Update on Surface Studies of n-on-p Silicon Strip Sensors after irradiation to HL-LHC fluences
Prague status

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ATLAS Upgrade Strip Sensor Collaboration

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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 the Czech Republic,
Queen Mary University of London, UC Santa Cruz, University of Sheffield,
Tokyo IT, University of Tsukuba, IFIC Valencia, CNM and HPK

Strip Sensors

Silicon strip sensors in upgraded ATLAS experiment at the HL-LHC will be exposed to radiation fluences up to 5.3×10^{14} n_{eq}/cm^2 (strip barrel) and 8.1×10^{14} n_{eq}/cm^2 (strip end-cap)

ATLAS12 sensors were developed for the upgrade of the strip tracker of the ATLAS experiment [Y. Unno et al. Nucl. Instr. Meth. A765 (2014) 80-90] and produced by Hamamatsu Photonics (HPK)

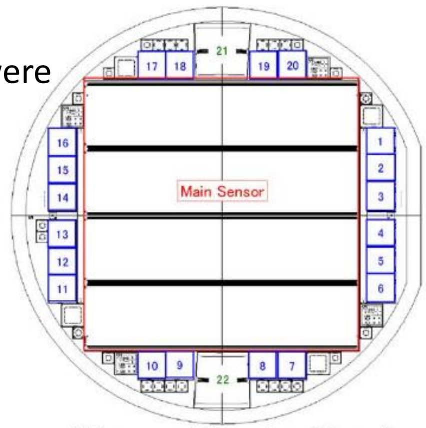
Sensor:
- n^+ - *strips* in - *p* type material (FZ) <100>
- thickness 320 µm
- AC-coupled readout
- main sensor (9.75cmx9.75cm) surrounded by mini's (1cmx1cm)
- 1280 strips in 4 segments

- ATLAS07 design:
  - 6 zones for mini's with different n-strip isolation
  - characterization of large sensor and of irradiated mini's were published in **[*Nucl. Instr. and Meth.* A636 (2011) Special issue]**

- ATLAS12 designs: ATLAS12A **all axial strips in main sensor**
  ATLAS12M **2 axial, 2 stereo segments**

  New features from 07 design:
  - implementation of 2 dicing lines
  - a new gated PTP structure in main sensor
  - bonding pads modified for the new ASIC readout
  - end-cap mini sensors for irradiation studies

6-inch
ATLAS12A Wafer Layout 320µm



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

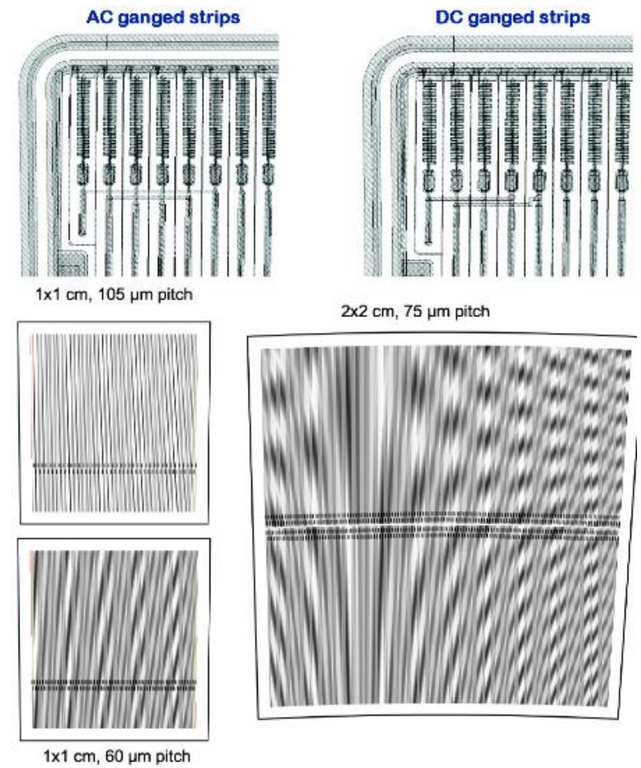
- Main sensor at the center of the wafer
- 1-24 Baby sensors in the peripheral of the main sensor

2013/5/13, Y. Unno 3

ATLAS12 mini sensors

ATLAS12A End-cap mini sensors of 10 different types:

- 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 (type C and E)



ATLAS12 mini sensors:

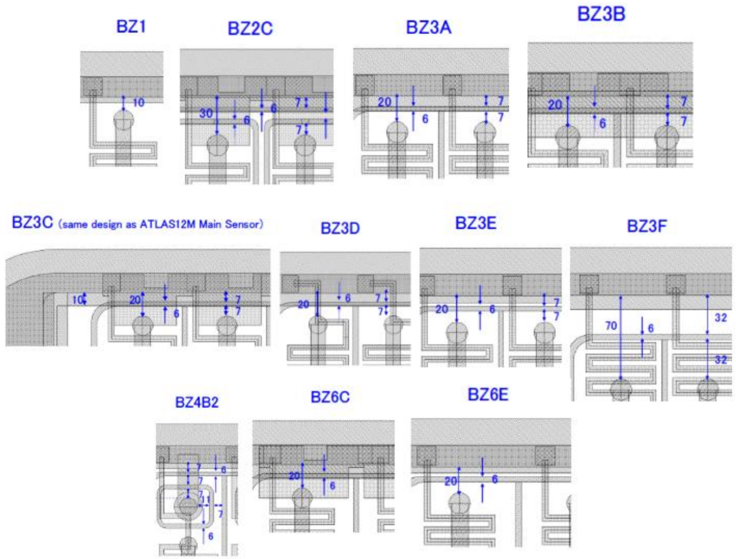


Fig. 9. Miniature sensors of axial geometry with or without a PTP structure in ATLAS12 wafers.

[Y. Unno et al. Nucl. Instr. Meth. A765 (2014) 80-90]

ATLAS12 sensor evaluation program

- **Strip Sensor Collaboration currently finishes extensive evaluation program of ATLAS12,**
- **Collaboration works on the summary of the recent results**
- **results are agreeing very well**
- **4 papers will be submitted to the Hiroshima conference in Sep. 2015**

- Large Sensors (Cambridge)
  - sensor shape
  - IV, CV
  - Full strip tests
- Bulk radiation hardness (Ljubljana, Liverpool, KEK/Tsukuba, Freiburg, Valencia, DESY, Glasgow)
  - Charge collection
  - Edge TCT
- Surface studies (Prague, UCSC, Freiburg, Glasgow, Lancaster, Tsukuba)
  - PTP, Cinter, Rinter
- Endcap studies (Valencia, Freiburg)
  - Laser tests
    - Strip integrity scans
    - Strip ganging performance
  - Beta source tests

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)

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Sensors tested in Prague

Samples:

- End-cap and barrel mini sensors **ATLAS12A** irradiated by:
  - **gammas (^{60}Co) at** BNL : 15 barrel and EC mini's to doses 0.1, 0.3, 1, 3, and 10MRad
  - **protons (27 MeV)** at Birmingham, UK: 20 end-cap, 3 fluences: 5E14, 1E15 and 2E15 n_{eq}/cm^2
  - **(25 MeV)** at Karlsruhe Inst. Tech., Germany: 5 end-cap mini's
  - **(70 MeV)** at CYRIC, Tohoku University, Japan, irradiation campaign: CYRIC exp.# 9774 (Sep., 2014): 2 barrel mini's to fluences 5E14 and 1E15 n_{eq}/cm^2

- 20 barrel **A12A, A12M and A07** for comparison irradiated in the same irradiation campaign by:
  - **protons** CYRIC, Tohoku University, Japan, irradiation campaign: CYRIC exp.# 9726 (Feb., 2015)

Barrel TYPE	PTP	Wafer ρ [kΩcm]	FDV [V]	Dicing cut	Strip isolation
ATLAS12A	C	~3	~350	standard	p-stop
ATLAS12A	F	~3	~350	standard	p-stop
ATLAS12M	C	~ 4.5	~225	slim (inner cut)	p-stop
ATLAS07	-	~6.7	~200	standard	p-stop

- 5 samples of each type
- Each type irradiated to 5 different proton fluences: 1E14, 3E14, 1E15, 3E15 and 1E16 n_{eq}/cm^2

Electrical tests of irradiated ATLAS mini sensors in Prague

- IV characteristics - breakdown voltage
- CV characteristics and Full depletion Voltage (FDV)
- Inter-strip Resistance R_{int}
- Inter-strip Capacitance C_{int}
- Bias Resistance R_{bias}
- PTP

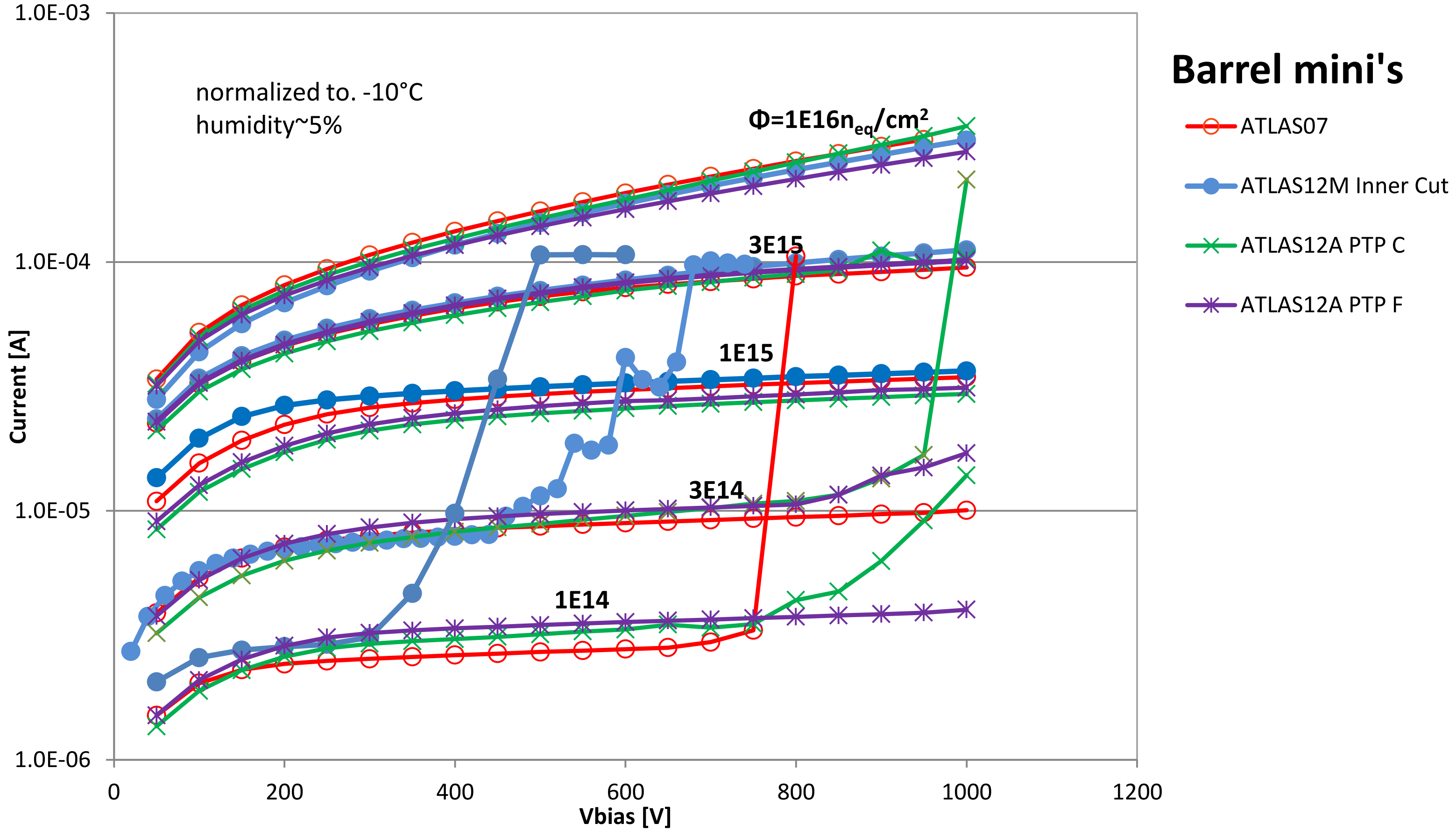
Result presented in this talk:

- Comparison of A12A, A12M and A07 irradiated in the same campaign
- Comparison of R_{int} at different proton irradiation sites
- Fluence, voltage and temperature dependence of R_{int}
- Annealing of R_{int} at 60°C
- Stability measurements

Measurement conditions:

