Radiation Hard Sensor Materials for the CMS Tracker Upgrade
The CMS HPK Campaign

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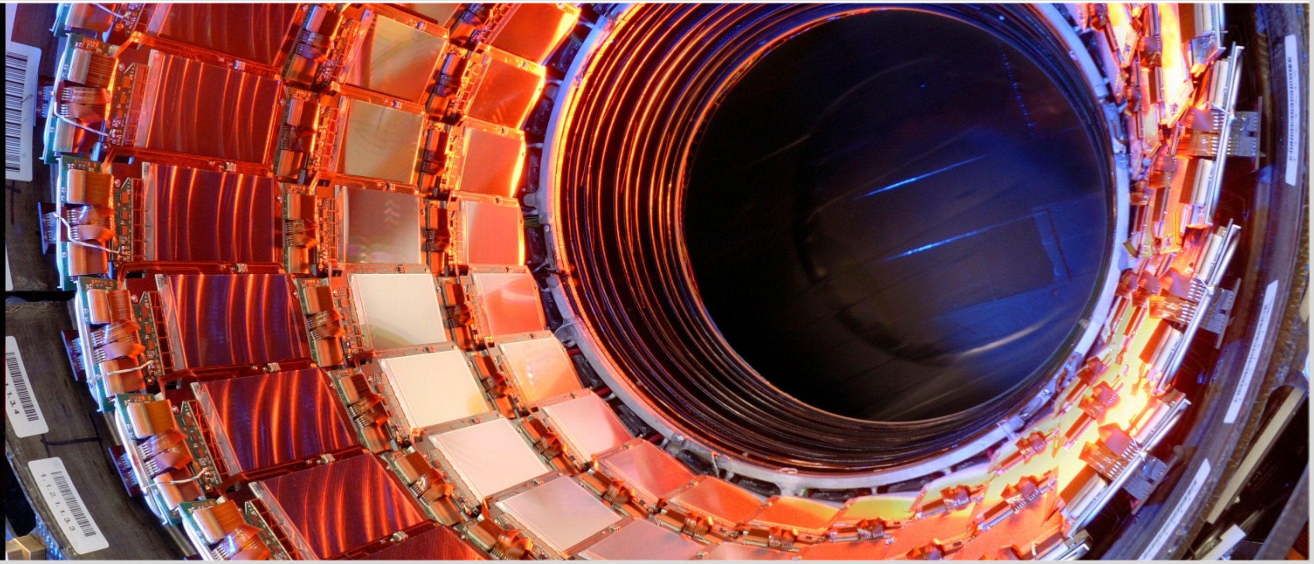

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KIT – University of the State of Baden-Wuerttemberg and National Research
Center of the Helmholtz Association

Goals of the HPK Campaign

- Identify the material baseline for the Tracker Upgrade Phase II
  - float-zone (FZ) material: 320µm and 200µm
  - magnetic Czochralski (MCz): 200µm
  - p-in-n (N) vs. n-in-p (P,Y) technology
- Identify the main layout parameter:
  - Strip pitch
  - width/pitch-ratio
  - Isolation techniques of P-type sensors
    - p-spray (Y)
    - p-stop (P)
- Identify possible new sensor design with intergrated PA or higher granularity
- Labeling example for strip sensor: float-zone, 320µm, p-stop = FZ320P

HPK Campaign terms:

- Conditions:
  - Ordered 144 wafers of 6-inch size
  - Comparabiltiy given -> produced by one vendor: Hamamatsu Photonics K.K.
  - Measurements done at several Institutes across Europe (17 participating Institutes)
  - Cross-calibration of measurements

- Investigation of:
  - General dependence on fluences and particle type:

Overview of fluences (in$10^{14} N_{eq} cm^{-2}$) for different radial positions

Radius/cm	Protons	Neutrons	total
40	3	4	7
20	10	5	15

50% higher than nominal fluences

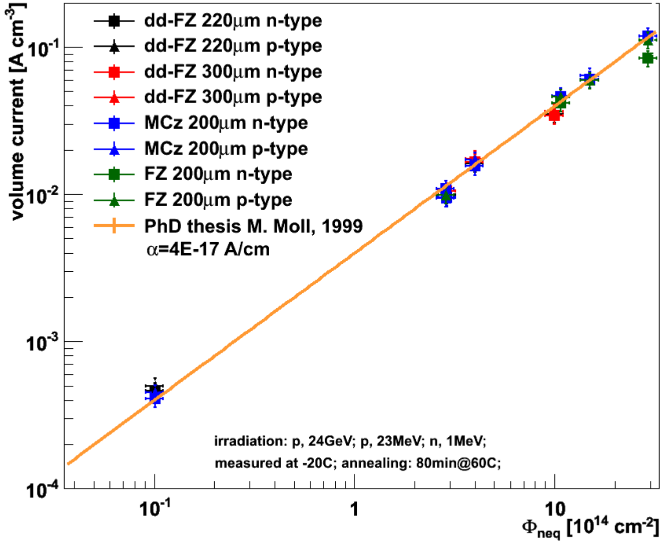
  - Volume currents
  - Strip parameters
  - Charge collection
  - Annealing behaviour of parameters

- T-CAD Simulation studies of sensor material and strip parmeters

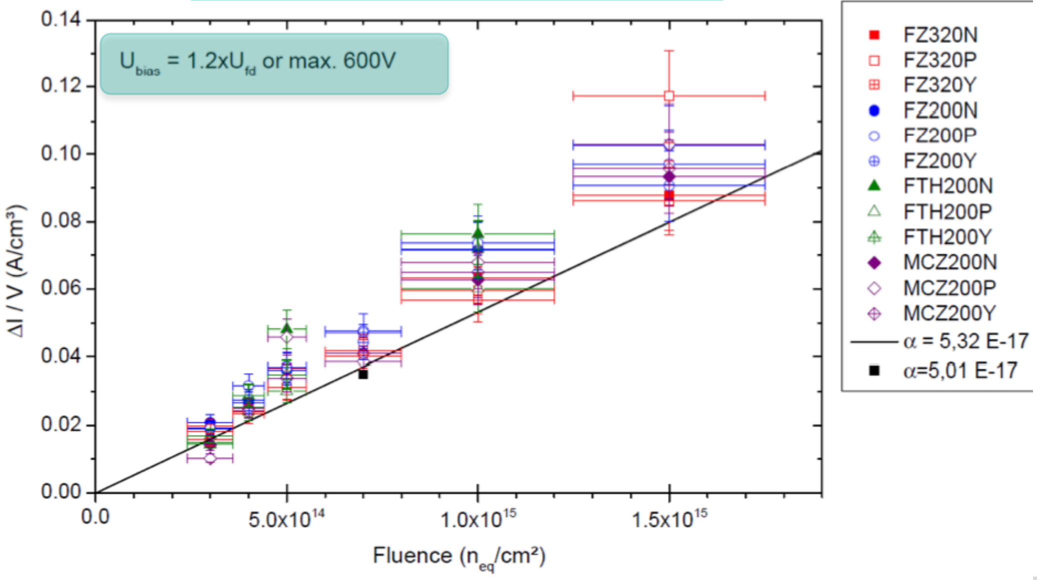
Total leakage current

- Alpha parameter: current related damage rate
- Independent of material, irradiation fluence and particle
- No correlation observed with sensor type and material
- Measured current for strip sensors higher compared to expectation

