Charge Collection Measurements of n-in-p strip detectors after mixed irradiation to HL-LHC fluences and annealing

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FSP 101 ATLAS

Outline

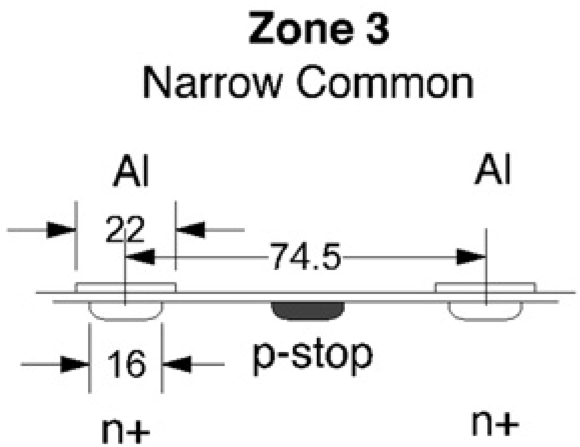
- Introduction
  - Sensors, mixed irradiation and annealing steps
- Measurement results
  - Collected charge, noise and signal-to-noise ratio
- Summary

Results without annealing presented at RESMDD 2012 in Florence.

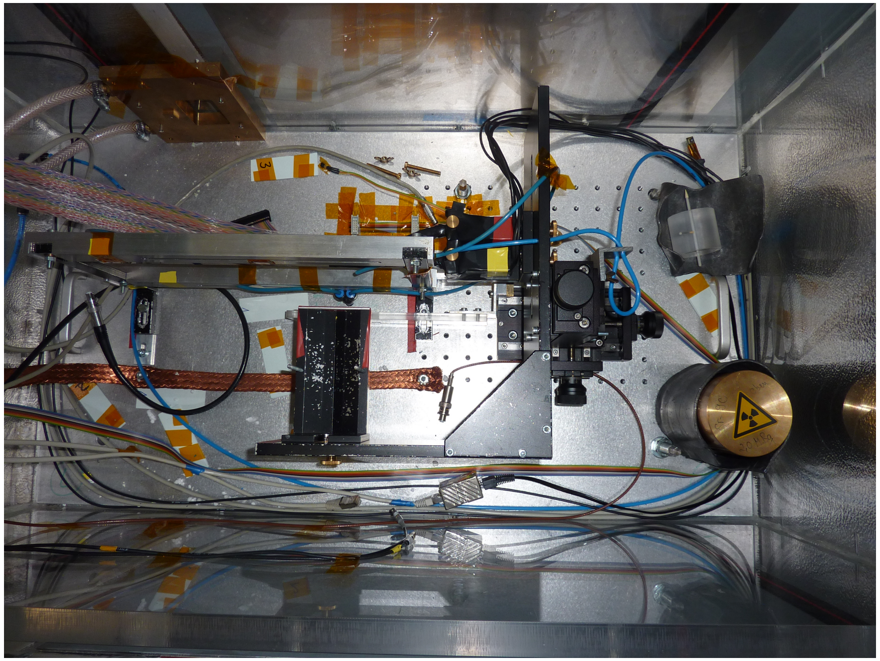
Most of the measurements have been performed by Adrian Driewer, who unfortunately left high energy particle physics.

Devices under test and test setup

Devices:
- Small n-in-p strip sensors from Hamamatsu, part of “ATLAS 07” production
- p-stop strip isolation, FZ silicon
- 320 µm thick, 74.5 µm strip pitch
- Size 1 cm x 1 cm (strip length 0.8 cm)
- AC coupling, 6.7 kΩcm resistivity



More details:
Y. Unno et al.,
NIM A 623, 1
p. 165-167



Beta source test setup:
- Sr^{90} -source with 37 MBq (rate up to 300 MHz)
- Cooling with freezer to -20 °C and liquid nitrogen cooling down to -40 °C possible
- Readout using AliBaVa-system, analogue readout based on Beetle-ASIC
- Gain uncertainty 6 %, temperature dependent calibration

Mixed irradiation to HL-LHC fluences and annealing

Radiation exposure to the tracking detectors up to $1*10^{15}$ neq/cm^2 in the strip region

Mixed irradiation:

- Irradiated with particle fluences corresponding to 3 specific radii in ATLAS ("strawman"' layout v14-2009)

	fluence in n_{eq}/cm^2			
radius	pions	protons	neutrons	sum
19.0 cm	9.3×10^{14}	1.9×10^{14}	9.5×10^{14}	2.1×10^{15}
17.6 cm	1.2×10^{15}	1.9×10^{14}	1.0×10^{15}	2.4×10^{15}
14.2 cm	1.4×10^{15}	2.6×10^{14}	1.1×10^{15}	2.8×10^{15}

Pion irradiation:

- At PSI, Villigen
- 280 MeV/c max. pion mom.
- 16 days beam time at room temperature (→ annealing)
- Uncertainty on fluence 8 %
- Thanks to M. Glaser/ T. Rohe

Proton irradiation:

- At KIT Proton Cyclotron, Karlsruhe
- Protons with 25 Mev/c
- Uncertainty 20 %
- Thanks to A. Dierlamm (HA-101)

Neutron irradiation:

- At Jožef Stefan Insitute, Triga Mark III
- Reactor neutrons
- Uncertainty 10 %
- Thanks to V. Cindro (FP 7 project AIDA)

Annealing:

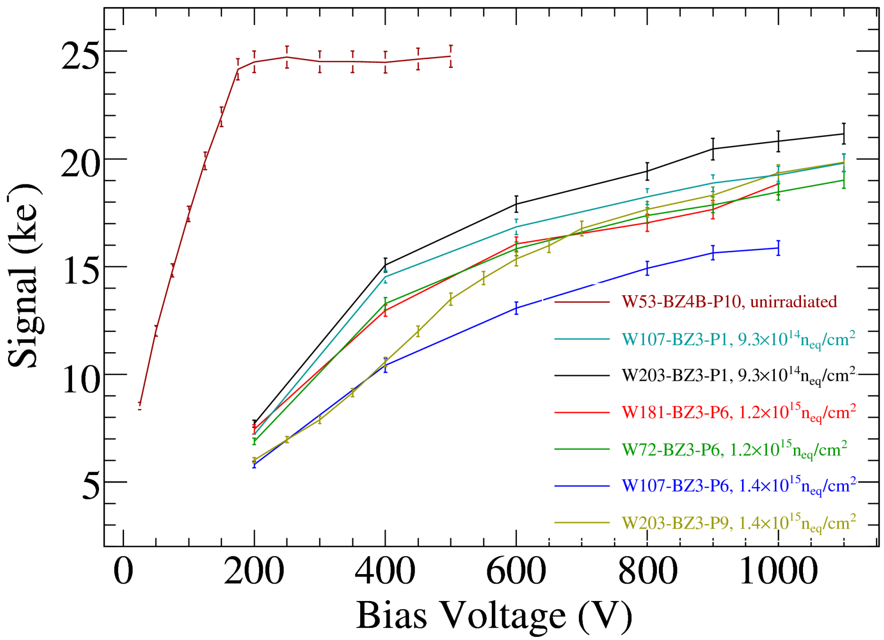
- Consecutive annealing steps at 60°C from 20 – 4200 min (20, 40, 80, 160, 320, 640, 1280, 2560, 4200 min)

