VERTEX 2019

Next-Generation Tracking System for Future Hadron Colliders

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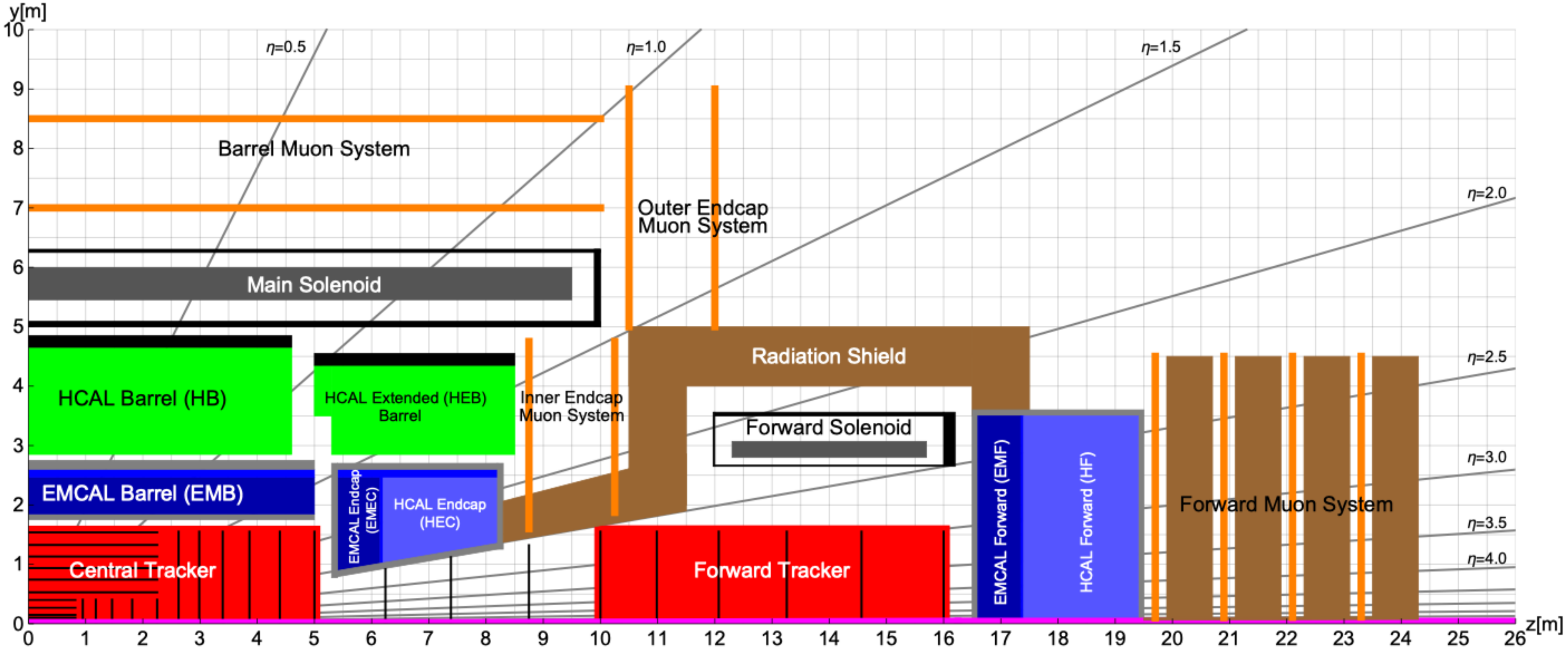
OUTLINE

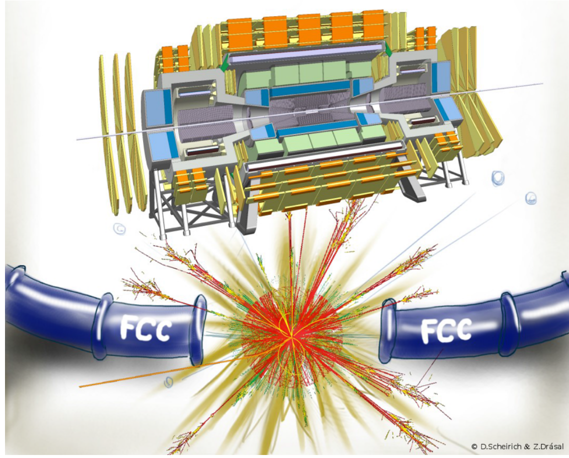
- ✎ **Tracking system for future high-intensity hadron colliders**
- ✎ **Tracking development**
- ✎ **Timing development**

TRACKING AT FUTURE HADRON COLLIDER

Next generation high-energy and high-intensity hadronic collider → FCC-hh

FCC-hh reference detector





[http://cds.cern.ch/record/2651300]

Cavern length: 66 m
Detector: 50 m long
20 m diameter

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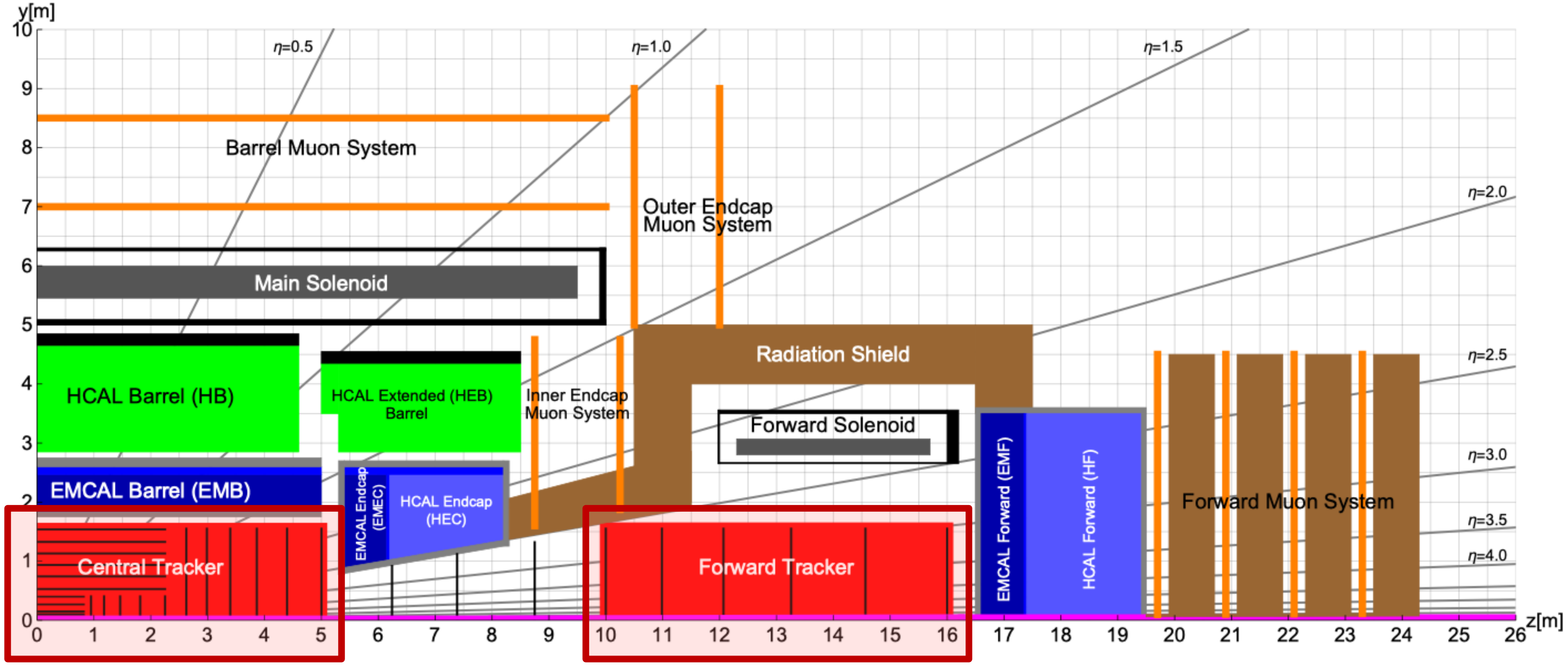


The tracker

Running conditions:

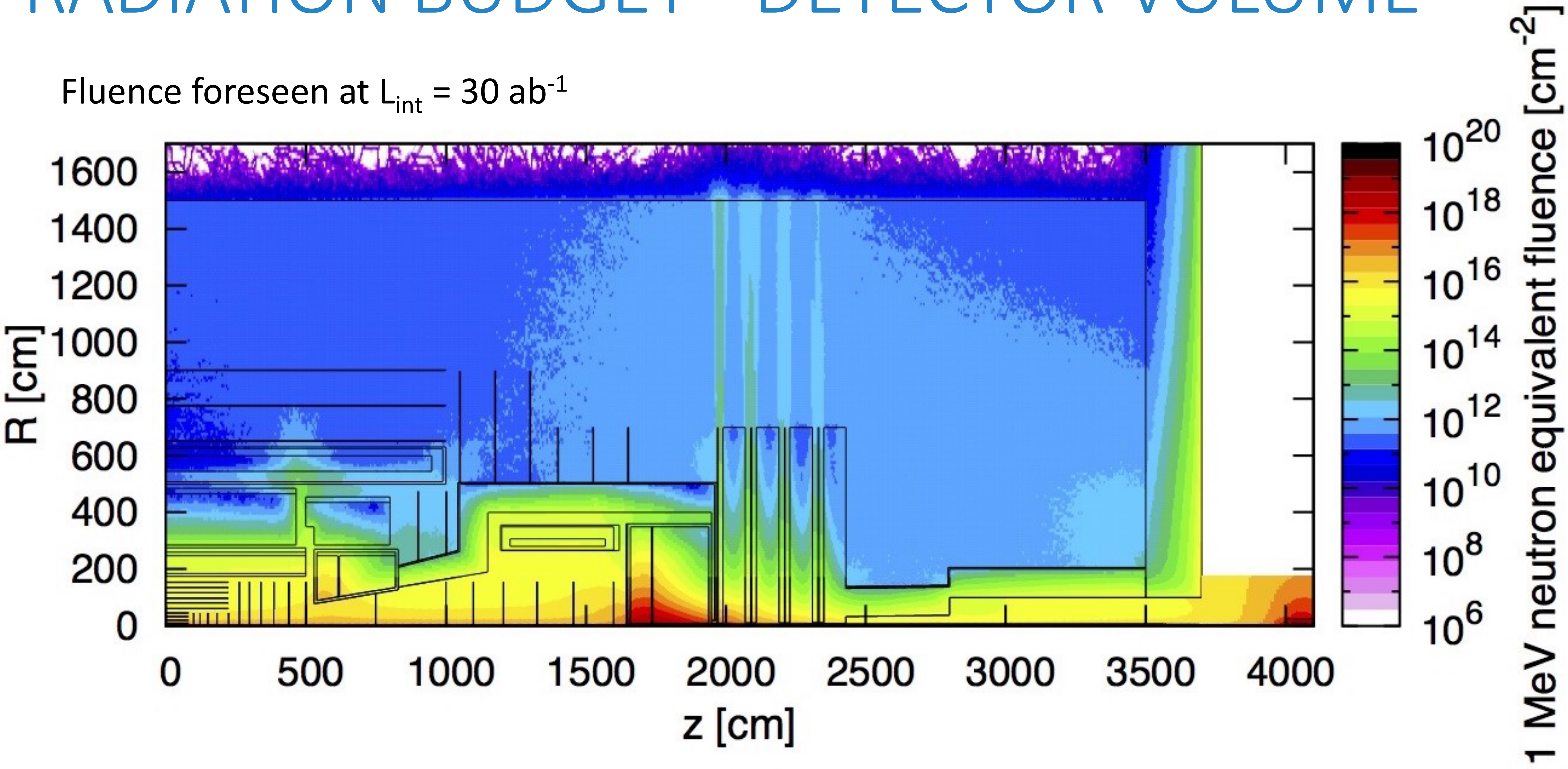
- Pile-up per bunch crossing ~ 1000
- Vertex region $\sigma_z \sim 44$ mm, $\sigma_t \sim 165$ ps
- Average distance between vertices at z = 0 is 125 μm

Tracker requirements:

- $\sigma_{r\phi} = 7.5 - 9.5\ \mu m$
- Low material budget $N_{layers} = 12$
- Effective pile-up = 1 $\sigma_t = 5$ ps

RADIATION BUDGET - DETECTOR VOLUME

Fluence foreseen at L_{int} = 30 ab^{-1}



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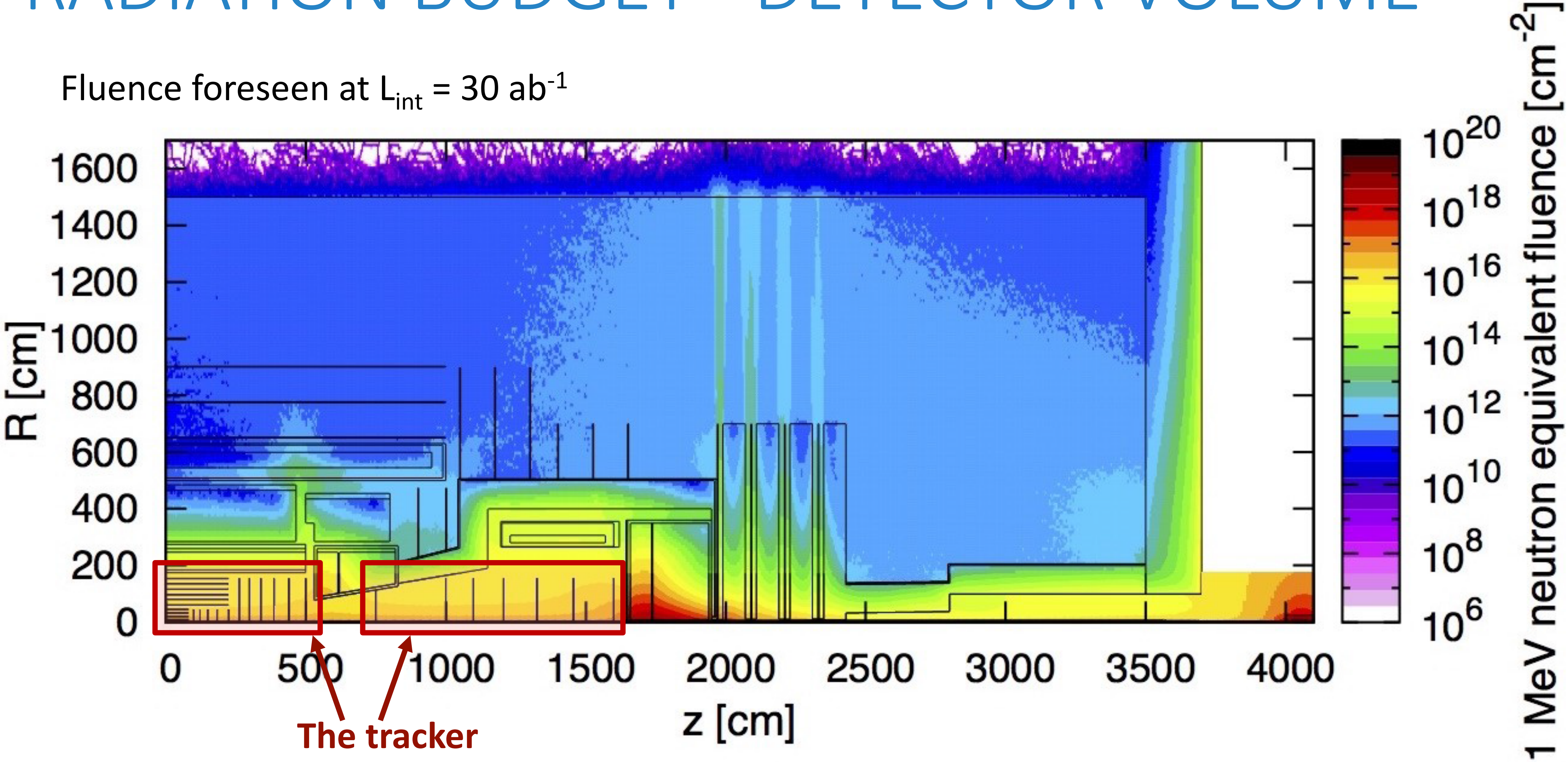

