Double-Sided Super-Module R&D for the ATLAS Tracker at HL-LHC – a Summary

9th Hiroshima Conference on Development and Application of Semicpnductor Tracking Detectors
(HSTD9)
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Outline:

1. Why: Global Requirements and Motivation
2. Recap of Super-Module scope and set-up
3. Electrical performance of the Super-Module
4. Mechanical status of the Super-module
5. The next steps:
    - what needs more work (cable bus)
    - design evolution
6. Comments and Summary

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Global Requirements and Motivation

Global Requirements

- Compatible with performance specifications of ATLAS but in high pileup
- Compatible with other R&D projects involving the groups
  - ABCN 250 nm and future ABCN 130 nm + HCC development
  - Sensor n-in-p R&D developments
  - ….
- Build on merits of proven ATLAS tracker, identify and correct limitations

Guidelines

- True stereo space-point reconstruction using stereo strips
- Ability to provide z-overlap for modules (high alignment modes) if chosen
- Long term stability during operation and good placement accuracy
  - Stiff supporting structures
- Minimize thermo-mechanical stress at all levels (low and compatible CTE)
  - Modules,
  - Local support and structure
- Modularity of components: (evolution of what learned on SCT)
  - Ease of prototyping, component supply, Q&A + rework, large-scale fabrication and construction
- Low material budget
- Good electrical performance at operating voltages > 500V

Project Status

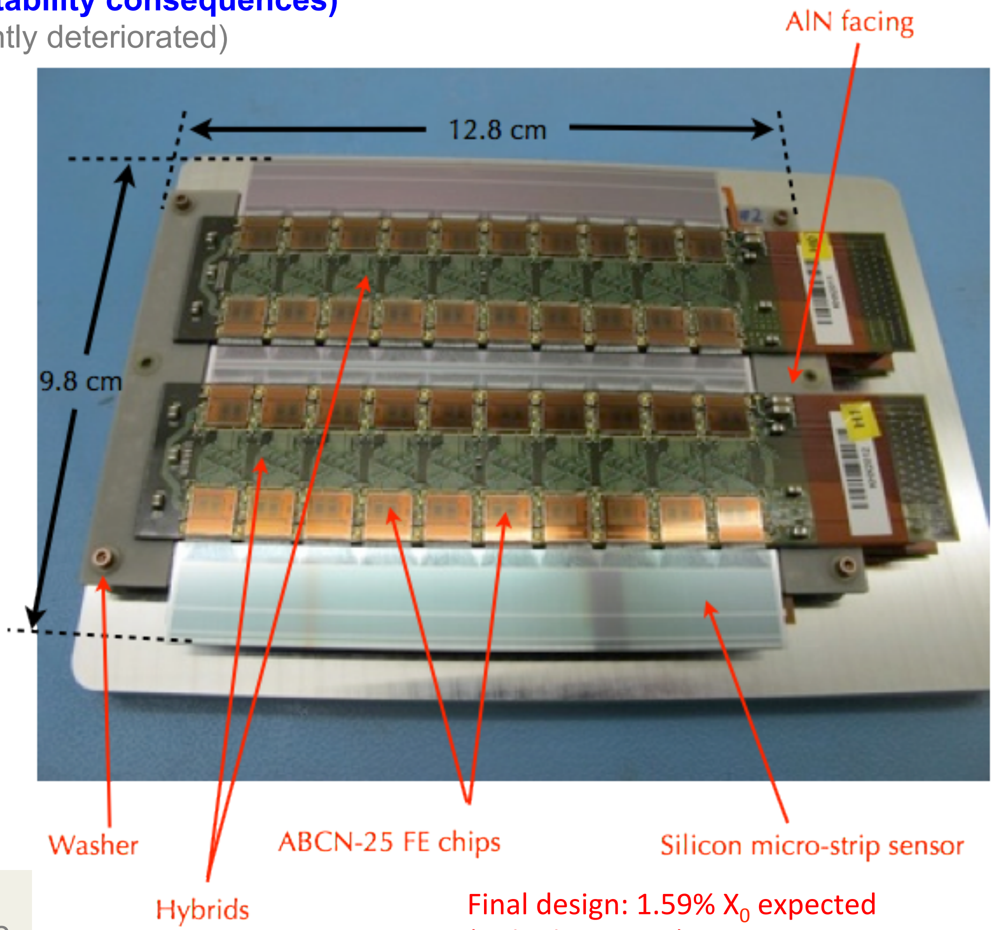
- Backup option for ATLAS Tracker at HL-LHC* (STAVE option is ATLAS base-line)
- Scope of R&D project using the ABCN 250 nm FE chip successfully completed
  - Separate summary publications on electrical and mechanical aspects currently in preparation
- Future developments will use the ABCN 130 nm FE chip and the HCC readout controller

* ATLAS Phase II LOI
CERN-2012-022
LHCC-I-023

Module Design and Status – 1

- **Detectors are mounted back-to-back, true stereo reconstruction (400 μm sensor separation, will be 300 μm)**
  - Space point determined by the module assembly with the precision of the jigs (build precision < ±1 μm rms)
  - Sensor (n-in-p Hamamatsu) 96 x 96 mm^2, (short) strips 24 x 0.075 mm^2, (long) strips 48 x 0.075 mm^2
- **Precise module location on a local structure**
  - Centering bushes: origin + alignment - (mounting precision on support ±10 μm)
- **Bridge hybrid allows FE thermal path different from Si (stability consequences)**

  (NB: Direct mounting is feasible, thermal performance slightly deteriorated)
- **Low CTE material and good thermal conductivity:**
  - **Si, TPG, CC, AlN**
  - Low deformation @ -35°C (FEA)
- **Hybrid pigtails + connector for electrical connections (option)**
  - Modularity and flexibility
- **Module assembly known and simplified WRT existing SCT modules in terms of procedure and QA**:
  - > 950 SCT modules were fabricated by HPK and Seiko in Japan
  - 6 ABCN 250nm modules fabricated by industry (HAYASHI) + 3 in-house at KEK
  - Hybrids industrialized (Taiyo Industrial Co.)
  - > 650 SCT modules were fabricated by UniGe
  - 7 ABCN 250 nm modules fabricated in-house



Final design: 1.59% X_0 expected
(as built 2.4% X_0)

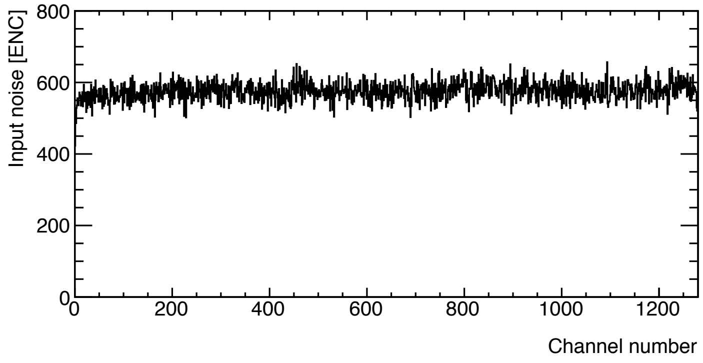
See
ATL-UPGRADE-PUB-2011-002

Module Design and Status – 2

Assembly Site	Module id	Sensor type	Hybrid version	Super-module	Comments
KEK	KMX-1000	FZ1 p-stop	v1		- long strip test module
KEK	KMX-1001	FZ1 p-stop	v1		
KEK	KMX-2002	FZ1 p-stop	v2		
KEK	KMX-2003	FZ1 p-stop	v2		- 5 dead ABCN-250 asics
KEK	KMX-2004	FZ1 p-stop	v2		- sensor crack during assembly
KEK	KMX-2005	FZ1 p-stop	v2	Yes	- industry
KEK	KMX-2006	FZ1 p-stop	v2	Yes	- industry
KEK	KMX-2007	FZ1 p-stop	v2	Yes	- industry
KEK	KMX-2008	FZ1 p-stop	v2	Yes	- industry
Geneva	GMX-1000	FZ1	v1		- "half module" used for irradiation studies - manual assembly of SMD's
Geneva	GMX-1001	FZ1	v1		- manual assembly of SMD's
Geneva	GMX-2002	FZ1 p-stop	v2	Yes	
Geneva	GMX-2004	FZ1 p-stop	v2	Yes	
Geneva	GMX-2006	FZ1 p-stop	v2	Yes	
Geneva	GMX-2007	FZ1 p-stop	v2		- electrical coupling between HV and V_{dd}
Geneva	GMX-2008	FZ1 p-stop	v2	Yes	

see also ATL-UPGRADE-PUB-2011-002

- Table shows modules constructed in Japan and CH + modules used in 8-module electrical super-module
- Module GMX-1000 used for radiation studies at level expected for LHC (previously reported)
  - ✓ Noise level after irradiation very satisfactory
  - ✓ Similar excellent results from STAVE R&D for single module
  - x But … sensor leakage current high (low temperature operation)
  - x no test-beam results

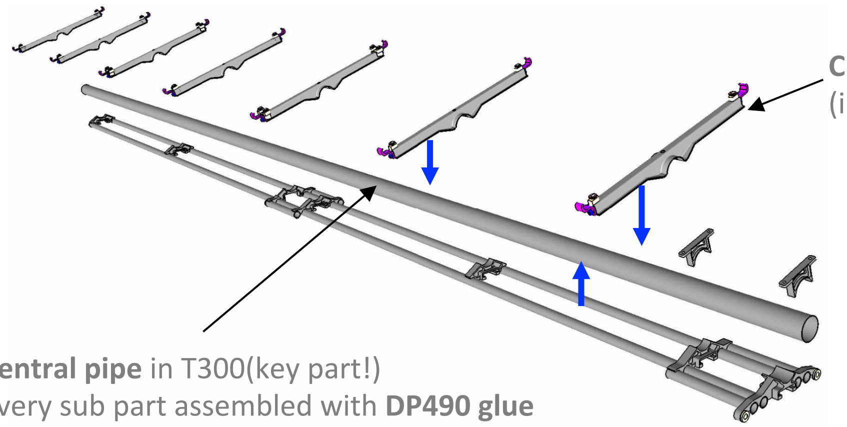


✓ Typical individual module input noise (ENC) using direct powering (10 ASICS of a single hybrid shown):
- <ENC> ~ 575 - 600
- σ_{ENC} ~ 25

x No modules used so far in test-beam

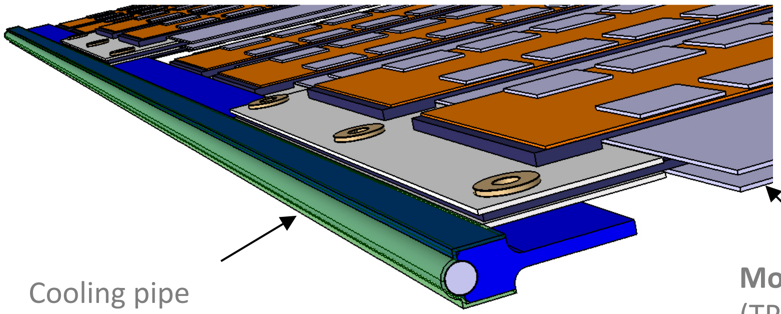
Super-Module Mechanical Design

CAD view of the SM (modules removed for clarity)



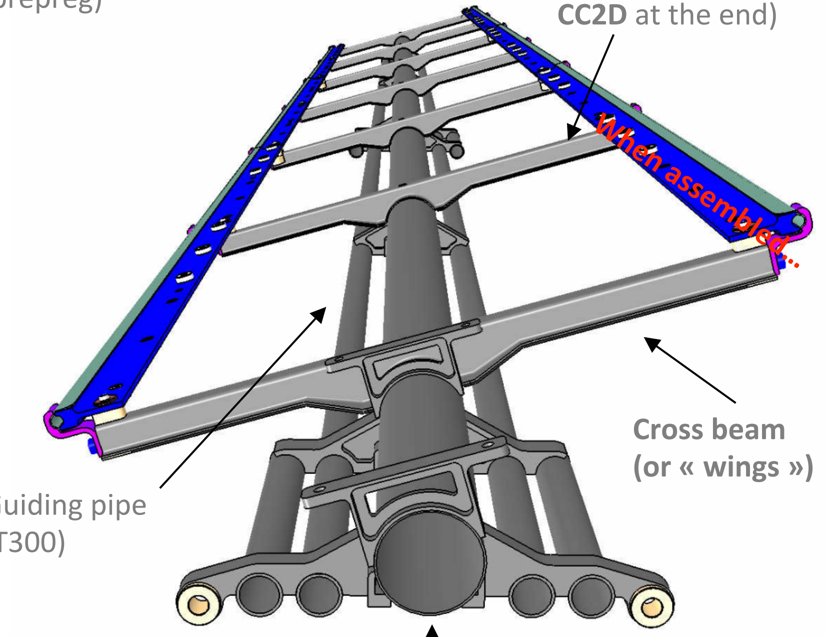
Cross beam x7
(in T300 prepreg)

