VERTEX 2014
23rd International Workshop on Vertex Detectors
Mácha Lake | Doksy, Czech Republic
September 15 - 19, 2014

Evaluation of Bulk and Surface Radiation Damage of Silicon Sensors for the ATLAS Upgrade

Marcela Mikeštíková, Jan Šťastný, Zdeněk Kotek

Institute of Physics, The Academy of Sciences of the Czech Republic, Prague

Introduction:

• Silicon strip sensors in upgraded ATLAS experiment at the high luminosity Large Hadron Collider (HL-LHC) will be exposed to radiation fluences up to 1.2x10^{15} n_{eq}/cm^2 which will substantively affect their properties: bulk damage will increase the leakage current (I) and the voltage needed for full depletion (FDV), surface damage will raise the charge in SiO_2-Si interface which will alter the inter-strip properties.

• The silicon trackers used in present LHC experiments are based on microstrip sensors made with *p*-strips implanted on *n*-type silicon bulk (*p*-in-*n*). Radiation harder ***n+*-in-*p*** type sensors are now considered to be used in the HL-LHC trackers. *N*-strip readout allows sensor operation in partially depleted mode after high fluences. However *n+*-in-*p* sensors need additional strip isolation.

• The purpose of this study is to characterize the *n*-in-*p* type sensors developed by ATLAS upgrade collaboration R&D group [1] produced by Hamamatsu Photonics (HPK) and verify the sensor performance required by the Technical Specification [2] before and after irradiation.

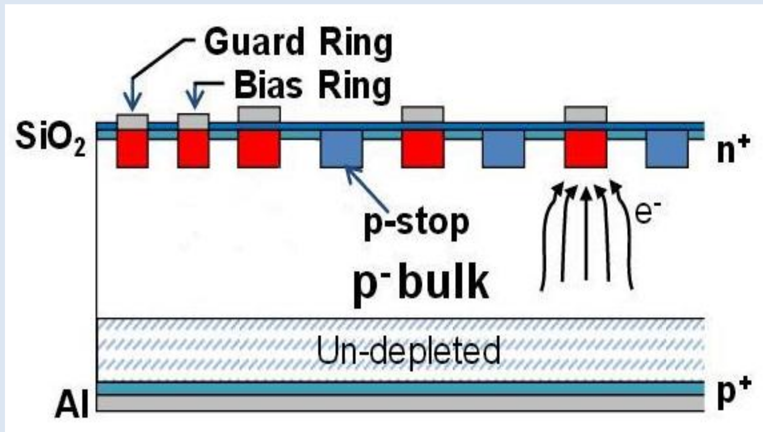
• Previous studies performed in Institute of Physics were done using large area ATLAS07 sensors [3].

• The samples for this irradiation study are ATLAS12A Endcap mini sensors with fan geometry of strips (~1 cm long). The isolation is done with p-implant (p-stops). The sensors vary in strip pitch, in stray strip ganging, in fan geometry (stereo strips or skewed layout) or in "Punch-through Protection" structure (PTP) [4].

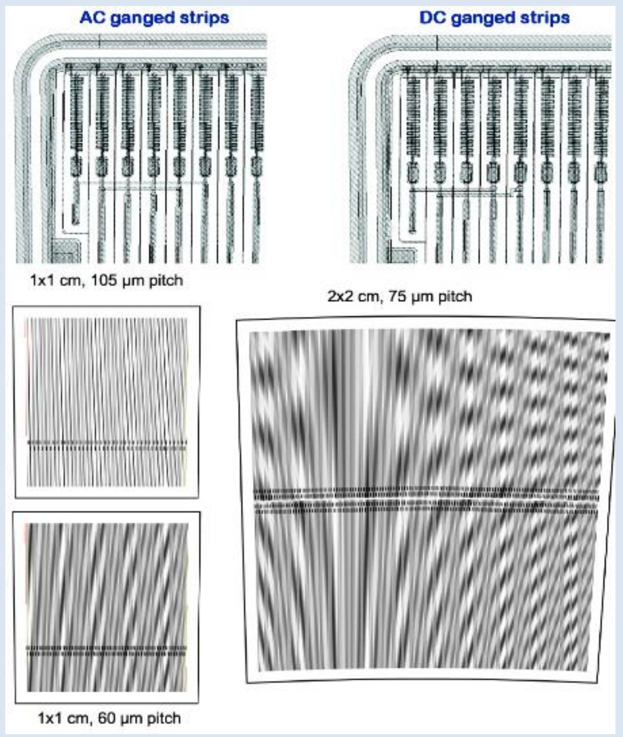
They have been irradiated with 27 MeV protons at Birmingham and Karlsruhe up to fluences 5*10^{14}, 1*10^{15} and 2*10^{15} n_{eq}/cm^2 and with gamma in BNL to doses 1, 3 and 10 MRad.