current of diodes

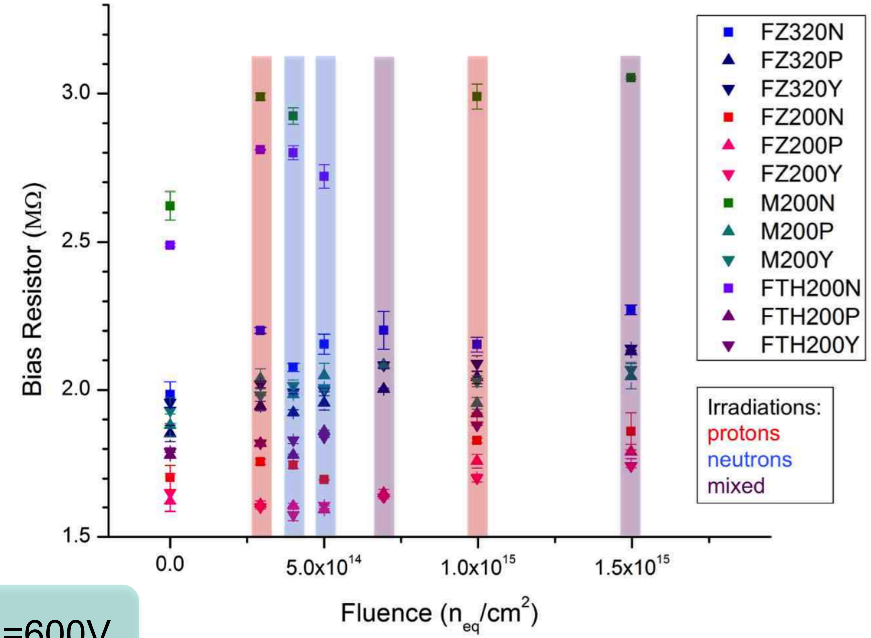


current of strip sensors

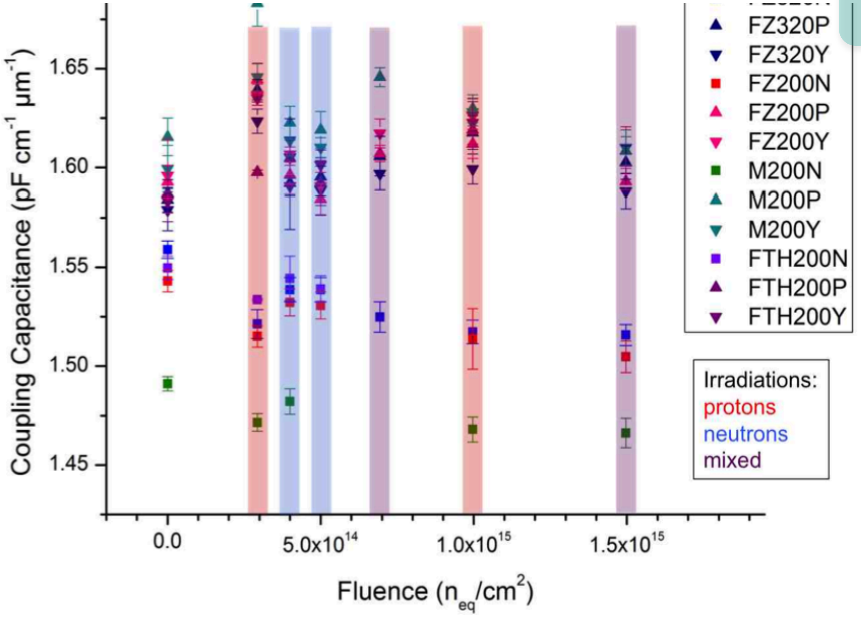


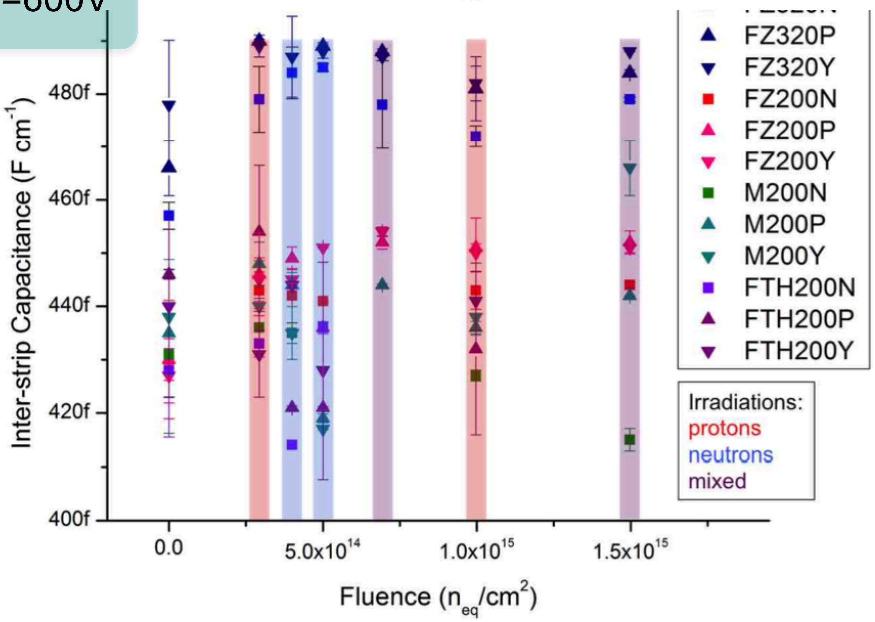
Strip parameters I

- Coupling capacitance $C_{c:}$
- Interstrip capacitance $C_{int:}$
- Polyresistance R_{poly}
  - No significant change with irradiation



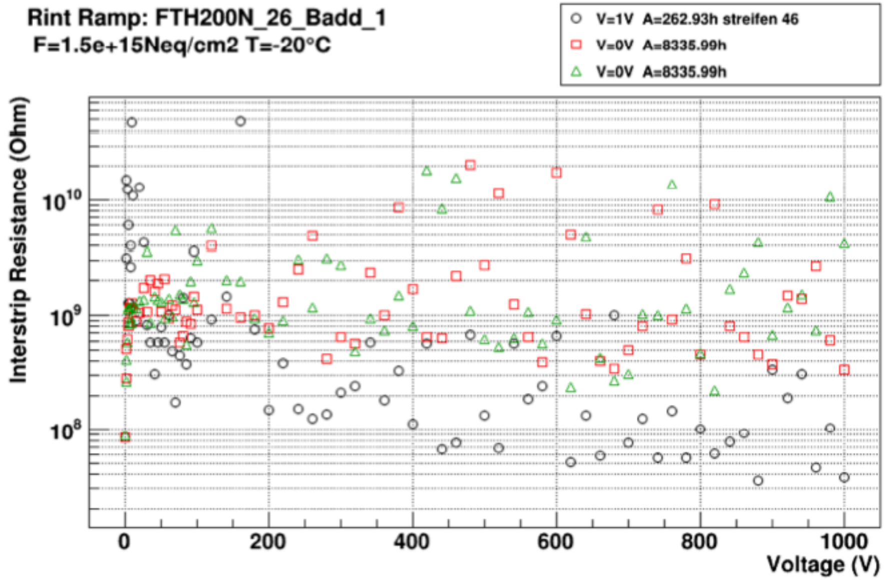
V_{bias}=600V

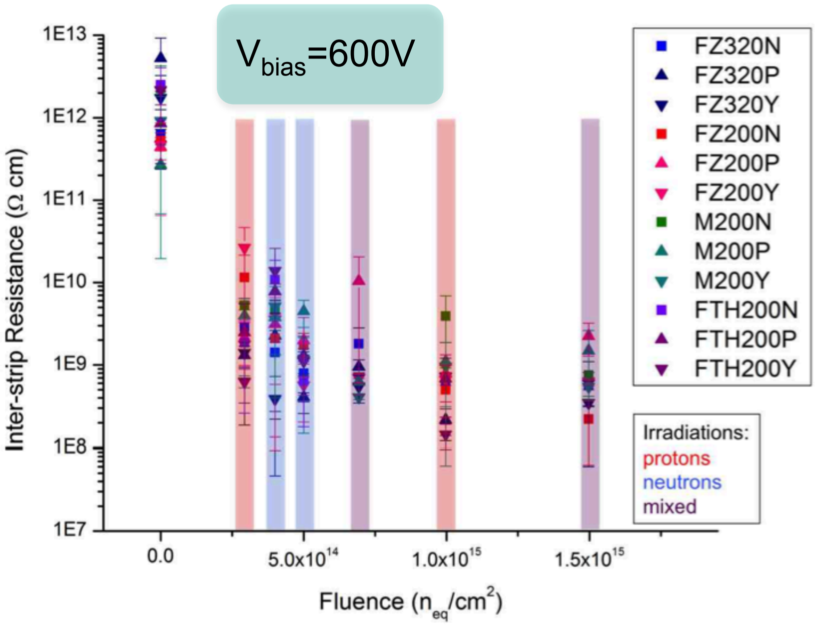


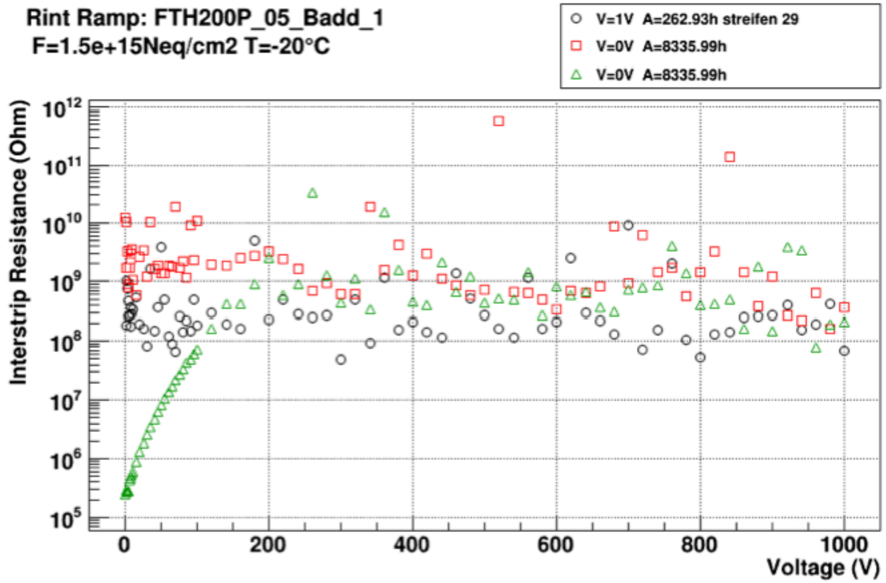


Strip parameters II

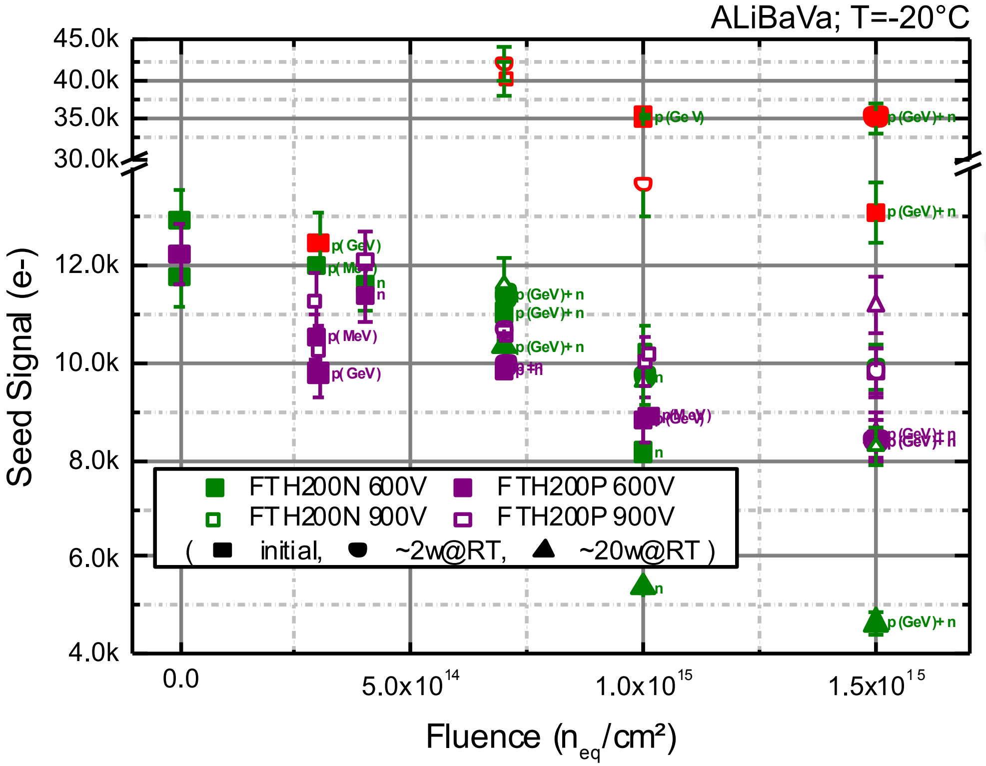
- Interstrip Resistance R_{int}
  - R_{int} drops with fluence from several GOhmcm to some 100MOhmcm
  - Nevertheless R_{int} still much higher compared to R_{poly}(~2MOhm) -> strip isolation is sufficient
  - No dependence on annealing, P and N, p-stop and p-spray

