UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

ATLAS ITk strips ASICs: design and radiation hardness

L. Gonella on behalf of the ITk Strips ASICs working group

12th ”Trento” Workshop on Advanced Silicon Radiation Detectors

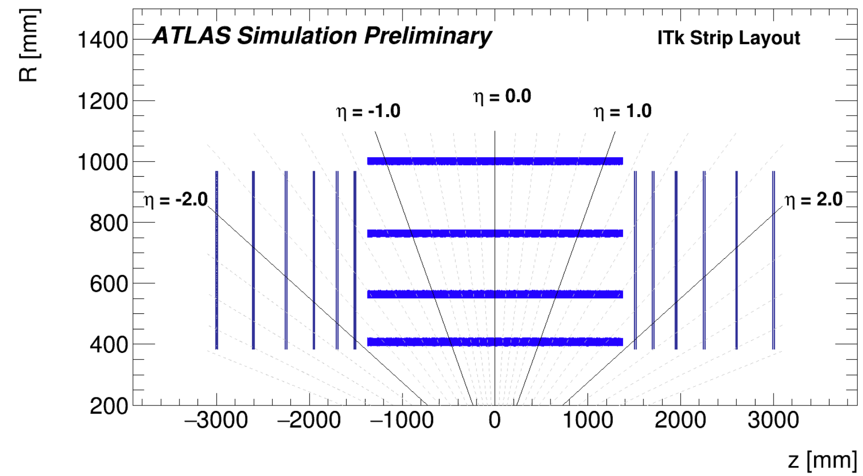
Outline

- **ITk Silicon Strip detector**
- Readout ASICs
- Results of ABC130 irradiation tests
- Conclusion

Note: plots are from the Technical Design Report for the ATLAS ITk Strip Detector, unless otherwise stated

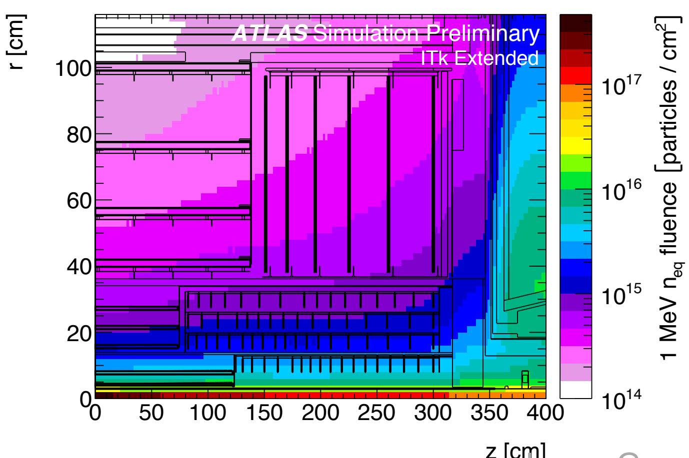
ITk Silicon Strip Detector

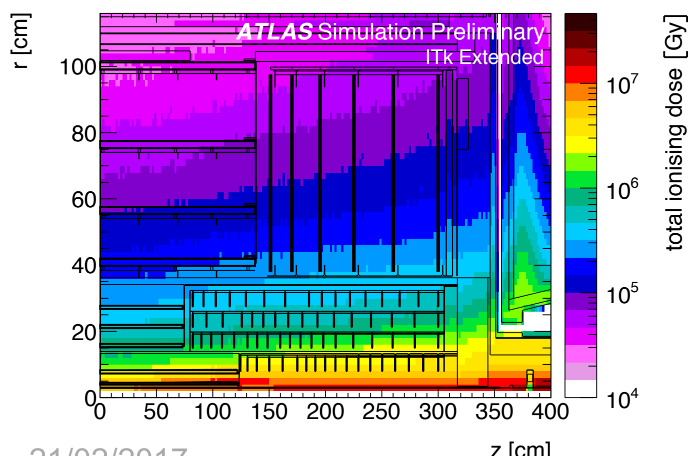
- 4 barrel layers (z = ± 1.4m)
- 2 end-caps of 6 disks each (z = ± 3m)
- 60M channels over 165m^2
- 17888 modules



Max fluence [1MeV n_{eq}/cm^2]
Barrel: 8.1×10^{14}
End-cap: 1.2×10^{15}

Max dose [Mrad]
Barrel: 35.7
End-cap: 50.4

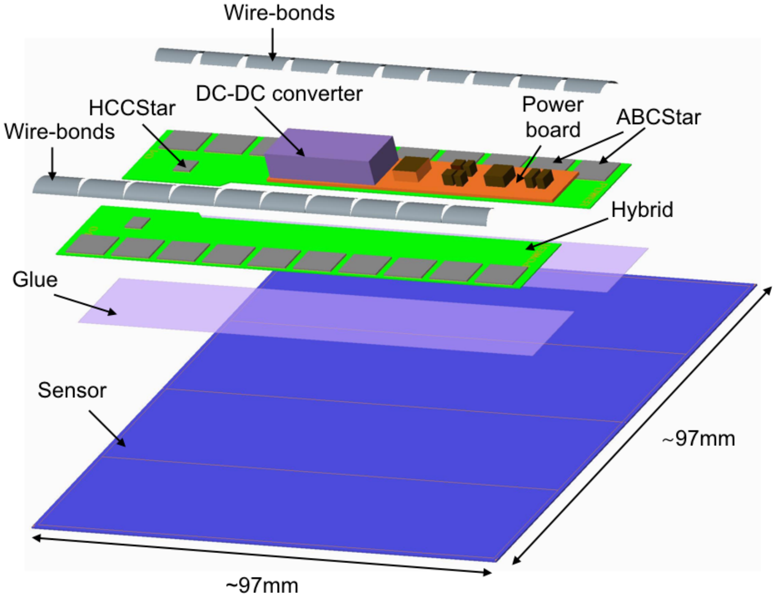




Modules

- Sensor
  - n+-in-p FZ
- Hybrid
  - Low mass PCB hosting the readout ASICs: **ABCStar & HCCStar**
- Power board
  - DC-DC converter
  - HV multiplexer
  - AMAC (autonomous monitor and control) chip for monitoring and interrupt