n+-in-*p* strip sensor for ATLAS Upgrade at HL-LHC

- **Collects electrons - faster signal, reduced charge trapping**
- **Depletes from the strip side - sensor can be operated under-depleted**
- **More cost-effective than *n*-in-*n* (double-side lithography) [1]**



Endcap mini sensors design:



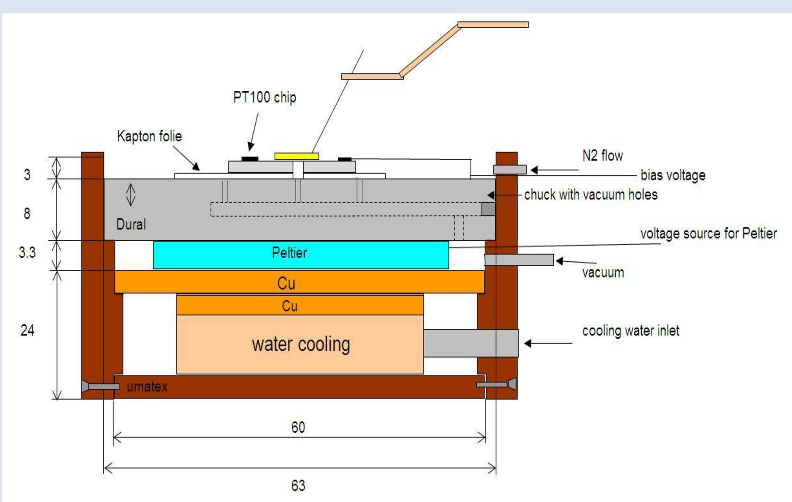
Sensor design:
- ***N+*-strip in *p* type material (FZ)**
- **AC-coupled readout**
- ***n*-strips biased through poly-silicon resistors**
- **"p-stop" isolation**
- **thickness 320 µm**

10 types of ATLAS12A Endcap mini sensors:
- **Fan geometry of strips with stereo strips or "skewed" layout**
- **2 different pitches**
- **2 types of stray strips ganging (AC and DC)**
- **2 different types of PTP structures [4]**

Experimental methods and results:

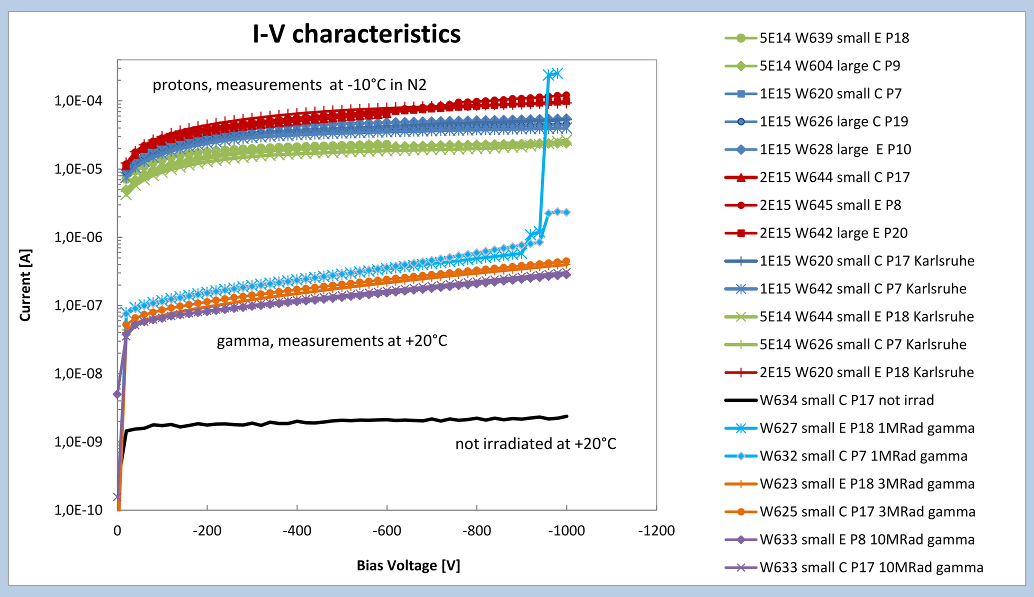
Sensors have been measured in Silicon lab at Institute of Physics on semi-automatic probe-station. Sensors have been tested at room temperature and at -10°C with nitrogen flow. The cooling of probe-station chuck was performed by Peltier module.