Central pipe in T300(key part!)
Every sub part assembled with **DP490 glue**
(with jig and centering pieces)



Cooling pipe
Cover (T300)

Modules
(TPG, Si, Hybrid,…)



Cooling Plates x6
(prototyped in
aluminum…
CC2D at the end)

Cross beam
(or « wings »)

Guiding pipe
(T300)

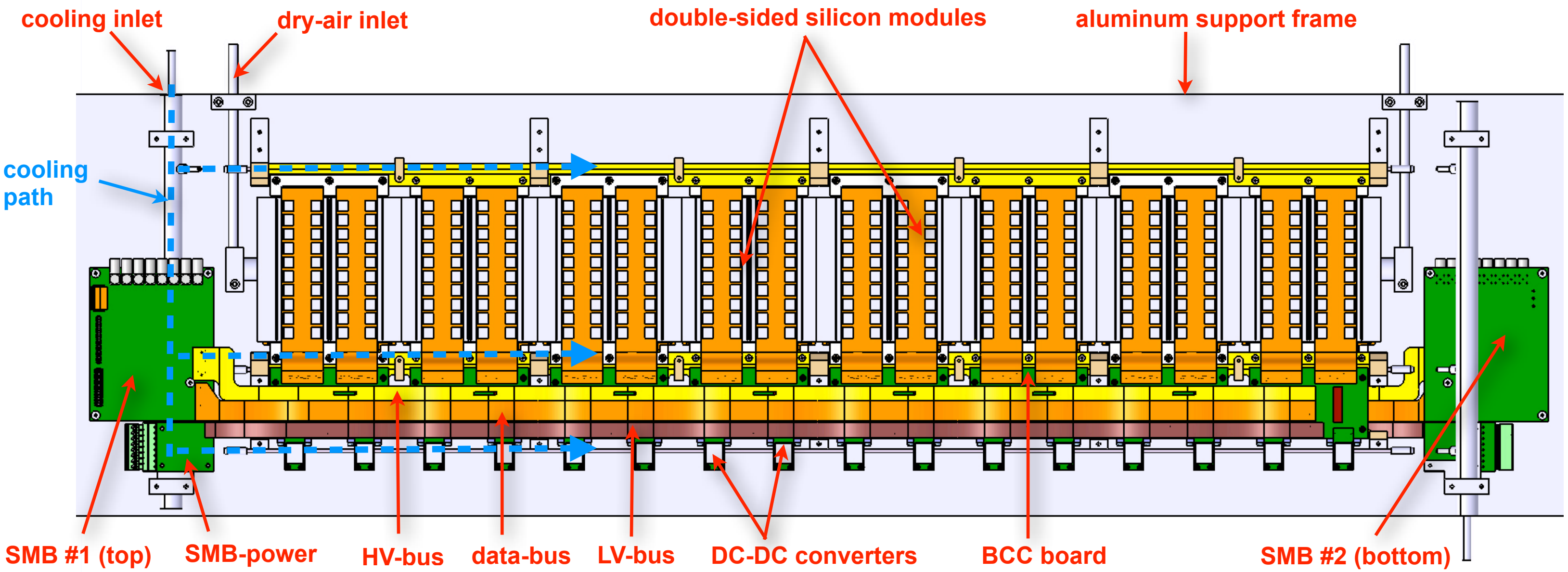
Joint pieces in plastic
(polycarbonate for proto)

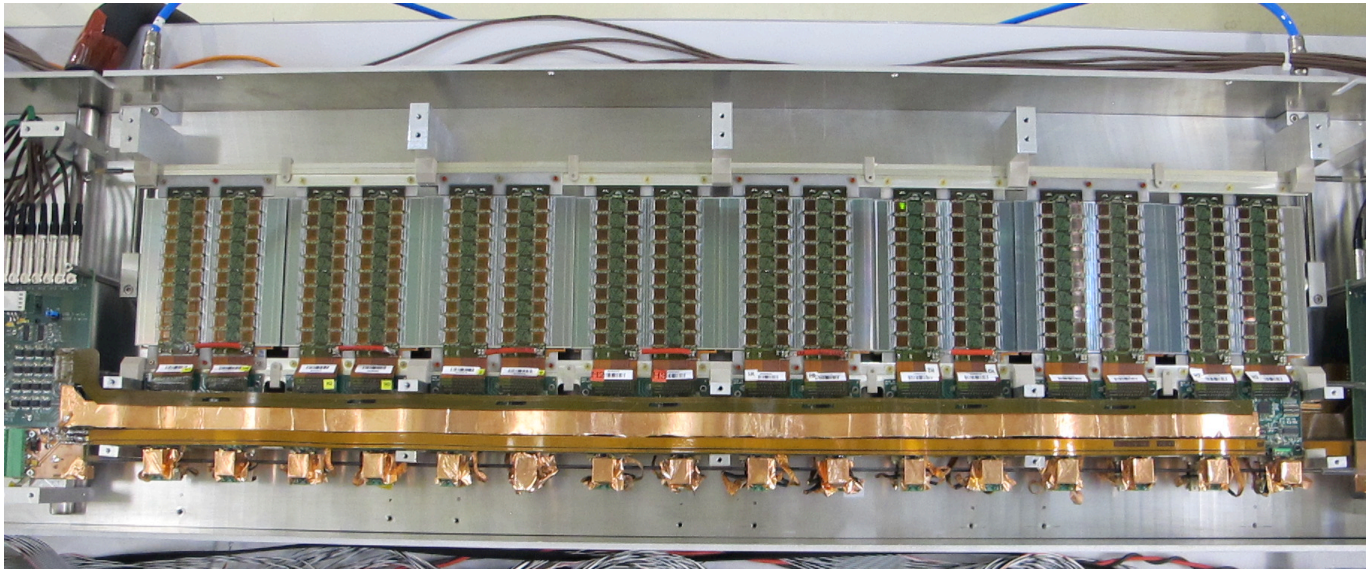
Mechanical studies discussed later
(baseline ATLAS layout foresees 13 modules, studies for this R&D assumed 12 modules))

In parallel an 8-module electrical prototype has been developed, replicating all electrical and cooling aspects and allowing parallel prototype development

Super-module Electrical Prototype – 8 modules

8 modules = 16 sensors = 32 hybrids = 640 ABCN250 FE chips = 81920 channels



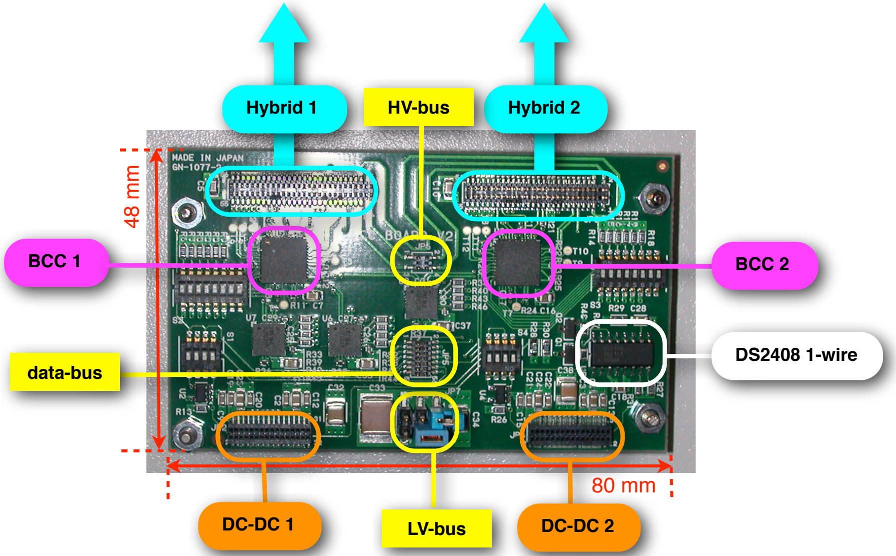


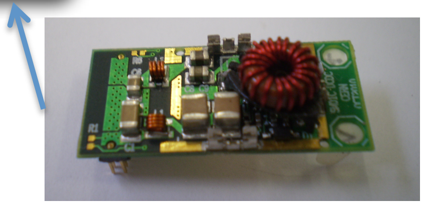
4 x larger than any other DC-DC implementation for HL-LHC R&D

Modules with service buses, BCC boards and DC-DC

Super-module Electrical Prototype – off-module interfaces

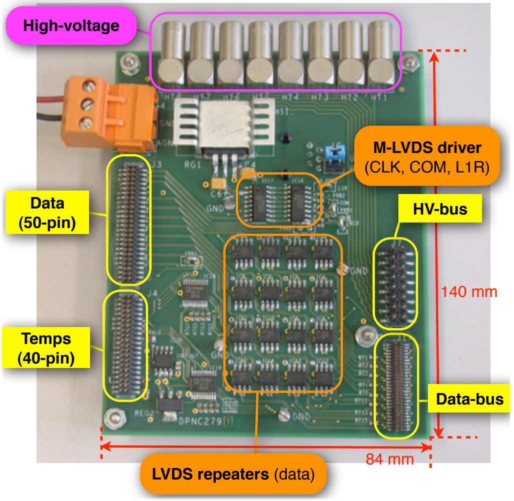
- BCC chip (common with stave R&D):
  - clock multiplier for 80 MHz readout
  - LVDS buffering, command decoder, configuration register
  - data multiplexing
- BCC Board (KEK) – 1 each side of module
  - **2 BCC chips (packaged)**
  - **interface for 2 hybrids+ 2 DC-DC boards**
  - **service bus connection**
  - **prototype usage only**





Cable bus

- SMB board (1 per Super-Module side)
  - Interface to DAQ (HSIO/USB), (similar for Seabas DAQ developed by KEK)
  - Provides DC-DC control, monitoring
  - Interface to HV, LV and data buses



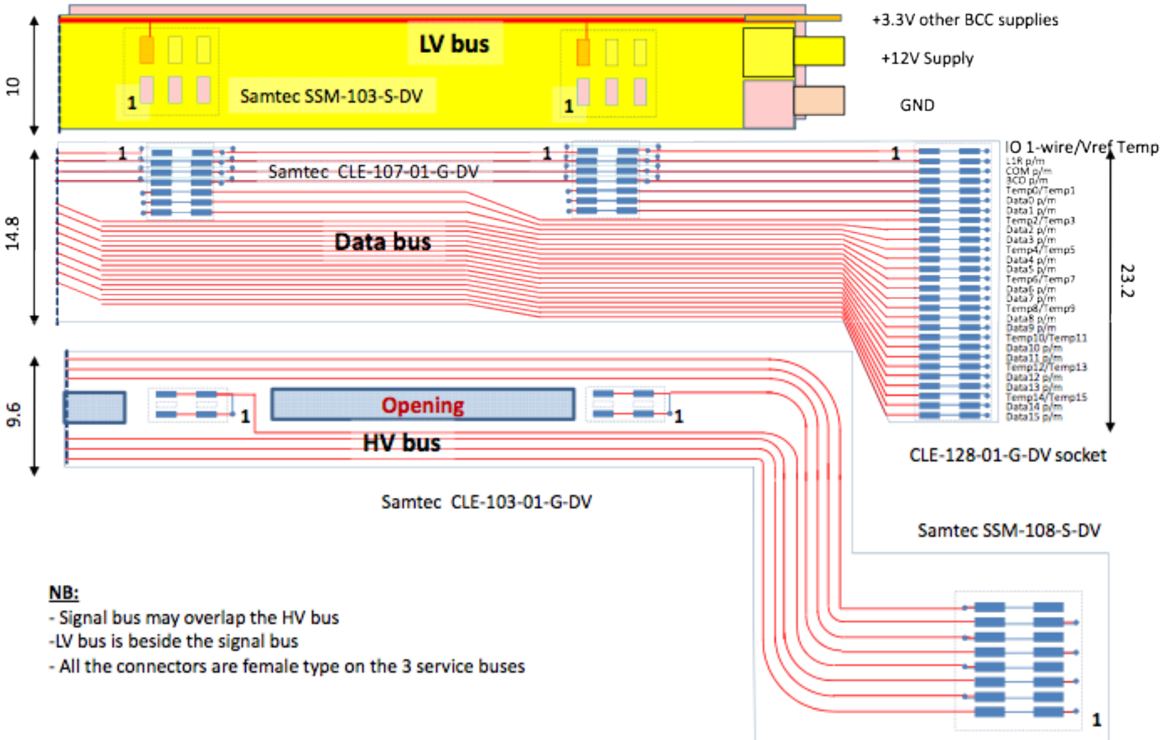
Super-module Electrical Prototype – cable bus

