Ultra-fast Silicon Detectors UFSD

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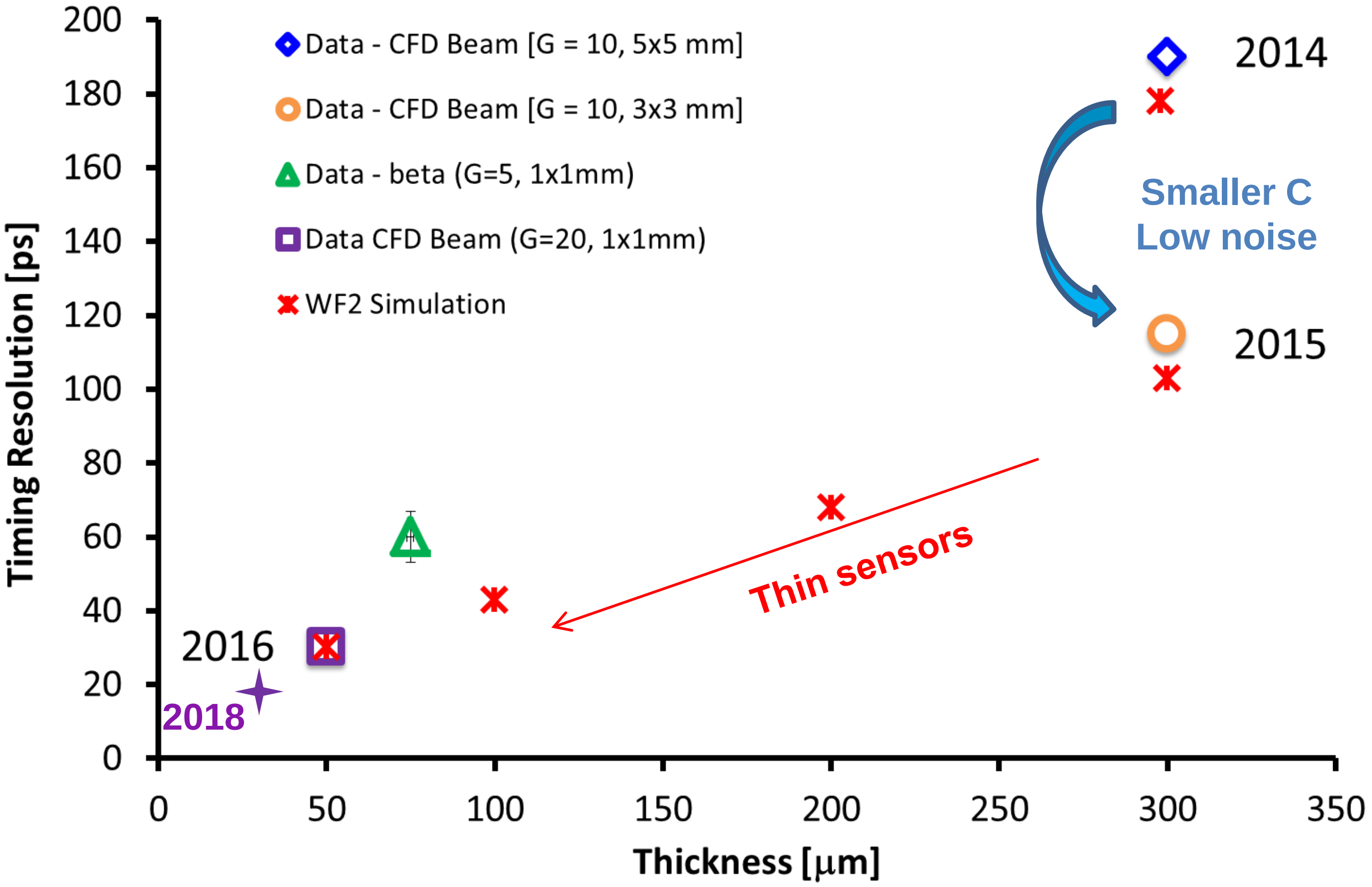
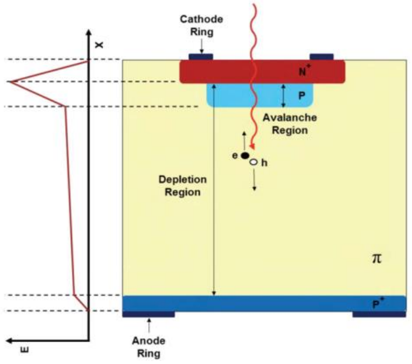
Gain,
Resolution,
Depletion voltage
vs.
Doping of the gain layer
Thickness

2012….go thin, young man!



..still not done yet: are testing now 20 µm

Low-Gain Avalanche Detectors (LGAD)

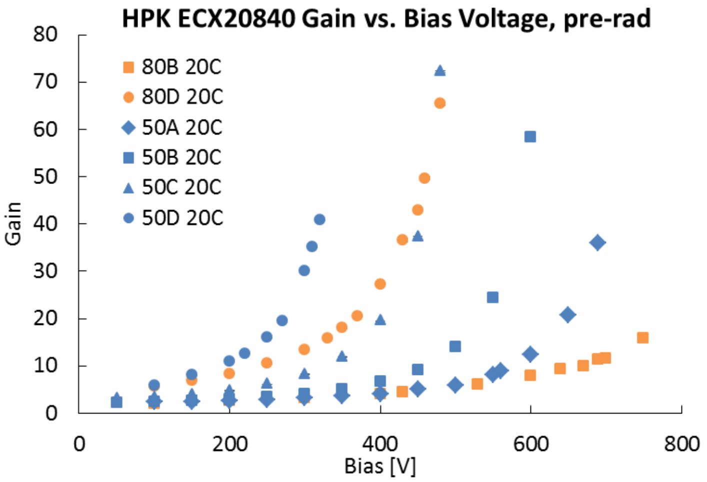


Principle:

Add to n-on-p Silicon sensor an extra thin p-layer below th junction which increases the E-field so that charge multiplication with **moderate gain** of 10-50 occurs without breakdown.