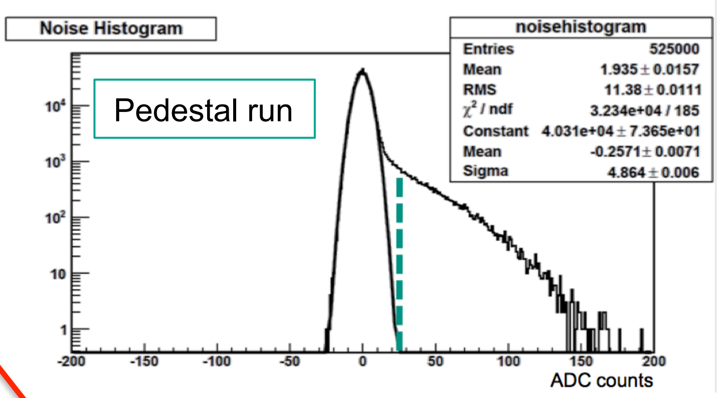



V_{bias}=600V



Signal FTH200

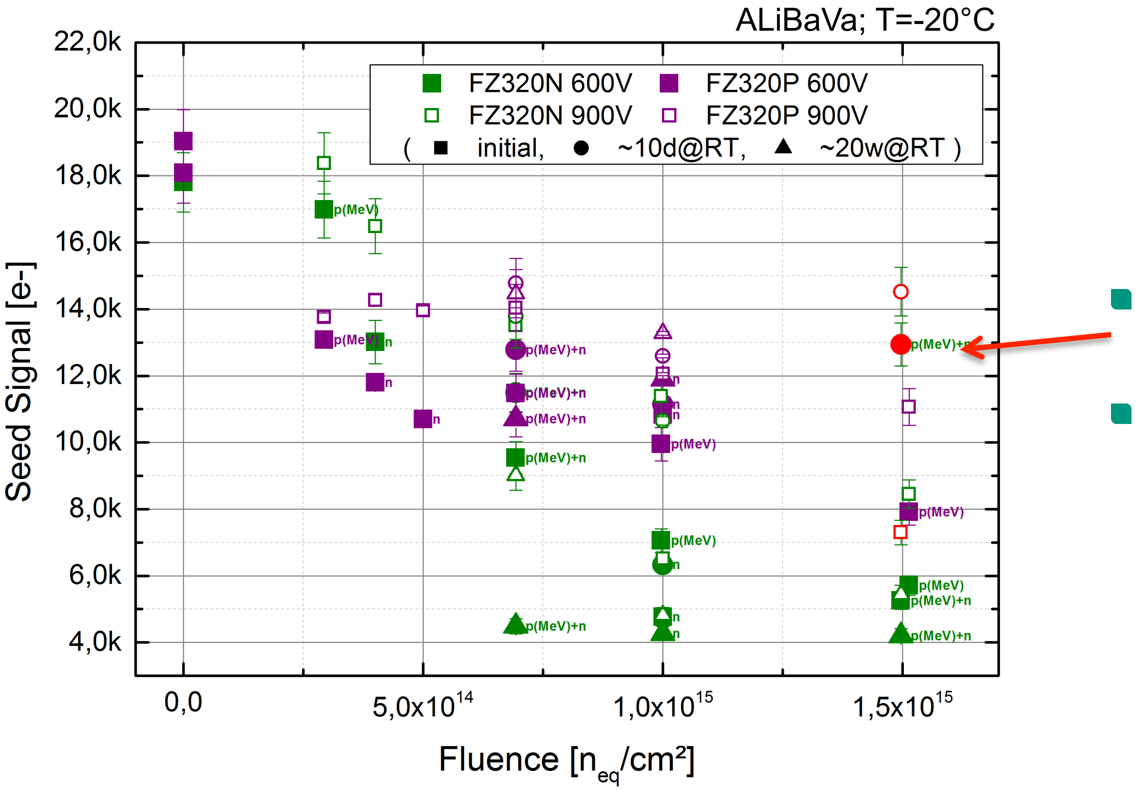




- non-gaussian noise contribution
- just N-type affected
- increases with fluence
- appears at V_{bias} ≥ 600V
- See more later...

- F ≤ 7e14n_{eq}/cm^2 (R~60cm): N-type at 600V shows higher seed signal than P-type, due to cluster size
- After F ≥ 7e14n_{eq}/cm^2 (R~40cm): N-type has smaller signal if not noisy
- After F ~ 1.5e15n_{eq}/cm^2 (R~20cm): N-type small signal/ high noise
- P-type signal ~ 8 ke$^-$ at 600V / ~10 ke$^-$ at 900V
  - proposed binary chip threshold: 6 ke$^-$

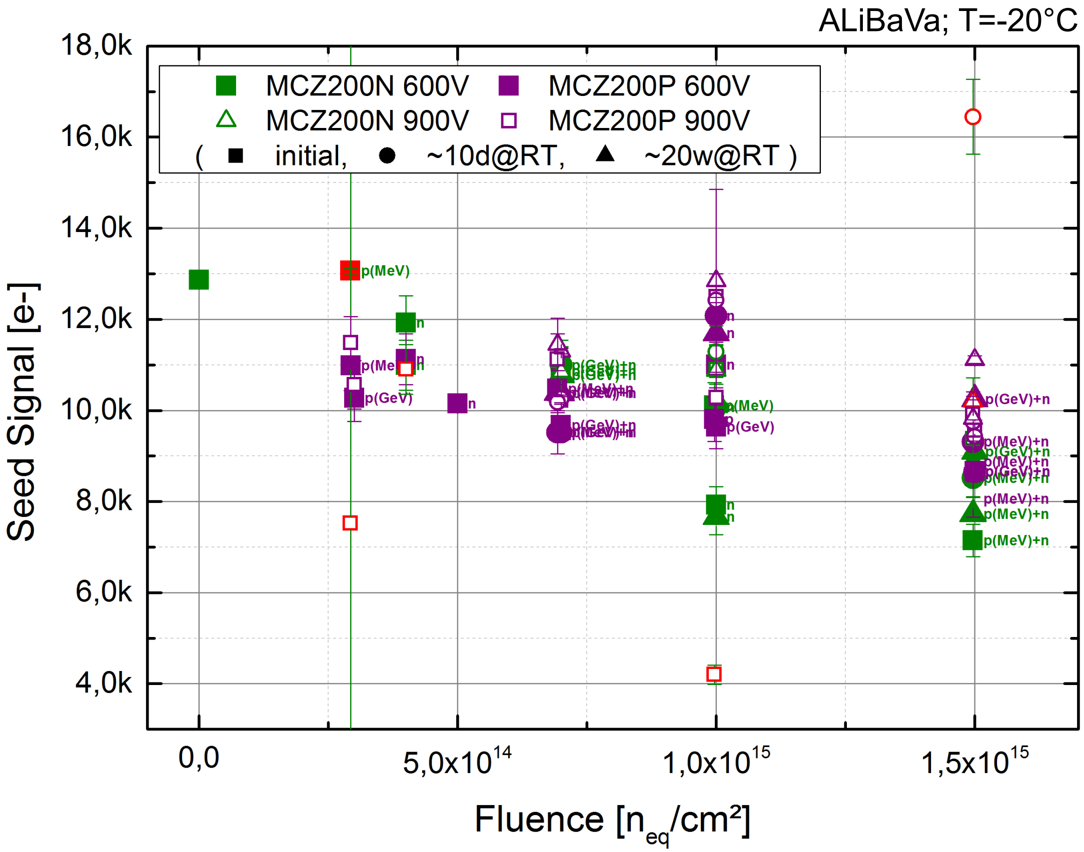
Signal FZ320



- again: red points are noisy measurements
- P-type not affected

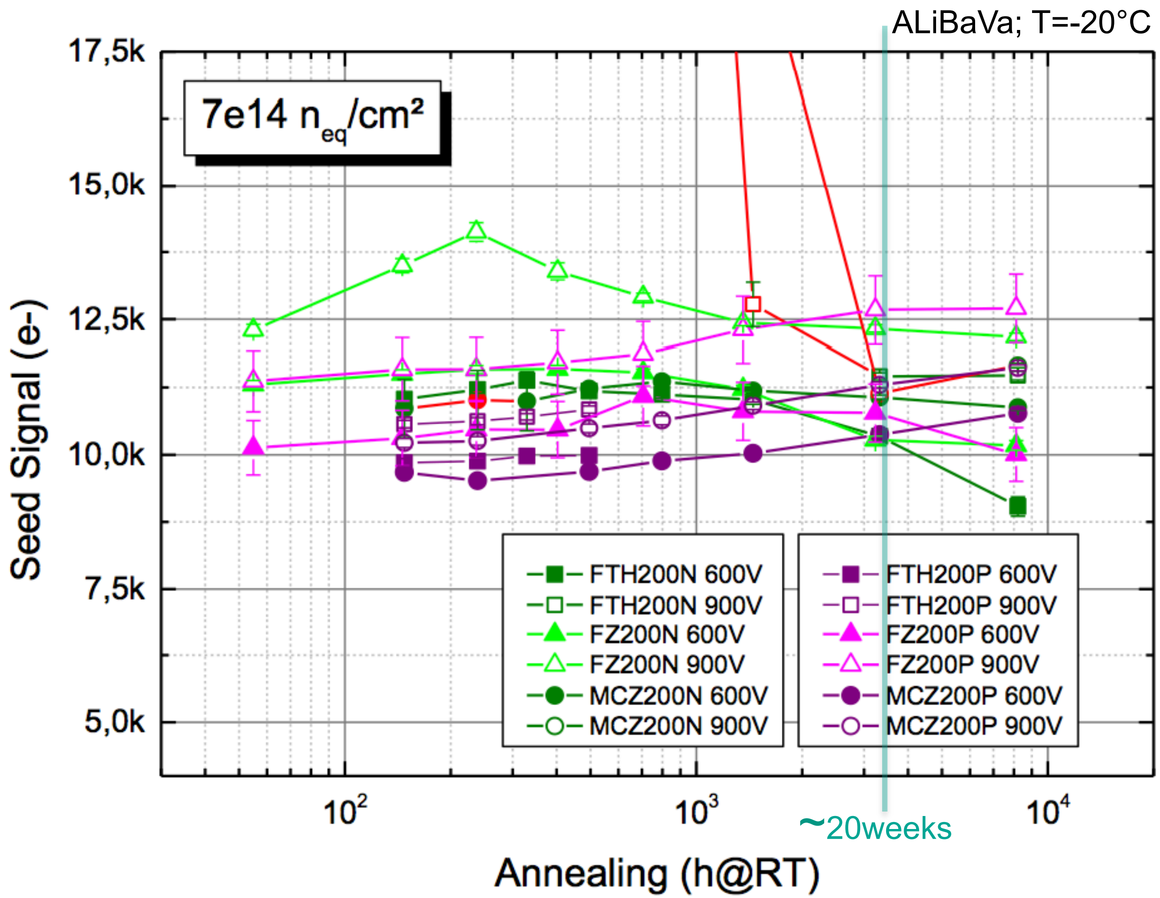
- F < 7e14n_{eq}/cm²: P-type signal lower than N-type
- F ≥ 7e14n_{eq}/cm^2: N-type generates much smaller signal
- F ~ 1.5e15n_{eq}/cm^2: N-type below 6 ke$^-$, or noisy
- P-type ~8 ke$^-$ at 600V/ 11 ke$^-$ at 900V; comparable to FTH200P

Signal MCz200



- F ≥ 7e14n_{eq}/cm^2: N-type generates smaller signal at 600V for n irradiation
- N-type shows RGHs for p irradiation
- F ~ 1.5e15n_{eq}/cm^2: N-type noisy; P-type > 8 ke- for 600V and 900V

