UFSD Charge Collection Studies with the UCSC β-Telescope

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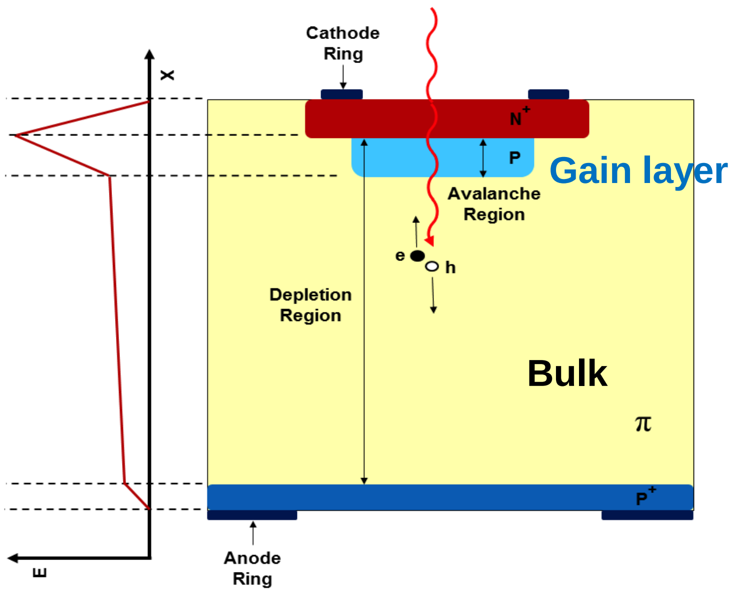
Measurements of the gain and the time resolution of neutron irradiated Ultra-fast Silicon Detectors (UFSD)

- **FBK: LGAD with carbon-implanted boron gain layer (B+C)**
- **HPK: LGAD with thin bulk (35 µm)**

Issues for Low-Gain Avalanche Diodes LGAD

By now we have been working on Ultra-fast Silicon Detectors for about 6 years.
LGAD sensors were proposed and manufactured first by CNM Barcelona and with the addition of FBK and HPK we have now (at least) three commercial manufacturers.



Even then, radiation damage is still an issues which limits the designs and applications of the LGADs. This is due to the fact that we have to consider the effects in both sections of the LGAD:

1. **acceptor removal In the p-multiplication gain layer**
2. **acceptor generation, trapping, leakage current, drift time etc in the p-type bulk.**

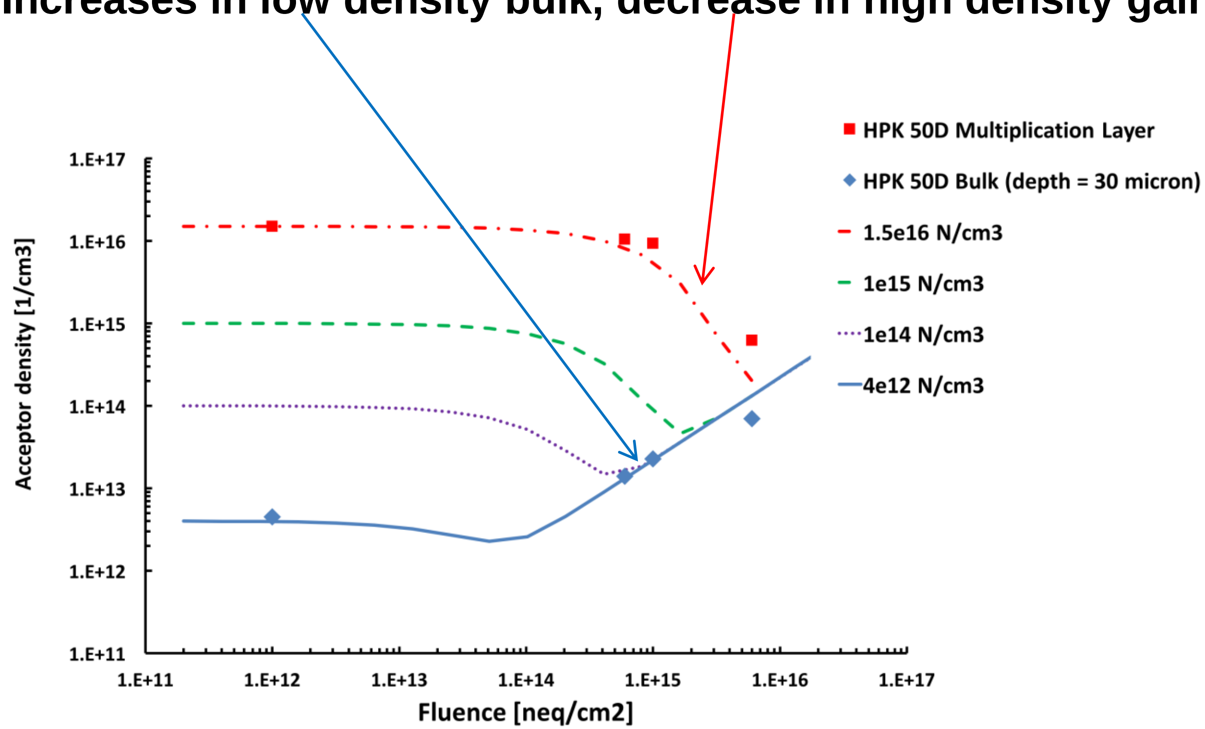
We have measured the charge collection in LGAD designs which address mitigation steps of radiation damage in the two sensors sections:

1. **Addition of carbon in the gain layer (FBK)**
2. **Reduction of the drift distance , i.e. the thickness of the bulk (HPK)**

Acceptor Removal & Creation

All silicon sensors experience creation of acceptors proportional to fluence,
An LGAD specific effect is the gain decrease due to acceptor removal in the gain layer.

Acceptor density vs. fluence:
Increases in low density bulk, decrease in high density gain layer.



Z. Galloway et al, arXiv:1707.04961

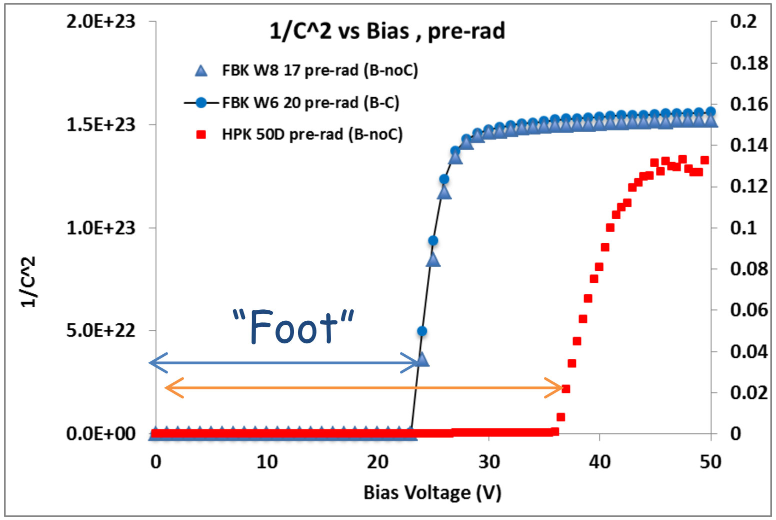
Data from C-V scans on HPK 50D
Simulation from Weightfield 2 (WF2) incorporating G. Kramberger's work.