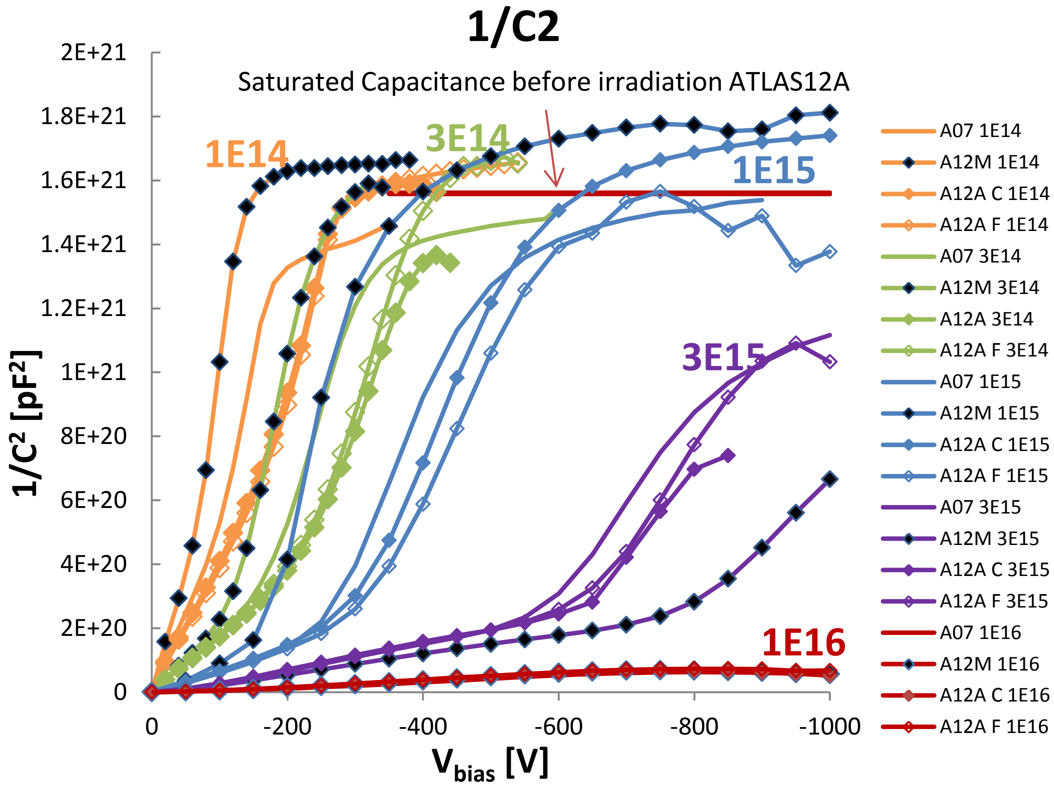
- Measurements done after annealing 80 minutes at 60°C
- Measurement temperature -10°C
- Nitrogen environment (humidity < 10%)

Leakage Current – CYRIC proton irradiation

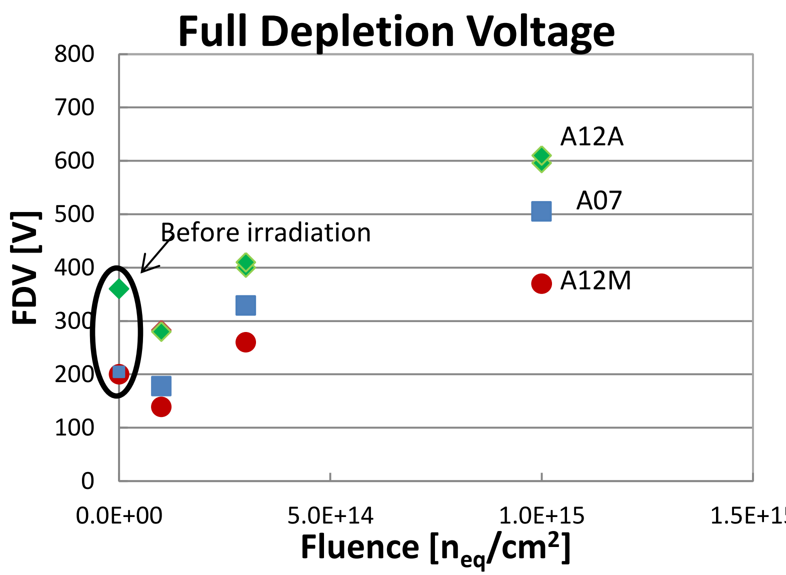


- In all types of sensors no breakdown was observed up to 1000V after high fluences $\Phi \geq 1E15\ n_{eq}/cm^2$
- ATLAS12M with Inner Cut at lowest fluences 1E14 and 3E14 – soft breakdown at 350 and 500V
- ATLAS07 and ATLAS12A at lowest fluence 1E14 soft breakdown at 800V

CV characteristics for Full Depletion Voltage (FDV) estimation



CYRIC irradiation



FDV > 1000V for 3E15 and 1E16 n_{eq}/cm^2 which is expected for 302 µm silicon

Initial 15-30% drop of FDV is probably associated with initial acceptor removal (see Gregor's talk)

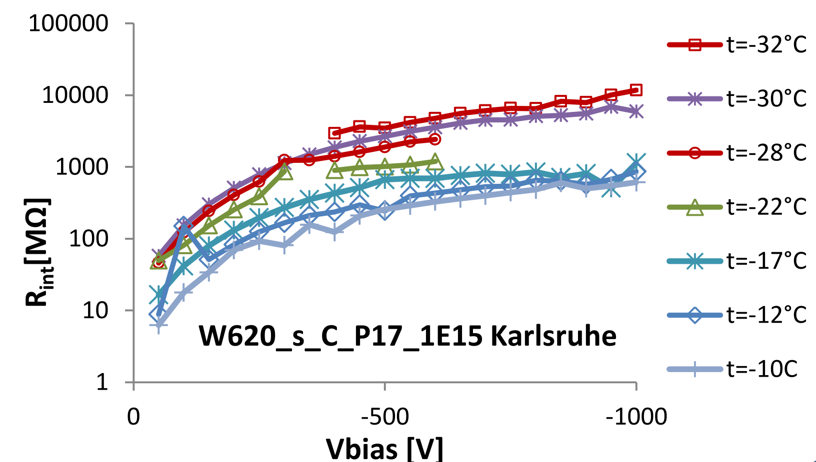
Different wafer's resistivity used for A12A , A12M and A07

Temperature dependence of Inter-strip resistance

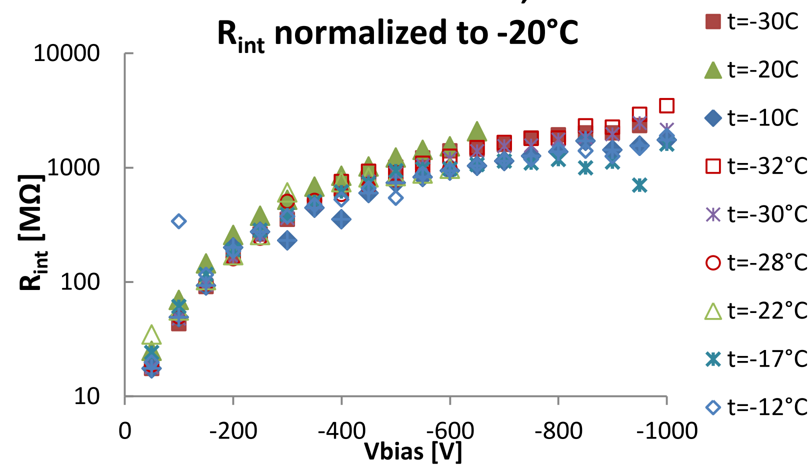
Karlsruhe irradiation

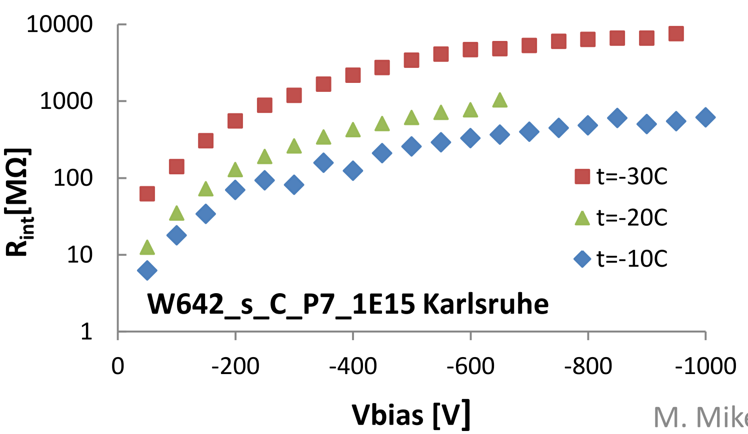
- Inter-strip resistance is temperature dependent
- Inter-strip current has the same temperature dependence as bulk generation current
- **all data in this talk are normalized to -20°C** $R(T_{-20})=R(T_M)*(T_{-20}/T_M)^2*\exp[-E/2k_B*(1/T_{-20}-1/T_M)]$ with energy $E=1.2eV$

R_{int} at different temperatures

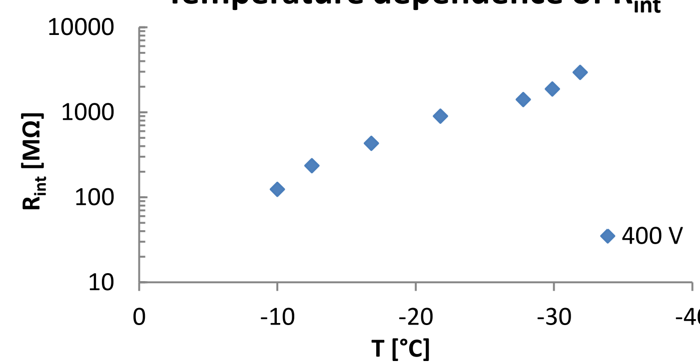


W620 and W642, R_{int} normalized to -20°C



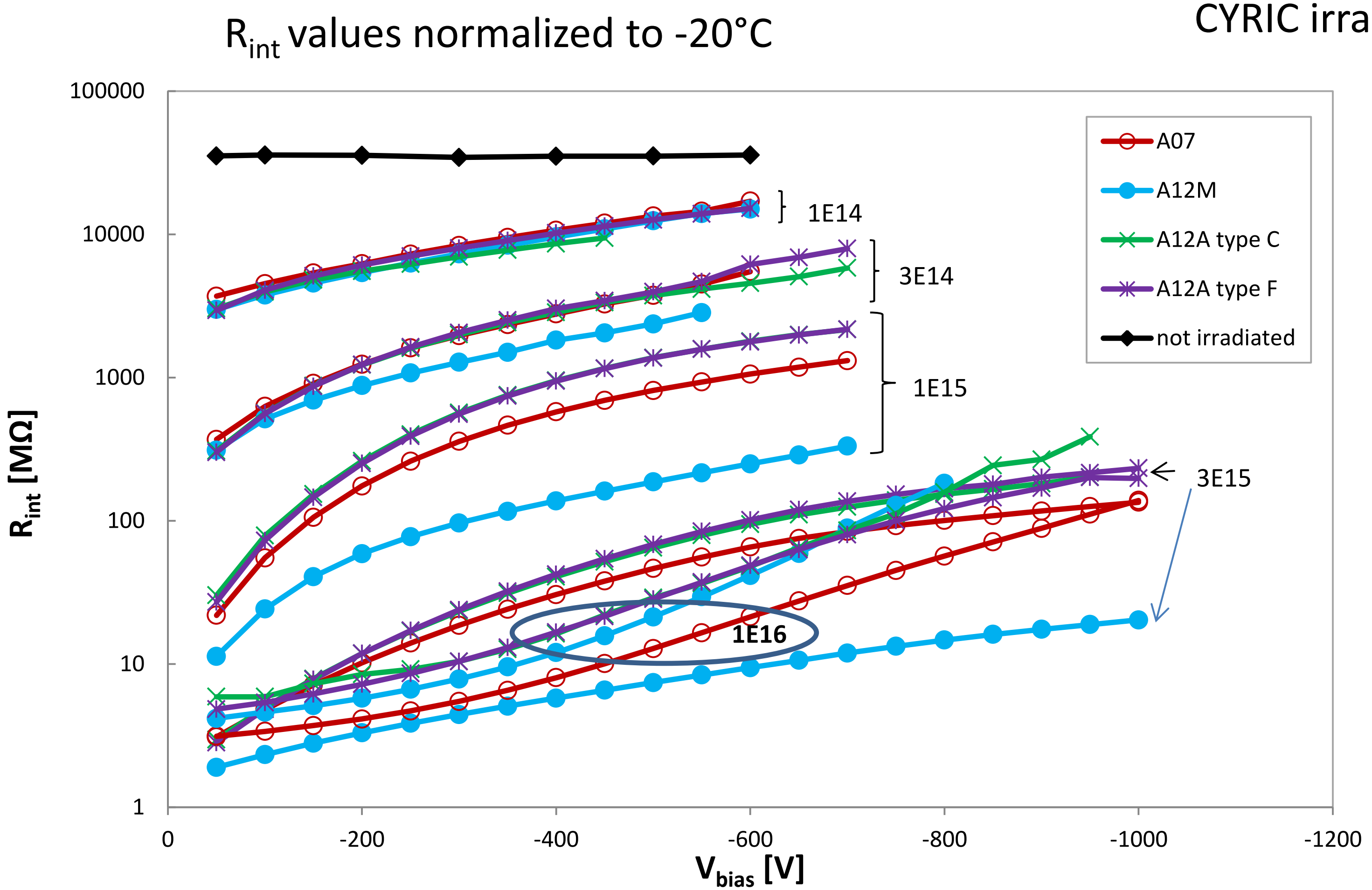


Temperature dependence of R_{int}



Inter-strip Resistance Comparison between ATLAS07, ATLAS12M and ATLAS12A PTP type C and F