Semi-automatic probe-station KarlSuss PA200 in Prague



Peltier module for cooling the manual probe-station chuck.

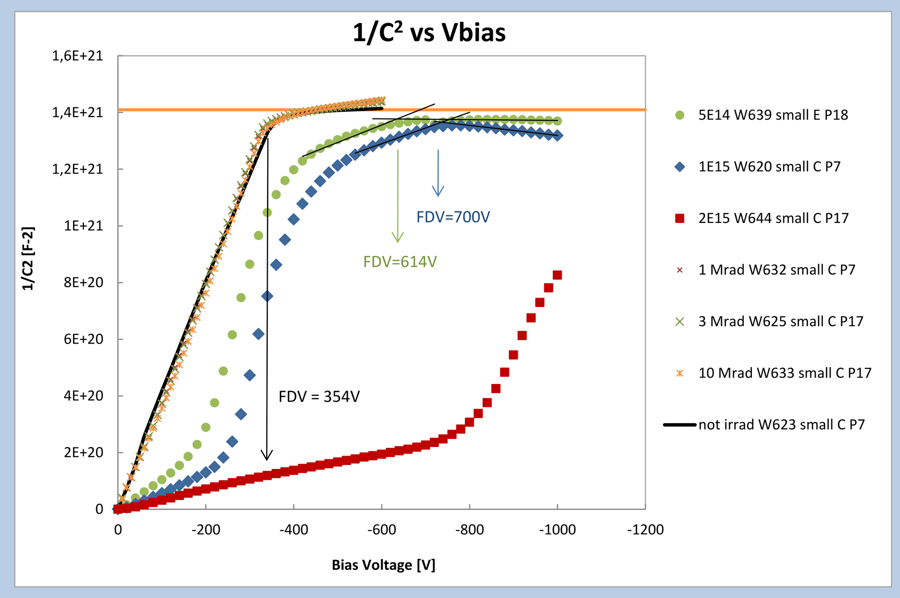
Leakage current



The leakage current vs. bias voltage for various sensors after proton and gamma irradiation compared with not irradiated sensor (black line).

- **I ≈ 3nA/cm^2 (not irradiated sensors) is well below technical spec's limit <2µA/cm^2.**
- **No breakdown observed up to 1000V sensor bias before and after irradiation with an exception of sensors irradiated by 1 MRad gamma dose.**
- **Microdischarge breakdown at 900V is well above the maximum operating voltage 600V and disappears after annealing and additional irradiation.**

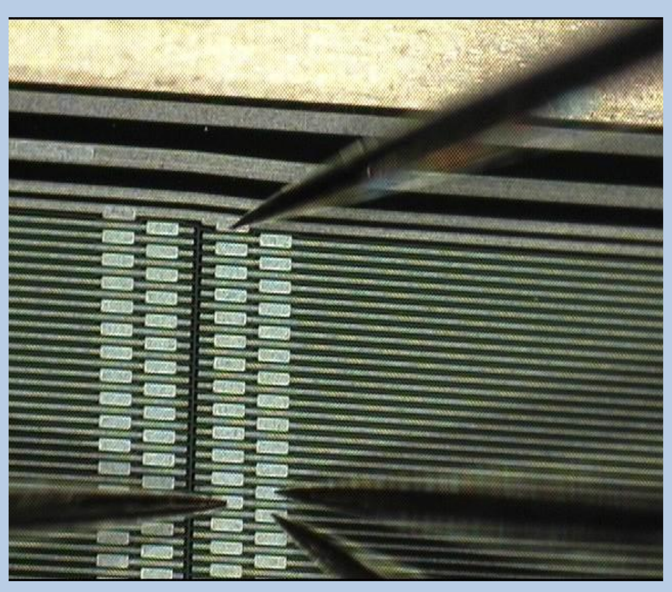
Full depletion voltage (FDV) Determination



