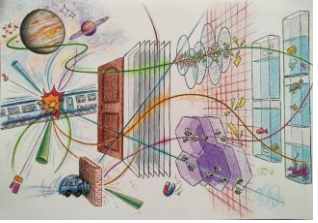

WG3: Radiation Damage & Extreme Fluences

Extreme Fluences

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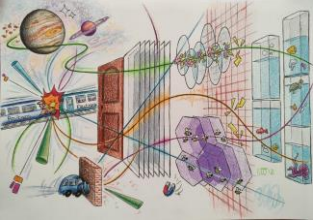
on behalf of the DRD3 proposal writing team



Extreme fluences ?

DRD3

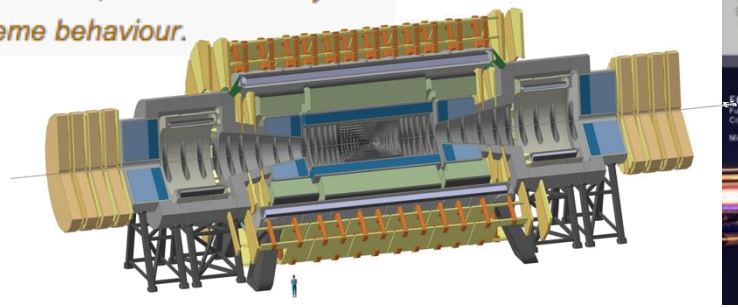
- What is extreme ?

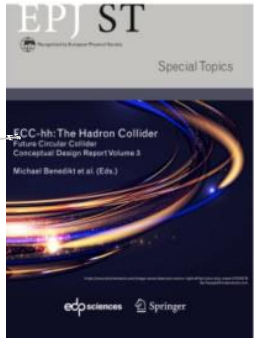
extreme (ɪk'stri:m)

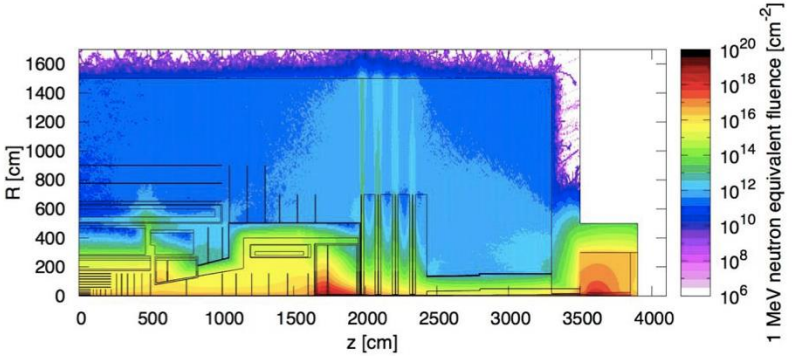
adj

1. being of a high or of the highest degree or intensity: *extreme cold*; *extreme difficulty*.
2. exceeding what is usual or reasonable; immoderate: *extreme behaviour*.

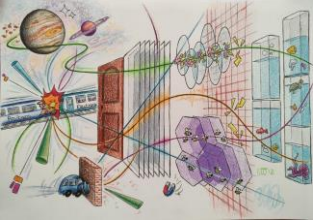
- A rather subjective measure
  - for *LHC* 10^{15} n_{eq}/cm^2 was considered extreme
    - design was 730/fb @14TeV...
  - *HL-LHC* takes it to nx10^{16} (vertex) or even 10^{17} (FW calo)
    - 4000/fb @14TeV
  - *FCC-hh* is *specifying* towards 10^{18} for the tracker (*FCC-hh CDR*)
    - 30/ab @100TeV
    - 300 MGy TID in addition
  - Ratio 1:20:600 !
    - well, you *need* ~7^2≈50 in HL/FCC lumi…
- What is the limit of tracking sensors ?
  - *TRIGA*, *NPP* and *ITER* are 10^{21} ↔10^{24}







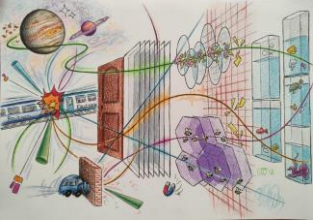
First tracking layer:
- 10 GHz/cm^2 charged particles
- 10^{18} hadrons/cm^2 for 30/ab