CYRIC irradiation

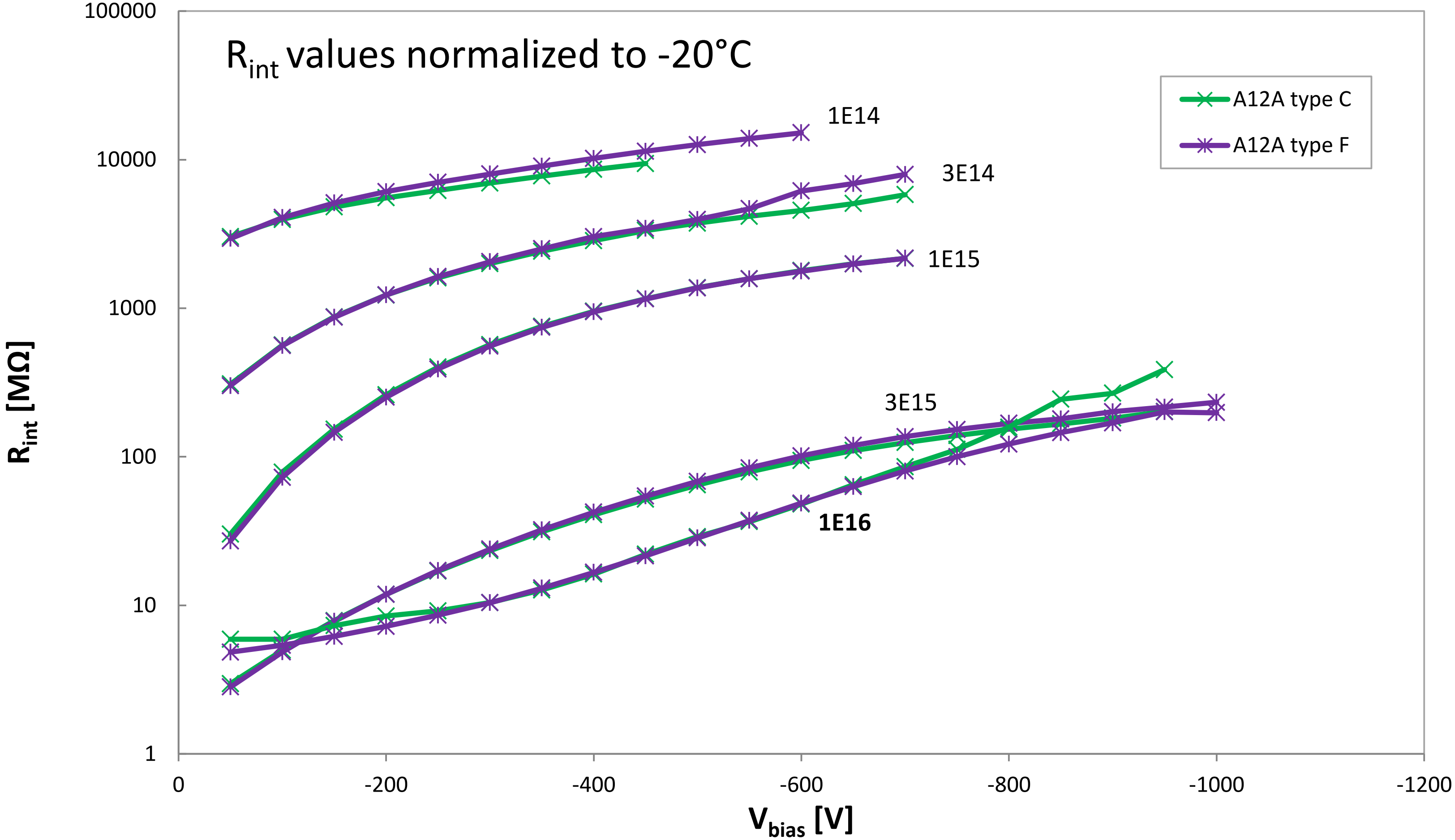


R_{int} is decreasing with increasing fluence for all type of sensors and increases with V_{bias}

R_{int} of ATLAS12M seems to degrade more strongly with increasing fluence

Inter-strip resistance Comparison: PTP type C and F ATLAS12A

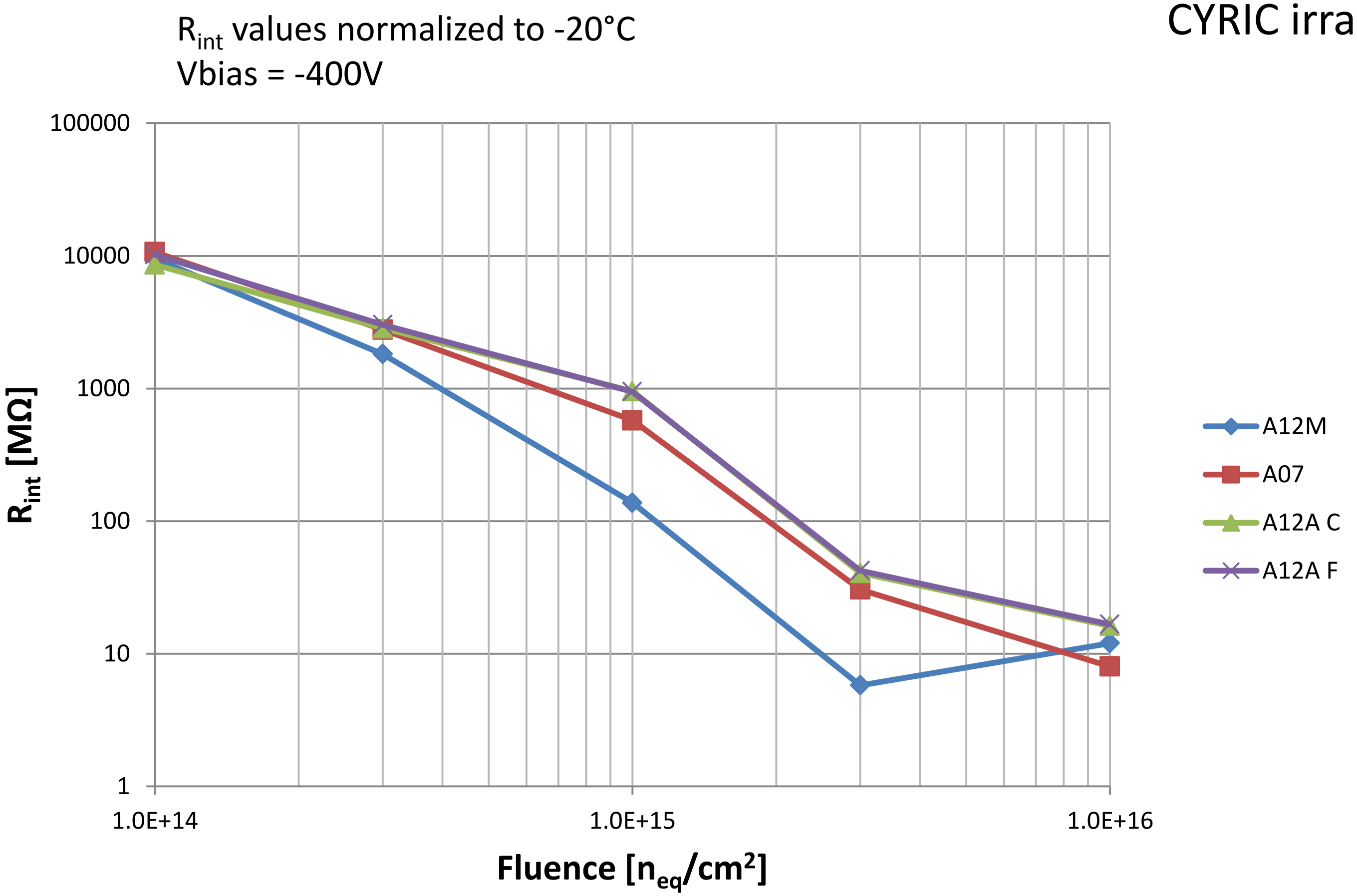
CYRIC irradiation



- No difference in R_{int} for “gated” PTP structure C and structure F without PTP for all fluences and V_{bias}

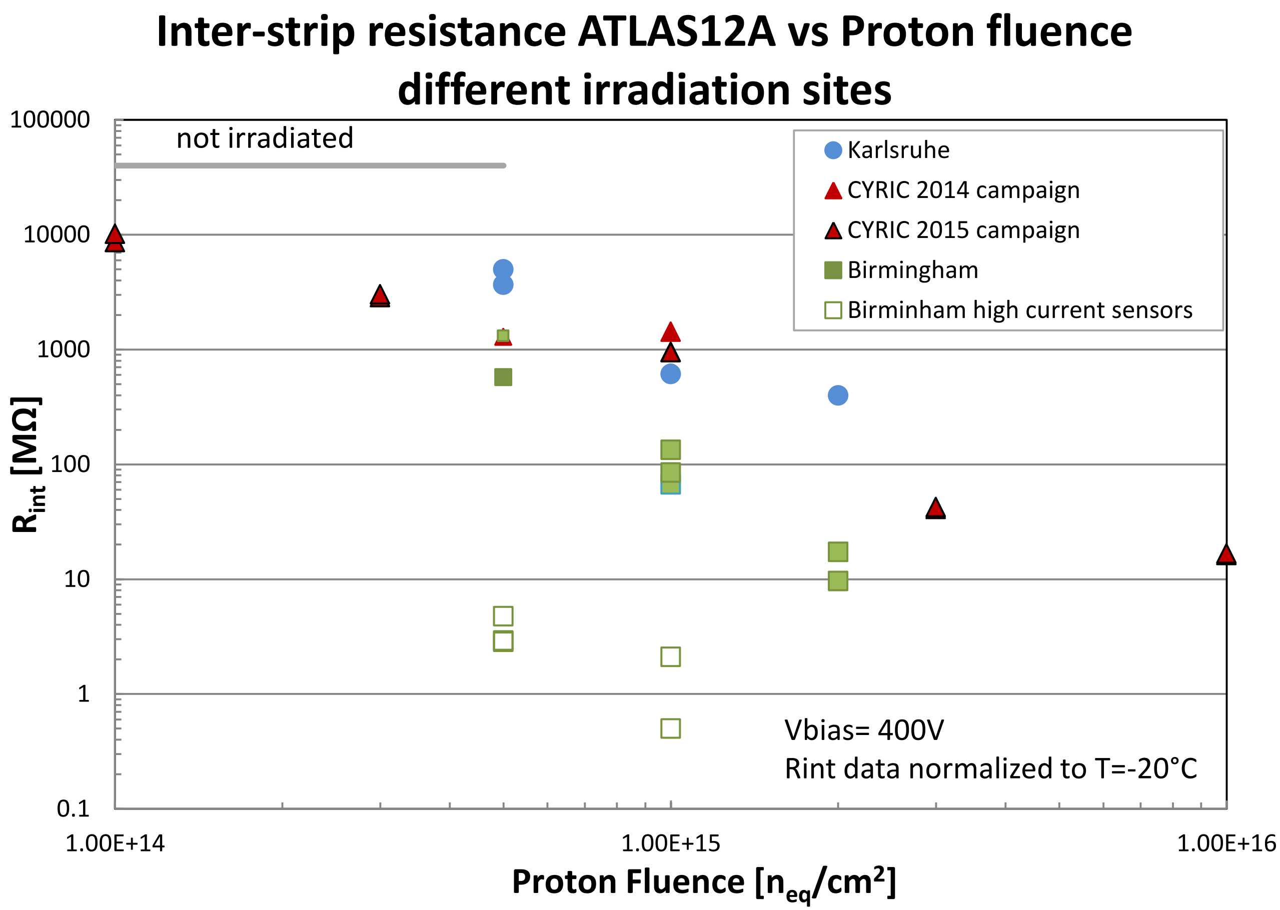
R_{int} vs Proton Fluence

CYRIC irradiation



- ATLAS07 and ATLAS12A have similar R_{int} decrease
- R_{int} of ATLAS12M seems to degrade more strongly with fluence