Annealing of signal for 200µm – F = 7e14 n_{eq}/cm^2



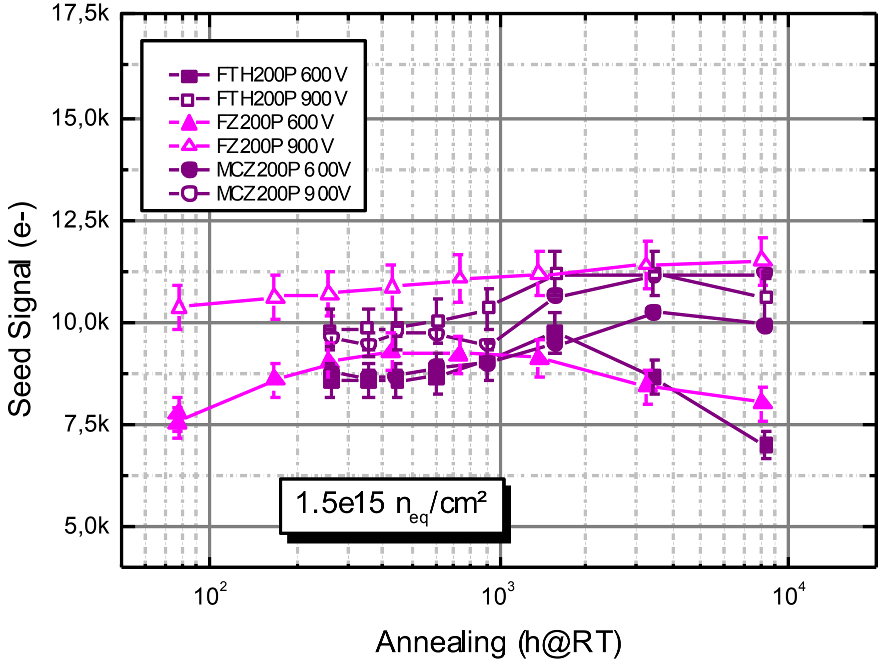
- F = 7e14n_{eq}/cm^2: 200µm sensors well in a band above ~10 to 12 ke^-
- signal constant for all annealing times

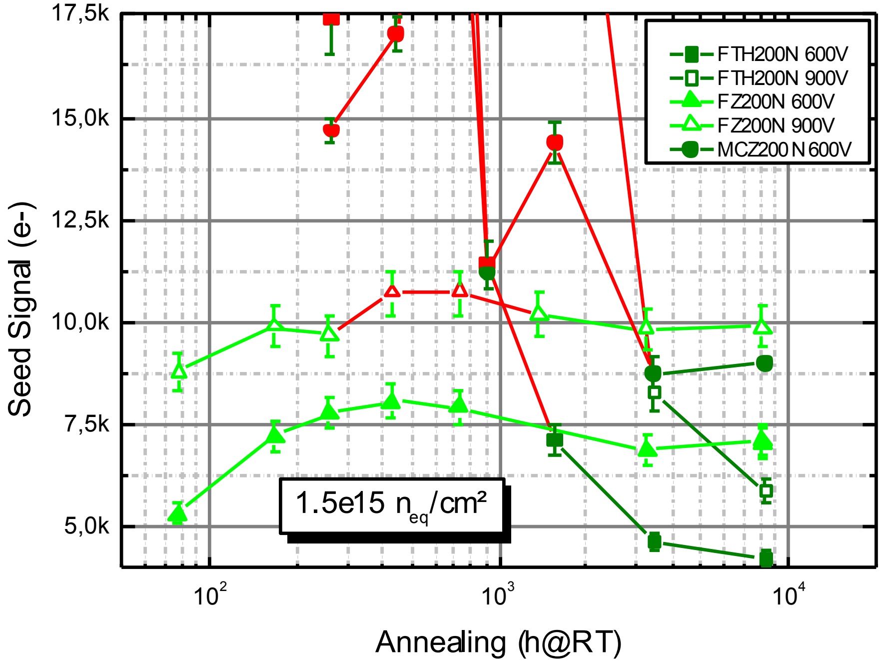
Annealing of signal for 200µm – F = 1.5e15 n_{eq}/cm^2

P-type

ALiBaVa; T=-20°C

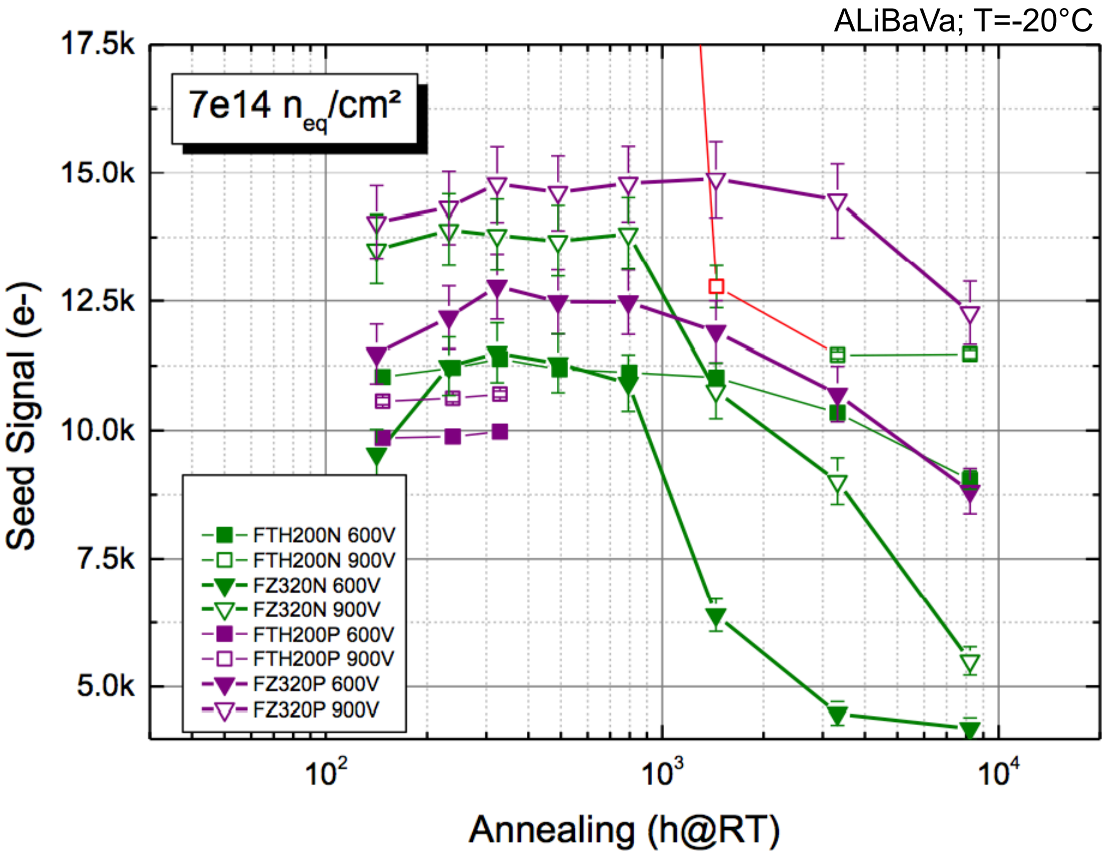
N-type





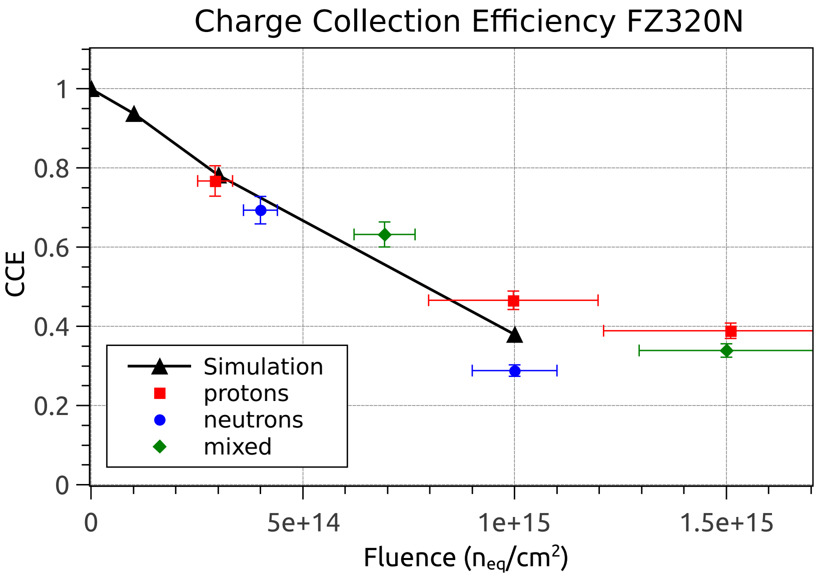
- F = 1.5e15n_{eq}/cm^2: P-type well above 7.5 ke^- until ~20w@RT
- N-type drops sharply with annealing time
- Most of the time N-type sensors show huge number of RGH (red points >1%)

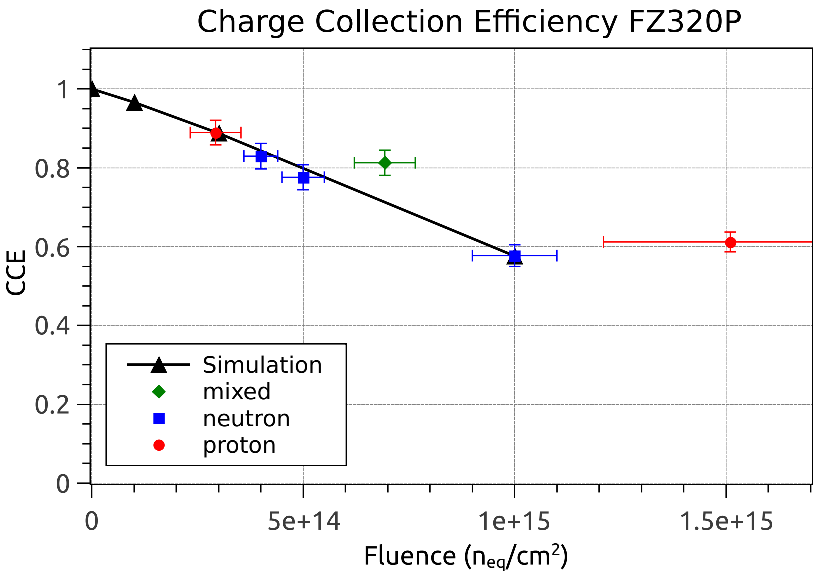
Annealing of signal for 320µm and 200µm



- signal of 320µm higher compared to 200µm for most of annealing time
- N-type drops strongly after ~40 days of annealing @RT; P-type little less
- 320µm annealing not constant over time -> more control during operation necessary