RADIATION BUDGET - TRACKER VOLUME

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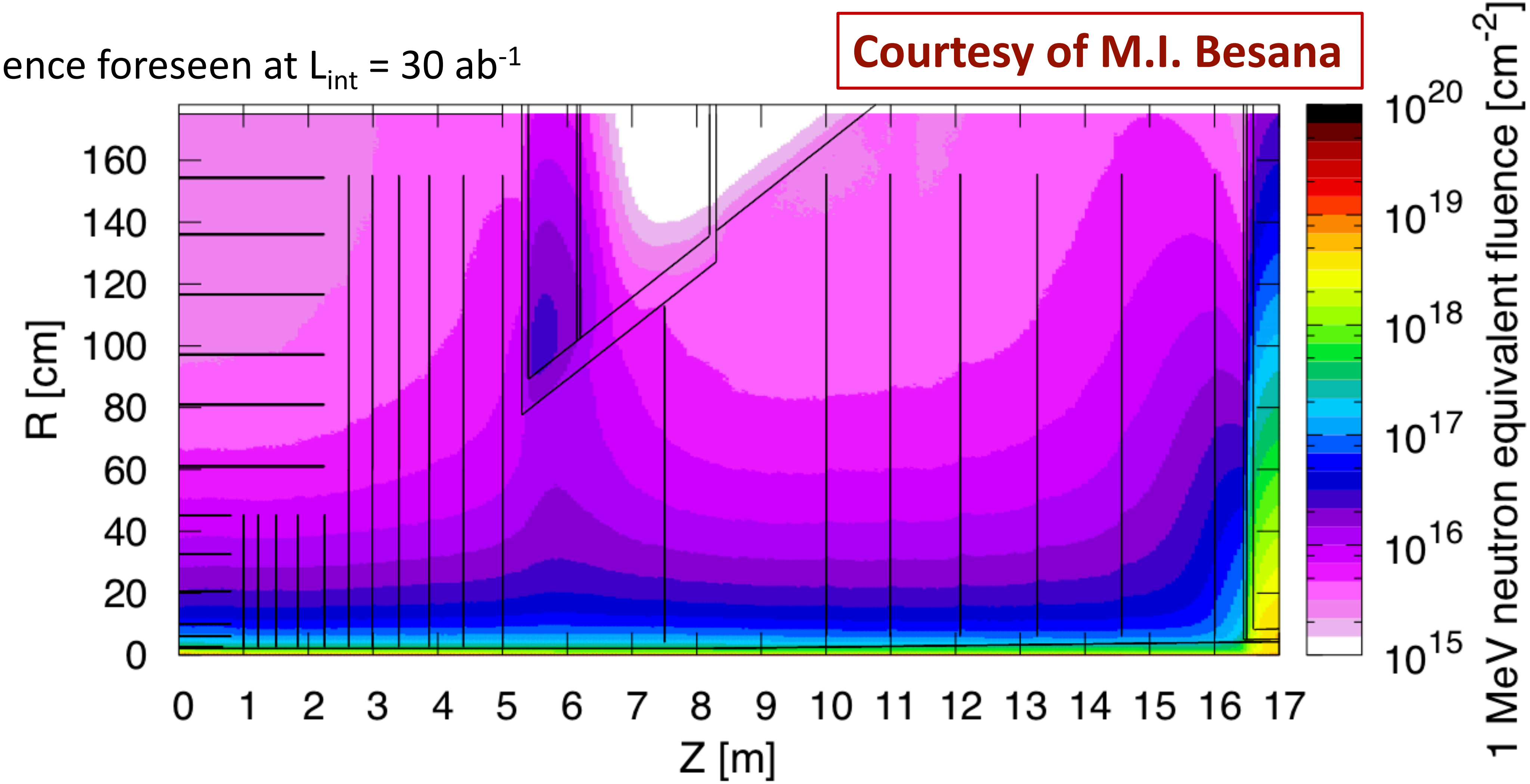
Courtesy of M.I. Besana



R&D PROPOSAL

✎ Tracking

- ✏ First layers with fluence above 10^{17} n_{eq}/cm^2, up to $5{\cdot}10^{17}$ n_{eq}/cm^2
- ✏ Can we do sensors that tolerate that fluence?

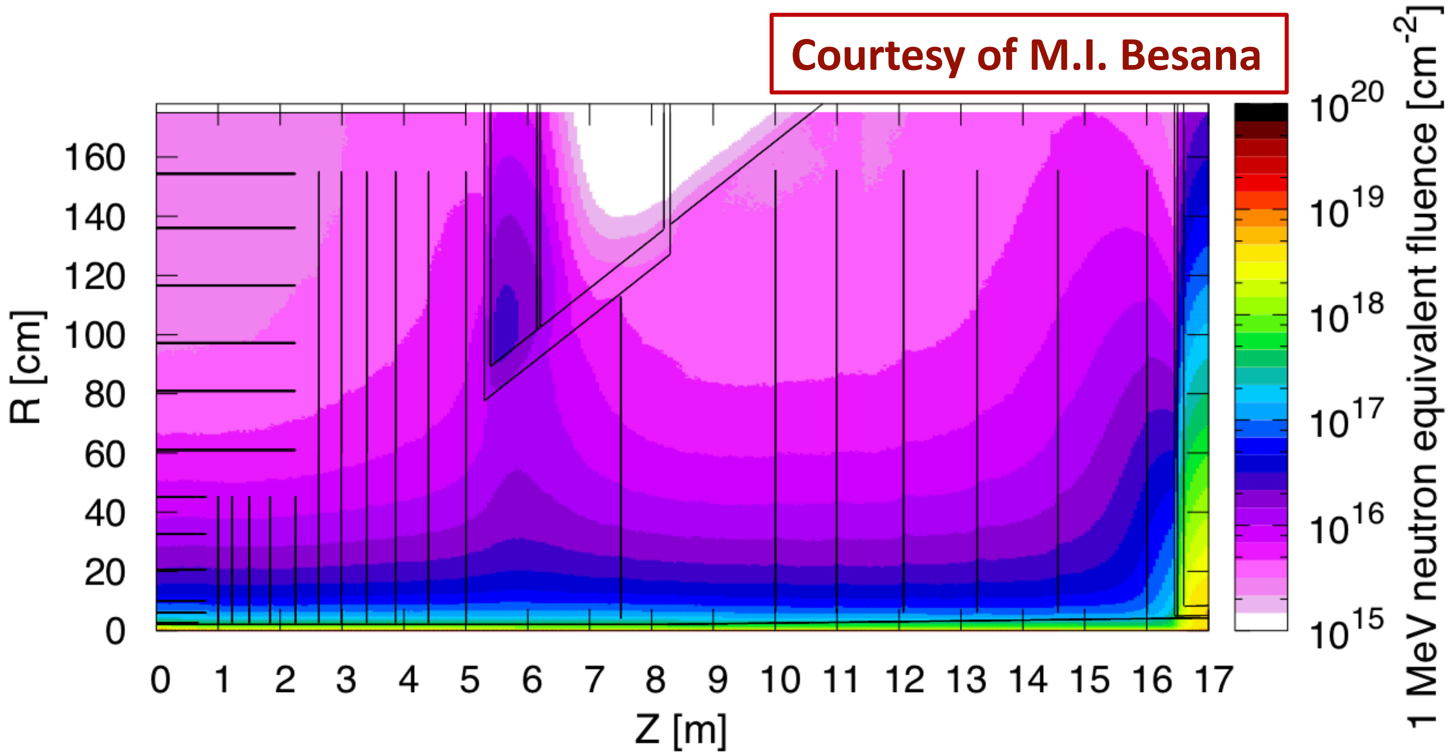
☞ **Go thin**

✎ Timing development

- ✏ 5 ps are the target resolution → more than one timing layer
- ✏ What is maximum fluence for good timing?

☞ **Go up to $5{\cdot}10^{16}$ n_{eq}/cm^2**

Courtesy of M.I. Besana



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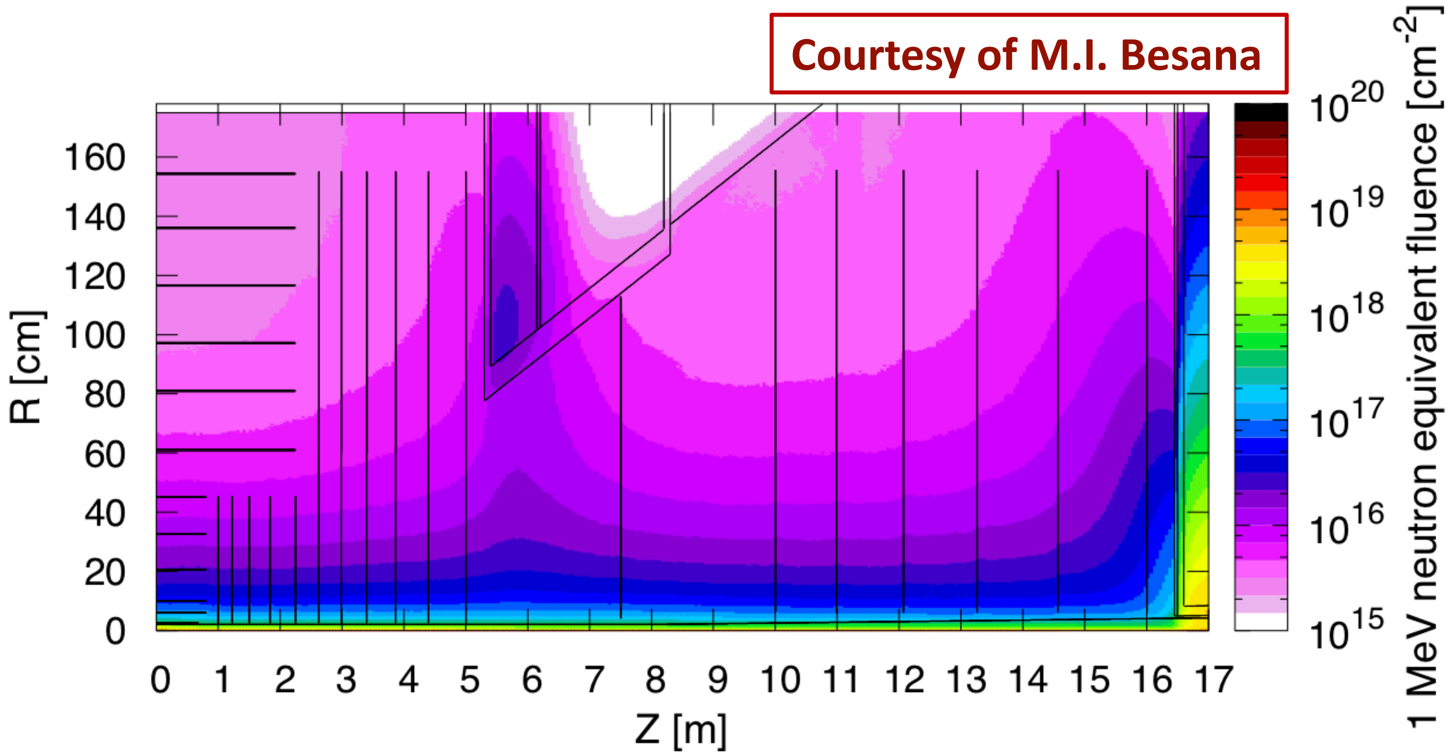
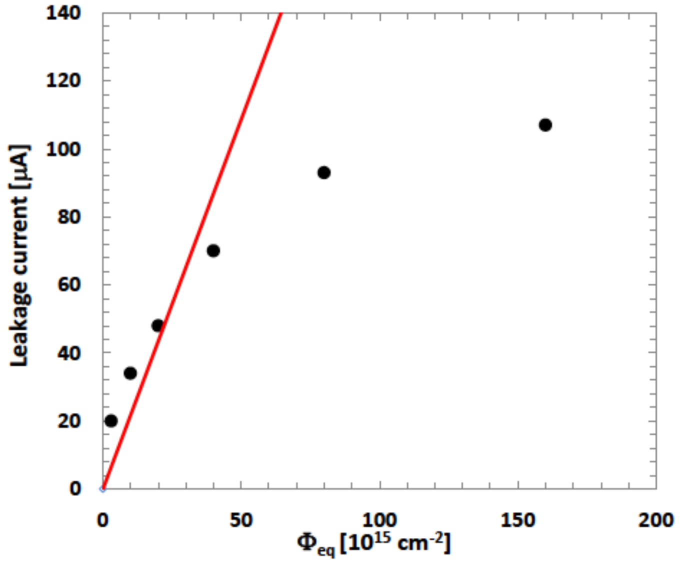
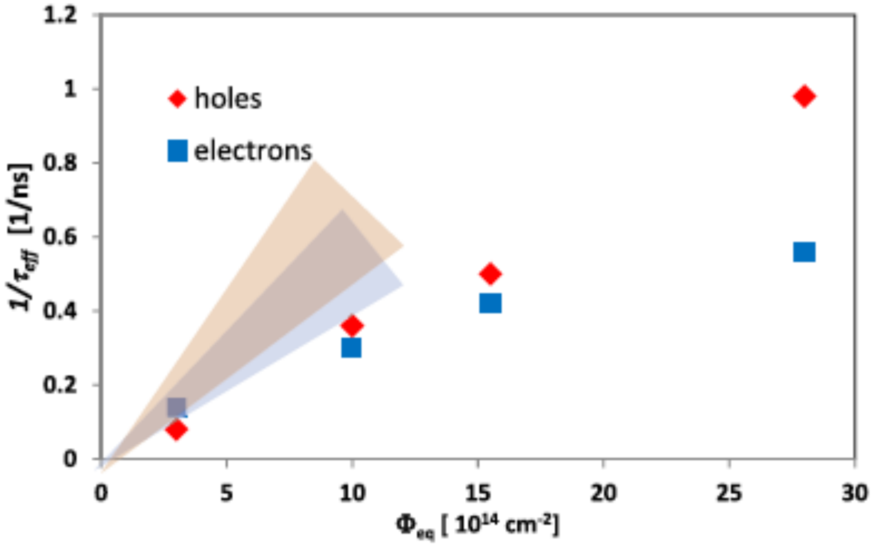
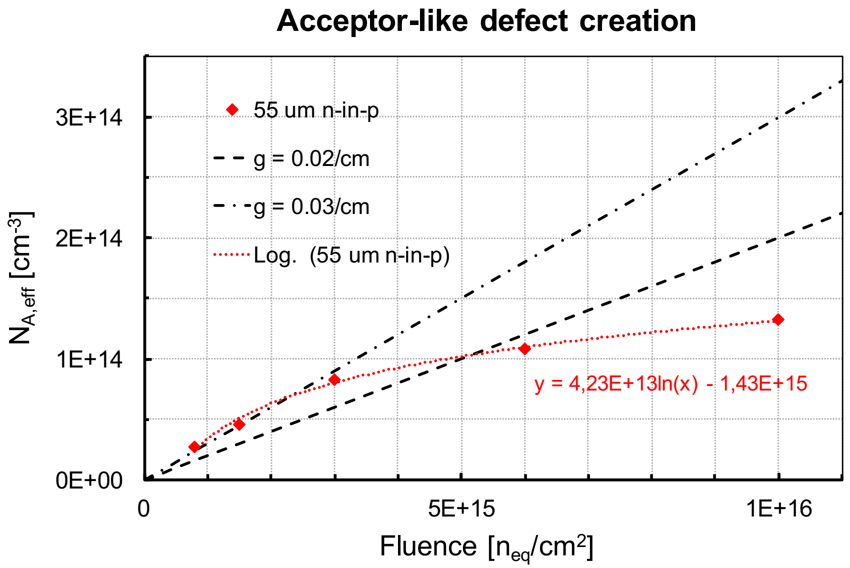