Carbon implanted LGAD: Doping

- FBK 50 µm
  - W6: B-doping with Carbon (B+C)
  - W8: B-doping without Carbon (B-noC)

  :
  (compare to):

- HPK 50 µm LGAD without Carbon
  - 50D (B-noC)

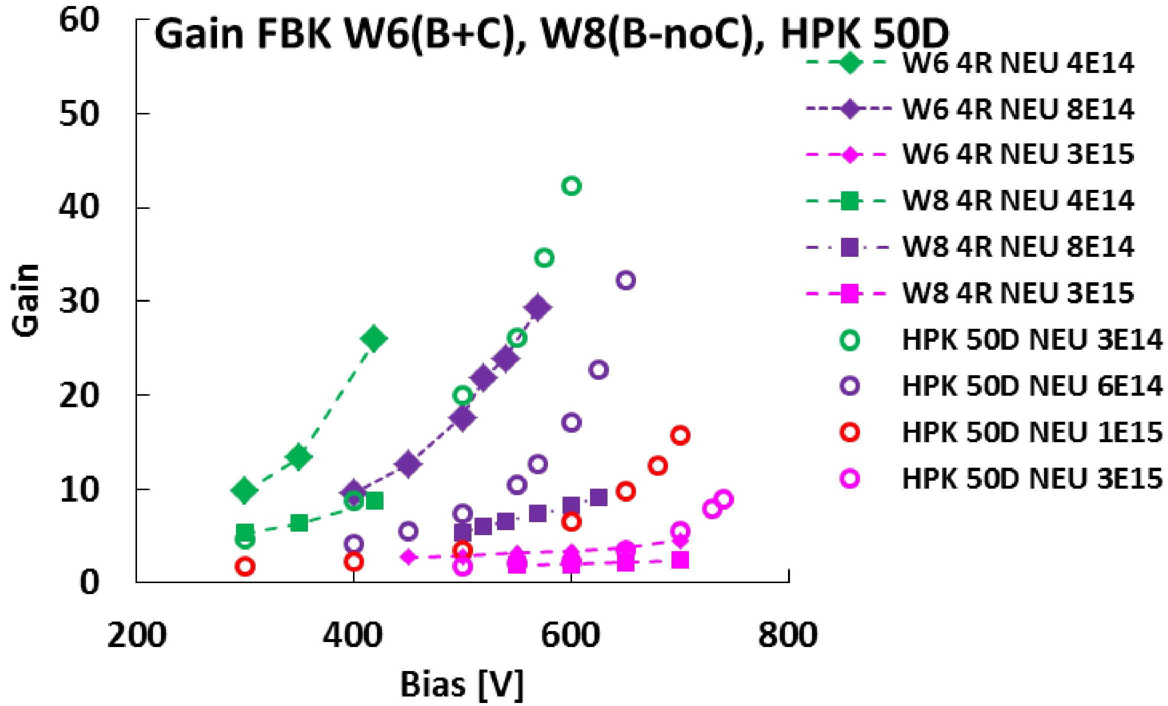


Identical C-V curves for FBK W6(B+C) and W8(B-noC)
Different doping profile of multiplication layer and bulk for FBK and HPK
Rise time difference between FBK and HPK indicates small difference in thickness

Depletion Voltage of gain layer ("Foot"):
FBK: 23 V
HPK: 36 V
Slope (reflects the doping of the bulk):
Lower in HPK: -> higher doping in bulk, higher bias needed

Details of the carbon-implanted LGAD are presented in papers 92,93,95

Bias Dependence of Gain



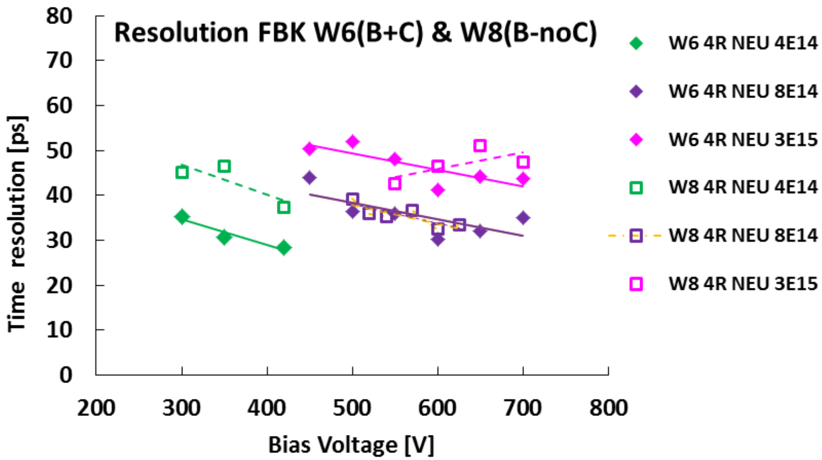
FBK devices have filled symbols and are connected by lines

Fluence color code
3e14, , 4e14
6e14, 8e4
1e15
3e15

Effect of Initial conditions:
Consequence of higher doping in HPK: **higher bias**
Consequence of carbon implantation in FBK W6(B+C): **higher gain** than W8(B-noC**)**

Time Resolution (optimized CFD%)

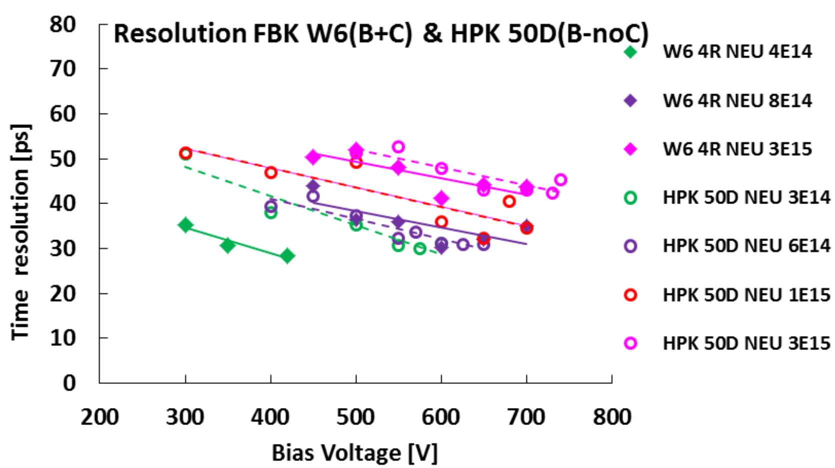
Fluence color code
3e14, , 4e14, 6e14, 8e4,1e15, 3e15



(N.B. Straight lines to guide the eye only)

All LGAD achieve time resolution below 50 ps at all fluences

Compare FBK C vs. noC
W6(B+C) superior to W8(B-noC) at fluences below ~ 8e14 n/cm^2, but equivalent to it above.