Expectations for 10^{17} n_{eq}/cm^2

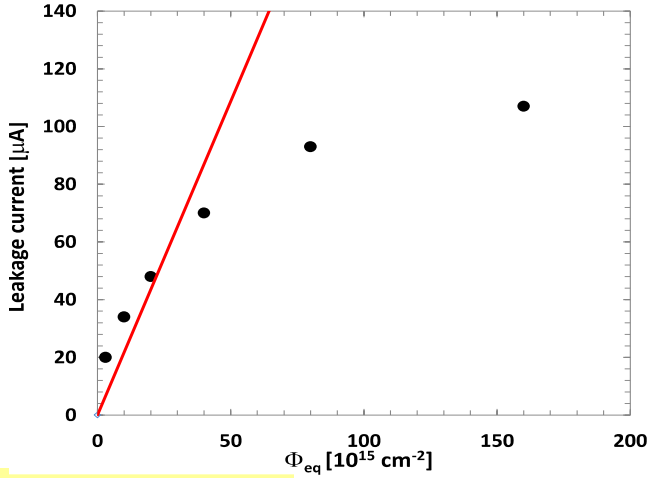
- For a ~yearly replacement of *FCC-hh* inner tracker !
  - Or a 2-stage operation 5->30/ab
- Linear extrapolation from low fluence data
  - Current: I_{leak} = 4 A/cm^3 @20°C
    - 2 mA/cm^2 (2W @ 1 kV) for 300 µm thick detector @ -20°C
  - Depletion: $N_{eff} \approx 1.5 \times 10^{15}$ cm^{-3}
    - $FDV \approx$ 100 kV
  - Trapping $\tau_{eff} \approx$ 1/40 ns = 25 ps
    - $Q \approx Q_0/d\ v_{sat}\tau_{eff} \approx$ 80 e/µm 200 µm/ns 1/40 ns = 400 e in very high electric field (>>1 V/µm)

- But what about data ?
  - Unfortunately, very little experimental data exist beyond 10^{17} n_{eq}/cm^2…



CCE measurements up to 1.6×10^{17} n_{eq}/cm^2

- n^+p "spaghetti" strips, 300 µm
- Observed signal not at all compatible with expectations
  - Above 3×10^{15} linear $CCE(V_{bias})$
  - Power law scaling with fluence, $b \approx -2/3$
  - Leakage current "saturating"

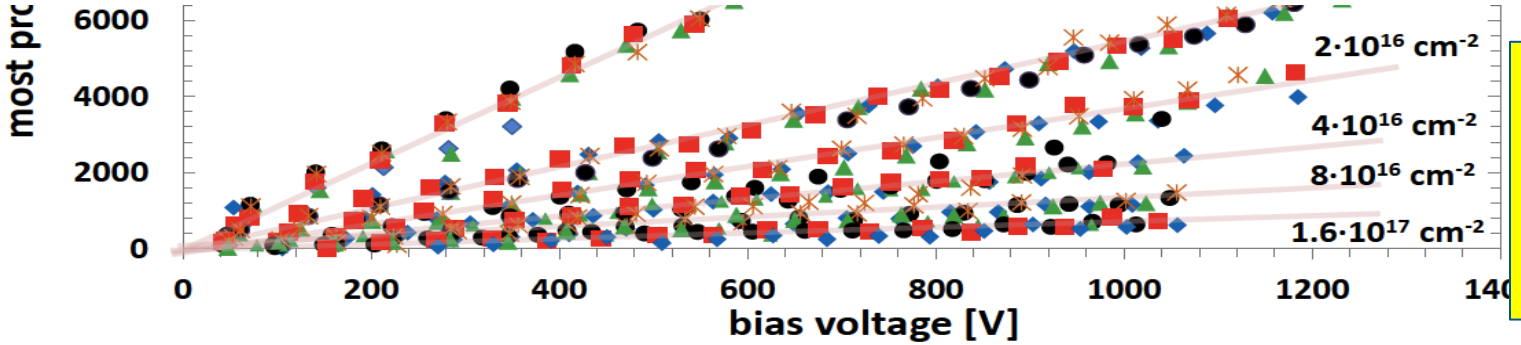


$$Q_{MPV}(V,F) = k \times (F/10^{15}\ n_{eq}/cm^2)^b \times V$$

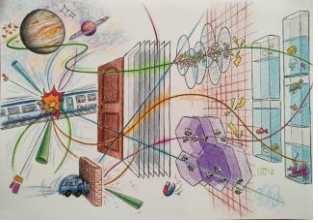
$$k = 26.4\ e_0/V$$

$$b = -0.683$$

"Magic formula"