Least developed aspect of SM program
- electrical
- mechanical

Intended as a first version prototype
- initial conservative design

2 identical **765 mm long** sets of **LV**, **HV** and **data** buses, 1 on each side of SM
- design and constructed at CERN
- HV bus drives HV for 8 sensors
- LV bus drives 10-12 V lines for DC-DC converters + 3.3 V BCC supply
- Data bus has 16 LVDS pairs (2 per module)
- Currently use Samtec connectors to BCC and SMC boards (excepting LV)

Expected evolution of cable bus considered later in this talk



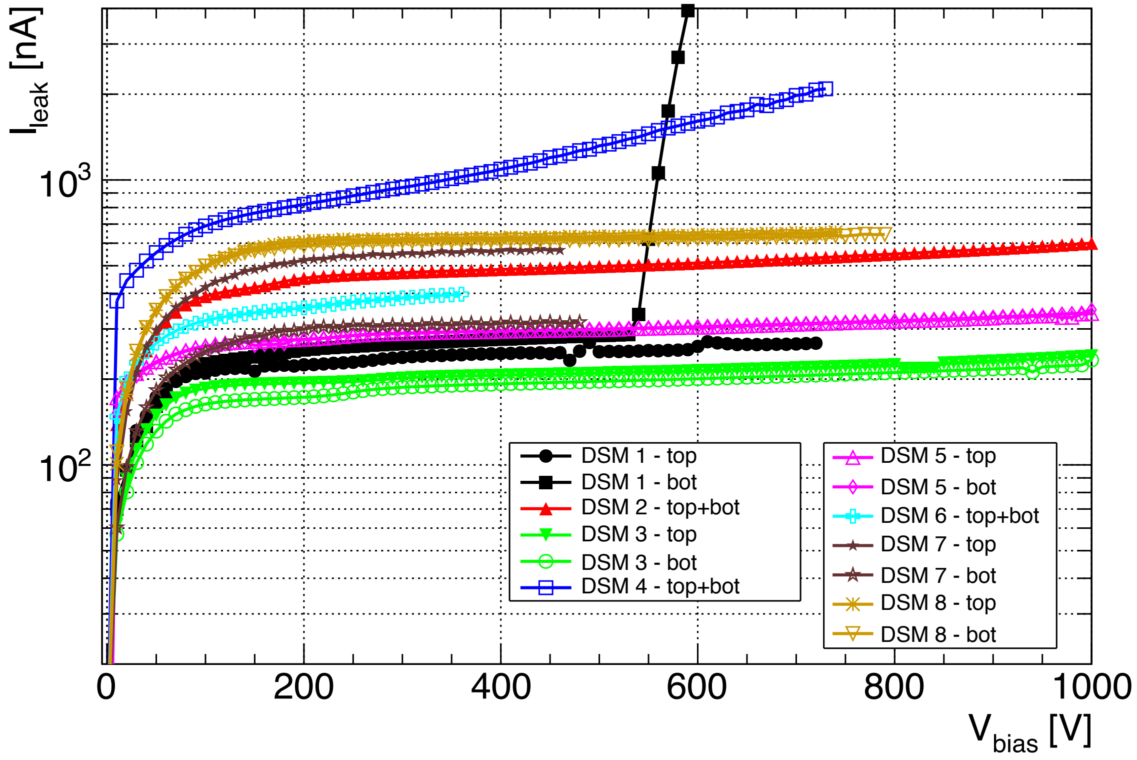
NB:
- Signal bus may overlap the HV bus
-LV bus is beside the signal bus
- All the connectors are female type on the 3 service buses

	HV	Data	LV
Total number of layers	2	2	2
Total number of traces:			
• Layer 1	8	28	2
• Layer 2	8	28	1
Trace width	0.2	0.1 - 0.2†	2.2 - 9.5*
Cu-layer thickness	0.035	0.035	0.2
Minimum / Maximum bus width	9.6 / 22.3	16.0 / 26.0	10.0 / 10.0

Parameters of the service buses. Thicknesses and widths are given in mm.

I-V Performance of the 8 Modules

- HV provided individually to top and bottom sides of each module via HV bus
  - iSEG EHS-8210n-F (2 cards with 8 6U channels): 1 kV & 8 mA

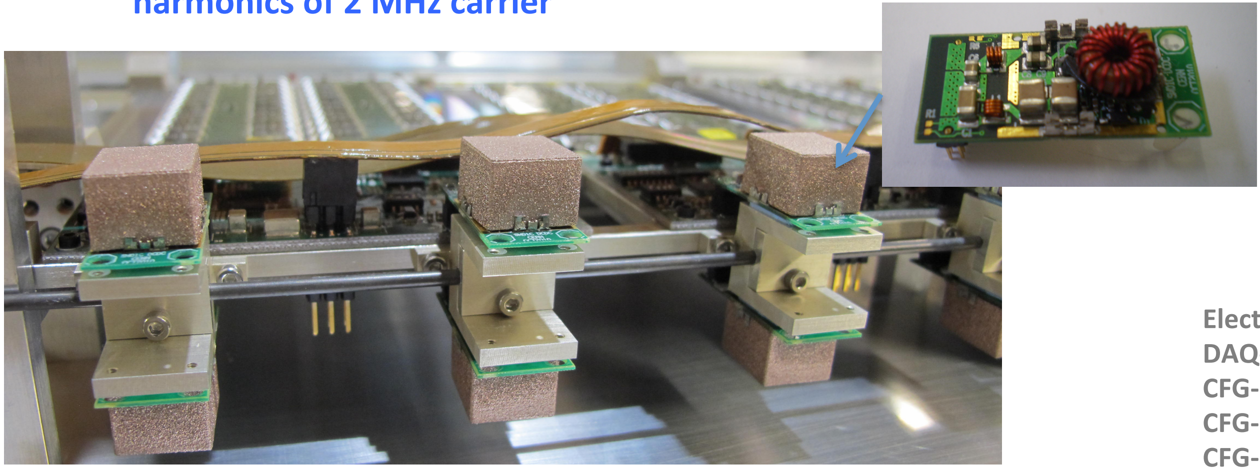


- Good HV behaviour for all modules
  - Breakdown of DSM1 top side at 550V
  - DSM2, DSM4 and DSM6 have HV coupling between top and bottom sides (pin-holes in TPG coating?)
- Future designs will use single HV channel for several modules to reduce service material

Low Voltage Performance of the 8 Modules

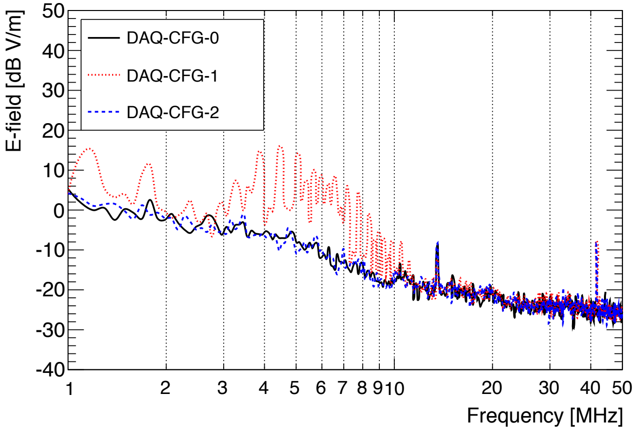
- Low voltage supplied using a TDK supply
  - **Constant voltage source maximum 20 V and 76 A**
  - **Supplied with common 10-12 V line to DC-DC converters**
- Each hybrid supplied via DC-DC converter (developed at CERN)*
  - **SM01C prototype using air-core toroidal inductor**
  - **Shielded to reduce EM emissions (10 µm Cu cover)**
  - **Some variabilty in DC-DC shielding and peaks at harmonics of 2 MHz carrier**

*G. Blanchot et al., TWEPP 2009 Proceedings, pp276-280.



- Additional noise sources identified from the LV supply (~5 MHz) HSIO board (1-10 MHz) and the DAQ (42 MHz)
  - **Effect on noise measurements for modules difficult to quantify**
  - **Consequence on noise of DC-DC not fully understood**

Electric field on one hybrid in different DAQ-HSIO configurations
CFG-0: **HSIO DAQ off**
CFG-1: **HSIO DAQ on**
CFG-2: **HSIO DAQ on, external 12 V supply**



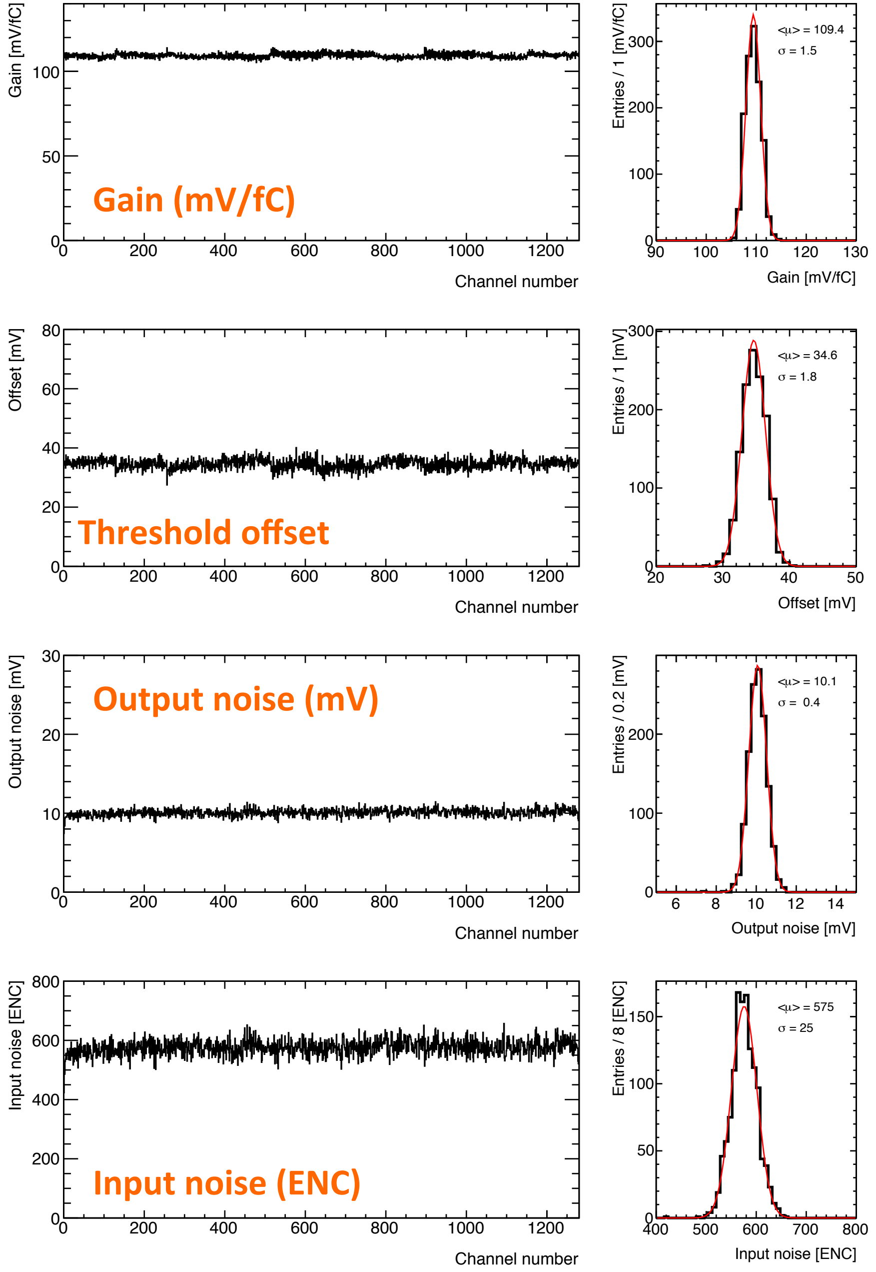
Rhode & Swartz EM analyzer

Calibration of Modules – 1

- Initial channel-by-channel calibration of each ABCN 250 ASIC
  - Calibration delay
  - Discriminator threshold corrections
- Gain and noise (ENC) evaluation using threshold scans
  - 3-point gain test uses 3 input charges

3-pt gain for 1280 channels of a single hybrid column (10 ABCN ASICS)