Compare FBK W6(B+C) to HPK 50D (B-noC)
W6(B+C superior at same bias or fluences below 8e14.
But HPK(B-noC) reaches same resolution as W6(B+C) at higher bias

Once the acceptors are mostly removed and a major part of the gain originates in the bulk, (i.e. fluences > 1e15n/cm^2) the time resolution appears to be the same for B+C and B-noC.

Data acquisition and analysis :
Z. Galloway et al, arXiv:1707.04961

“..to carbon or not to carbon..”

Largest beneficial effect of C-implantation is observed at fluences below 1e15 n/cm^2 where a large part of the gain is due to the multiplication layer doping.

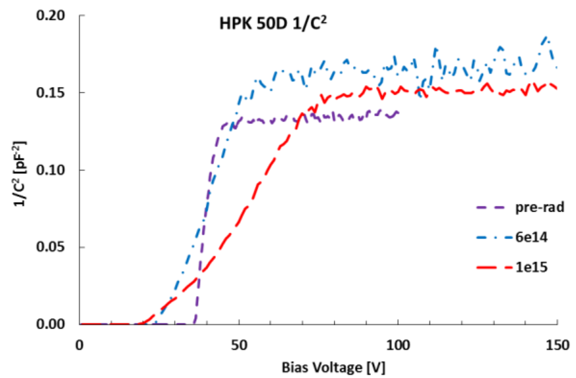
An observed benefit of the C-implantation is the reduced bias voltage required for the same gain and resolution, which might mitigate the problem of supplying bias to a detector with large fluence variation like the HGTD in ATLAS.

At higher fluences, the benefit of C-implantation could not be established.

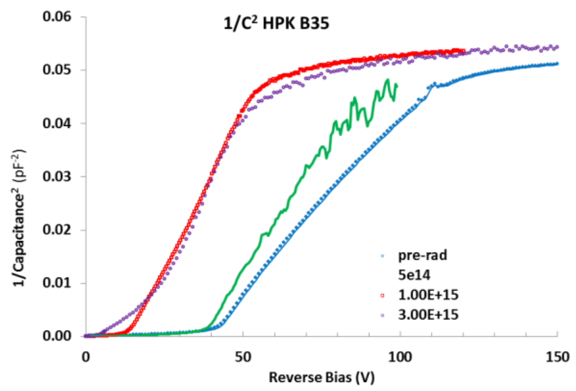
One possible explanation is that at that point the gain from the bulk is dominating.

Comparison HPK 50 µm and 35 µm LGAD

50 µm thick LGAD (HPK 50D)
Z. Galloway et al., arXiv: 1707.04961
Multiplication layer ("foot"): 36 V
Depletion Vdep = 45 V
Pre-rad bulk: 2e12



35 µm thick LGAD (HPK B35)
Multiplication layer ("foot"): 41 V
Depletion Vdep = 130 V
Pre-rad bulk: 1e14, "sweet spot" bulk doping:
almost constant during irradiation



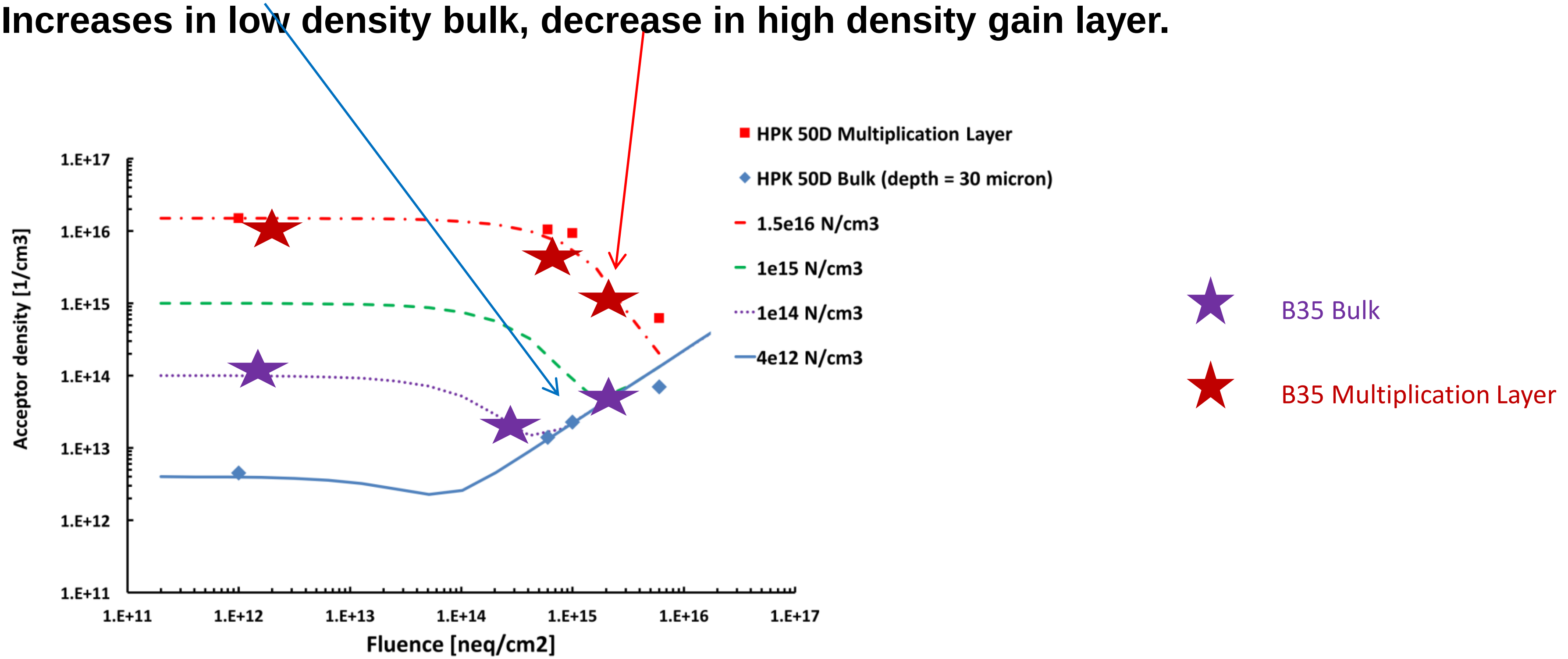
Question:
is B35 fluence really 5e14 or actually 1e14??
Will later assume the latter.