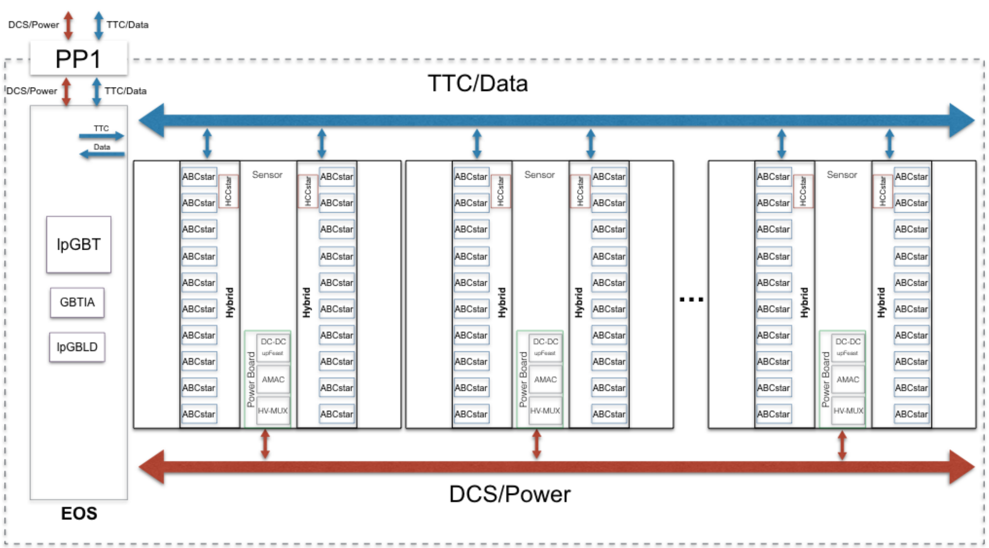
Drawing of a barrel short strip module



Overall electronics architecture

- Bus tape servicing a group of modules
  - Copper/kapton tape co-cured onto the local support structure
  - Routing TTC, data, power and DCS between modules and EOS card

- End Of Substructure card
  - Electrical interface between on- and off-detector (data and power)



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Readout ASICs

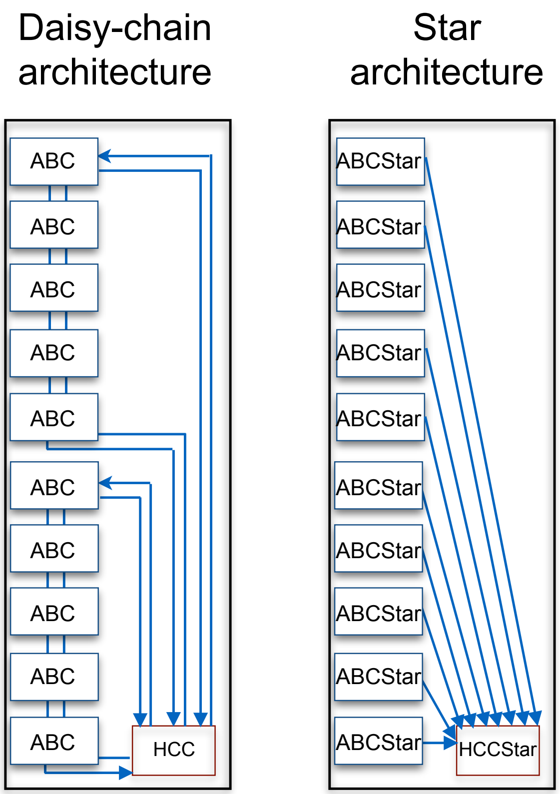
- ABC: ATLAS binary chip
  - Strips readout ASIC
  - Converts incoming signal from the sensor to binary hit information
  - Production chip: **ABCStar**
  - Prototype: **ABC130**

- HCC: Hybrid Controller Chip
  - Interface between ABCStar chips and off-detector
  - Production chip: **HCCStar**
  - Prototype: **HCC130**

- Technology: GF (ex IBM) **130nm** CMOS8RF technology

Star architecture

- L0/L1 rate = 500kHz/200kHz → **1MHz/400kHz**
- Daisy-chain readout architecture as implemented in the prototype chips cannot support new trigger requirements
- Serial transfer of data between ABCs to HCC → direct communication from all ABCs to the HCC = star architecture
- Changes required in the design of both ASICs wrt. prototypes
  - For the HCC almost a complete redesign is needed



Multi-trigger data flow

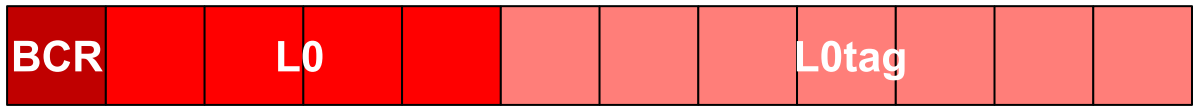
Trigger options:		
Original trigger scheme:		
1 MHz L0	10% R3	400kHz L1
Single Trigger Scheme:		
1MHz L0		
Low Latency L0 Scheme:		
2-4 MHz L0	<10% R3	600-800kHz L1
(with constraint that 10% ROIs + L1s < 1 MHz readout of everything)		

- **L0**
  - Synchronous to bunch crossing
  - Select data for readout
  - Global readout in single trigger mode
- **R3** (regional readout request)
  - Asynchronous readout request with priority (**PR**) and low latency
  - Distributed to part of the detector to get tracking data participating to the L1 trigger
- **L1**
  - Asynchronous readout request with low priority (**LP**)
  - Readout of the complete detector

LCB protocol

- **L0** signal, **commands** and **BCR** (bunch counter reset) signal are encoded in one data stream, the LCB
- The LCB data stream is **6b/8b** encoded and sent at **160MBit/s**
- A pair of 8b symbols is a **frame** and lasts **4BC** (bunch crossings), i.e. 100ns
- Allows triggering on multiple successive beam crossing and a tagged triggered readout

