Tracking at fluences $1E16 - 1E17$ n/cm$^2$

At HL-LHC, in the inner layers of the tracker, fluences will be of the order of $\Phi = 2-3E16$ n/cm$^2$

⇒ In the present plan, Silicon detectors are replaced once at HL-LHC.

⇒ At FCC (?) fluences will be even higher, let’s suppose $\Phi = 1E17$ n/cm$^2$: do we replace the Silicon sensors 10 times at FCC?

Question:
Can we design a Silicon tracker that can still work at $\Phi = 1E17$ n/cm$^2$?
Why is it possible? (maybe)

The bottom line is:
Silicon irradiated at fluences $1 \times 10^{16} - 1 \times 10^{17}$ n/cm$^2$ does not behave as expected, it behaves better.

Extrapolations from Silicon sensors irradiated in the fluence range $1 \times 10^{14} - 1 \times 10^{15}$ n/cm$^2$ predict a hopeless situation.

Example:
1) Leakage current saturates
2) Trapping

G. Kramberger et al., *JINST* 8 P08004 (2013).

W. Adam et al 2016
*JINST* 11 P04023
Effects of radiation: decrease of CCE

Degradation of the CC(V) with fluence at 600 and 1000V

Note: regardless of the sensors thickness, the signal at 2E16 n/cm² is almost a constant, 3-5k electrons.
Why are the sensors still working?

The depletion is ~ 30 micron for every sensor thickness

Consider the point at $2 \times 10^{16}$ n/cm$^2$

The bulk should be doped $N \sim 4 \times 10^{14}$ n/cm$^3$ and the E-field should be way above breakdown

However it works well....

Less doped? Smaller mobility?
The plan: use very thin sensors and gain..

At high fluences, $1 \times 10^{16} \text{ – } 1 \times 10^{17} \text{ n/cm}^2$, the depleted region is very shallow ➔ use thin sensors

3D sensors decouple drift path and total charge deposition by collecting the charge carriers perpendicularly to the particle path.

Can we decouple drift path and total charge deposition using gain?

Why this can be possible?

• The acceptors creation by irradiation slows down at high fluence, so the bulk is not as doped as we forecast
• Using $V_{bias}$, we can still start multiplication if the mobility stays high enough
How to obtain gain in silicon: $E \sim 300\text{kV/cm}$

1) **Use external bias:**

$E_{\text{critical}} = \sim 10-15\ \text{V/\mu m}$

Possible only in thin sensors:
50 microns need 500-750V

2) **Use Gauss Theorem:**

$$\sum q = 2\pi r \times E$$

$E = 300 \text{ kV/cm} \Rightarrow q \sim 10^{16}\ /\text{cm}^3$

Implant charges to obtain enough field
Gain and $E_{\text{field}}$ in Si detector

Critical field, gain near this line

Thickness

$p$-$n$ junction

High-resistivity PiN

Low-resistivity PiN

High gain everywhere in the sensor, tend to quickly go in breakdown

Possibly well behaving

Well behaving, lot's of experimental data

Field due to $V_{\text{bias}}$

Slope due to bulk

$E_{\text{field}}$

Thickness

$n$-$in$-$p$
**E-field in various sensors**

- **(a) Low Gain Avalanche Detector**
  - Control Gain: high $E_{bulk}$ only in the gain layer.
  - $200 - 300 V$

- **(b) $V_{FD} << V_{Bias}$**
  - Unstable gain: high $E_{bulk}$ everywhere in the bulk.

- **(c) $V_{FD} \sim 0.5 V_{Bias}$**
  - Control Gain: high $E_{bulk}$ only near the junction.

- **(d) $V_{FD} >> V_{Bias}$**
  - Unstable gain: $E_{bulk}$ very steep.

**Controlled gain: it happens when** the $E_{field}$ is controllable by $V_{bias}$ and the contribution of the doping to the field accounts for a part ($\sim 50\%$) of the total $E_{field}$.
Gain from un-irradiated to a fluence \(=1\times10^{17}\) n/cm\(^2\)

We need to have a plan to deliver \textbf{at least} \textbf{1 fC} throughout the sensor lifetime. In thin sensors you need to have always gain.

Let us consider a 50 microns thick sensor.