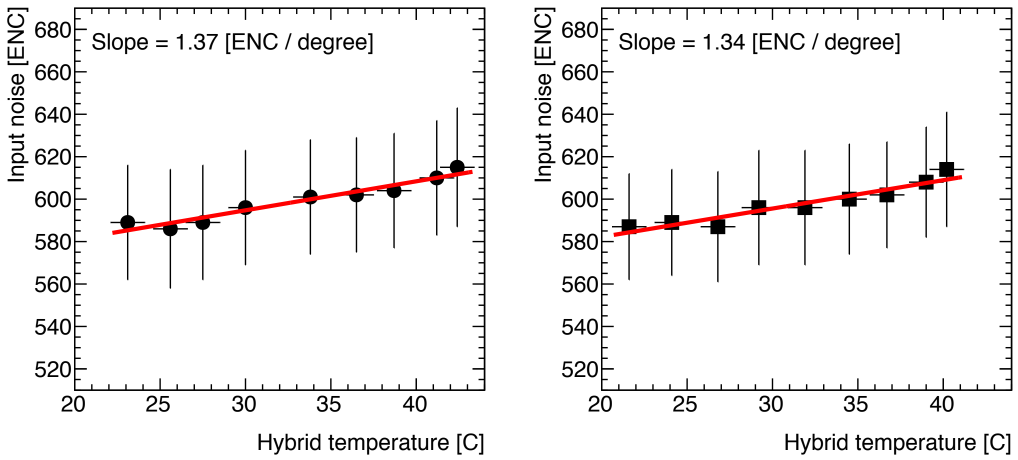
Noise (~ 600 ENC) and gain (~ 110 mV/fC) are as expected



Calibration of Modules – 2

Dependence of ENC on hybrid temperature (2 hybrids)

- No corrections made
- $\Delta_{ENC} \sim 1.37\ ^{o}C^{-1}$



Noise measurements made at:

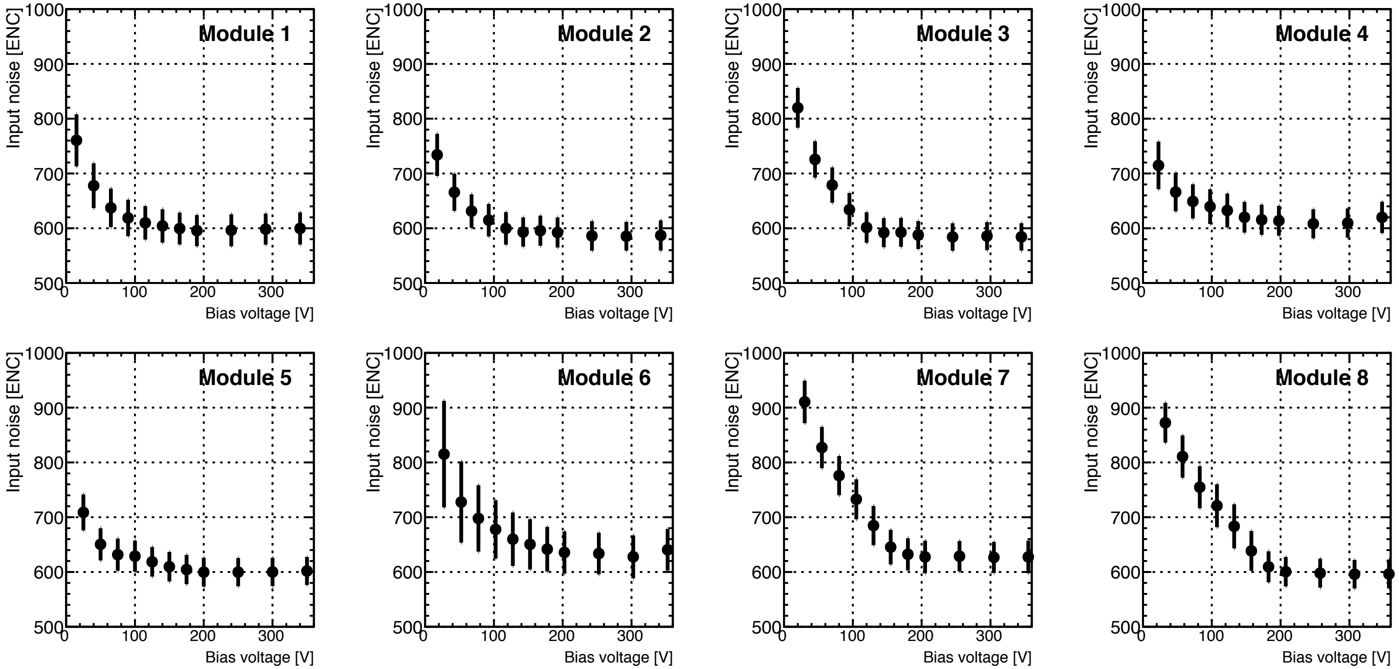
Coolant: ~ 5 ^{o}C

Hybrid: ~ 32 ^{o}C

Sensor: ~ 20 ^{o}C

ENC vs. V_{bias}

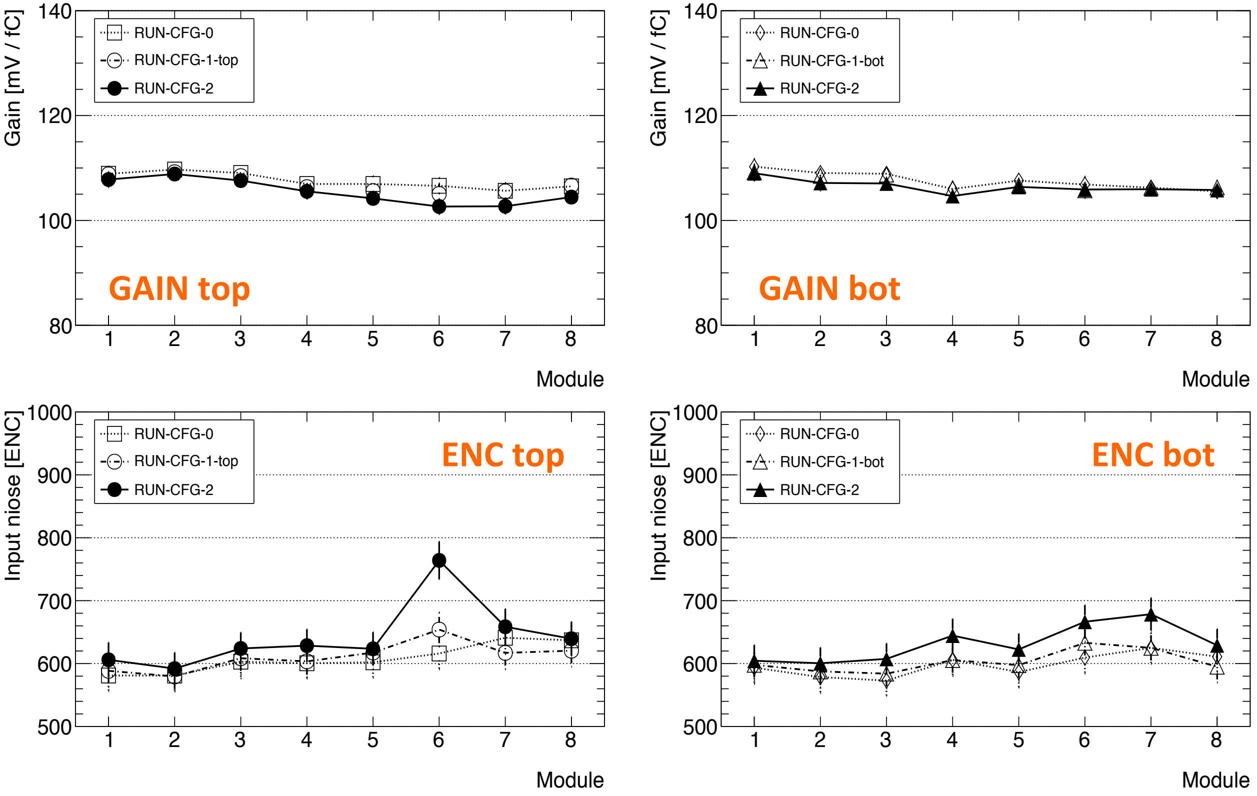
- Top side of each module shown
- Saturation knee consistent with V_D (ENC primarily from sensor)



Gain and Noise Measurements

Run configuration	Description	# DC-DCs enabled
RUN-CFG-0	- A single side of each module tested individually	2
RUN-CFG-1-top	- 8 module-sides (SM top-side) tested simultaneously - DC-DCs on opposite sides disabled	16
RUN-CFG-1-bot	- 8 module-sides (SM bottom-side) tested simultaneously - DC-DCs on opposite sides disabled	16
RUN-CFG-2	- 8 module-sides (SM top and bottom-sides) tested simultaneously - DC-DCs on opposite sides enabled	32

- When operated in CFG-2 mode, noise increases in range 10 – 60 ENC
- No significant DC-DC effect on same side (CFG-1)
- **Deteriorated performance of module 6 (hybrids 3 and 4) is not understood**
- **Also deterioration of common mode noise for module 7**



Results very satisfactory but further work on coupling of DC-DC converters needed between top and bot

Double Trigger Measurements

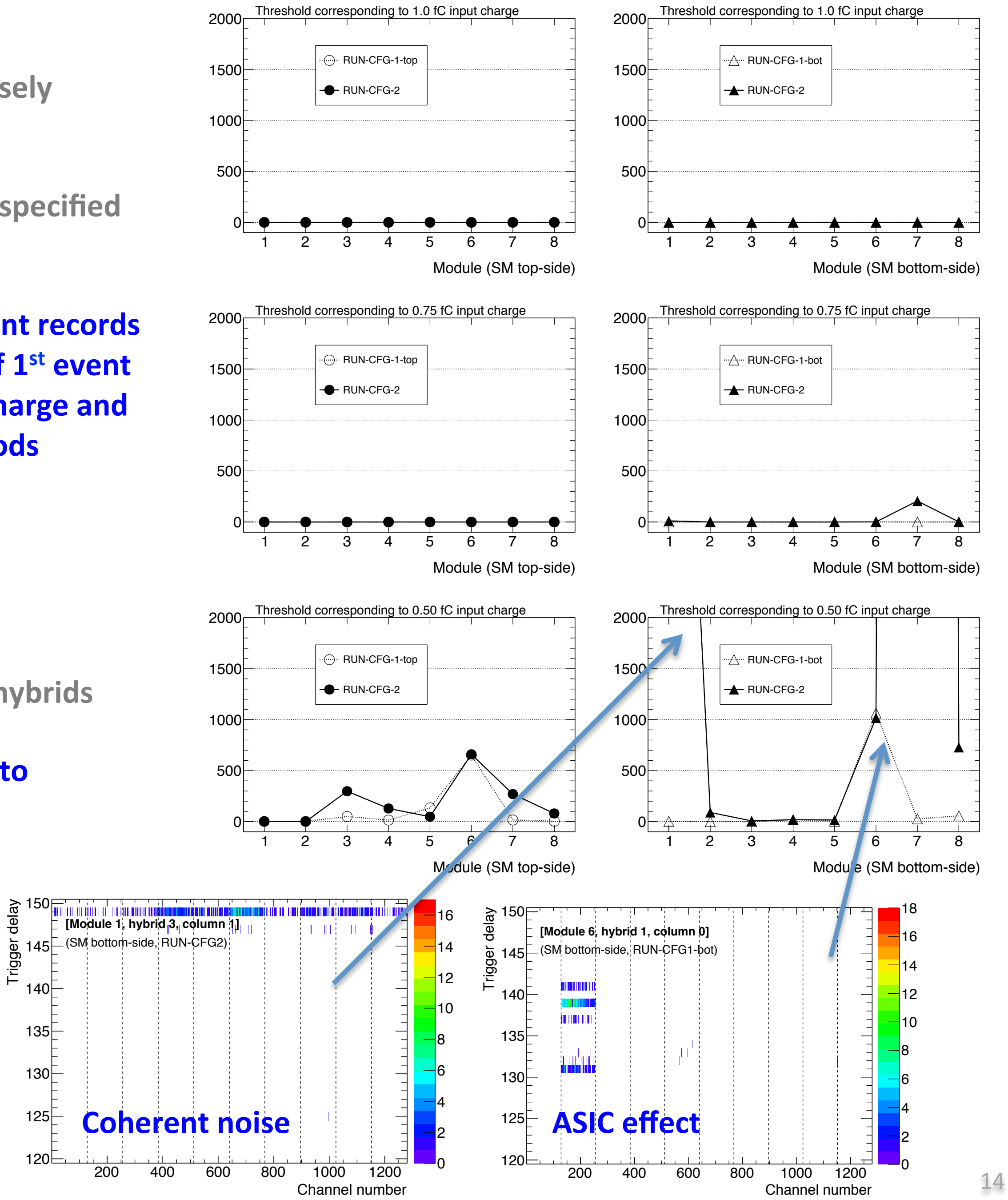
In collider operation, triggers are random and closely spaced triggers can occur

DTN measurements send 2 triggers separated by specified # of clock periods

- 2^{nd} trigger read out
- If spacing close to pipeline length, the 2^{nd} event records module occupancy at start of readout cycle of 1^{st} event
- Measurements made as a function of input charge and for trigger separations of 120 - 150 clock periods

