Current and low-field carrier mobility in silicon sensors irradiated to extreme fluences

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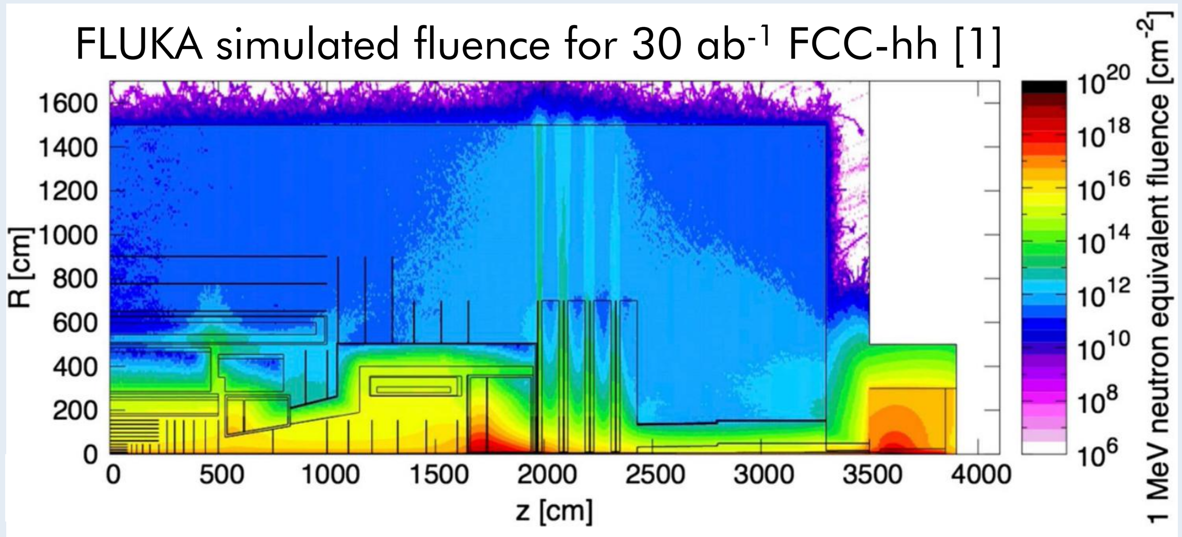
Introduction

Silicon is the material of choice for highly granular and radiation-hard detectors. However, at the innermost tracking layers of the **FCC-hh**, particle fluences are expected to reach up to **$6\cdot10^{17}$ n_{eq}/cm²**



Defect introduction rates typically ~1 cm⁻¹, leading to:

- ➢ Defect concentrations ~$6\cdot10^{17}$ cm⁻³ >> initial doping concentration ~10^{13} cm⁻³
- ➢ As original doping becomes compensated, sensor behavior changes drastically

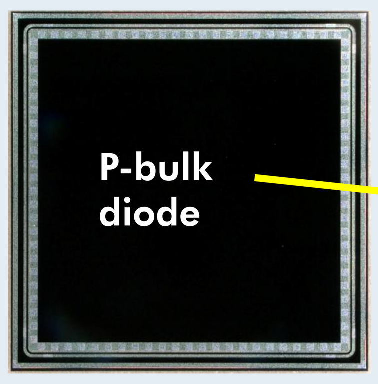
Is silicon still a viable option for FCC-hh?

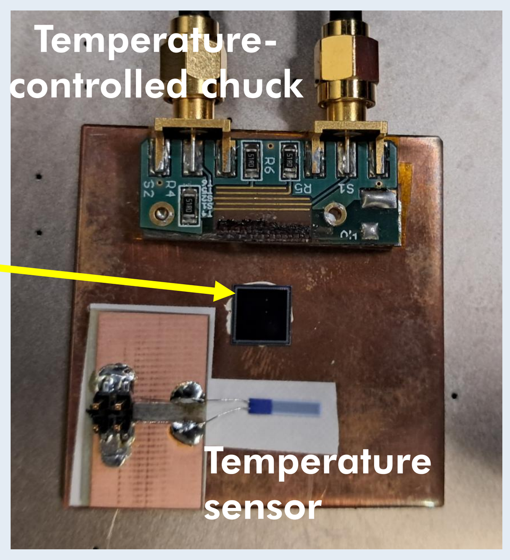
➡️ **We must study the effects of extreme radiation damage**

Method

Goal:

Understand how extreme fluences alter silicon sensor electrical properties and whether radiation-damage models for TCAD can reproduce those changes





Measurements:

I–V and C–V on ATLAS ITk Strip 8×8 mm² n^+–p–p^+ diodes

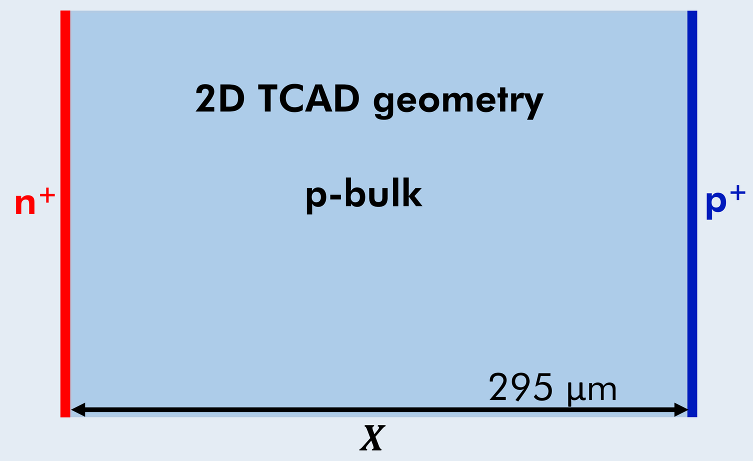
- 295 µm active bulk with 4×10^{12} cm⁻³ p-type doping
- Irradiated to 2.3×10^{17} and 5.0×10^{17} n_{eq}/cm² with neutrons (JSI, Ljubljana)

Simulations:

Synopsys TCAD: simple 2D pad geometry

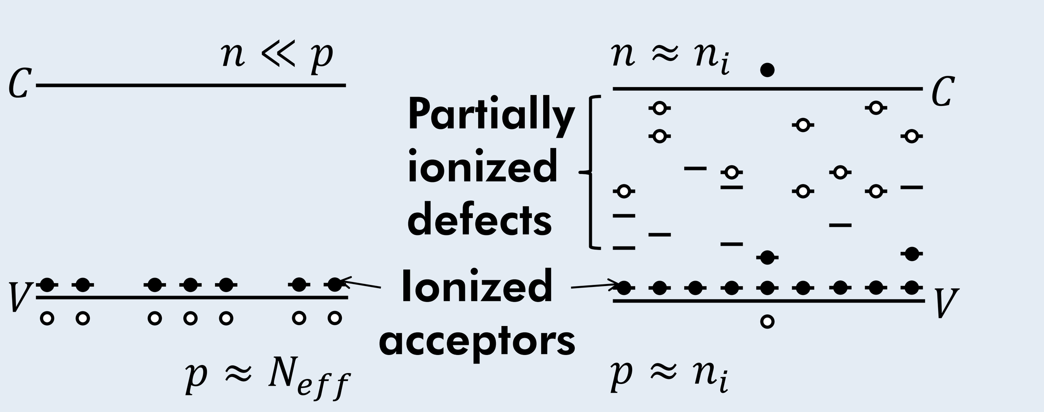
- Effective HPTM* [2] and Perugia [3] bulk defect models

*) Modified by activating Poole-Frenkel field-enhanced emission



What we already knew

Bulk band structure in equilibrium



High concentration of radiation-induced defects in the band gap

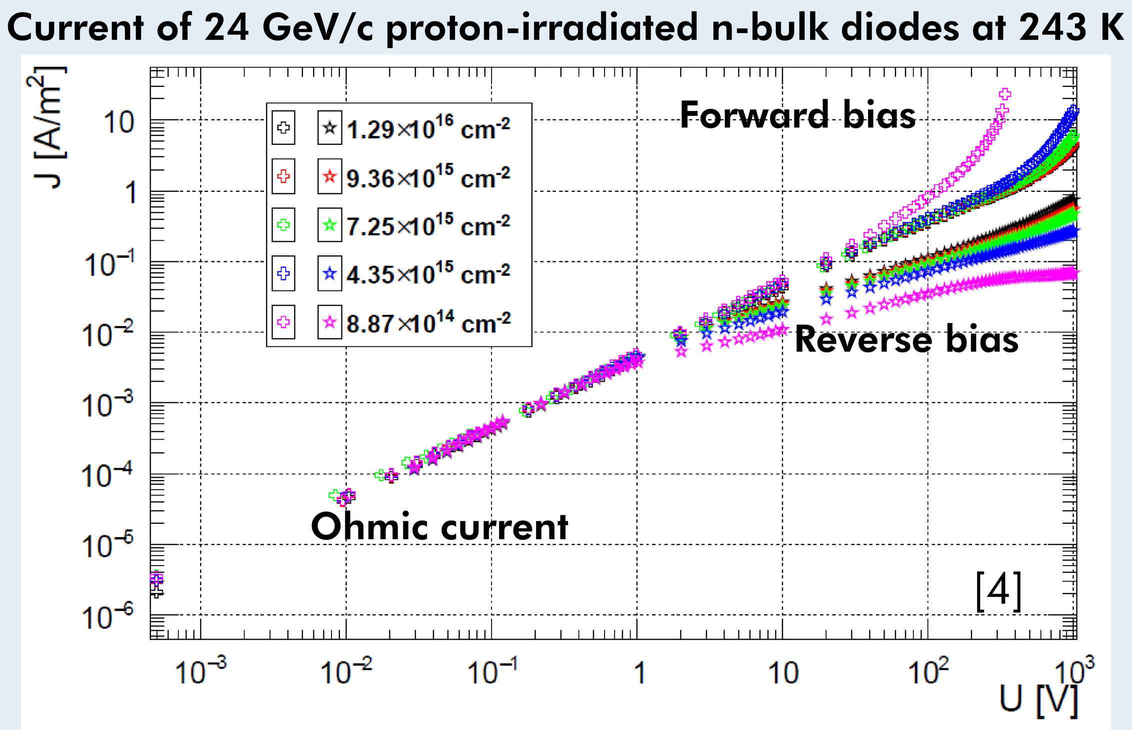
Equilibrium ($U_{bias} = 0$ V)