Signal – T-CAD Simulation studies



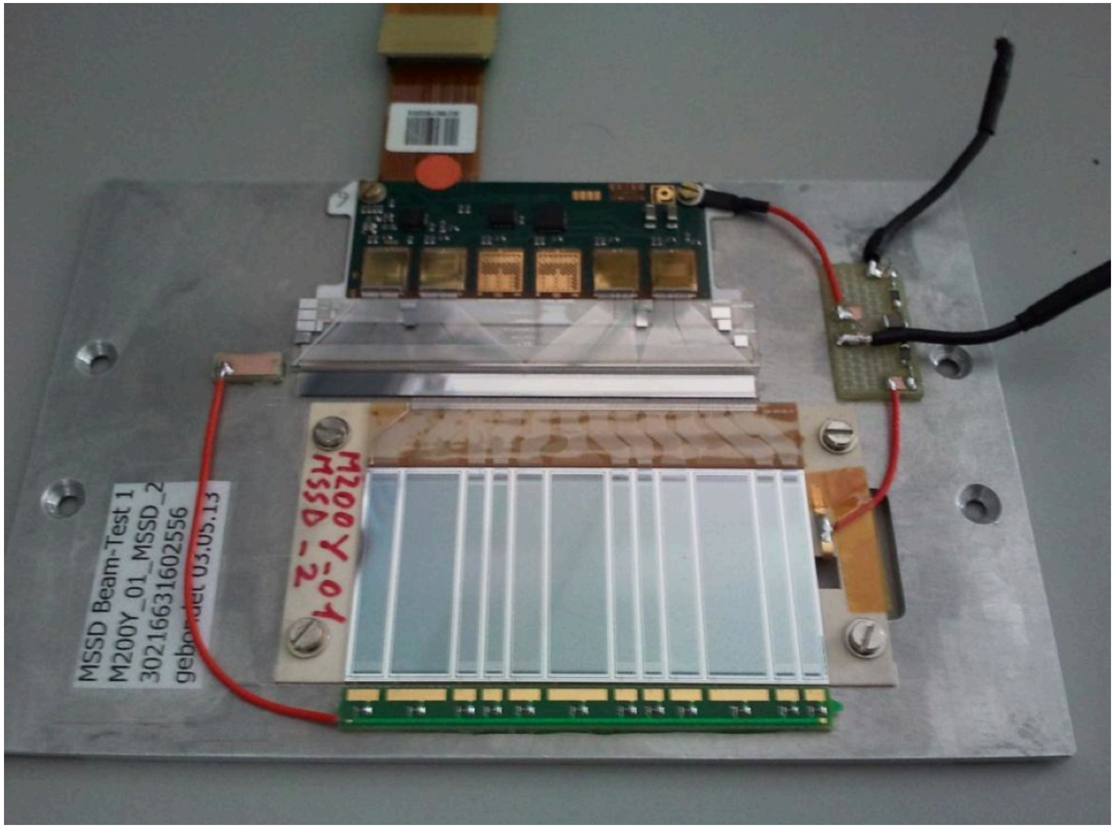


- Simulation studies of charge collection efficiency CCE:
  - radiation damage models developed for neutrons and protons
  - Reproduction of measurements succesful
  - Predictions for new sensors and runs possible

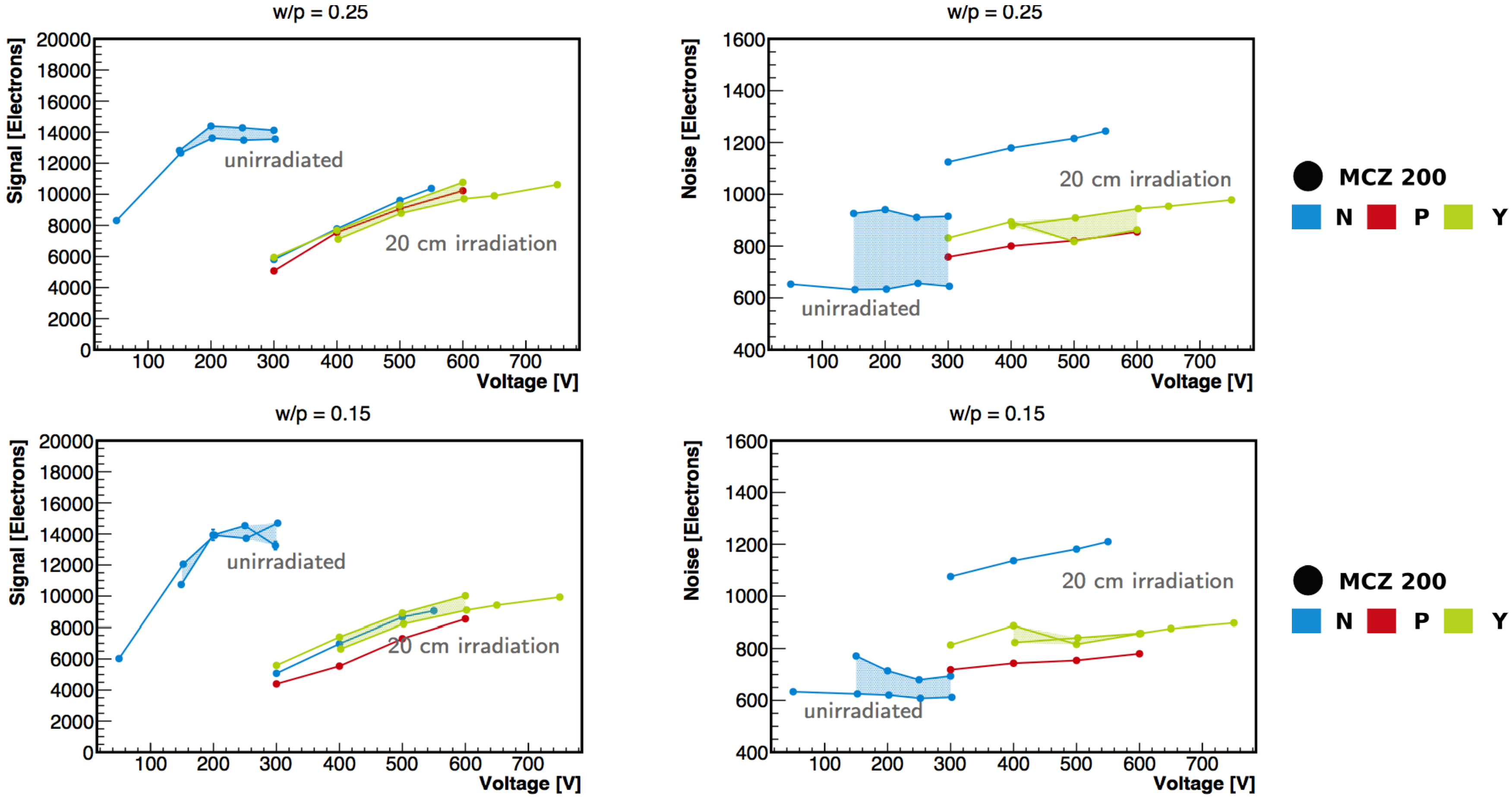
MSSD – multi-geometry sensor

- 12 regions, each 32 strips with different pitches and w/p-ratios
- P= 70µm, 80µm, 120µm, 240µm
- w/p= ~0.15, ~0.25, ~0.33
- FZ, FTH, MCz; N- and P-type

- MSSD samples irradiated:
  - 20cm: p and n
  - 40cm: p or n



MSSD – BeamTest results



- cluster signal ~10 ke$^-$ in accordance to seed signal of ~8 ke$^-$
- noise of N-type much higher compared to P-type

Noise contribution

- Symmetric and asymmetric noise seen dependend on material
    - Pedestal runs in AliBaVa station with BeetleChip

- Non-gaussian noise/ Random Ghost Hits RGH mainly on n-type sensors irradiated with charged hadrons
    - Random ghost hits (RGH): number of hits per strip and event above 5σ of gaussian fit divieded by #strips and #events in a pedestal run without source
    - A number above 1% was defined as bad, since this would generate 1% occupancy with fakes
    - fake hits equally distributed over all strips