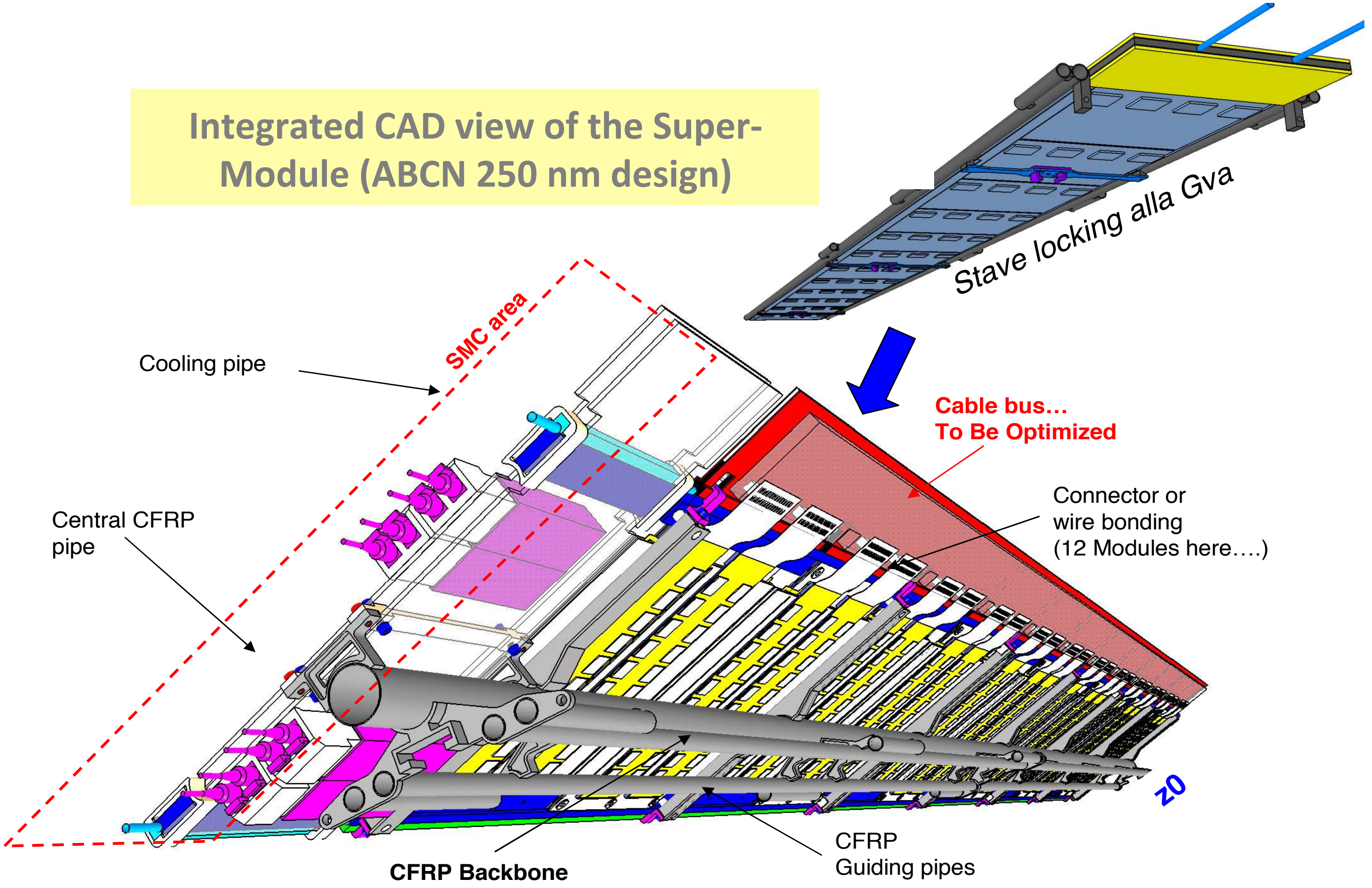
For 0.5 fC input, significant occupancy for a **FEW** hybrids (ASICS) in CFG-2 mode

- Further work required in future design to mitigate this



Super-module Mechanical Design Features

Integrated CAD view of the Super-Module (ABCN 250 nm design)



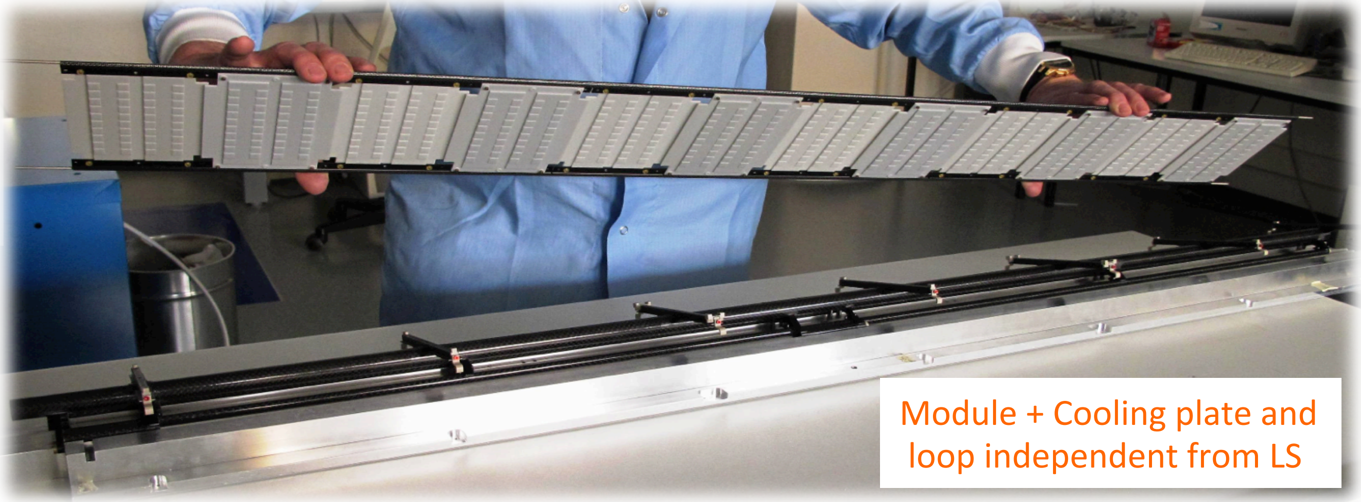
Low thermo-mechanical stress: Avoid all CTE mis-match. Service bus separated, cooling pipe uses sliding joints.
Precision of module on local support at room temperature ~ ±10 μm – surveyed
Precision of local support on structure ~ ±10-20 μm
Module position at -35^{0}C coolant determined by CTE and ΔT of local support

Mechanical prototype previously described (photos next page)

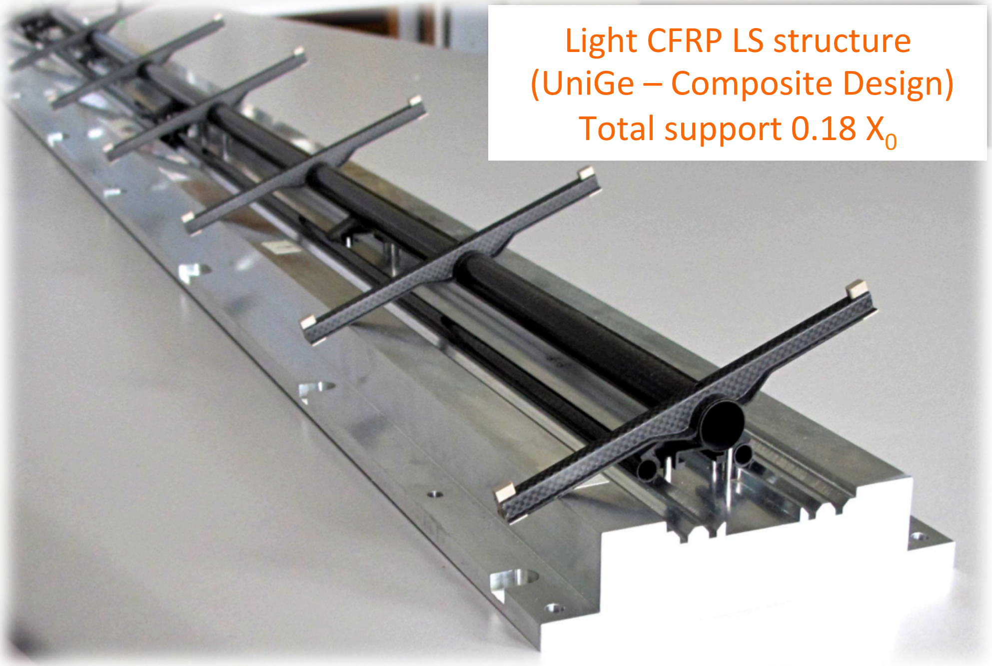
A few comments on this

Super-module Mechanical Prototype

Concept validated with stress-free end-insertion interfacing dummy barrel locking system



Module + Cooling plate and loop independent from LS



Light CFRP LS structure (UniGe – Composite Design) Total support 0.18 X_0

Prototype previously described, no new results (publication in preparation)

Status and Outstanding Issues

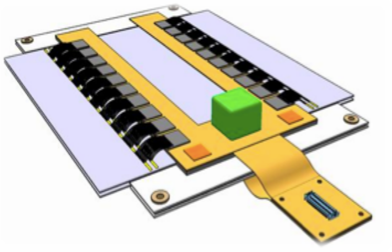
Status: Feasibility and practicability of Super-Module demonstrated
(except possibly mechanical and electrical aspects of cable bus)

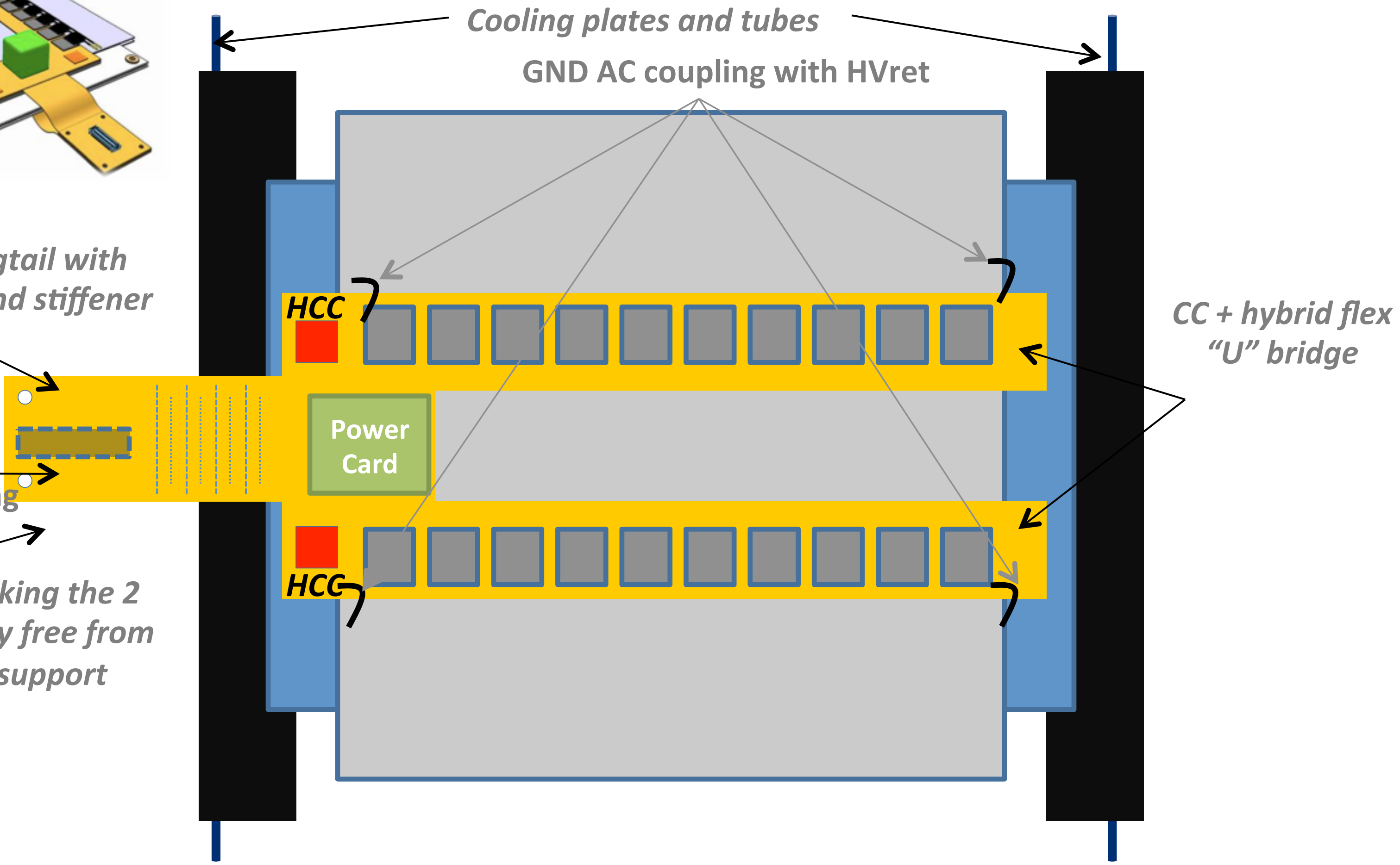
- Mechanical demonstration made
- Very successful multi-module electrical performance, although detailed studies of grounding and shielding remain important
- DC-DC architecture validated but EM interference needs optimization, as well as material (serial powering remains a valid option)
- Question of HV powering not yet addressed