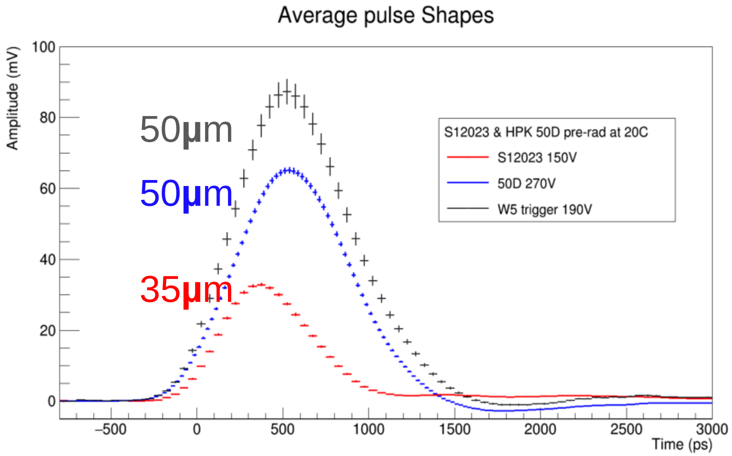
Tuning of the gain with bias voltage & modification of the doping layer:

- Doping concentration
- Modification of dopants



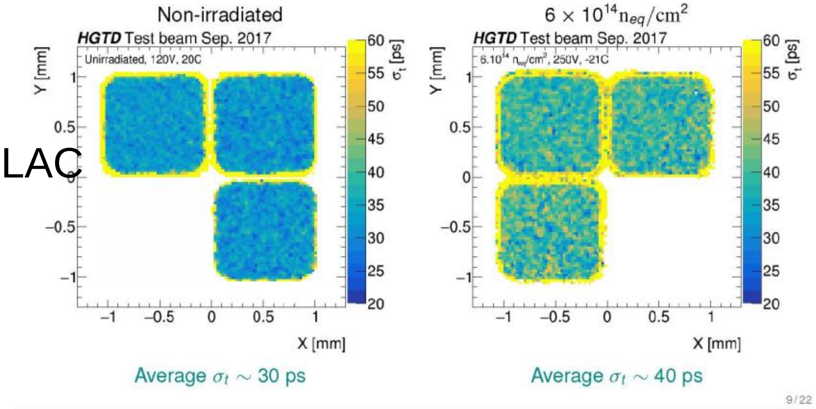
R&D in UFSD

Manufacturers of LGAD (30 µm – 300 µm):
CNM Barcelona (arrays)
HPK Hamamatsu (thickness)
FBK Trento (doping profile)
Micron
BNL



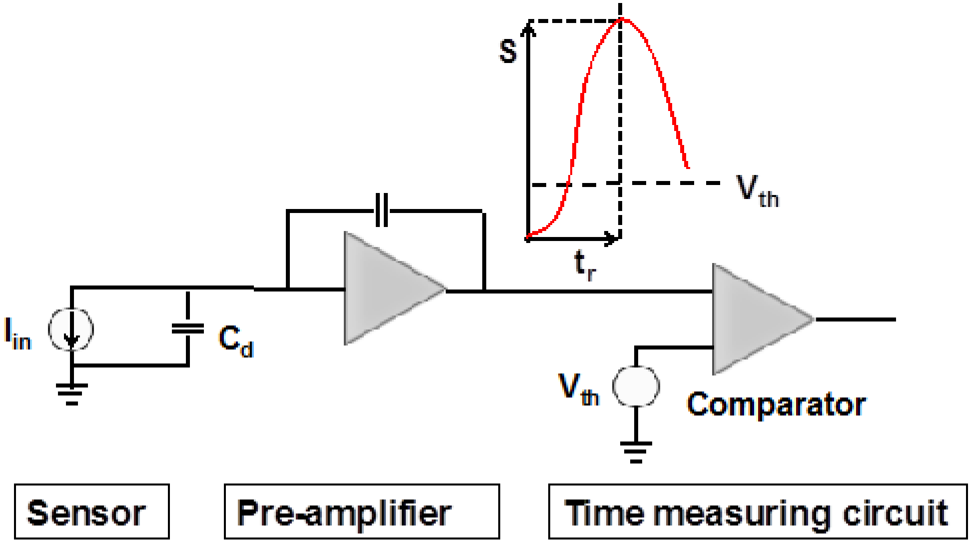
At 50 µm thickness, very similar behavior with exception of breakdown voltage.
35 µm thickness promises of faster pulses.