**In high resistivity silicon**, the field is almost constant in the sensor,
- It reaches the critical value at the same voltage everywhere in the detector.
- It burns the sensors.
Is gain in high-resistivity PIN reliable?

Not really....
The plan - I

Select a thickness that can still be depleted after a fluence ~ 1E17 n/cm²
Assuming standard rate of acceptor creation a thickness of ~ 20 micron should be OK

Such thin detector will not provide enough charge ➔ make an LGAD of ~ 20 micron

1) up to ~5E15 n/cm² LGAD will provide enough charge
3) In the $\sim 1\times 10^{15} - 5\times 10^{15}$ n/cm$^2$ the gain from $V_{\text{bias}}$ in the bulk starts to be important.

4) Above $5\times 10^{15}$ n/cm$^2$: this is the fun part...

**Condition to have gain:**
1. High $E_{\text{field}}$
2. The width of a space charge region $>>$ the mean free path between two ionizing impacts.

Irradiation decreases the mean free path, so even if the field is high, the sensors are not in breakdown, the gain is quenched, but maybe still reachable in thin sensors.
Fill factor: how to minimize gain termination

We aim for 100% active surface, however there is a gap between pads.. The gap between pads is due to two components:

1) Adjacent gain layers need to be isolated (JTE & p-stop)
2) Bending of the E field lines in the region around the JTE area
Fill factor solution: trenches

**Trenches** (the same technique used in SiPM):

- No p-stop,
- No JTE $\Rightarrow$ no extra electrode bending the field lines

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**Trench isolation technology**

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO$_2$, Si$_3$N$_4$, PolySi

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FBK run @ RD50
Below 5E15 n/cm2
- It looks possible to have a gain of ~ 5 without breakdown
- Vbias controls gain

above 5E15 n/cm2
- is the gain still there?
- Is the mobility decreasing to a point where no gain is possible?
- Damaged bulk acts as a quenching resistor?
- No holes multiplications?
1) We are going to study the behavior of very thin Silicon sensors above fluences of $1E16 \text{n/cm}^2$: thin sensors are particularly well suited since they have small leakage current, small trapping, and they can still be depleted.

2) We propose to use 3 types of gain:
- Due to Gain Layer
- Due to $V_{bias}$
- Due to the bulk doping

to obtain a simple sensor that can deliver good signals for fluences above $1E16 \text{n/cm}^2$. 
• We can see gain in high-resistivity 55-micron thick PiN for Bias > 700 V
• The gain is either small or too large
• Lot’s of burnt sensors to achieve this curve
• Difficult to use it..
Can we simulate the bulk gain?

van Overstraeten and Massey fit the behavior of the data

Very steep gain curve, difficult to have a stable working point
Lesson learnt from 55-micron thick PiN sensors

- It is possible to have bulk gain
- **High-resistivity not-irradiated sensors**: it is difficult to control the gain in
  - Gain develops quickly into Geiger mode
  - Gain happens everywhere in the sensor
- **High-resistivity irradiated sensors** (above 2-3E15 n/cm2)
  - It looks possible to have a gain of ~ 5 without breakdown
  - High field only in a small part of the sensor
  - Damaged bulk acts as a quenching resistor?
  - No holes multiplications?
- We don’t have information above 1E16
  - is the gain still there?
  - Is the mobility decreasing to a point where no gain is possible?
- Move the onset of gain to lower bias to avoid lateral breakdown
  - 50 microns is probably too much

Need to explore 25-35-micron sensor
What can we do below 5E15 n/cm²?

We need to have stable gain also for non-irradiated sensors, up to 5E15 n/cm². How can we do it?

**Two possibilities:**

1. **Low-resistivity PiN.** They also have a peaked Efield
   Is Initial doping providing the same feature of irradiated bulk?

2. **LGAD**
25-micron thin LGAD sensors for TRK16

Possible starting devices:

1. thin LGAD sensors to have short drift distance and large signals
2. thin low-resistivity PiN

Let’s consider as an example 25-micron thin sensors

• Charge deposited ~ 0.25 fC

→ Need a gain of at least ~ 5 in order to provide enough charge

What does it happen to a 25-micron sensor after at fluences >1E16 n/cm²?

• Trapping is almost absent
• the bulk becomes doped to ~E15 n/cm³
• No double junction due to the moderate leakage current
The LGAD gain is used on the very first part (<50E14 n/cm²) to allow:
- using a lower Bias setting
- obtaining stable operations before irradiation.
Plan summary

• Very thin sensors “in theory” can be biased to have enough gain to provide the necessary charge for position measurements.