Evolution: Evolution of sensor and module design with ABCN 130 nm and HCC submission
Evolution and implementation of read-out architecture and cable bus
Optimization of the mechanical support structure
Major test beam campaign with new design important ← A few slides

Issues: Adapt to evolutions of the ATLAS tracker layout
: optimization of the service bus
: LV services (DC-DC or SP powering)
: HV services (4 modules per HV line or HV multiplexer)
: Tradeoff between performance (material, noise pickup) and robustness

Module Design Evolution





Cooling plates and tubes

GND AC coupling with HVret

Flexible pigtail with connector and stiffener

CC + hybrid flex "U" bridge

Input Filtering

Stiffener linking the 2 sides possibly free from the local support

Comments:

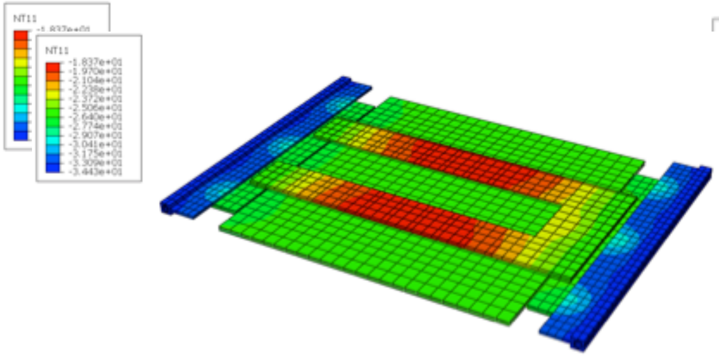
- Symmetry between the two rows is important. Also 1 hybrid type
- Power card (DC-DC or SP) is quite challenging and needs study – profit from cooling path
- Pigtail flexibility is essential to pass over the cooling plate
- EMI vs ground and shielding investigation is essential when considering DC-DC
- 1.59%X_0 with 12 mm width CC hybrid bridge, 1.49% X_0 if hybrid glued to sensor

FEA of Module Design

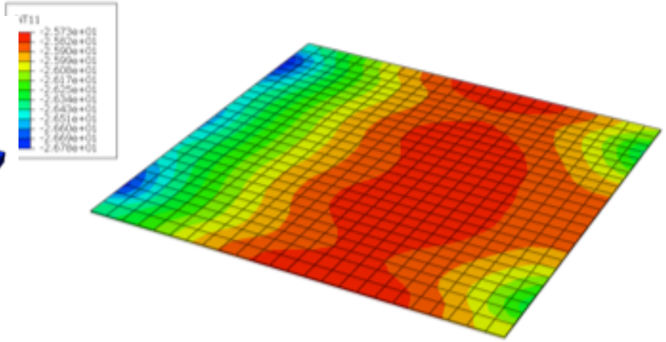
Thermal

ABCN250: 0.3W per chip(80)
ABCN130: 0.15W per chip(40)
+ 0.8W per DC-DC(2)
+ 0.15W per HCC(2)

CO2 T (coolant) = -35 °C
T(dry air) = 0 °C
2mm ID Ti cooling pipe

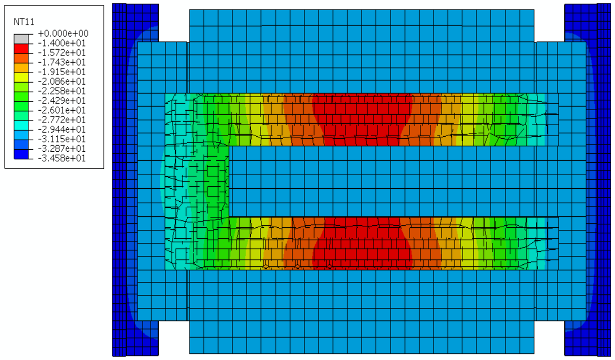


Contact at 3 points, T(hybrid) = -18 °C



T (sensor) in range [-26.7, -25.3]
(for no hybrid bridge ΔT ~ +4 °C)

More optimistic - full coverage of module and cooling plate with thermal grease (1W/mK, 50 µm thick)



T (sensor) in range
[-29.4, -31.1]

FEA of Module Design

Mechanical deformation

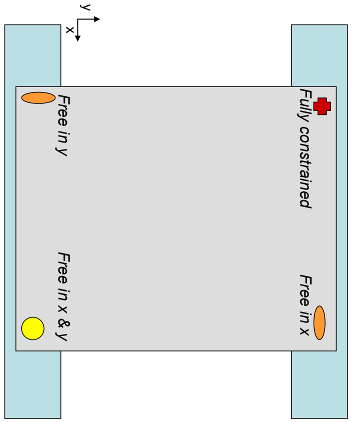
ABCN130: 0.15W per chip + 0.8W per DC-DC
+ 0.15W per HCC
T (dry air) = 0 ^{o}C
T (coolant) changed from T = +20 ^{o}C to T = -35 ^{o}C

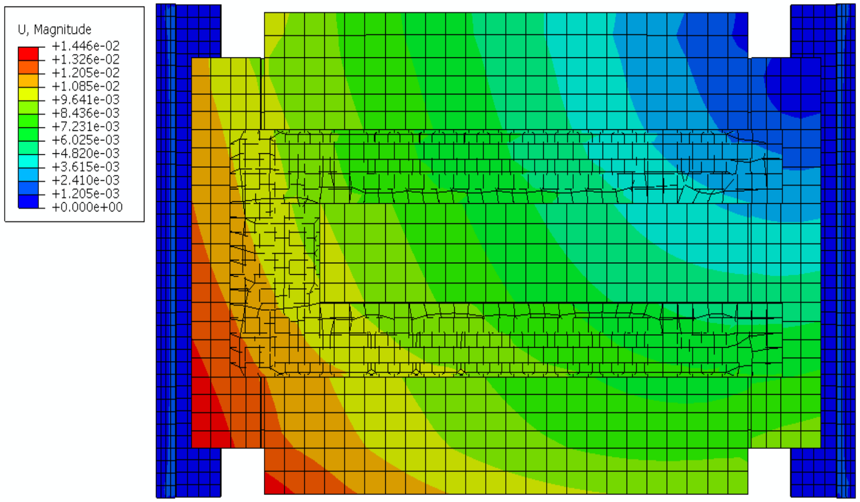
Assembly: sensor-to-sensor ± 1 µm
module fixation < ± 10 µm

Stress in TPG base-board: < 16 Mpa for ΔT = 40 ^{o}C
(TPG tensile strength is 40 MPa)

Max. in-plane module deformation: < 14.5 µm
(< 1.5 µm deformation for ΔT = 5 ^{o}C,
Important for long-term stability)

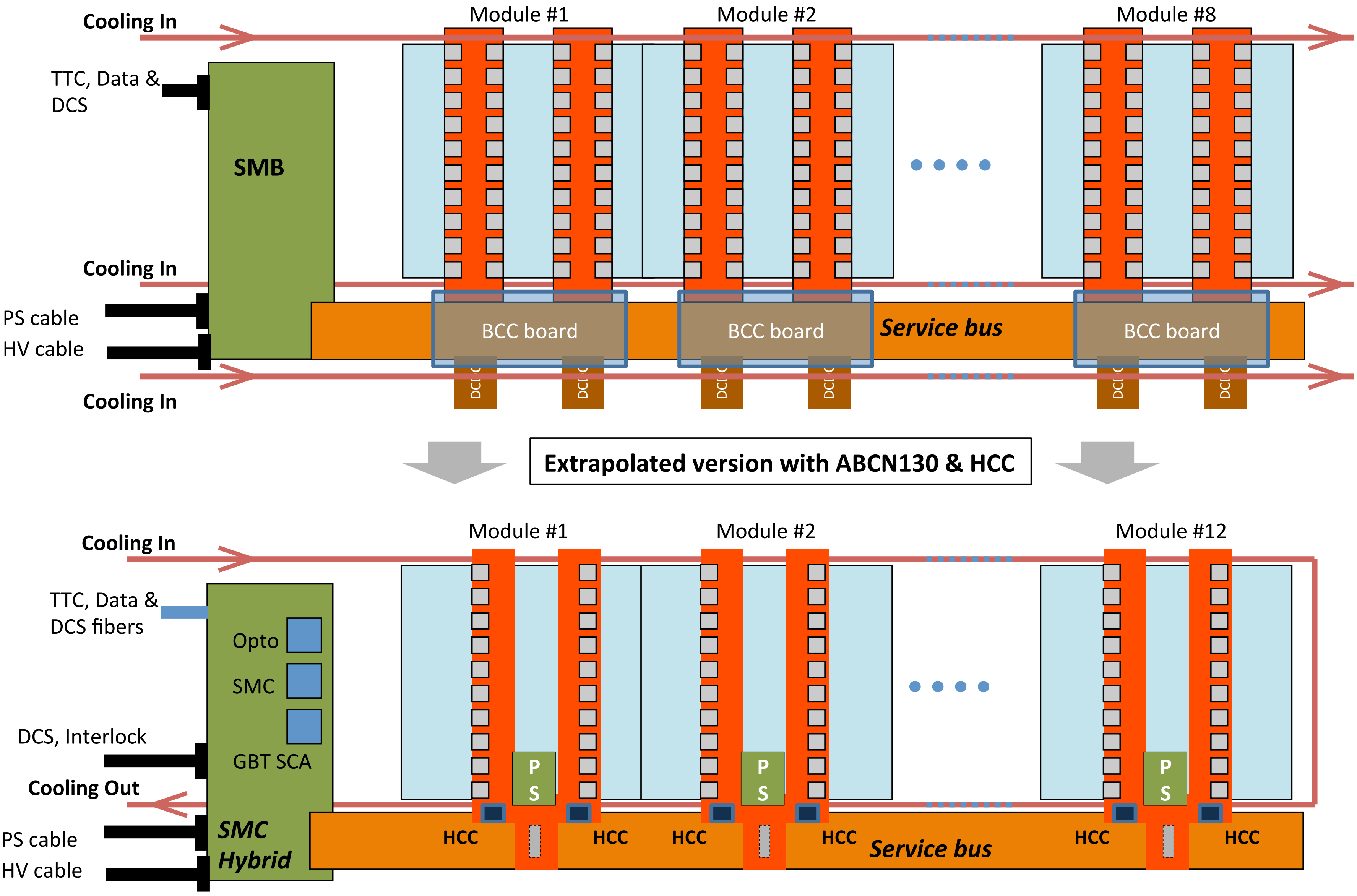
Max. out-of-plane module deformation: < 1.5 µm
(TPG baseboard)





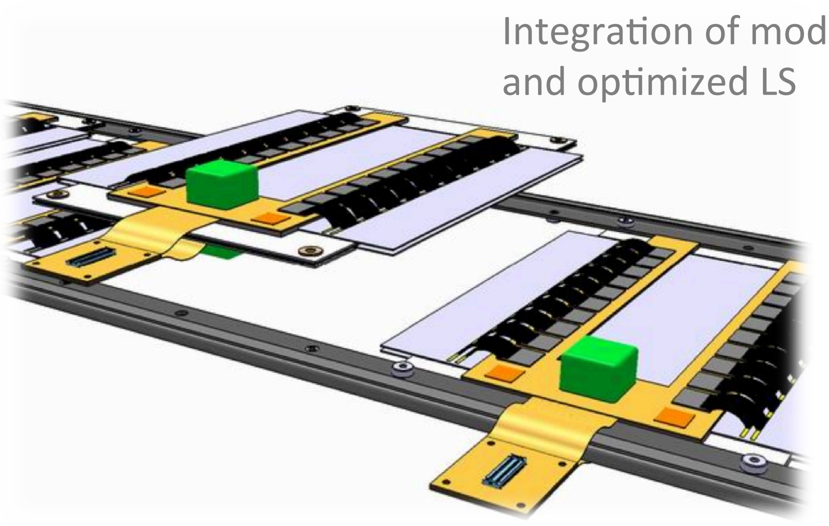
CTE (TPG)	(1.2, 1.2, 25)	ppm/^{o}K
CTE (Si)	3	ppm/^{o}K
CTE (AlN)	4.5	ppm/^{o}K
CTE (kapton)	18	ppm/^{o}K
CTE (glue)	25	ppm/^{o}K

