Evolution of the electrical characteristics of the ATLAS ITk strip sensors with HL-LHC radiation exposure range

J. Fernández-Tejero [a,b*], È. Bach [c], V. Cindro [d], V. Fadeyev [e], P. Federicova [f], C. Fleta [c], S. Hirose [g], J. Kroll [f], I. Mandic [d], K. Maeyama [g], M. Mikestikova [f], L. Poley [a,b], B. Stelzer [a,b], P. Tuma [f], M. Ullán [c], Y. Unno [h]

[a] Simon Fraser University (SFU), Burnaby, Canada
[b] TRIUMF, Vancouver, Canada
[c] Centro Nacional de Microelectrónica (IMB-CNM), CSIC, Barcelona, Spain
[d] Jozef Stefan Institute, Ljubljana, Slovenia
[e] Santa Cruz Institute for Particle Physics (SCIPP), University of California, Santa Cruz, USA
[f] Institute of Physics, Academy of Science of the Czech Republic, Prague, Czech Republic
[g] Institute of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[h] Institute of Particle and Nuclear Study, KEK, Tsukuba, Japan

*Corresponding author: Javier Fernández-Tejero (e-mail address: xavi.fdez@cern.ch)

iWoRiD 2024 – 25th International Workshop on Radiation Imaging Detectors, June 30th – July 4th 2024

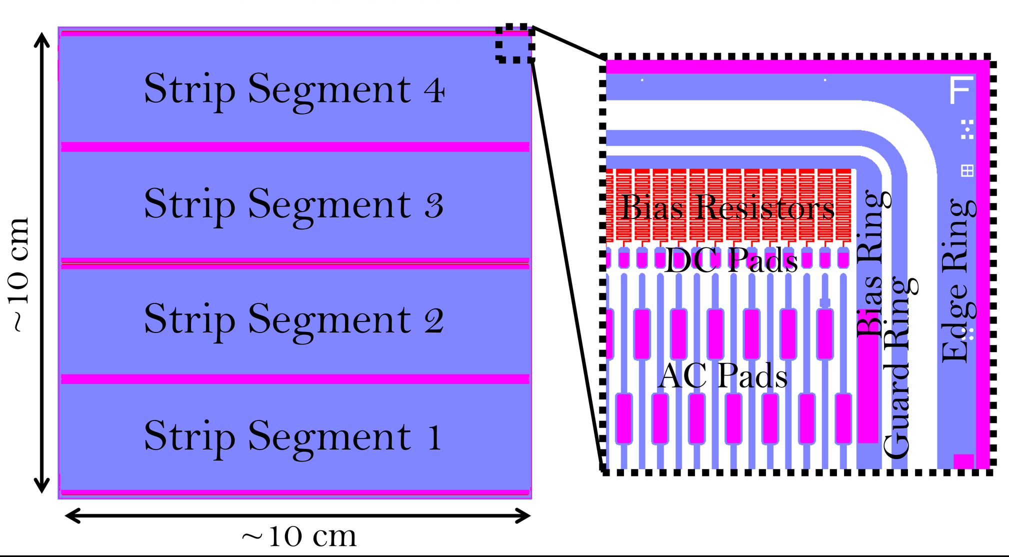
Abstract

The objective of the study is to evaluate the evolution of the performance of the new ATLAS Inner-Tracker (ITk) strip sensors as a function of radiation exposure, to ensure the proper operation of the upgraded detector during the lifetime of the High-Luminosity Large Hadron Collider (HL-LHC). Full-size ATLAS18 Barrel Short-Strip sensors with final layout design have been irradiated with neutrons and gammas, to confirm the results obtained with mini-sensors during the development phase. The irradiations cover a wide range of fluences and doses that ITk will experience, going from 1e13 n_{eq}/cm^2 and 0.49 Mrad, to 1.6e15 n_{eq}/cm^2 and 80 Mrad. The split irradiation enables a proper combination of fluence and dose values of the HL-LHC, including a 1.5 safety factor. A complete electrical characterization of the key sensor parameters before and after irradiation is presented, studying the leakage current, bulk capacitance, and single-strip and inter-strip characteristics. The results confirm the fulfillment of the ATLAS specifications, and the study of a wide range of fluences and doses allows to obtain detailed results about the frequency dependence of the bulk capacitance measurements, or the evolution of the punch-through protection and inter-strip resistance with radiation.