Measurements

- Measurements after each irradiation step of the collected charge and noise at different V_{bias} from 200 V to 1100 V (if leakage current limit allows)
- Test for each fluence two sensors (+ additional sensors measured at Liverpool)
- Test one unirradiated sensor for comparison
- Measurements after highest fluences and each annealing step

→ Estimate radiation damage induced effects due to damage of crystal lattice
  - Degradation of collected charge due to charge trapping
  - Reduction of signal-to noise ratio

Results after pion irradiation



Unirradiated sensor:

- Collects 24.7±1.2 ke (as expected)
- Depleted above V_{bias} = 200 V
- I_{leak} = 0.02 µA at V_{bias} = 400 V and -20 °C

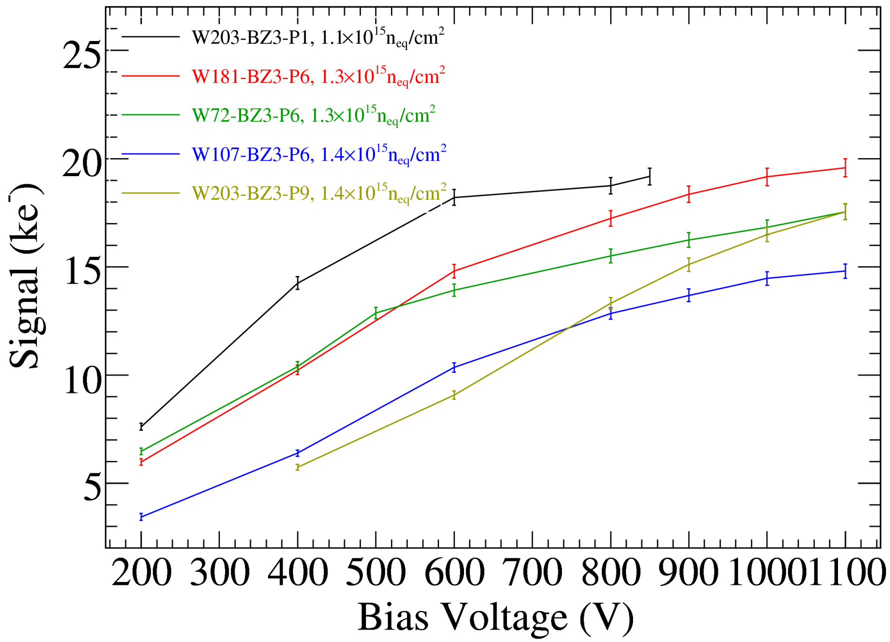
All sensors measurable after pion irradiation:

- No saturation of signal visible, V_{fd} after $1.4*10^{15}$ neq/cm^2 at 1000 V expected
- I_{leak} = 9-16 µA at 400 V and -20 °C
- After highest pion dose of $1.4*10^{15}$ neq/cm^2:
  13.3±0.7 ke (at 500 V), 19±1 ke (at 1000 V)
- Max. signal after $9.3*10^{14}$ neq/cm^2: 21±1 ke (at 1000 V)

Comparison to results with same devices from Liverpool:

- After $1.4*10^{15}$ neq/cm^2 results are comparable
- For lower doses more charge collected in Freiburg

Results after pion and proton irradiation



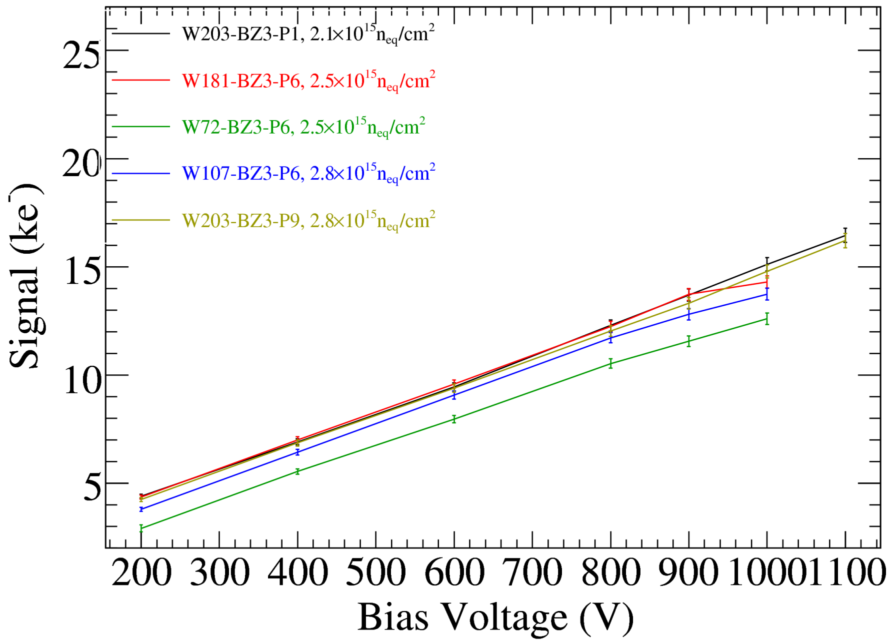
I_{leak} at 400 V and -21 °C:

- After $1.1*10^{15}$ neq/cm^2: 18.8 µA
- After $1.4*10^{15}$ neq/cm^2: 23.6 µA

One sensor with lowest dose not measurable → 5 sensors left for neutron irrad.

- Max. collected charge 12-18 ke (at 1000 V)
- At V_{bias} of 600 V only 9-11 ke signal left

Results after mixed irradiation: CCE



No charge multiplication seen without further annealing

I_{leak} at -21 °C similar values for all fluences:

- At 400 V: I_{leak} = 40 µA
- At 800 V: I_{leak} = 64 µA

Collected charge increases with bias voltage:

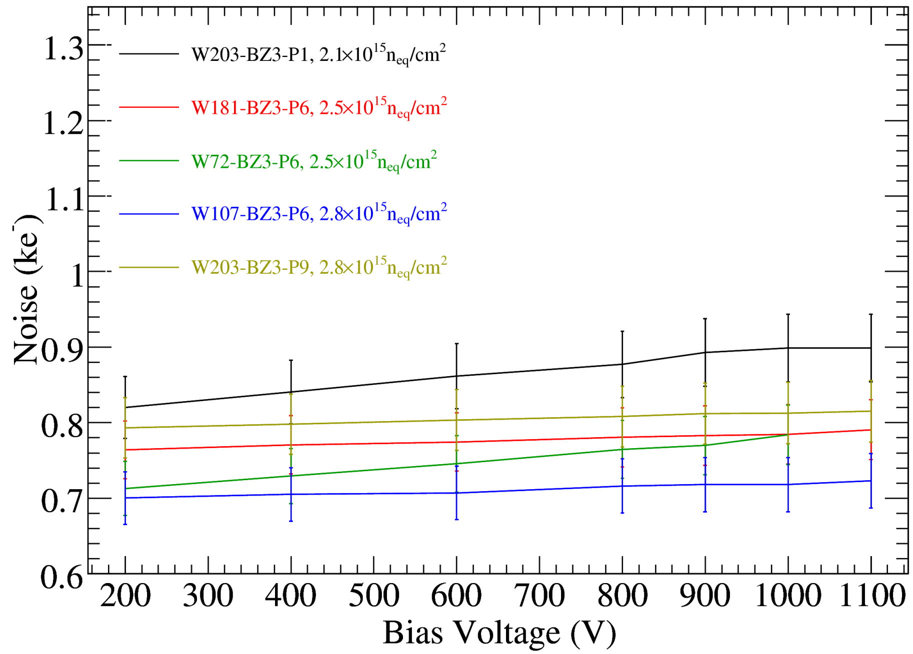
- Max. signal after $2.8*10^{15}$ neq/cm^2: 11-16 ke (at 1000 V)
- Full depletion at 2000 – 2500 V expected
- No charge multiplication seen

Comparison to results with same devices from Liverpool:

- After $2*10^{15}$ neq/cm^2 and $2.4*10^{15}$ neq/cm^2 results are comparable
- For highest dose more charge collected in Freiburg.

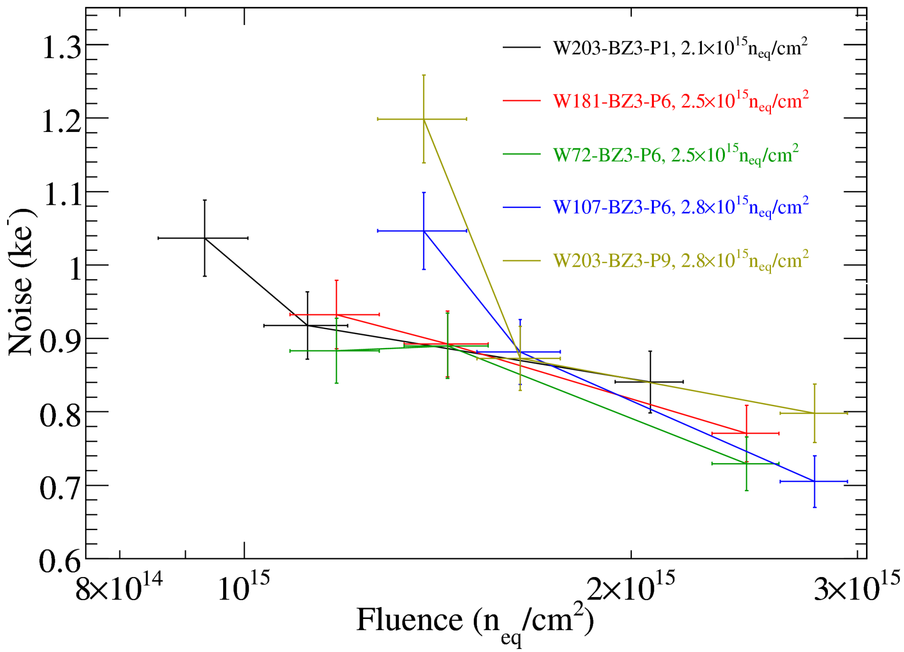
Next: More detailed investigation after mixed irradiation

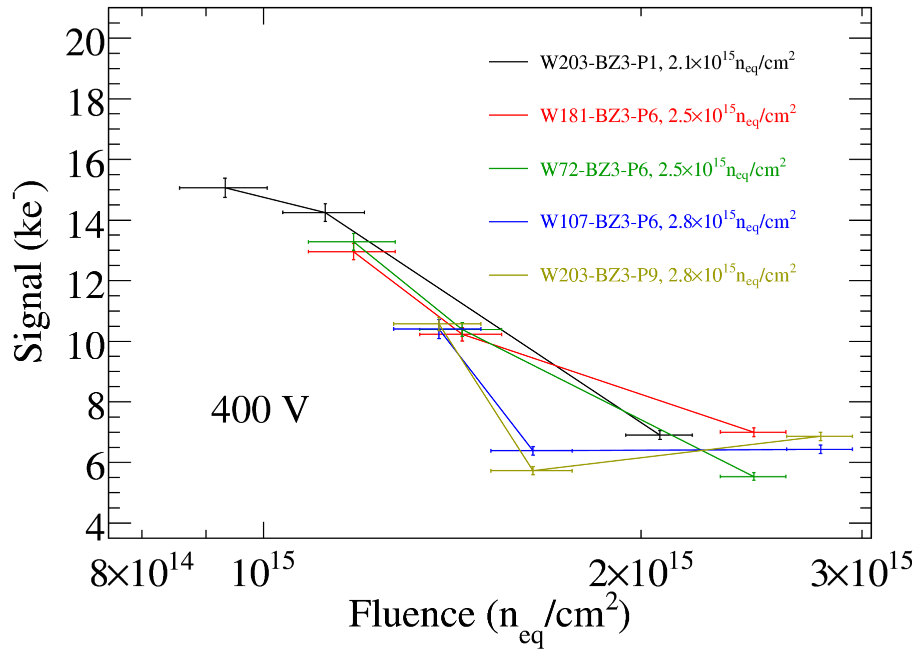
Results after mixed irradiation: Noise



- Noise weakly dependent on bias voltage, only shot noise
- Max. noise after $2.8 \cdot 10^{15}$ neq/cm^2: 0.81 ± 0.04 ke (at 1000 V)
- Noise measurements at -21 °C and -43 °C result in similar values

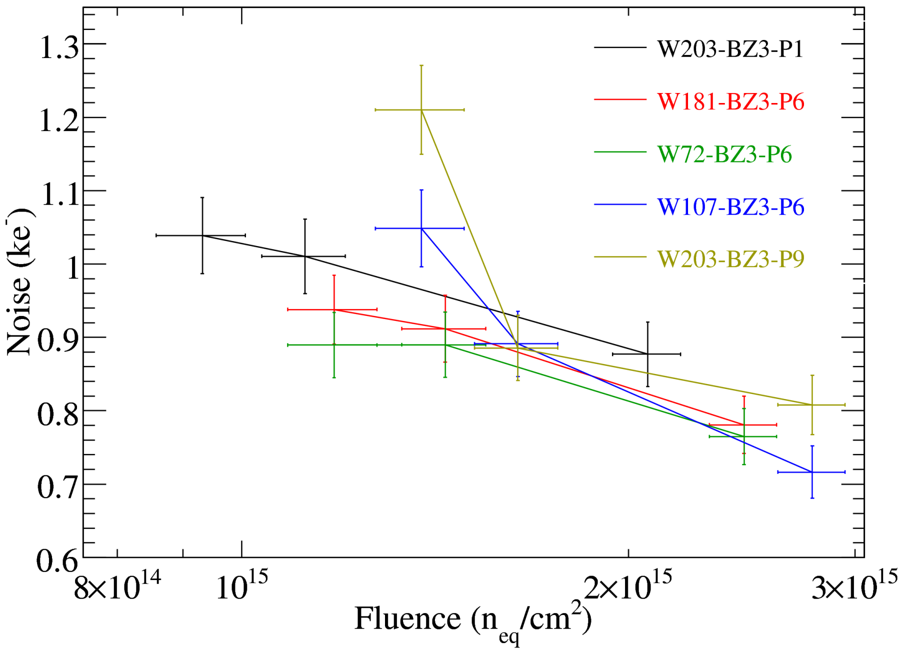
Results after mixed irradiation: V_{bias} = 400 V