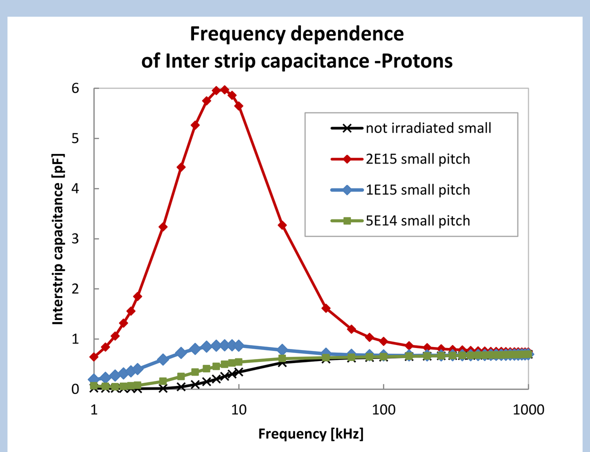
- **The FDV was extracted from CV characteristics as crossing of rising straight line of the 1/C^2(V) and the saturated value.**
- **FDV ≈ 350 V before irradiation.**
- **The FDV increases with increasing proton fluence. At the highest proton fluence 2E15 n_{eq}/cm^2 the FDV was not reached even at 1000V.**
- **The FDV is independent on gamma irradiation.**

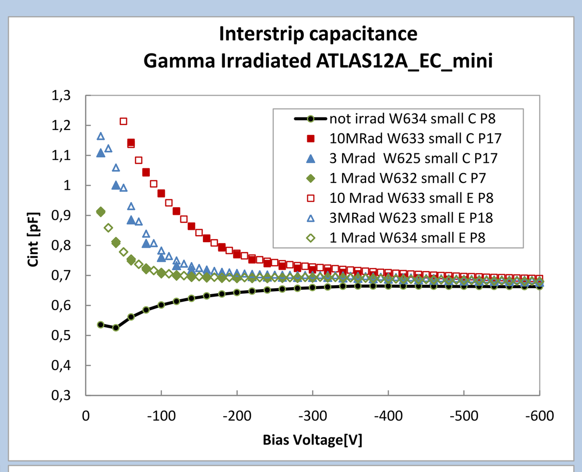
Inter-strip capacitance

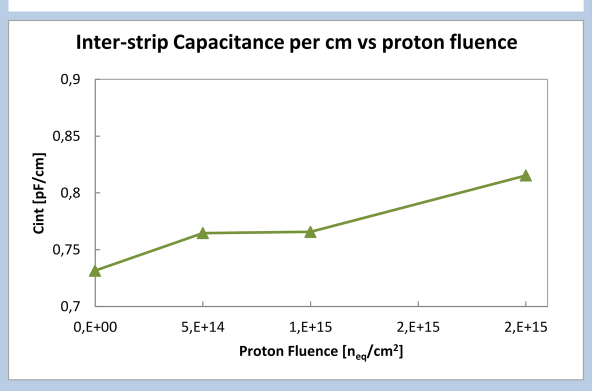
Inter-strip capacitance contributes to the input capacitance of FE electronics and determines the noise level of the detector. It should be as low as possible.