- ➢ **Excess carriers captured by defects**
- ➢ **Bulk doping** and oxide charge **compensated by deep defects**
- ➢ Free carrier concentrations become intrinsic in equilibrium
- ➢ Mobilities decrease due to ionized-defect scattering

Steady state ($U_{bias} \neq 0$ V)

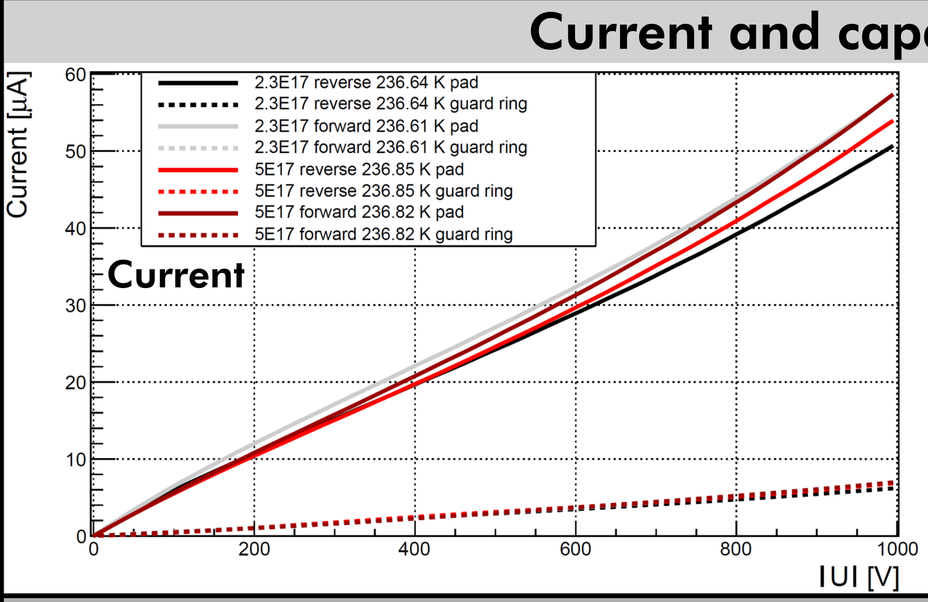
- ➢ Space-charge region (**SCR**) development suppressed
- ➢ Thin SCR regions with very high space charge concentrations
- ➢ SCR generation has limited influence on the current
- ➢ Bulk stays near-intrinsic even at high electric field