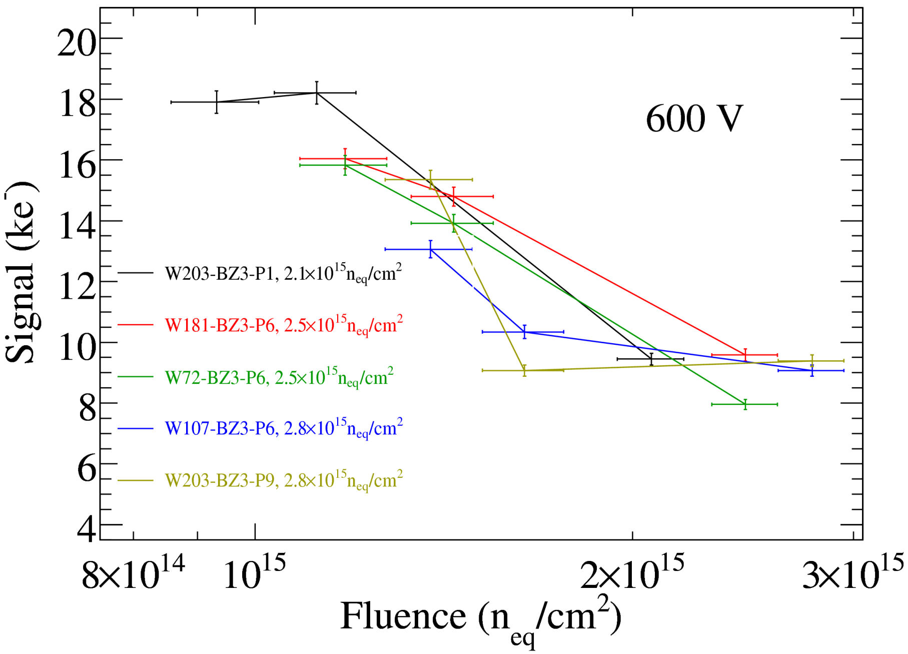




- Noise reduces with higher fluences because of trapping and reduced active detector thickness
- Noise reduces less compared to collected charge, since shot noise still occurs
- Collected charge reduces after highest dose to 6.5±0.5 ke at 400 V
- Damage from protons seems to be larger than from neutrons

Results after mixed irradiation: V_{bias} = 600 V





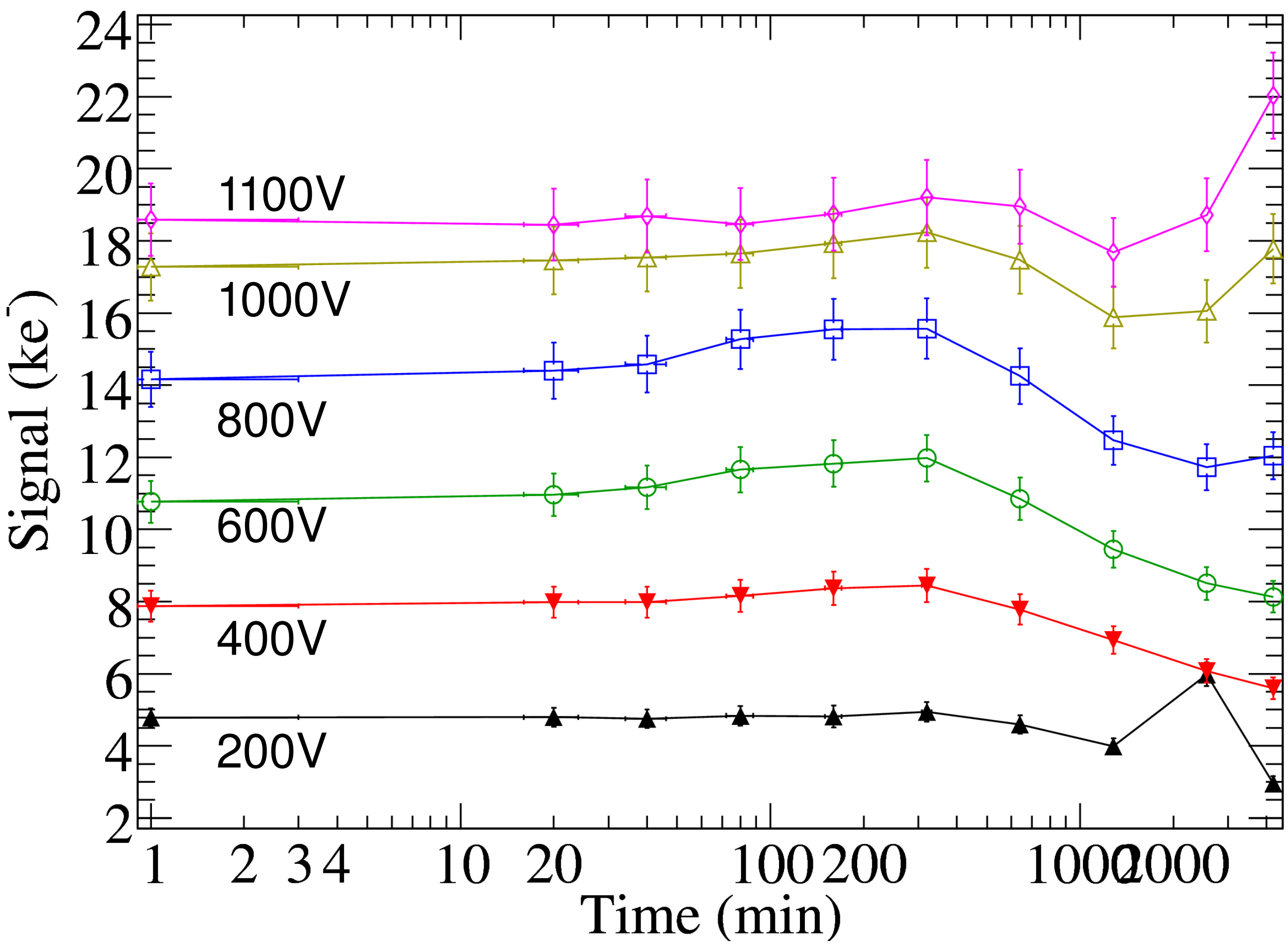
- Collected charge reduces at 600 V to 9.0±0.7 ke
- After $2.8*10^{15}$ neq/cm^2: signal-to-noise ratio 12.3±0.1!