SOME OPTIMISM – SATURATION

At fluences above $5 \cdot 10^{15}$ n_{eq}/cm^2 → **saturation of radiation effects observed**







[G. Kramberger et al., doi:10.1088/1748-0221/8/08/P08004]

[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

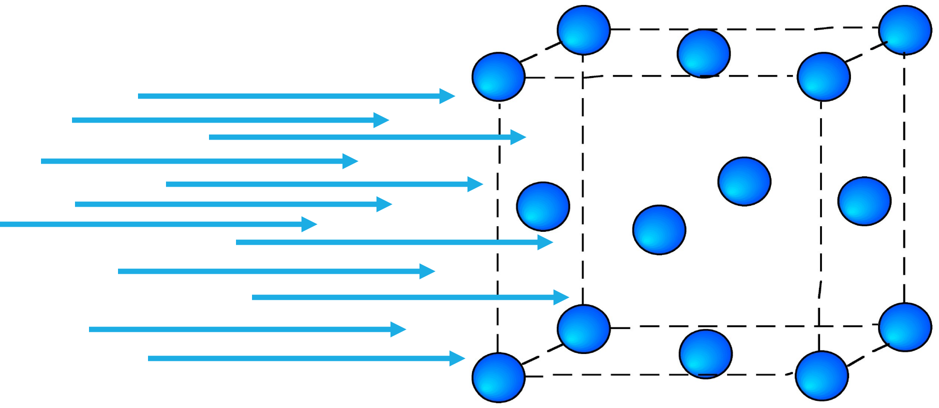
[M. Ferrero et al., 34th RD50 Workshop, Lancaster, UK]

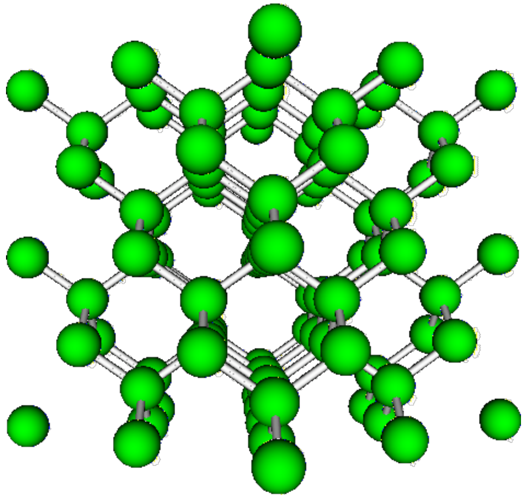
Leakage current saturation
$I = \alpha V \Phi$ → **α from linear to logarithmic**

Trapping probability saturation
$1/\tau_{eff} = \beta\Phi$ → **β from linear to logarithmic**

Acceptor creation saturation
$N_{A,eff} = g_c\Phi$ → **g_c from linear to logarithmic**

WHY SATURATION?



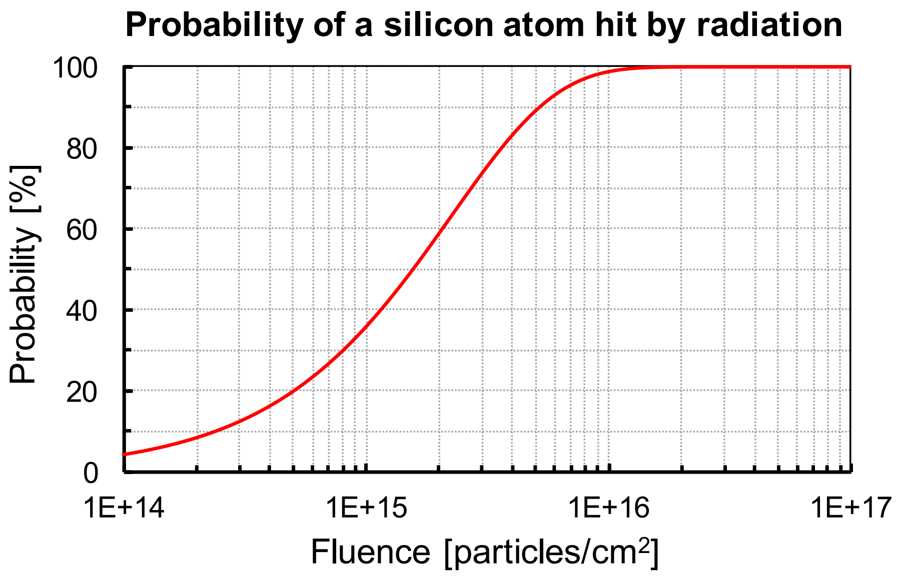


Possible explanation:

Silicon lattice parameter = 5.43 $\cdot 10^{-8}$ cm

At a fluence of $5 \cdot 10^{15}$ particles/cm^2 every lattice cell has been crossed by 12 particles on average

Silicon radius (minimum distance between silicon atoms) = 1.18 $\cdot 10^{-8}$ cm

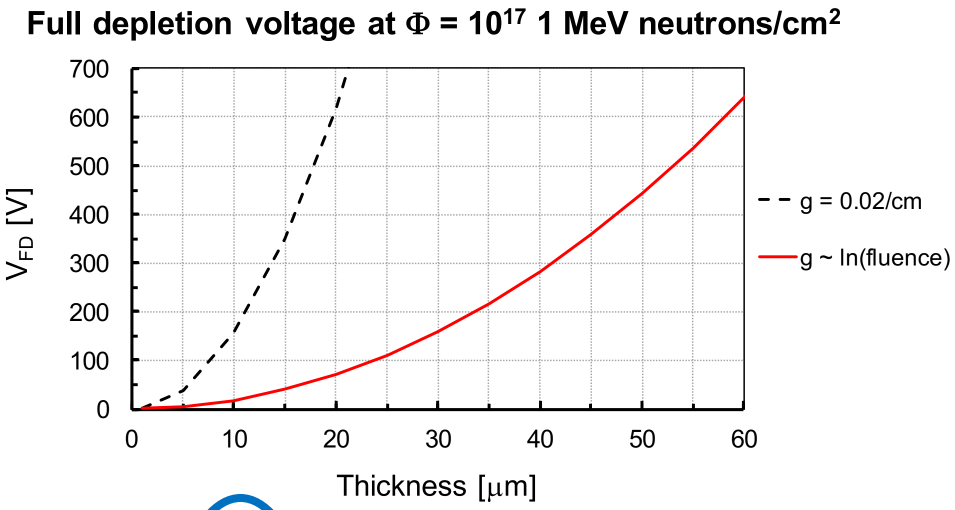


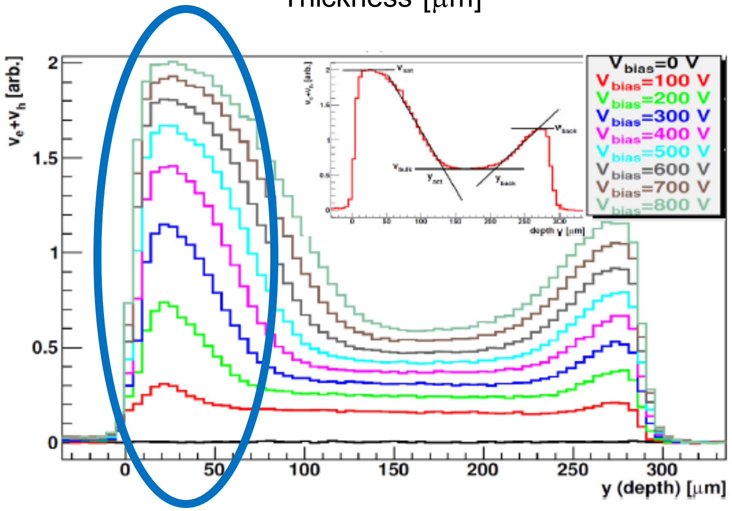
GO THIN

$I = \alpha V \Phi \rightarrow$ Reduce V $\rightarrow$ **Reduce thickness**

$V_{FD} = e|N_{eff}|d^2/2\varepsilon$ $\rightarrow$ **Reduce thickness**

Double junction $\rightarrow$ **Reduce thickness (?)**





$\Phi = 1.6 \cdot 10^{16}/cm^2$
23 MeV/c protons

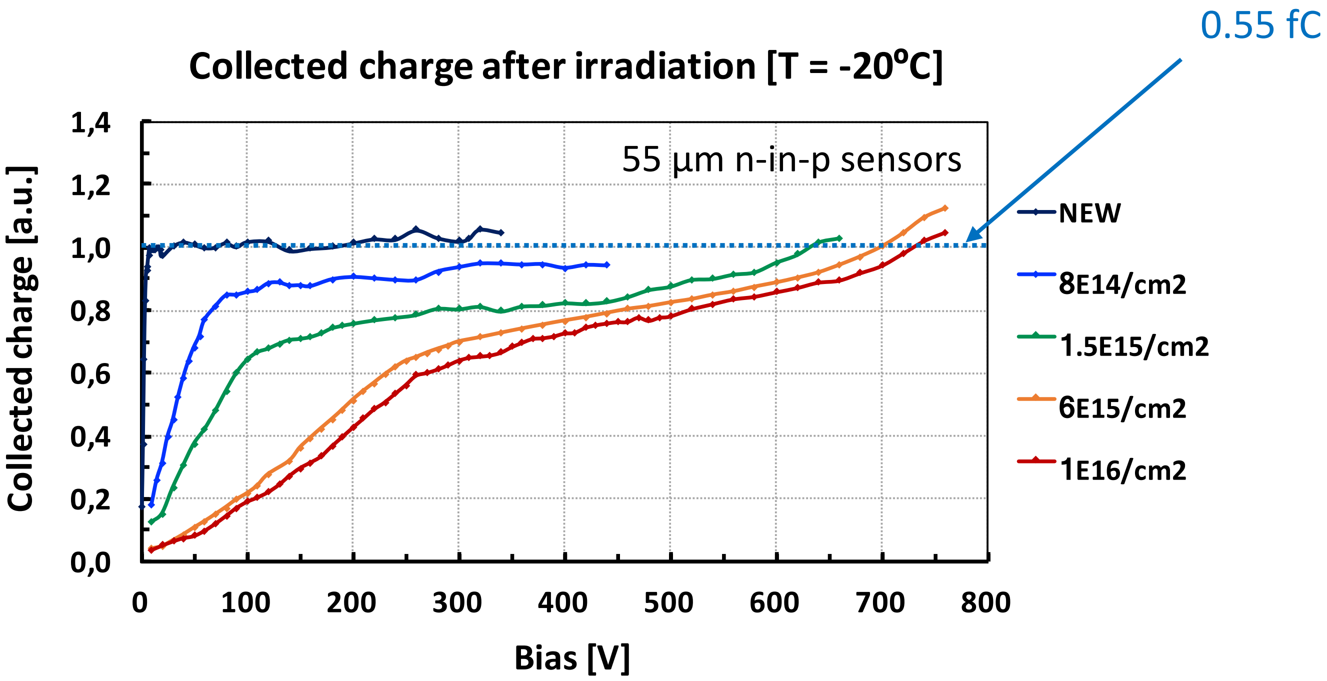
[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

HOW THIN?

To efficiently record a hit, electronics require al least **1 fC**

MPV charge from a MIP crossing silicon ~ 75 e-h/µm
50 µm thick → 0.5 fC
20 µm thick → 0.2 fC

Signal multiplication by a factor of 5-10 is needed

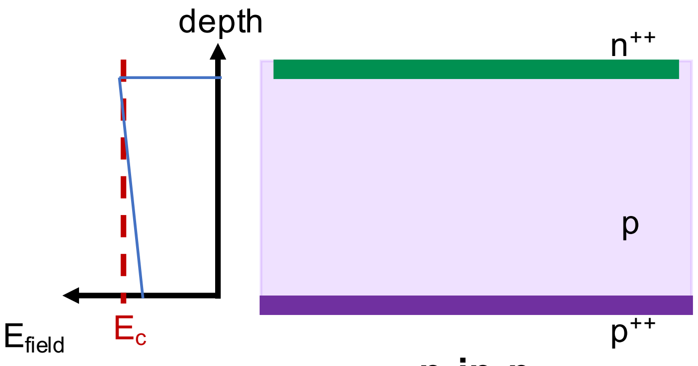


SENSOR CHOICE

How to get internal multiplication of 5-10?