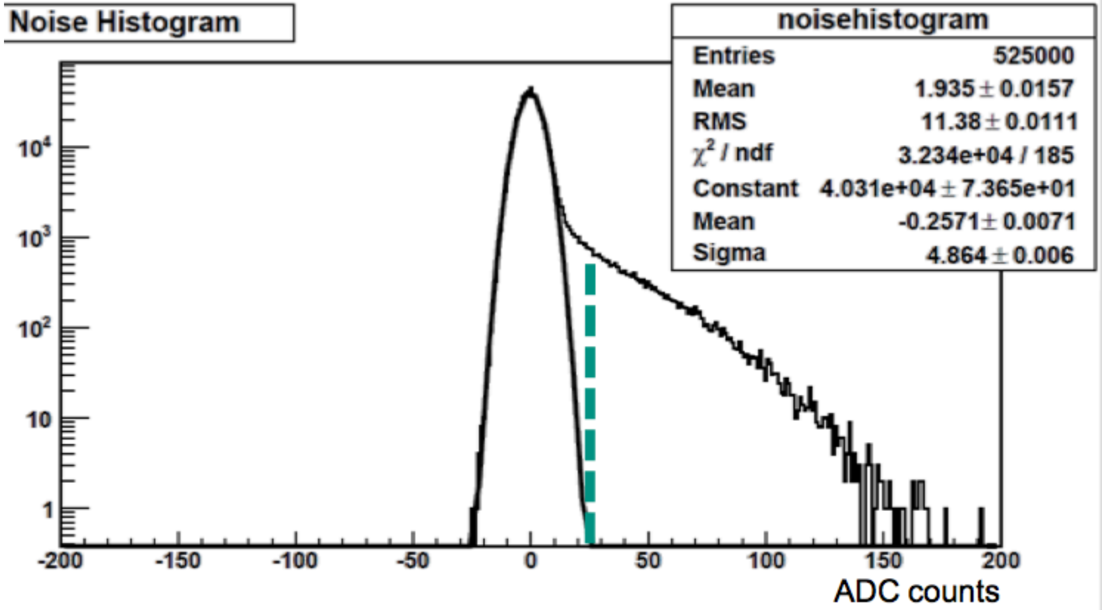


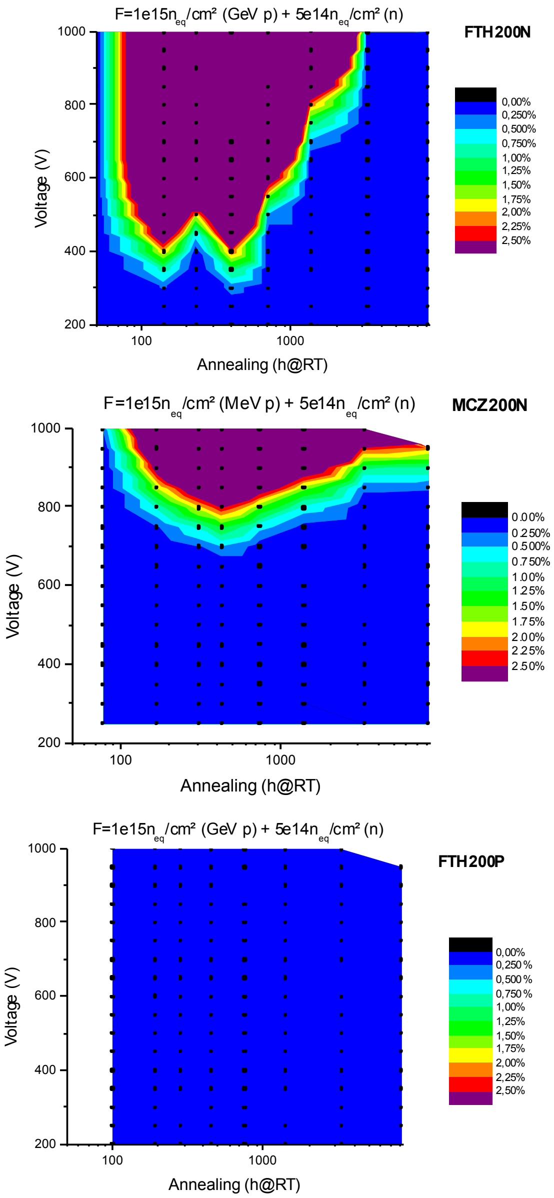
Fig.: Noise histogram from pedestal run

Random Ghost Hits

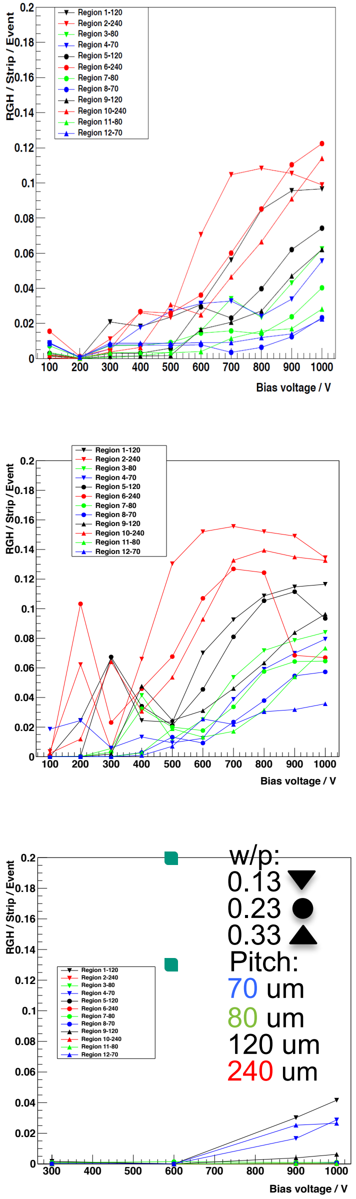
- Non-gaussian noise seen for N-type FZ and MCz material after short annealing
  - large RGH phase space for N-type
  - P-type almost not affected

- MSSD:
  - Increase of RGH occupancy with bias voltage for all regions in N-type
  - Regions with larger pitch affected first
  - Regions with small strip width affected first
  - P-type almost no RGH

Standard sensor



MSSD



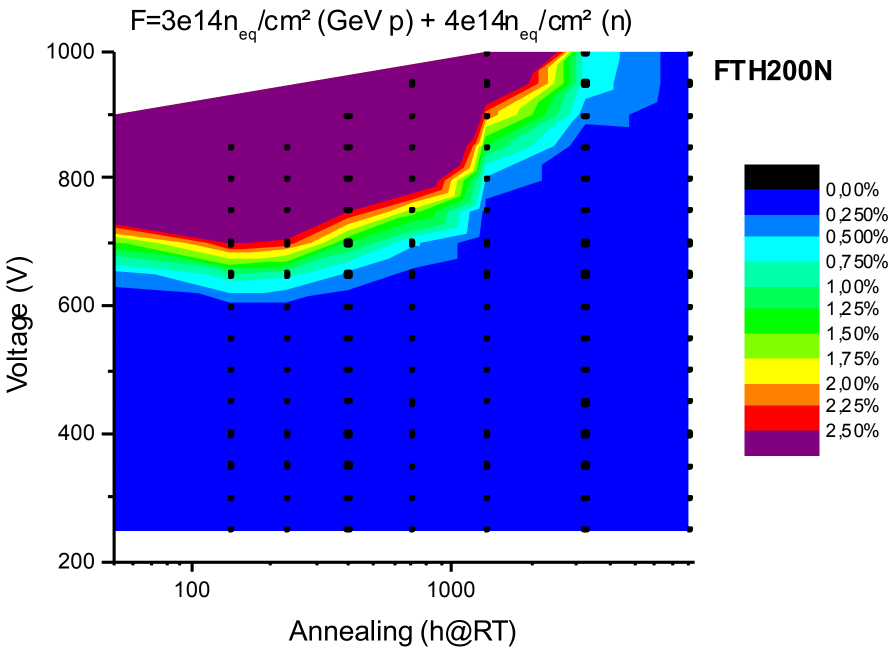
FTH200N

MCz200N

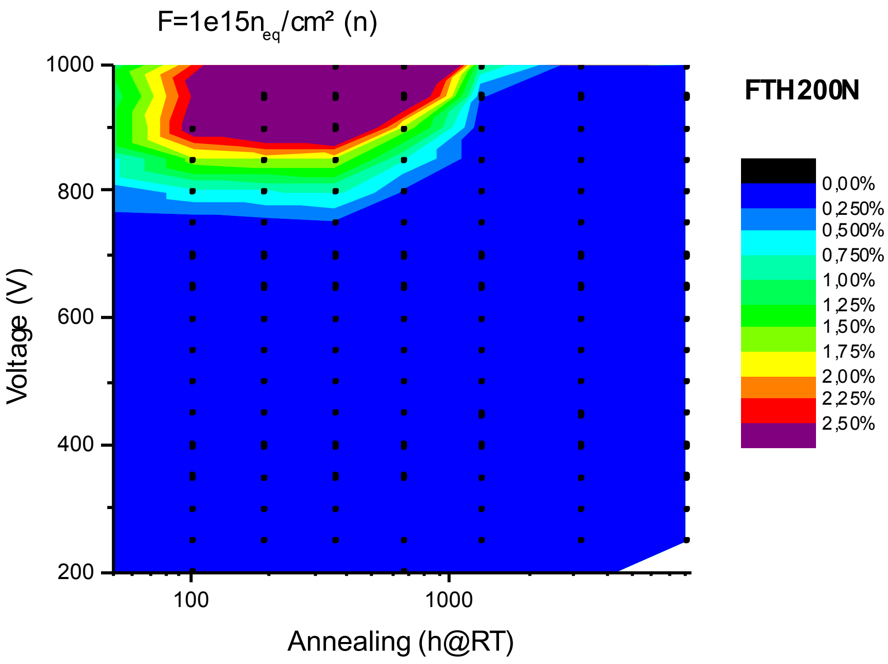
FTH200P

Neutrons only

7e14n_{eq}/cm² mixed

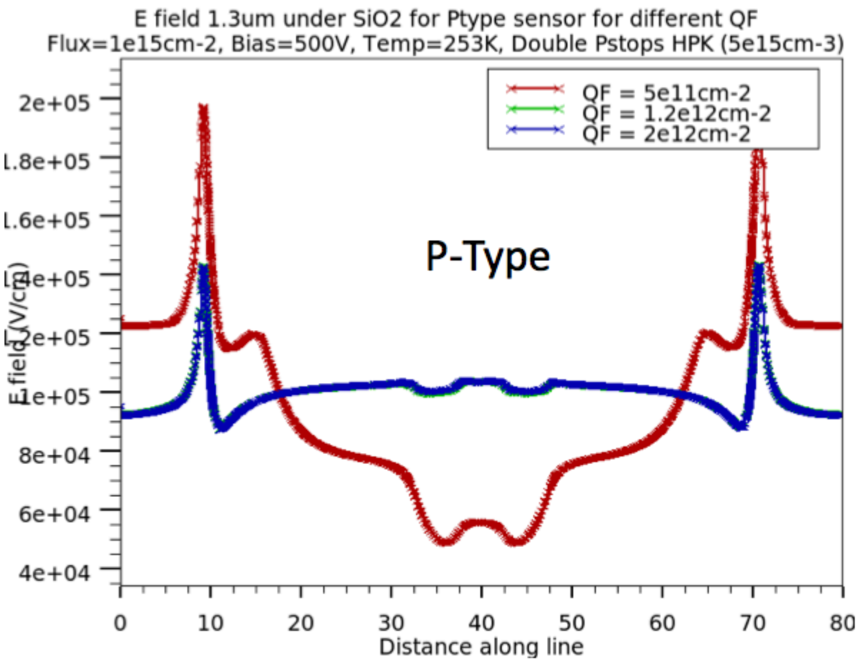


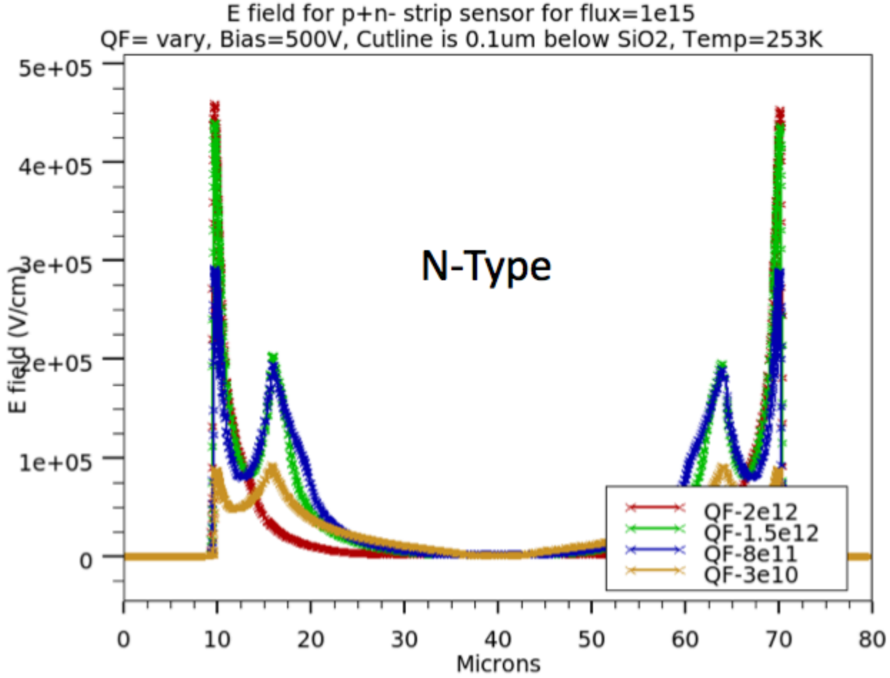
10e14n_{eq}/cm² neutrons



- Effect is much reduced for neutron only irradiation
- Dependence on ionizing radiation hints towards a combined effect of bulk damage and surface charge Q_f

Simulation of electric fields in N- and P-type





- Peak electric field is higher for N-type compared to P-type sensor
- P-type: peak E-field decreases with increasing surface damage Q_f
- N-type: peak E-field increaes with Q_f
    - Micro-discharge possibility higher for N-type sensors

Sum up

- Strip parameters slightly affected by radiation for N- and P-type but R_{int} which is still high enough to ensure strip isolation

- N-type material shows higher seed signal than P-type when:
  - irradiated with pure protons up to ~3e14n_{eq}/cm² for 320µm thickness
  - up to 7e14n_{eq}/cm² for 200µm

- Above 7e14n_{eq}/cm² signals in N-type material are smaller than in P-type, since the required higher operation voltage generates RGHs

- Long annealing leads to strong decrease of CCE in thick N-type sensors

- Signal of thin sensors constant over annealing time; ensures correct operation

- All N-type sensors show non-gaussian noise after hadron irradiation , P-type sensors don‘t

- T-CAD Simulation studies:
  - Very good agreement with measurements even for the irradiated sensors
  - N-type show higher electric field strenghts compared to P-type

KIT
Karlsruher Institut für Technologie

Thank you and especially to the sensor group and the people who provided results and the plots!