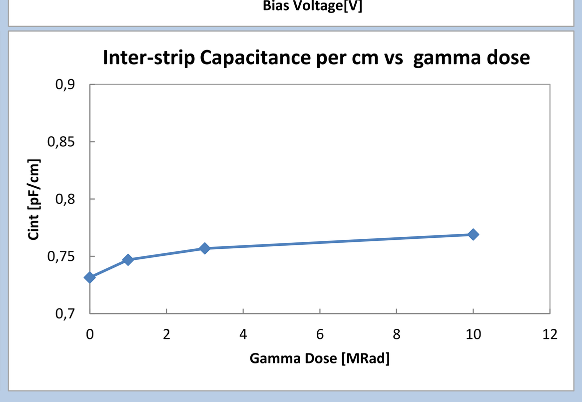


Inter-strip capacitance measuring method:
3 AC pads of metal strips are contacted with probes. The capacitance between the central strip and its neighbors is measured by LCR meter.







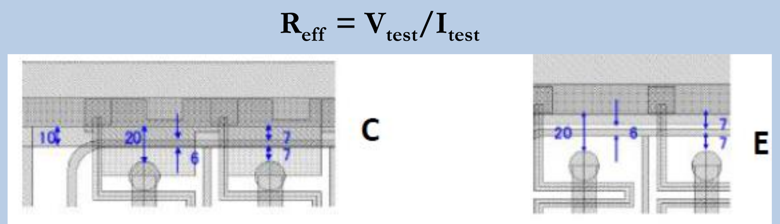


The inter-strip capacitance measurements are dependent on the frequency of the AC signal. 1MHz test frequency is more relevant than 100kHz indicated in specs. C_{int} is increased by 12% after proton irradiation and by 5% after gamma irradiation. At the highest proton fluence C_{int} slightly exceeds the specs value 0.8 pF/cm which is still acceptable with regard to low noise.

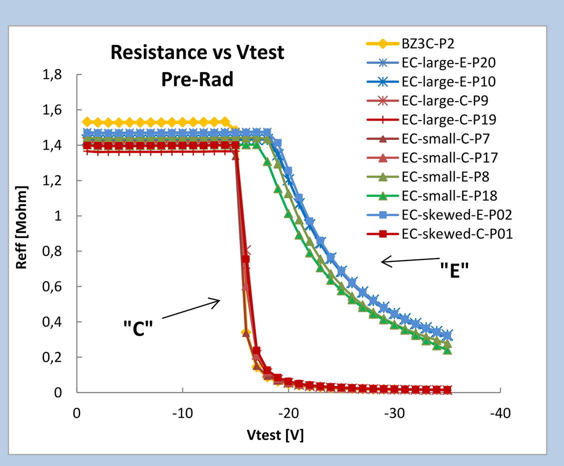
Punch-Through Protection

The effectiveness of punch-through protection structure is tested by DC method: The test voltage V_{test} is applied between the implant (DC pad) and the grounded bias rail. The effective resistance R_{eff} is calculated from the resulting current I_{test} and V_{test}:

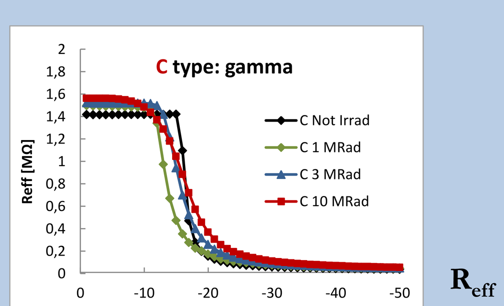
$$R_{eff} = V_{test}/I_{test}$$

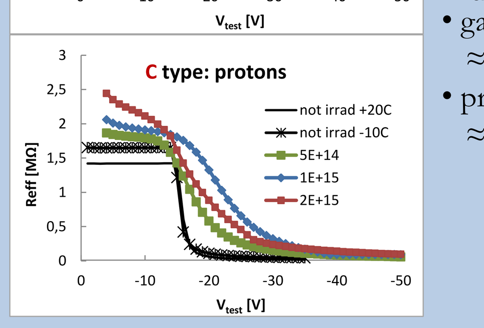


New PTP structure with gate effect (C-type) and standard structure with no gate (E-type) [4]



- Better performance of C-type than E-type
- Effective resistance at 35V: ~10kΩ for C ~300kΩ for E
- PT voltages <50V, below the hold-off voltages of the coupling capacitor (tested to 100V)