Results after mixed irradiation:

V_{bias} [V]	Collected charge [ke]	Noise [ke]	SNR	I_{leak} [µA]	Temp. [°C]
R = 19.0 cm, Φ = 2.1*10^{15} neq/cm^2					
400 V	7.9±0.4	0.83±0.04	9.51±0.08	41	-21
600 V	10.8±0.6	0.85±0.04	12.71±0.09	53	-21
800 V	14.2±0.8	0.87±0.04	16.3±0.1	64	-21
1000 V	17.3±0.9	0.88±0.04	19.6±0.1	74	-21
R = 17.6 cm, Φ = 2.5*10^{15} neq/cm^2					
400 V	6.2±0.1	0.75±0.04	8.34±0.08	30	-21
600 V	8.8±0.2	0.76±0.04	11.5±0.1	47	-21
800 V	11.4±0.3	0.77±0.04	14.8±0.1	63	-21
1000 V	13.5±0.3	0.78±0.04	17.2±0.1	76	-21
R =14.2 cm, Φ = 2.8*10^{15} neq/cm^2					
400 V	6.5±0.5	0.72±0.04	9.0±0.1	40	-21
600 V	9.0±0.7	0.73±0.04	12.3±0.1	48	-21
800 V	11.6±1.1	0.74±0.04	15.7±0.1	64	-21
1000 V	13.3±1.3	0.75±0.04	17.7±0.1	68	-21

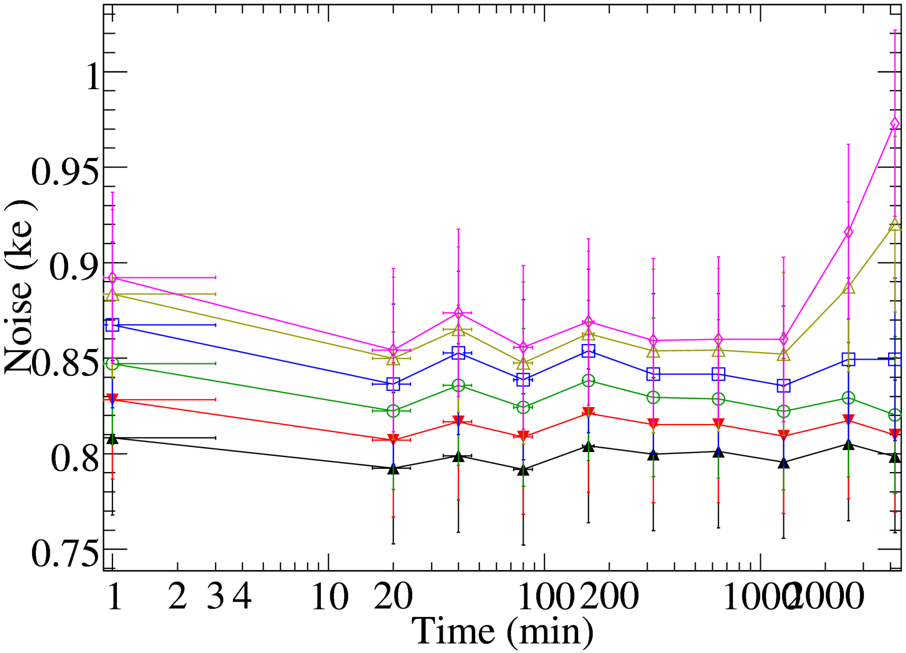
Annealing studies after $2.1*10^{15}$ neq/cm^2

Collected charge for different bias voltages:

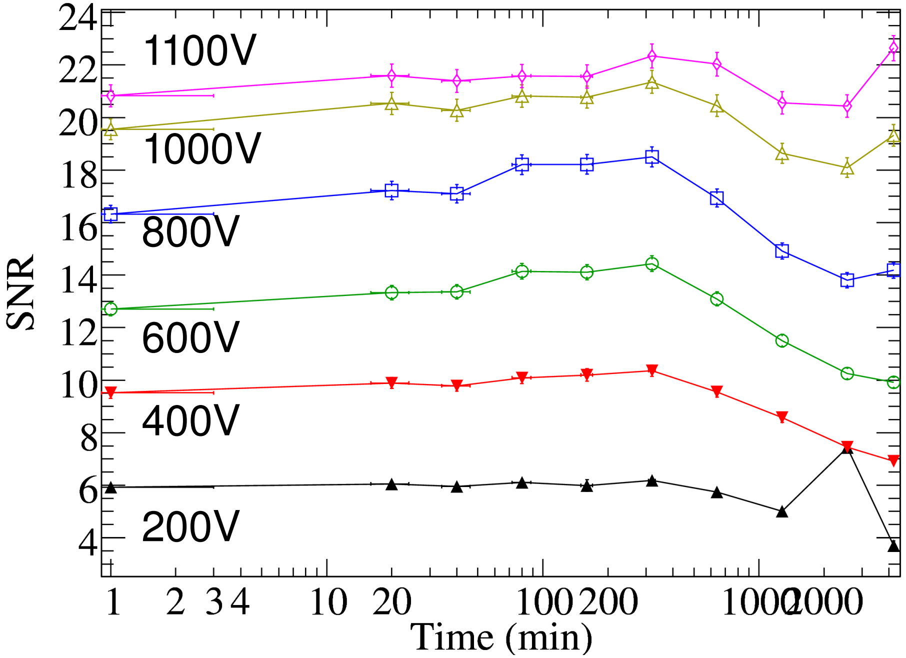


- Different steps of annealing visible
- Collected charge stable until 320 min (~120 days at room temperature)
- Charge multiplication after 2560 min for voltages above 800 V observed