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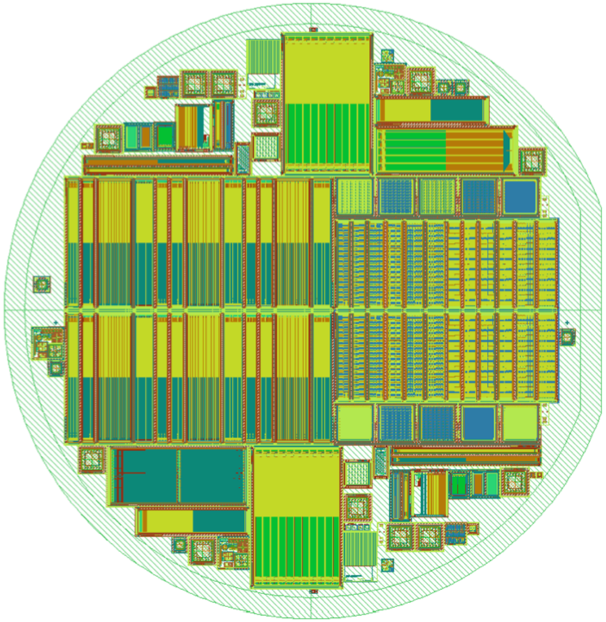

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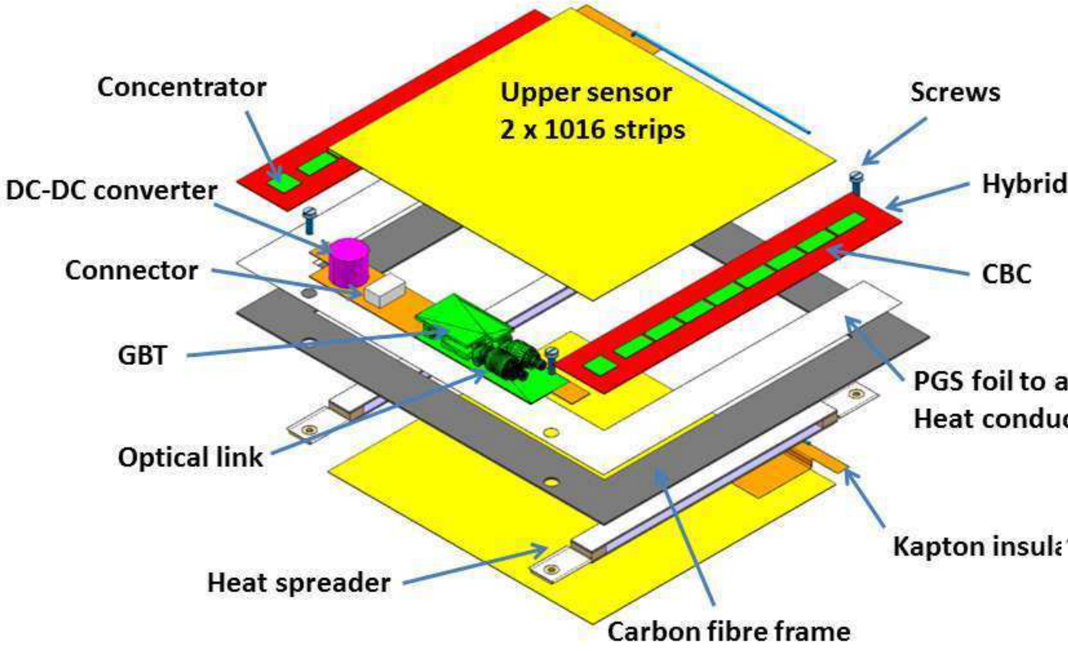
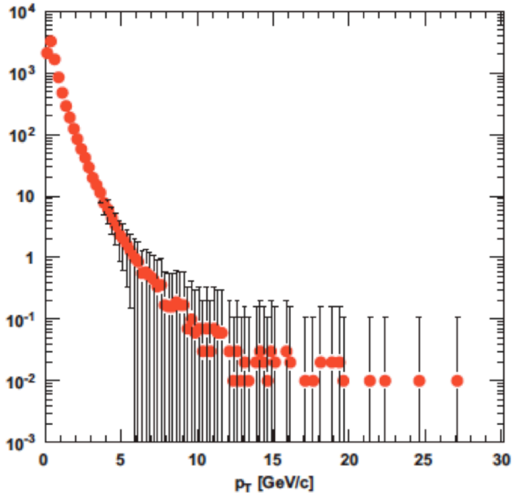
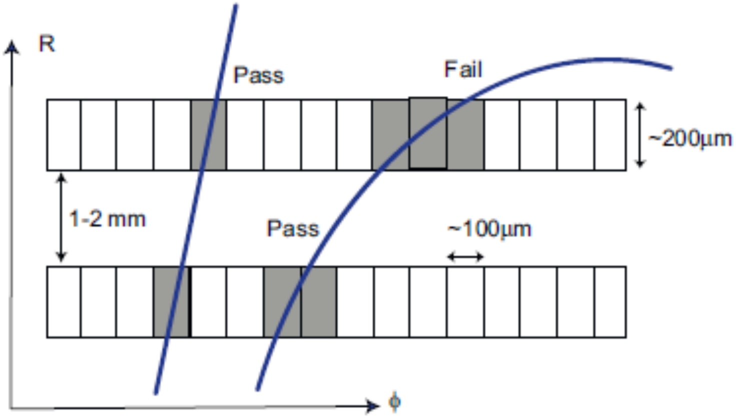
Backup