LCB protocol: L0/BCR frame

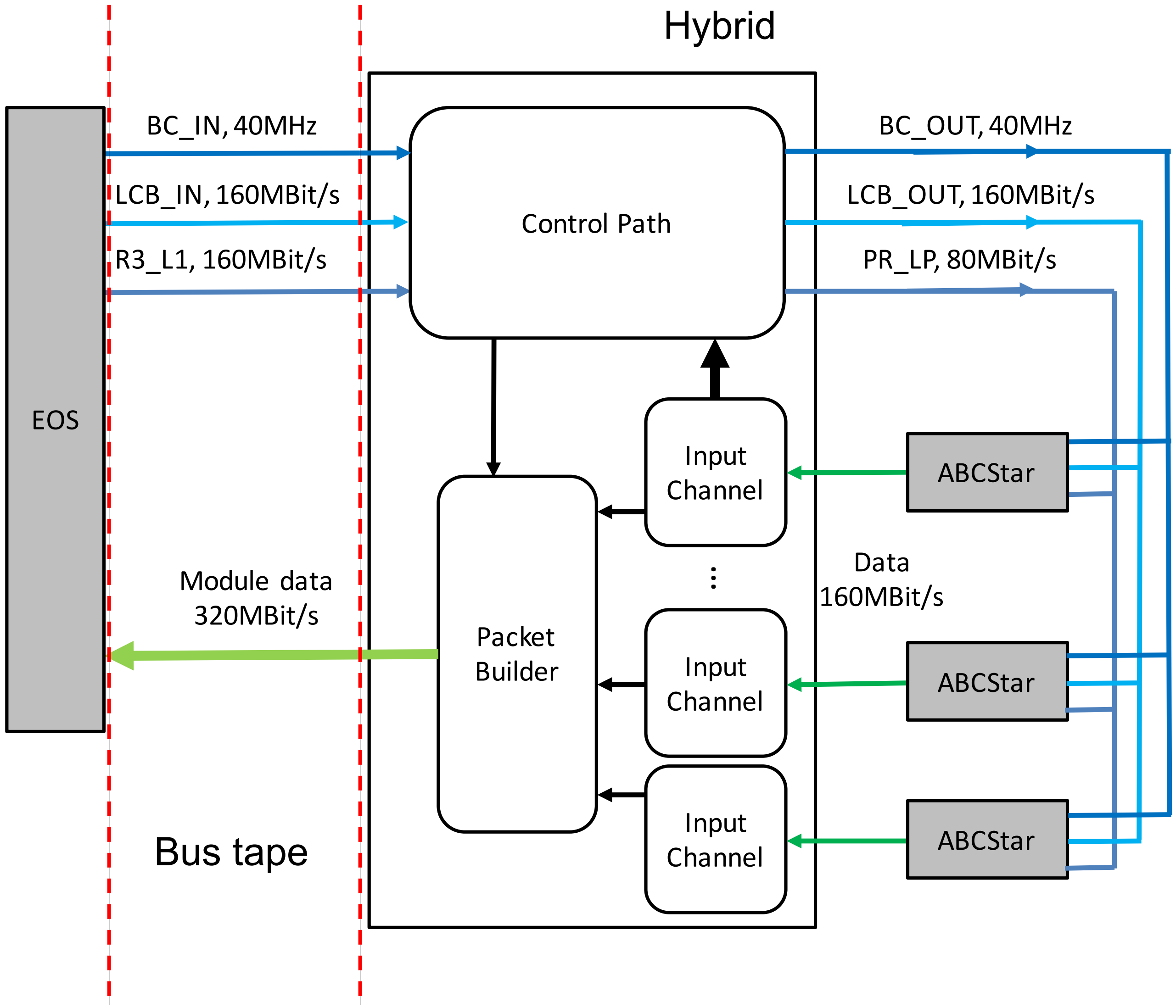


- BCR (1bit)
  - 1 means that there is a BCR in last of the 4 BC always
- **L0 signal for up to 4 consecutive BC** (4 bits)
  - One of the four bits = 1 → L0 in the corresponding BC
- **L0tag** of the first L0 (7 bits)
  - **L0 identifier** to associate events to the correct trigger
  - Subsequent L0 have incrementing tags

L0tag

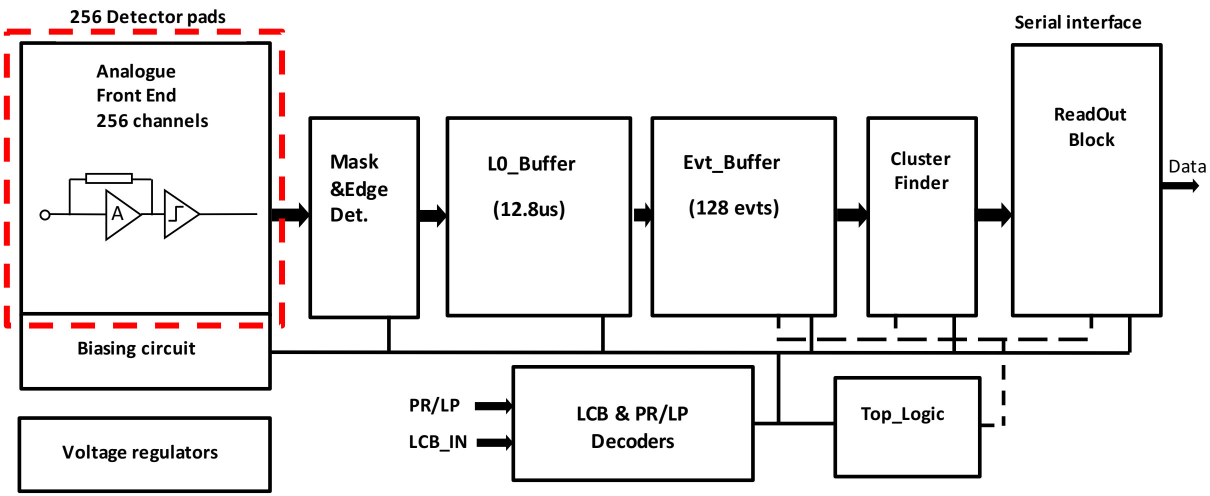
- Current scheme for silicon detectors
  - Data from modules are sent with two identifiers: **L0ID** and BCID
  - These are used by the off-detector DAQ to assign data to the correct trigger
  - For this mechanism to work, the on-chip and DAQ ID counters must be in synch
  - On-detector counters are susceptible to radiation induced errors and buffer overflow
  - A loss of synch results in a **loss of data for successive events** until synch is recovered by resetting the counter
- L0tag scheme
  - The L0ID is generated by the DAQ and attached as a tag to the L0
  - Modules receive the L0ID and send back data with this identifier
  - **Errors affect only one frame** (i.e. 4 triggers)
  - **No need for synchronized counters**