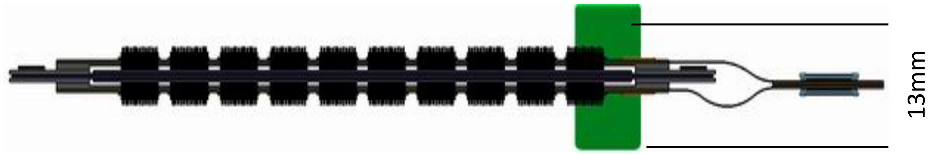
Super-Module Design Evolution

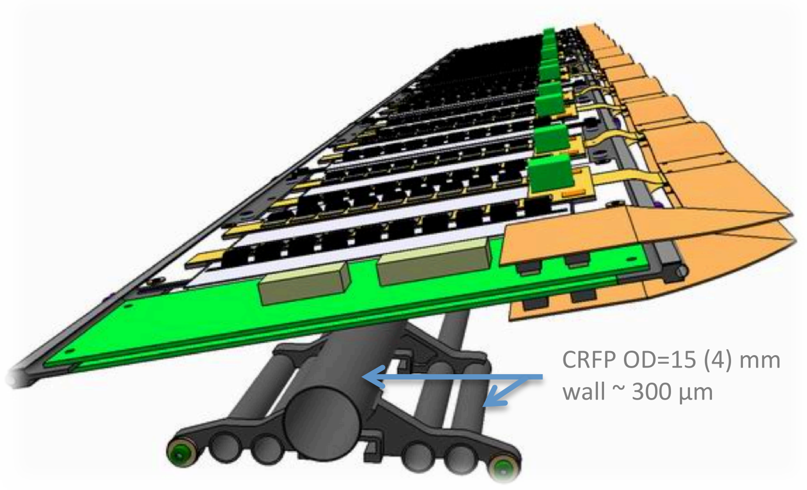


Super Module Thermo-Mechanical FEA

Integration of modules on the cooling plates and optimized LS







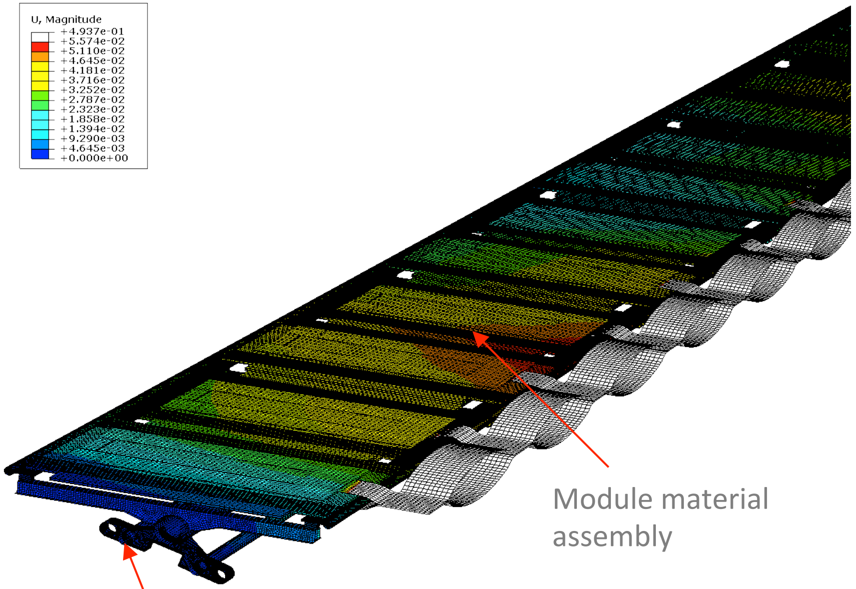
CRFP OD=15 (4) mm
wall ~ 300 μm

- 1-unit and 3-unit cooling blocks being considered
- CTE of back-bone and cooling plates: 0 – -0.5 ppm/^{0}K (tuned)
  deflection between 0 and -25 μm for ΔT = 40 °C
- CTE of service bus: 18 – 20 ppm/^{0}K
  deflection of order 1 mm for ΔT = 40 °C
- No "distortion" acceptable from service bus
- Service bus must be stabilized:
  - wavy bus attached at each module?
  - stabilized with bonded carbon fibre?

Thermo-mechanical behaviour to be understood:

- Modules on LS (kinematic mounting)
- Cable bus with respect to modules
  (the major unresolved issue)

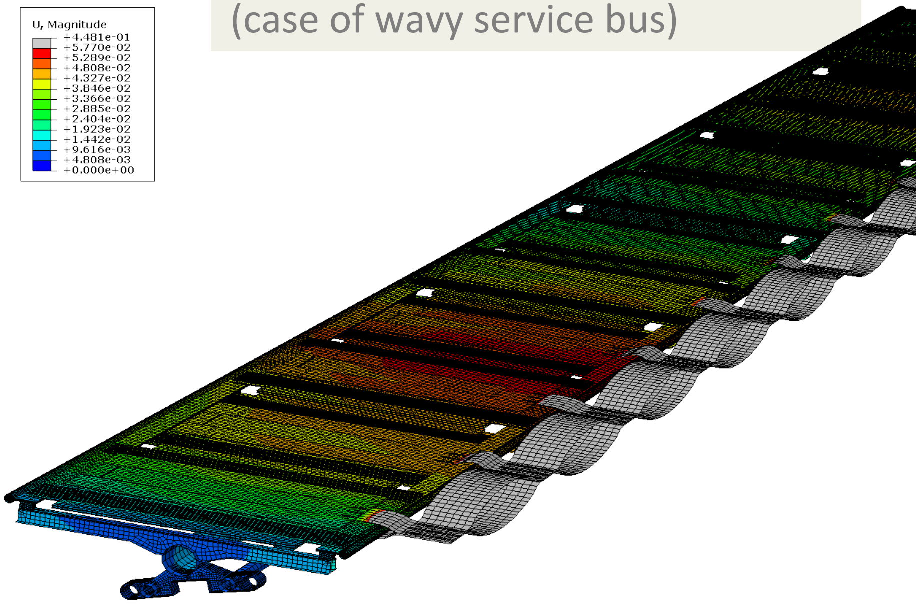
ABCN130 – Thermo-mechanical FEA at SM Level – Sag and Distortion



Module material assembly

Carbon fiber Layup (M55J)

(case of wavy service bus)



Maximum distortion including:
- gravitational sag
- service bus 55 µm

Maximum distortion including:
- gravitational sag
- service bus
- T(coolant) = -35 °C 57 µm

Worst-case: vertical (other orientations significantly less)

Final detailed result will be determined by:
- final service bus construction and attachment
- Number and rigidity of fixed supports
- CTE tuning of the LS and cooling blocks

Maximum stress: LS < 8 Gpa, mounted modules < 21 Gpa

Material Budget Estimation

Item	Rad. length [% X0]	
Module with CC bridge (12mm width)	-	1.59
Module without CC bridge	1.49	-
Local support	0.18	0.18
Cooling plates	0.17	0.17
Bracket, inserts (interface to cylinder)	0.08	0.08
Cooling pipe (Ti 2mm)	0.04	0.04
Cable bus Al/Cu	0.11	0.11
Total	**2.07**	**2.17**

Conservative
Needs optimization

Extracted from evolving excel spreadsheet

NB:

- The sensor thickness is considered 320 μm. If 250 μm one gains 0.15%.
- List above does not include the power cards: serial power interface or DC-DC card
- Module without CC bridge means that the hybrid flex is directly glued on top of the Si-sensor.

Comments and Conclusions

1. **The double-sided super-module prototype R&D using ABCN250 chip now concluded (currently back-up option in ATLAS Phase II LOI)**
    - **Required noise performance** on single module test box, combined module test box and 8-module SM prototype achieved (DC-DC LV powering, individual HV powering)
    - Ground and shielding Improvements for next-generation SM identified
    - **Position accuracy and mechanical (thermo-mechanical) stability for modules, and super-modules on LS demonstrated** (design optimized for thermal stability)
    - **Competitive material budget** while retaining good thermal-mechanical behaviour

    +

    - **Design flexibility** enables parallelism of procurement and construction
    - Construction **modularity** expected to minimize rework and component cost

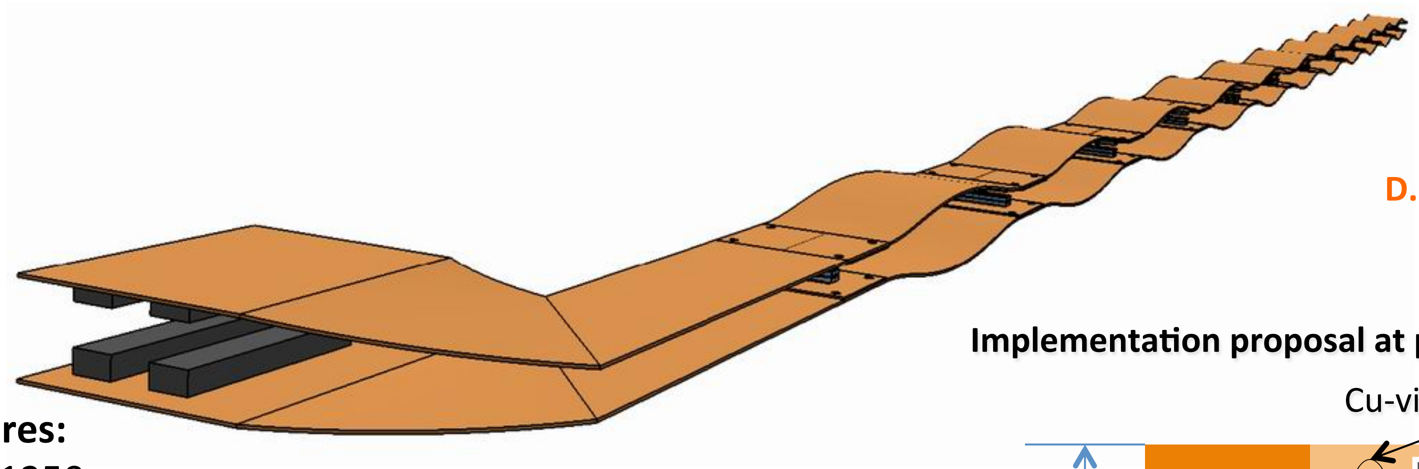
    Not discussed here

2. **Preparation for realistic "pre-production" prototype described**
    - Use ABCN130, HCC and a dedicated service bus
    - Optimization of service bus for selected LV and HV powering schemes a key issue
    - Test beam studies of "pre-production" module before/after irradiation a priority

Many thanks for your attention

BACKUP

Service Bus Design Evolution – based on IBL experience



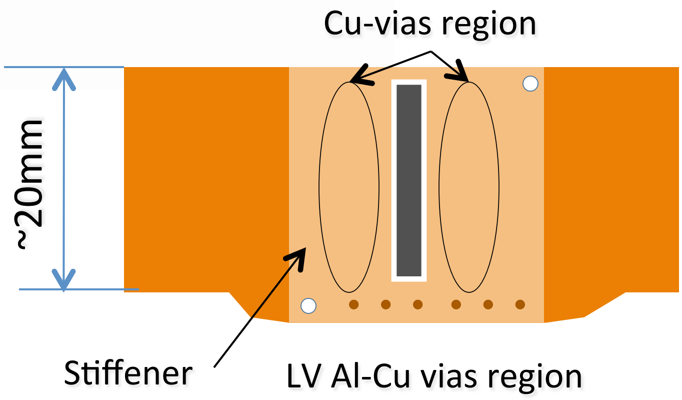
D. Ferrere, Y. Unno

Bus features:

- Length: 1250mm
- Width: 20 - 22mm
- Al layers: 2 x 50 microns (width from 11 to 20mm step)
- Cu layers: - 2 layers of 15 microns: LVDS + HV + DCS
  - 1 mesh layers of 5microns for LVDS impedance

Bus material	X/X0 [%]
Al layers - GND + bias (100 microns)	0.0174
Kapton + glue (240 microns)	0.0136
Other Cu layers (eq. 10 microns)	0.0155
Stiffeners (22x14x0.3 mm3)	0.0029
Connector (estimate)	0.0050
Total (1 side)	0.0544
Total (2 sides)	**0.1088**

Implementation proposal at pigtail connection



NB:

- *Optimization of Al thickness vs resistivity and cable power loss*
  100μm Al → 1.8W
- *Time scale for design + fab: 5 -6 months*