Impact ionisation occurs when $E_{field} > E_c = 25$ V/µm

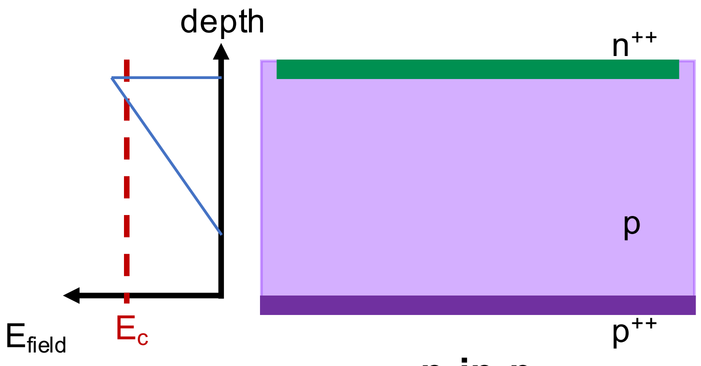
Stable gain if E_{field} is controlled by applied V_{bias}



n-in-p
p ~ 10^{12} cm^{-3}

E_{field} above E_c
over long distance

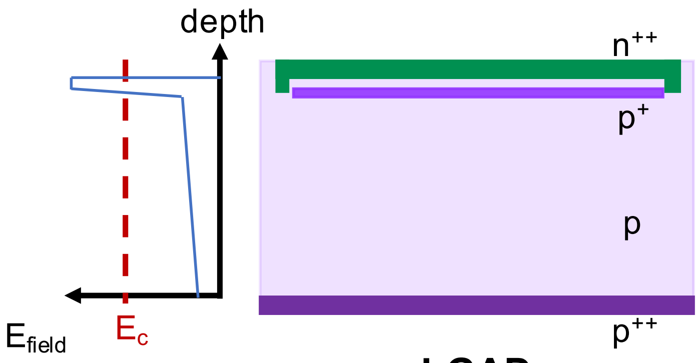
AVALANCHE



n-in-p
p ~ 10^{14} cm^{-3}

Difficult to precisely
control E_{field}

RISK OF AVALANCHE



LGAD
p ~ 10^{12} cm^{-3}, p^{+} ~ 10^{16} cm^{-3}

E_{field} above E_c
for shord distance
well controlled by V^{bias}

CONTROLLED GAIN

SENSOR CHOICE

How to get internal multiplication of 5-10?

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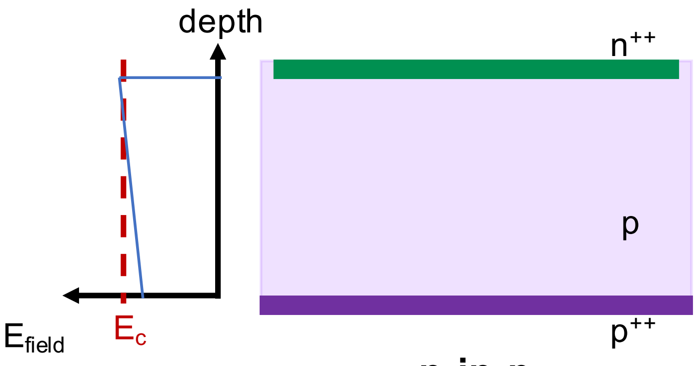

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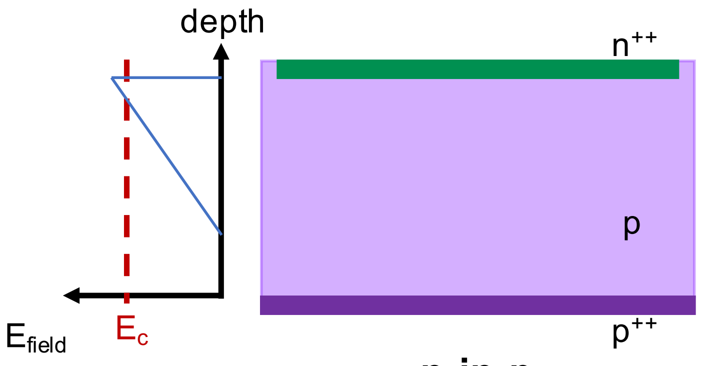

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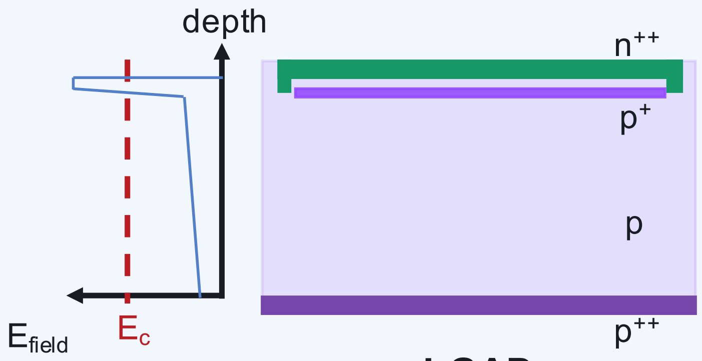
RISK OF AVALANCHE



LGAD
p ~ 10^{12} cm^{-3}, p$^+$ ~ 10^{16} cm^{-3}

E_{field} above E_c
for shord distance
well controlled by V^{bias}

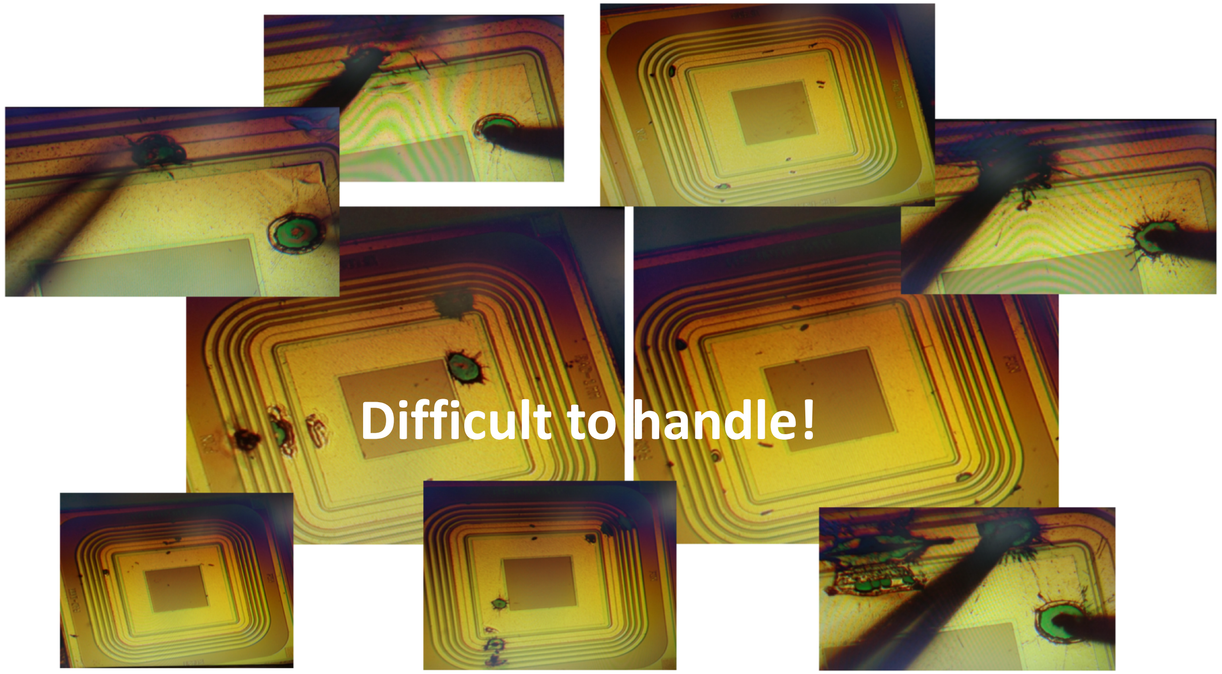
CONTROLLED GAIN

IRRADIATED n-in-p

High resistivity n-in-p

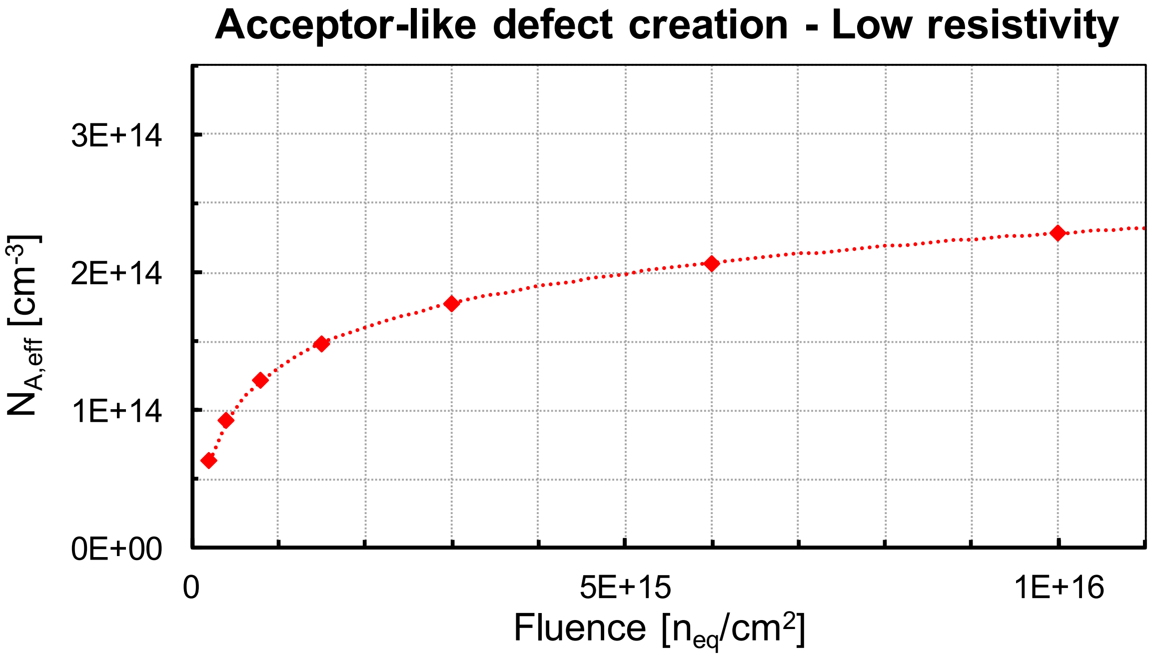
The field is almost constant vs sensor depth
→ it reaches E_c at same V_{bias} everywhere in the sensor

$\Phi = 10^{16}\ n_{eq}/cm^2$

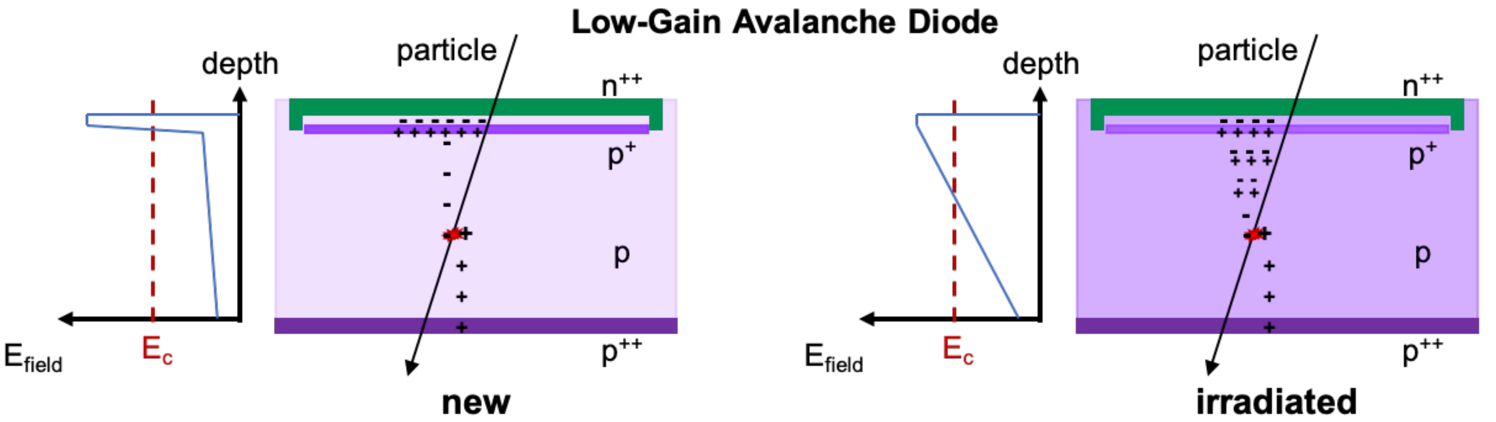


Low resistivity n-in-p

Higher initial N_{eff}
→ higher V_{FD}values



IRRADIATED LGAD



With irradiation the multiplication region migrates from gain layer to the bulk region

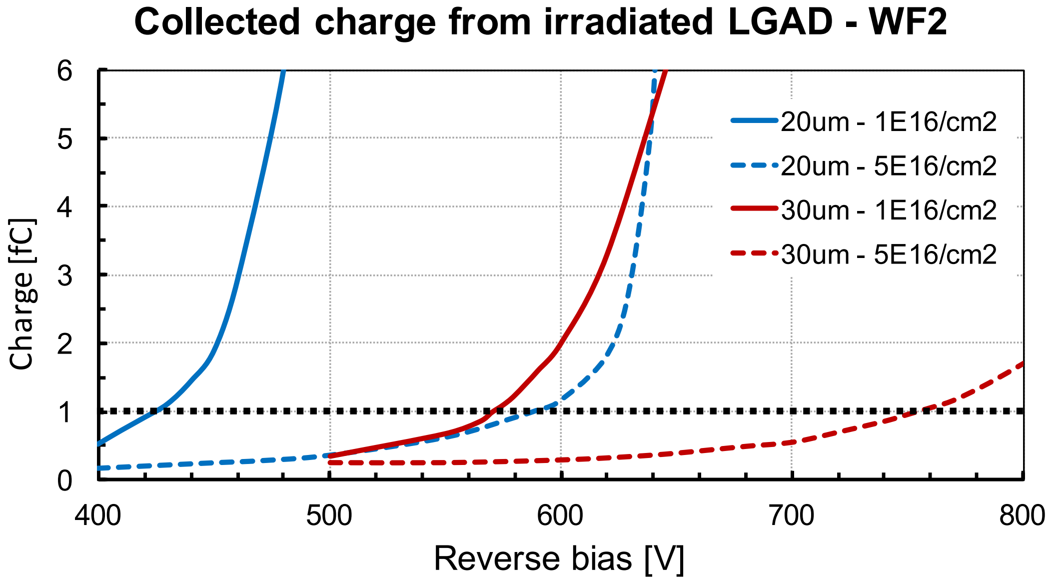
Avalanche is prevented by charge trapping

