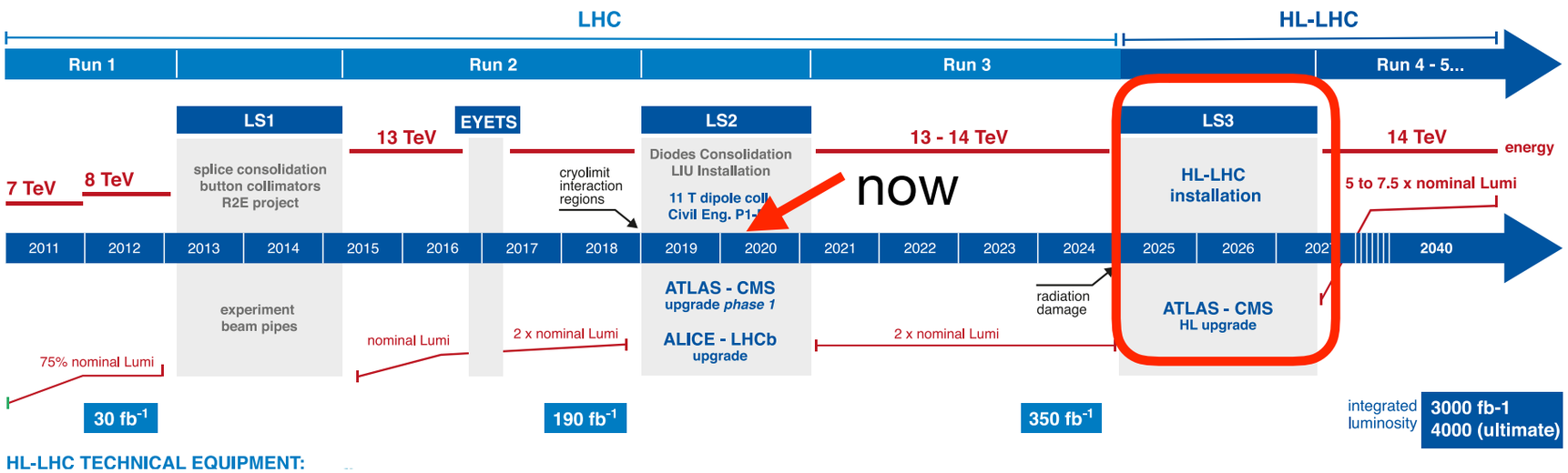
15th Trento Workshop on Advanced Silicon Radiation Detectors

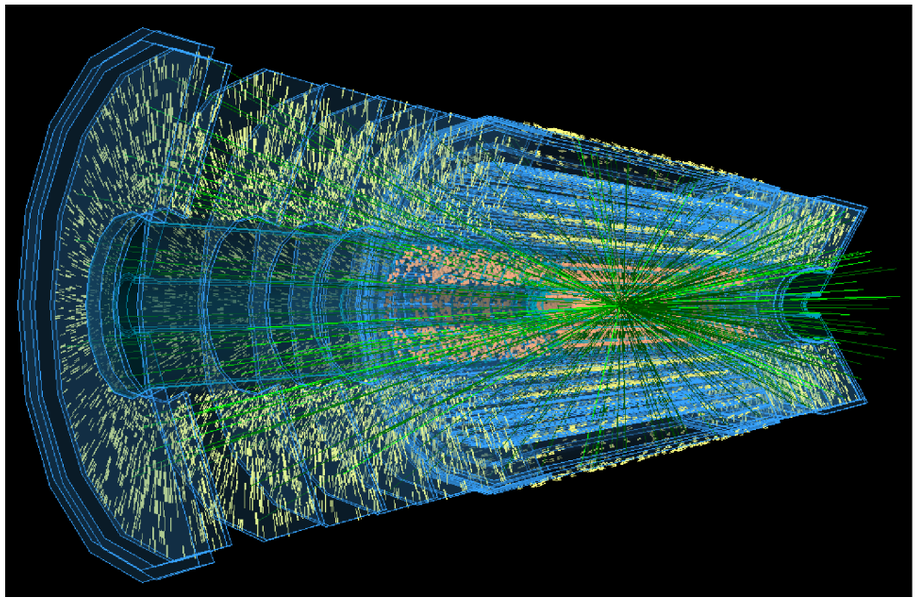
Development and evaluation of prototypes for the ATLAS ITk pixel detector

Quentin Buat (CERN) on behalf of the ATLAS ITk collaboration

HL-LHC and the ATLAS detector upgrade



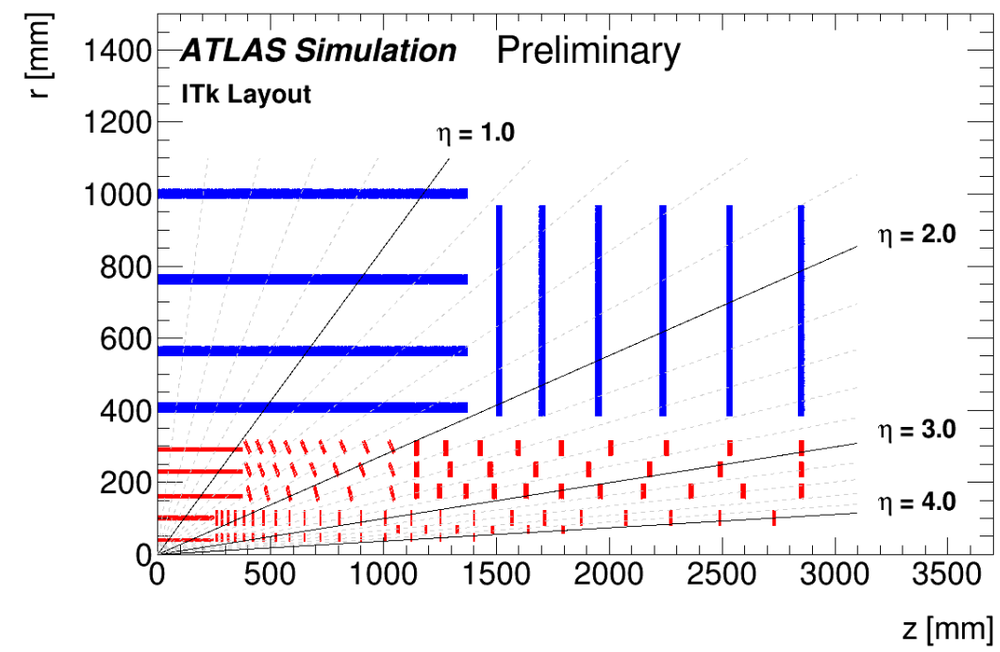
- Upgrades of the CERN accelerator complex in 2025-2027: HL-LHC
  - Instantaneous luminosity 5-7x nominal LHC
  - Integrated luminosity 10x nominal LHC
  - Up to 200 interactions per bunch crossing
- Major upgrade of the ATLAS detector required

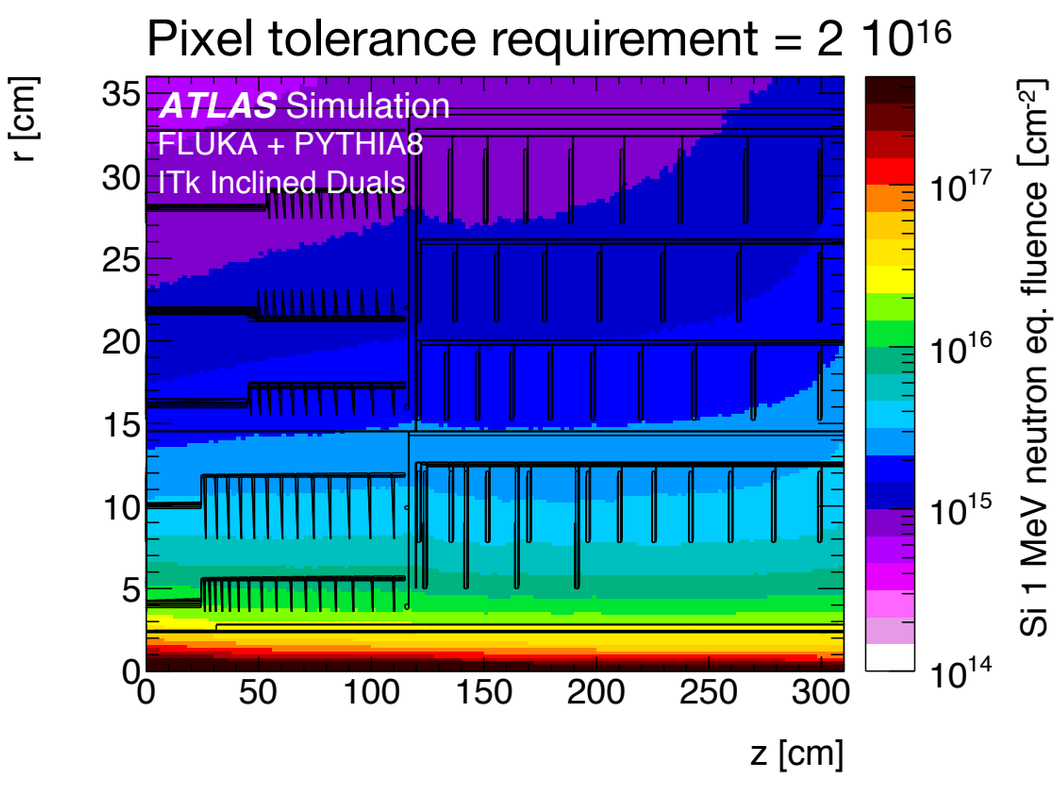


A new tracking system for ATLAS: ITk

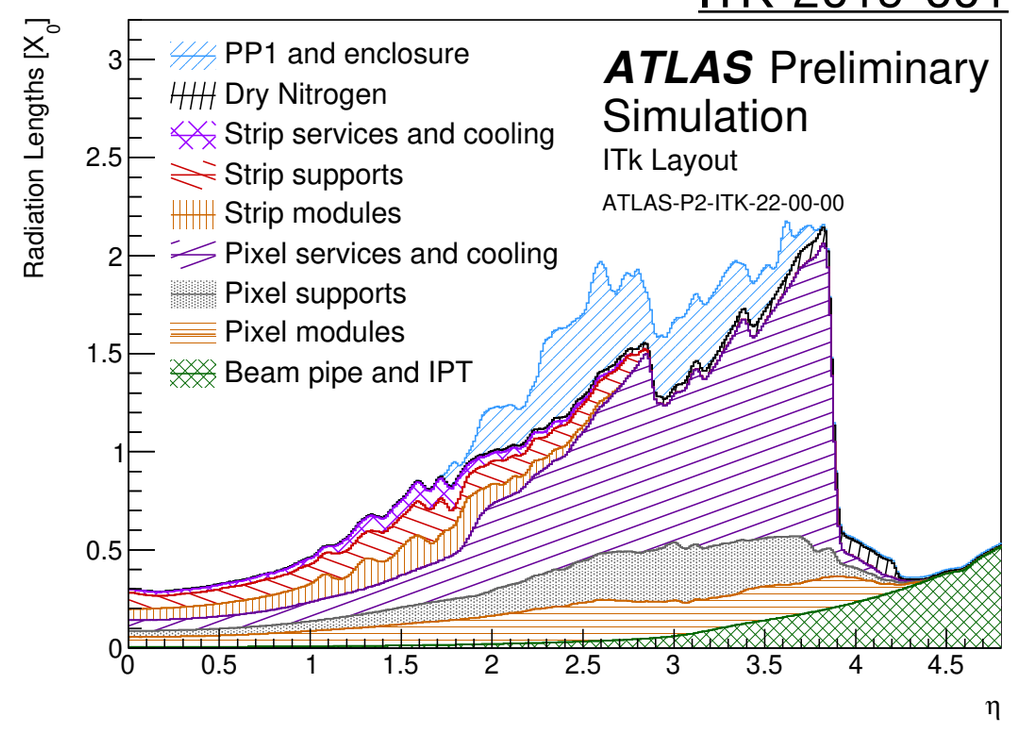
- Current ATLAS tracker can not cope with the HL-LHC running conditions:
  - Replace with an all-silicon detector
- Pixels: 13 m² of silicon, ~5 billions channels
- Strips: 160 m² of silicon: ~50 millions channels
- Extreme radiation tolerance, high granularity and acceptance, low material budget