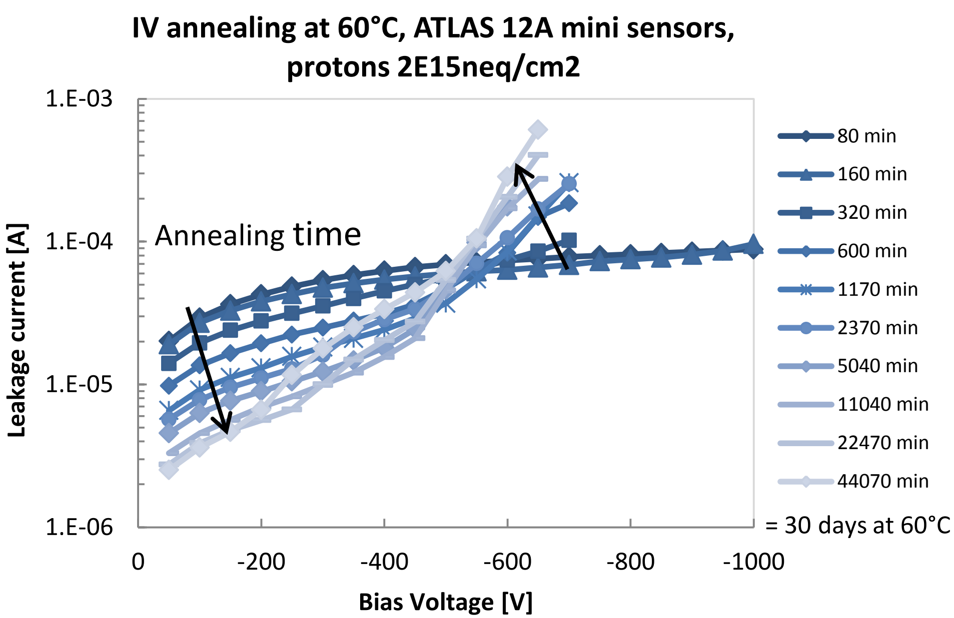
R_{int} vs Proton Fluence

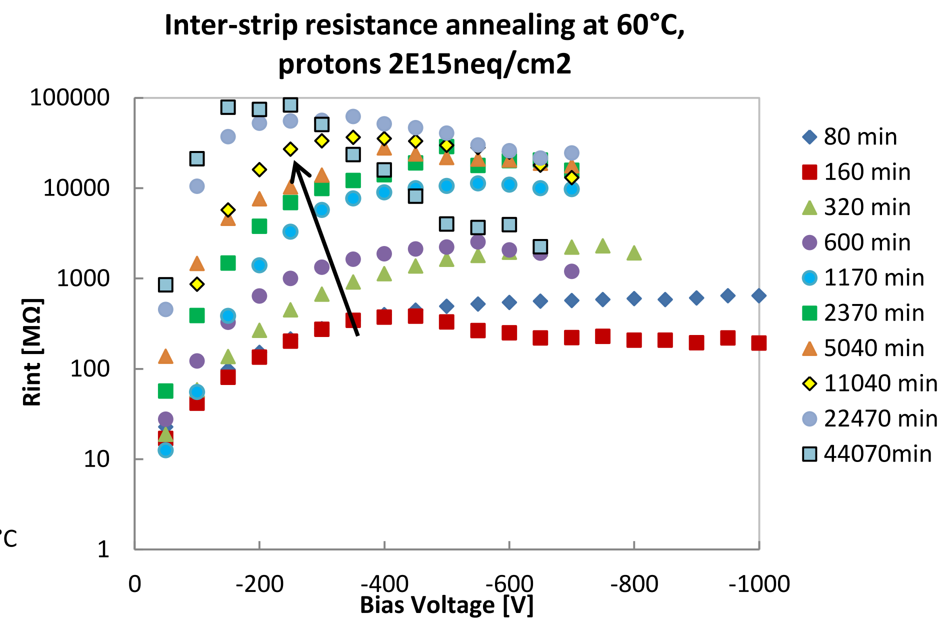


- Decrease of inter-strip resistance with fluence
- Higher degradation of R_{int} in Birmingham Irradiated sensors
- Karlsruhe and CYRIC irradiation – similar degradation of R_{int}
- **Inter-strip resistance at bias voltage -400V (~operational voltage) and at -20°C is high enough up to 1E16 n_{eq}/cm^2**

Annealing of leakage current and R_{int} at 60°C

Karlsruhe irradiation





Annealing of Leakage current

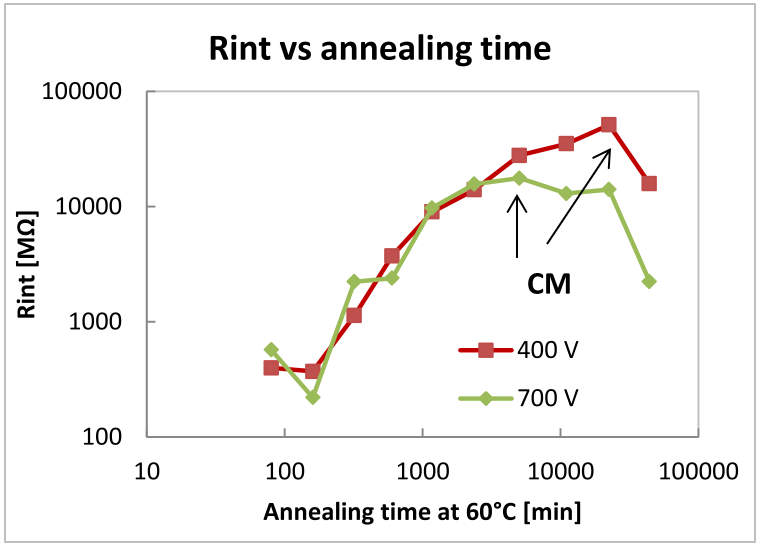
- At low V_{bias} current decreases in time
- At high voltages current increases with annealing due to charge multiplication (CM)
- With annealing time the space charge concentration rises and higher electric field near strips causes CM
- With longer annealing time multiplication starts at lower bias voltages

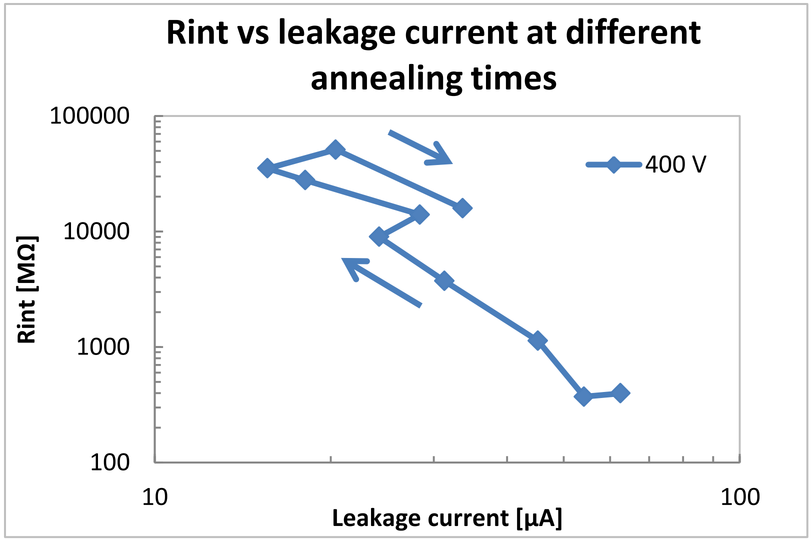
Annealing of Inter-strip resistance

- The Inter-strip resistance increases with annealing time significantly as the leakage current decreases
- Annealing 5000 min at 60°C causes R_{int} change from 400MΩ to 30GΩ which is comparable with value before irradiation, but the leakage current is still 4 orders of magnitude higher then before irradiation

Annealing of Inter-strip resistance at 60°C

Karlsruhe irradiation

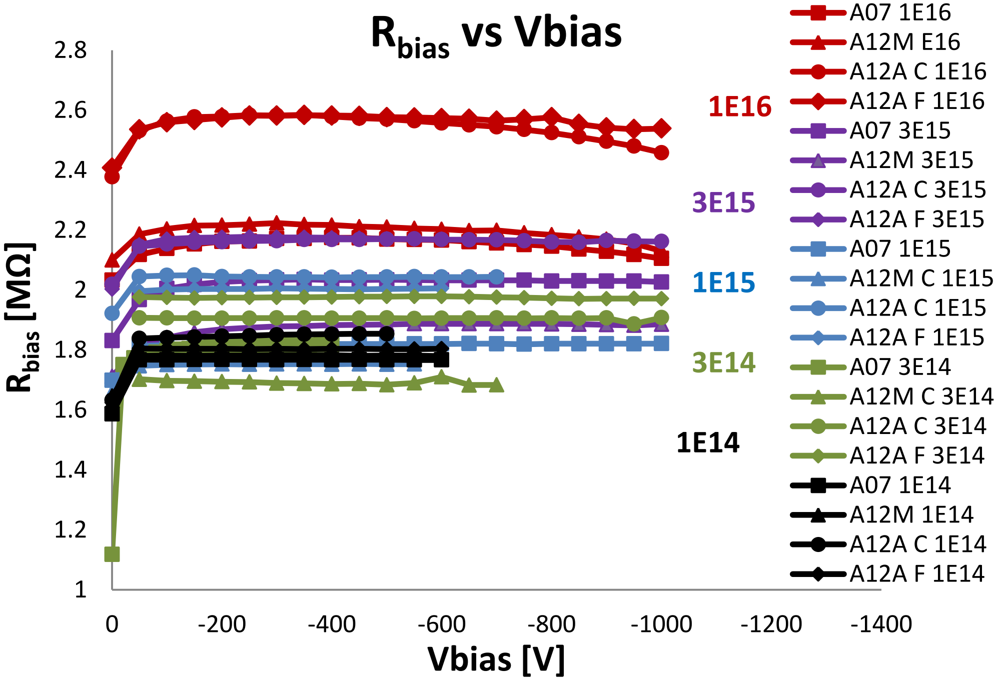


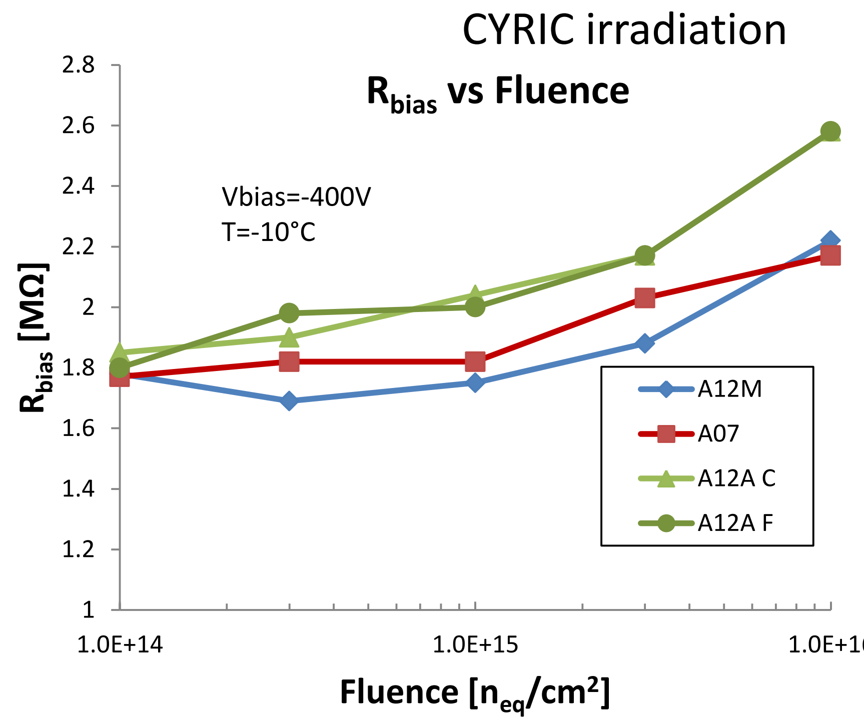


CM = Charge multiplication

Charge multiplication near the strips influences the Rint at 700V after annealing time 5000 min and at 400V at > 22000 min