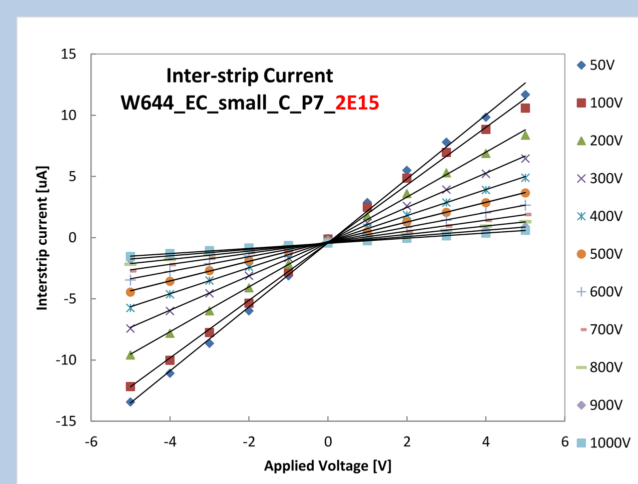
R_{eff} at 50V:
- gamma: ≈ 50 kΩ
- protons: ≈ 100 kΩ

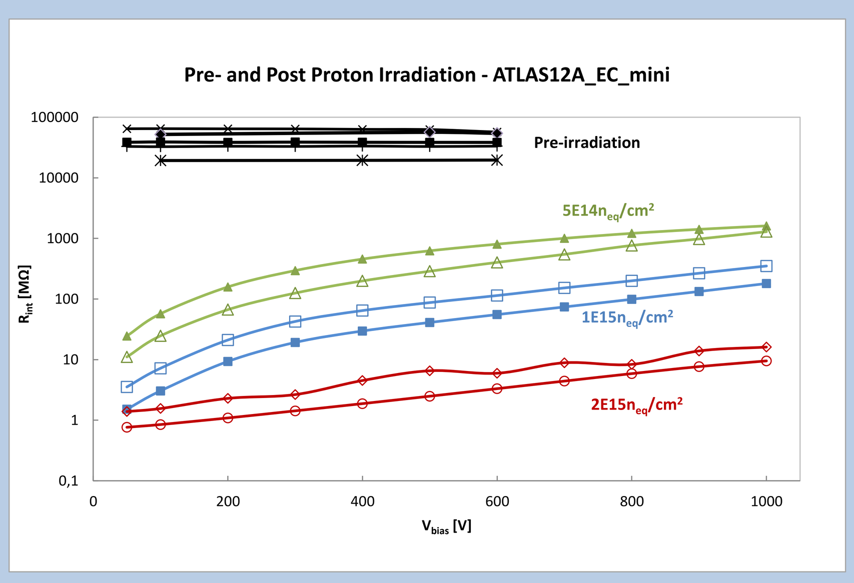
Inter-strip resistance

The isolation between neighboring strips is well demonstrated by the inter-strip resistance values (R_{int}).

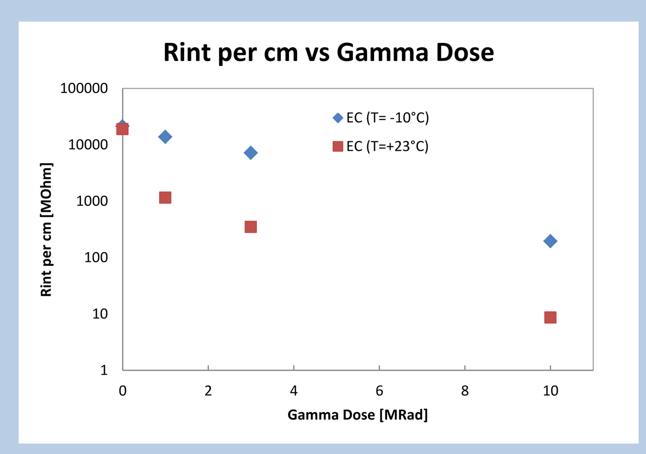
Inter-strip resistance measuring method:
3 adjacent DC pads are contacted with probes. On the outer strips is applied voltage V_{app} by SMU, the current I_{int} is measured on the central strip.