TDR: CERN-LHCC-2017-005 (strips), CERN-LHCC-2017-021 (pixels)



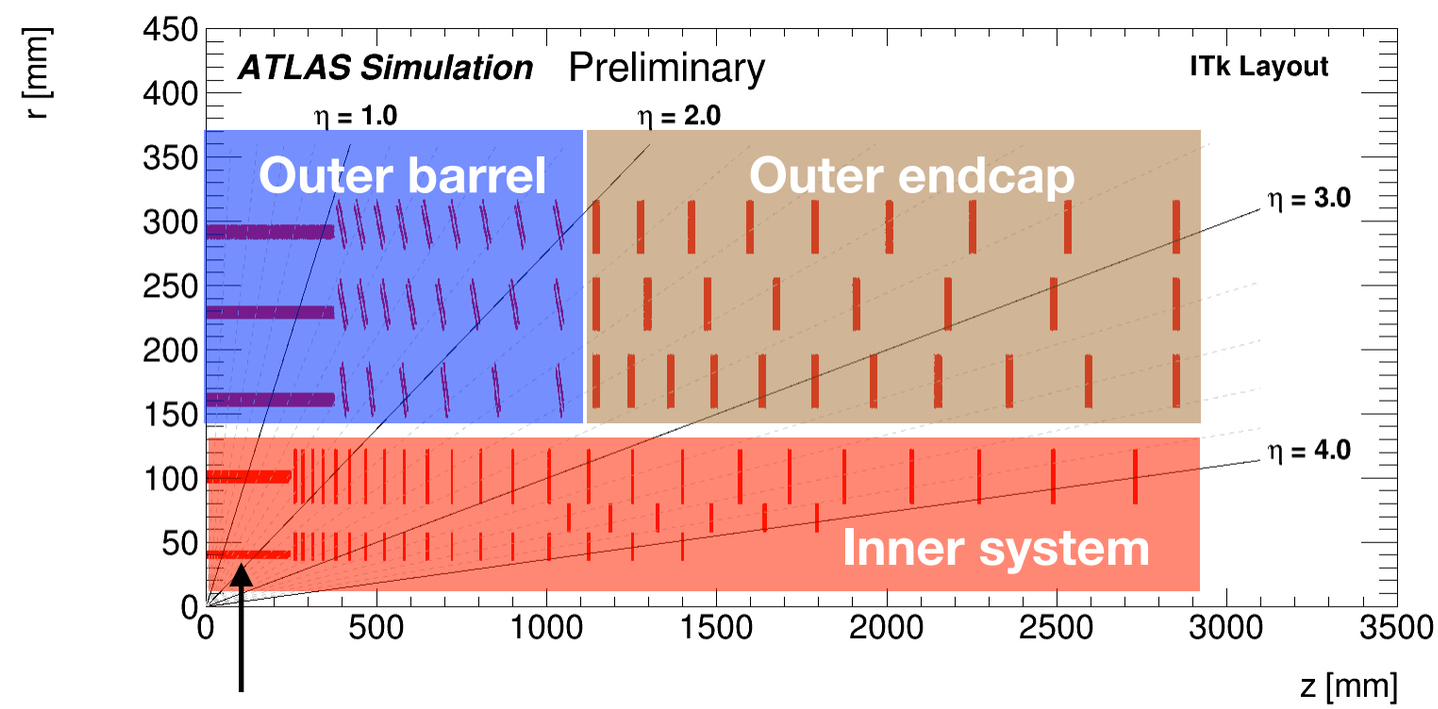


ITK-2019-001



The ITk pixel detector

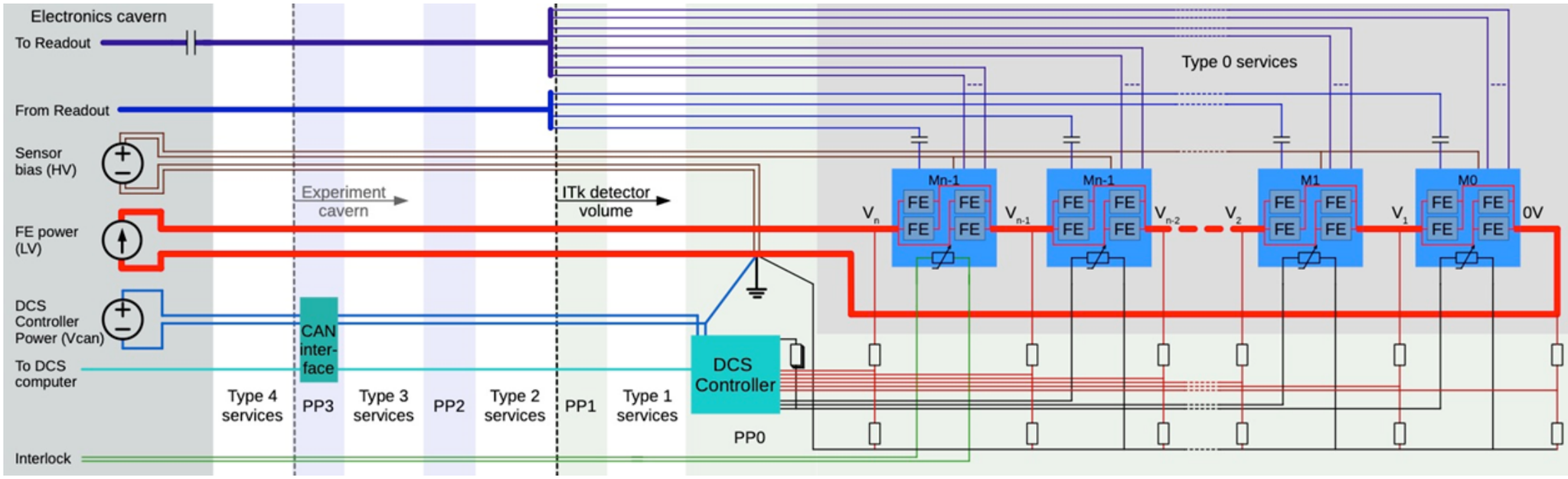
- 3D sensors in the innermost layer,
  planar sensors in other layers
- Pixel size: 100x25 μm² for the flat section of the innermost layer
  50x50 μm² everywhere else
- Coverage up to |η|=4
- Fast data transmission with up to 4x1.28 = 5.12 Gbit/s per FE chip
- Minimisation of material budget:
  - $C0_2$ cooling, serial powering, lightweight carbon structure
- 5 pixel layers:
  - ~10k modules,
    ~35k readout chips



100x25 μm²

Serial Powering

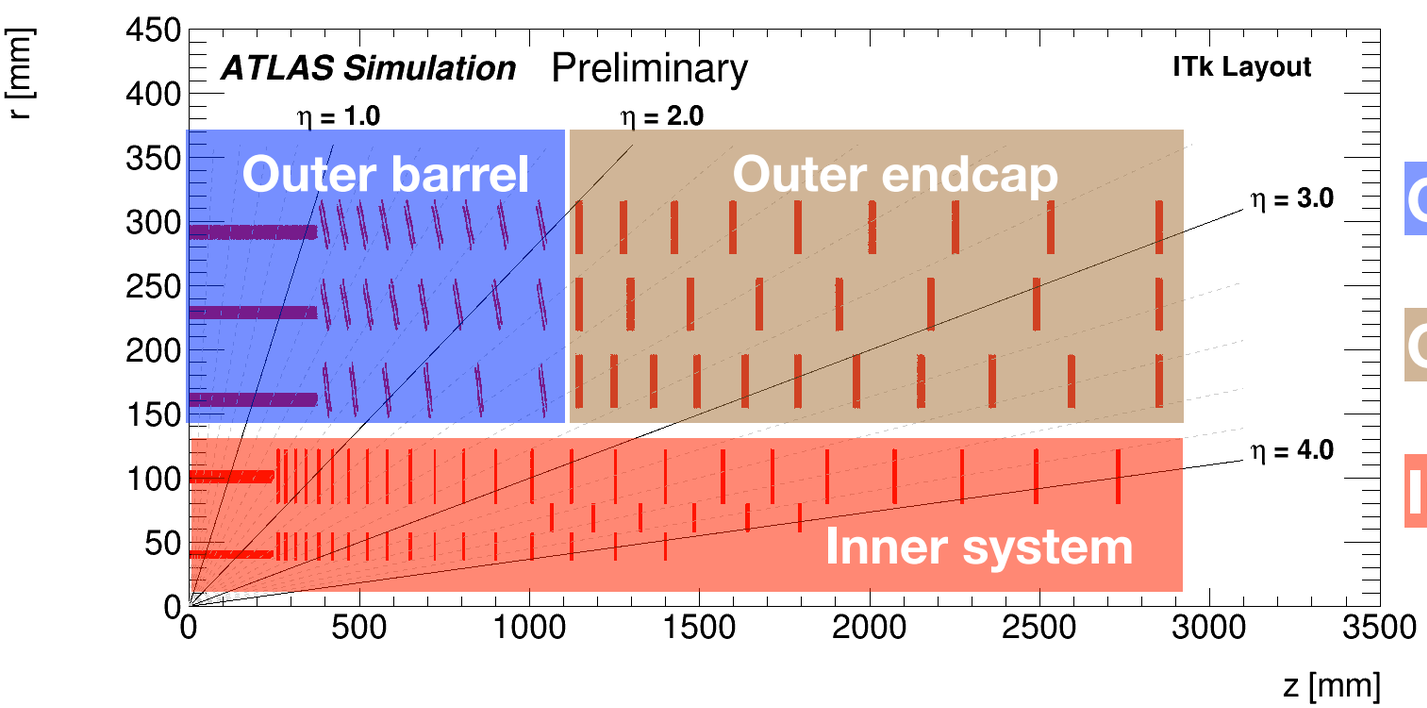
Serial powering:
T. Stockmanns et al., NIM A511 (2003) 174-179
D. Bao Ta et al., NIM A557 (2006) 445-459
L. Gonella et al., JINST 5 (2010) C12002



- 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

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)

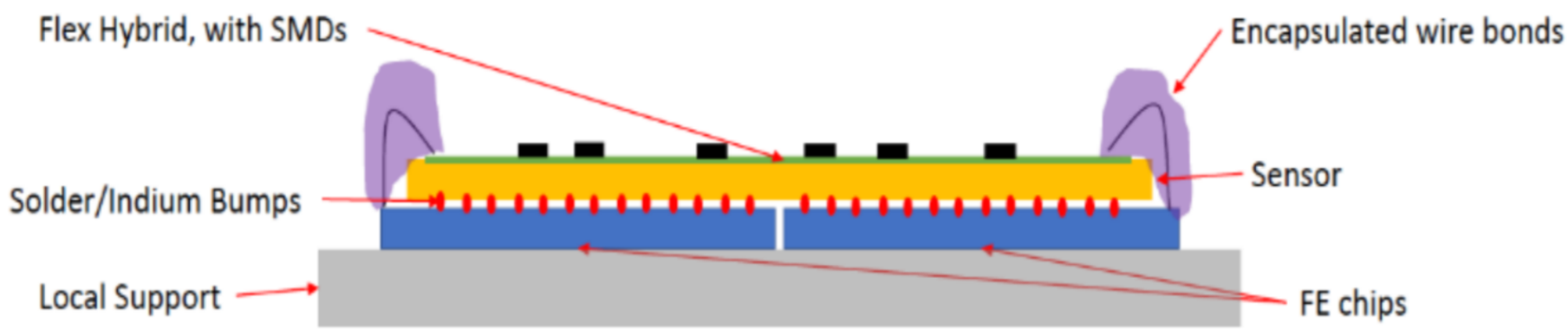


Outer barrel: main focus of this talk

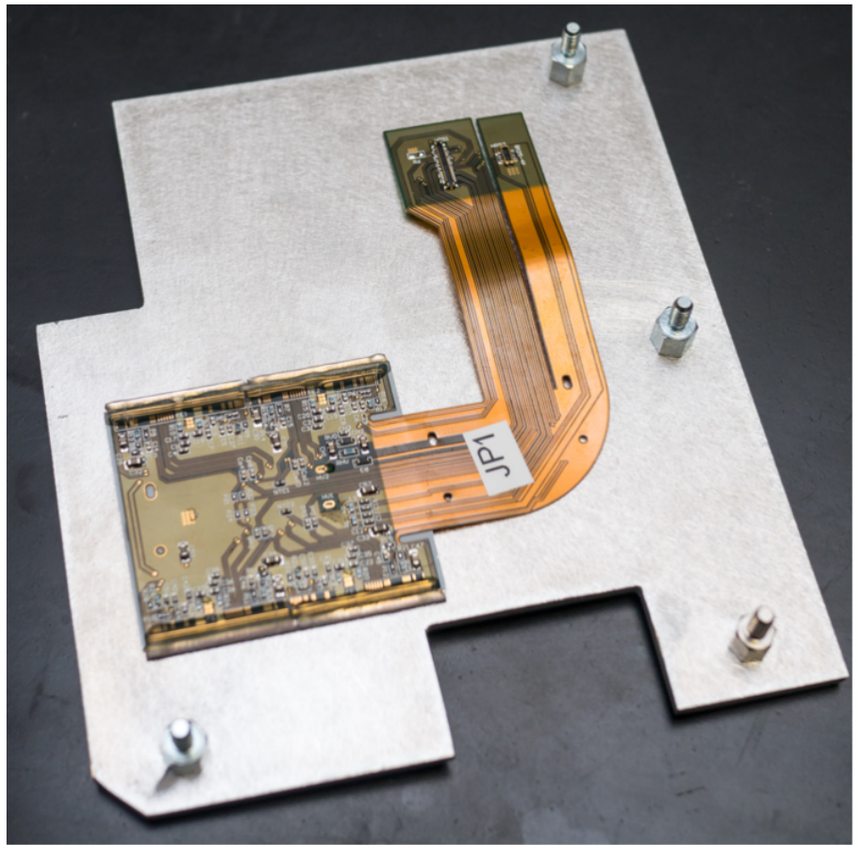
Outer endcap: first prototypes under test