R_{bias}



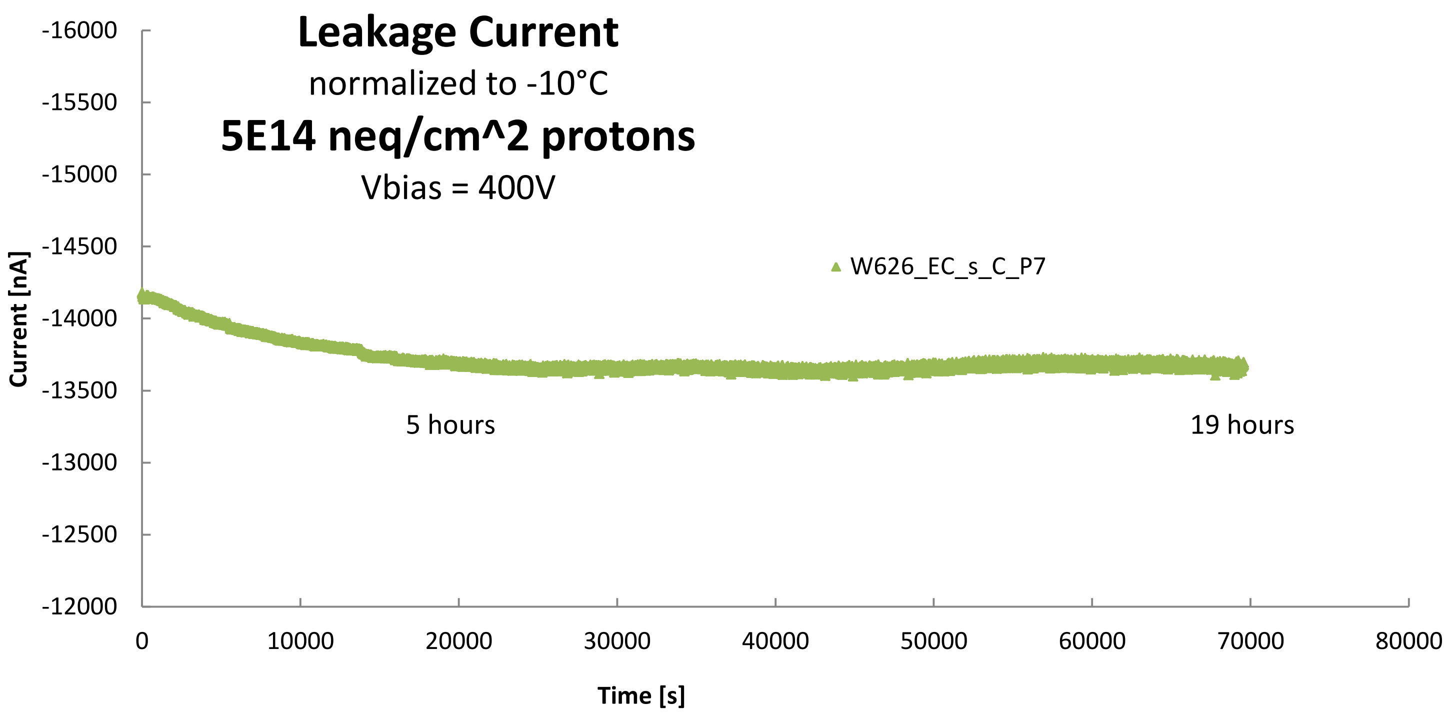


- R_{bias} slightly increasing with proton fluence
- ATLAS12A higher R_{bias} then ATLAS12M and ATLAS07
- R_{bias} slightly temperature dependent: not irradiated: R_{bias} (+23° C) = 1.45 MΩ
  R_{bias} (-10° C) = 1.65 MΩ

Measuring method: 3 probe
to exclude inter-strip effects in irradiated sensors the V_{test} is applied also on 2 neighbors at the same time,
IV is performed on the central strip

Leakage current stability measurement

Karlsruhe irradiation

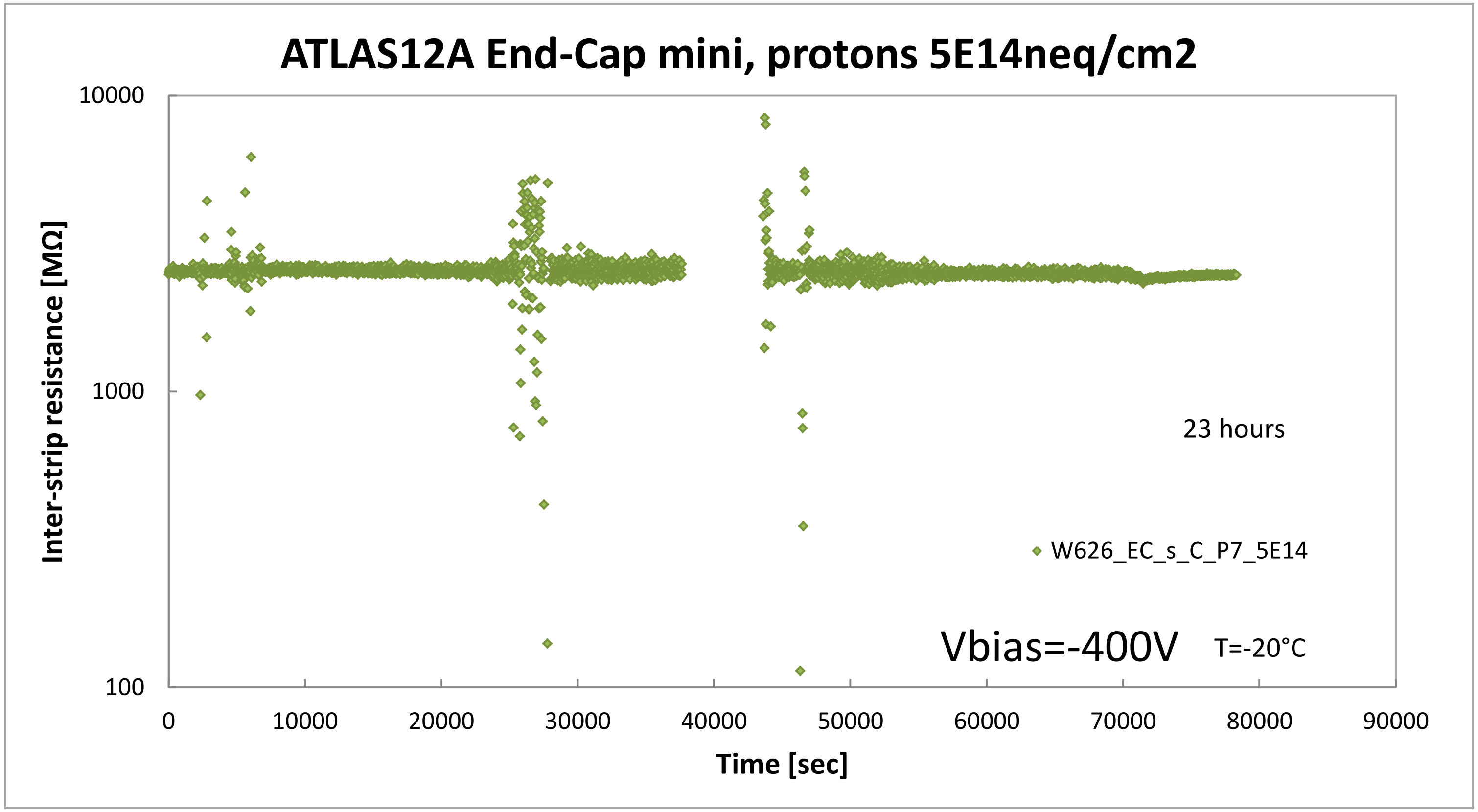


- **Leakage current is decreasing first 5 hours (3.5%), then is stable.**

Nitrogen flow throughout the test period

Inter-strip Resistance stability

Karlsruhe irradiation



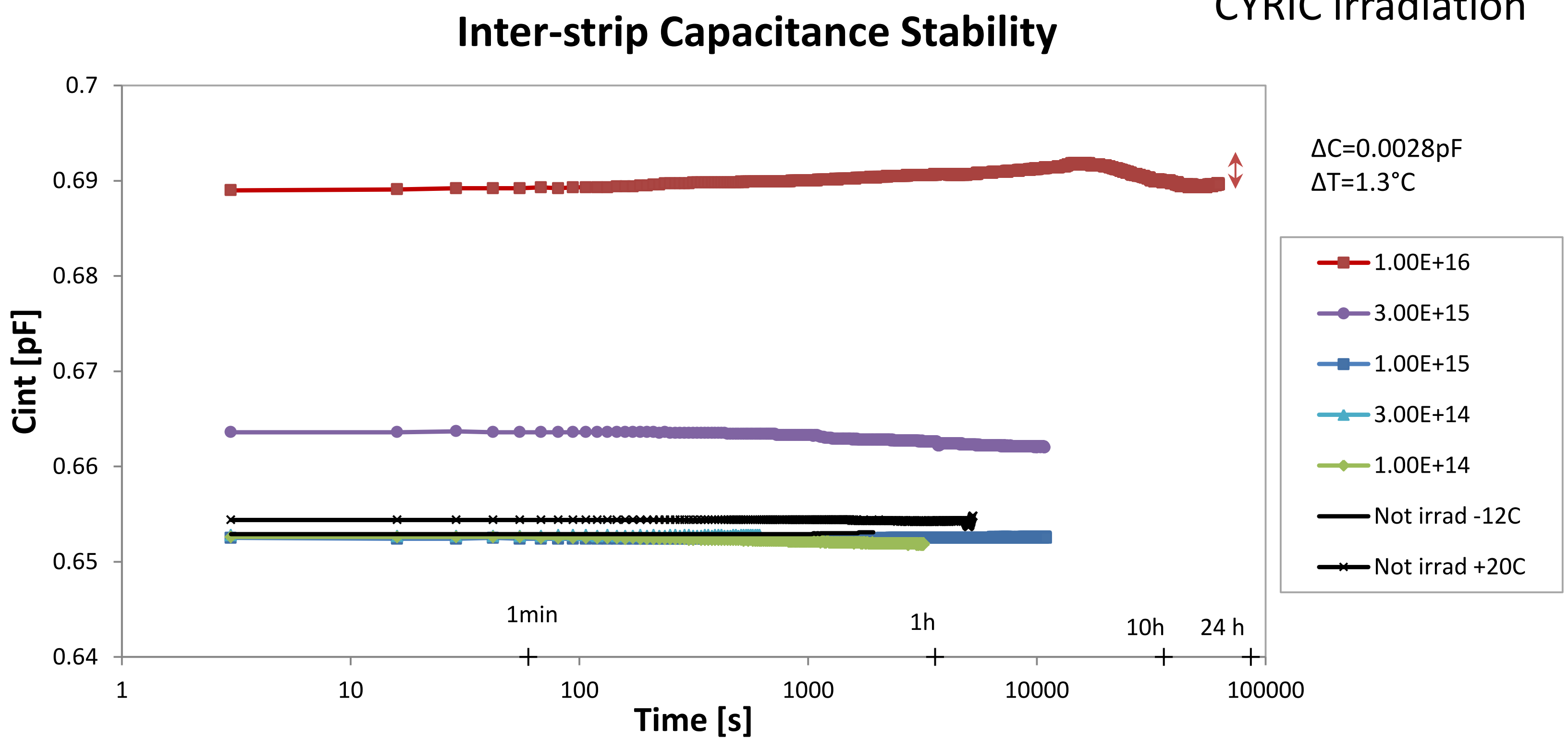
measurement with nitrogen flow over 23 hours

R_{int} is stable in time –> 2.5 GΩ

Instabilities are not caused by instabilities in sensor

Inter-strip Capacitance stability

CYRIC irradiation



- Measurements done at -10°C, rel. humidity <10% (N2 flow)
- No change in inter-strip capacitance with time observed.
- The capacitance changes copies the temperature changes.
- During 24 hours ΔT=1.3°C -> ΔCint 0.4%

Conclusions

New measurements of ATLAS12A, ATLAS12M and ATLAS07 strip mini sensors after 2015 irradiation campaign at CYRIC were performed.