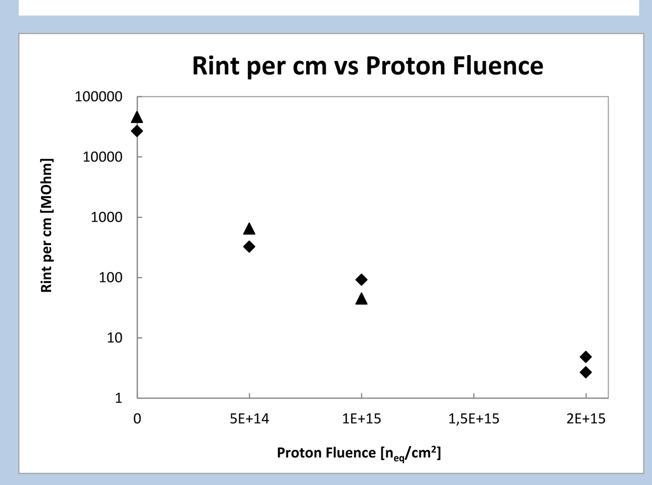
$$R_{int}=2/(dI_{int}/dV_{app})$$





The inter-strip resistance vs. bias voltage for proton irradiated sensors compared with not irradiated sensors





Inter-strip resistance after proton and gamma irradiation is
- **reduced,**
- **strongly dependent on temperature,**
- **strongly dependent on bias voltage.**

The values of R_{int} measured at =-10°C:
Pre-Irradiation: R_{int} ≈14-63GΩ/cm
Post- Gammas: R_{int} reduced to 200 MΩ/cm (at 10MRad)
Post-protons: R_{int} reduced to 2.4 MΩ/cm (for 2E15 n_{eq}/cm^2)

The inter-strip resistance is related to the bulk resistivity and thus with the bulk leakage current, that changes with fluence and temperature [5]. By scaling the values of R_{int} measured at -10°C to the operational temperature in ATLAS upgrade (~ -30°C) the R_{int} values are increased by factor of ~8.

Conclusions:

- Electrical characteristics of endcap mini sensors ATLAS12A before and after proton and gamma irradiation were evaluated in Prague.
- All tested sensors meet the specs for electrical properties [2], however after irradiation some parameters (R_{int}, C_{int}) are close to the limit.
- All sensors have a high microdischarge breakdown voltage > 1000V (not irradiated) and > 900V (irradiated) which is well above the operational voltage.
- The full depletion voltage doesn't change with gamma irradiation but rises with proton irradiation. At the highest tested fluence 2E15 n_{eq}/cm^2 the FDV >> 1000V. It is expected that sensors will operate in partial depletion in upgraded ATLAS at HL-LHC.
- The inter-strip capacitance is increased by 12% after proton and by 5% after gamma irradiation which is still acceptable.
- The inter-strip resistance degrades strongly with proton and gamma irradiation, however for the highest tested proton fluence 2E15 n_{eq}/cm^2 and gamma dose 10MRad its value is much larger than the typical amplifier's input impedance of 1kΩ and thus the strip isolation is sufficient.
- Radiation damage reduces the effectiveness of PTP structure, however the new PTP structure with gate (C-type) shows significantly better protection than standard E-type without gate. The gate PTP structure functions well even at the highest proton fluence.

Acknowledgement:

We acknowledge the support by the European Commission within the Framework Programme 7 Capacities, Grant Agreement 262025 and by the Ministry of Education, Youth and Sports of the Czech Republic under the project Nr. 7E12050 .
We express our thank to the team from Karlsruhe, Birmingham and BNL irradiation facility.
We appreciate the discussions with Yoshinobu Unno and Hartmut Sadrozinski .

References:

[1] Y. Unno, et al., NIM A, Vol. 636 (2011) S24-S30
[2] ATLAS Upgrade Sensor Collaboration, Technical specification: Supply of Silicon Microstrip Sensors of ATLAS 12 specification, 23th July 2014
[3] J. Bohm, et al., NIM A, Vol. 636 (2011) S104-S110
[4] Y. Unno, et al., NIMA (2014) article in press, http://dx.doi.org/10.1016/j.nima.2014.06.086i
[5] Y. Unno et al., Nucl. Instr. Meth.A 731 (2013) 183–188