ATLAS ITk Strip Sensors

n^+-in-p barrel Short-Strip (SS) sensors, with final production layout [1] (so-called ATLAS18) for the ATLAS ITk upgrade, fabricated by Hamamatsu Photonics KK

- Float zone (FZ) p-type 6-inch, 320 µm thick, silicon wafers
- 97621 x 97950 µm²
- 4 segments, 1280 strips/segment
- Parallel strips, 75.5 µm strip pitch



Irradiations

- Combination of neutron and gamma irradiations, covering the fluences/doses expected from the first days of the HL-LHC, to the end of the lifetime of the experiment
- Neutron irrad. at TRIGA reactor (Ljubljana, Slovenia)
- Gamma irrad. at UJP Praha (Prague, Czech Republic)

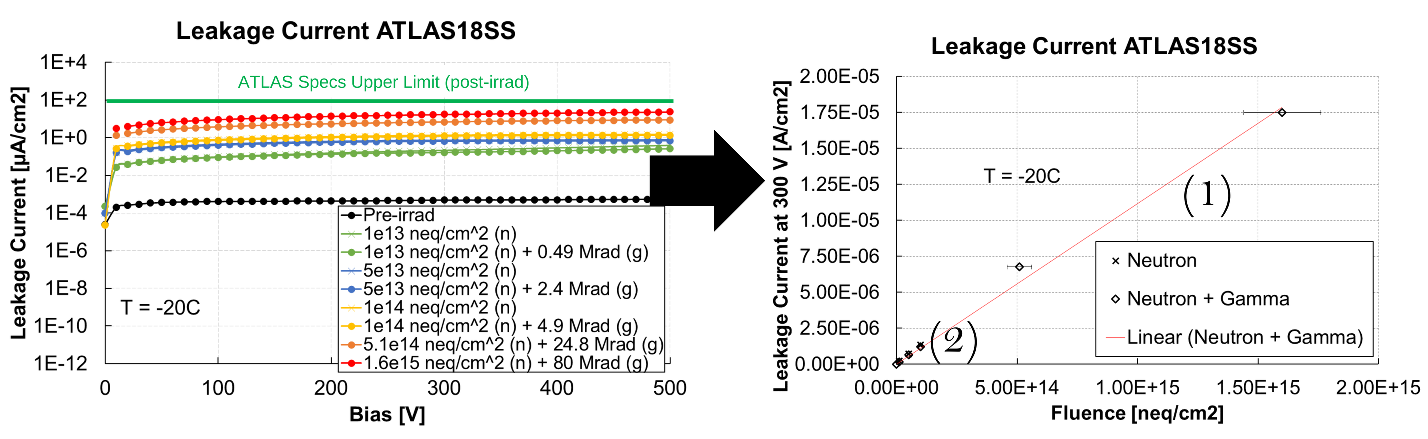
Sensor Type	1st Irradiation (n: neutrons)	2nd Irradiation (n: neutrons, g: gammas)
ATLAS18SS	[pre-irrad tests]	[pre-irrad tests]
ATLAS18-MiniSS	[pre-irrad tests]	[pre-irrad tests]
ATLAS18SS	1e13 n_{eq}/cm^2 (n)	0.49 Mrad (g)
ATLAS18SS	5e13 n_{eq}/cm^2 (n)	2.4 Mrad (g)
ATLAS18SS	1e14 n_{eq}/cm^2 (n)	4.9 Mrad (g)
ATLAS18SS	-	5.1e14 n_{eq}/cm^2 (n) + 24.8 Mrad (g)
ATLAS18SS	-	1.6e15 n_{eq}/cm^2 (n) + 80 Mrad (g)

Results

Leakage Current

ATLAS Specs:
- Breakdown Voltage (V_{bd}) > 500 V
- I at 500 V < 0.1 µA/cm² (20C pre-irrad), < 100 µA/cm² (-20C post-irrad)