HCC star


Hybrid
EOS
BC_IN, 40MHz
LCB_IN, 160MBit/s
R3_L1, 160MBit/s
Control Path
BC_OUT, 40MHz
LCB_OUT, 160MBit/s
PR_LP, 80MBit/s
Input Channel
ABCStar
Data 160MBit/s
Module data 320MBit/s
Packet Builder
Input Channel
ABCStar
Input Channel
ABCStar
Bus tape

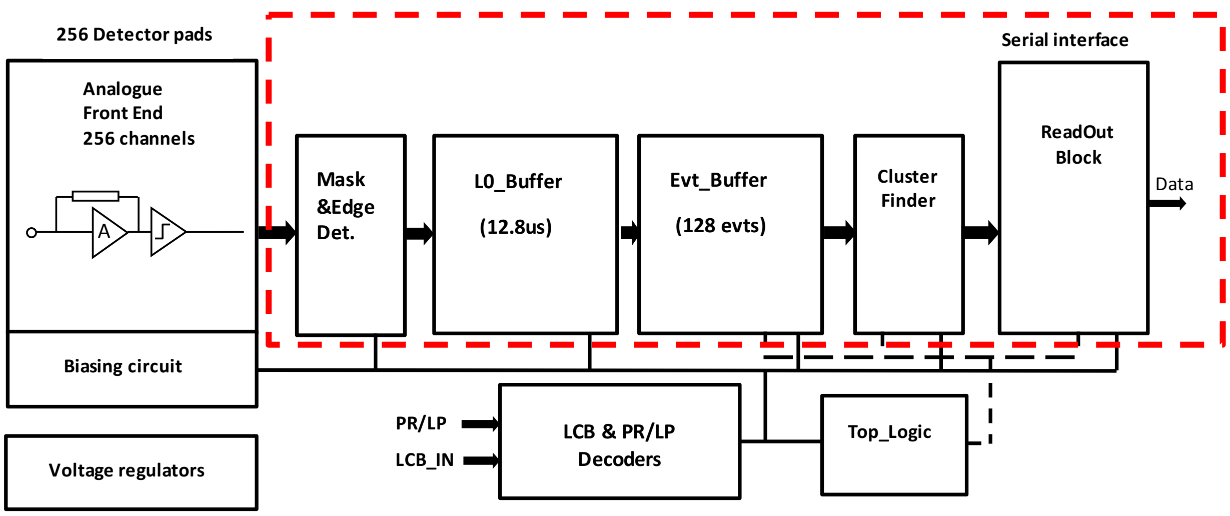
ABCStar: analogue FE

- 256 channels with amplifier, shaper, and discriminator
- Modified with respect to the ABC130 FE to improve noise operation with n^+-in-p sensors before and after irradiation
  - Amplifier feedback changed from active to resistive
  - Transistors critical for noise have enclosed layout geometry



ABCStar: digital functionality

- The outputs of the discriminator are sampled at 40MHz and stored in the L0_buffer for a fixed (programmable) latency
- @L0 data with the correct latency are transferred to the Event Buffer, with **L0ID = L0tag received with the L0**
- @PR/LP data with the correct L0ID are transferred to Cluster Finder
- The readout block transmits data serially at **160MBit/s** to the HCCstar



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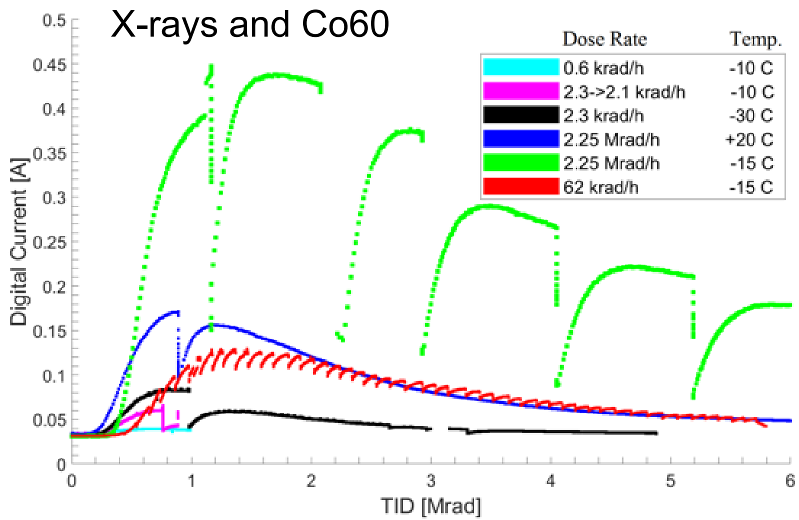
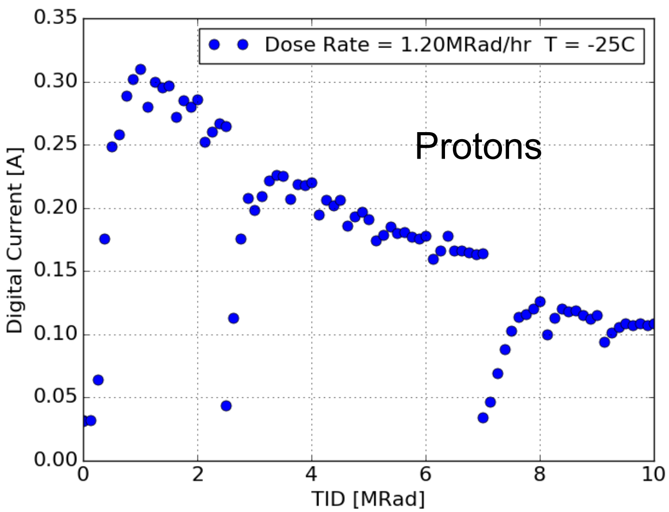
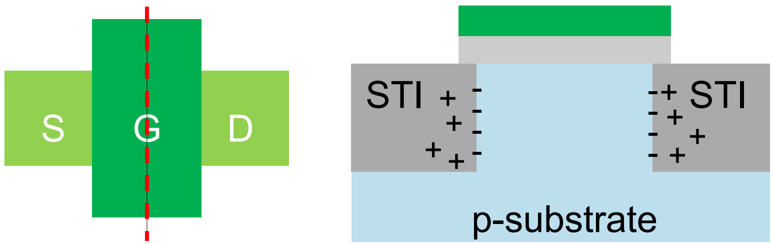
Digital current increase