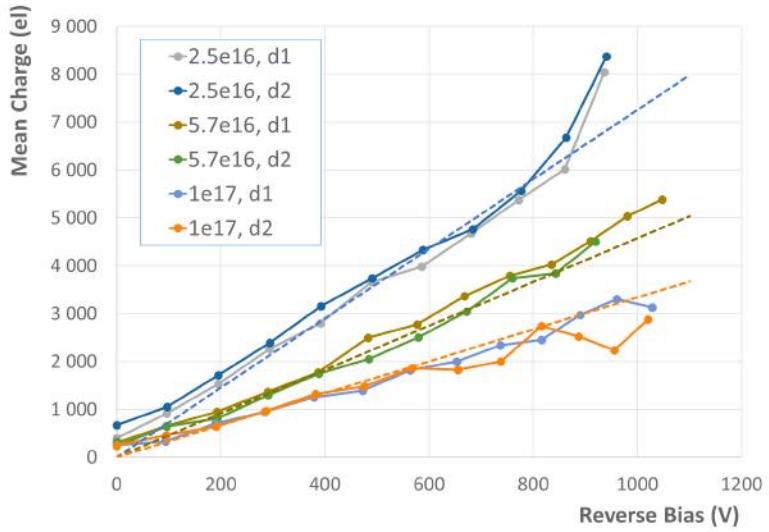
From:
G. Kramberger et al., *JINST 8 P08004 (2013)*.

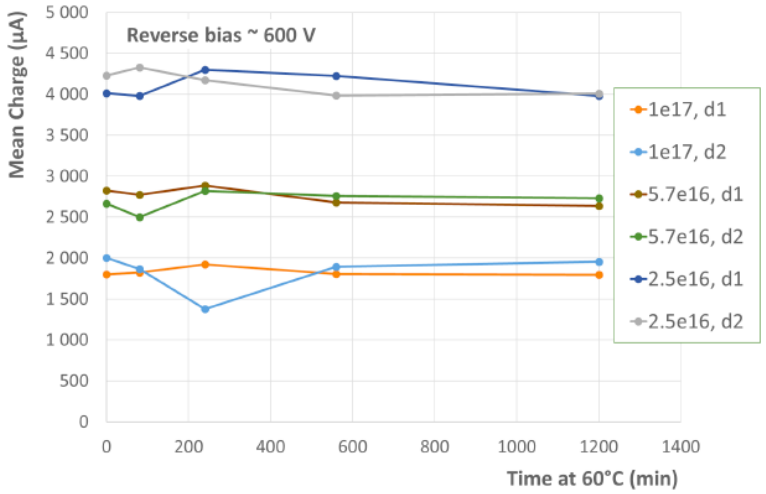


More measurements on thin detectors

DRD3

- 75 µm epi detectors from CNM on low-resistivity substrate
- Irradiated to 0.25, 0.57 and 1.0×10^{17} n_{eq}/cm^2
- *CCE* in reverse and FW
- Annealing 1200 min @ 60°C





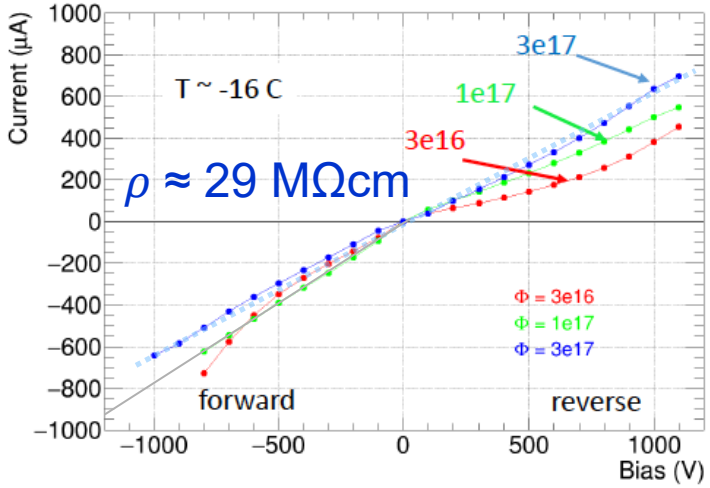
From:
I.Mandić et al.,
JINST 15 P11018 (2020).