ATLAS-HGTD Beam test CNM 1.3x1.3 mm^2
S. Sacerdoti et al, Torino ps-timing Workshop



Investigating radiation performce of UFSD:
Lab charge collection: lasers and sources
C-V measurements: covered by Marco Ferrero
Multi-pad sensors: beam test CERN, FNAL, DESY, SLAC

Timing with Silicon



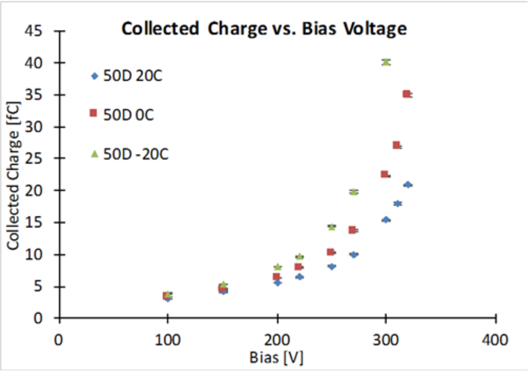
$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$

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

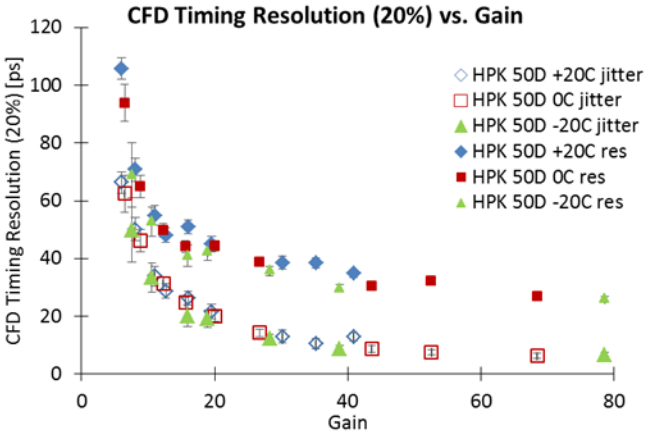
- Maximize slope dV/dt (i.e. large and fast signals)
- Signal ~ gain, expect jitter ~ 1/G
- Gain = Collected charge in UFSD/ Collected charge in PIN (no gain)
- Minimize noise N
- Time walk is corrected by using constant-fraction discriminator CFD

Time Resolution vs. Gain

β-source : explore LGAD performance without position information in-house and in time wrt process parameters, geometrical variations, operating bias & temperature..

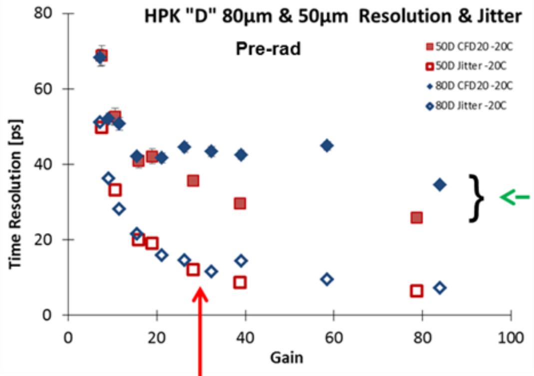


Strong bias and temperature dependence of the gain



Investigate resolution vs. temperature:

only gain matters!



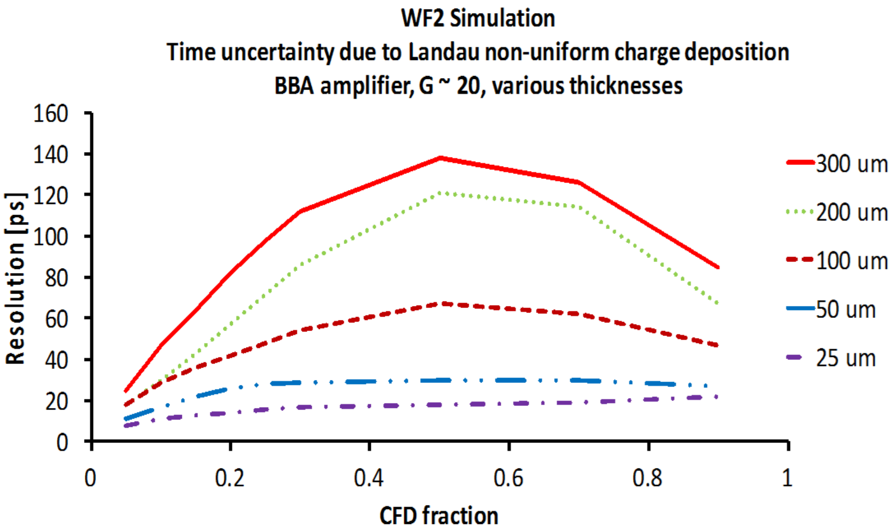
Landau Fluctuations:
≈ 35 ps for 80 µm
vs.
≈ 25 ps for 50 µm

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

Investigate resolution vs. thickness

……but only for the same thickness: observe Landau fluctuations at large gain.

Limiting the resolution: Landau Fluctuations



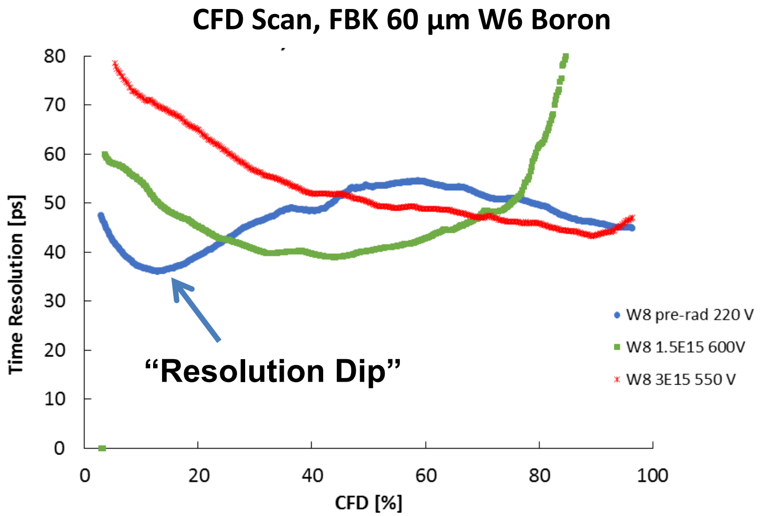
Contributions of Landau fluctuations to the time resolution as a function of the Constant Fraction Discriminator value for different detector thicknesses. Based on simulations.