Measured in the UCSC β-telescope at -20º & -30º C
pre-rad and after neutron fluences (5e14) 1e14, ~ 1e15 n/cm², & proton fluence 3e15 n/cm²

Acceptor Removal & Creation

All silicon sensors experience creation of acceptors proportional to fluence,
An LGAD specific effect is the gain decrease due to acceptor removal in the gain layer.

Acceptor density vs. fluence:
Increases in low density bulk, decrease in high density gain layer.



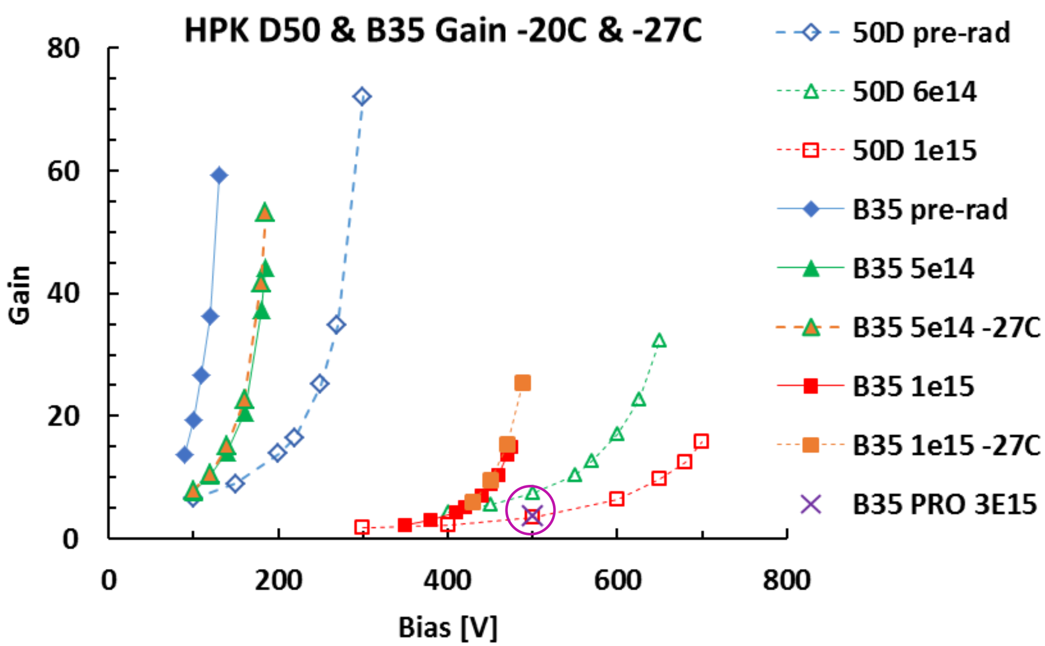
Data from C-V scans with B35
Simulation from WF2 incorporating G. Kramberger's work

Bias Dependence of Gain

Gain determines the signal strength and thus jitter.
Bias determines the signal shape and thus the rise time and jitter.

$$\sigma_{TimeWalk} = \left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS} \propto \left[\frac{N}{\frac{dV}{dt}}\right]_{RMS},$$

$$\sigma_{Jitter} = \frac{N}{dV/dt} \approx \frac{t_{rise}}{S/N}$$



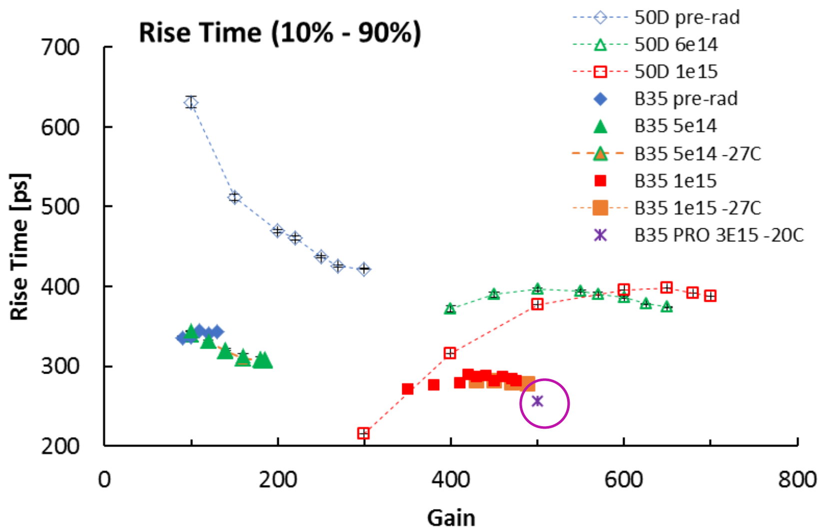
Sharp rise of gain with bias.

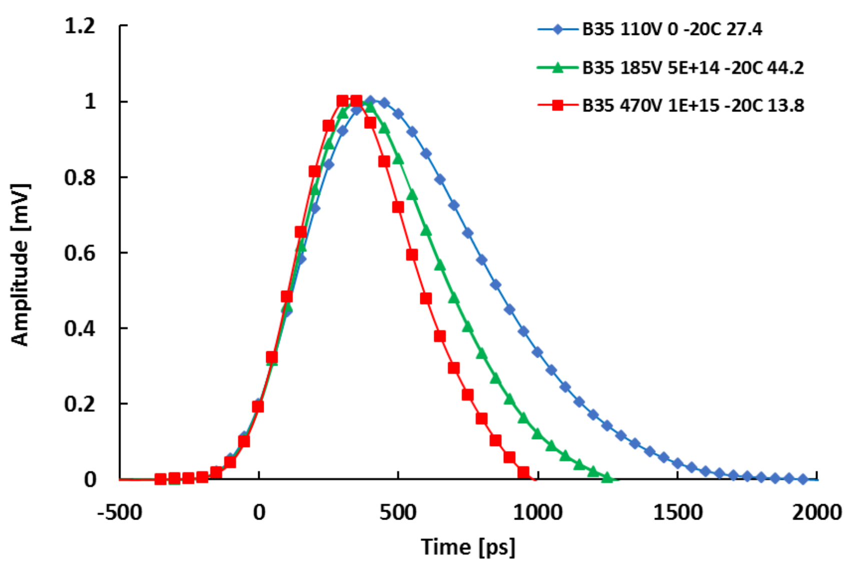
Doping of B35 gain layer is too high such that it can only be operated at low bias (close to depletion)

Lower temperature permits higher bias.