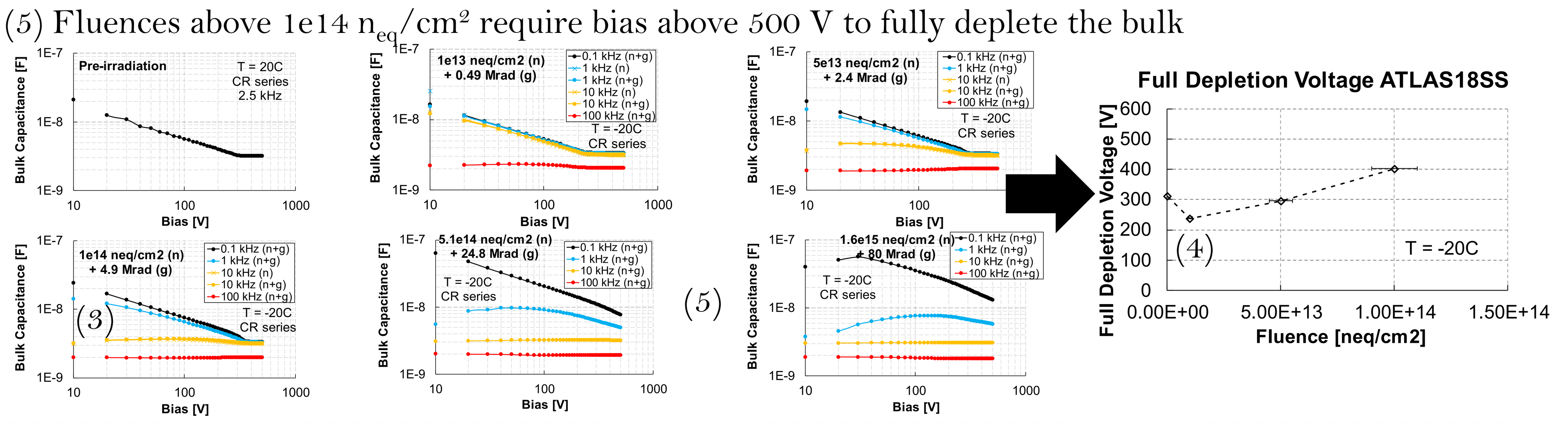
(1) Linear increase of leakage current as a function of fluence
(2) No significant variation on leakage current with gamma irradiation after neutron irradiation



Bulk Capacitance

ATLAS Specs: Full depletion voltage (V_{fd}) < 350 V (pre-irrad)

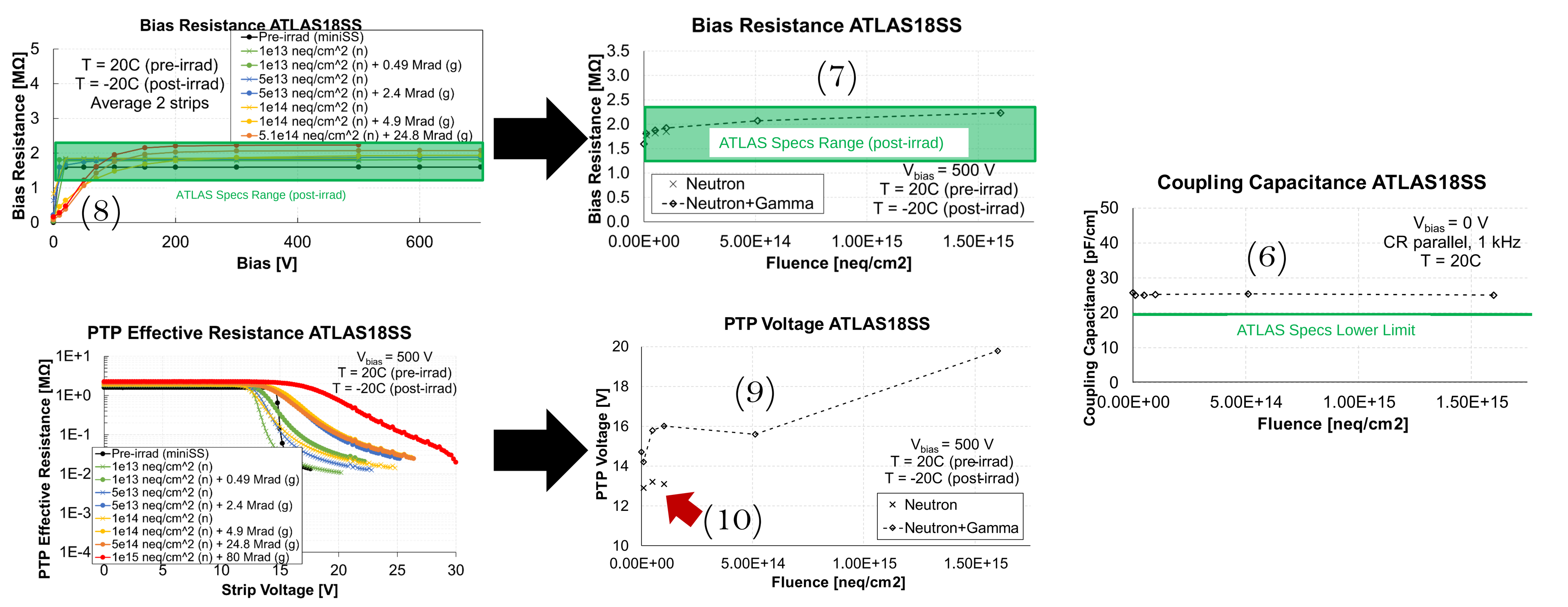
(3) Lower frequencies needed to extract V_{fd} after irradiation. Frequency should be lower enough to interact with the deep traps created during irradiation [2]
(4) Reduction V_{fd} for 1e13 n_{eq}/cm^2, increase above 5e13 n_{eq}/cm^2, probably caused by the acceptor removal effect in p-type material irradiated with protons or neutrons [3]
(5) Fluences above 1e14 n_{eq}/cm^2 require bias above 500 V to fully deplete the bulk