2S-module





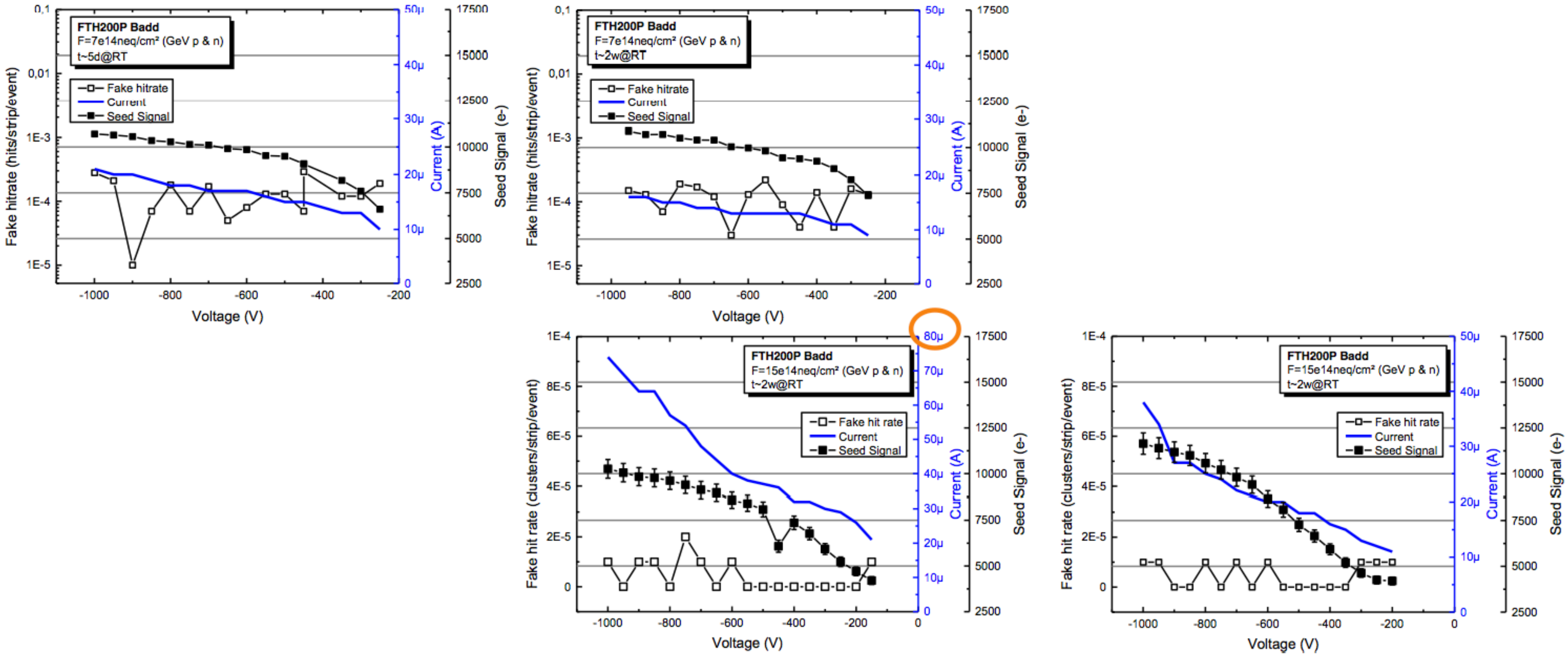


Voltage Ramps – FTH200P

short 2w@RT 20w@RT

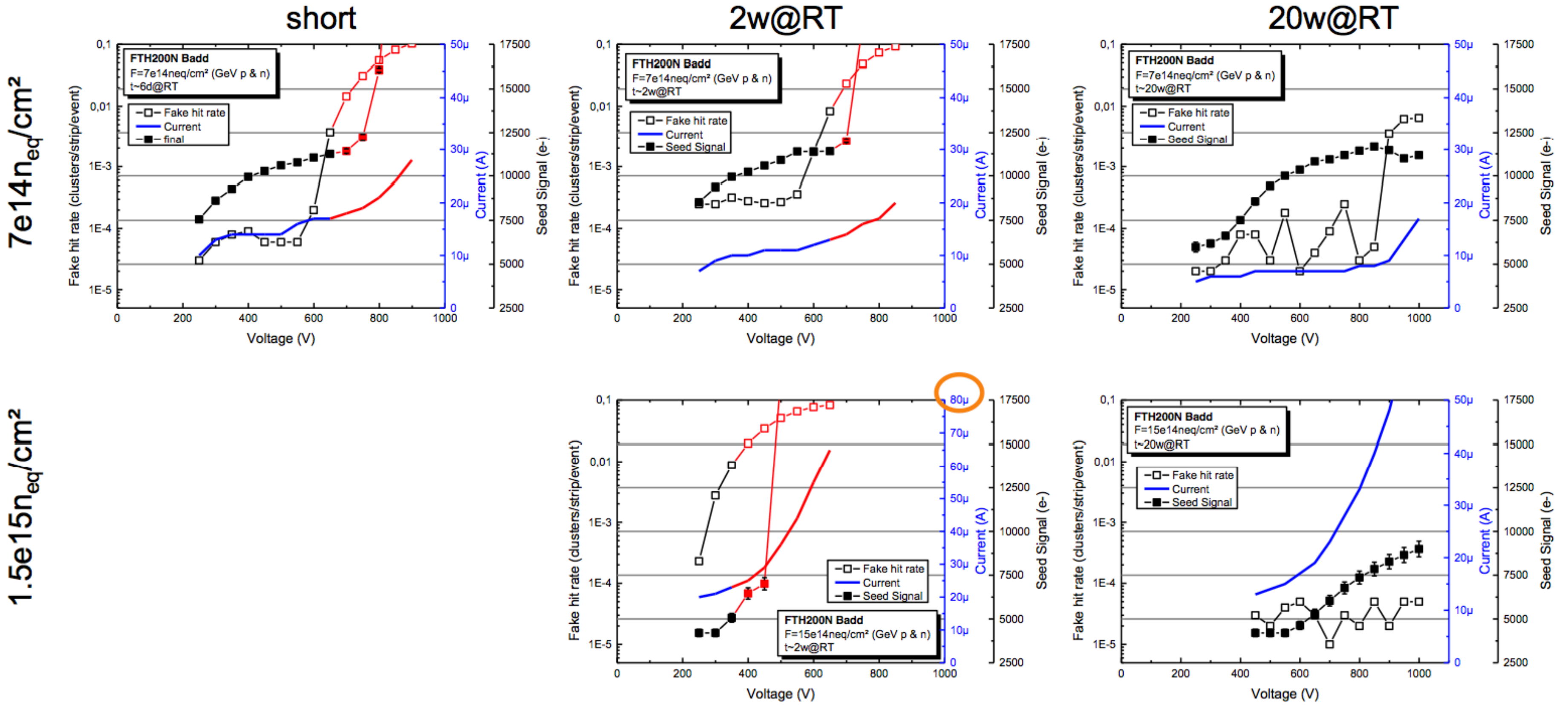
$7e14 n_{eq}/cm^2$

$1.5e15 n_{eq}/cm^2$



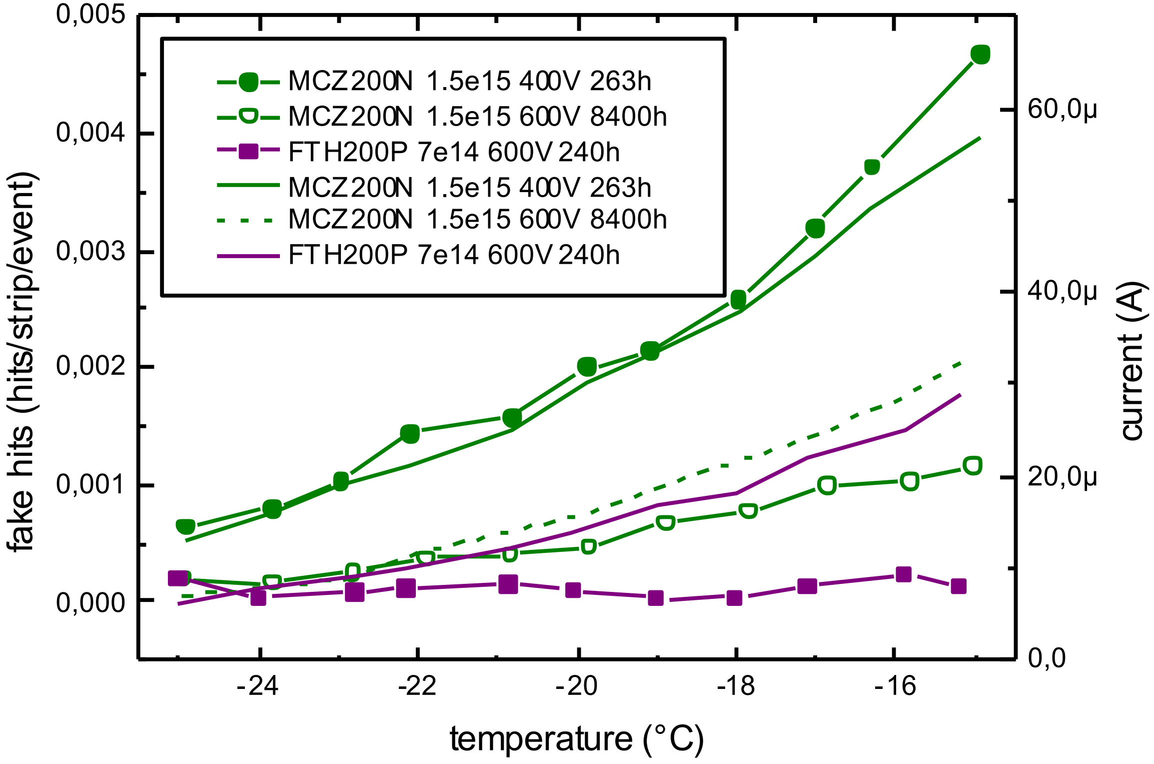
- p-type also shows steeper current increase at HV in some cases

Voltage Ramps – FTH200N



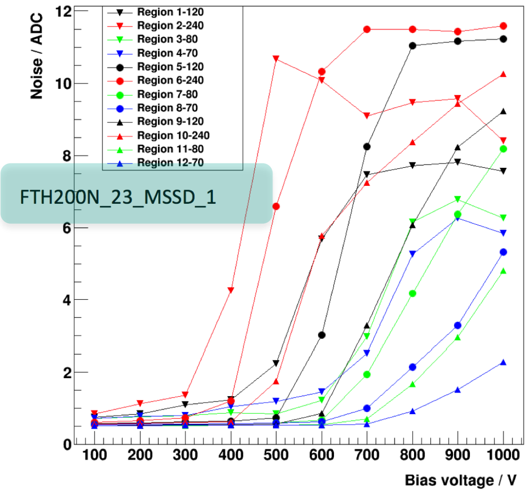
- Steep current increase at HV not necessarily linked to RHGs, but seem to increase when RGH rate increases as well

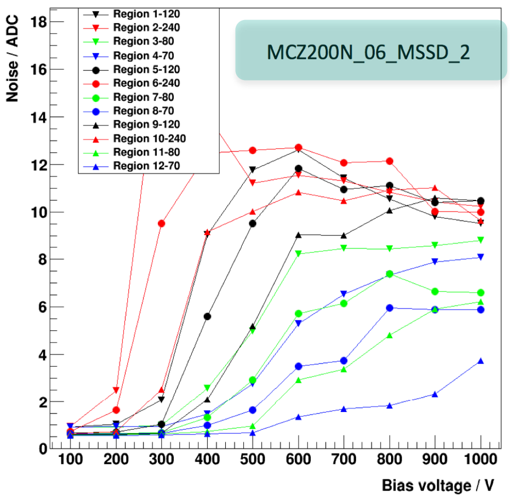
Temperature Dependence of RGHs

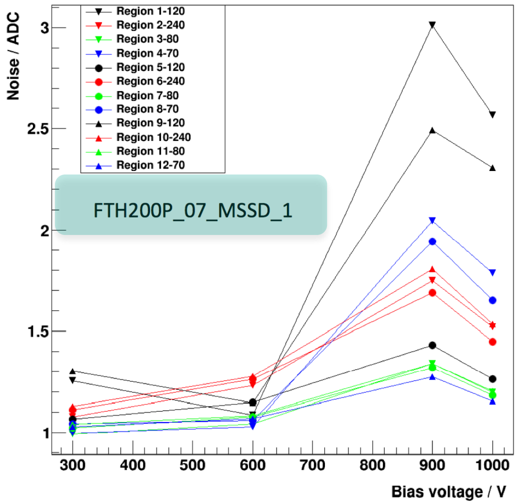


- Fake hit rate increases with temperature following current!
- The increase of fake hit rate is typically linked to an increase in current.
  But an increase in current does not necessarily lead to fake hits.

Symmetric Noise of MSSD sensors

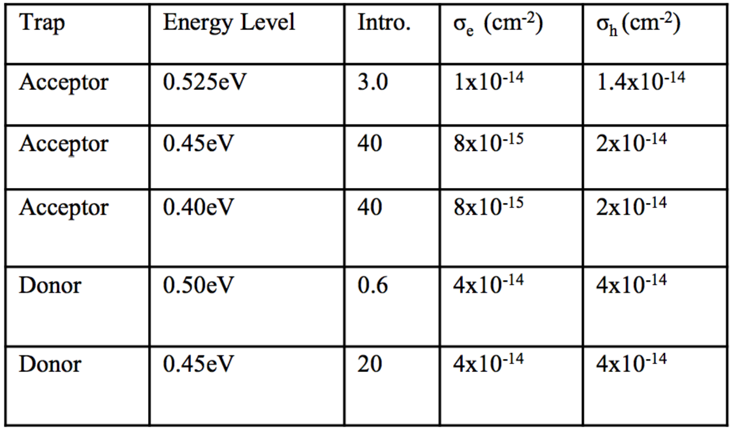

FTH200N_23_MSSD_1


MCZ200N_06_MSSD_2


FTH200P_07_MSSD_1

Five trap model

- Two shallow acceptors and one shallow donor in addition to two deep levels
- Able to remove accumulation e-
- Produce very high E field near n+
- Reproduce experimental observed good Rint and Cint



Trap	Energy Level	Intro.	σ_e (cm^{-2})	σ_h (cm^{-2})
Acceptor	0.525eV	3.0	$1x10^{-14}$	$1.4x10^{-14}$
Acceptor	0.45eV	40	$8x10^{-15}$	$2x10^{-14}$
Acceptor	0.40eV	40	$8x10^{-15}$	$2x10^{-14}$
Donor	0.50eV	0.6	$4x10^{-14}$	$4x10^{-14}$
Donor	0.45eV	20	$4x10^{-14}$	$4x10^{-14}$

- ➢ With one deep acceptor, it is not possible to create enough E field (similar to measurement) near n+ strip along with correct current.
- ➢ We can not use deep acceptors with higher introduction rates as it will change space charge significantly leading to very high avalanche multiplication & simulated current become very high compare to measured one.
- ➢ Moreover, in reality also, shallow levels are created in much more amount compare to deep trap levels