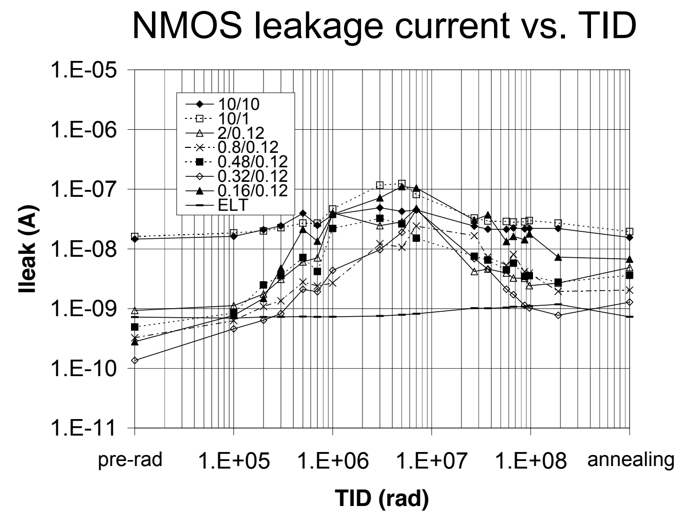
- Irradiation campaigns
  - X-rays, Co60 source, 23MeV protons
  - Dose rate = **2.35Mrad/h to 0.6krad/h**
  - T = **+20C to -10C**
- Increase of digital current observed for TID up to 1-2Mrad. Recover towards pre-rad values at higher TID
  - **Dependent on dose rate and T**
- When the irradiation stops, the current decreases towards pre-rad value and starts increasing again when the irradiation restarts



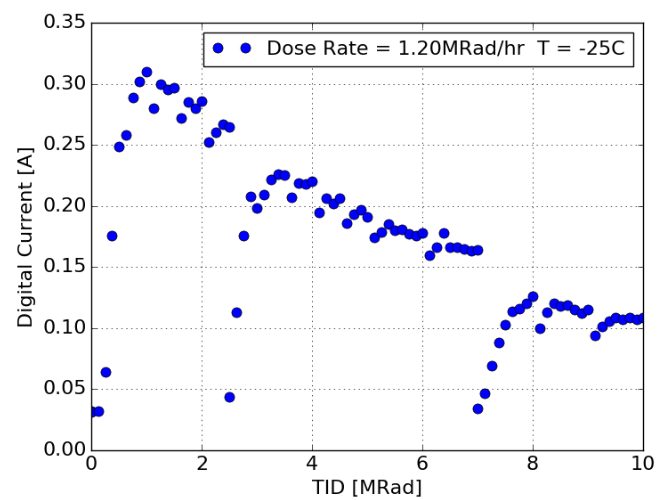


NMOS leakage current increase with TID





L. Gonella, Master Thesis, https://cds.cern.ch/record/2252791



<u>Charge trapped in the STI oxide</u>

- +Q charge → lateral parasitic transistors activate → I_{leak} increase
- Fast creation
- Annealing already at T_{room}

<u>Interface states at STI-Silicon interface</u>

- -Q for NMOS (+Q for PMOS) → counterbalance +Q → I_{leak} decrease
- Slow creation
- Annealing starts at 80-100^{o}C

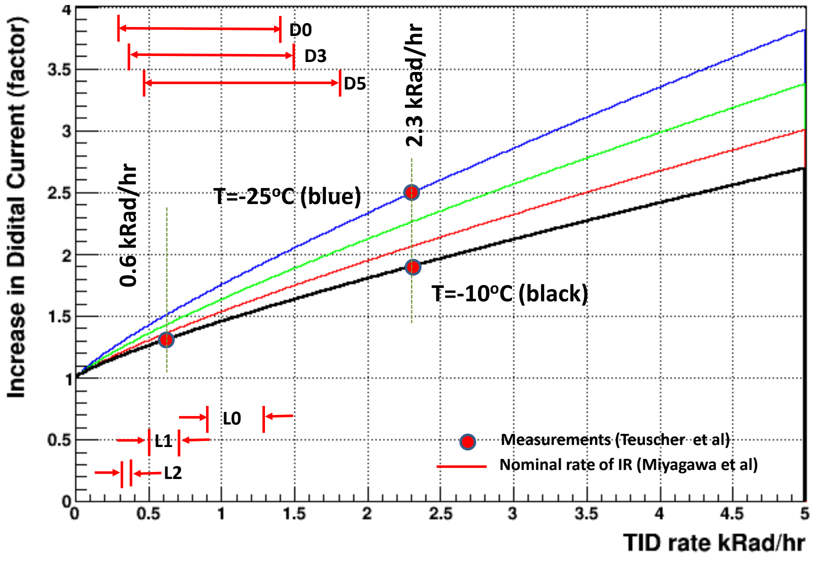
Model of current increase

- The current increase factors at different temperatures and dose rates have been fitted

- The fit functions can be used to calculate the maximal current increase in different regions of the detector → **define specifications for detector services** (cables, cooling, mechanics, ...)