• Unfortunately un-irradiated PiN sensors have very steep gain curves, not suited for reliable operation

• Fortunately at fluences > 3E15 PiN sensors have a fairly mellow gain curve, usable for stable operation

• Very thin LGADs offer good gain from gain layer when new, and enough gain up to 5E15 n/cm².

The merging of the above points suggests that thin LGAD might be the enabling technology for particle tracking above 1E16 n/cm².
Sensor Challenges

Irradiated thin sensors:

1. Is the gain in thin sensors mellow enough to allow stable running conditions?
   ➔ better starting with high or low resistivity bulk?
   ➔ Epi or FZ substrate?

2. What is the optimal thickness?
   ➔ It is easier to achieve gain in thinner sensors, however they provide less charge and have higher capacitance

3. Can we design thin sensors that hold reliably >6-700V
   ➔ Guard-rings?
   ➔ Microdischarges?

Fill factor:

1. How do we produce LGAD with 100% fill factor.
   ➔ Trenches? Resistive AC LGAD?

2. If 1) fails, we might need to pre-irradiate PiN sensors
Modelling gain in irradiated sensors

What does it happen to gain in irradiated sensors?
Is the mobility decreasing too much?
Is there gain above fluences 1E16 n/cm2
Is trapping still irrelevant?
Goals

1. **Study of gain in irradiated sensors:**
   - Can we model gain in the bulk of new sensors?
   - Is neutrons and protons irradiation the same?
   - Is there a difference between slow and fast hadrons?
   - Do we know how to model gain with increasing irradiation?
   - Is the mobility decreasing to a point where no gain is possible?

2. **Provide in 2-year time sensors prototypes for TRK16:**
   - with 100% fill factor
   - matching the RD53 chip prototypes
   - able to withstand the full HL-LHC lifetime
   - irradiated up to $5 \times 10^{16}$ n/cm$^2$

3. **Results using RD53 prototype chips**
   - Laboratory measurements
   - Beamtest results
Requests

1. **One production at FBK**
   The project needs two productions, we are confident one can be done parasitically by inserting thinner wafers in other productions.

2. **Cost for bump-bonding**

3. **Irradiations and beam test**

4. **Lab equipment for cold testing of irradiated sensors ➔ switching matrix?**

5. **Model developing**
Gain and Efield in Si detector

High-resistivity PiN:
- High gain everywhere in the sensor, tends to quickly go in breakdown.

Low-resistivity PiN:
- Possibly well behaving, no experimental data.

LGAD:
- Well behaving, lots of experimental data.

Critical field
p-n junction
Why is the gain unstable in HR new sensors?
In high resistivity silicon, the field is almost constant in the sensor,
⇒ It reaches the critical value at the same voltage everywhere in the detector

![Drift Potential V [V] vs y [um]](image)

Field: high everywhere

![E Amplitude |E| [kV/cm] - Dashed: breakdown field](image)

![Eff. Doping e(N_D - N_A) + rho_{Bias} [n/cm^3*10^{12}] vs y [um]](image)

![Incremental gain as a function of y](image)
Is there gain in irradiated PiN diodes?

- The onset of gain at lower Bias is clear for fluences >3E15
- The slope is rather mellow, no real risk of breakdown
  ➔ this fact is most likely due to the irradiated bulk acting as quenching resistor
Gain difference in HR and LR new sensors

In high resistivity (HR) silicon, the field is almost constant in the sensor,
→ It reaches the critical value at the same voltage everywhere in the detector
→ It burns the sensors

In low-resistivity (LR) silicon, the field is peaked at the junction,
→ It reaches the critical value only in a small part of the detector
→ LR PiN should have a more controllable gain than HR PiN

→ Is it true? Do we have controlled gain in LR pin?
Gain and Efield in Si detector

High gain everywhere in the sensor, tend to quickly go in breakdown

Possibly well behaving, no experimental data

Well behaving, lot's of experimental data
No breakdown, no gain

Condition to have gain:
1. High Efield
2. the width of a space charge region $>>$ the mean free path between two ionizing impacts

Irradiation decreases the mean free path, so even if the field is high, the sensors are not in breakdown, the gain is quenched