Inner system: prototype design ongoing

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

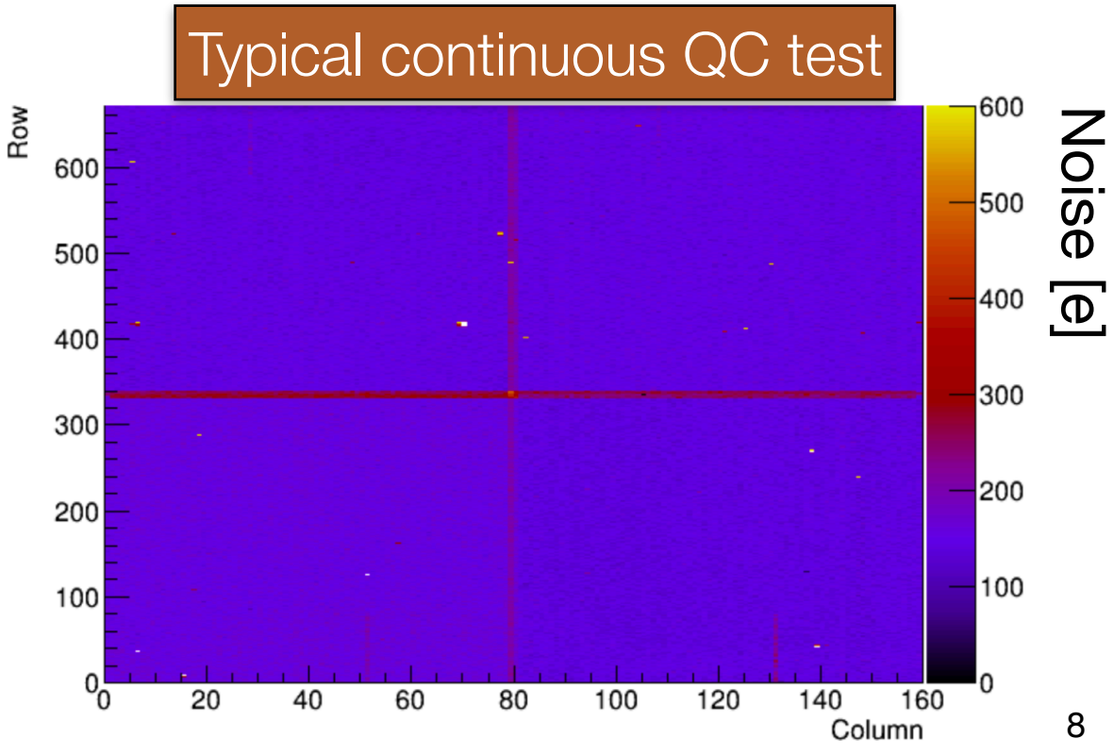


Small electrical prototype for outer barrel

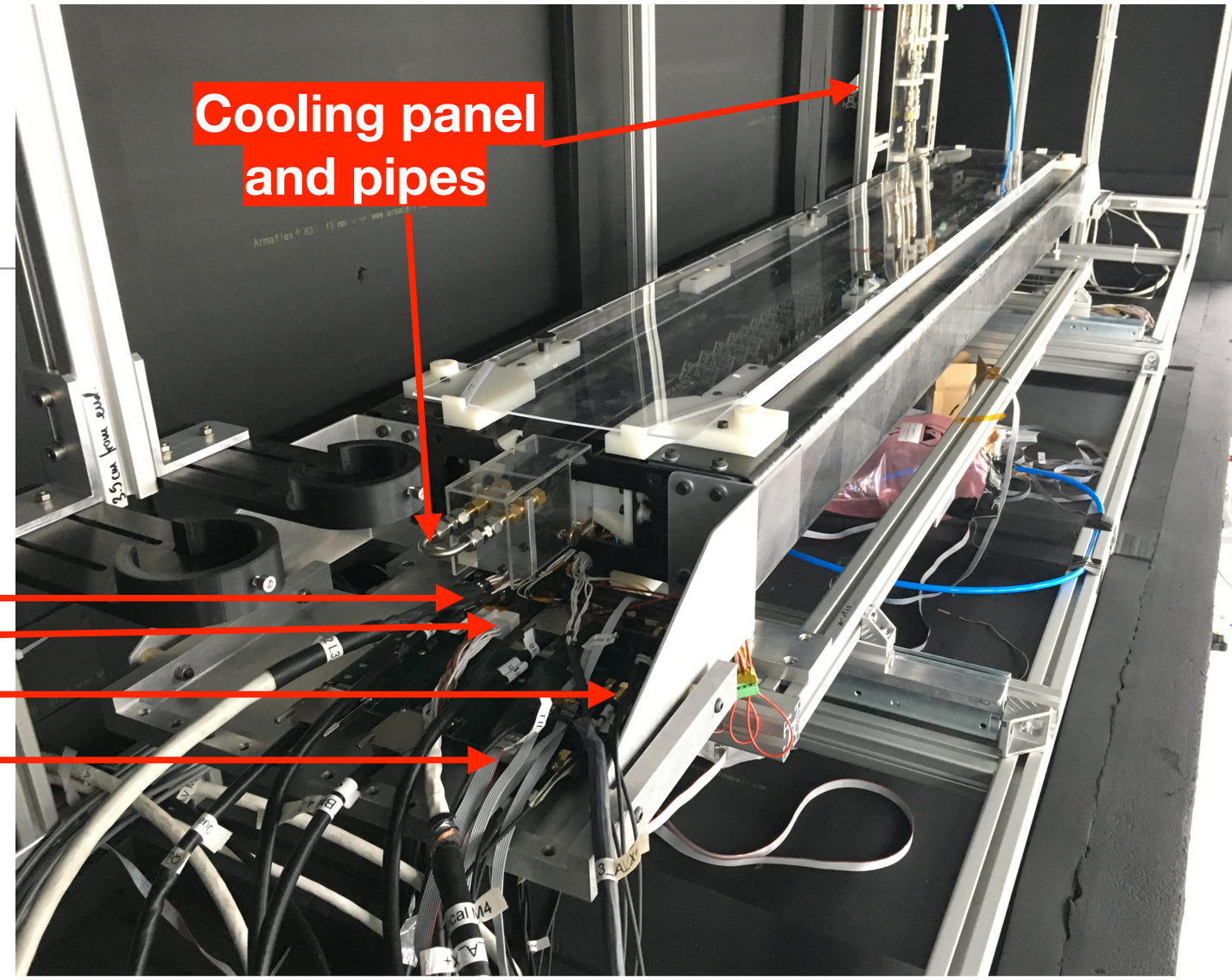
- Electrical 7-quad module structure as first step before full-size prototype
- HV power supply used had high-ohmic off mode inducing a forward bias in the last sensor

Module ID	1	2	3	4	5	6	7
Sensor current (μA)	-4.8	-3.7	-*	-*	-19.9	-2.3	**30.3**

  - 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

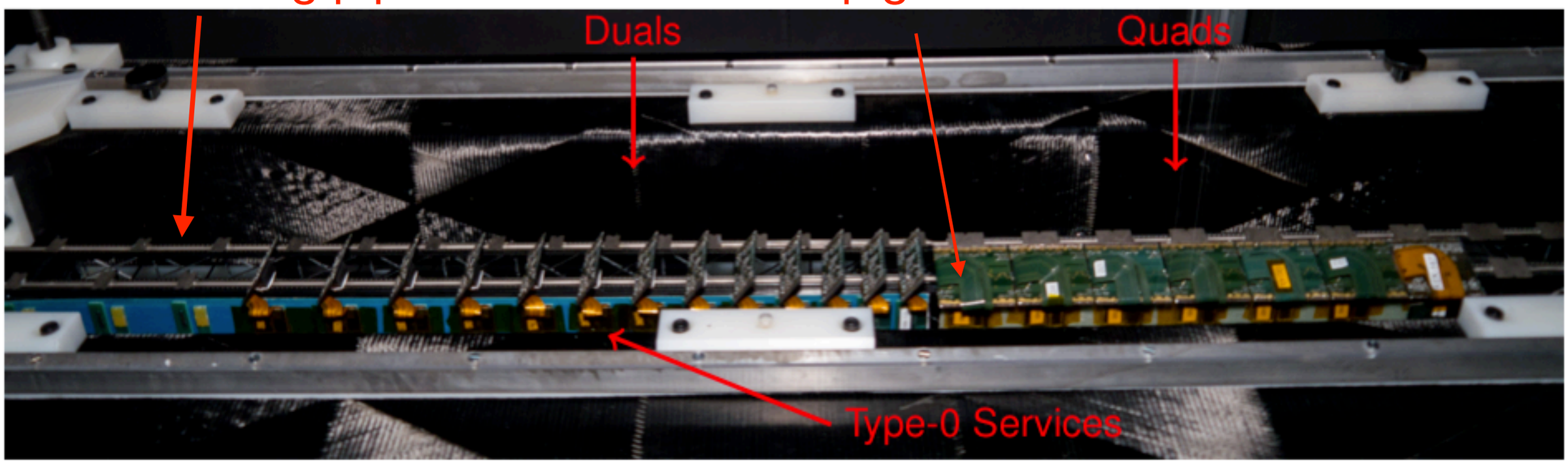


Outer Barrel Demonstrator



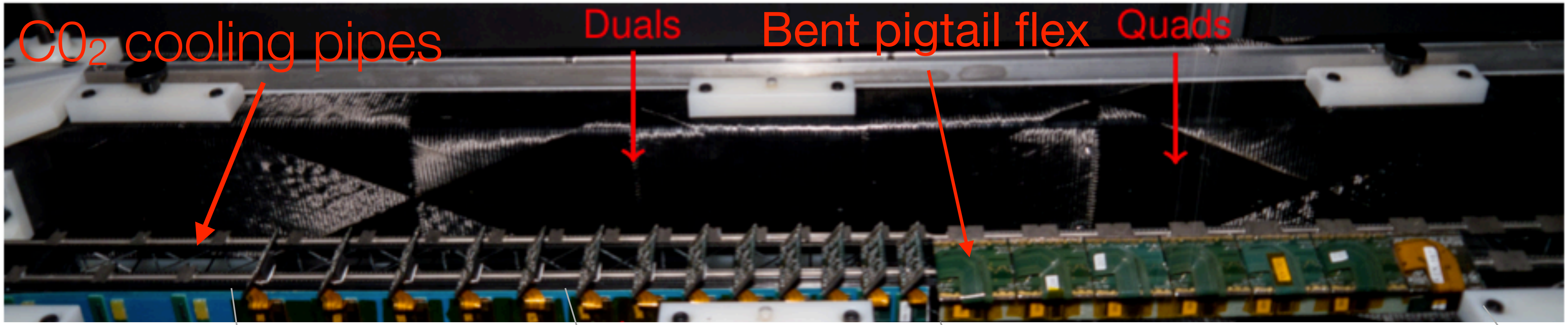
- Full size local support: 1.6m long
- CO_2 cooling
- Environment-controlled and monitored box
- 32 Duals and 14 Quads modules: 120 FE-I4 (currently under test 54)
- 6 Serial Powering Lines (currently under test: 3)
- Realistic FE-I4 services, cables, PSUs, DCS, interlock, etc…