→ **Thinner sensors provide higher gain after irradiation**

Predictions from Weightfield2 using van Overstraeten – de Man model

20 and 30 µm sensors, providing 5 fC of charge at 120 V when new

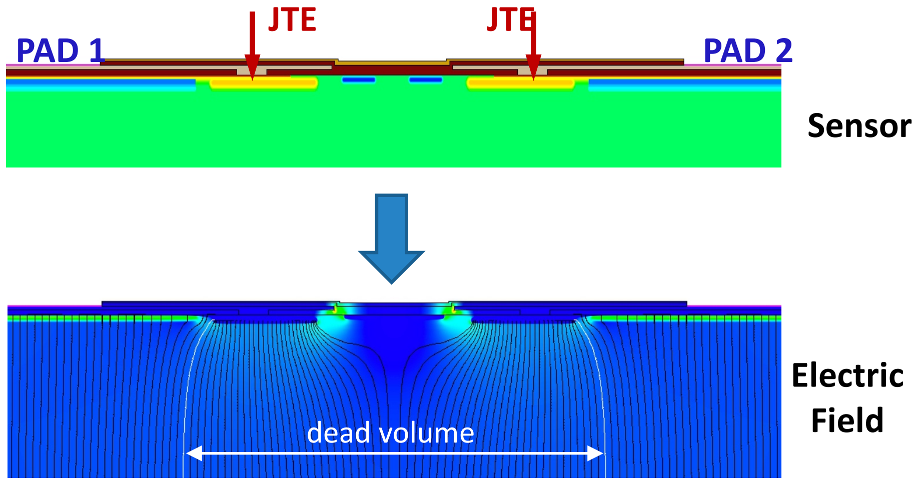
`[personalpages.to.infnf.it/~cartigli/Weightfield2/Mail.html]`

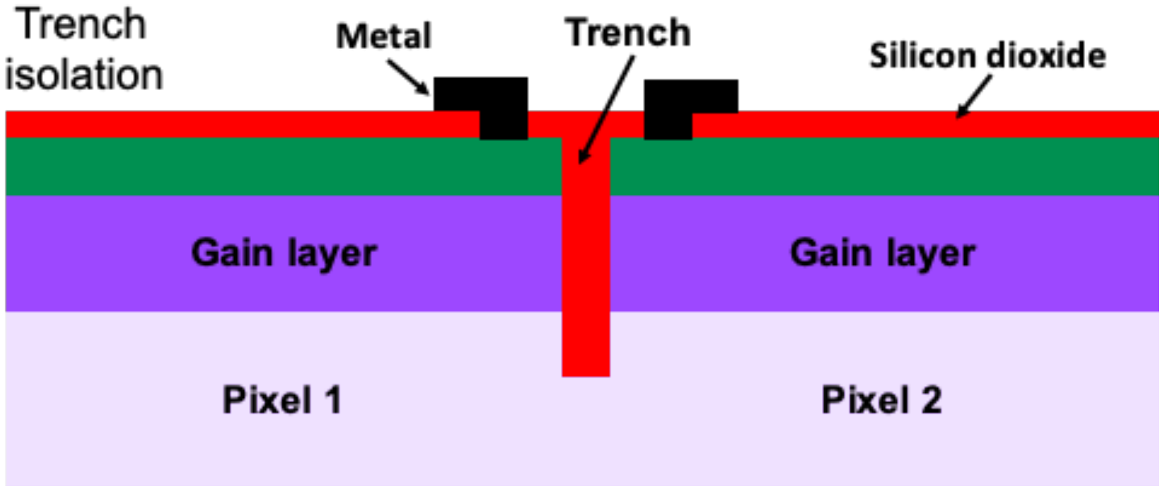


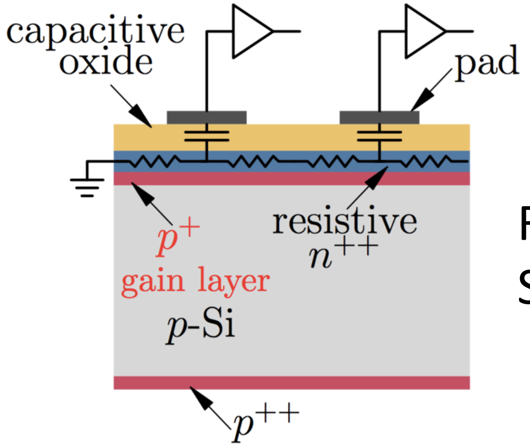
JUNCTION TERMINATION EXTENSION

Gain termination - JTE
At present → 30 µm no-gain width

R&D on trench terminations and AC coupled LGAD
→ **Radiation tolerance needs to be investigated**







RSD
See F. Siviero's poster

RADIATION TOLERANCE AND TIMING

To reach ~ 30 ps resolution per hit, electronics require al least **5 fC**
Present limit for 30 ps time resolution is $3{\cdot}10^{15}\ n_{eq}/cm^2$

Goal: retard multiplication transition from the gain layer to the bulk region

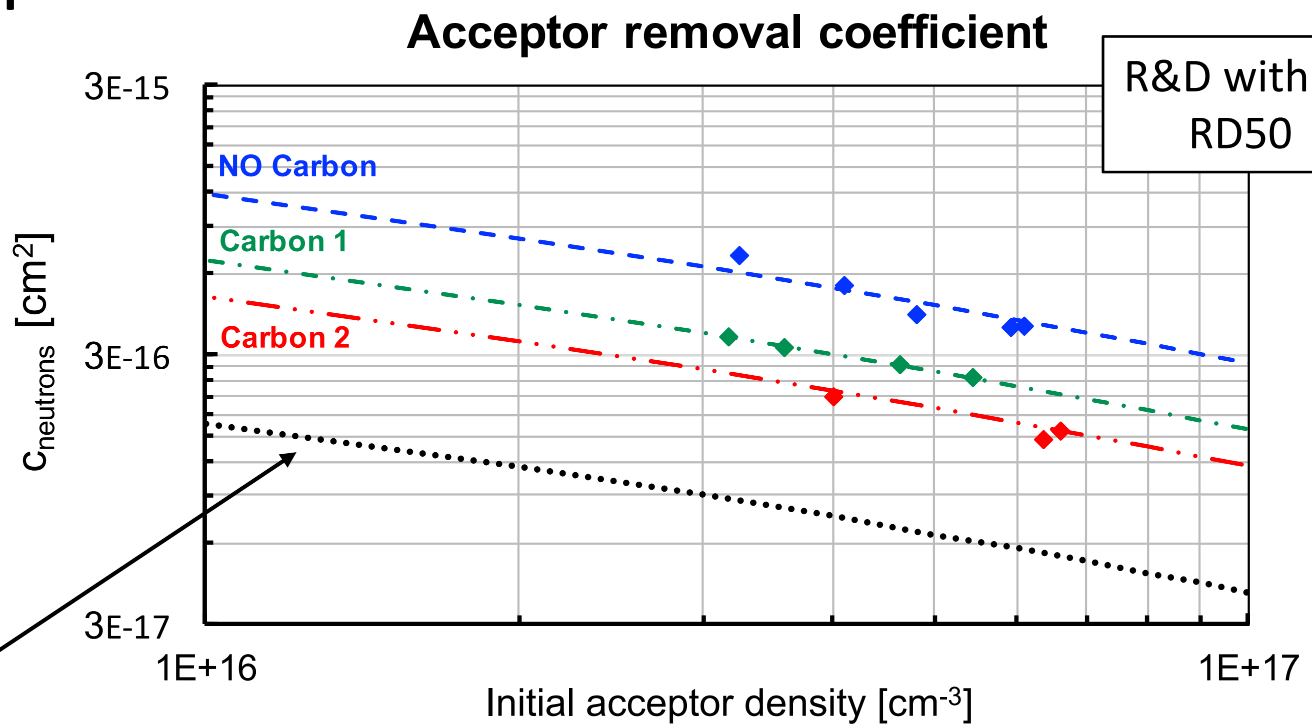
Acceptor removal (see M. Moll's talk)

$$N_{A,eff} = N_{A,0}{\cdot}e^{c\Phi}$$

Adding carbon protects boron from removal
Different carbon concentrations have different impact on boron protection

→ **Gain layer engineering to extend precise timing to $5{\cdot}10^{16}\ n_{eq}/cm^2$**

Possible?



R&D within RD50

[M. Ferrero et al., doi: 10.1016/j.nima.2018.11.121]

RADIATION TOLERANCE AND GAIN LAYER

To reach ~ 30 ps resolution per hit, electronics require al least **5 fC**
Present limit for 30 ps time resolution is $3\cdot10^{15}$ n_{eq}/cm^2

Goal: retard multiplication shift from the gain layer to the bulk region

Acceptor removal (see M. Moll's talk)

$$N_{A,eff} = N_{A,0}\cdot e^{c\Phi}$$

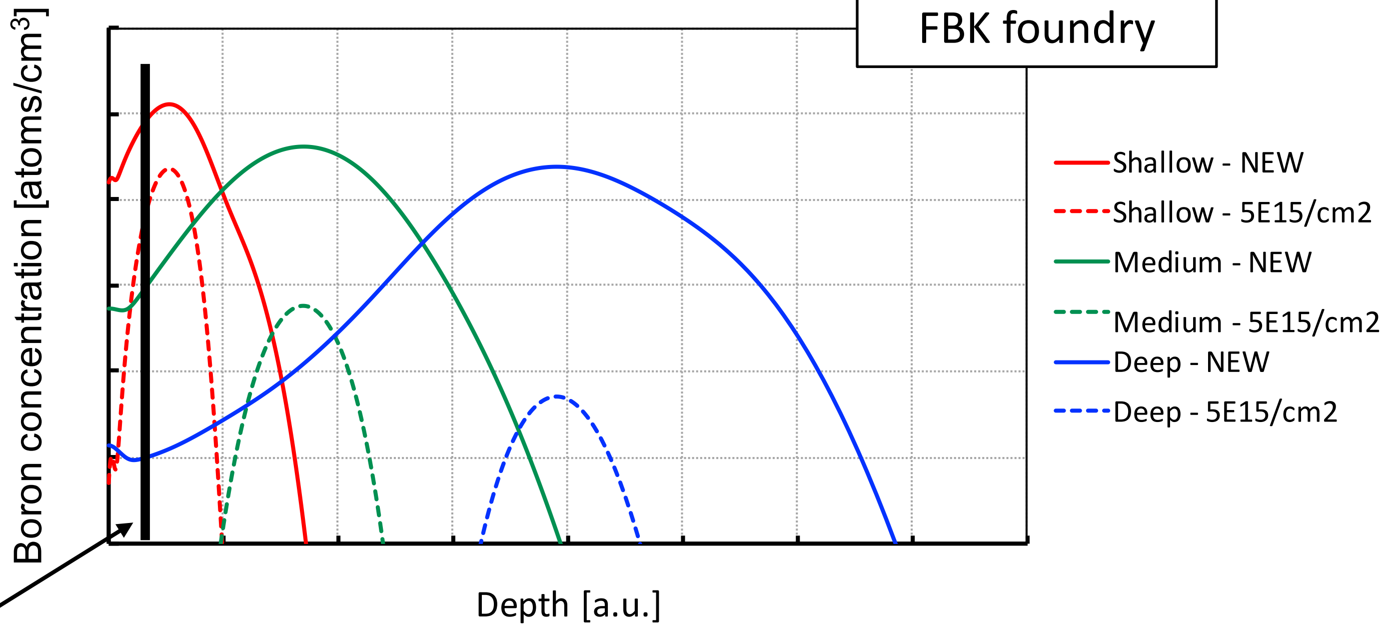
Defect engineering and different gain layer implantation strategies will be investigated

$$\mathbf{c \cdot N_{A,0} = 60\ cm^{-1} \rightarrow\ < 10\ cm^{-1}}$$

for $N_{A,0} = 10^{17}$ atoms/cm^3

Gain layer implant

R&D effort with FBK foundry



Possible?

SUMMARY

- Next-generation hadron colliders
  - R&D on next-generation silicon detectors
- Possibility to track particles up to $5 \cdot 10^{17}$ n_{eq}/cm^2
  - Saturation of radiation damage effects can be exploited to reach the target
  - 20-30 μm thick LGAD with gain 5-10 are suitable detectors
  - Suitable environment to study radiation damage effects at high fluences
- Possibility to have precise timing up to $5 \cdot 10^{16}$ n_{eq}/cm^2
  - R&D on gain layer implant is mandatory

ACKNOWLEDGEMENTS

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- Horizon 2020, grant UFSD669529
- Horizon 2020, grant INFRAIA
- AIDA-2020, grant agreement no. 654168
- INFN, Gruppo V
- Ministero degli Affari Esteri, Italy, MAE, “Progetti di Grande Rilevanza Scientifica”
- MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- U.S. Department of Energy, grant DE-SC0010107
- RD50, CERN