Annealing studies after 2.1*10^{15} neq/cm^2



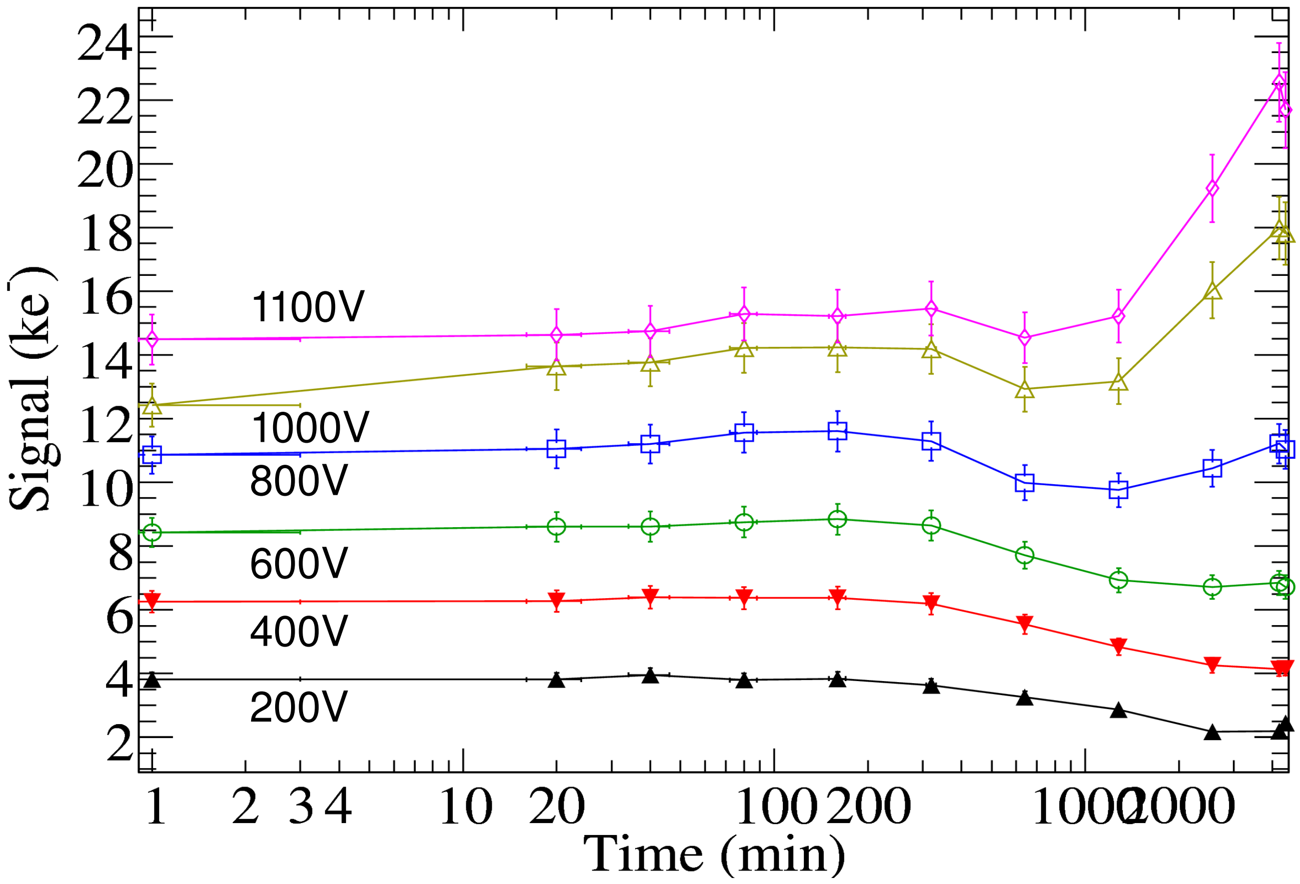
Noise



SNR

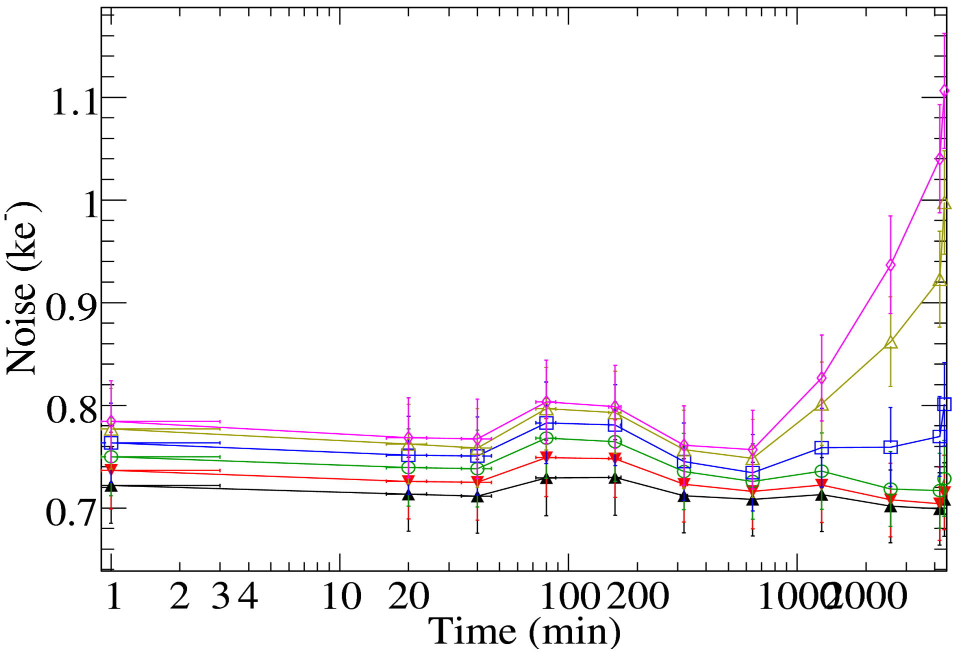
Annealing studies after 2.8*10^{15} neq/cm^2

Collected charge for different bias voltages:

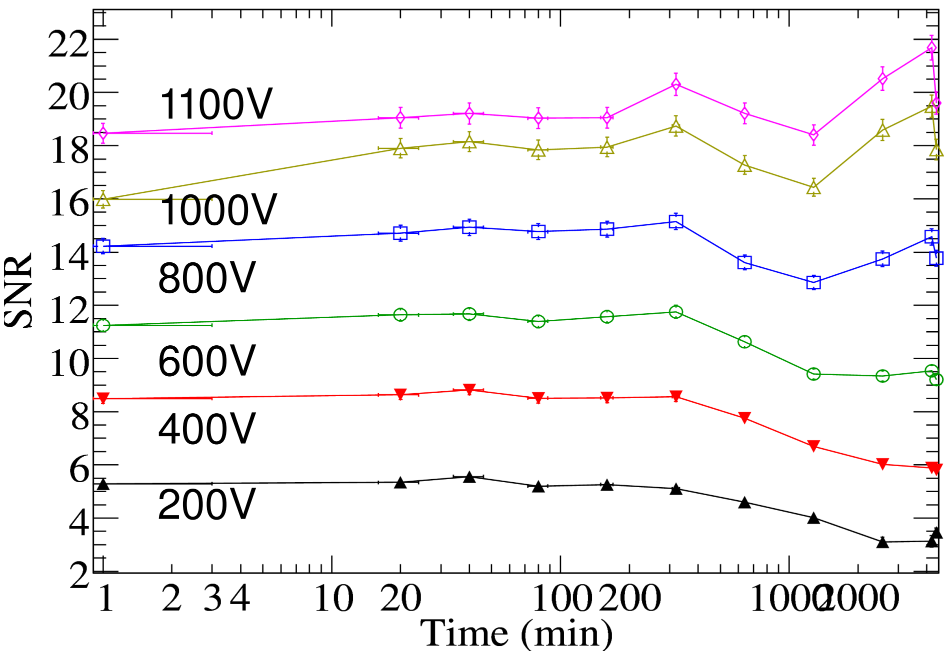


- Collected charge stable until 320 min (~120 days at room temperature)
- Charge multiplication after 1280 min for voltages above 600 V observed

Annealing studies after $2.8*10^{15}$ neq/cm²



Noise



SNR

Application

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For the ATLAS experiment: Current maximum bias voltage of 500 V!

