Surface Properties of Proton and Gamma Irradiated HPK ATLAS12A Mini Sensors

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ATLAS Upgrade Strip Sensor Collaboration

**University of Birmingham, BNL, Cambridge University, DESY,
University of Freiburg, University of Geneva, Glasgow university, KEK,
Kyoto University of Education, Lancaster University, University of Liverpool,
JSI and University of Ljubljana, University of New Mexico, NIKHEF,
Osaka University, Charles University in Prague, Academy of Sciences of Czech R.,
Queen Mary University of London, UC Santa Cruz, University of Sheffield,
Tokyo IT, University of Tsukuba, IFIC Valencia, CNM and HPK**

ATLAS12 sensor evaluation program

ATLAS12 sensors manufactured and delivered in 2013-2014
currently underway extensive evaluation program of ATLAS12:

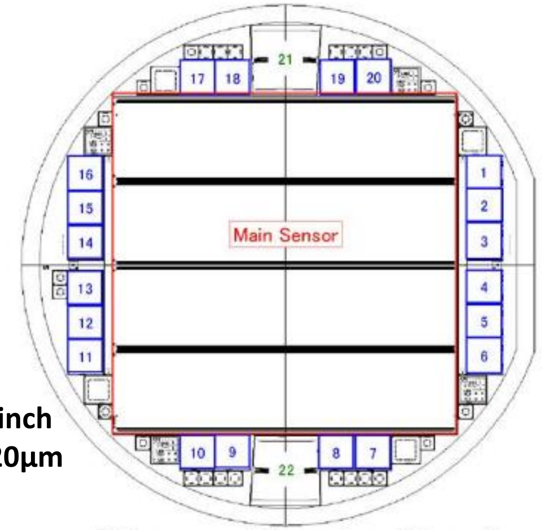
- Large Sensors (Cambridge)
  - sensor shape
  - IV, CV
  - Full strip tests
- Charge collection (Ljubljana, Liverpool, KEK/Tsukuba, Freiburg, Valencia, DESY, Glasgow)
  - Bulk radiation hardness – presented by Sven on Wednesday
- Surface studies (Prague, UCSC, Freiburg, Glasgow, Lancaster, Tsukuba)
  - PTP, Cinter, Rinter
- Laser scans (Valencia, Freiburg)
  - Strip integrity scans
  - Strip ganging performance
- Lorentz Angle studies (DESY)

- *n*-strip in *p*-type material (FZ)
- 6-inch wafer, 320µm thickness

Irradiations of mini sensors:

- CYRIC protons 70 MeV
- Birmingham protons 27 MeV
- Los Alamos protons 800 MeV
- Karlsruhe protons 23MeV
- PSI pions 300 MeV
- Ljubljana neutrons (reactor)
- BNL gamma (^{60}Co)

ATLAS12A Wafer Layout



1	BZ1 (PTP 10um)
2	BZ3C
3	BZ3F
4	BZ3C
5	BZ3F
6	BZ3C-unpassivation
7	EC-small pitch-C (AC gang)
8	EC-small pitch-E (AC gang)
9	EC-large pitch-C (AC gang)
10	EC-large pitch-E (AC gang)
11	BZ1 (PTP 10um)
12	BZ3C
13	BZ3F
14	BZ3C
15	BZ3C
16	BZ3C-unpassivation
17	EC-small pitch-C (DC gang)
18	EC-small pitch-E (DC gang)
19	EC-large pitch-C (DC gang)
20	EC-large pitch-E (DC gang)
21	EC-skewed-C
22	EC-skewed-E

- Main sensor at the center of the wafer
- 1-24 Baby sensors in the peripheral of the main sensor

2013/5/13, Y. Unno 3

Tested End-Cap sensors

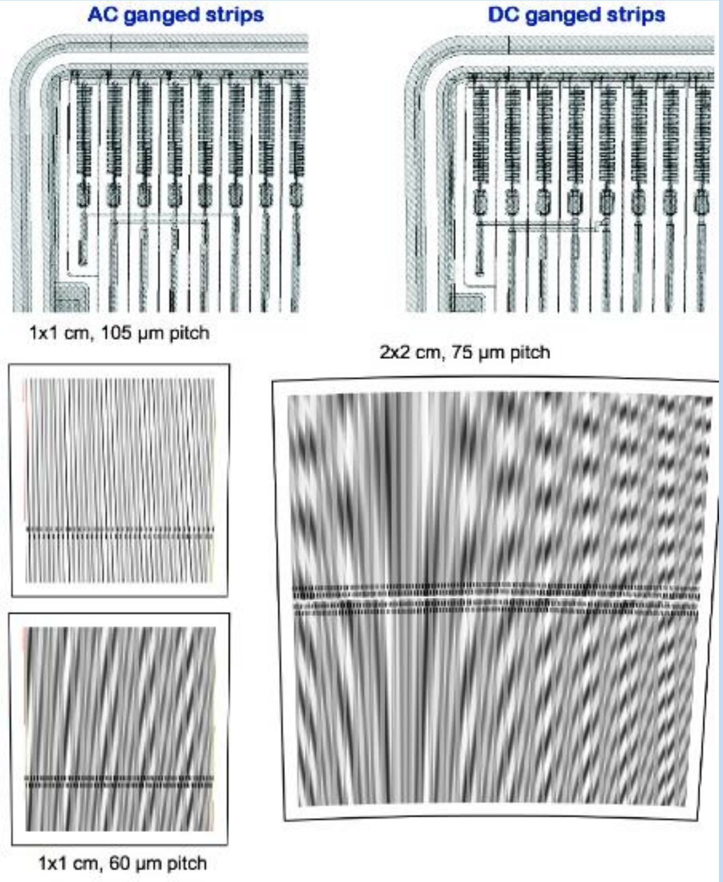
ATLAS12A End-cap miniature sensors
***n*-strip in *p*-type material (FZ)**
•produced by Hamamatsu Photonics (HPK)

10 different types of EC mini sensors:

EC-small pitch-C (AC gang) #P7
EC-small pitch-E (AC gang) #P8
EC-large pitch-C (AC gang) #P9
EC-large pitch-E (AC gang) #P10
EC-small pitch-C (DC gang) #P17
EC-small pitch-E (DC gang) #P18
EC-large pitch-C (DC gang) #P19
EC-large pitch-E (DC gang) #P20
EC-skewed-C #P01
EC-skewed-E #P02

barrel mini sensors for comparision:

BZ3C



Electrical tests in Prague
Proton and gamma irradiated
ATLAS12A EC mini sensors

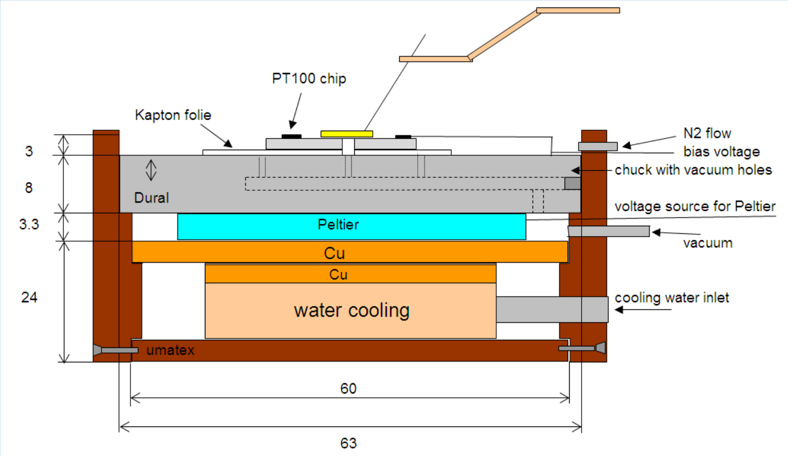
Proton irradiation (5E14, 1E15, 2E15 n_{eq}/cm^2)**:**