Single Strip Characteristics

ATLAS Specs:
- C_{coupl} ≥ 20 pF/cm (pre-irrad)
- R_{bias} = 1.5±0.5 MΩ (pre-irrad), 1.8±0.5 MΩ (post-irrad)
- PTP not defined

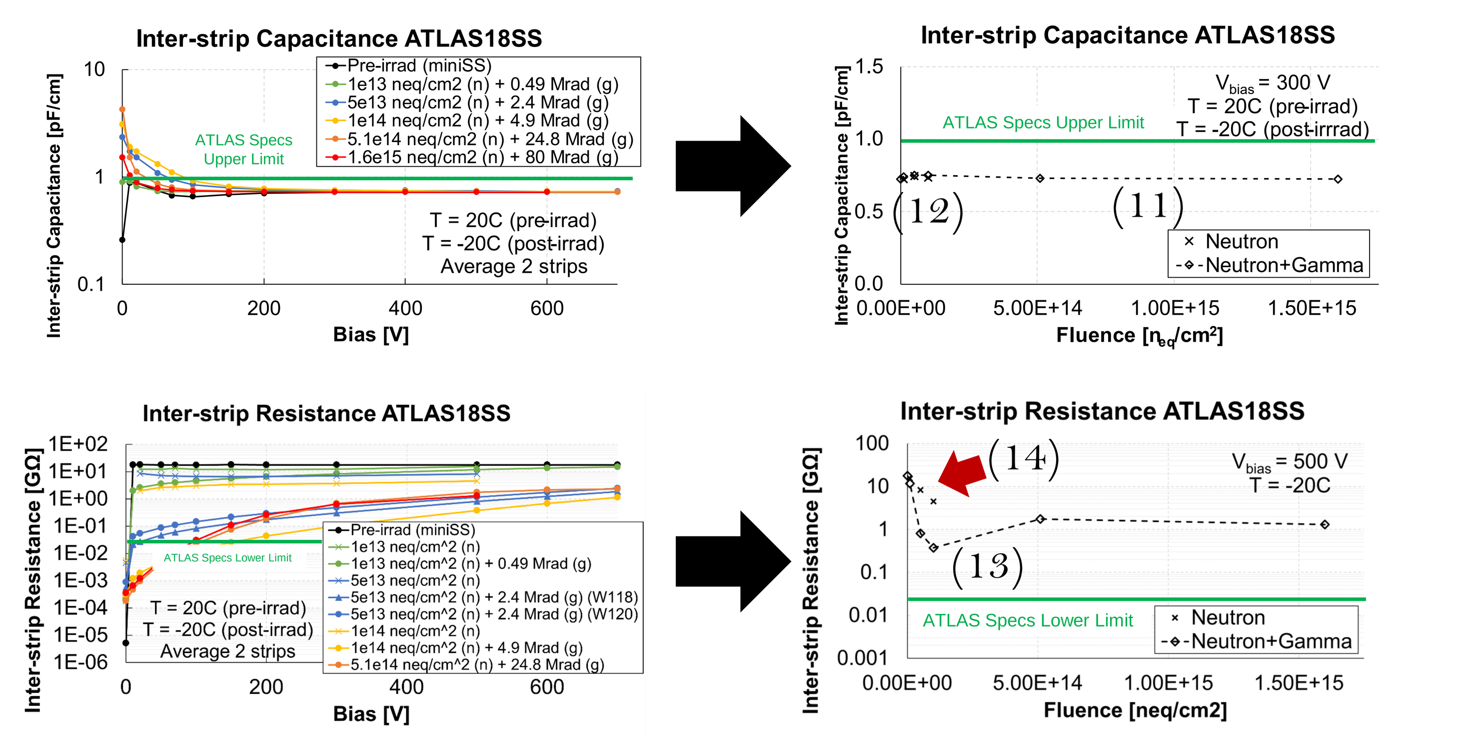
Coupling Capacitance (C_{coupl}): (6) No variation with irradiation [4]
Bias Resistance (R_{bias}):
(7) Increase of Rbias with irradiation [4,5]
(8) Lower R_{bias} obtained at lower bias voltages, due to reduction of R_{int} caused by gamma irradiation
Punch-Through Protection (PTP) voltage:
(9) Increase of PTP voltage with irradiation [5], but showing reduction between 5e13 - 5e14 n_{eq}/cm^2
(10) Sensors irradiated only with neutrons showing lower PTP voltage than sensors irradiated with neutrons+gammas