- Measurements before annealing result in 6 ke and signal-to-noise ratios < 10 at 400 V bias voltage
  But signal-to-noise ratio > 10 at 600 V reachable
  Differences between 600 V and 1000 V: ~ 50 % more collected charge and ~ 50 % higher signal-to-noise ratio
- After annealing stable collected charge observed until 320 min at 60°C (122 days at RT)
- At reverse annealing reduction of charge by 10-15% observed
- Charge multiplication only after long annealing times (1280 min) and at very high bias voltage

N.B.:

- Doses slightly higher than for innermost strip region expected and prediction of doses agrees well with measured values in LHC experiments (safety factor of 2 included)
- Investigated sensors have strip length of 0.8 cm instead of 2.4 cm
- Sensors even operational in outer pixel layers with bias voltages above 800 V

Summary - Outlook

- Measurements of p-type short strip sensors irradiated with pions, protons and neutrons up to $2.8*10^{15}$ neq/cm^2 and annealed up to 4200 min at 60°C presented.

- Collected charge and noise determined using a beta source setup and fast analogue readout.

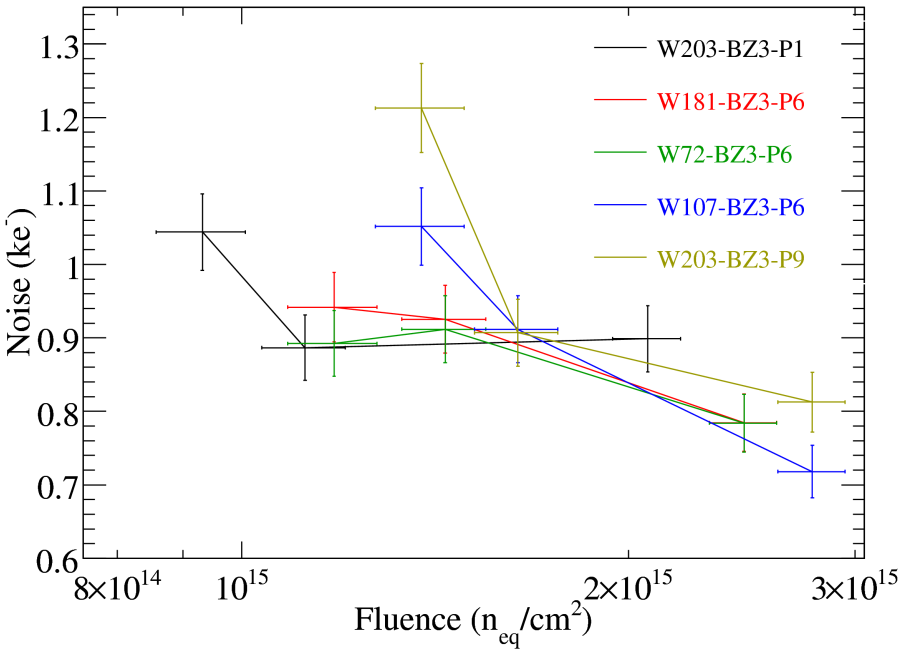
- Results show expected degradation of performance after irradiation, partially recovered after long annealing and at very high bias voltages.

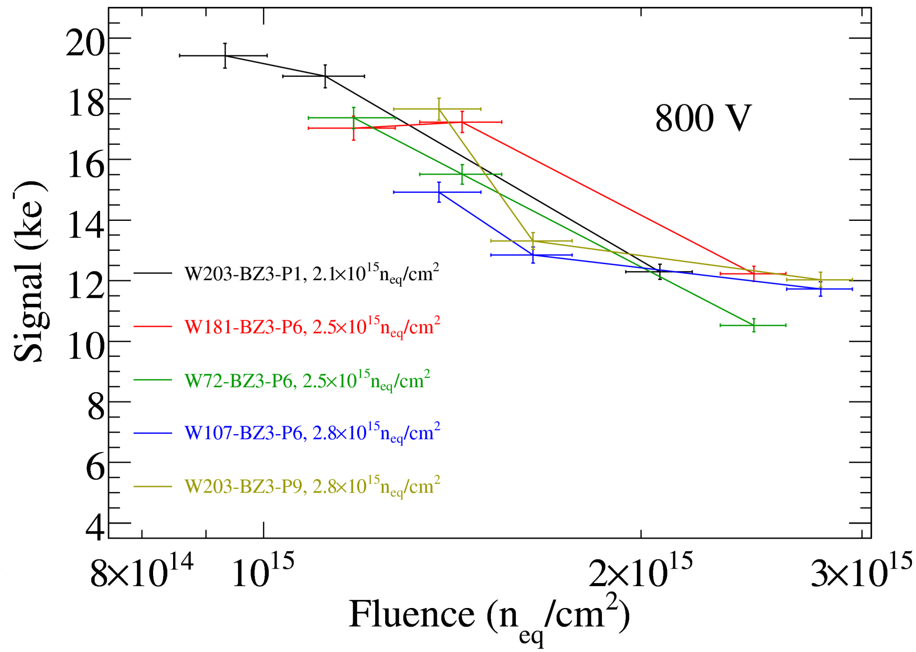
- Signal-to-noise ratios < 10 at 400 V bias voltage, but signal-to-noise ratio > 10, which are needed for the ATLAS inner tracker upgrade are with 600 V bias voltage reachable.

- Next: Combine results with Liverpool

Backup

Results after mixed irradiation: V_{bias} = 800 V





- Collected charge reduces at 800 V to 12±1 ke
- After $2.8 \cdot 10^{15}$ neq/cm^2: signal-to-noise ratio 15.7±0.1 **> 10!!**

ATLAS fluences

Sadrozinski, et al., NIMA, 658 (2011), 20–24

	R (cm)	Z (cm)	Number of segments	Strip length (cm)	Average pitch (μm)	Cload (pF)	T (°C)	2 × Fluence (10^{14} neq/cm^2)
Ring 1	33.6	214	4	2.8	70	2.8	– 15	14.4
Ring 2	44.4	279	4	2.3	73	2.3	– 15	13.4
Ring 3	54.1	279	2	3.6	89	3.4	– 17	11.4
Ring 4	61.7	279	1	12	88	11.2	– 20	10.2
Ring 5	73.6	279	1	11.3	78	11.4	– 20	8.6
Ring 4	61.7	279	2	6	88	5.6	– 20	10.2
Ring 5	73.6	279	2	5.7	78	5.7	– 20	8.6
Ring 6	84.9	279	1	10.1	88	9.4	– 20	7.8
Barrel short	38.0	117	4	2.4	75	2.4	– 18	12.0
Barrel long	74.3	117	1	9.5	75	9.5	– 18	5.6