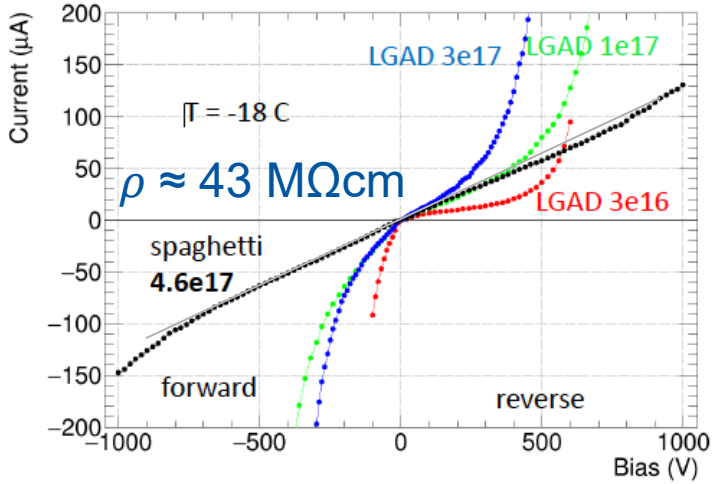
$$Q_{mean} = k \cdot \phi^b \cdot V$$
$$k_{75} = 44\ \mathrm{e_0/V}$$
$$b_{75} = -0.56$$

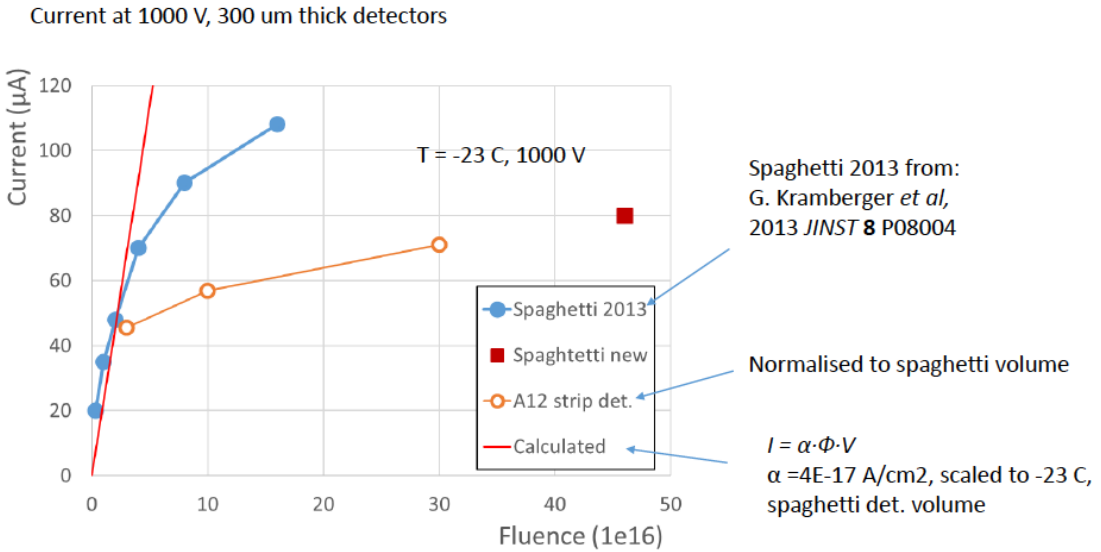
Thinner is better!