Inter-strip Characteristics

ATLAS Specs:
- C_{int} < 1 pF/cm at 300 V
- R_{int} > 10 x Rbias at 400 V (pre-irrad), at 500 V (post-irrad)

Inter-strip Capacitance (C_{int}):
(11) No significant variation of C_{int} with irradiation above 300 V [4]
(12) No clear influence of gamma irradiation on C_{int}
Inter-strip Resistance (R_{int}):
(13) Reduction R_{int} with irradiation [4,5]. Lowest values between 1-5e13 n_{eq}/cm^2
(14) Sensors irradiated only with neutrons showing higher R_{int} than sensors irradiated with neutrons+gammas [4]



Conclusions

All the parameters measured fulfill the ATLAS specifications before/after irradiation, confirming the results obtained with mini-sensors during the development phase. Additionally, some interesting results were observed:
- Frequency dependence of bulk capacitance measurements after neutron+gamma irradiation up to 1.6e15 n_{eq}/cm^2 + 80 Mrad
- Increase of R_{bias} and PTP voltage with irradiation, but showing a plateau of PTP voltage between 5e13-5e14 n_{eq}/cm^2 (*)
- Reduction of R_{int} with irradiation, but showing the lowest values between 1e13-5e13 n_{eq}/cm^2 (*)
- Additional gamma irradiations (ionization) after neutron irradiations (displacement), increases PTP voltage (*) and reduces R_{int}

(*) These results were not observed previously with prototypes. Further studies needed to understand the mechanisms responsible.

References

[1] Y. Unno, et al. JINST 18 (2023) T03008)
[2] A. Chilingarov, et al. RD48, ROSE/TN/2002-02
[3] M. Moll, PoS (Vertex2019) 027
[4] M. Mikestikova, et al. NIM A 983 (2020) 164456
[5] È. Bach, et al. NIM A 1064 (2024) 169435

This work was supported by the Canada Foundation for Innovation and the Natural Sciences and Engineering Research Council of Canada; the Spanish R&D grant PID2021-126327OB-C22, funded by MCIN/AEI/10.13039/501100011033 and by ERDF/UE; the European Structural and Investment Funds and the Czech Ministry of Education, youth and Sports of Czech Republic via projects LM2023040 CERN-CZ, LTT17018 Inter-Excellence, and FORTE – CZ.02.01.01/00/22_008/0004632; and the US Department of Energy, grant DE-SC0010107. The authors would like to thank the crew at the TRIGA reactor in Ljubljana, with the support from the Slovenian Research and Innovation Agency (research core funding P1-0135 and project J1-3032), and also the technical team at CYRIC of Tohoku University (Japan), supported by JSPS KAKENHI 23K13114.