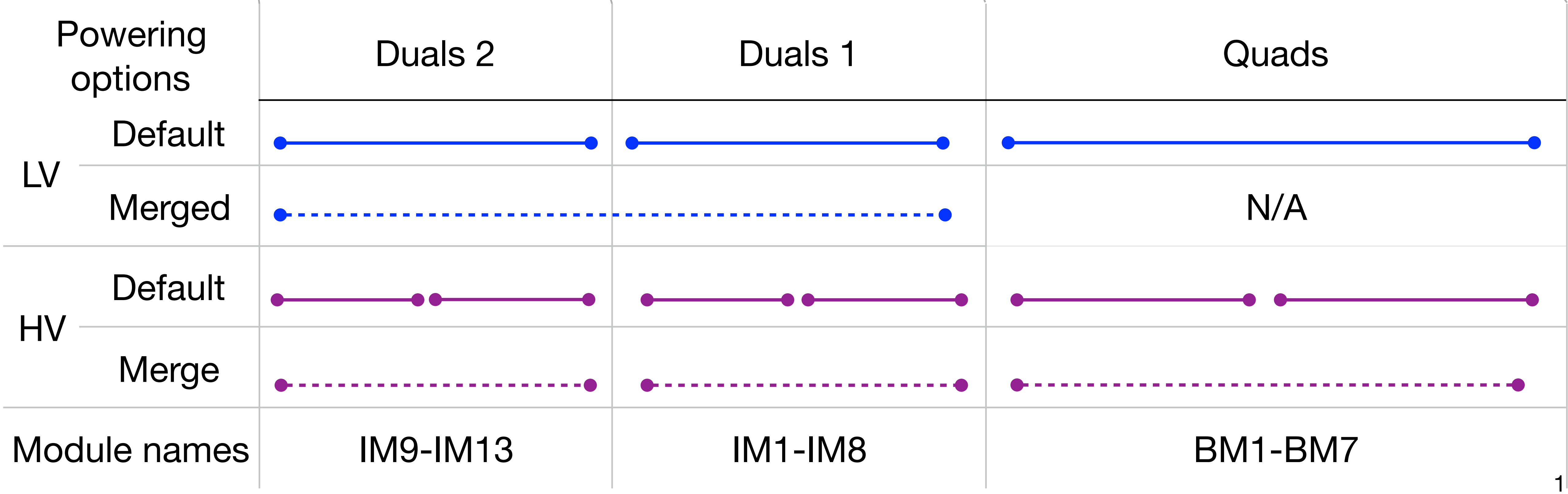
Half-cooling line setup



		Half cooling line setup		
		Inclined modules (FE)	Flat modules (FE)	Module type
Demonstrator		13 (26)	7 (28)	duals/quads
ITk OB design	Layer 2	6 (24)	9 (36)	quads
	Layer 3	8 (32)	9 (36)	quads
	Layer 4	9 (36)	9 (36)	quads

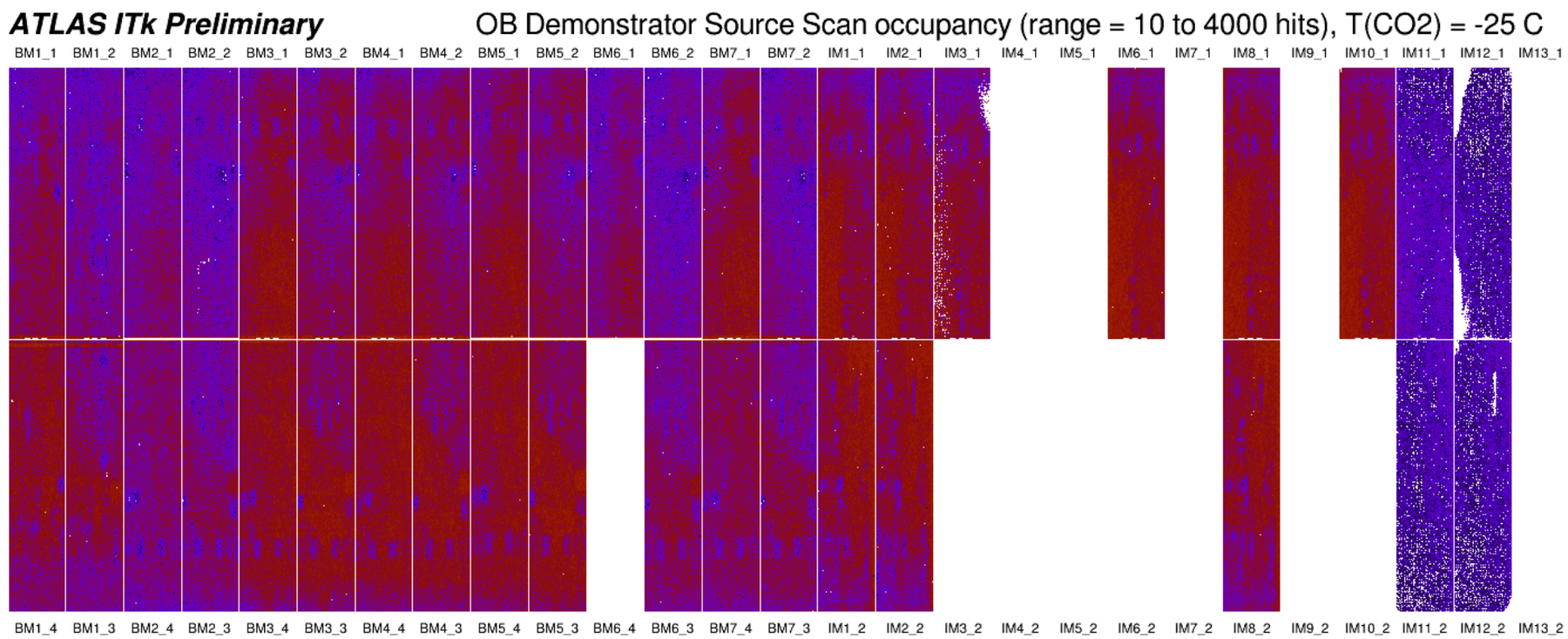
Versatile system for electrical studies

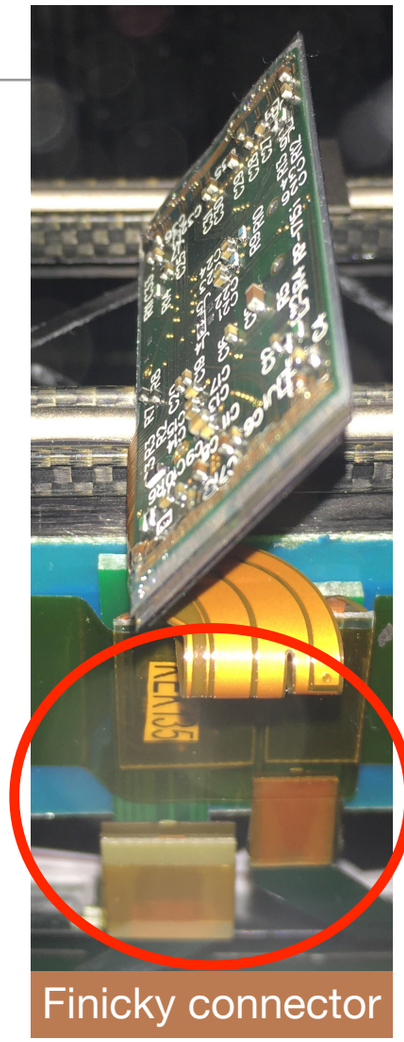




Powering options		Duals 2	Duals 1	Quads
LV	Default	●——●	●——●	●——●
	Merged	●- - - - - - - -●		N/A
HV	Default	●—● ●—●	●—● ●—●	●—● ●—●
	Merge	●- - -●	●- - -●	●- - -●
Module names		IM9-IM13	IM1-IM8	BM1-BM7

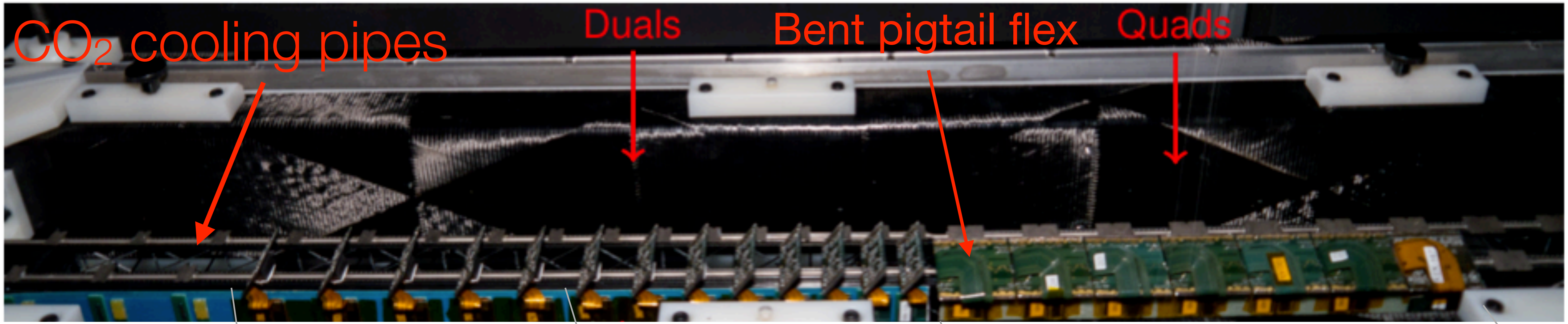
Operations at low temperature ($T(CO_2)$ = -25C)

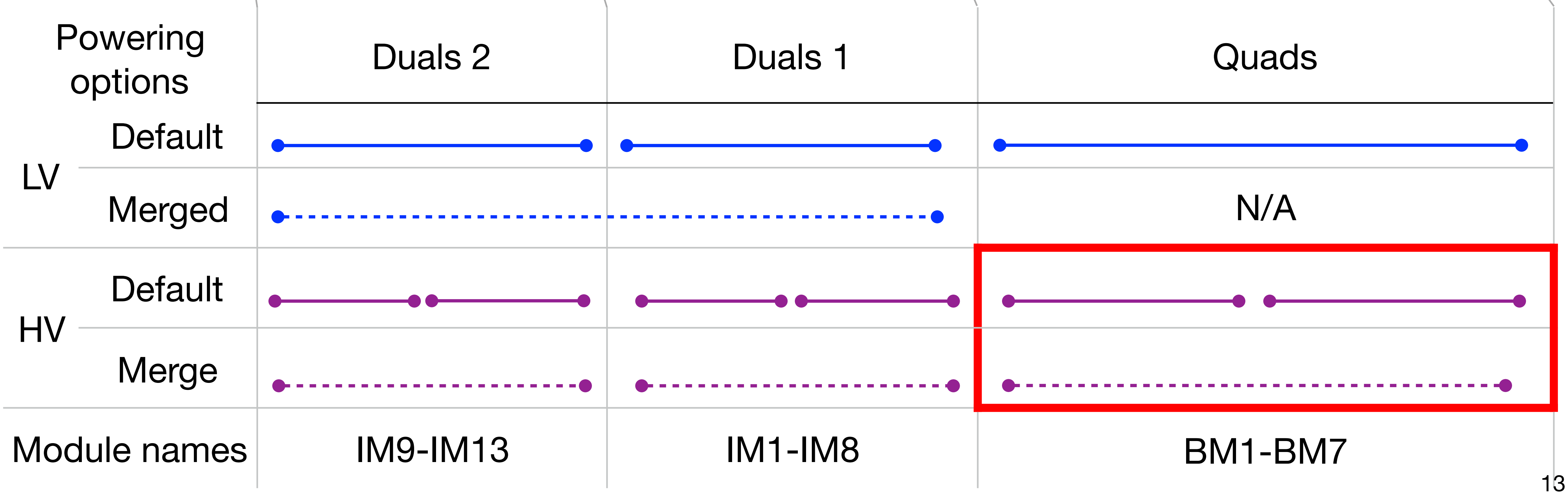




- Three serial powering lines connected on a single cable saver board
  - BM1-BM7 (quads), IM1-IM8 (duals), IM9-IM13 (duals)
- **Successful operations of three serial powering lines on a single local support!**
  - Lost communication with some modules due to finicky connection between pigtail and flex
  - 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