- Birmingham
- Karlsruhe

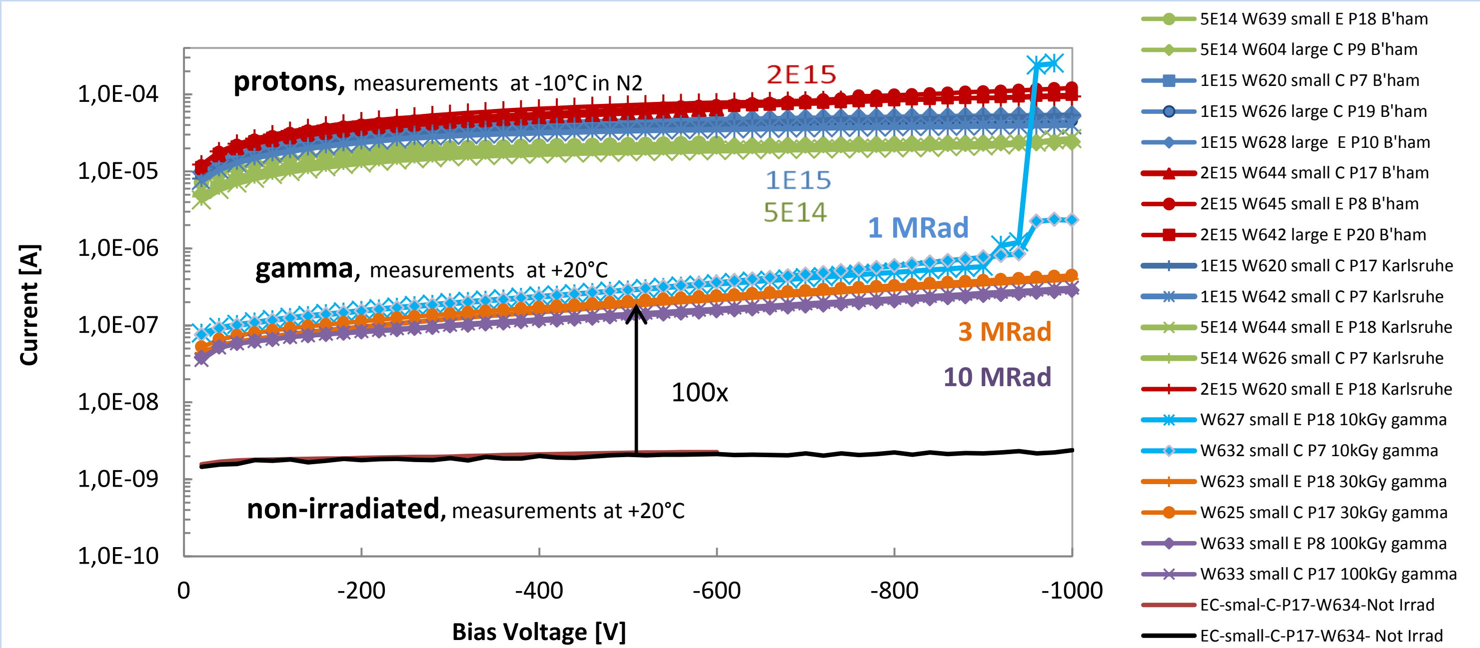
Gamma irradiatiaon (doses 1, 3, 10MRad)**:**
- BNL

Electrical tests:
- IV (current, Break down voltage))
- CV (Full Depletion Voltage)
- Cint
- Rint
- PTP (beamloss potection)

Measurement conditions:
- at Room Temperature and at -10°C
- at laboratory environment (humidity ~30%) and with Nitrogen flow (humidity < 10%)



Total Leakage Current: Pre- and post proton and gamma irradiation



Non-irradiated:

- **I = 4.8 ± 1.5 nA/cm²** (average value of 28 EC minies measured in Freiburg, Prague and Valencia)
- **Breakdown voltage > 600/1000V**

Proton-irradiated:

- **I = 114 *μA/cm²* for 2E15 n_{eq}/cm² (-10C)**
- **Breakdown voltage > 1000V**

Gamma-irradiated:

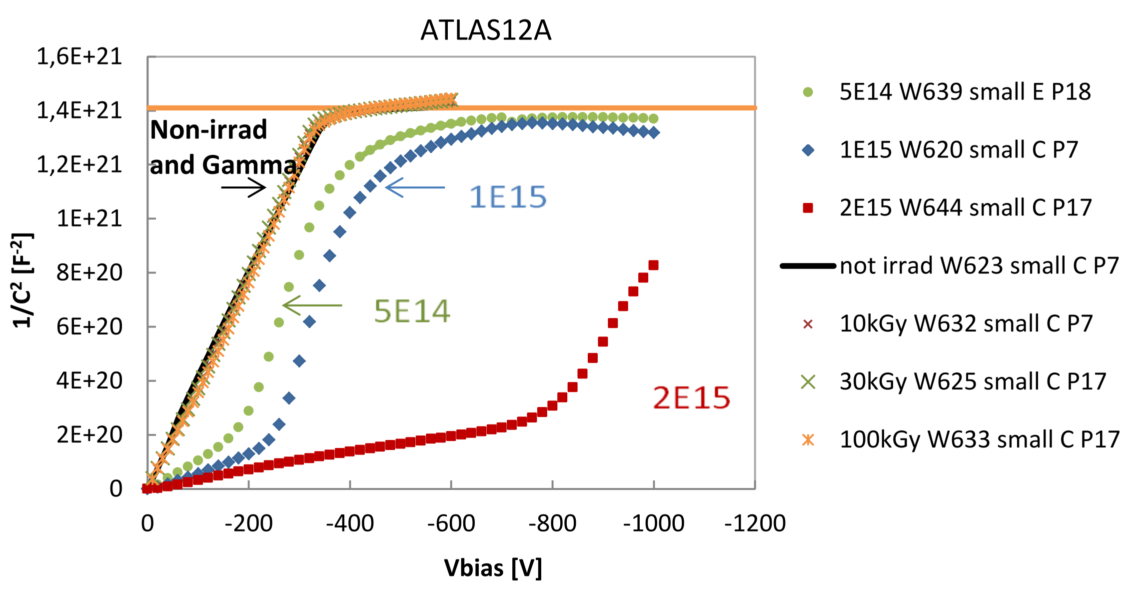
- **100 x current increase**
- **Micro-discharge breakdown at V_{Bias} ~ 900V of 1 MRad gamma sensors disappears after additional irradiation or after annealing.**

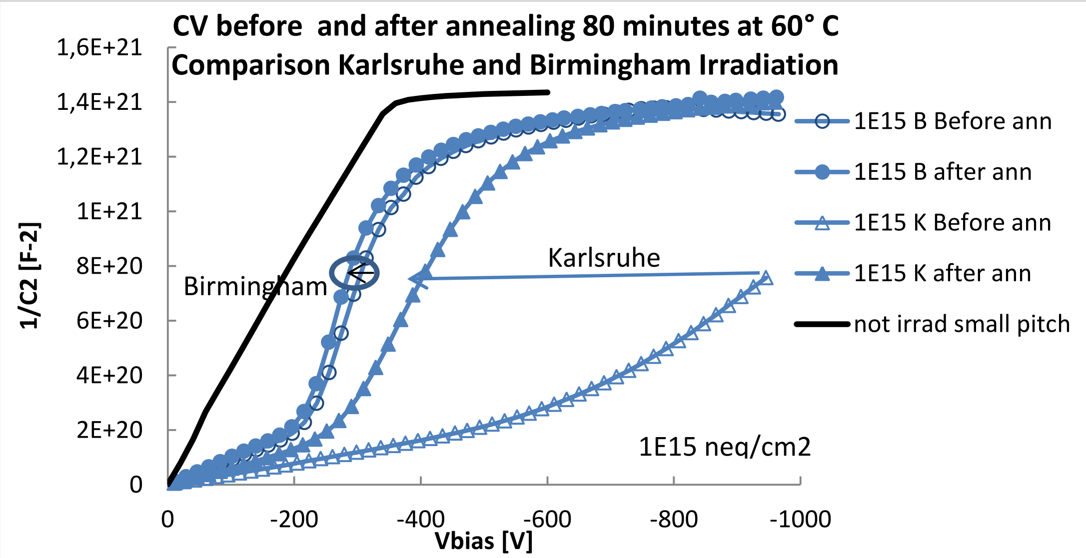
The same instability at low radiation gamma dose reported by K.Hara [*Nucl. Instr. and Meth. A699* (2013) 107.] and explained by the large charge collected in the AC pad corners; after accumulating higher dose, charges trapped in oxide layers act to reduce the el. field, enhancing the stability of the sensors.

- **The higher the gamma dose the lower the current - subject of further studies**

All sensors before and after irradiation have a high micro-discharge breakdown well above the maximum operational voltage. It shows that different geometries of end-cap sensors do not influence theirs stability.

Full depletion voltage (FDV)





FDV extracted from CV characteristics as crossing of the rising straight line of $1/C^2$ and the saturated value,

Non-irradiated:

- **FDV = 354±20 V** (average value of 28 EC minies measured in Freiburg, Prague and Valencia)
- Resistivity: $\rho = 2.8 \pm 0.15$ kΩ*cm, calculated from: $\rho = d^2/(2\varepsilon^*\mu^*V_F)$, where d = 302µm is active thickness

Gammas:

- The FDV and thus effective doping concentration (Neff) are independent on gamma irradiation.

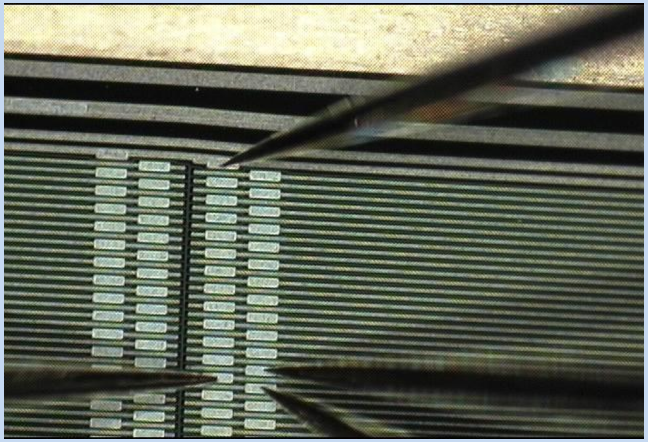
Protons:

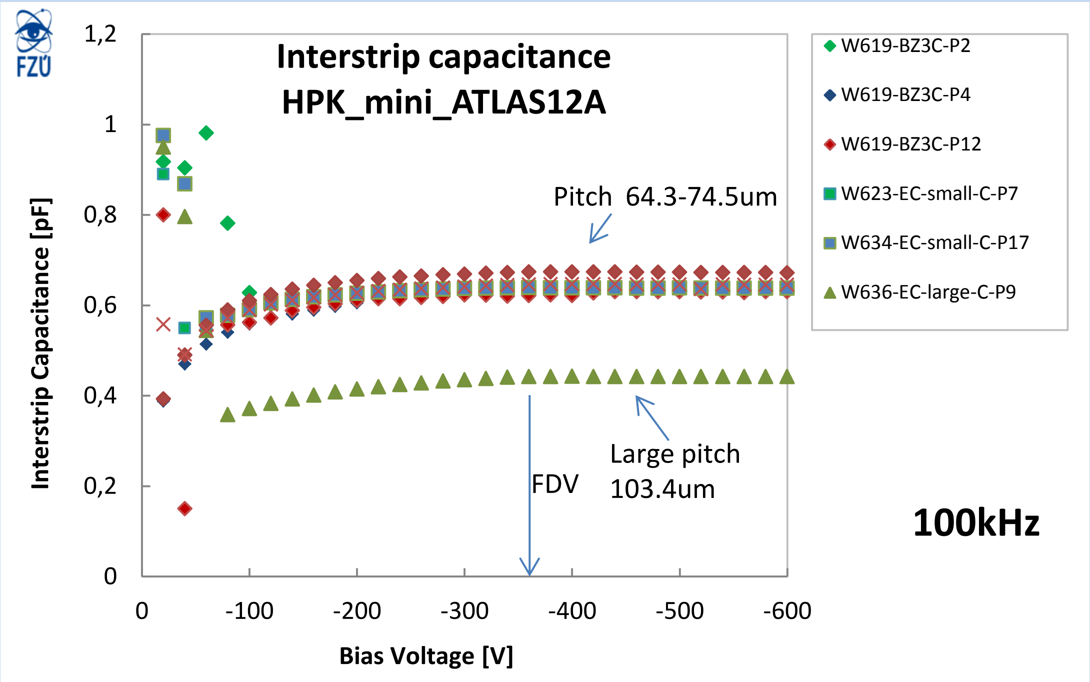
- The FDV increases with increasing proton fluence.
- FDV ≈ 560-800 V for 5E14 n_{eq}/cm^2
- FDV ≈ 700-880 V for 1E15 n_{eq}/cm^2
- FDV >> 1000V for 2E15 n_{eq}/cm^2 which is expected for 302 µm silicon
- Birmingham facility has issues with sensor annealing at high temperature, we'll re-confirm the conclusions with further irradiations

Inter-Strip Capacitance - non irradiated

3 probe method:

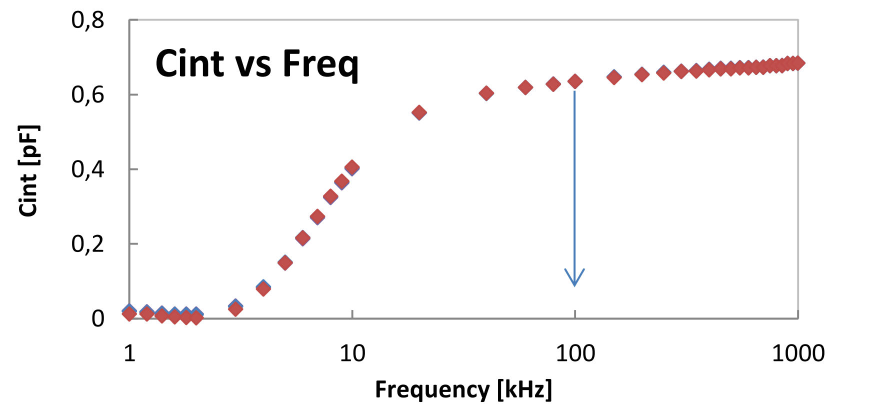
The capacitance between the central strip and its neighbors is measured by LCR meter (CPRP)



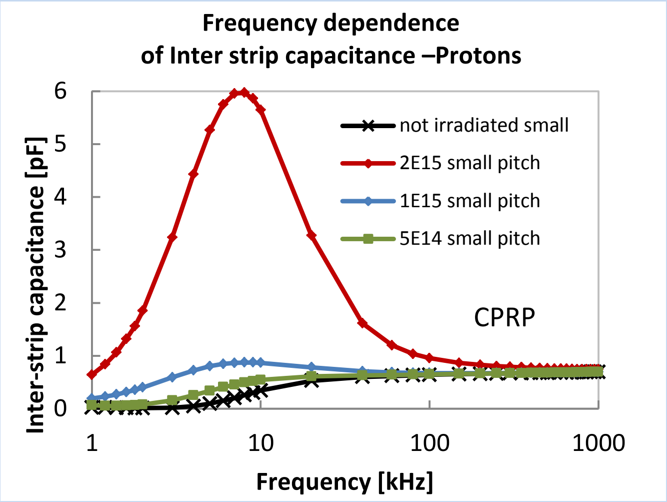


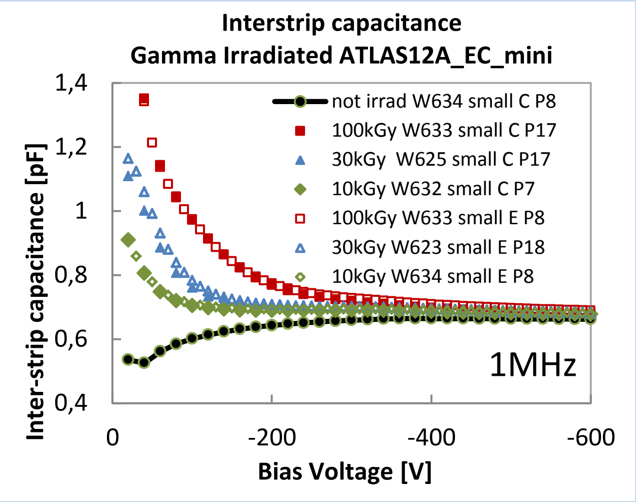
	Average pitch [µm]	C_{int}/cm [pF]
Barrel mini	74.5	0.78
EC Small pitch	64.3	0.79±0.003
EC Large pitch	103.4	0.55±0.007
EC Skewed	69.4 S2 66.1 S1	0.74±0.003 0.76±0.004

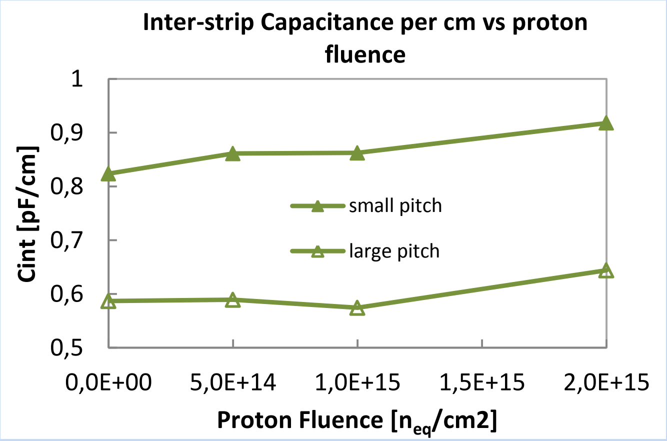
average value measured in Freiburg, Prague