B35 irradiated up to 5e15 protons/cm^2 has gain of about 4

Rise time (10% - 90%) and Pulse shapes





Rise Time

Before radiation:

- 343 ps (35 µm) vs. 422 ps (50 µm)

After 1e15 n/cm^2

- 284 ps (35 µm) vs. 387 ps (50 µm)

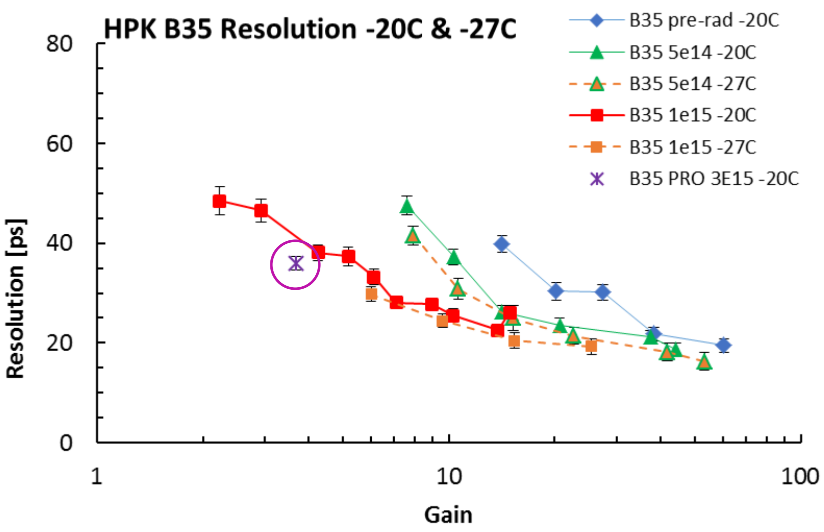
B35 irradiated up to 5e15 protons/cm^2 has a rise time below 250 ps:

Can an ASIC be built which can explore this?.

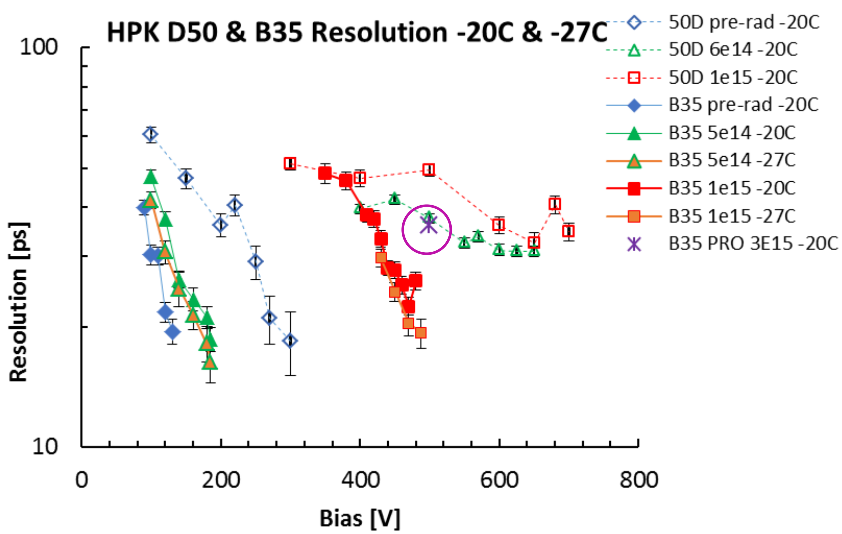
Pulse shapes

Normalized pulse shapes show that the low bias voltage of B35 pre-rad causes slower charge collection and larger rise time

Time resolution vs. Gain & Bias

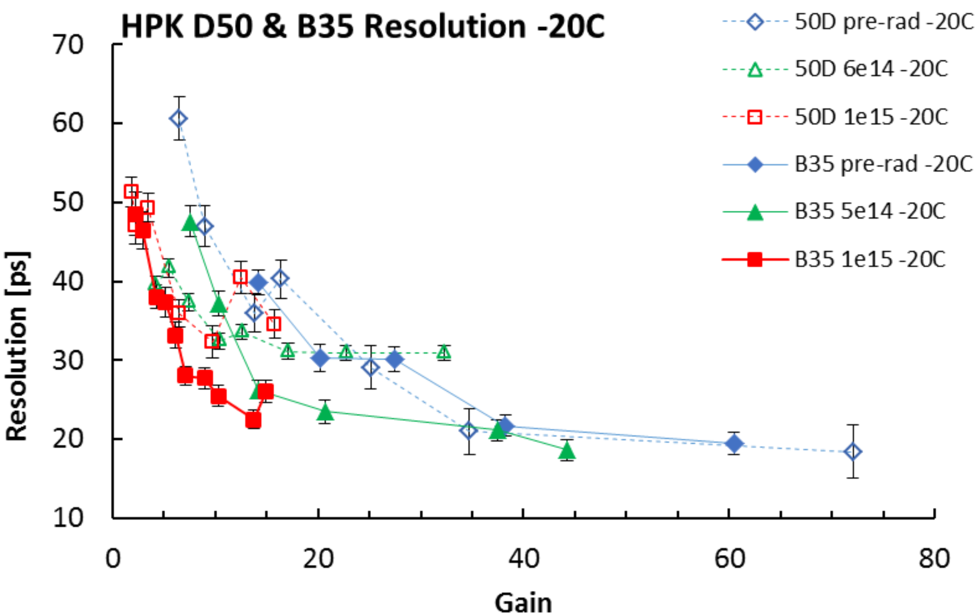


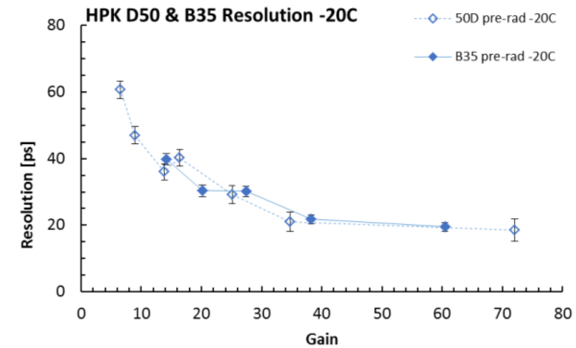
Lowered temperature permits larger gain and improves time resolution

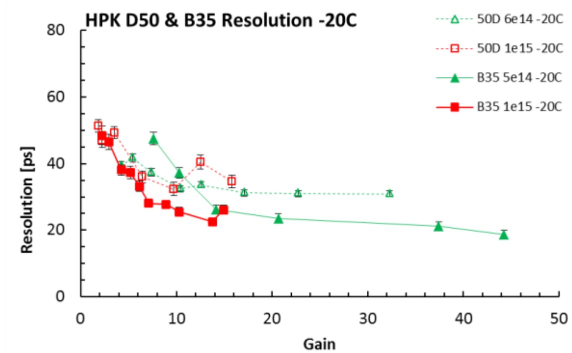


Steep voltage dependence of B35: gain layer doping too high (?)