Current of 24 GeV/c proton-irradiated n-bulk diodes at 243 K



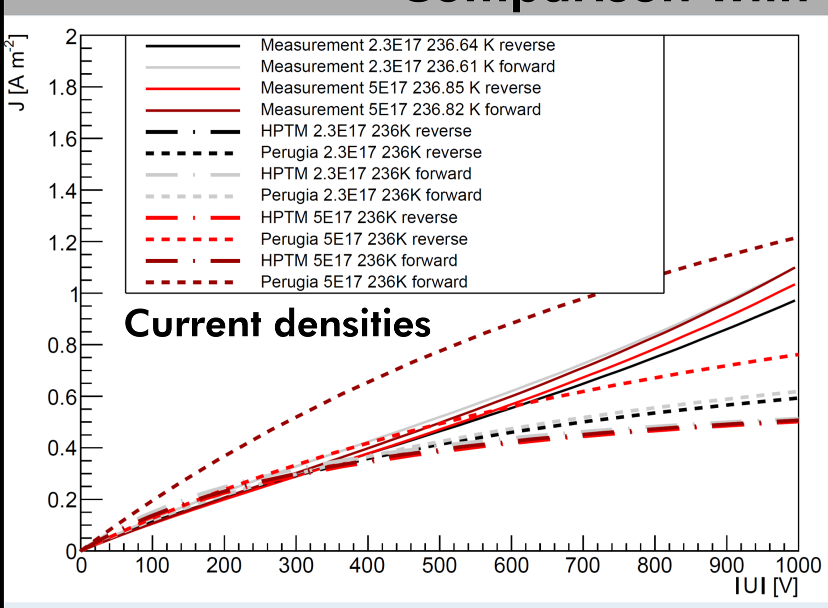
Results

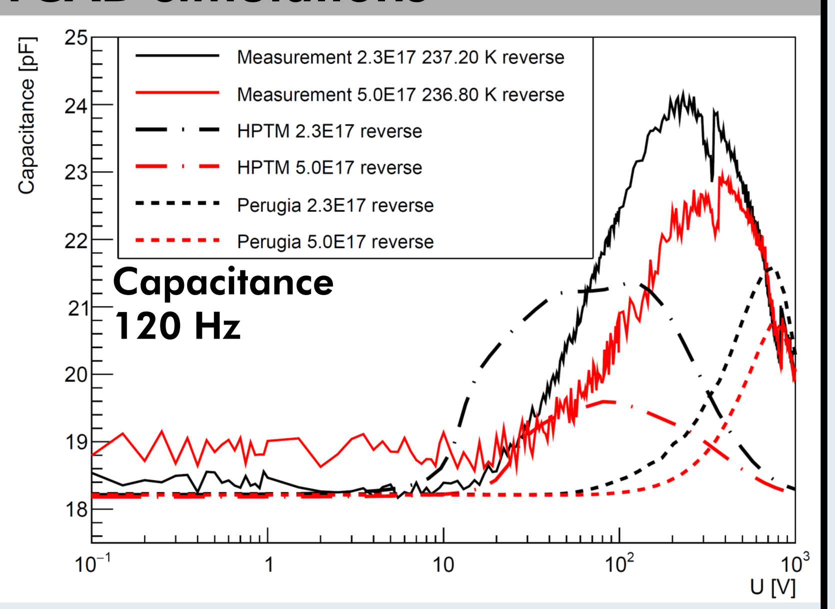
Current and capacitance



- Current very similar for forward and reverse bias and no major change between the two fluences
- Guard ring current very low
  - ➢ No major influence of surface currents

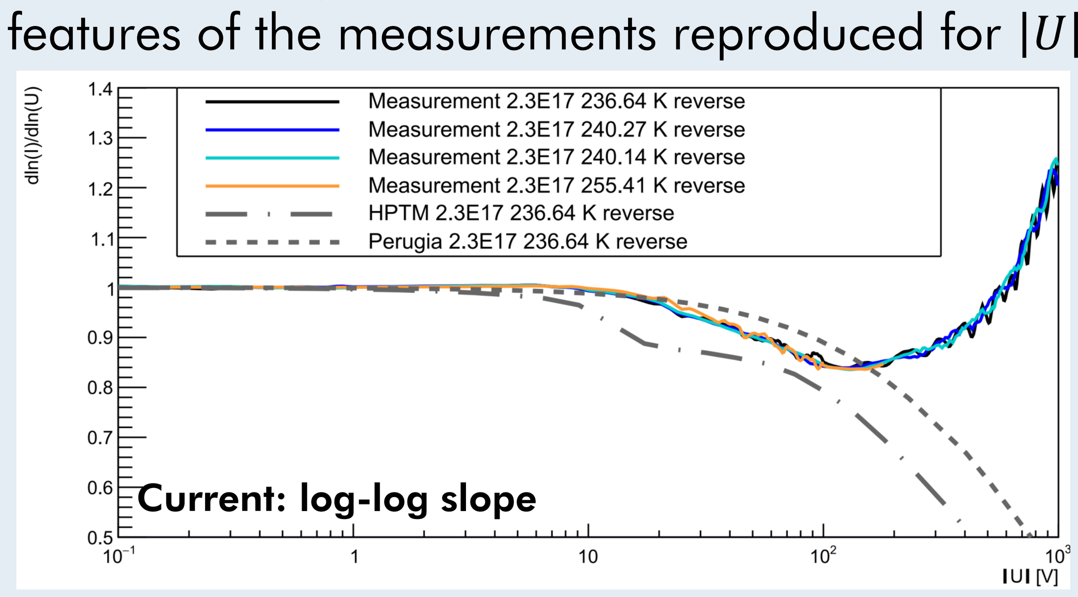
Comparison with TCAD simulations





TCAD radiation-damage models reproduce only **order of magnitude** of the measured current and capacitance, not the voltage dependence