BACKUP

FCC-hh PARAMETER TABLE

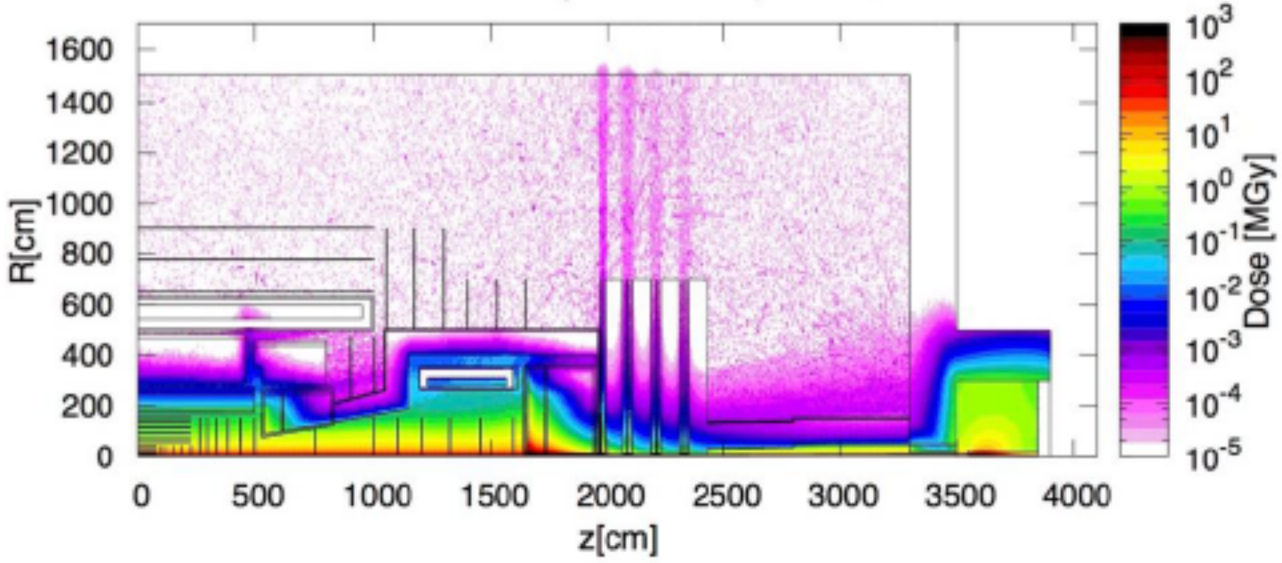
Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [331]	mb	80	80	86	103
σ_{tot} [331]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Rms luminous region σ_z	mm	45	57	57	49
Line PU density	mm^{-1}	0.2	1.0	3.2	8.1
Time PU density	ps^{-1}	0.1	0.29	0.97	2.43
$dN_{ch}/d\eta\|_{\eta=0}$ [331]		6.0	6.0	7.2	10.2
Charged tracks per collision N_{ch} [331]		70	70	85	122
Rate of charged tracks	GHz	59	297	1234	3942
$<p_T>$ [331]	GeV/c	0.56	0.56	0.6	0.7
Bending radius for $<p_T>$ at B=4 T	cm	47	47	49	59
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0

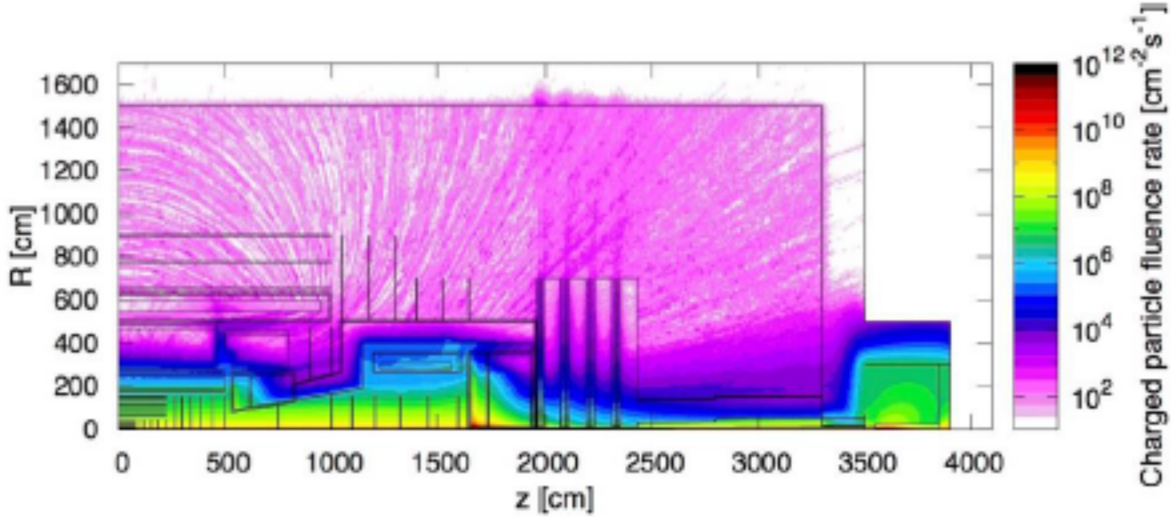
To define the specifications and requirements for the detector

To relate the challenges for the detector at the between LHC / HL-LHC / HE-LHC and FCC-hh

FCC-hh CHARGED PARTICLES



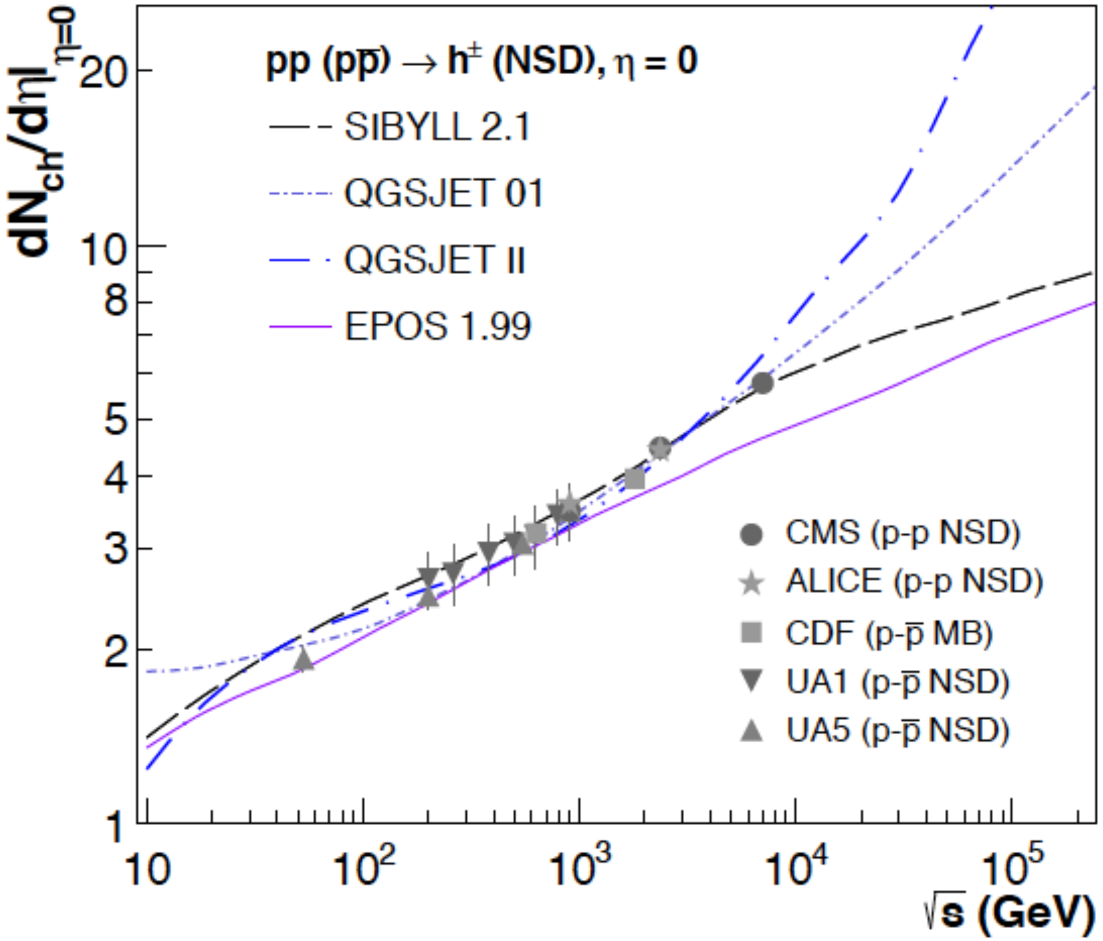
Dose of 300MGy in the first tracker layers.
<10kGy in HCAL barrel and extended barrel.



Maximum of 10kHz/cm^2 of charged particle rate in the Barrel and Forward Muon System, similar to HL-LHC Muon Systems.

In the tracker volume the charged particle rate is just a function of distance from the beampipe with rather small dependence on z.

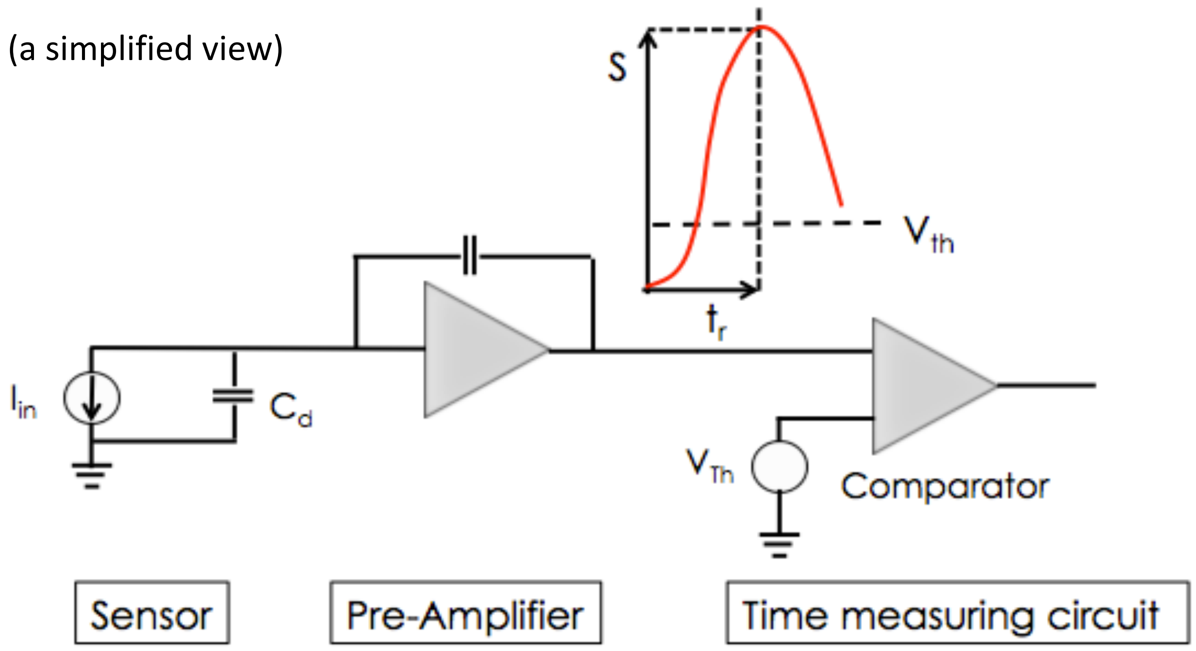
Underlying events in high energy pp collisions



Scaling of the central charged multiplicity for the SIBYLL, QGSJET, and EPOS models compared to collider data for NSD events

A TIME-TAGGING DETECTOR

(a simplified view)



Time is set when the signal crosses the comparator threshold

The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning

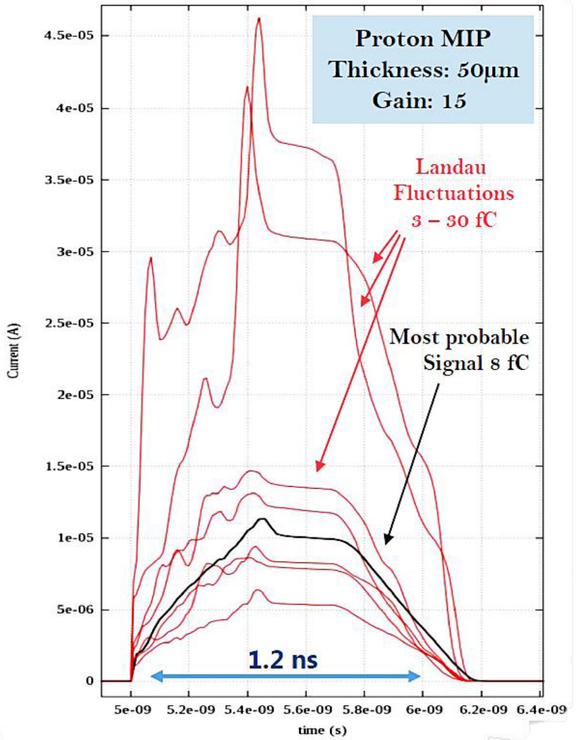
▻ **Strong interplay between sensor and electronics**

FAST TIMING - THE INGREDIENTS

For a planar detector geometry $\sigma_t^2 = \sigma_{Current}^2 + \sigma_{Jitter}^2 + \sigma_{Time\ Slewing}^2 + \sigma_{TDC}^2$

with a saturated velocity, the σ_t main contributors are **current fluctuations** and **jitter**