Timing resolution vs. Gain: Saturation







$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

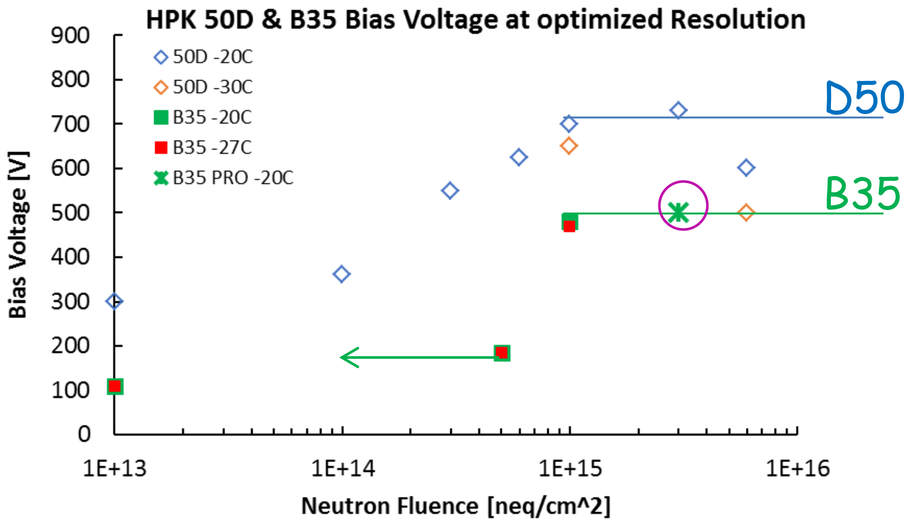
Resolution saturating in gain:

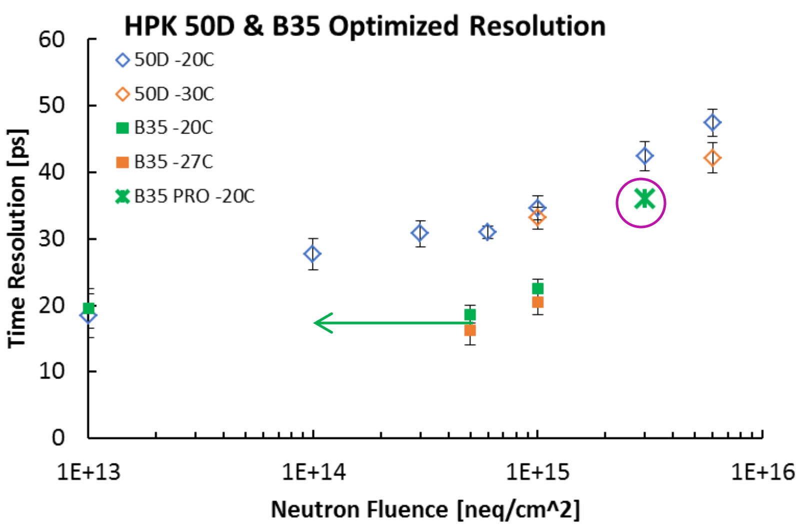
pre-rad: 50D and B35 same, indicates saturation of B35

“5e14” and 1e15: B35 is lower than 50D as expected

-> Both Landau fluctuation & low drift can saturate the resolution!

Bias and Time Resolution during Operation





Bias Voltage to get optimum time resolution as a function of neutron fluence:

50D: Increases from 300 V pre-rad to 700 V beyond 1e15 n/cm^2

B35: Increases from 100 V to 500 V beyond 1e15 n/cm^2
Constant difference of 200 V

Optimized time resolution as a function of fluence:

B35 lower by ~ 10 ps wrt 50D.

”… to thin or not to thin”

Advantage of 35µm HPK LGAD

Biasing & Power
The bias voltage of B35 is 200 V lower than that of 50D.
Power of B35 can be 10x lower than that of 50D after irradiation

Time resolution:

σ_t = 27 ps up to 1e15 n/cm^2
σ_t = 36 ps for protons at 3e15 n/cm
σ_t~ 10 ps better than 50D
σ_t~ 5 ps better at -20 C -> -27 C

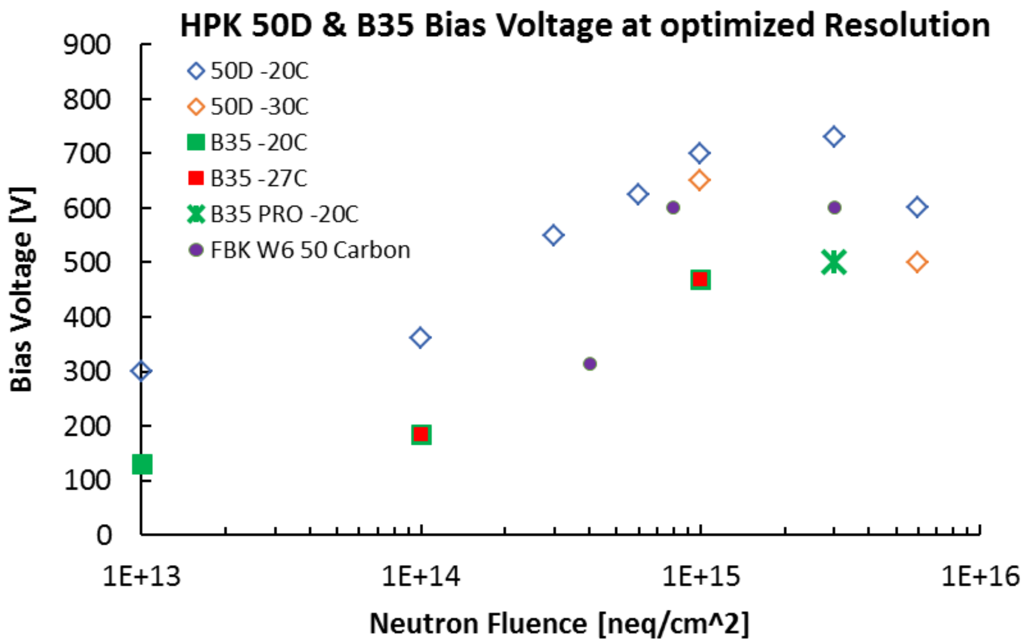
To be solved for 35 µm LGAD: (with WF2?)