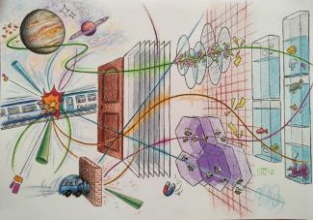
Basic Measurements above 10^{17} n_{eq}/cm^2

- *I-V* for 3&4.6e17 looks very linear with little difference between reverse/FW bias
  - No breakdown, as observed in LGAD's
- *I* @1000 V does not scale linearly with fluence !
  - Not governed by generation current ?
- Tried to measure 4.6e17 spaghetti *CCE* with ^{90}Sr
  - No signal above background observed up to 320 V
  - Magic formula predicts 120e for 4.6e17 @320 V









Mobility Analysis

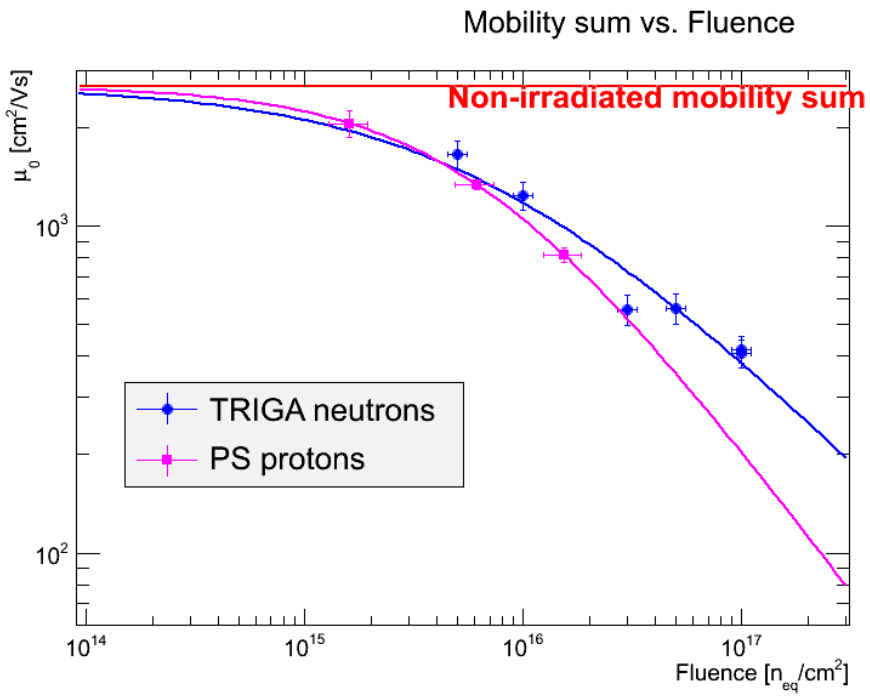
- Mobility governed by hard scattering on acoustic phonons and traps

$$1/t = 1/t_{ph} + 1/t_{trap}$$

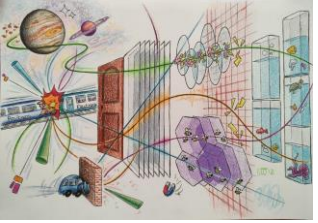
- Fit mobility dependence on fluence with a power law

$$\mu_{0,sum}(F) = \frac{\mu_{0,sum,phonon}}{1+\left(\frac{F}{F_{1/2}}\right)^{a}}$$

- Fits perfectly, value of *a* close to linear
  - 10% error assumed for all neutron data
- At same NIEL, mobility decrease worse for protons
  - NIEL violation ? Large errors ?



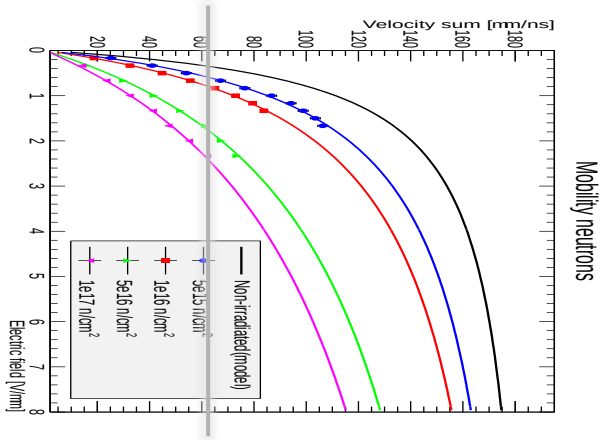
Irradiation particle	a	σ_a	$\Phi_{1/2}$ /10^{15}	$\sigma_{\Phi 1/2}$ /10^{15}
Reactor neutrons	-0.68	0.08	6.9	1.7
PS protons	-0.90	0.19	6.1	1.0