Current fluctuations are due to the physics of MIP ionization

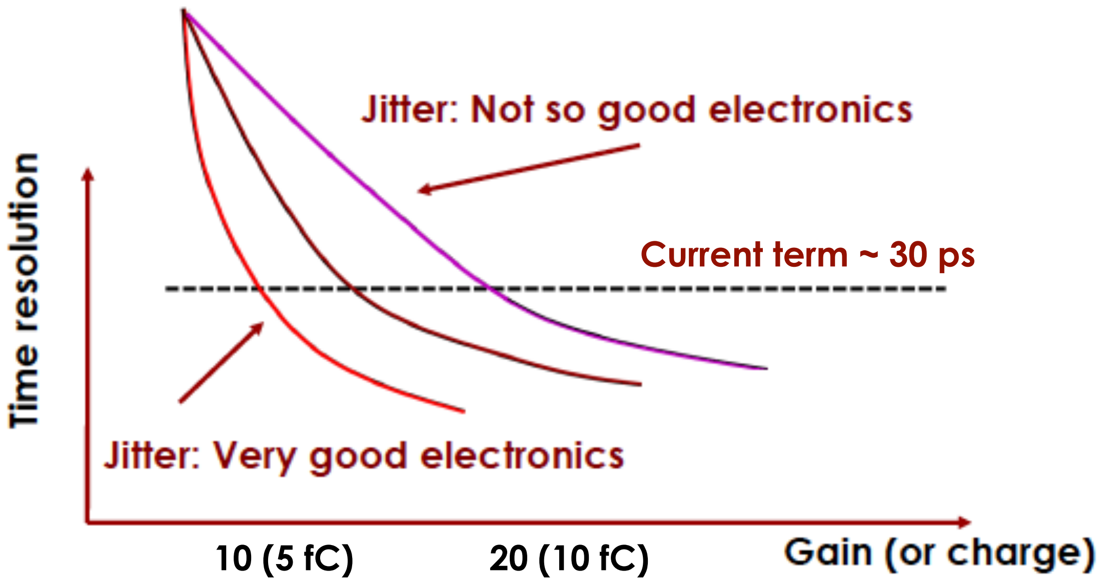


✎ Improves with thin sensors
✎ Does not depend on the gain

For 50 µm thick sensors contribute ~ 30 ps

→ **Physical limit to time resolution**

Jitter is driven by the electronics



$$\sigma_{jitter} = \frac{N}{(dV/dt)_{V_{th}}} = \frac{t_{rise}}{S/N}$$

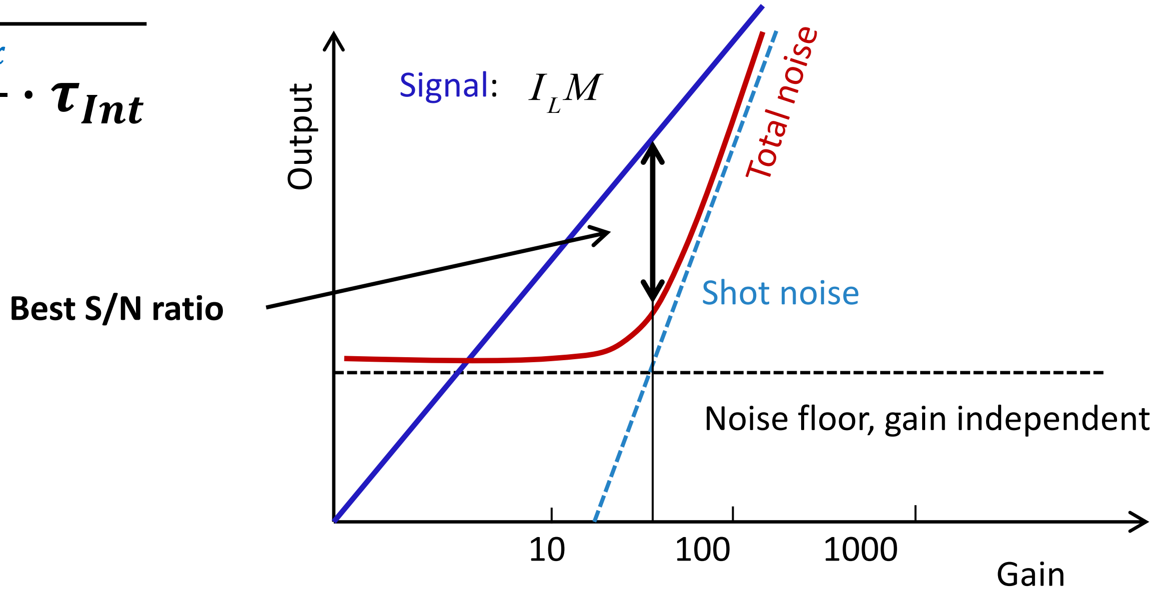
SHOT NOISE

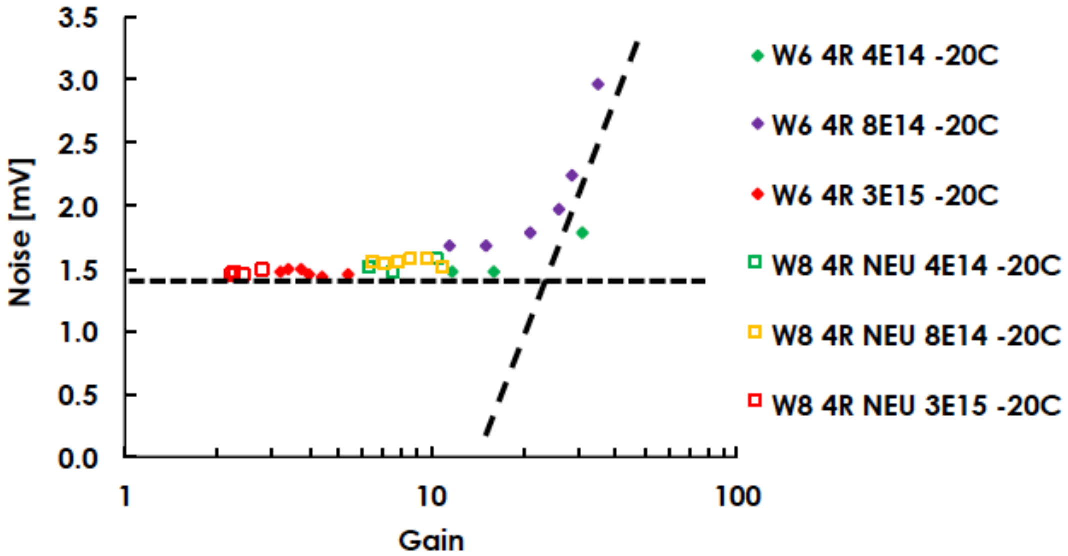
Shot Noise: $ENC = \sqrt{\int i_{Shot}^2 df} = \sqrt{\frac{I \cdot (Gain)^{2+x}}{2e} \cdot \tau_{Int}}$

Shot noise increases faster than the signal
$\rightarrow$ the ratio S/N becomes worse at high gain

To minimize the shot noise

- **Low gain (G = 10-20)**
- **Cool the detector**
- **Use small pads to have less leakage current**

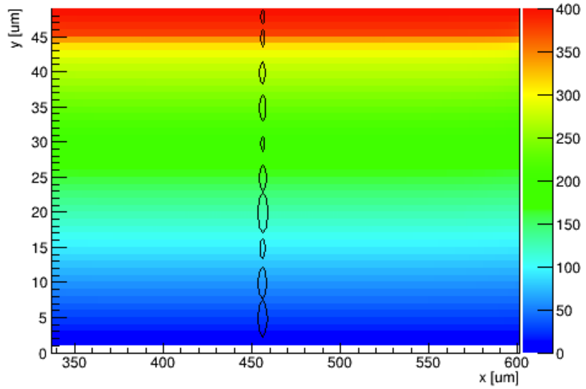




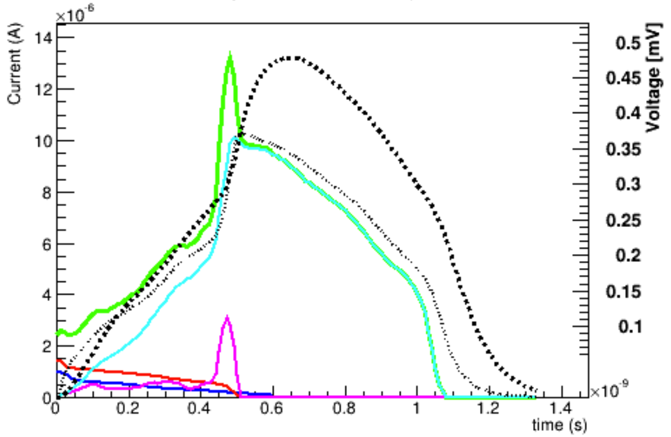
It has been measured that the values of Shot Noise are below the Current fluctuations

ELECTRONICS - THE PRE-AMP CHOICHE

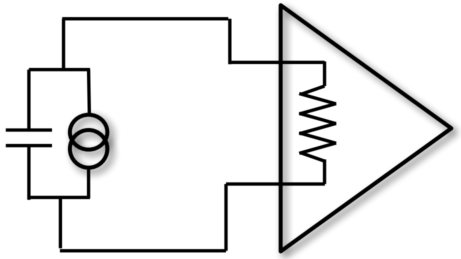
Energy deposition in a 50 µm sensor



Current signal in a 50 µm sensor

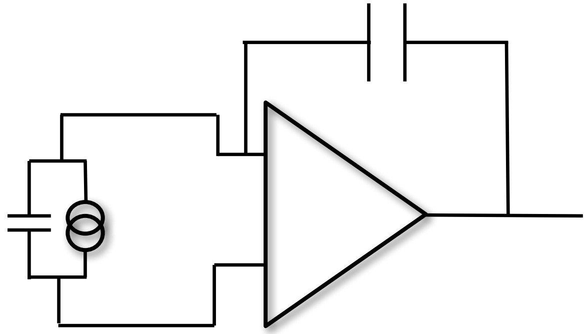


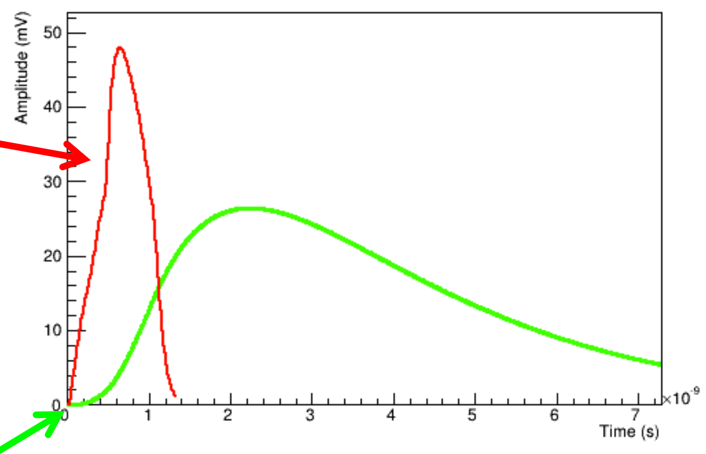
Current Amplifier



- Fast signal steepness
- Higher noise
- Sensitive to Landau bumps
- More power

Charge Sensitive Amplifier



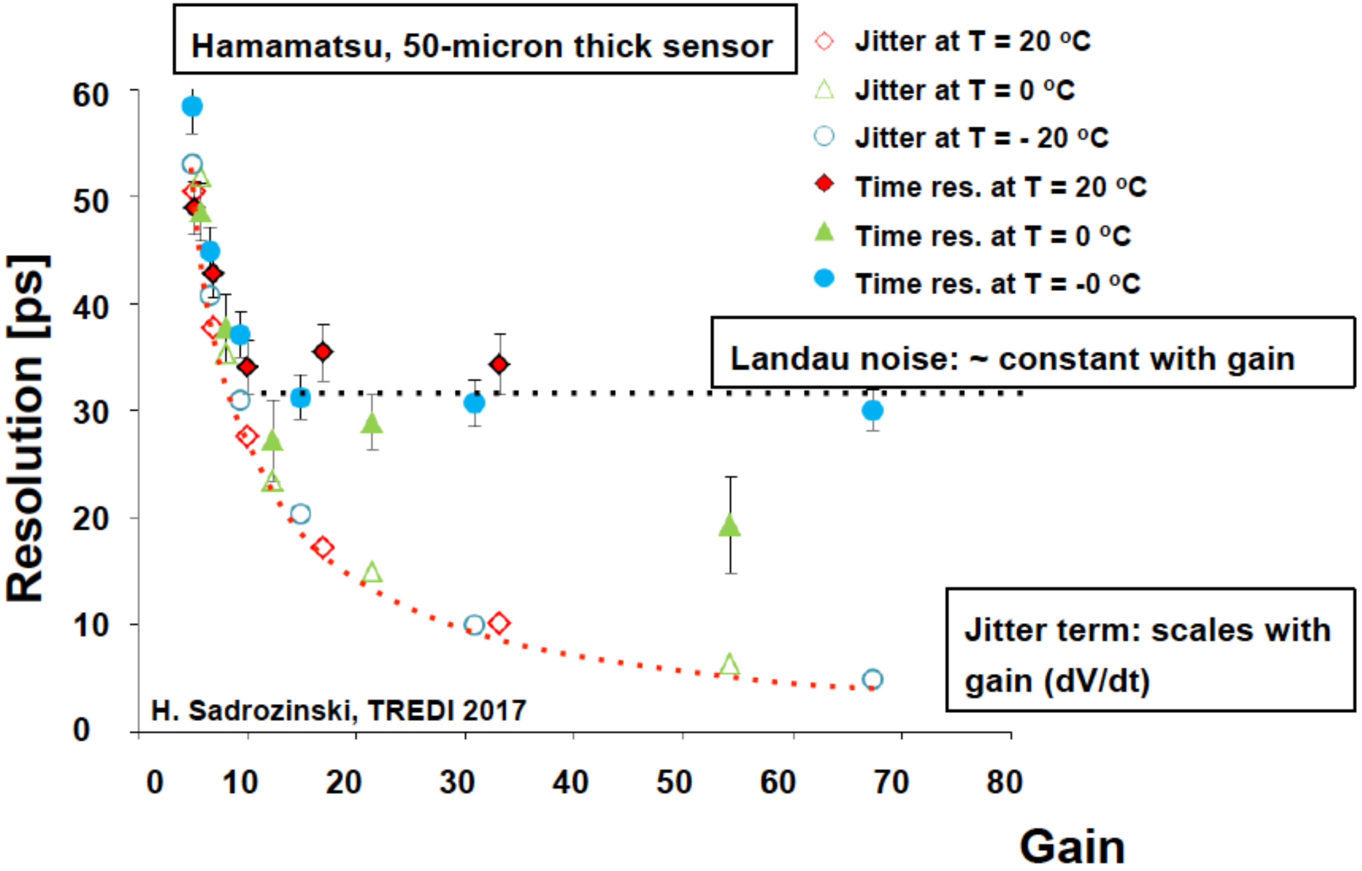


- Slower signal steepness
- Lower noise
- Signal smoothing
- Less power

MEASURED TIME RESOLUTION

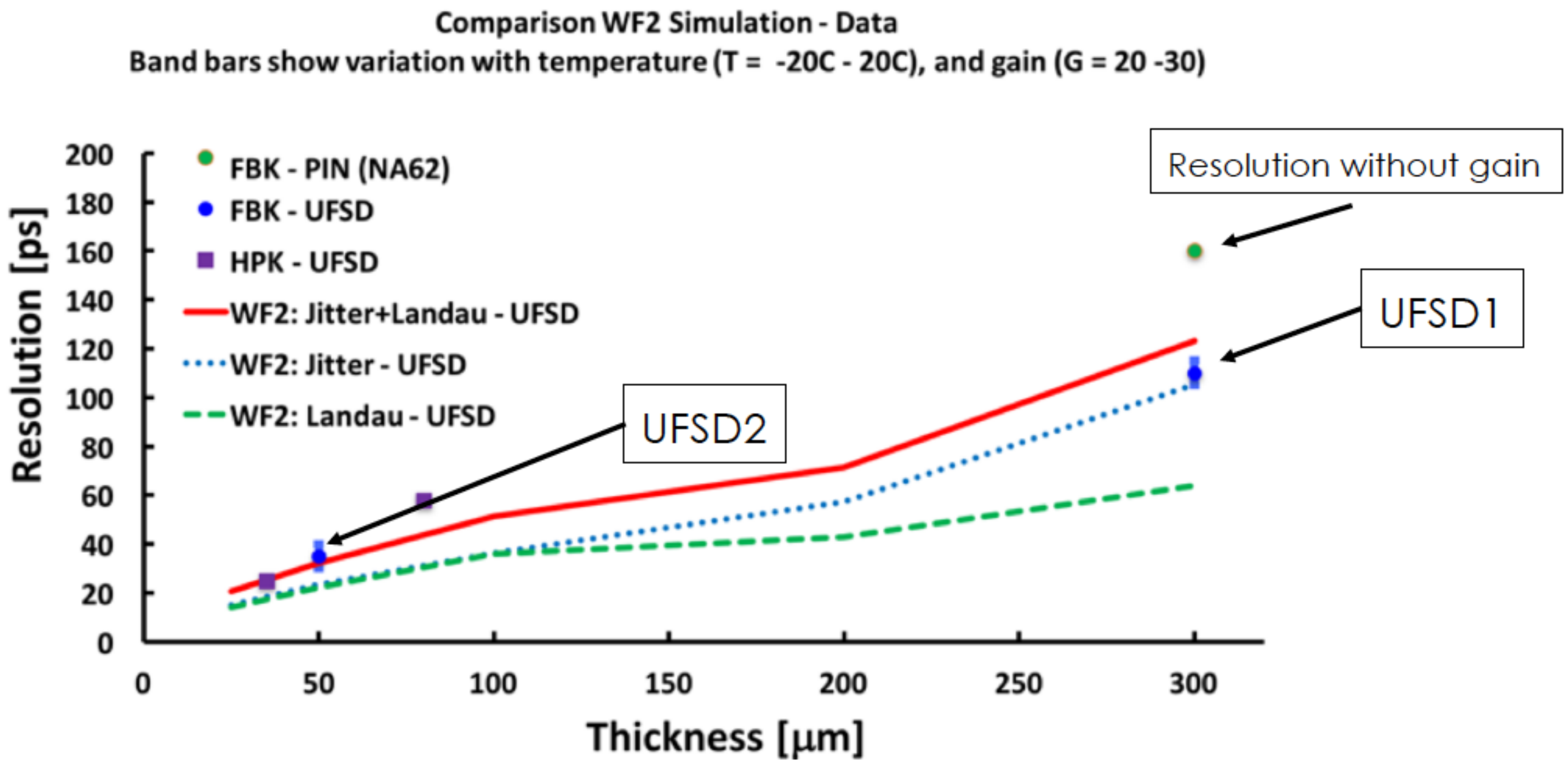
UFSD from Hamamatsu: 30 ps time resolution