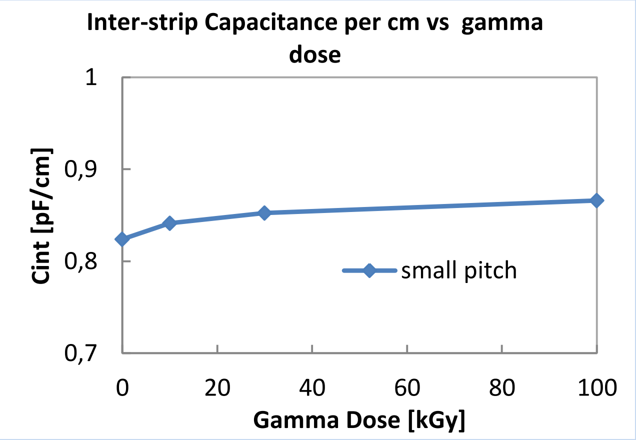


Inter-Strip Capacitance - irradiated



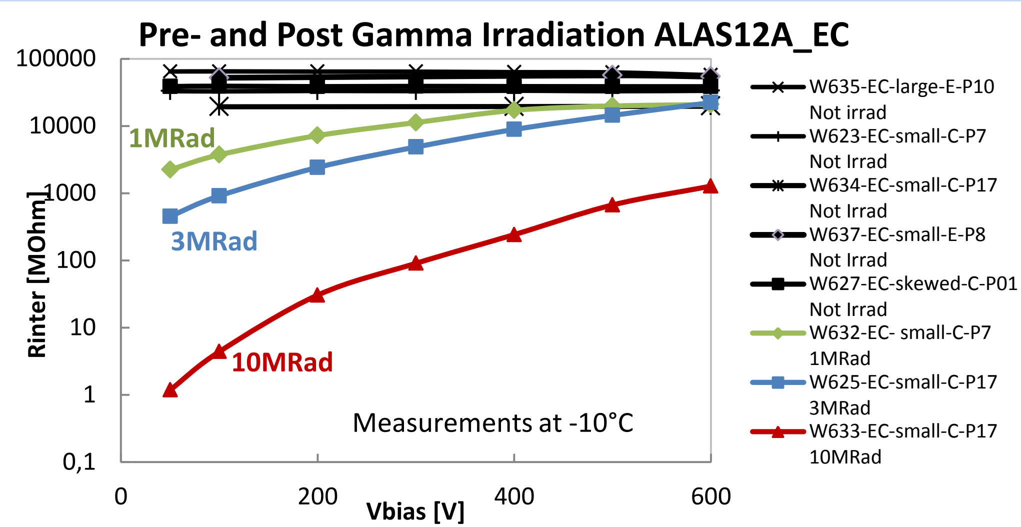


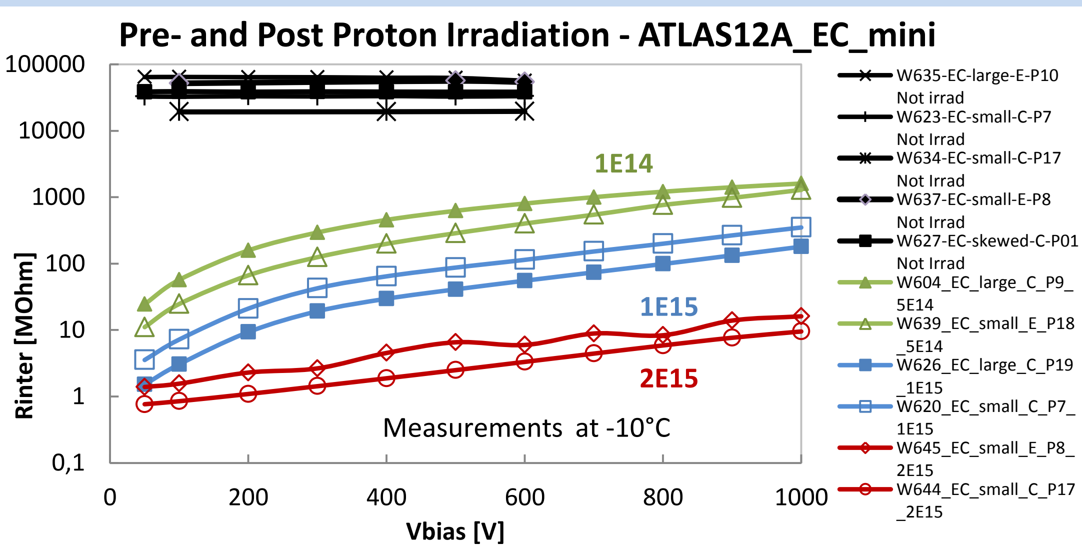




- The frequency dependence of Interstrip Capacitance is stronger for heavy irradiated samples.
- For irradiated sensors the 1 MHz test frequency is more appropriate.
- The higher the radiation dose then the higher bias voltage needed for C_{int} to saturate.
- Beyond FDV the C_{int} becomes constant for both types of irradiation and for all tested doses.
- **Cint is increased by 11% after proton irradiation and by 5% after gamma irradiation**

Inter-Strip Resistance – Pre- and Post Proton and Gamma Irradiated



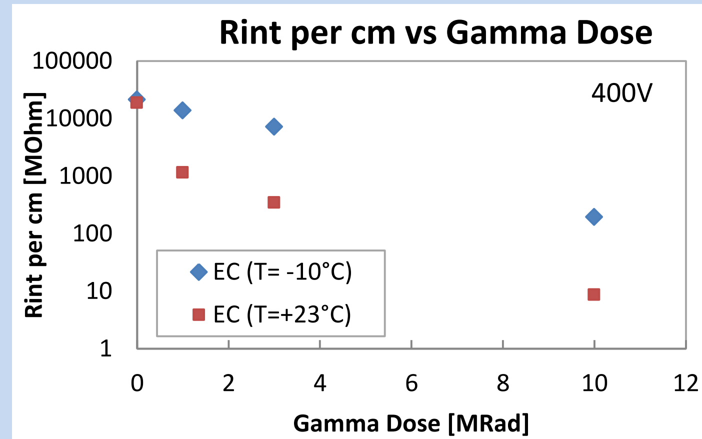


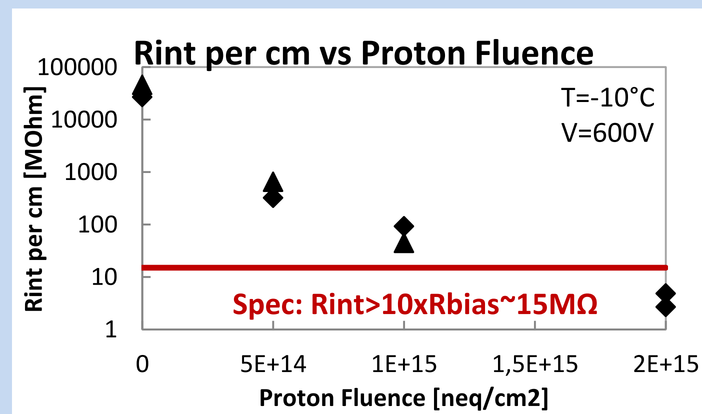
The values of R_{int} measured at =-10°C:

- 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)

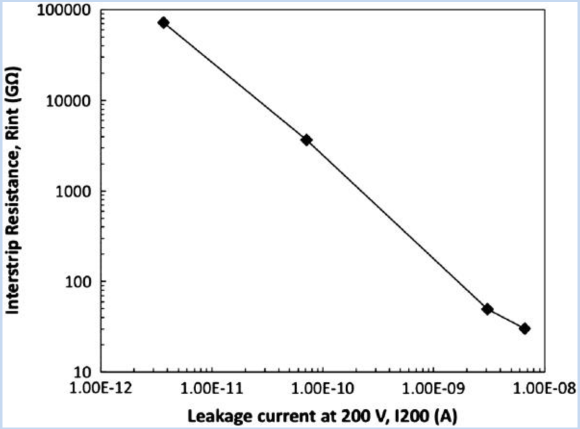
Rint after proton and gamma irradiation:

- **reduced**
- **strongly dependent on bias voltage**
- **strongly dependent on temperature**





Inter-Strip Resistance – Gamma and Proton Irradiated

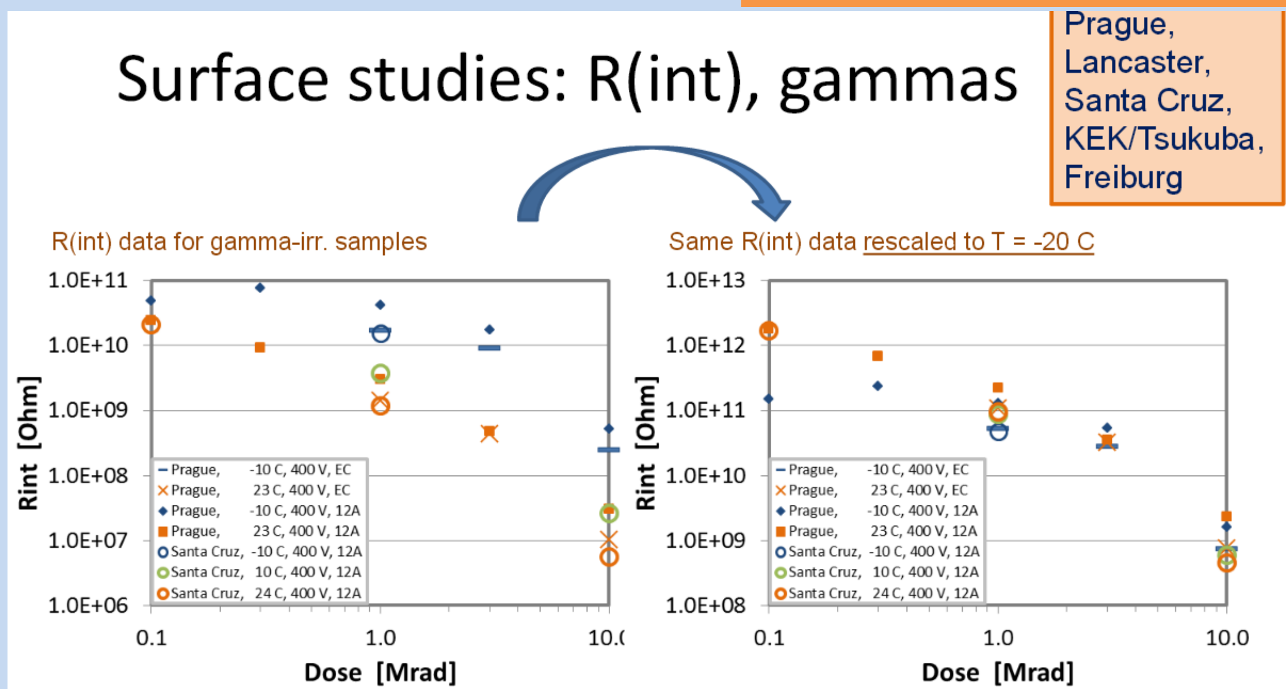


TCAD simulated interstrip resistance as a function of leakage current.

Y. Unno et al., *Nucl. Instr. and Meth. A731* (2013) 183
The inter-strip resistance is related to the bulk resistivity and thus with the bulk leakage current, that changes with fluence and temperature.

One can rescale the values of R_{int} measured at different temperature using the leakage current scaling.