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

Total current

- In all types of sensors no breakdown was observed up to 1000V after high fluences $\Phi \geq 1E15 n_{eq}/cm^2$
- ATLAS12M with Inner Cut exhibit soft breakdown at 350V(500V) at lowest fluences 1E14 ($3E14 n_{eq}/cm^2$)

Inter-strip resistance

- decreases with proton fluence for all type of sensors; is temperature dependent
- No difference observed in R_{int} of ATLAS12A for PTP structure C and F
- increases with annealing time, after 5000 minutes at 60°C to the values before irradiation
- Low R_{int} (< 1MΩ) of some of the B'ham sensors can't be explained by high temperature annealing
- **is high enough up to proton fluence 1E16 n_{eq}/cm^2**

Bias resistance

- Slightly increasing with proton fluence
- ATLAS12A higher R_{bias} then ATLAS12M and ATLAS07

Stability measurements:

- Inter-strip capacitance and resistance are stable in time (low humidity and -20°C)
- Leakage current is decreasing first 5 hours (3.5%), then is stable

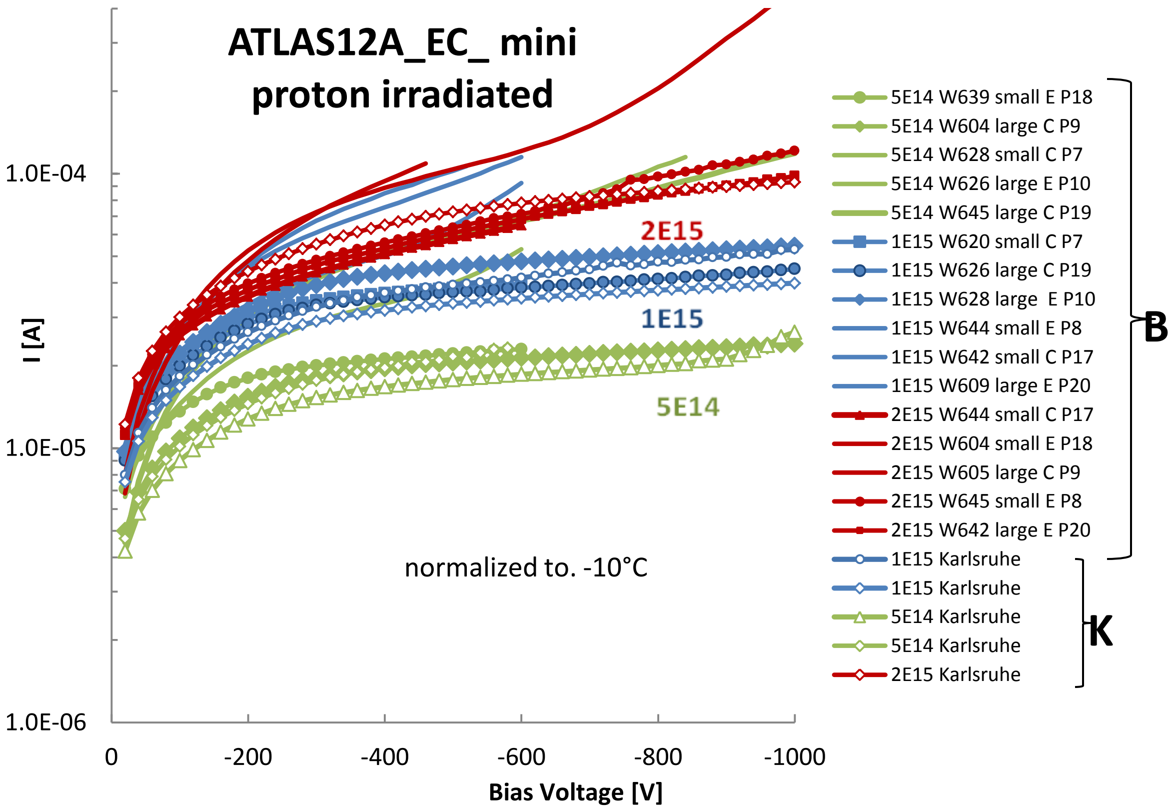
Backup

Results – proton and gamma irradiated ATLAS12 mini's

	Tech. Spec	Measurement		
		not irradiated	Protons $2E15n_{eq}/cm^2$	Gamma 10MRad
Leakage Current at RT non-irrad. at -25C after irrad.	< 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
Inter-strip Capacitance to neighbor pair	< 0.8 pF/cm at 100kHz	0.75 Small Pitch 0.74 Large P. **)	0.81 0.80 **)	0.77 - **)
Inter-strip Resistance	> 10x Rbias ~ 15 MΩ	14-63 GΩ	500 MΩ/cm ***)	200 MΩ/cm ***)

*) measured at -10°C, **) measured at 1MHz, normalized to pitch of barrel sensor, ***) at -20°C

Leakage Current – B'ham and Karlsruhe proton irradiation



Birmingham irradiation:

- 8 sensors have "good" IV behavior up to 600V/1000V (line with marker in the plot)
- 8 sensors have high currents even at low bias voltages (line with no marker)

<u>Possible reason:</u>

- ○ high temperature annealing during irradiation
- ○ high proton beam current 1μA
- ○ low scan speed of 1mm/s

Karlsruhe irradiation:

- all 5 sensors have "good" IV
- no breakdown observed up to 1000V

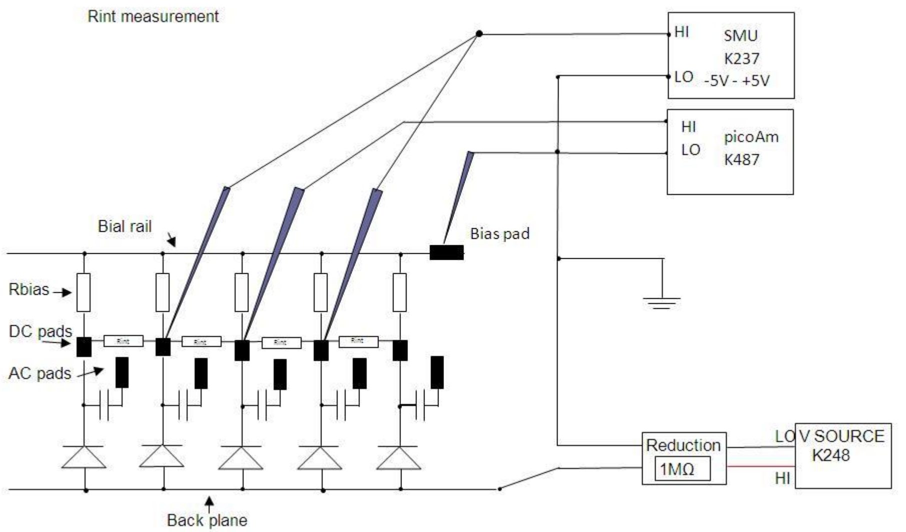
○ 10 times slower irradiation then in B'ham

Inter-Strip Resistance

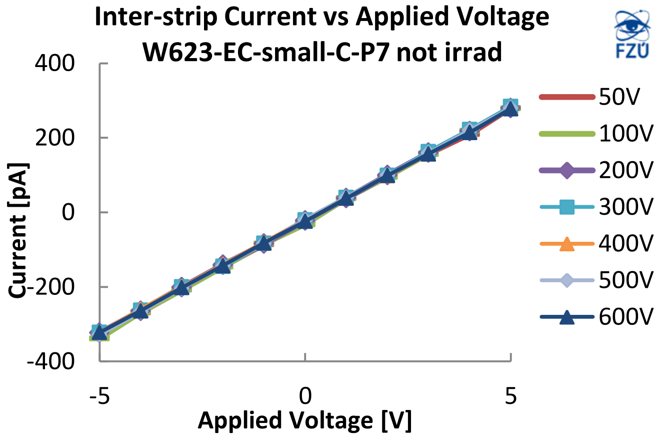
Measuring method:

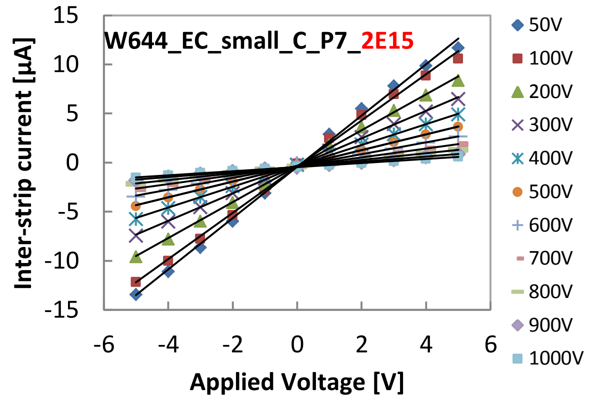
- Inter-strip resistance measured by induced current method.
- 3 adjacent DC pads are contacted with 3 needles. On the outer strips is applied voltage V_{appl} by SMU, the current is measured on the central DC strip.

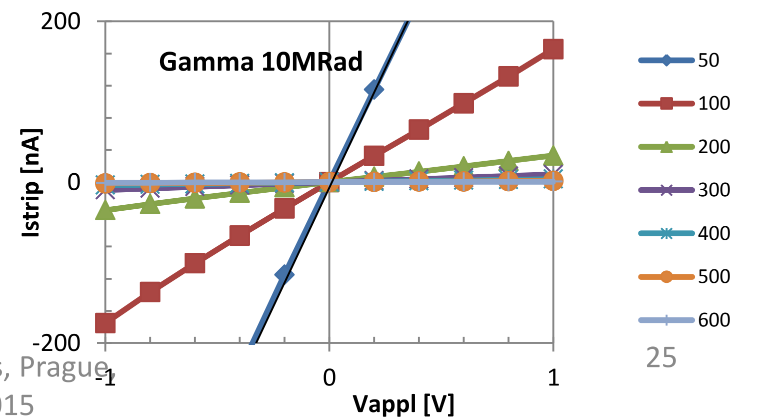
$$R_{int} = 2/(dI/dV_{appl})$$



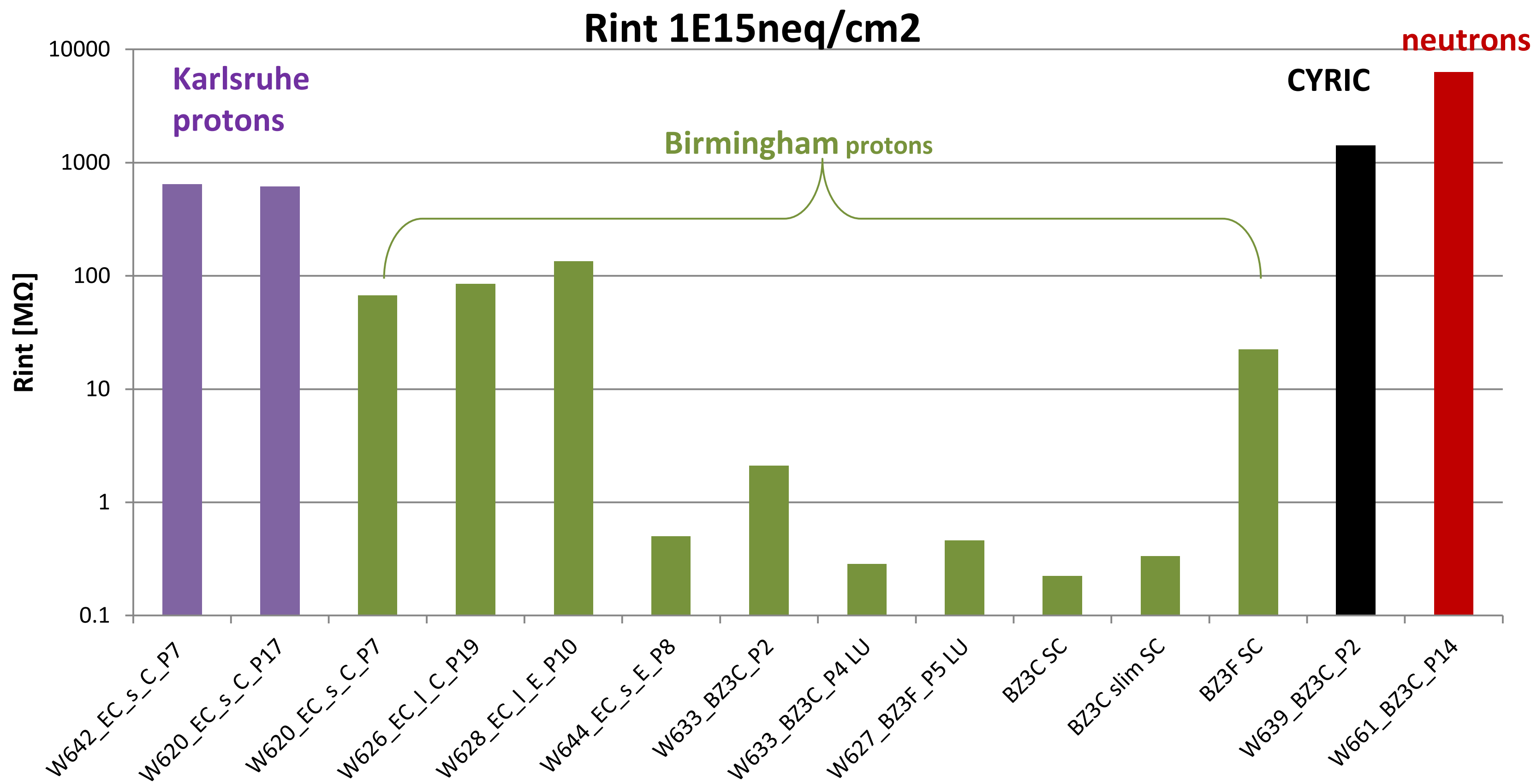
- Nitrogen gas was flowing over the sensor for moisture control