Beam Tests show that we can correct for time walk quite well using a constant fraction discriminator method.

At large gain, Landau fluctuations become the time resolution floor which we can’t go below.
They depend on the sensors thickness.

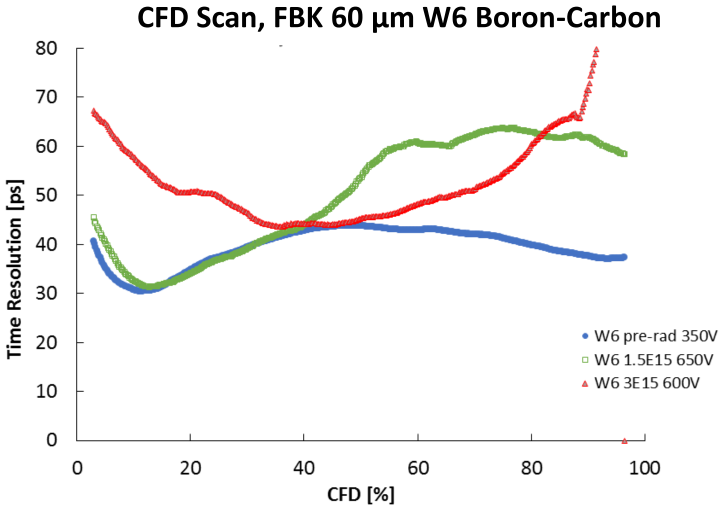
Both thin sensors, and low noise (for low threshold) are required for good timing resolution.

Carbon Infusion in CFD scan of FBK LGAD



At low fluences, i.e. high gain, the time resolution is optimized at very low CFD threshold = "Resolution dip": Landau contribution minimized

No carbon:
after 1.5E15 neq/cm^2, "resolution dip" at low CFD % has disappeared



With carbon:
after 1.5E15 neq/cm^2, "resolution dip" at low CFD % exists like before irradiation.
But it is gone at 3E15 neq/cm^2

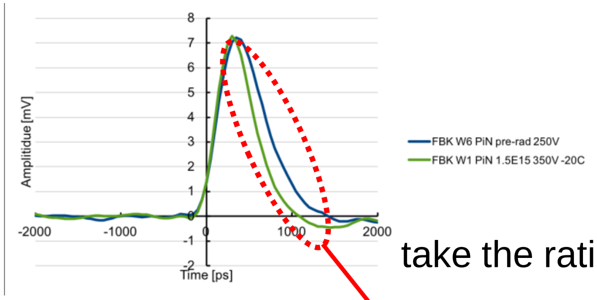
Clear sign that with carbon the gain layer contributes to the gain up to 1.5E15, but not at much higher fluences

Trapping in 60 µm FPK PIN

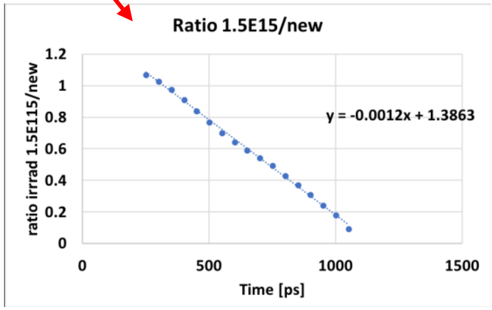
$$i(t)_{Measured} = i(t)_{Generated} * e^{-t/\tau} = i(t)_{Generated} * e^{-\beta * \emptyset * t}$$