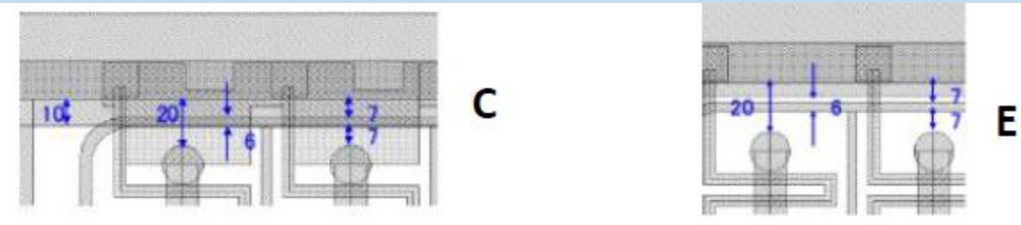
Compilation by: V. Fadeyev



- **by temperature correction the scatter is reduced**
- **by scaling the measured values of R_{int} to the operational temperature in ATLAS upgrade (~ -30°C) the R_{int} values are high enough at high doses and fluences and the strip isolation is sufficient**

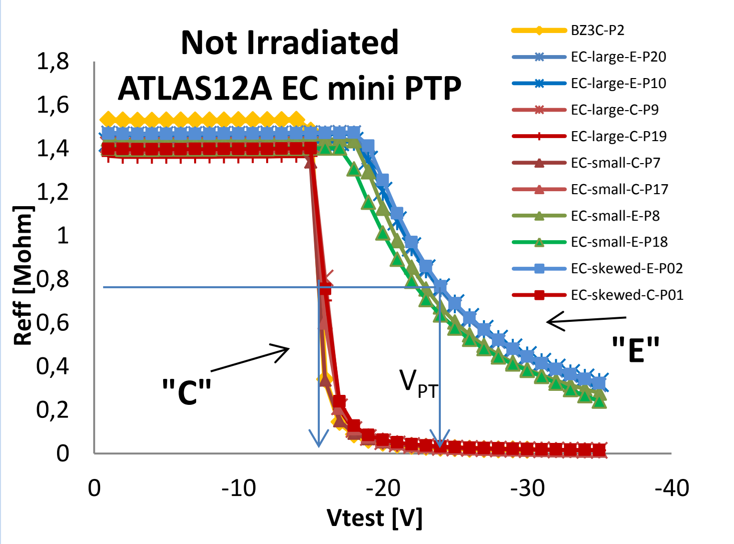
PTP measurements with DC method: non- irradiated

ATLAS12A EC mini sensors have implemented 2 types of PTP structures:
- gated PTP structure (type C)
- standard with 20µm gap (type E)



PTP structure with Gate effect (implemented in main ATLAS12A sensor)

Standard PTP - no gate



Not irradiated:

The effectiveness of PTP structure was measured using DC method: the test voltage V_{test} was applied between the implant (DC pad) and the grounded bias rail. The effective resistance Reff was calculated from the resulting current Itest and Vtest: **Reff = Vtest/Itest**

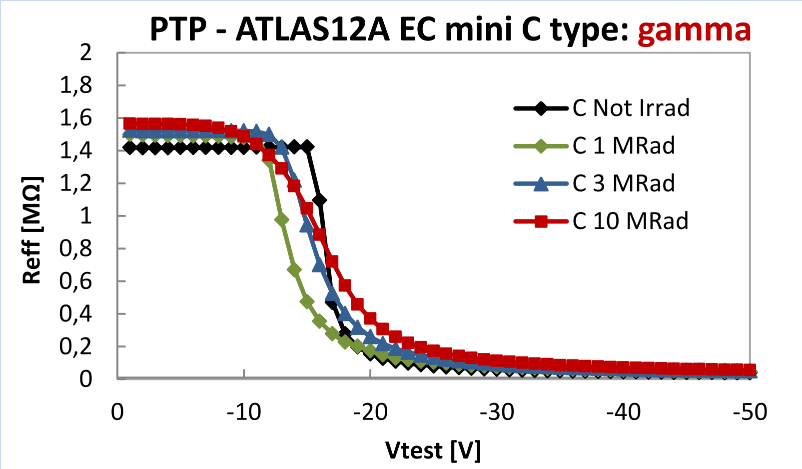
- **Better performance of "C" type than "E" type**
- **"C" type - lower onset voltage**
  - **very steep drop in Reff**
  - **lower saturation resistance:**
    effective resistance @35V: ~10kΩ for C
    ~300kΩ for E

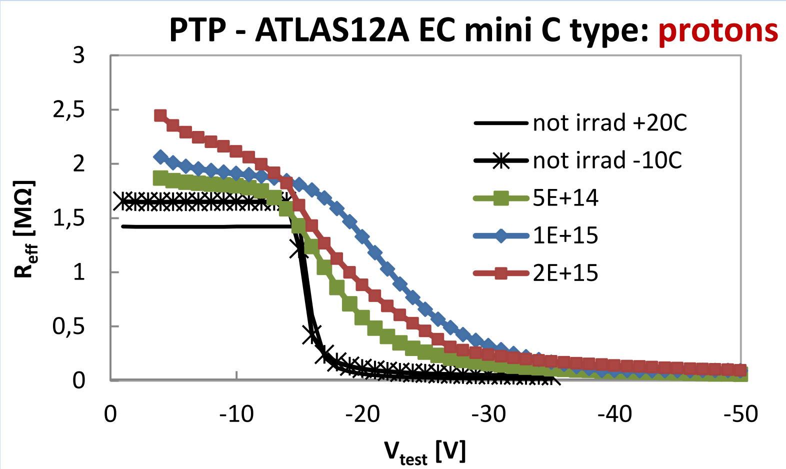
V_{bias} = 400V

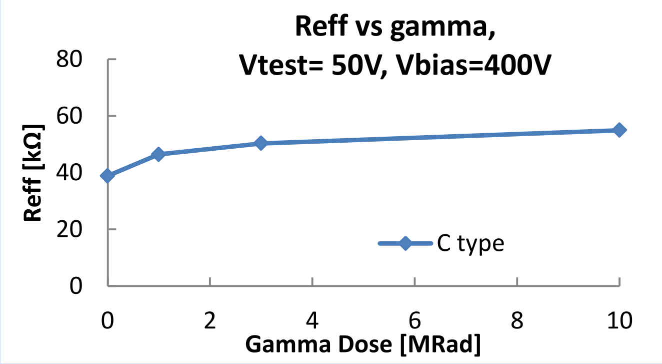
- **V_{PT} = 15.9 +/- 0.2 V for "C" structure**
- **V_{PT} = 24.0 +/- 0.7 V for "E" structure**

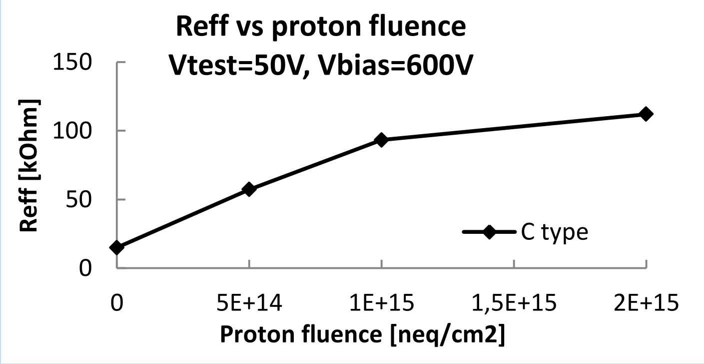
PTP measurements: Gamma and Proton Irradiated

- Gamma and proton irradiated sensors have lower inter-strip resistance. Inter-strip currents as well as current from the bulk influence the PTP measurements.
- To exclude inter-strip effects the voltage V_{test} was applied also on two neighbors at the same time, IV was performed on the central strip only (**3-probe** method).









- **Stronger influence of protons than gammas on the effectiveness of PTP structure**
- **The gate PTP structure functions well even at the highest tested proton fluence**

	R_{eff} at 50V	V_{PT}
Gamma (10MRad)	≈ 50 kΩ	14-17 V
Protons (2E15)	≈ 100 kΩ	18-24 V

Summary gamma and proton irradiated EC minies ATLAS 12A

All tested sensors show appropriate performance for operation in ATLAS Upgrade ITK

- **Total current**

  - all sensors have high micro-discharge breakdown before and after proton and gamma irradiation (> 900V) which is well above the maximum operational voltage.

  - it shows that different geometries of EC sensors do not influence theirs stability

- **Interstrip capacitance**

  - increased by 5% after gamma and 11% after proton irradiation which is still acceptable with regard to the low noise of these sensors

- **Interstrip resistance**

  - degrades strongly with proton and gamma irradiations; is temperature dependent

  - However for the highest tested proton fluence, $2x10^{15}$ n_{eq}/cm^2, and gamma dose, 10Mrad, at operating temperature ≈ -30°C the strip isolation is sufficient.