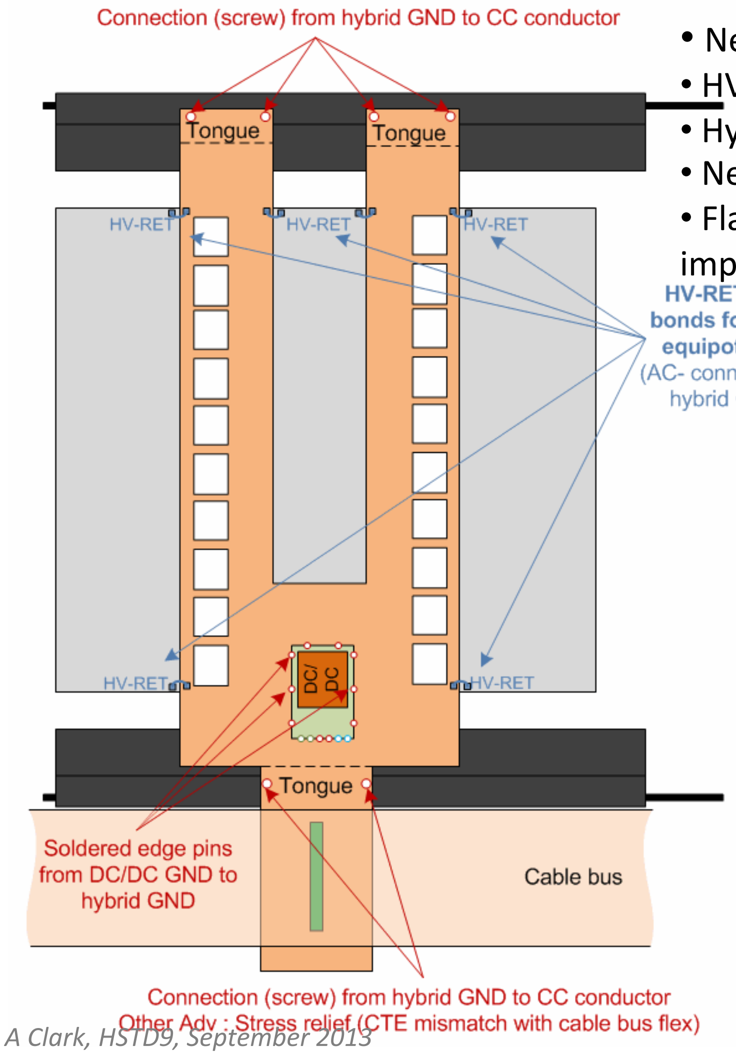
If 60 μm Cu → 0.204%
If 100 μm Cu → 0.291%

ABCN130: Common mode noise and Grounding

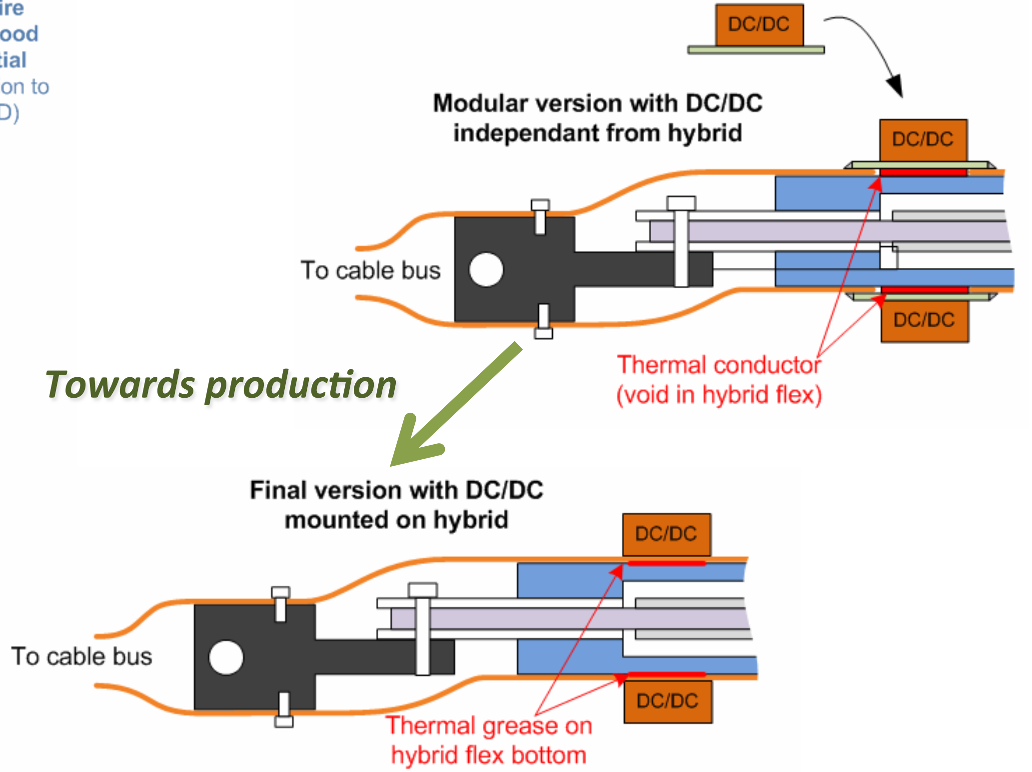
D. Ferrere, Y. Unno

On-detector noise due to local DC-DC converters and digital activities need to be considered when designing the module and the super-module

This has been investigated for the super-module prototype with success and some anticipations for grounding the hybrid, module and super-module to the surrounding is proposed:



- Need good shielding of DC-DC (noise source)
- HV return to be connected in AC to hybrid GND (several points)
- Hybrid GND to be connected to cooling plates (several points)
- Need to check the HF impedance of the cooling plate
- Flanges to be coupled to the ATLAS star point GND with very low HF impedance



ABCN130 Hybrid Considerations

D. Ferrere, Y. Unno

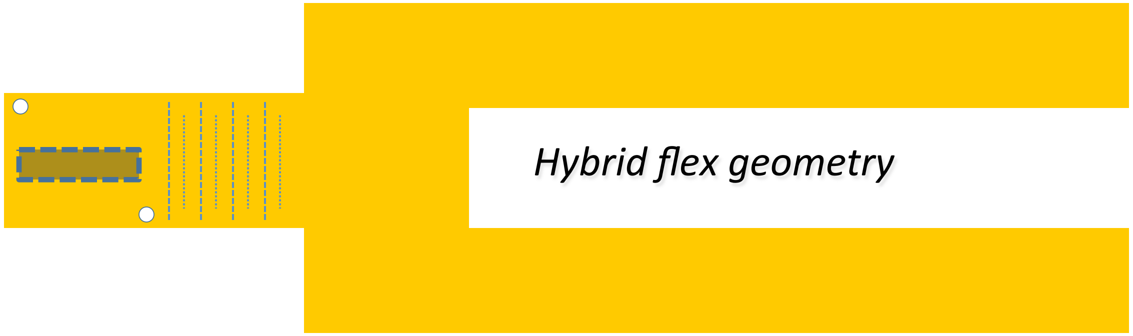
Hybrid:

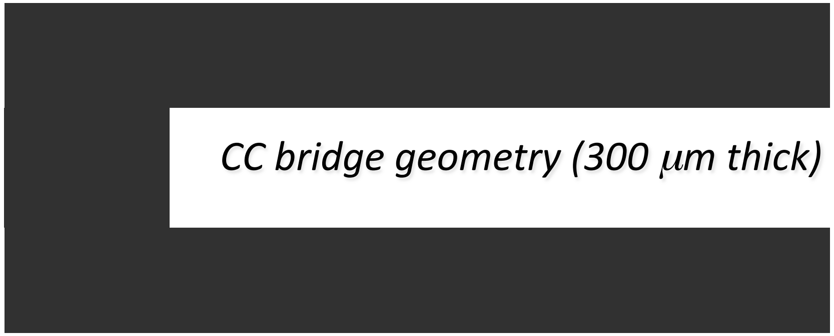
-Technology: same as for current ABCN250

- Same for the two module sides

AXT Panasonic connector:

- Same as for IBL PP0
- From 10 to 80 pin contacts in 2 rows
- Pitch 0.4mm → 19.5mm width for 80 pins.
- 0.3A per contact
- 1kV ok with 2 interleaved missing contact pins
- Insertion/removal 50 times guarantied





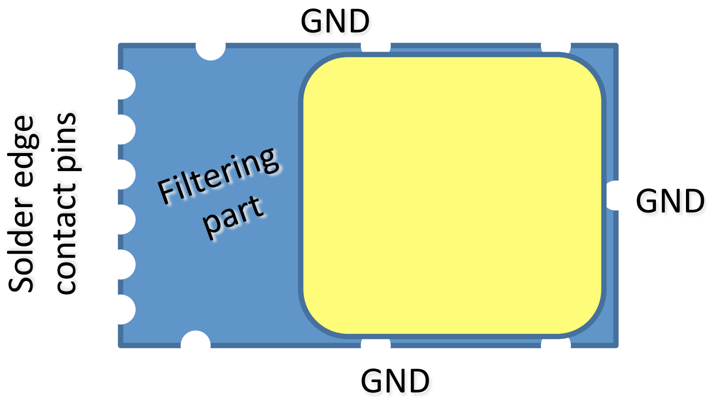

Socket


Header

DC-DC layout

-Targeting for future DC-DC converter board

- Estimated size: 20x13.5mm
- Height: should be reduced and hope for 5mm max
- Current estimates for 2 rows of 10 chips ABCN130: ~2.5A
- Local power dissipation due to inefficiency: 0.6 to 0.8W



NB:

- For prototype version: DC-DC board should be dismountable using SMD solder edge pins

- In production version: DC-DC should be integrated into the hybrid flex design (same GND, bias planes)

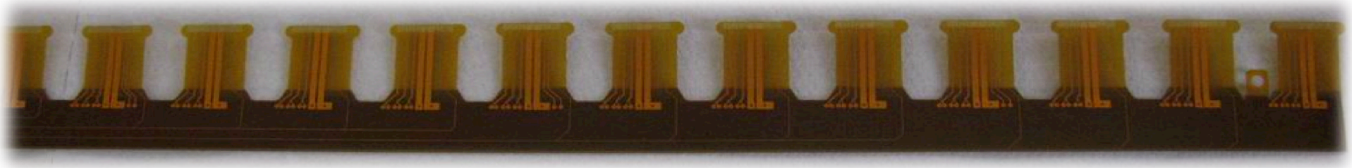
Service Bus Design Evolution

Alco flex made in fabrication for IBL (Genova – design, CERN – Fabrication)

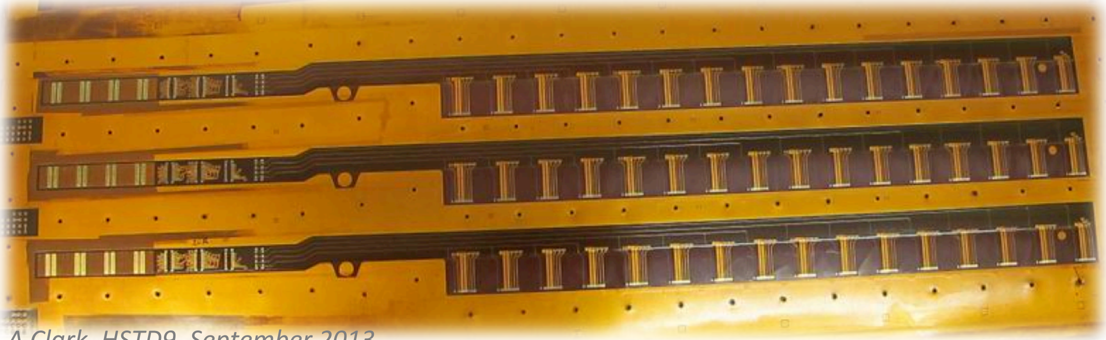
- 4 Cu layers (50 μm): 15μm for HV, 15 μm LVDS1, 5 μm for GND ref, 15 μm LVDS2
- 2 Al layers (100 μm): 50 μm per power layer
- Multilayer of dielectric kapton/Pyralux (212.5 μm)
- Glue layers (85 microns)

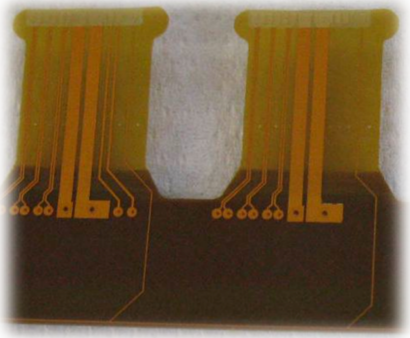
From D. Ferrere *(in discussion with Rui and in perspective of the Upgrade):*

- *The 4 Cu-layers are standard process that could be outsourced*
- *The 2 Al-layers needs to be processed with CVD for Chrome and Copper (vias)*
- *Maximum length that could be processed by Rui’s workshop 1.5m (not an issue / Super module)*
- *Flex production simpler than for IBL’s (no special cutting for some layers like the wings…)*
- *Wavy flex for CTE mismatch with local support.*
  Could be thermally formed in a press!



IBL production batch





Wing part (1 layer)