- More irradiations are currently ongoing at the Co60 source at BNL to cover more dose rate and T combinations

Source	T (°C)	Current Increase	Dose Rate (MRad/h)
^{60}Co CERN	−25	2.5	0.0023
^{60}Co CERN	−10	1.9	0.0023
^{60}Co CERN	−10	1.3	0.0006
Birmingham-p	−25	9.7	1.25
X-ray CERN	−15	3.9	0.062
(extrapolated)	−10	3.5	0.062
X-ray CERN	−15	13.6	2.25
X-ray CERN	+20	5.2	2.25



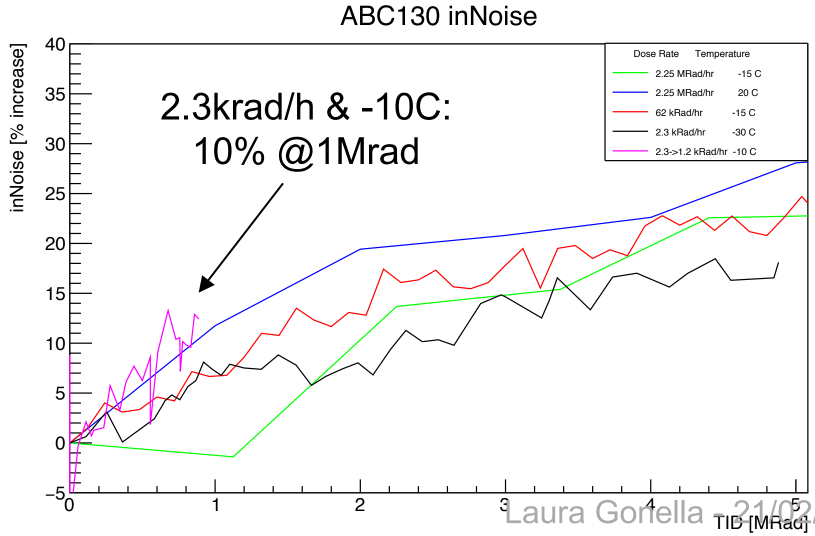
ENC

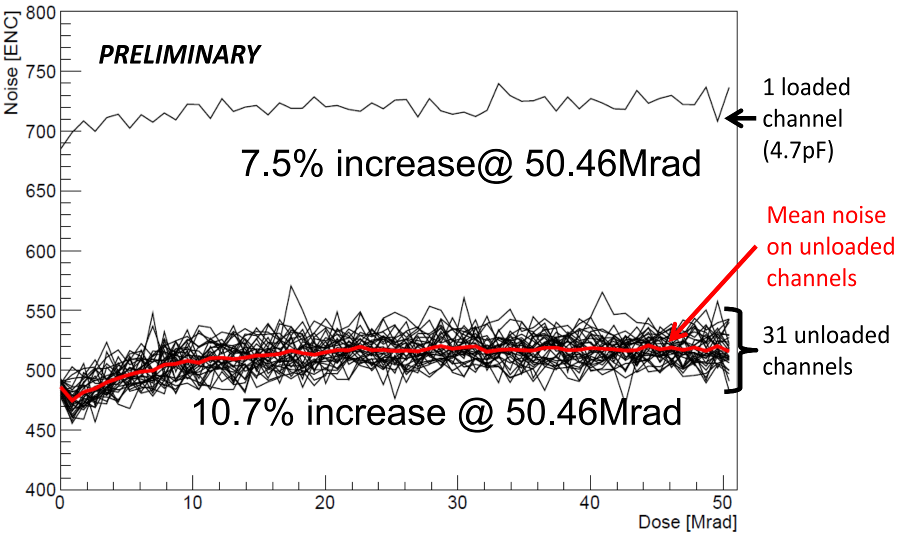
ABC130

- ENC increases with TID
- Possible reason: 1/f noise
- Reports from 130nm technologies show substantial increase of 1/f noise for NMOS transistors and no change for ELT

ABCstar FE prototype

- Noise increase **<10% @ 50.46Mrad**
- The use of ELT transistors improves noise performance

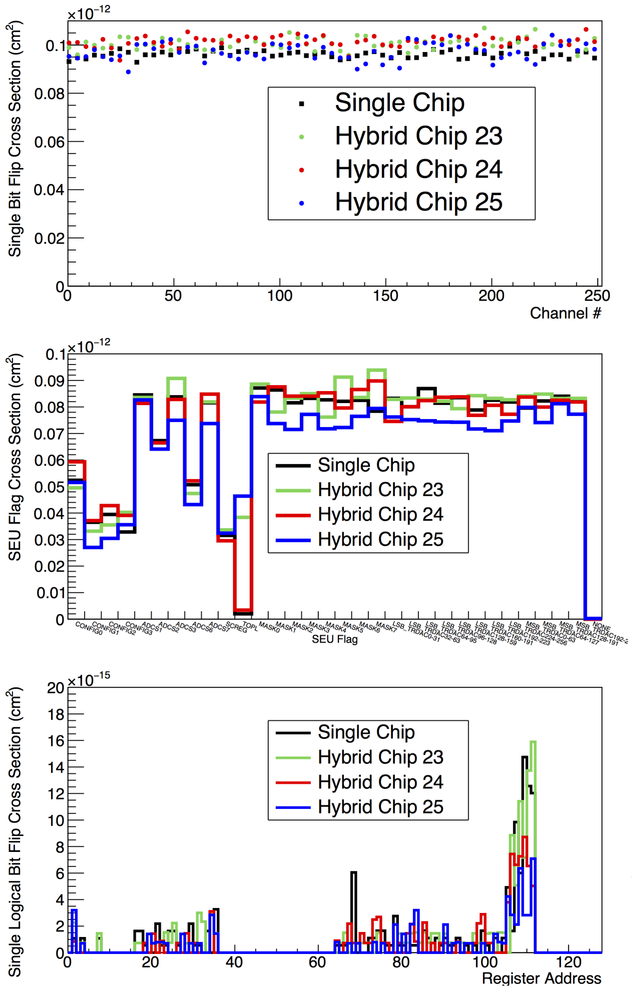




Plot by C. Sawyer (RAL)