Value of gain ~ 20



UFSD TIME RESOLUTION

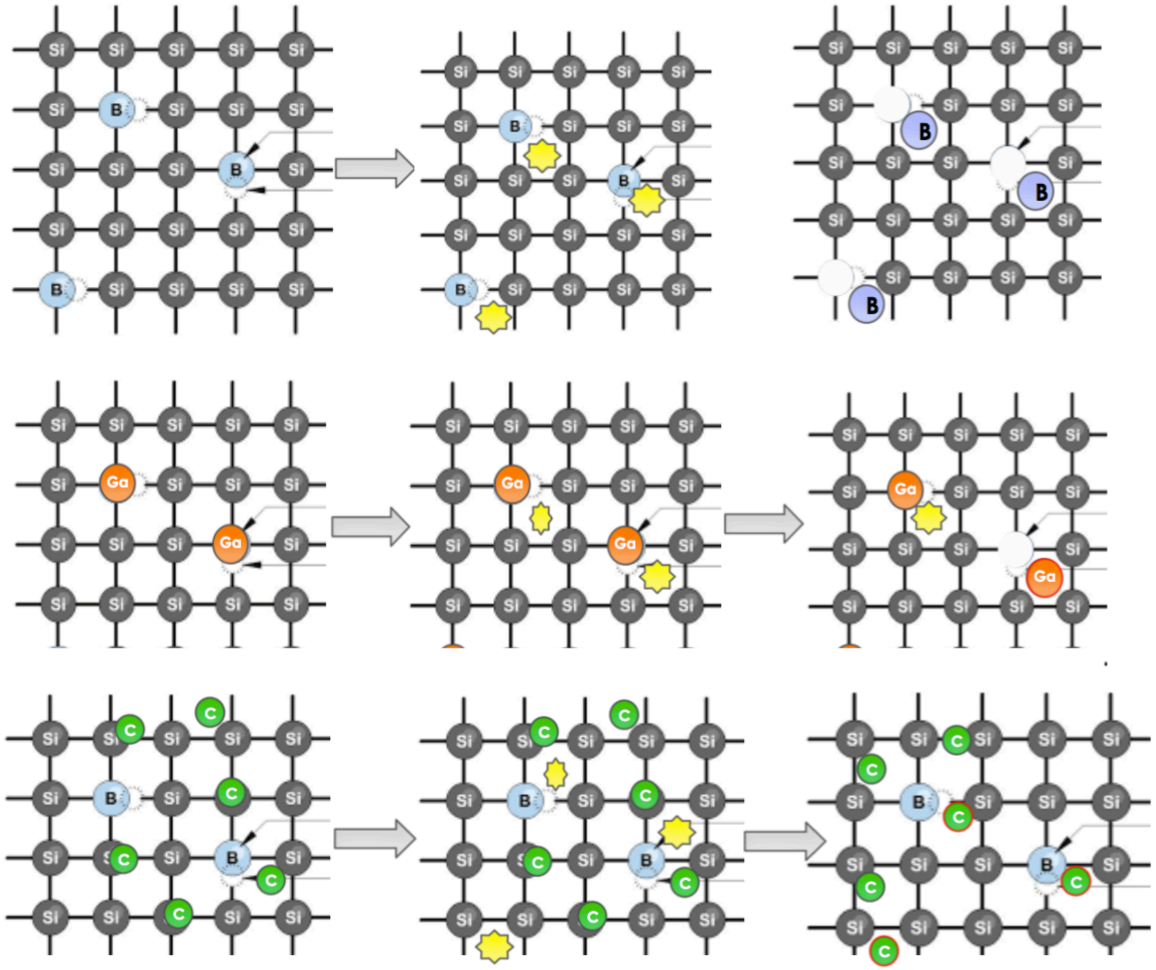
⇒ UFSD achieved 30 ps time resolution, in line with our target



DOPING STRATEGY MOTIVATION

From RD50 Collaboration

Different types of gain layer implant to study the radiation effects on the gain layer



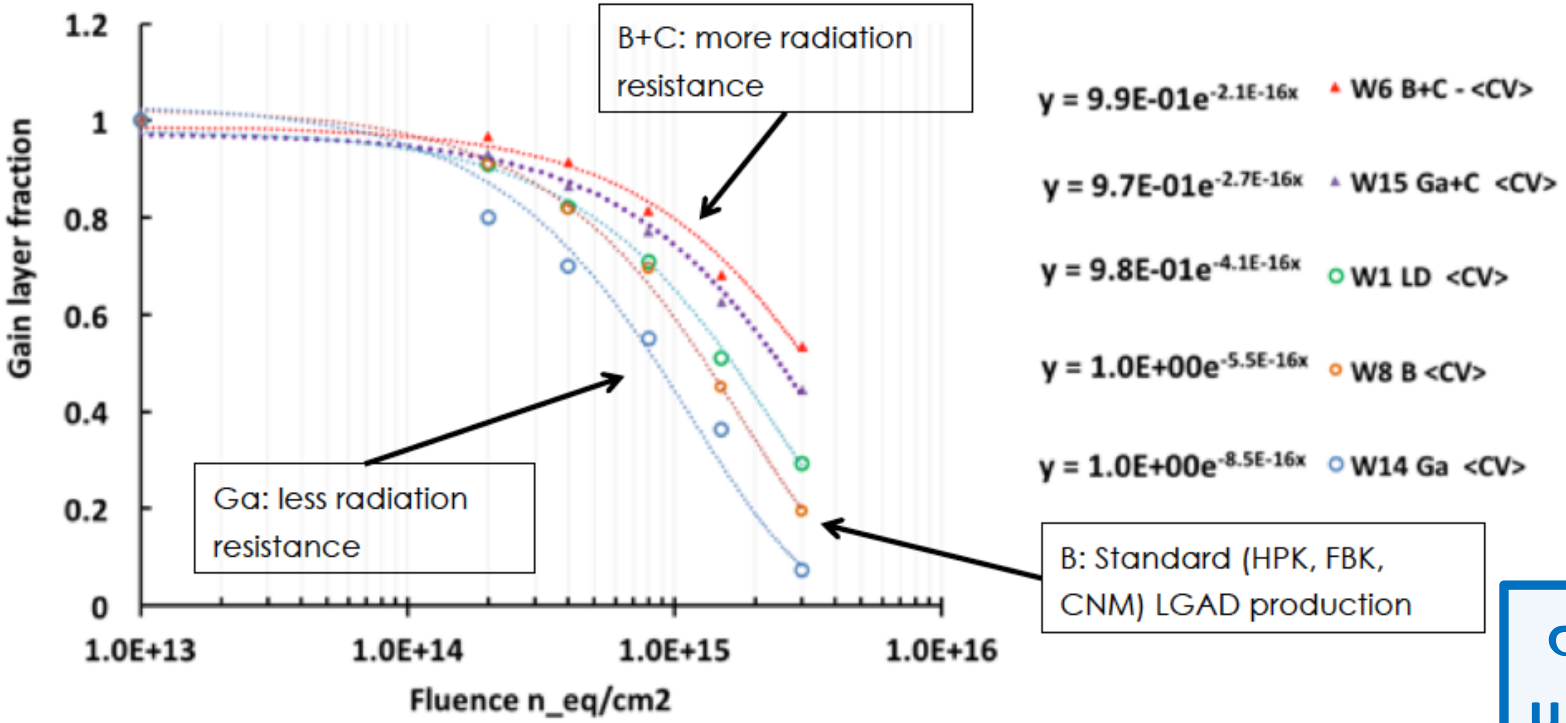
Boron
Radiation creates interstitial defects that inactivate the Boron

Gallium
From literature, Gallium has a lower possibility to become interstitial

Carbon
Interstitial defects filled with Carbon instead of with Boron and Gallium

GAIN LAYER RADIATION TOLERANCE

UFSD suffer for gain reduction due to irradiation
FBK used both Boron and Gallium as gain layer dopant, and added Carbon in the gain layer volume



$\Rightarrow$ **The usage of Carbon double the radiation hardness of UFSD**

$\sigma_t \sim$ 30 ps achievable up to $1.5 \cdot 10^{15}$ n_{eq}/cm^2 using Carbon

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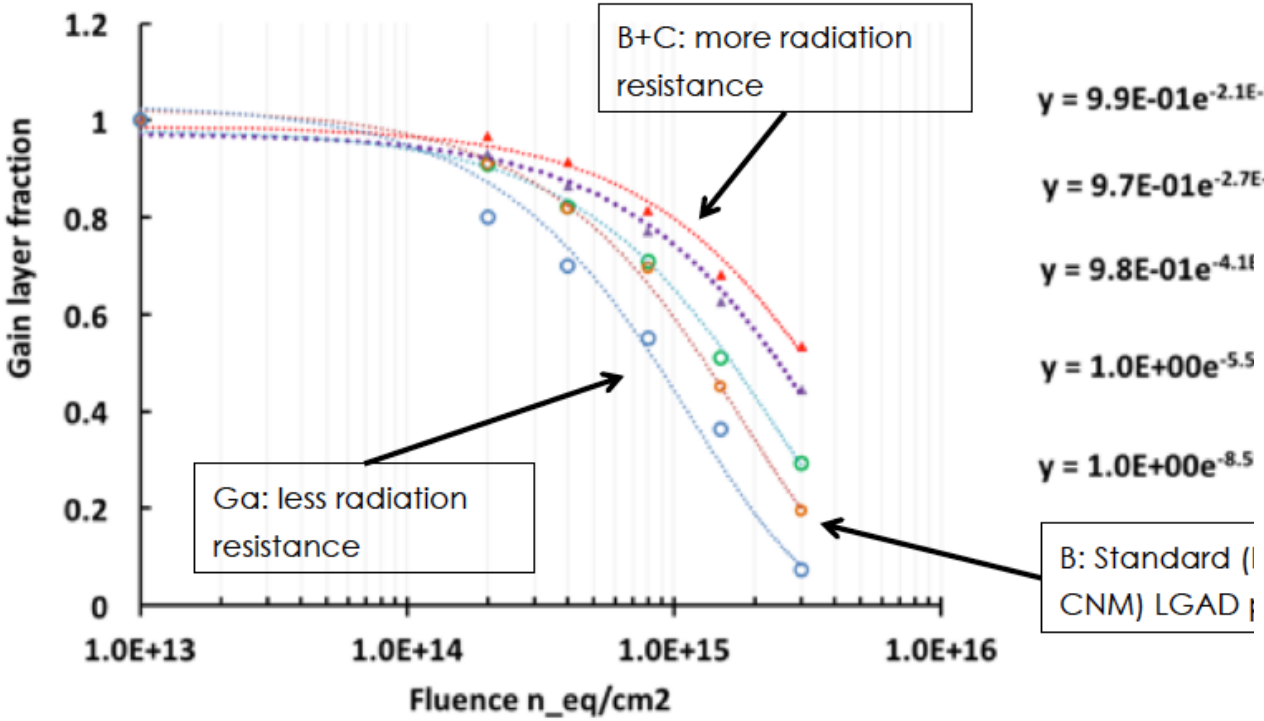
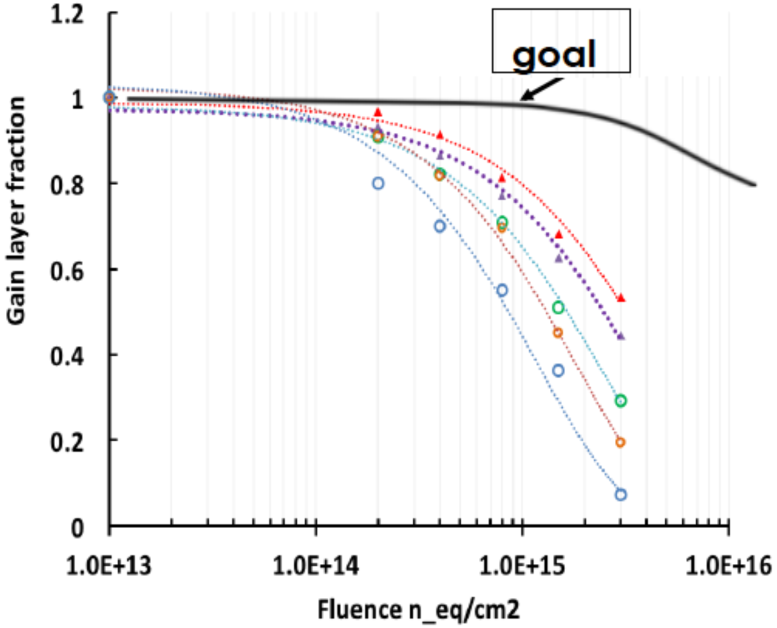


Future R&D



⇒ The usage of Carbon double the radiation hardness