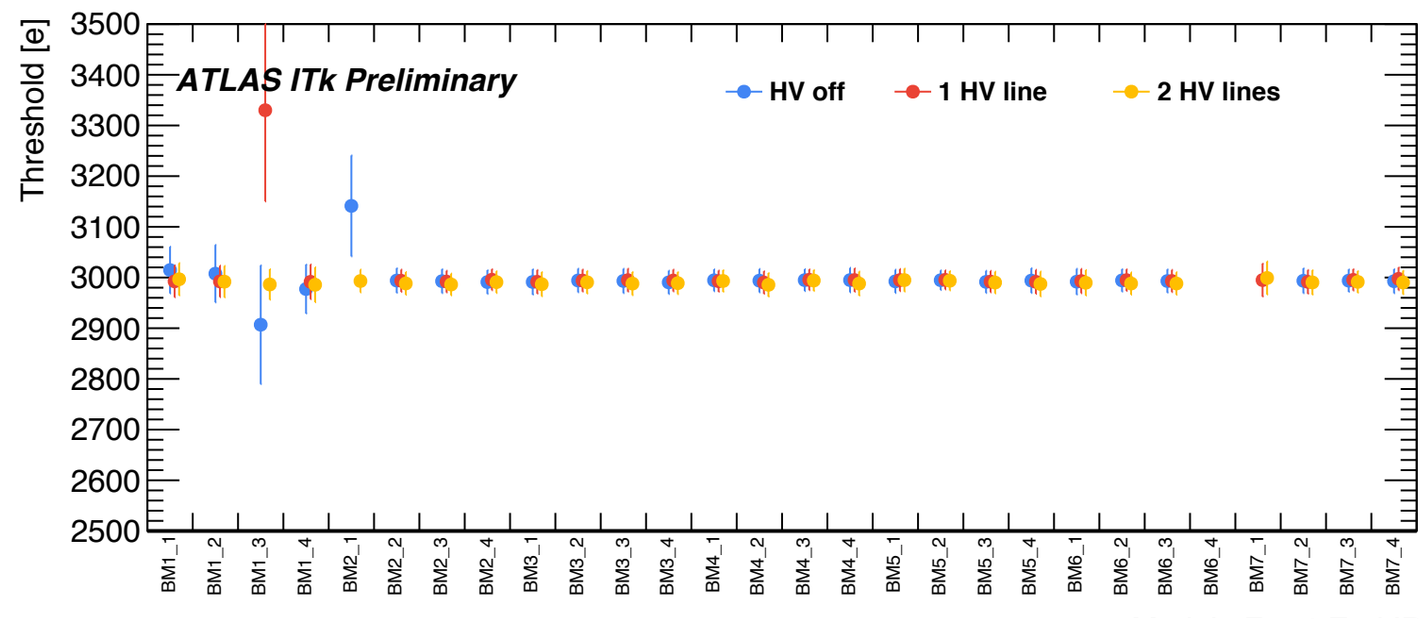


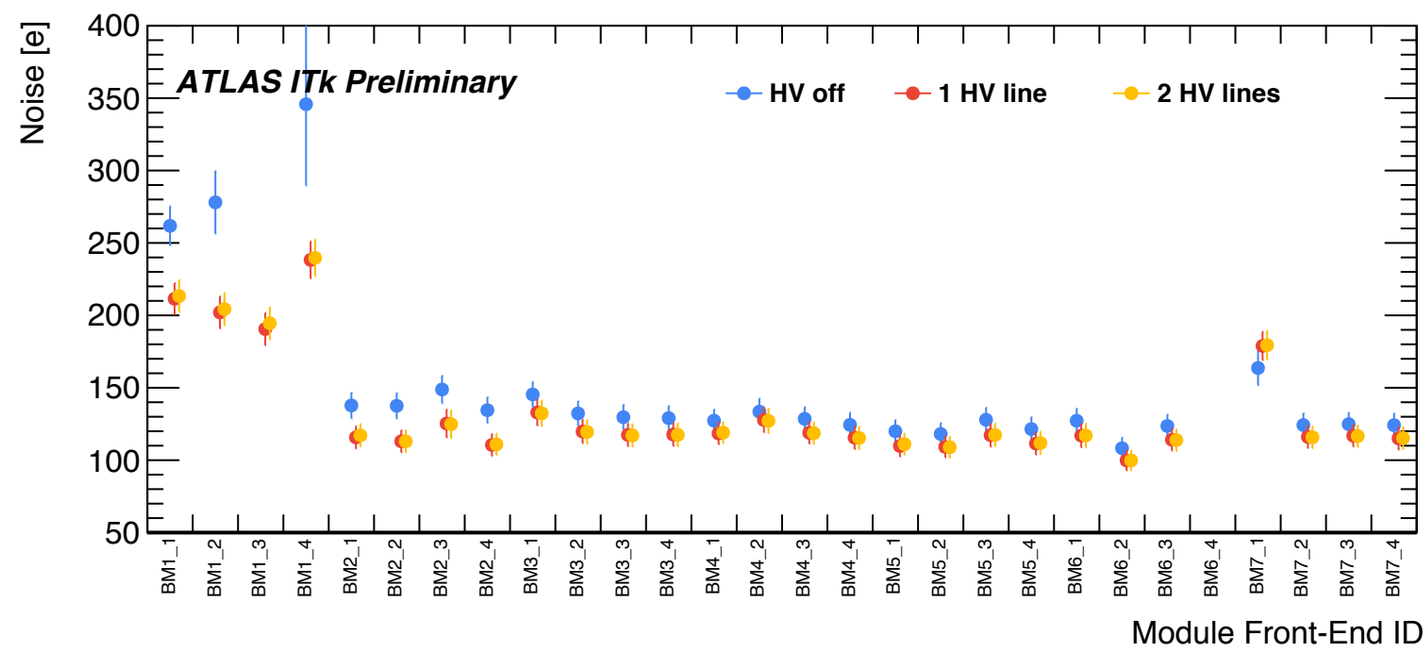


Powering options		Duals 2	Duals 1	Quads
LV	Default	●———●	●———●	●———●
	Merged	●- - - - - - - - - - - - - - - - - - - -●		N/A
HV	Default	●——● ●——●	●——● ●——●	●——● ●——●
	Merge	●- - - - -●	●- - - - -●	●- - - - - - - -●
Module names		IM9-IM13	IM1-IM8	BM1-BM7

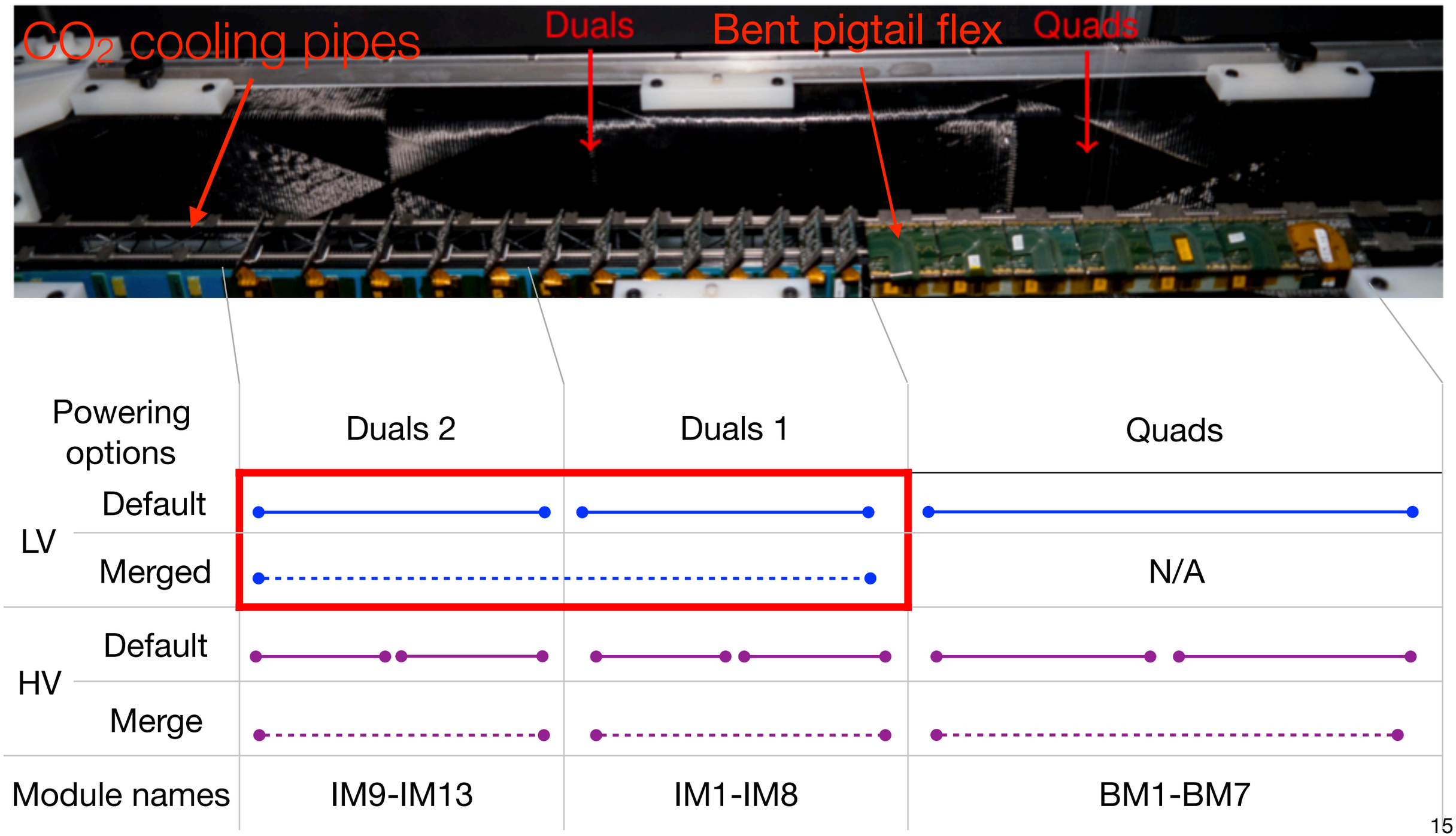
1 versus 2 HV lines for the flat section

- Tune and operate modules with no high voltage, 1 HV or 2 HV line
- $T(CO_2) = 17C$
- 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