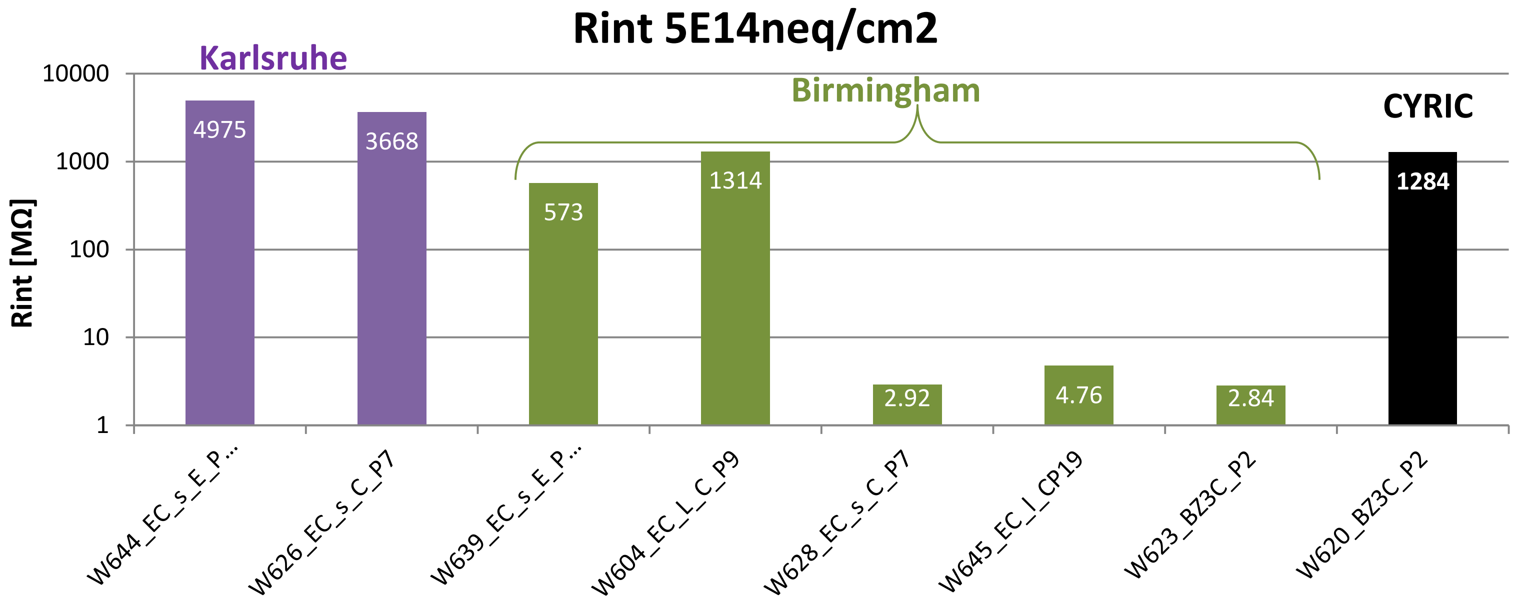


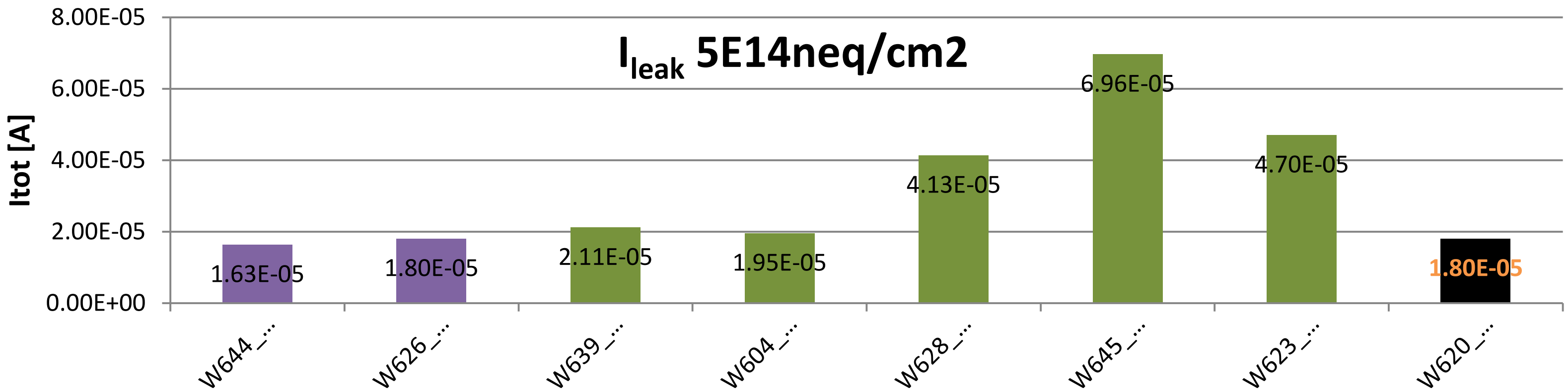
R_{int} at -20°C, V_{bias}=-400V, Prague, Santa Cruz and Lancaster results included



- high discrepancy in values of Inter-strip resistance in B'ham sensors irradiated to 1E15neq/cm2
- some B'ham sensors have Rint <1MΩ
- higher discrepancy in values of R_{int} maybe due to temperature discrepancy during irradiation
- annealing influence on the Inter-strip resistance?

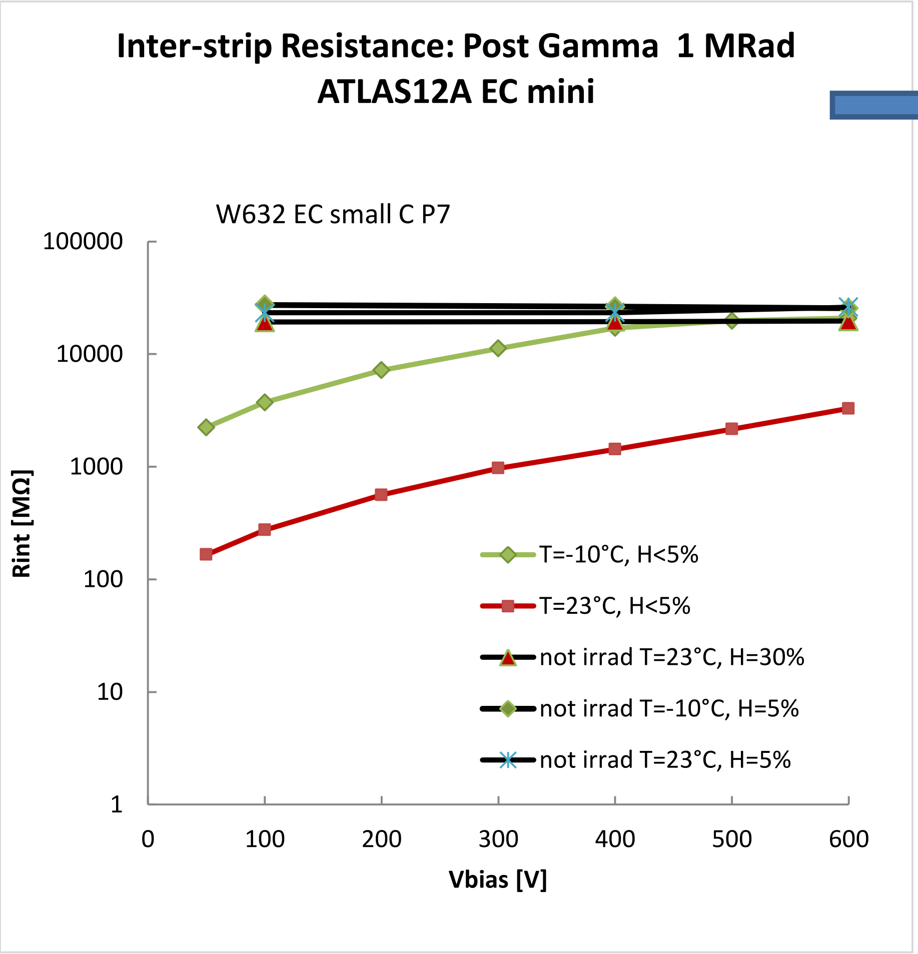
Comparison of R_{int} and Leakage current V_{bias}=-400V

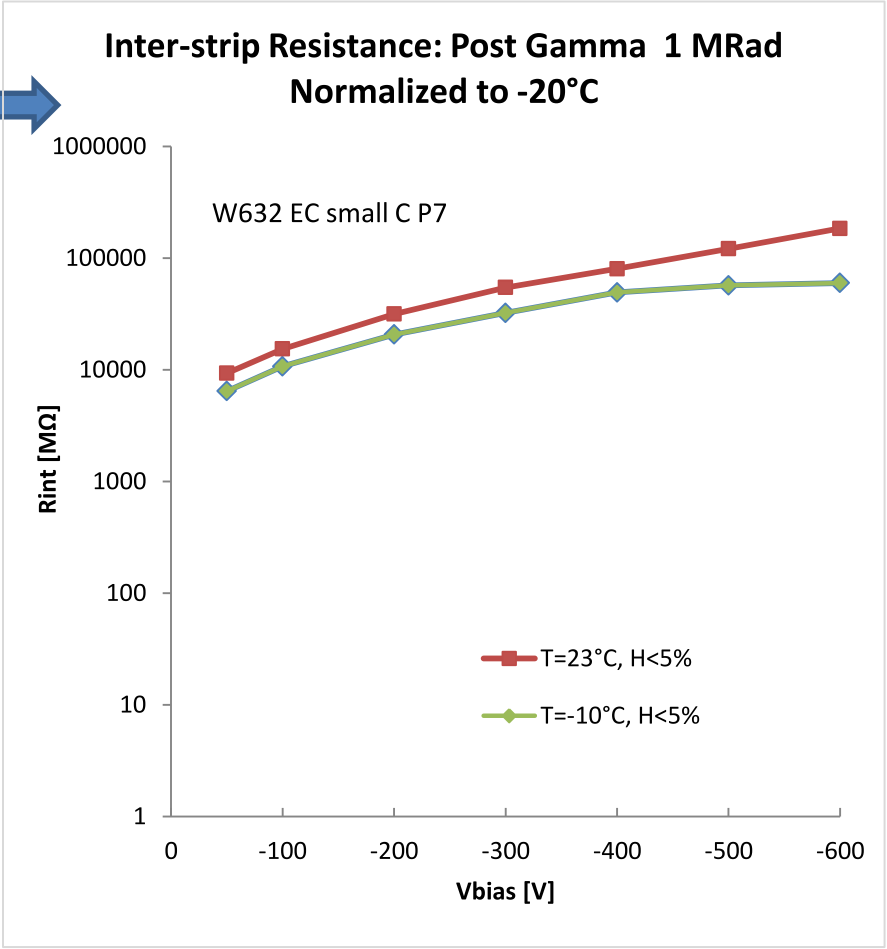




- High discrepancy in values of Inter-strip resistance in samples irradiated in Birmingham also to 5E14 neq/cm2
- The samples with higher leakage current (2-3x) have about three orders of magnitude lower Rint

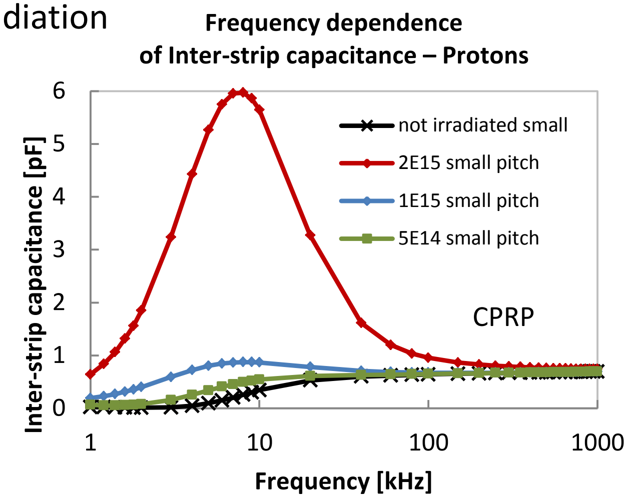
Inter-strip resistance vs bias voltage at different temperatures - gammas

