braze pipe extension
- Integrate staves on beam pipe
- Final on-surface tests and pre-commissioning

Insertable package

All far-side Type-1 services must pass through IBL aperture during insertion



Length in e[illegible] *PP1* is temporarily wrapped around beam-pipe extension