➔ **The current should be exponentially suppressed both vs time and fluence**

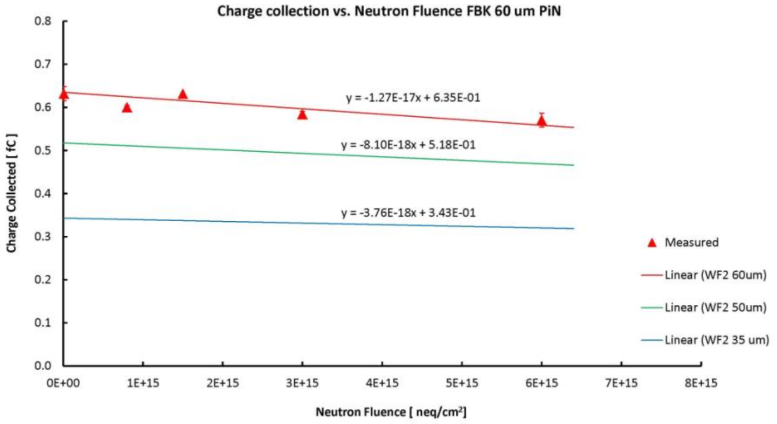
Trapping vs time



take the ratio



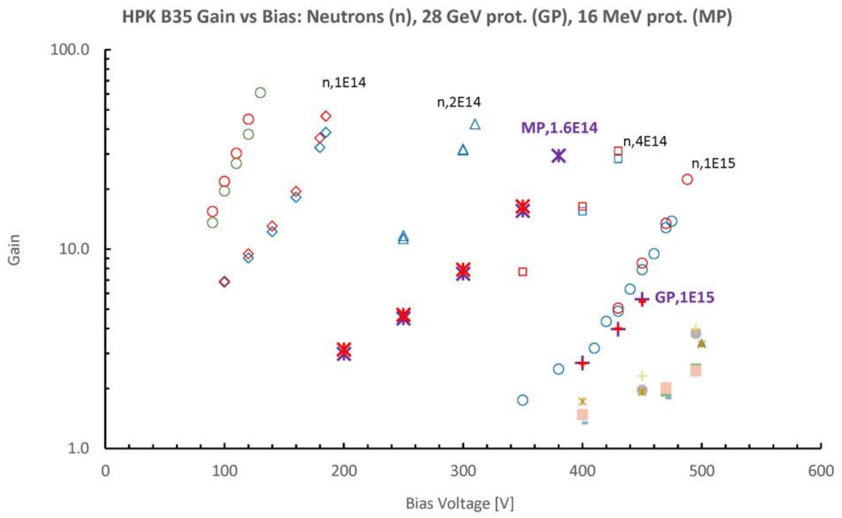
Trapping vs fluence

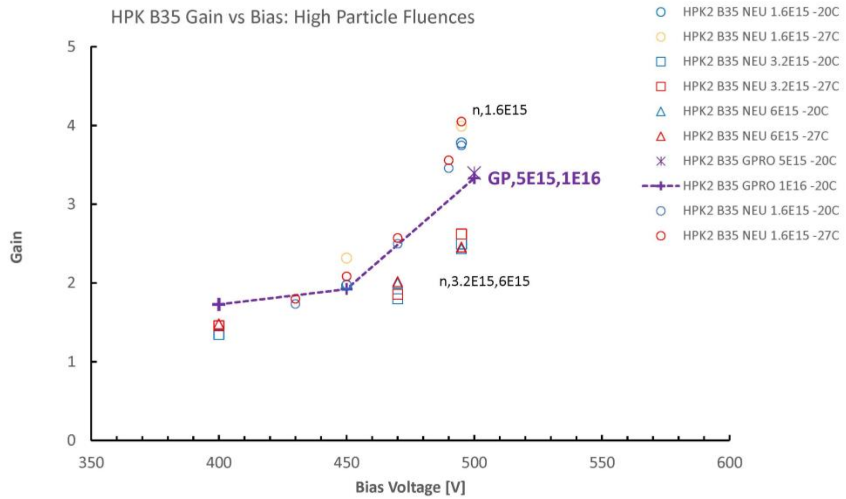


➔ **we measured that the current is linearly suppressed vs time and fluence.**

Why? Is it a thickness effect?

NIEL Violation in Gain





$$Gain = \frac{Collected\ UFSD\ charge}{Collected\ PIN\ charge\ (no\ gain)}$$

HPK 35 um UFSD
Irradiation:
JSI neutrons (n)
CERN 28 GeV protons (“GP”)
BERN 18 MeV protons (“MP”)

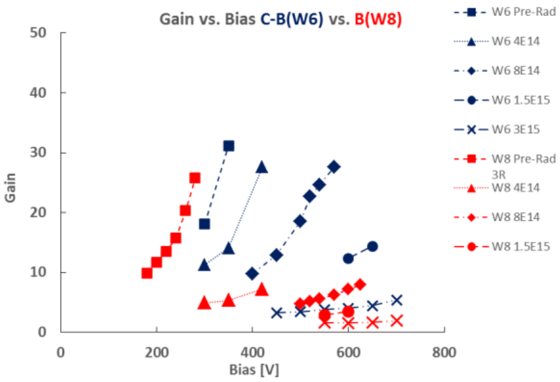
Compare fluence of neutrons and protons which results in the same radiation damage and extract damage constant κ.

Fluence(neq) = κ*Fluence(p)

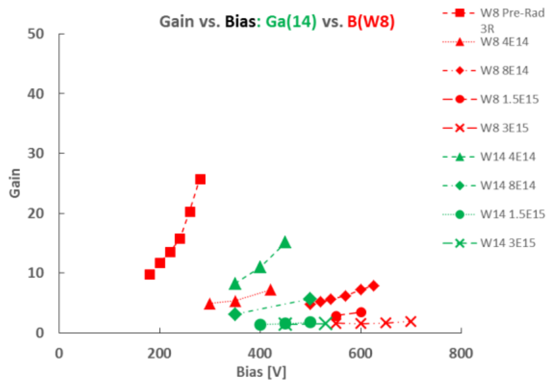
Particle	Fluence	K(obs)	κ (NIEL)
MP (18 Mev)	1.6E14	2	3.7
GP (28 GeV)	1E15	0.9	0.6
GP(28 GeV)	1E16	< 0.3	0.6

Less damage from protons than expected from NIEL

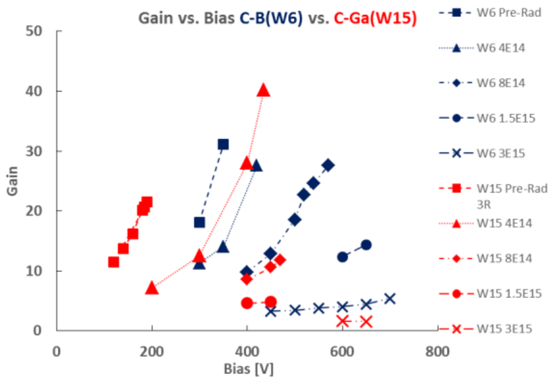
FBK: Carbon-infusion & B->Ga Replacement