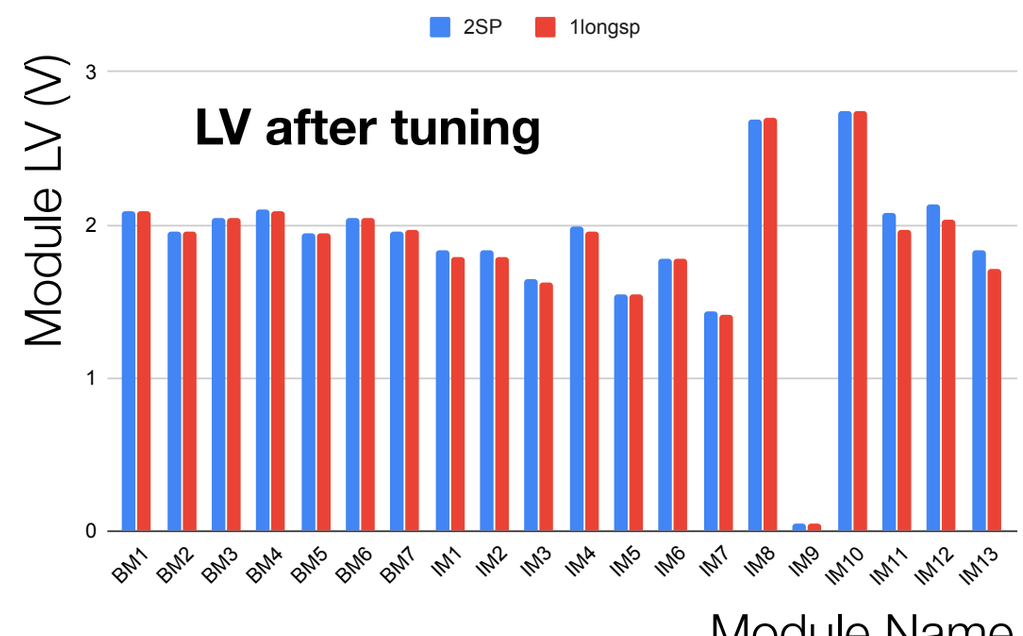


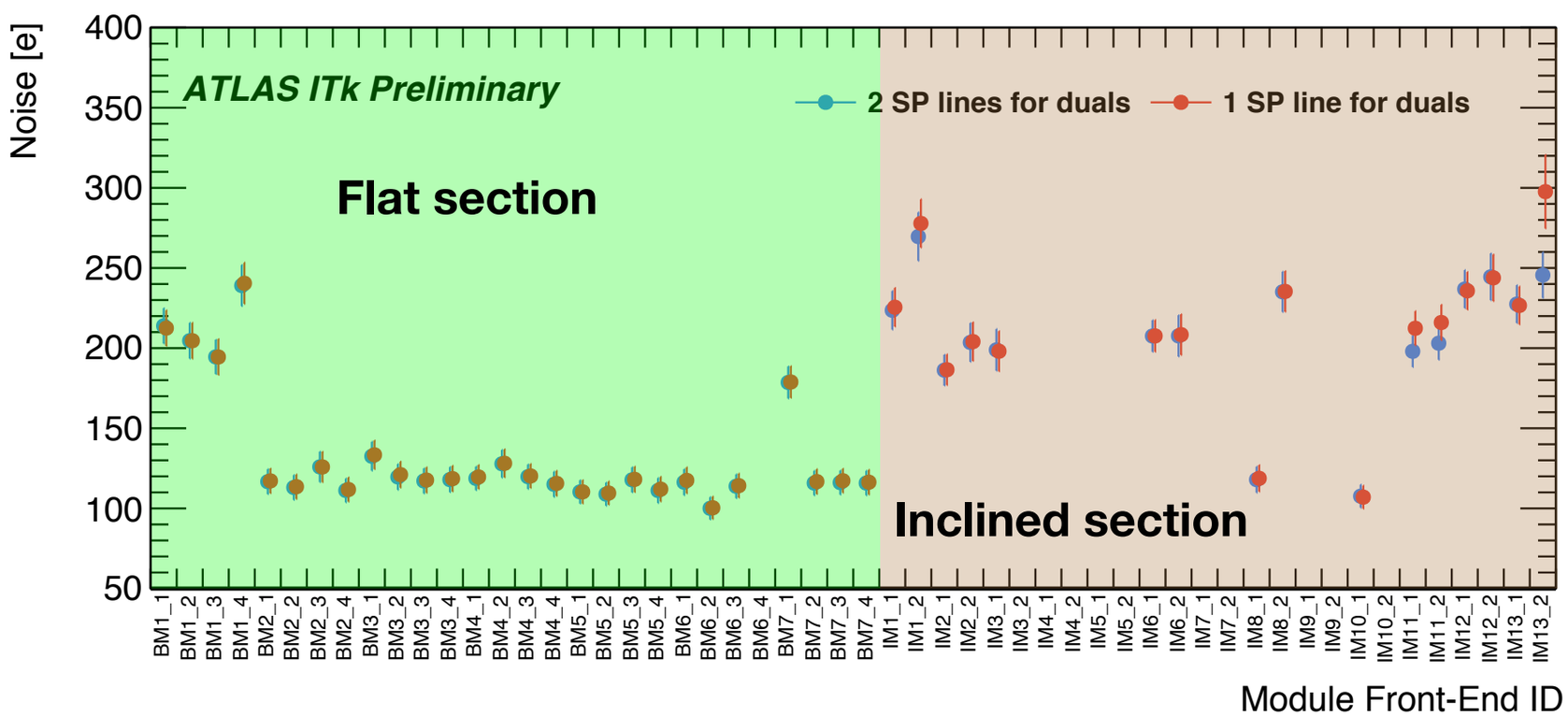
1 SP lines instead of 2 for the inclined section



2 SP chain versus 1 for the dual modules

- Tune modules in both setups at T(CO_2) = 17C
  - 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



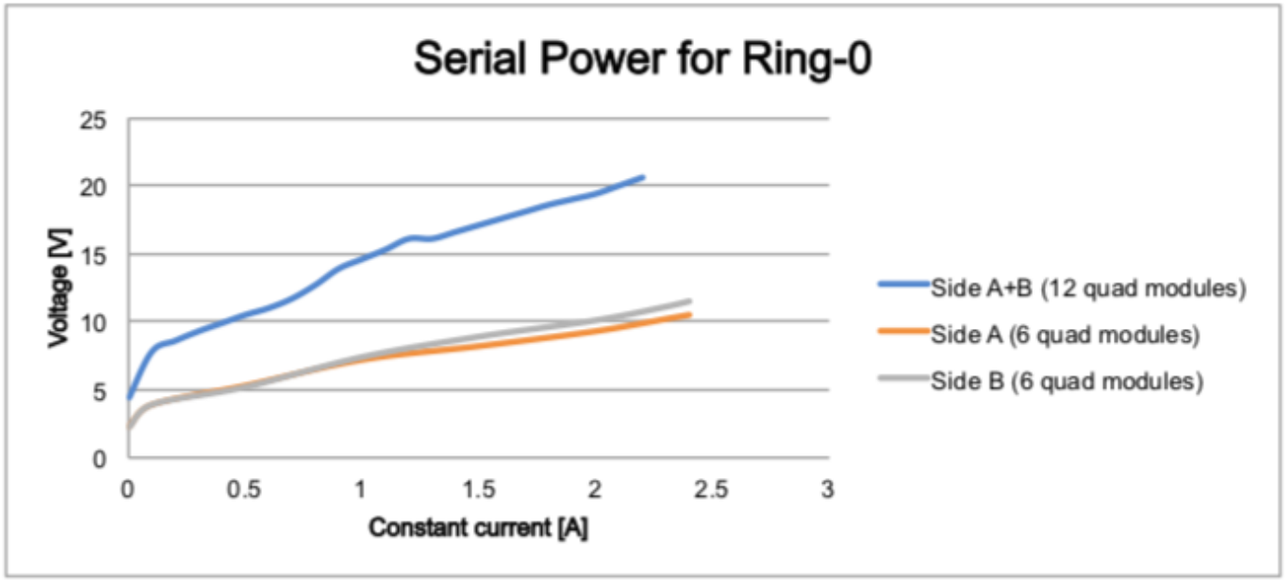


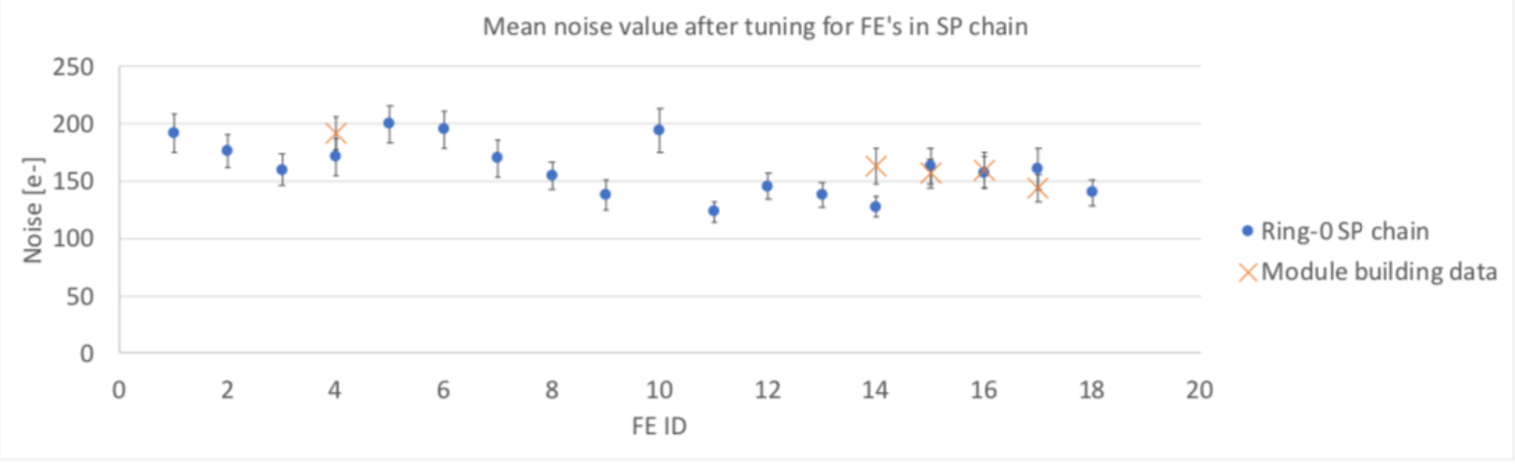
Confidence-building in the serial powering scheme