Test setup

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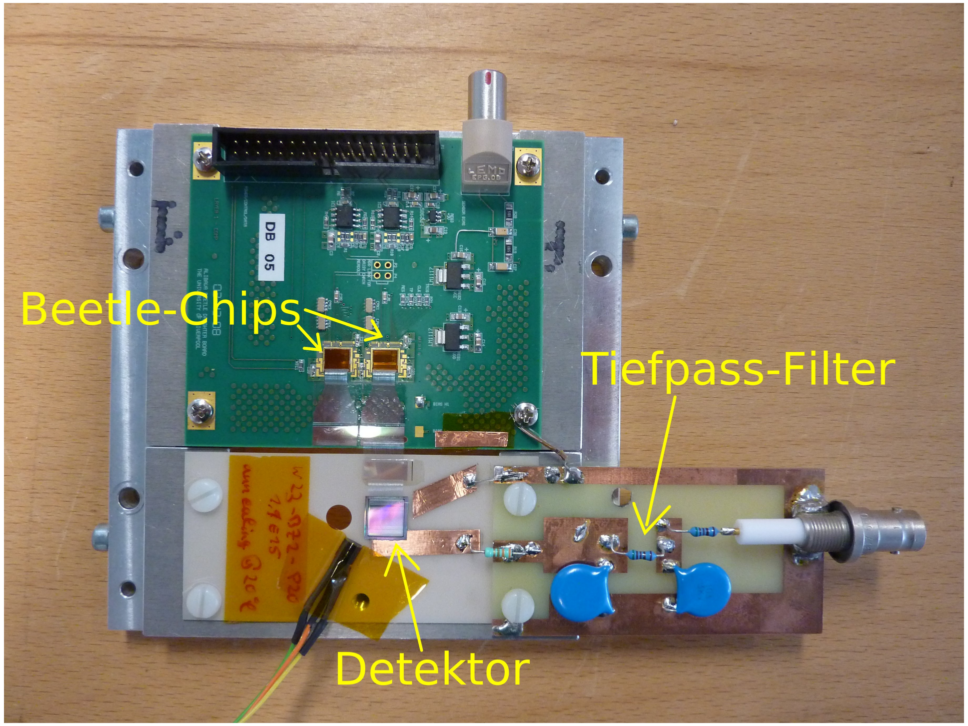
AliBaVa - readout:



Introduction: Challenges at the HL-LHC

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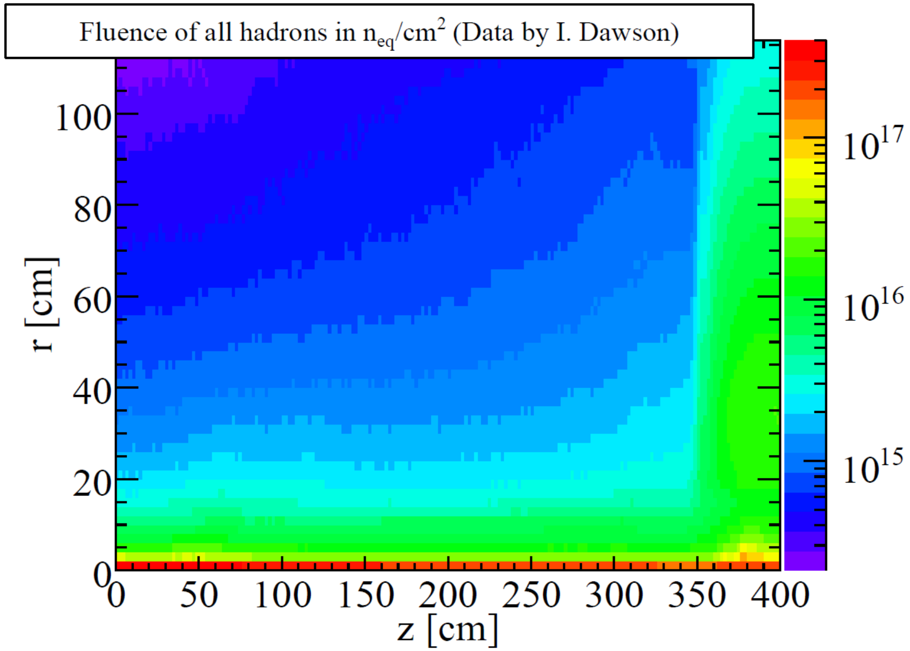
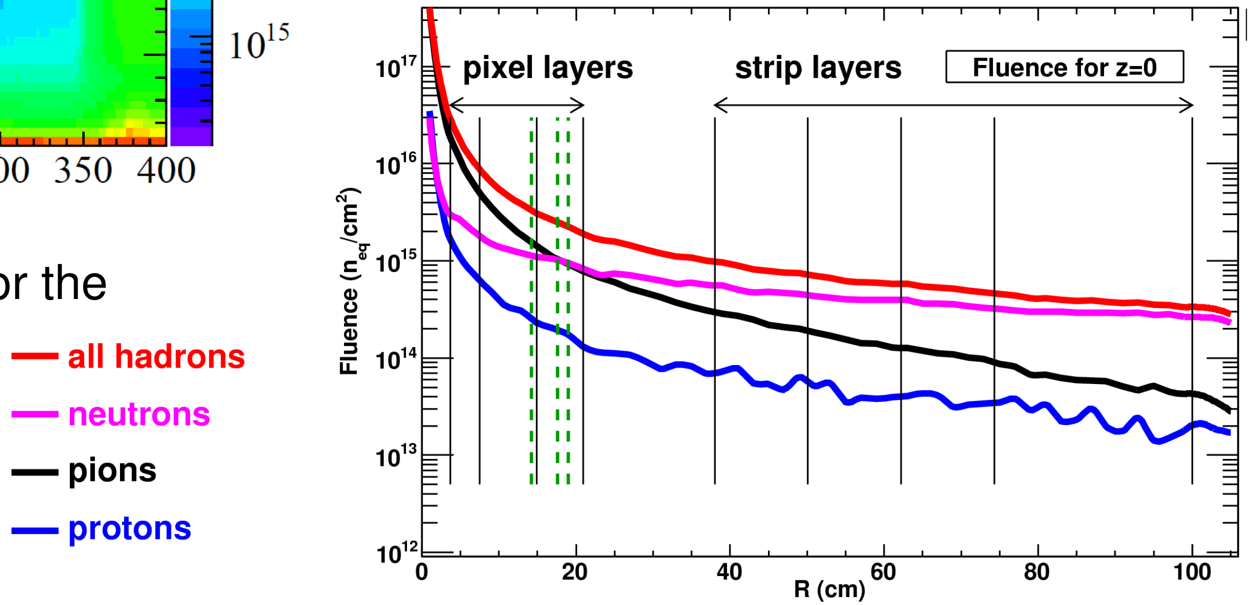
Planned upgrade of the LHC in ~ 2022:



- 3000 fb^{-1} expected integrated luminosity
- high radiation exposure to the tracking detector:
  - $2*10^{16}$ neq/cm^2 for inner pixel layers
  - up to $1*10^{15}$ neq/cm^2 in the strip region

Expected particle fluences for the ATLAS Inner tracker:



→ Investigation of radiation damage of sensors needed