  -the Rint of ATLAS07 sensors were tested in detail to $1.5\ x10^{13}$ n_{eq}/cm^2 and to 300V only => it would be useful to irradiate them along with ATLAS12 in the same irradiation campaign and measure at high voltage for comparison ATLAS07/ATLAS12

- **PTP**

  - the gated PTP structure shows significantly better protection than the standard type without gate and is efficient after gamma and proton irradiation

- Birmingham facility had issue with sensor annealing at high temperature, we'll re-confirm the conclusions with further irradiations

Backup

Results – proton and gamma irradiatd EC minies

	Tech.Spec.	Measurement		
		not irradiated	Protons $2E15 n_{eq}/cm^2$	Gamma 10MRad
Leakage Current at RT non-irrad at -25C after irr.	< 2 µA/cm² at 600 V < 2mA/cm²	0.004 µA/cm²	114 µA/cm² *)	0.23 µA/cm² *)
Full Depletion Voltage	< 300 V (for 4kΩcm) no criteria after irrad.	354 ± 20 V	> 1000V	341 ± 24
Coupling Capacitance at 1kHz	≥ 20 pF/cm	24 - 28	24	-
Poly Silicon Bias Resistance	1.5±0.5MΩ	1.45 ± 0.04	1.9	1.7
Punch-Through Voltage (C type)	No criteria	15.4 ± 1.2 V	23 V	17 V
PTP – Effective resistance at 50V (C type)	No criteria	10 kΩ	100kΩ	50 kΩ
Interstrip Capacitance to neighbour pair	< 0.8 pF/cm at 100kHz	0.75 Small Pitch 0.74 Large P. **)	0.81 0.80 **)	0.77 - **)
Interstrip Resistance	> 10x Rbias ~ 15 MΩ	14-63 GΩ	2-4 MΩ/cm *)	200 MΩ/cm *)

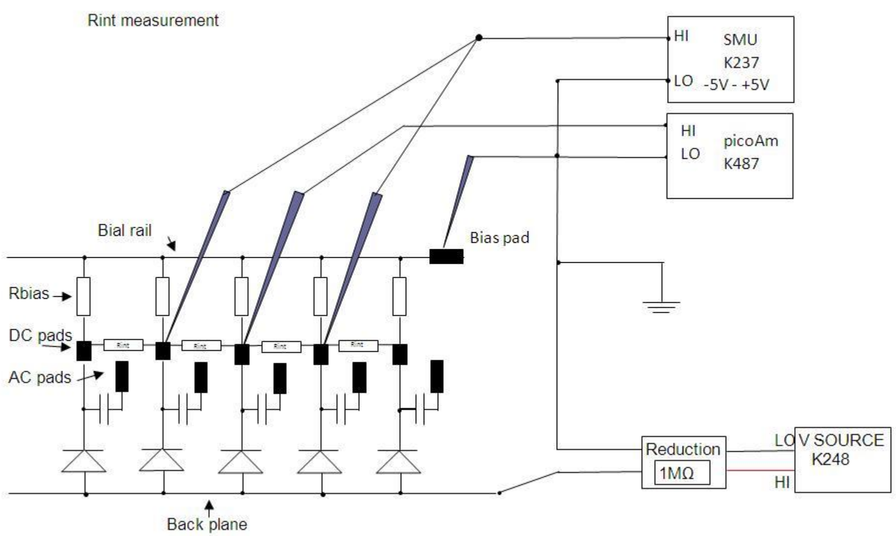
*) measured at -10C, **) measured at 1MHz, normalized to pitch of barrel sensor

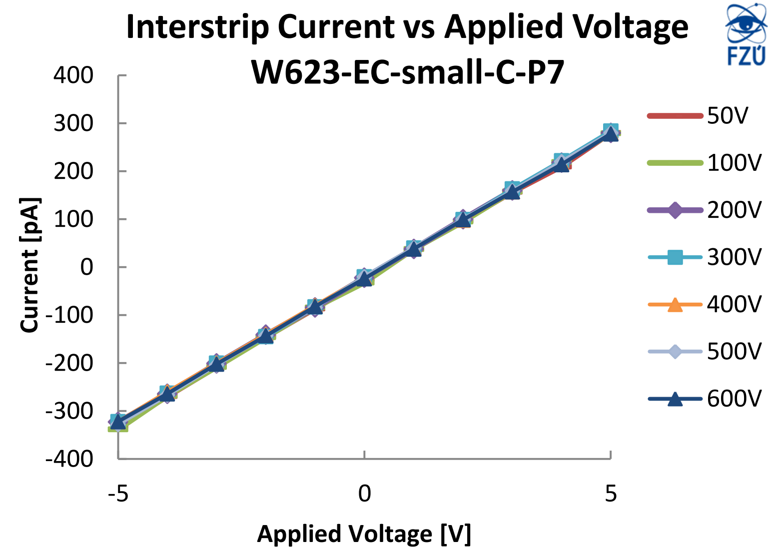
Inter-Strip Resistance

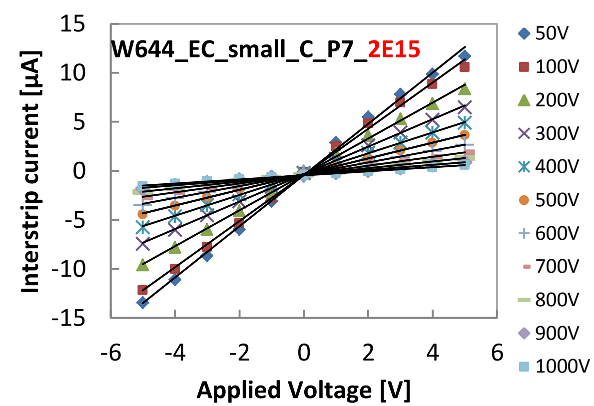
Measuring method:

- Interstrip resistance measured by induced current method.
- 3 adjacent DC pads are contacted with 3 needles. On the outer strips is applied voltage V_{appl} by SMU, the current is measured on the central DC strip.

$$R_{int} = 2/(dI/dV_{appl})$$





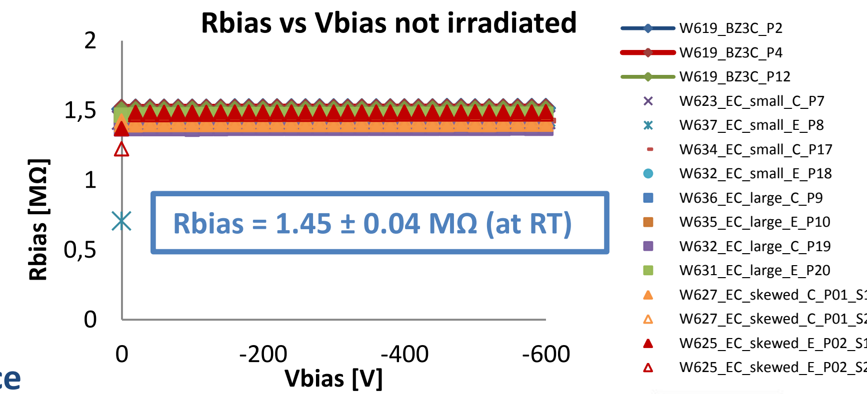


- Nitrogen gas was flowing over the sensor for moisture control

Polysilicon Bias Resistance: Measuring Methods

1 probe method

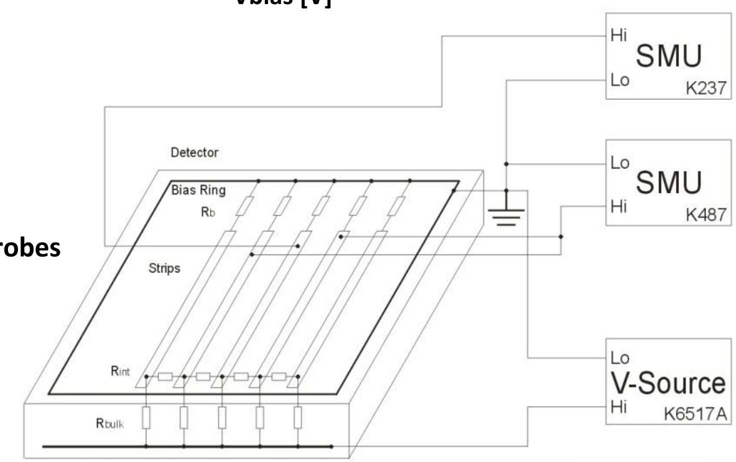
- used for measurement of **not irradiated sensors with high R_{int}**
- The test voltage V_{test} was applied between the implant and the grounded bias rail. IV was performed in range -1V-+1V to determine bias resistance



3 probe method

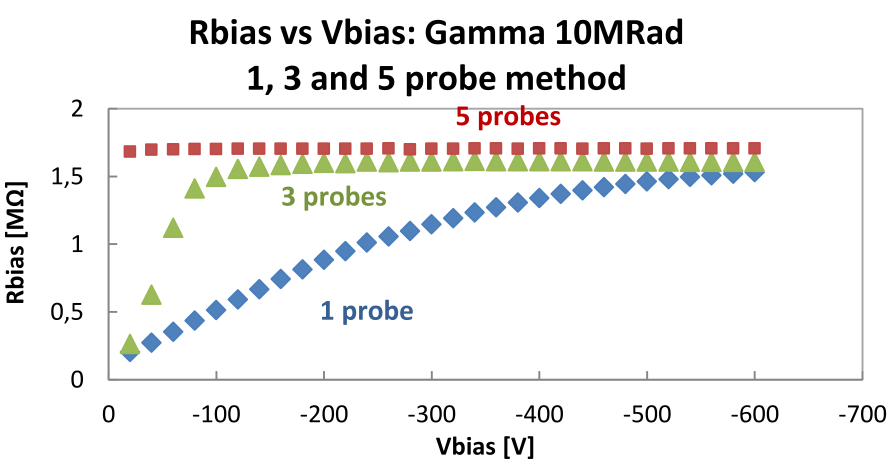
- gamma irradiated sensors have much **lower inter-strip resistance** and inter-strip currents and some extra current from the bulk influence the bias resistance measurements.
- To exclude inter-strip effects the voltage V_{test} was applied also on two neighbors at the same time, IV was performed on the central strip.