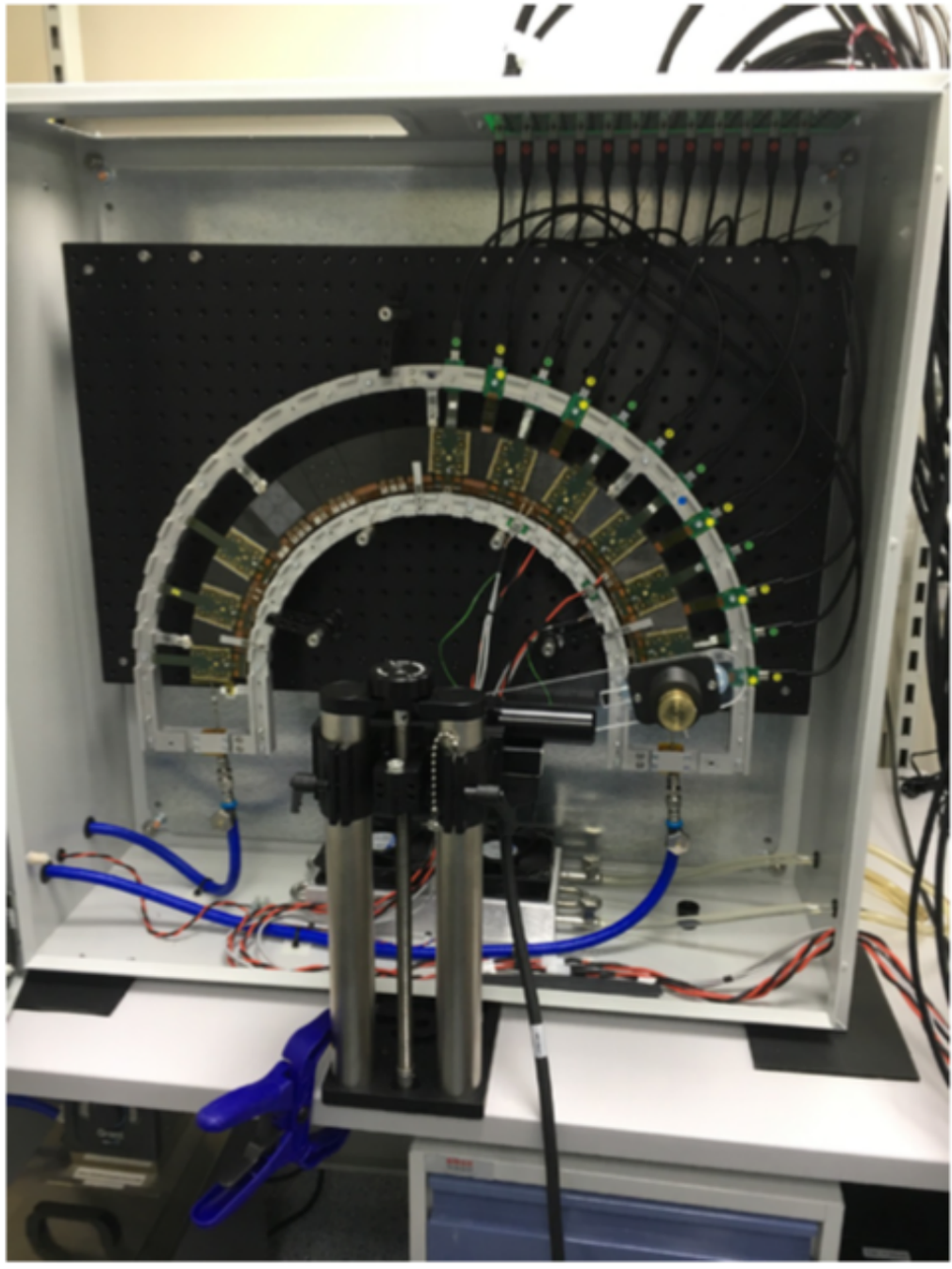
System tests for the endcaps

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**

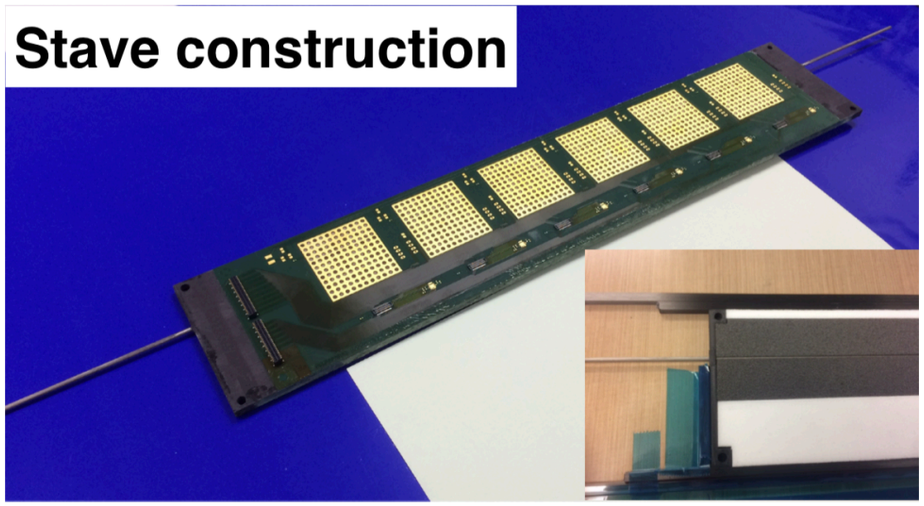
➡ **Valuable input for the design and specifications of the final detector (eg services)**

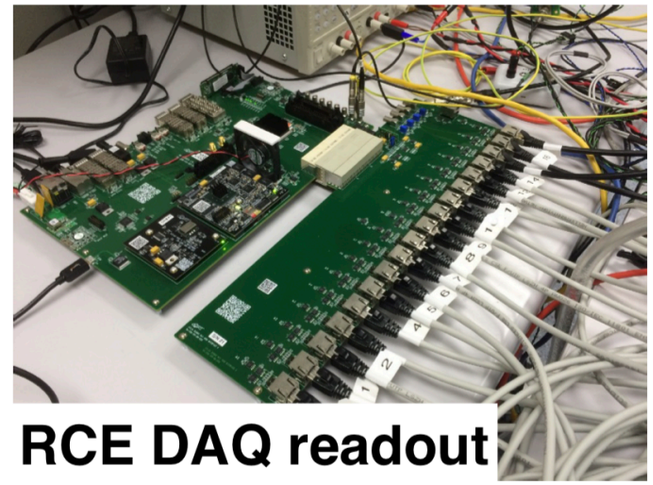
➡ **Lots of experience gained toward production**

- 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

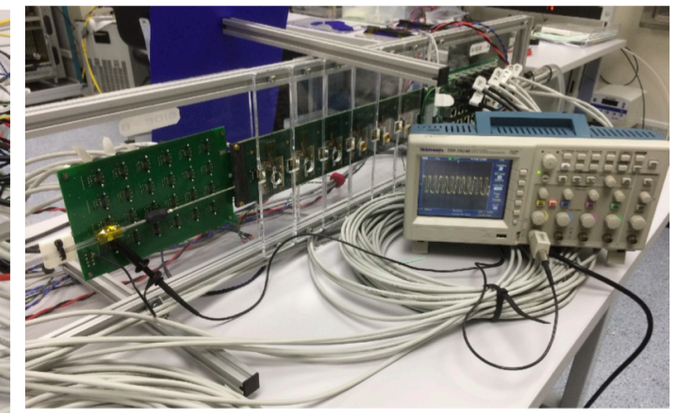
Additional material

Endcap FEI4 prototype



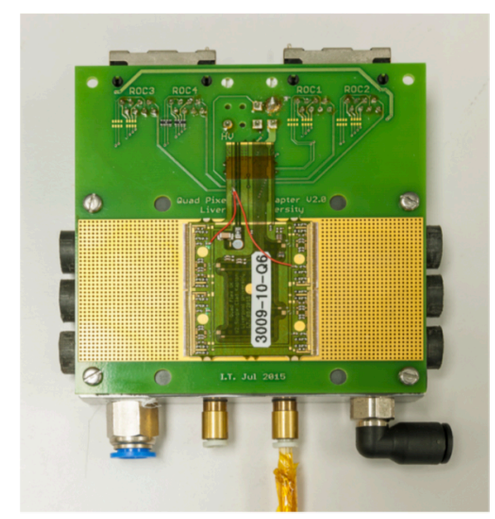


RCE DAQ readout



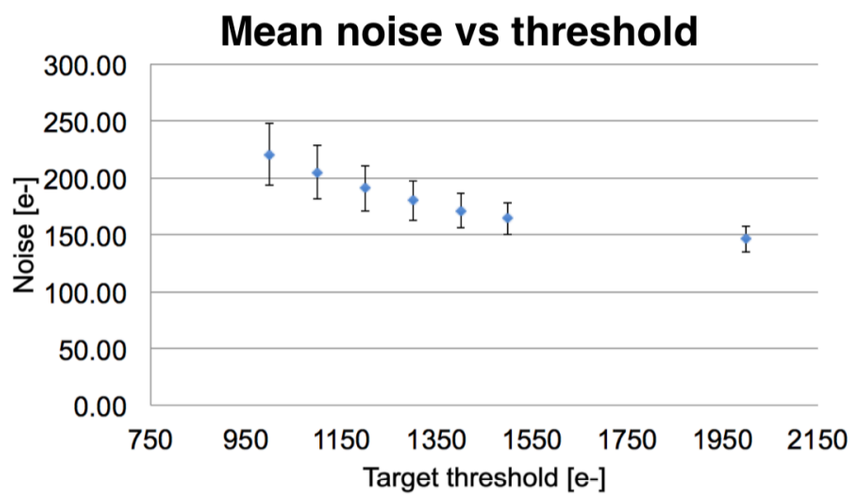
AC coupled clk/cmd/data

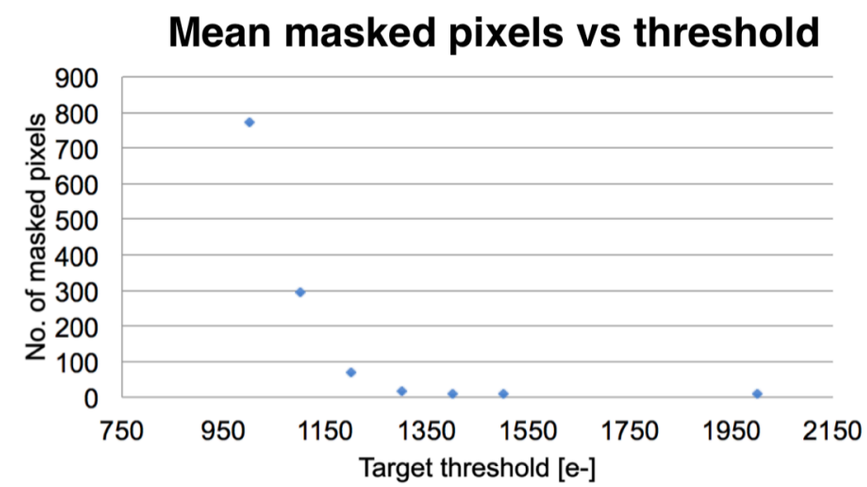
- Prototype Al stave with SP chain of 6 quads -> upgraded to double side CF stave with 12 quads
  - Materials: CFRP, Rohacell & All comp (carbon foam), boron loaded adhesive
  - Water cooling: titanium pipe (2.275mm diameter)
  - Low-mass structure ~100g / 55g (with / without tapes)
  - **Modules qualified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



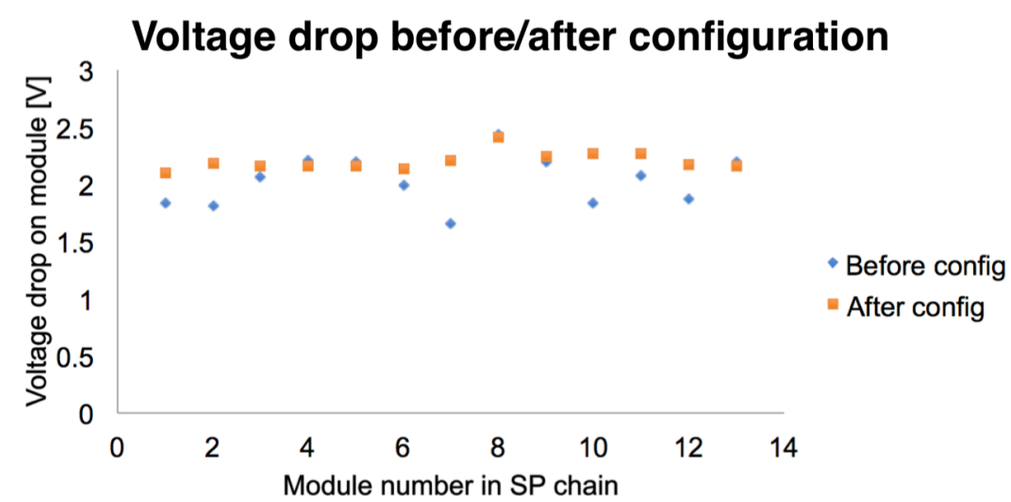
Module test jig

Endcap FEI4 prototype



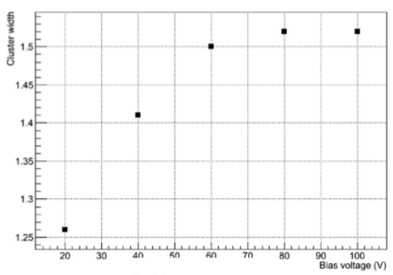


- **No additional noise** seen when modules are tested in isolation compared with tests in SP chain
- Different voltage drops seen on quads before configuring chip -> **requires specific power on sequence** -> issue with FE-I4
- **Tuning down to IBL QA levels is possible with SP chain**, 1500e- threshold, < 200e noise, < 270 pixels masked