Steep bias dependence of time resolution
-> (lower the doping concentration of the p-multiplication layer?)
Pre-rad bias voltage too close to depletion voltage:
-> lower the bulk doping concentration to ~ 1e12

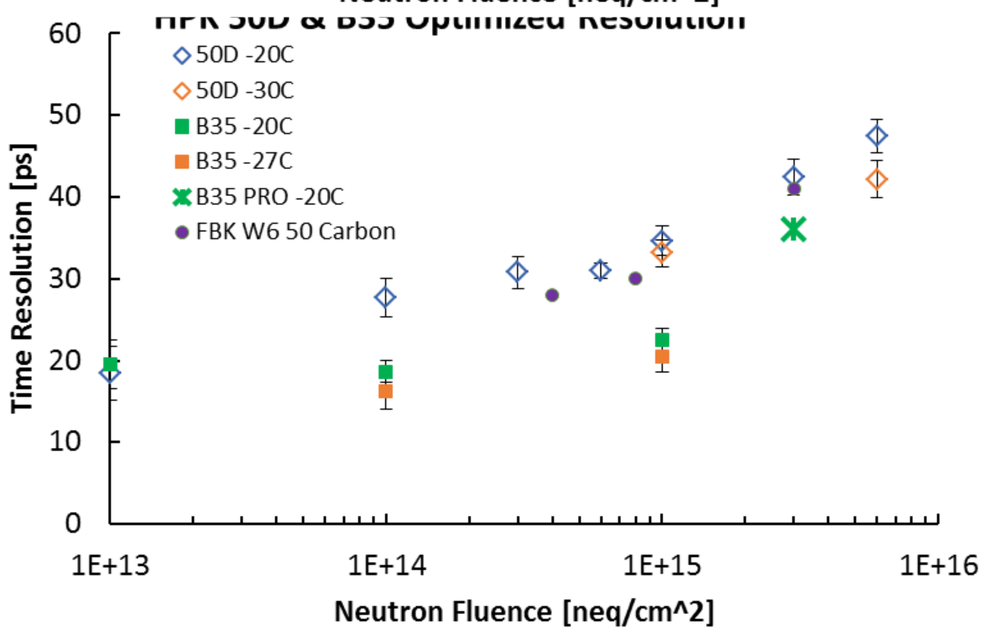
-> Lessons learned from proton data:

At very high fluences: bulk does not care if protons or neutrons had removed the acceptors in the multiplication layer

Where are we?



HPK 50D & B35 Bias Voltage at optimized Resolution
50D -20C
50D -30C
B35 -20C
B35 -27C
B35 PRO -20C
FBK W6 50 Carbon
Bias Voltage [V]
0
100
200
300
400
500
600
700
800
900
1E+13
1E+14
1E+15
1E+16
Neutron Fluence [neq/cm^2]



50D -20C
50D -30C
B35 -20C
B35 -27C
B35 PRO -20C
FBK W6 50 Carbon
Time Resolution [ps]
0
10
20
30
40
50
60
1E+13
1E+14
1E+15
1E+16
Neutron Fluence [neq/cm^2]

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This work was partially performed within the CERN RD50 collaboration.

Back-up

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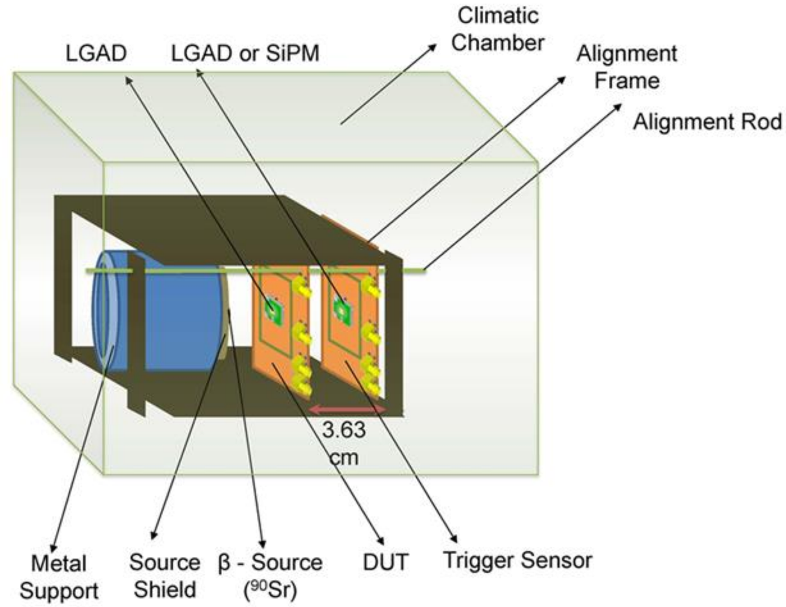
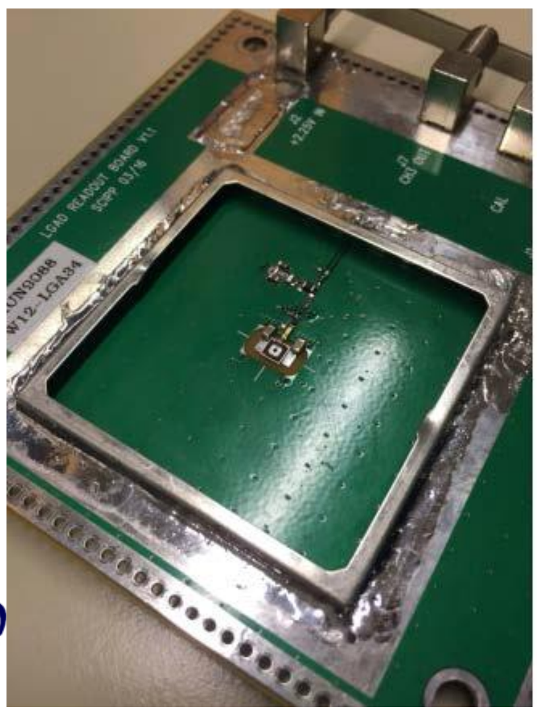
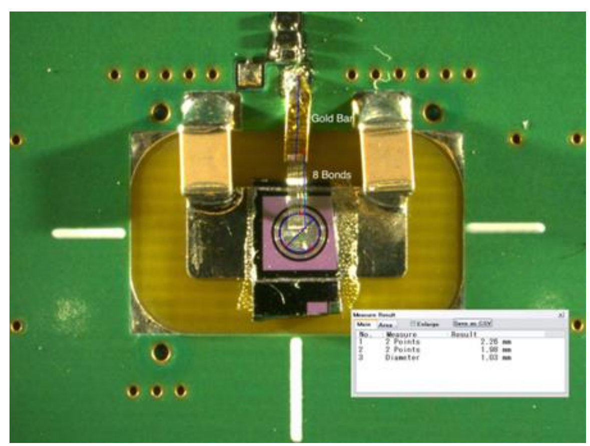
UCSC ^{90}Sr β-Source

^{90}Sr β-source Set-up:
DUT LGAD between source and trigger plane
Trigger and time reference: known LGAD with known time resolution.
Climate chamber allows operation between -30C and +20C.