3 probes

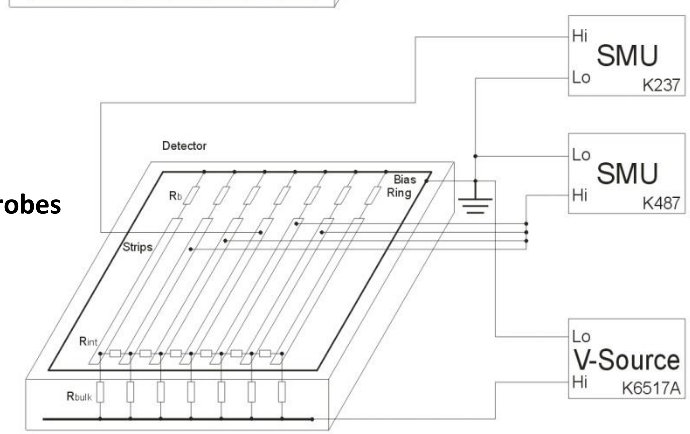


5 probe method

- best elimination of interstrip-effect in irradiated sensors
- V_{test} was applied also on neigbors and on next neighbors

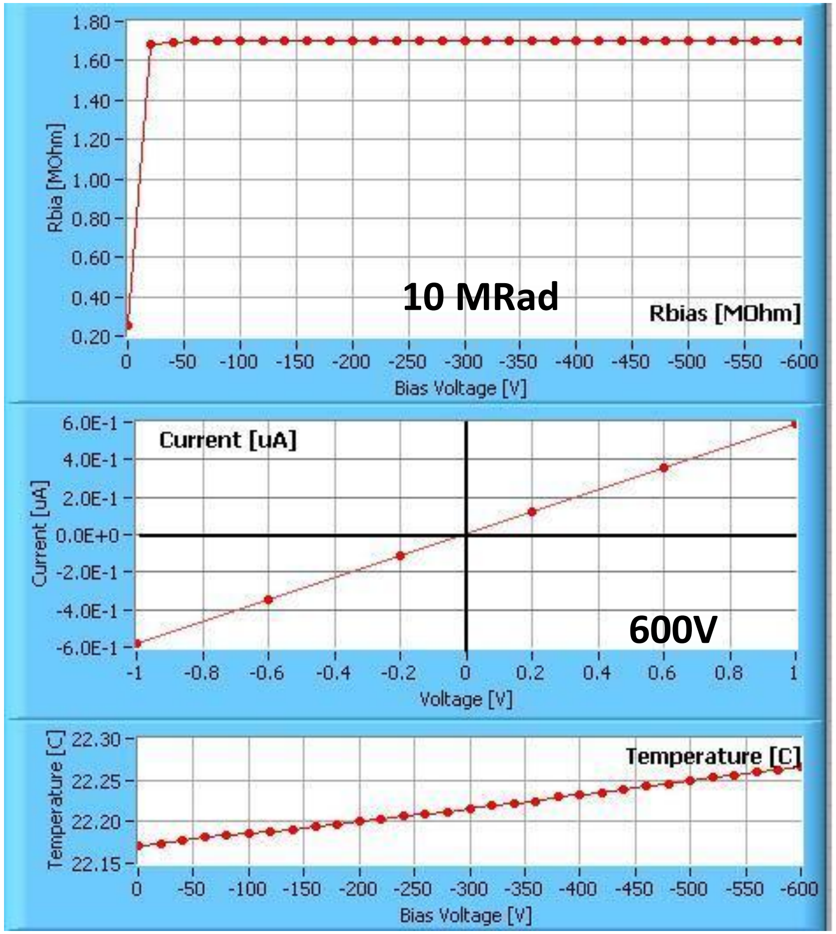


5 probes



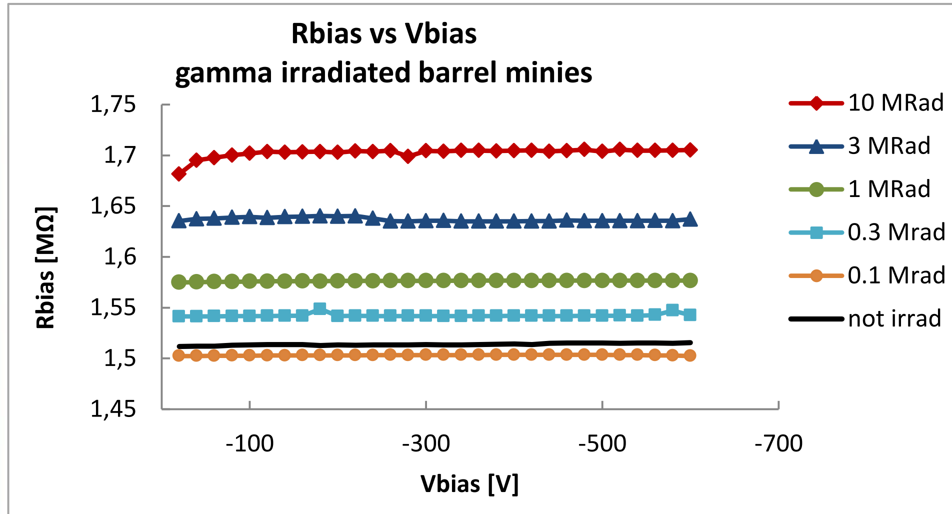
Polysilicon Bias Resistance: Pre- and post gamma irradiation

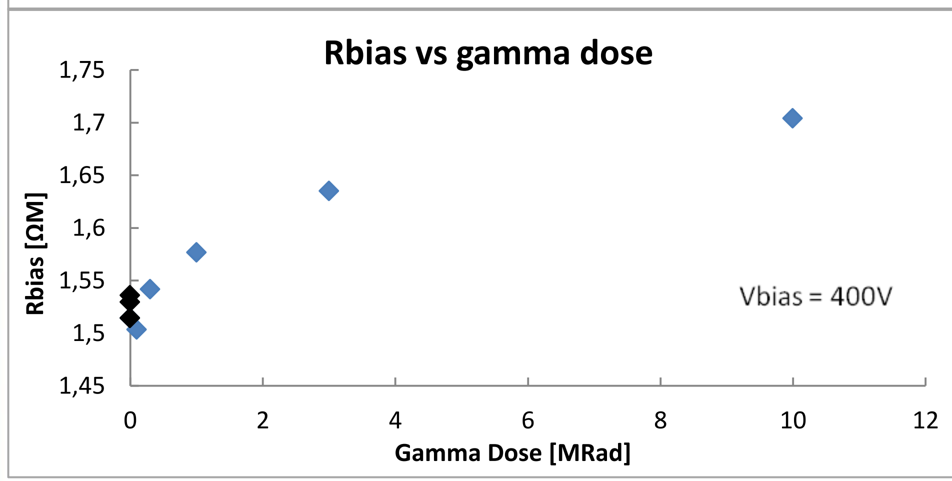
5 probe method:



- Linear behavior of the current vs applied voltage

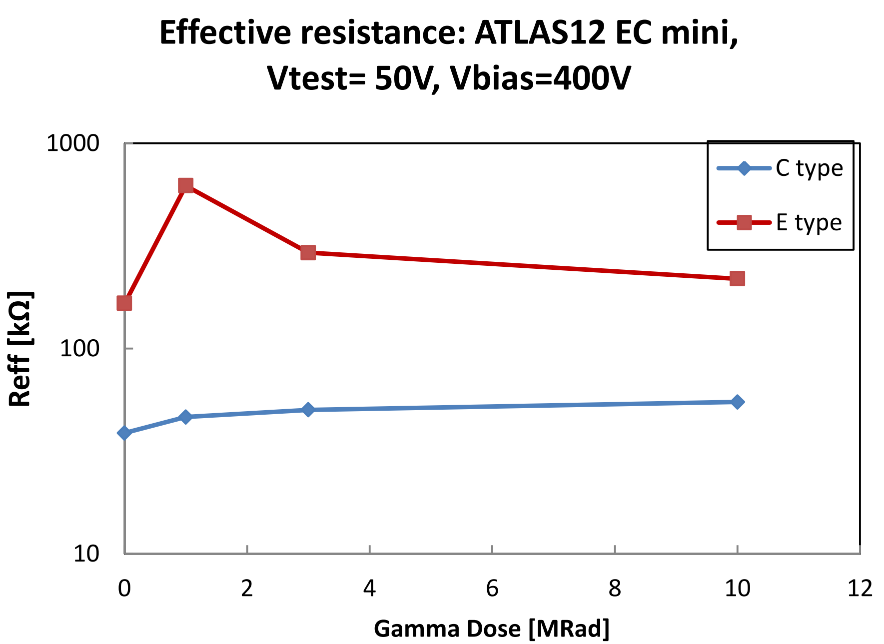
Gamma irradiated :
R_{bias} = 1.5 – 1.7 MΩ (at RT)
Agrees with specs: 1.5 ± 0.5 MΩ