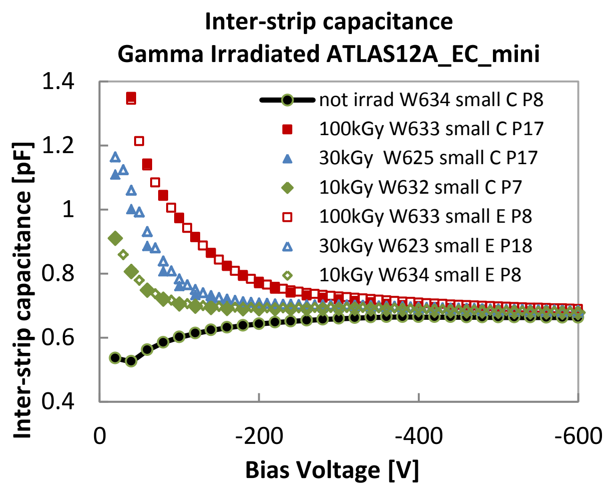


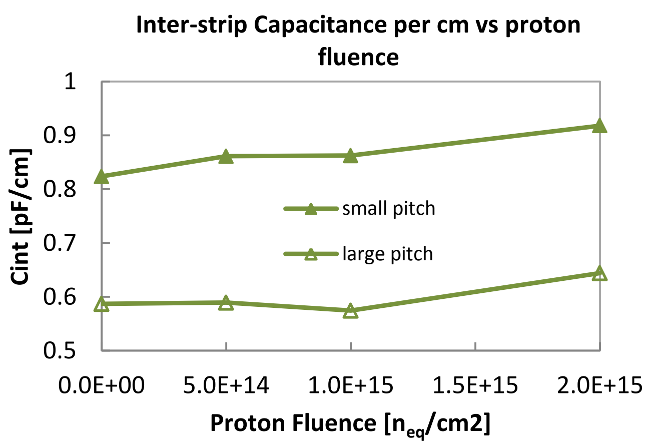


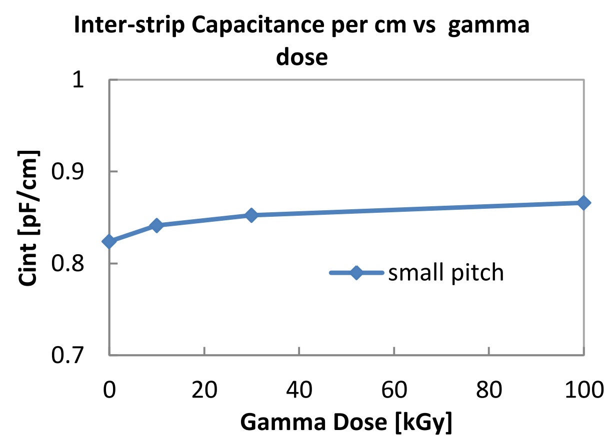
Inter-Strip Capacitance - irradiated

B'ham irradiation





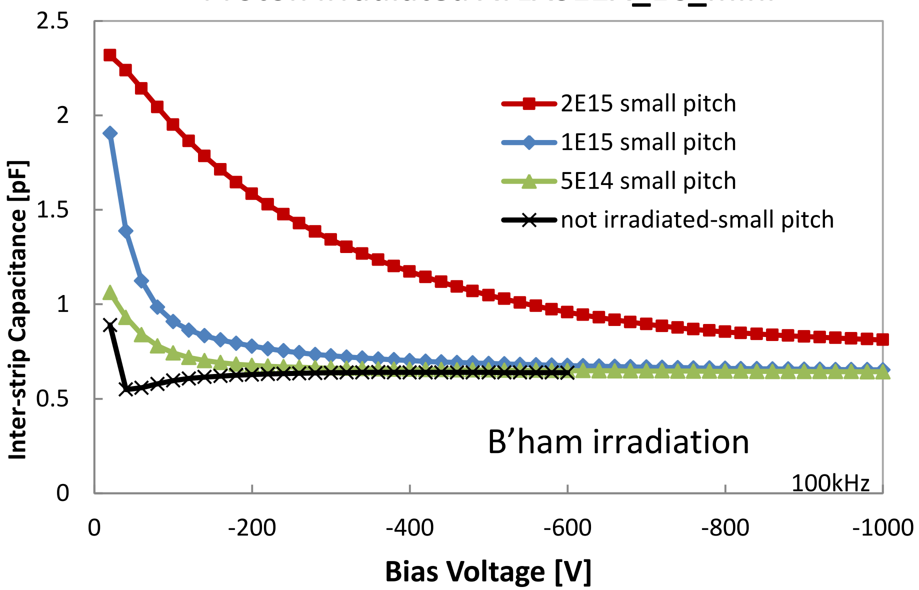


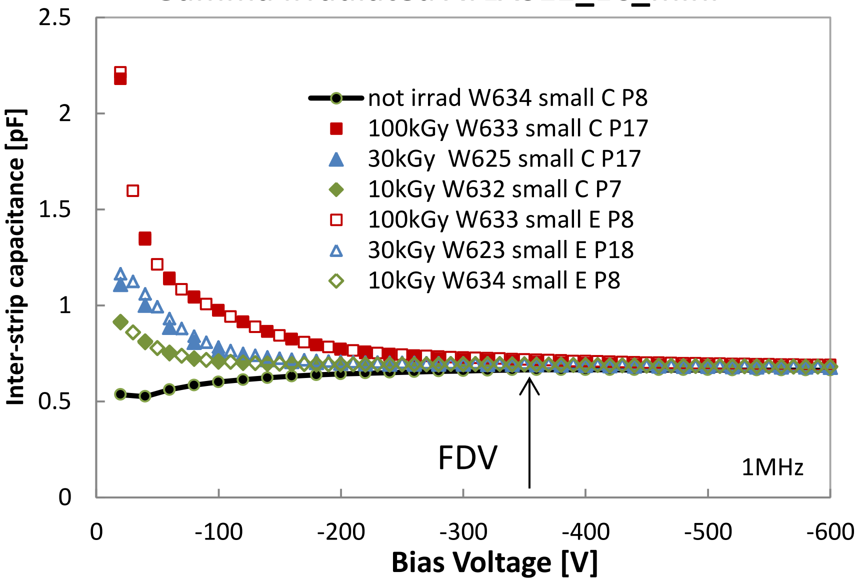


- The frequency dependence of Inter-strip Capacitance stronger for heavy irradiated samples.
- For irradiated sensors the 1 MHz Frequency is more relevant than the 100kHz indicated in specs.
- The higher the radiation dose then the higher bias voltage needed for C_{int} to saturate to the pre-rad value.

Inter-strip capacitance - Proton and Gamma Irradiated

- Inter-strip capacitance (C_{int}) measured between the central strip and its first neighbors (others floating)

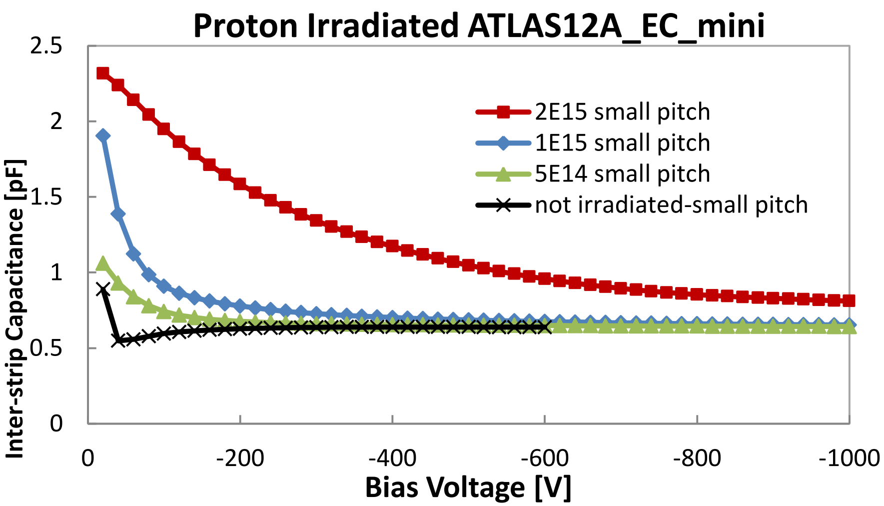


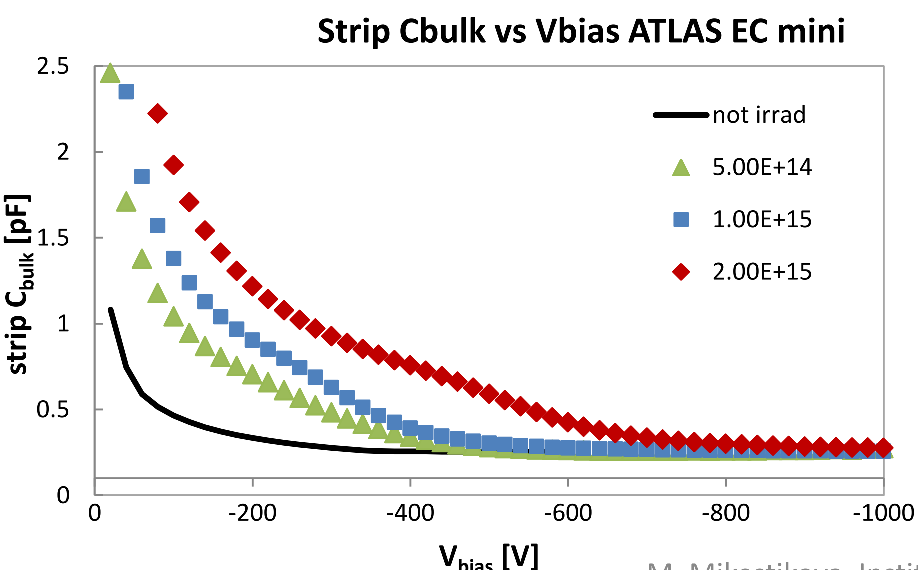


- The higher the irradiation dose the higher then the higher the bias voltage needed for C_{int} to saturate.
- The FDV of Gamma irradiated sensors is not changing with gamma dose => C_{int} constant above FDV~350V.
- The FDV of Proton Irradiated sensor is increasing with fluence => C_{int} not saturated up to 1000V for 2E15.
- C_{int} measurements influenced by the contribution of the strip-to-backplane capacitance (C_{bulk}).

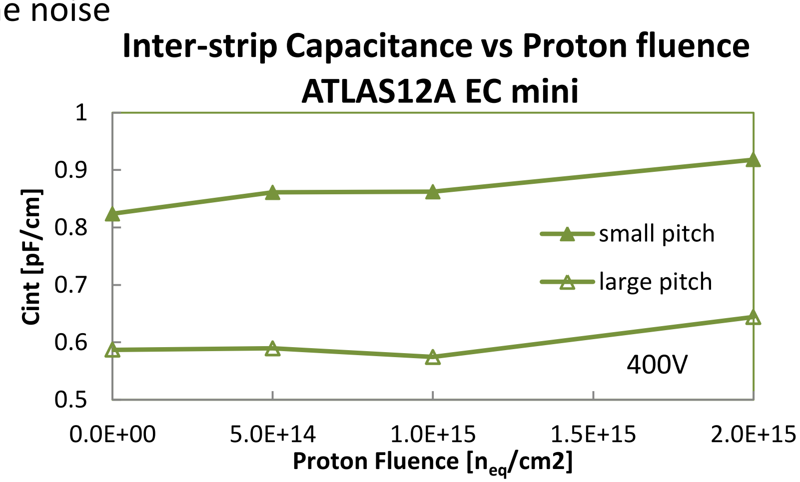
Inter-strip capacitance after proton irradiation

B'ham irradiation





- **Inter-strip capacitance is not changing with proton fluence.**
- Small changes in values of measured C_{int} is probably due to the contribution of $C_{bulk.}$
  - C_{bulk} of depleted sensor is ~ 0.25pF (0.31pF/cm).
  - C_{bulk} at 400V for 2e15 sensor ~0.75pF (0.93pF/cm)
  - C_{int} (saturated value) ~ 0.65pF (0.81pF/cm)
- But … both the C_{int} and C_{bulk} contribute to the noise of the front-end electronics and C_{bulk} dominates in heavy irradiated sensors.
- Need to be verified by simulation and by measuring effect on the noise



Cint stability