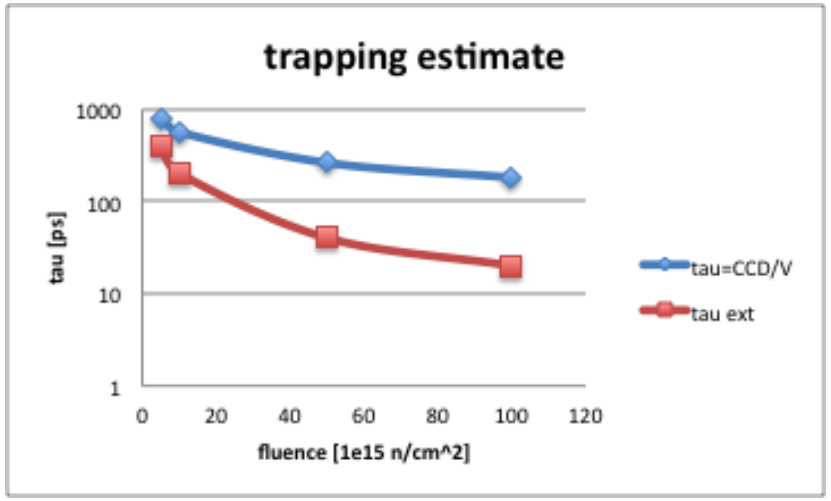
Trapping analysis

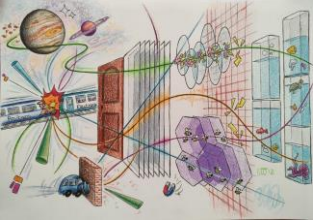
- Take v_{sum} at average E = 3.3 V/μm
- Calculate *CCD* from "magic formula"

Φ [1e15]	5	10	50	100
v_{sum}(3.3 V/μm)	137	126	90	77
$CCD_{1000\ V}$ [μm]	110	70	23	14
$\tau \approx CCD/v$ [ps]	800	560	260	180
τ_{ext} [ps]	400	200	40	20



- Implies factor of 6-9 less trapping at highest fluences
  - lowest fluence still x2 from extrapolation
  - weak dependence on fluence as anticipated
  - CM would effectively shorten trapping times
  - not good when large *E* variations (*v(E)* saturates)
  - not good when *CCD* ≈ thickness (less signal at same *τ*)





Trapping revisited

- From *I.Mandić et al., JINST 15 P11018 (2020)*
  - FW bias *CCE* estimated by

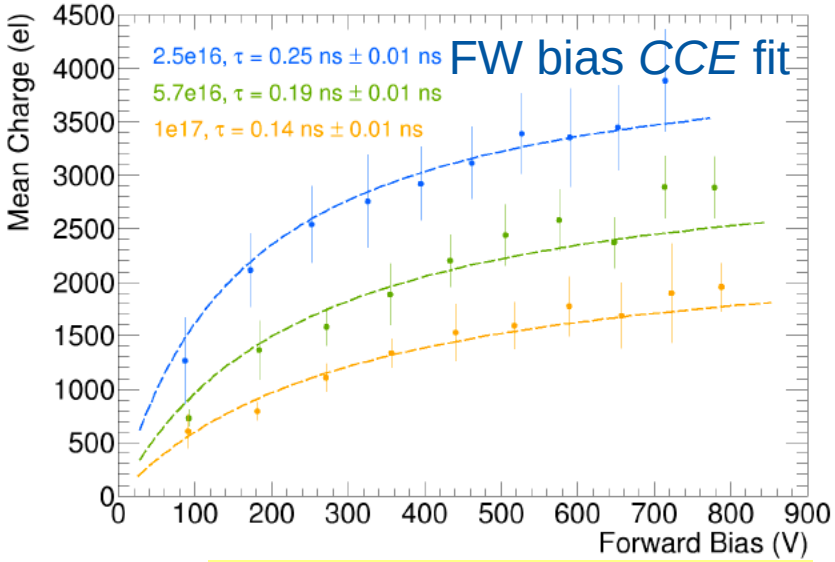
$$Q = \frac{\Delta Q}{\Delta x} \cdot v \cdot \tau$$