SEU tests

- 24GeV protons at CHARM, ABC130 and 3 ABC130 + HCC130
- Bit flips in data stored in the **event buffer** → 1×10^{-13} cm^2
- Single physical bit flips in **configuration registers** as indicated by internal SEU flags stored on the chip → 9×10^{-14} cm^2
- Logical bit flips in **triplicated registers** → 2×10^{-15} cm^2
- Based on SEE test on the SCT, these cross sections are considered acceptable for ITK
- In addition, the ABCStar will feature triplicated registers auto correction and improvements of state machines



Conclusion

- The readout chips for the ITk strip detector are designed to satisfy ATLAS trigger and radiation hardness requirements
  - Star readout architecture, multi-trigger data flow, LCB protocol & L0tag
  - ABCStar analogue FE with resistive feedback and ELTs

- TID tests at different dose rates and temperature
  - Allow to estimate current increase in different part of the detector over the experiment life-time
  - Confirm low noise operation after irradiation

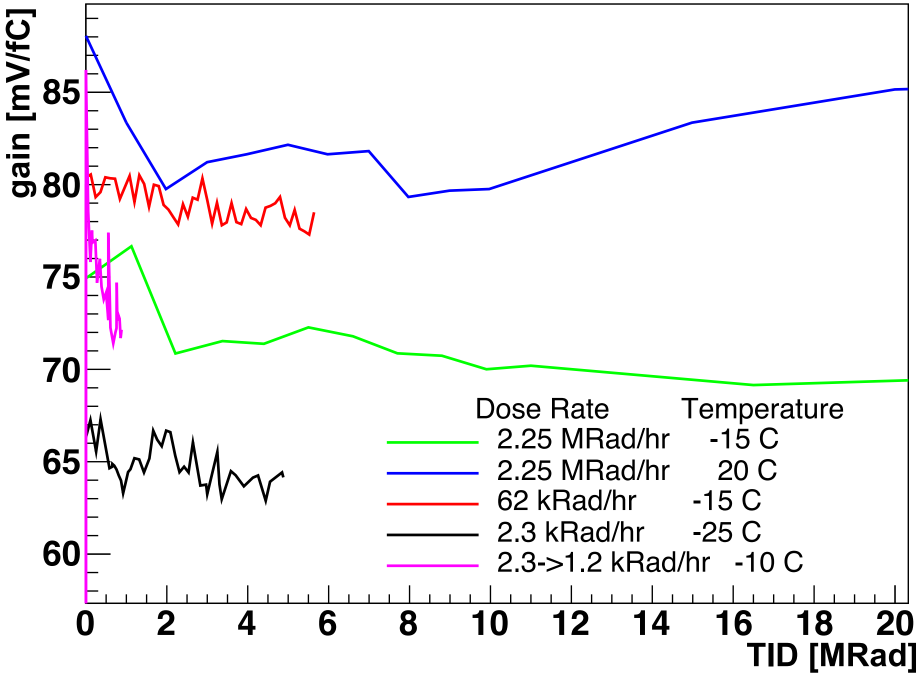
- Measured SEU cross-sections are acceptable for operation at HL-LHC

Backup

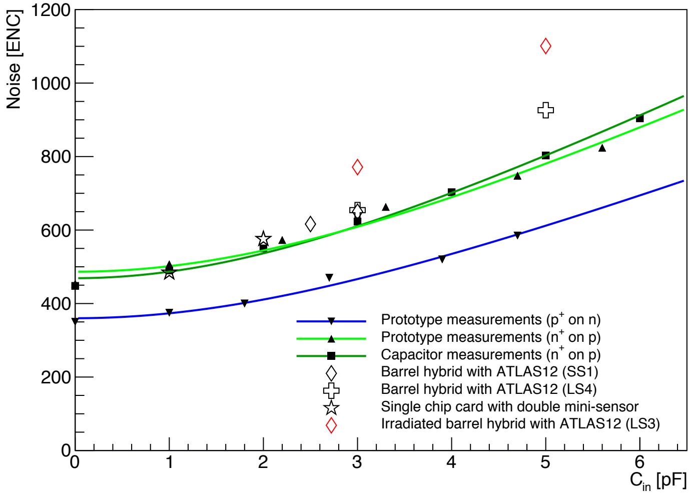
Numbers

Barrel Layer:	Radius [mm]	# of staves	# of modules	# of hybrids	# of of ABCStar	# of channels	Area [m^2]
L0	405	28	784	1568	15680	4.01M	7.49
L1	562	40	1120	2240	22400	5.73M	10.7
L2	762	56	1568	1568	15680	4.01M	14.98
L3	1000	72	2016	2016	20160	5.16M	19.26
Total half barrel		196	5488	7392	73920	18.92M	52.43
Total barrel		392	10976	14784	147840	37.85M	104.86
End-cap Disk:	**z-pos. [mm]**	**# of petals**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
D0	1512	32	576	832	6336	1.62M	5.03
D1	1702	32	576	832	6336	1.62M	5.03
D2	1952	32	576	832	6336	1.62M	5.03
D3	2252	32	576	832	6336	1.62M	5.03
D4	2602	32	576	832	6336	1.62M	5.03
D5	3000	32	576	832	6336	1.62M	5.03
Total one EC		192	3456	4992	43008	11.01M	30.2
Total ECs		384	6912	9984	86016	22.02M	60.4
Total		**776**	**17888**	**24768**	**233856**	**59.87M**	**165.25**