Carbonated Boron vs. Boron
Large mitigation of gain loss with Carbon

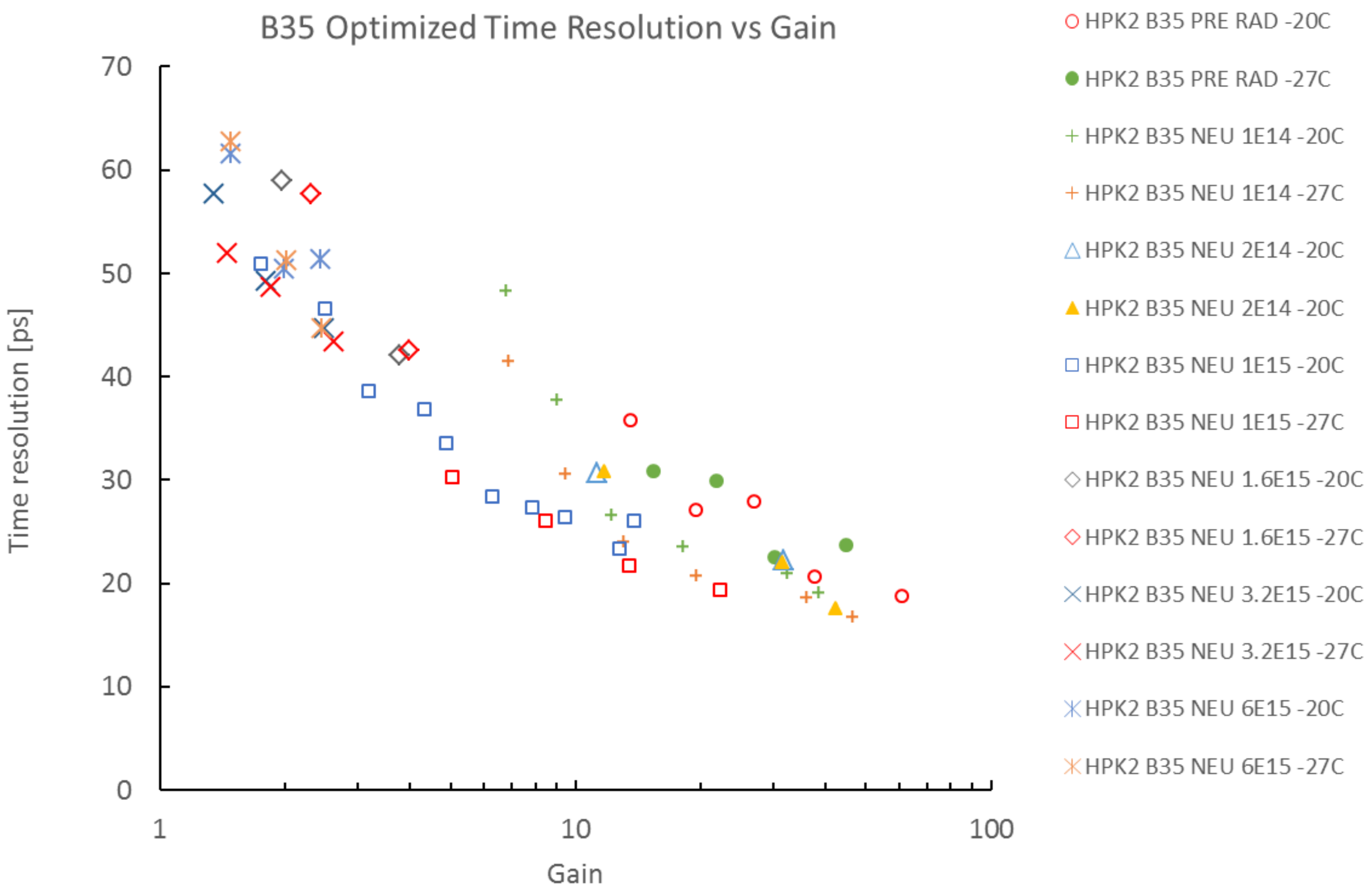


Gallium vs. Boron
Limited bias reach of Gallium
No improvement with Gallium at high fluences