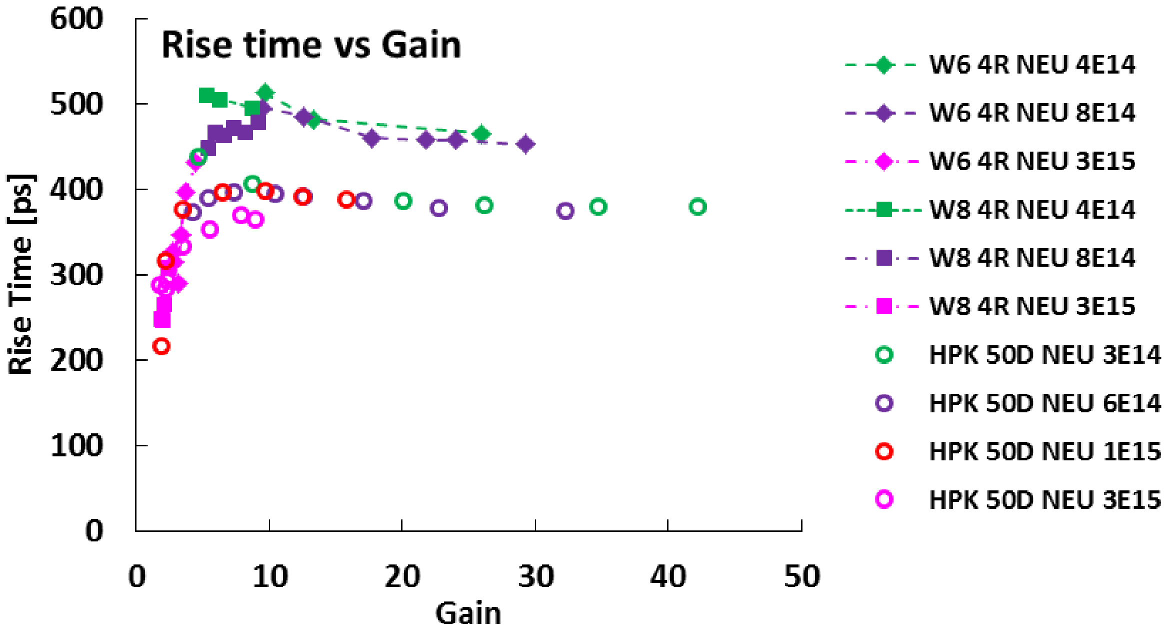






Measurement of pulse shapes with amplifier board
(Low-noise, fast ~3Ghz) developed at UCSC, now available from CERN) and digital scope (2.2 GHz , 25 ps time digitization

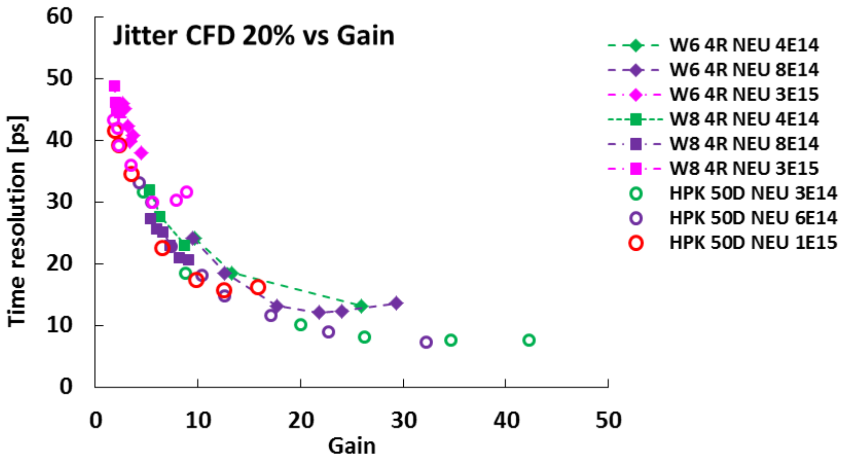
Gain Dependence of the Rise time (10-90%)



Same thickness for HPK W8 and W6

Different thickness FBK (60 µm) and HPK (50 µm) TBC

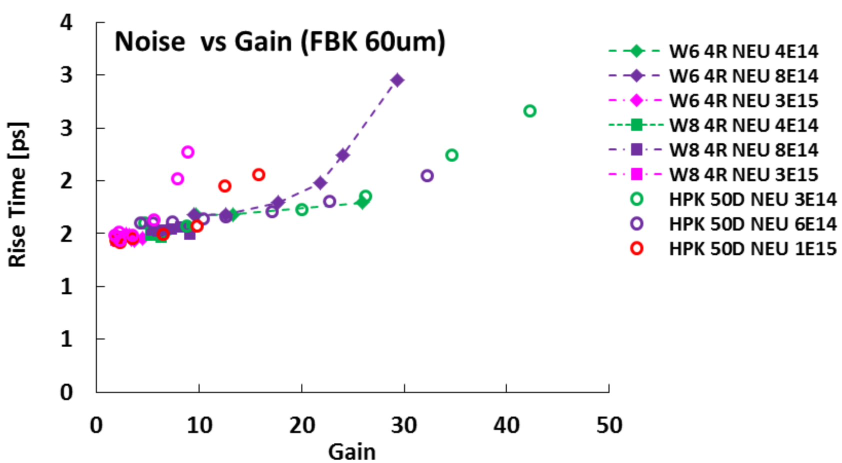
Jitter and Noise vs. Gain



$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

$$\sigma_{TimeWalk} = \left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS} \propto \left[\frac{N}{\frac{dV}{dt}}\right]_{RMS},$$

$$\sigma_{Jitter} = \frac{N}{dV/dt} \approx \frac{t_{rise}}{S/N}$$



noise excursions flatten the 1/gain dependence of the jitter