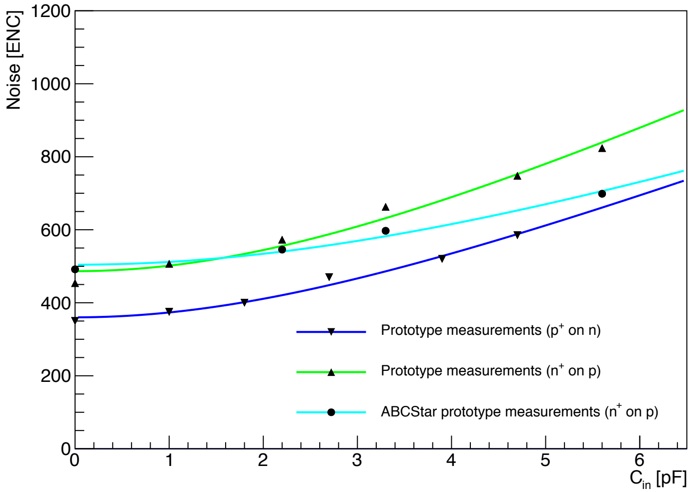
ABC130 TID irradiations: gain



ENC before irradiation



ABC130:
Difference between positive and negative signal response and ENC up to 20% (simulated 5 to 8% depending on model and accuracy)

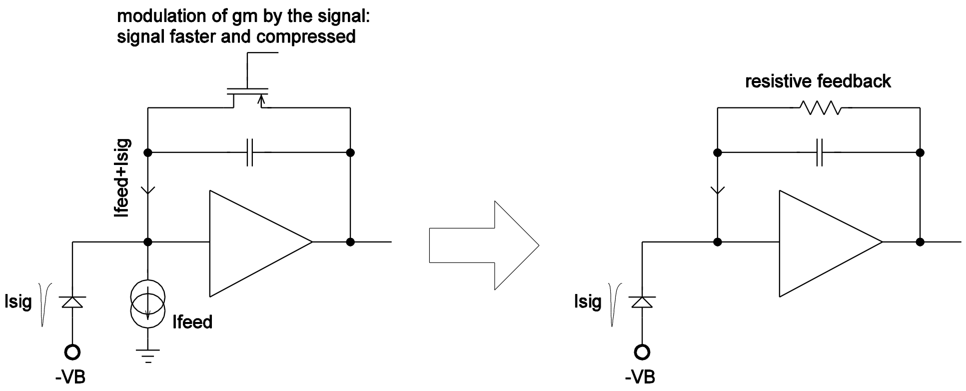


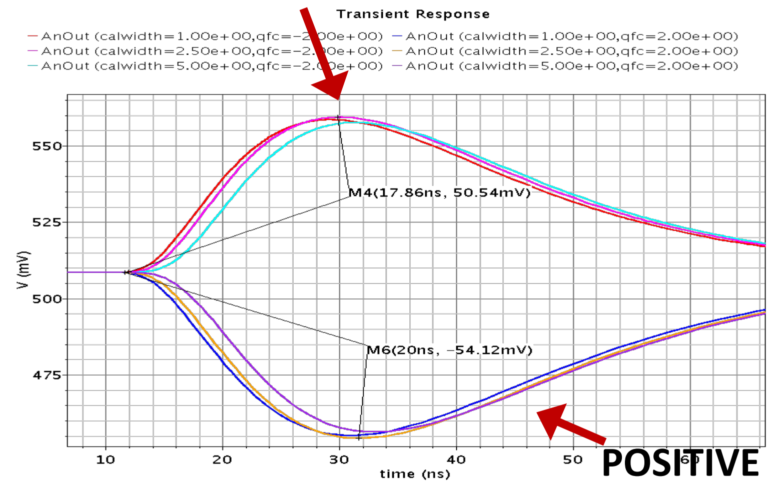
ABCStar prototype FE:
Lower noise wrt. ABC130 FE for negative signal.
Agreement with simulations

Performance Difference with Signal Polarity

- Noise performance is worse after sensor polarity swap: effect of signal compression.

NEGATIVE (faster, lower in amplitude, more noisy)





- **Effect of compression for negative signals (modulation of feedback transistor gm) simulated at the 6% level, in reality (prototype measurements) as high as 20%.**
- **This can be resolved by changing to a resistive feedback for ABCStar.**

Changes to the ABCStar FE

- Feedback change to improve gain and noise (+20% impact on power)
- ELT layout to reduce excess noise after radiation
- Channel-to-channel mismatch improvements
- Optimization for the measured detector parameters after full radiations

ABCStar FE prototype

- 32 channel of preamp/shaper/discriminator
- Input/output multiplexer for calibration injection and data readout
- One channel with analog outputs
- 7 channels connected to input pads for capacitor loading
- Submitted in May 2016
- Received in September 2016

SEU tests

- CHARM 24 GeV protons.
- Beam spills every O(5s) for 300ms, 3×10^9 protons/cm^2 per spill
- Total dose of 6 MRad reached in one week
- Two independent read-out systems
  - One ABC130 located at the center of the beam spill
  - Three neighboring ABC130 chips on a hybrid read out by an HCC130 with the beam spot centered on the middle of the three ABC130s.
- The beam spot FWHM = 10 cm (parallel to the hybrid), 5cm (perpendicular to the hybrid)

SEU tests

- The chip was prepared in a configured state with known register values and known hit patterns loaded into the event buffer before the spill.

- During each spill no commands were sent to the chip. After each spill the chip registers and event buffer were read out then reset.

- The values read from the registers and event buffer were compared with the expected values and analyzed for Single Event Upsets (SEUs) and functional interruptions.

More on SEU results

- Misconfigurations of the chips are expected to be kept well under control with occasional reconfigurations as is done in the SCT.
- The rate of noise in the form of extra or missing hits introduced in the data pipeline due to SEUs has been calculated as one bit flip per 7.6 million data packets transmitted.
- The rate of misidentifying the event to which a data packet corresponds due to SEUs has been calculated as approximately one misidentification per 109 packets transmitted.
- It is calculated that each ABC130 will send back a corrupted event no more than once for every 2×10^9 readout requests. Here a corrupted event is an event with at least one missing or duplicated packet. The rate of packets in an unexpected or unknown format being returned is found to be much smaller than the rate of duplicate or missing packets.

HCC irradiation