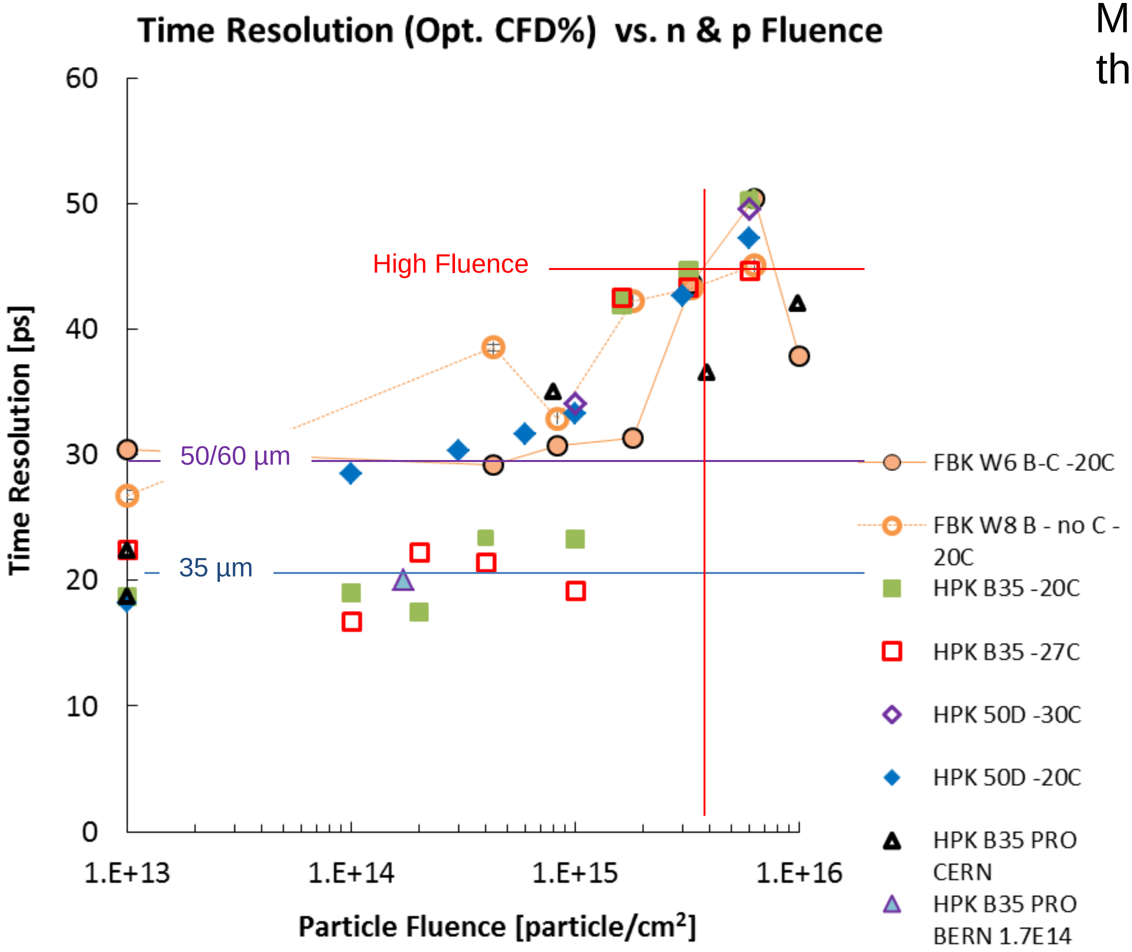
Carbonated Boron vs. carbonated Gallium
No improvement with carbonated Gallium

HPK B35: Time Resolution vs. Gain



Landau Fluctuations limit time resolution to about 20ps

Time Resolution vs. Particle Fluence



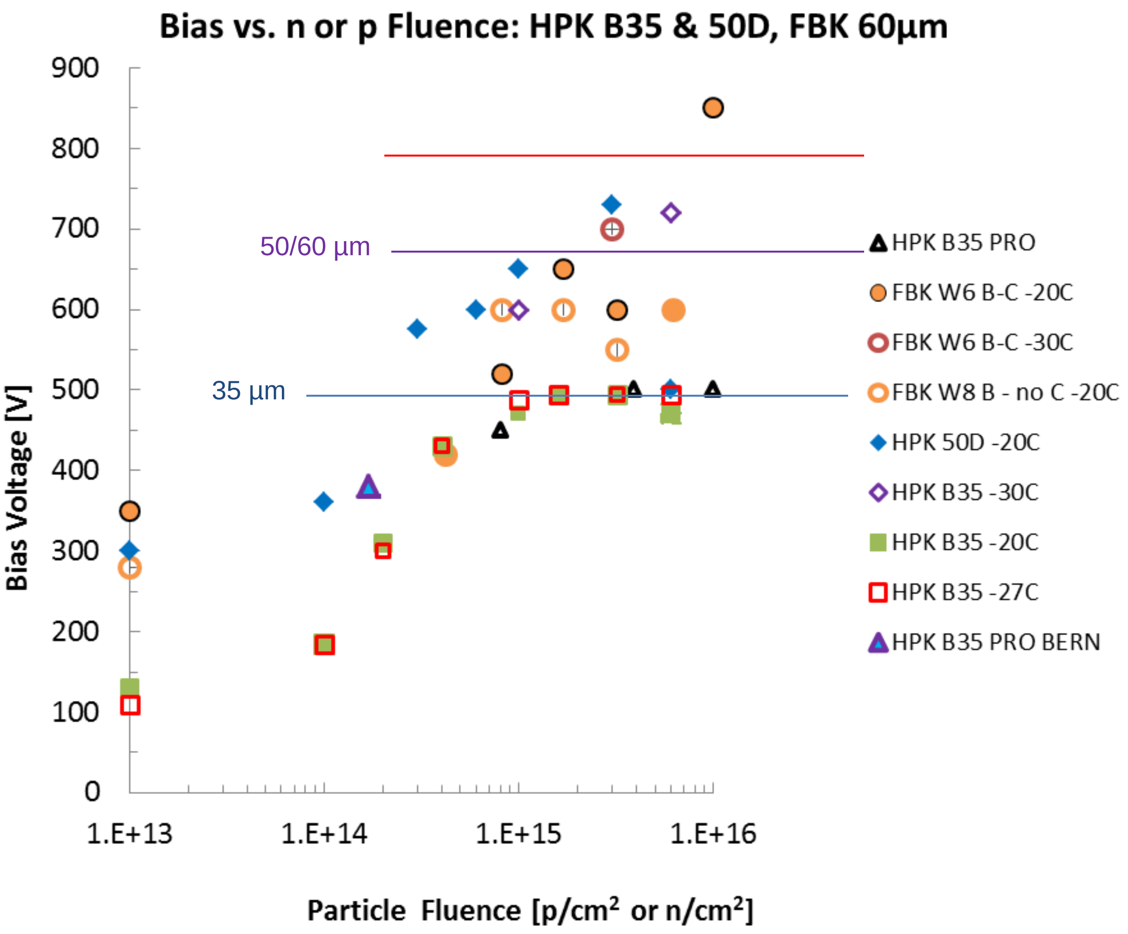
Measurements were done with the UC Santa Cruz β-telescope