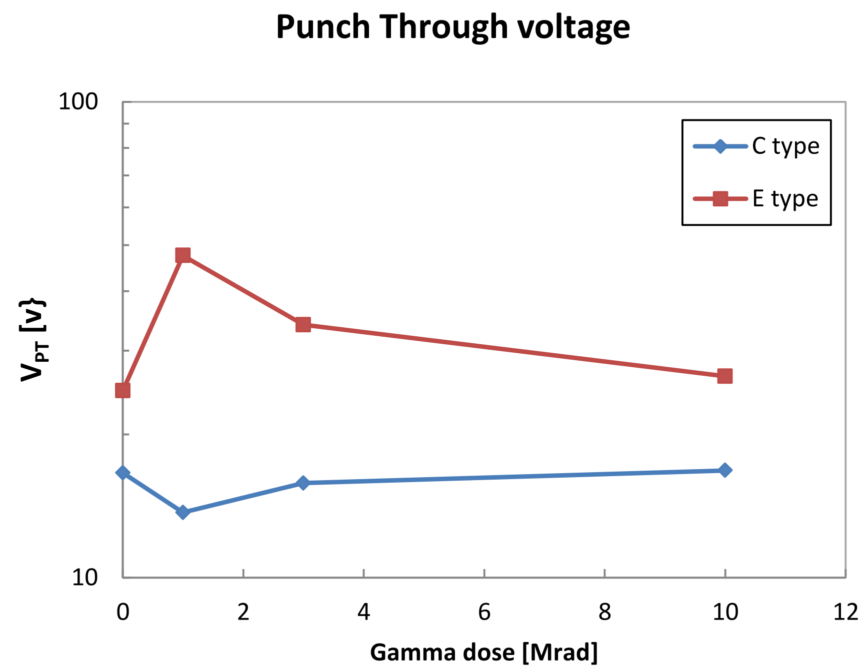




Very small changes in R_{bias} values with gamma dose are caused rather by changes of inter-strip effects after gamma irradiation than by changes in bias resistance value.

PTP vs gamma dose





- **Effective resistance at 50 V is increasing with gamma dose very slightly for C type of PTP structure.**

  C type: Reff = 10's of kΩ

  E type: Reff = 100's of kΩ

- **The value of punch through voltage is not changing much with gamma dose for C type, but is increased for E type structure:**

  C type: V_{PT}= 14-17V for all gamma dose

  E type: V_{PT}= 24-47V

- **C type of punch though protection structure is sufficient at all doses.**

Status of endcap mini sensors I

Distribution and irradiation of EC mini sensors:

Unirradiated sensors (measurements done):

-10 unirradiated sensors at each participating institute Prague, Valencia and Freiburg for testing.
Results of testing are presented in this talk

Irradiatiated sensors (measurements done):

- 60 sensors were irradiated in Birmingham with protons:
  3 fluences (2 sensors of each type): 5E14, 1E15, 2E15 Neq/cm2
  Sensors will be distributed to Prague, Valencia, Freiburg for testing

- 30 sensors were irradiated at BNL with gamma: 1MRad, 3MRad, 10MRad
  with 2 sensors per dose. Only sensors with ganging and small pitch (#7,#8,#17,#18,#21)

-12 sensors were irradiated in Karlsruhe Synchrotron with protons for comparison
to irradiation in Birmingham:
3 fluences (1 sensors of type #7,#8,#17,#18): 5E14, 1E15, 2E15 Neq/cm2

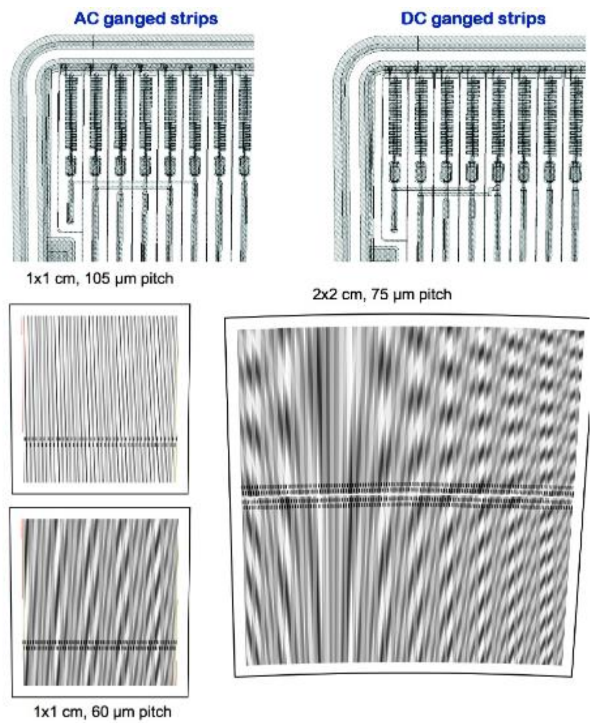
Proton Irradiated EC mini sensors in Prague

20 sensors Irradiated in Birmingham, 16 tested

5E14 n_{eq}/cm^2	1E15 n_{eq}/cm^2	2E15 n_{eq}/cm^2
✓W628-EC-Small-C-P7	✓W620-EC-Small-C-P7	✓W645-EC-Small-E-P8
✓W604-EC-Large-C-P9	✓W644-EC-Small-E-P8	✓W605-EC-Large-C-P9
✓W626-EC-Large-E-P10	✓W628-EC-Large-E-P10	✓W644-EC-Small-C-P17
✓W639-EC-Small-E-P18	✓W642-EC-Small-C-P17	✓W604-EC-Small-E-P18
✓W645-EC-Large-C-P19	✓W626-EC-Large-C-P19	✓W642-EC-Large-E-P20
W620-Skewed-C-P01 (upper)	✓W609-EC-Large-E-P20	
W644-Skewed-E-P02 (lower)	W645-Skewed-E-P02 (lower)	W630-Skewed-C-P01 (upper)

5 sensors Irradiated in Karlsruhe

✓W626-EC-Small-E-P8	✓W642-EC-Small-C-P7	✓W620-EC-Small-E-P18
✓ W644-EC-Small-E-P18	✓W620-EC-Small-C-P17	



Leakage Current

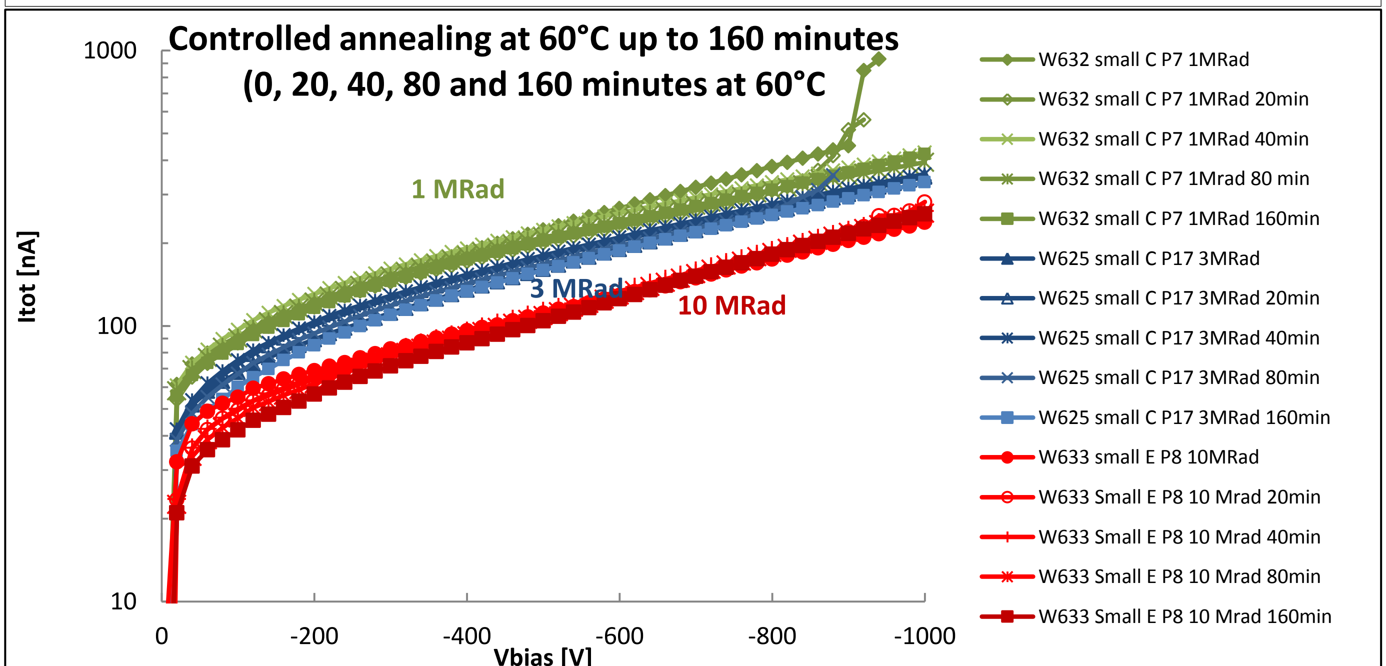
Why the leakage current is lower for higher gamma doses ?

Were sensors heated due to gamma irradiation and underwent annealing?

- dose rate 22kRad/hour; error +/-10%
- 10MRad sensors irradiated 19 days in total (10+3+1+4+1)
- Sensors kept at RT during irradiation

Mass of mini sensor (10mmx10mmx300um) = 7x 10^{-5} kg
Specific heat capacity of Silicon 703 J/(kg·K)

Dose rate 220 J/(kg*hour) —> **4.3 microWatts …very small for heating up the sensor**
if no heating exchange —> 7°C per day temperature increase



breakdown at ~ 900V of 1MRad sensors disappeared after annealing 40 minutes at 60°C

Controlled annealing up to 160 minutes at 60°C didn't change current significantly.
Annealing effect can't explain the lower current for higher doses.