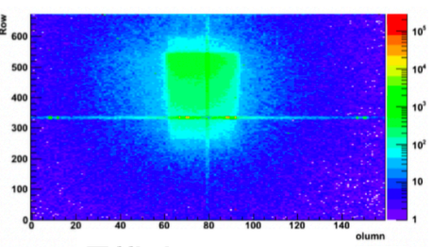


Endcap FEI4 prototype

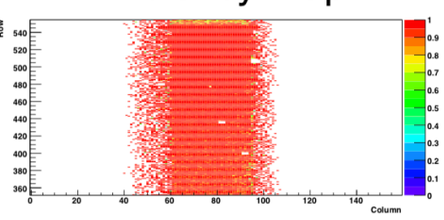
Cluster width vs bias

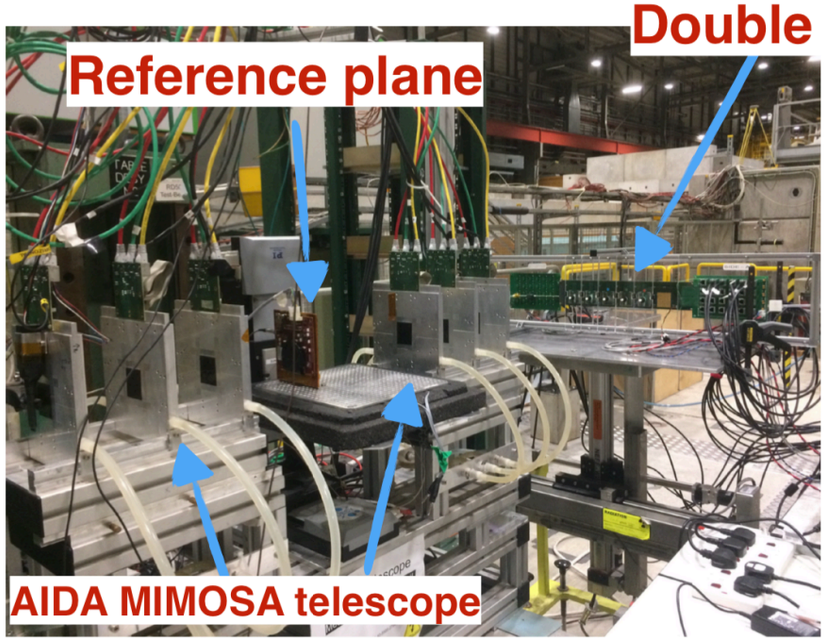


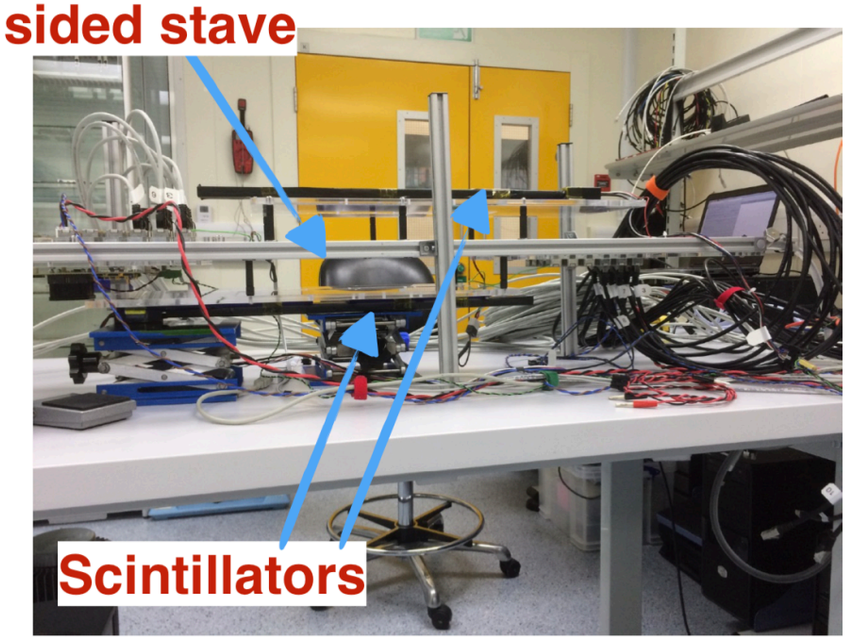
Hit map

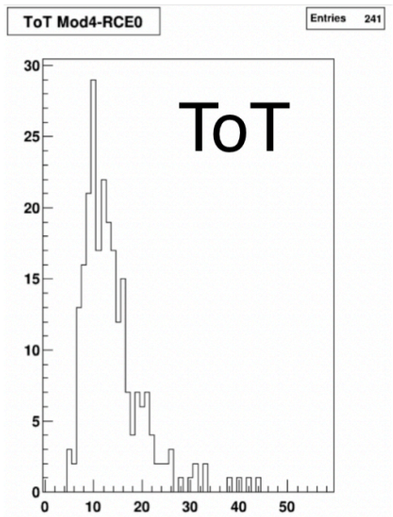


Efficiency map

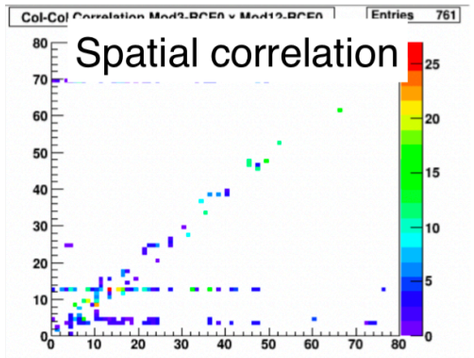








Double sided stave with 8/12 quads in SP chain - testing with external trigger



- Test beam at CERN SPS 120 GeV π^-
  - 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)

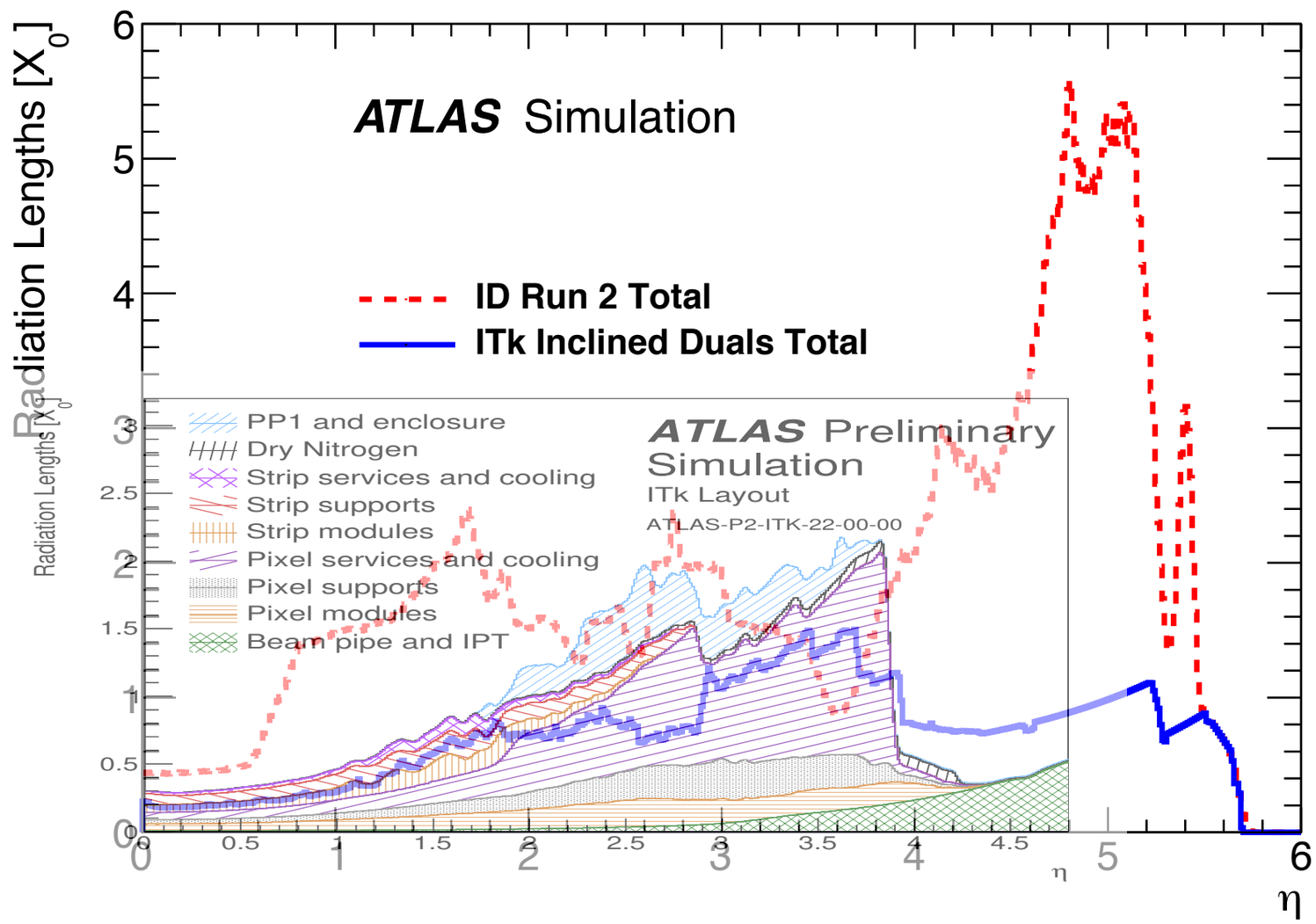
Table 5: Parameters for the ITk outer pixel inclined section. The number of rows of sensors is the same per-layer as in Table 6. The radii refer to the innermost point of the sensors. The total length in z of the outer barrel sections (flat and inclined) is 104.7 cm.

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

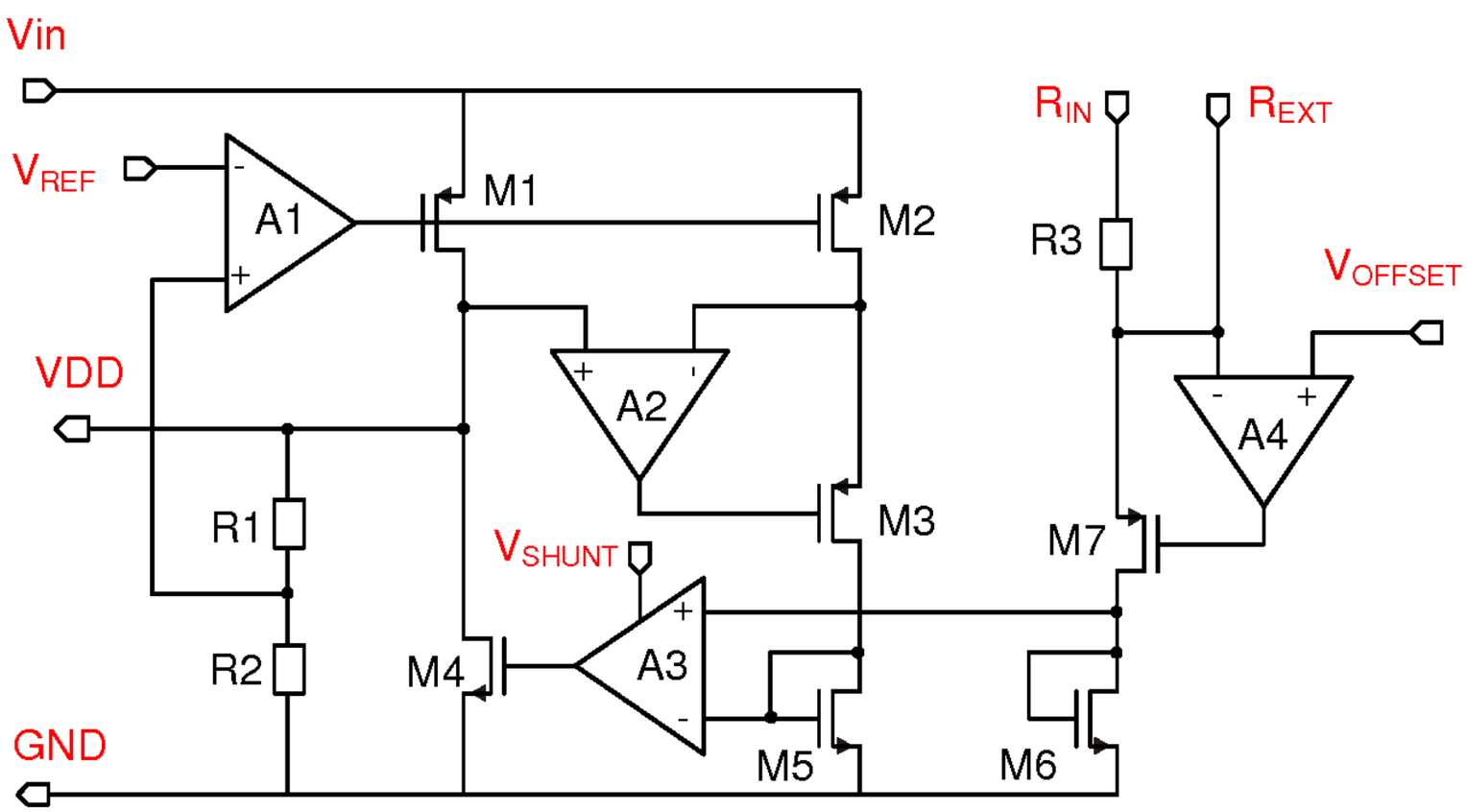
Table 6: Parameters for the ITk pixel flat barrel. The number of sensors per row refers to a half-row ($z > 0$ mm) in the central, flat part of the barrel where sensors are placed parallel to the beam line.

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


Vin
VREF
A1
M1
M2
RIN
REXT
R3
VOFFSET
VDD
A2
A4
M3
M7
R1
VSHUNT
R2
M4
A3
M5
M6
GND