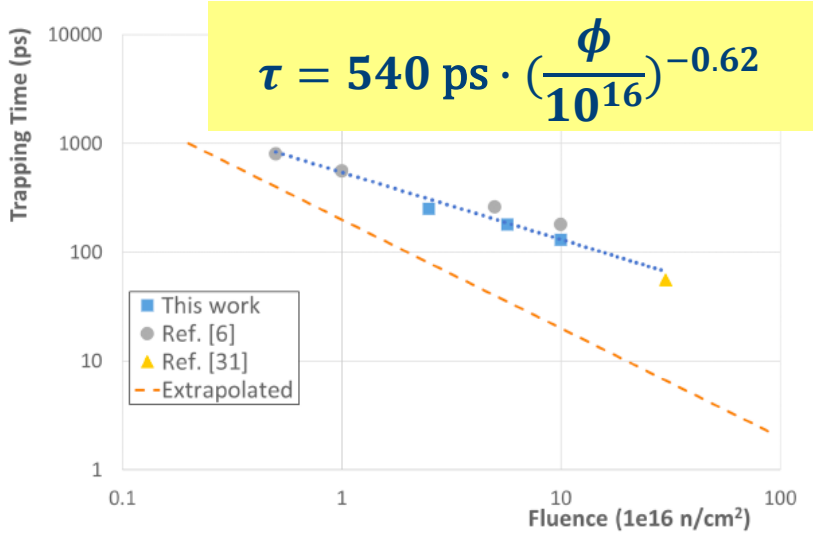
    - *v(E)* with fluence dependent *μ*
    - constant *E=V/D* (FW)

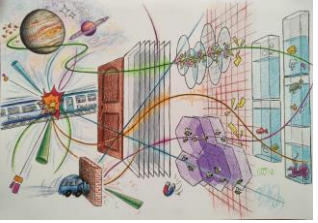
😀 Order of magnitude smaller than extrapolated !

😀 Agrees with estimates from reverse bias *CCE*

- Trapping independent of bias, seen in wave-forms





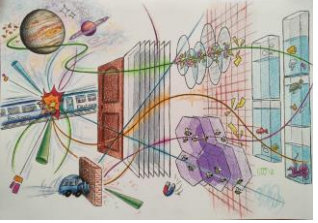


State of the Art at Extreme Fluences

DRD3

- Measurements performed on Si detectors irradiated to extreme fluences
  - Neutrons from 10^{15} to 4.6×10^{17} n_{eq}/cm^2 , PS protons from 5×10^{14} to 3×10^{16} p/cm^2
  - Velocity vs. electric field radiation impact observed and interpreted as reduction of zero field mobility
    - Zero field mobility follows power law with $|a| \leq 1$, $\Phi_{½} \approx 10^{16}$ n/cm^2
    - Protons degrade mobility more than neutrons
    - Induces resistivity increase in-line with measured *I-V*
    - Exhibits adverse effect on charge multiplication !
  - Simple field profile for very high neutron fluences
    - Diminishing SCR and highly resistive ENB
    - Effective acceptor introduction rates reduced by factor ~100 wrt low fluences
    - Current much lower than anticipated. Generated in SCR only ? Ohmic at highest fluences…
  - Trapping estimates for very high neutron fluences
    - from charge collection in FW and reverse bias
    - from waveforms
    - All estimates point to severe non-linearity of trapping with fluence, 10x lower at 10^{17}
    - Trapping appears independent of electric field
- Conclusion: ***Low fluence extrapolations do not work at all !***

… go out and ***measure*** to get anything working at ***extreme*** fluences !!!



Implications for WG3 of DRD3

- Basic bulk silicon properties in the fluence range to master are the prerequisite to any inner tracking detector design for *FCC-hh*
- They need to be ***measured***
  - Only pioneering consistency checks done so far
- Need resources **far beyond** current ones
  - Facilities (EURO-LABS, LDG/ECFA WG…)
    - There are 4 slots with up to 10^{18} secured within EURO-LABS at JSI !
  - Measurement techniques
  - **People**

  at least for the first ~5 of the 20++ years
- WG3 within DRD3 Collaboration essential for achieving the goal
  - Nice to observe big interest for working on the subject !
  - EU funding should help to rise funds at national level