High Fluences: “all sensors look the same”

Protons seem to damage less
Thickness matters at fluences up to 1E15 neq/cm^2 since Jitter is small, Landau fluctuations dominate
Carbon Infusion helps up to 3E15 neq/cm^2

HPK 50µm: Z. Galloway et al, https://arxiv.org/abs/1707.04961
Comparison HPK 35 & 50µm: Z. Zhao et al, https://arxiv.org/abs/1803.02690
FBK Gallium and Carbon S. Mazza et al, https://arxiv.org/abs/1804.05449

Bias Voltage vs. Particle Fluence



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Bias
Thickness (& doping profile) dependence

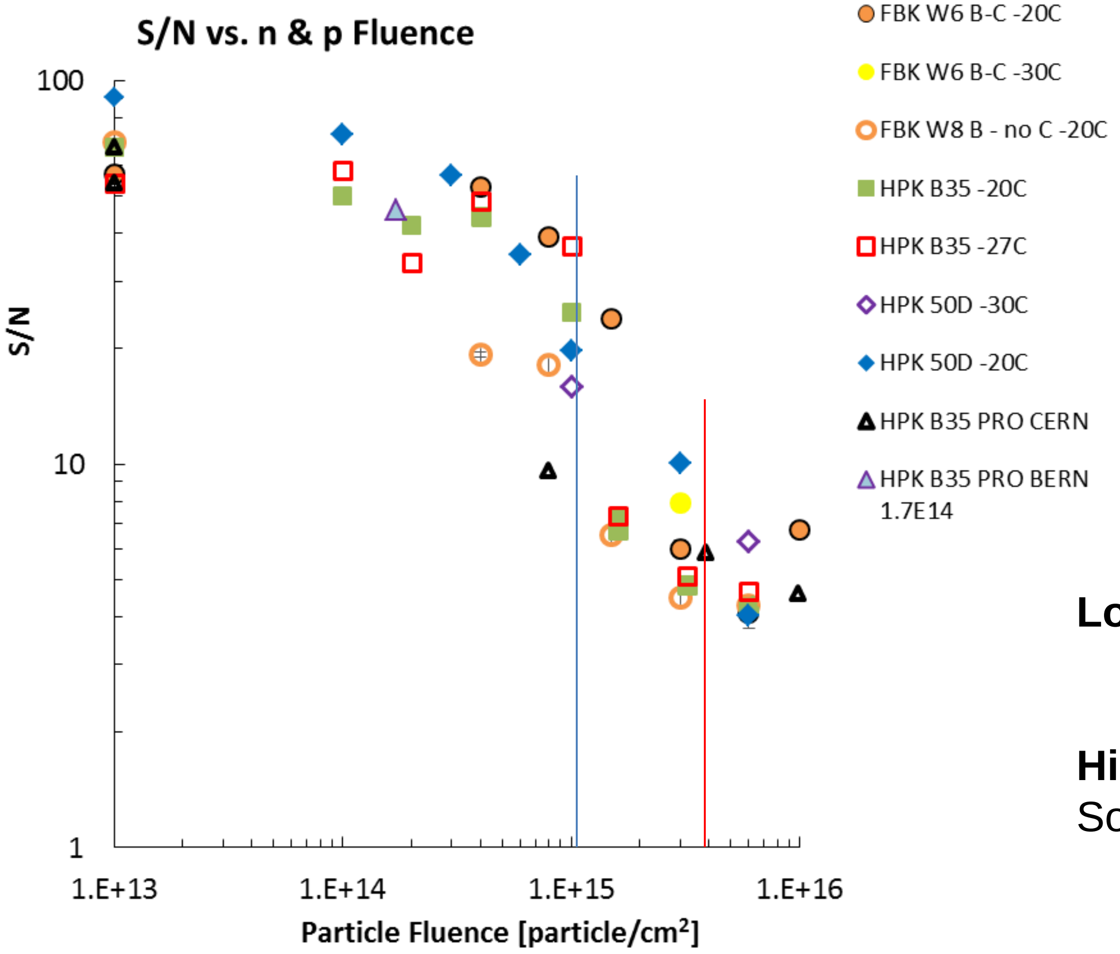
Level off above 1.5 neq/cm^2
HPK B35: 500V
HPK 50D: 700 V
FBK 60µm: 650 V

No difference in protons

Lower temperature allows higher bias voltage

Low Initial increase of bias with Carbon

Signal-to-Noise Ratio vs. Particle Fluence



Requirement for good efficiency:
S/N > 7.

Low fluences < 1E15 neq/cm^2
S/N > 10

High fluences > 1E15 neq/cm^2
Solutions: 50 µm, -30 C, Carbon

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Conclusions

- **Very active R&D in UFSD: acceptor removal main problem**
  - **Thinning sensors:**

    needs improved breakdown behavior: at 35 µm a bias brickwall of 500V limits the performance;

    issue capacitance: limitation of pixel size
  - **C-infusion:**

    very promising, requires to be used with thin sensors to exploit reduced acceptor removal;

    narrow bias voltage window as a function of fluence could be very useful in large-scale applications
  - **B -> Ga replacement:**

    ro advantage wrt to B even with C-infusion;

    requiring Ga would be an issue with some manufacturers
  - **Proton irradiation:**

    Lower acceptor removal than with neutrons at 28 GeV, ½ the NIEL fluence at 18 MeV.
  - **Trapping:**

    Trapping in 60 µm UFSD PIN diodes without gain is measured to be linear in time and fluence.

Contributors

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