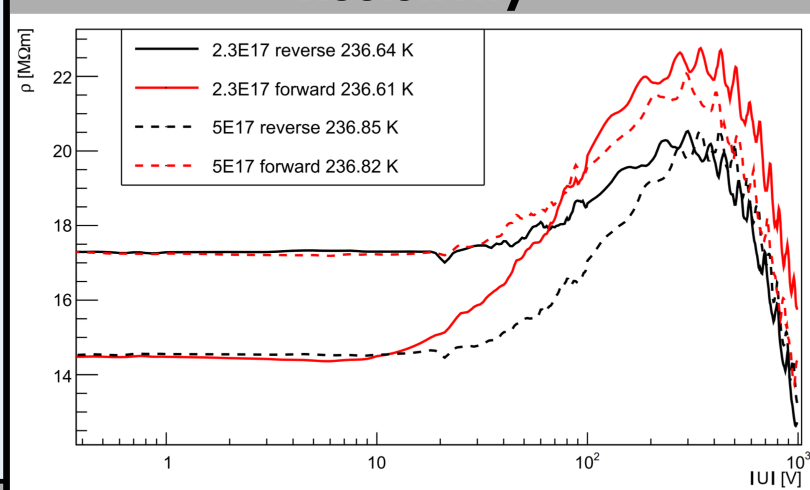
- Perugia model predicts **reverse** trend for forward current
  - ➢ Excluded from further considerations in this work
- HPTM model promising:
  - ➢ Main features of the measurements reproduced for $|U| < 100$ V



- Exponential current increase at high bias voltages not reproduced by damage models
- The shape seems not to depend on the temperature
  - ➢ Increase could be due to SRH generation from cluster defects
  - ➢ **Needs further study and improved damage models!**

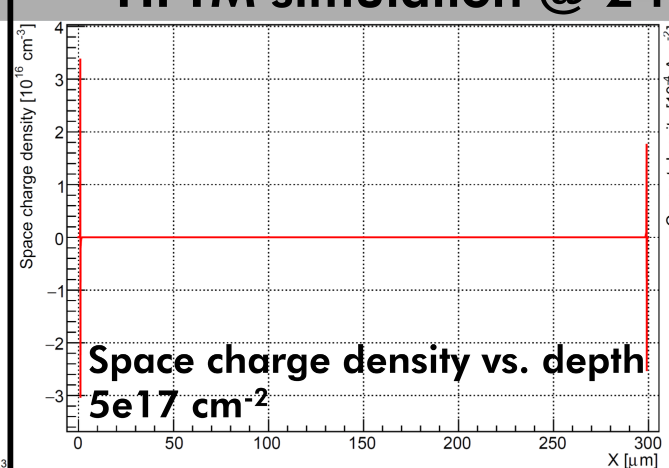
Resistivity and mobility

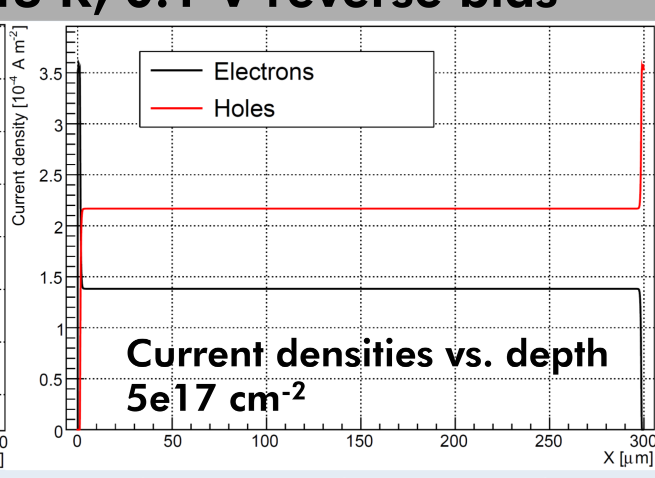
Resistivity



- **Resistivity** at low voltages **increases with fluence** due to reduction of the carrier mobilities
- Resistivity increases at intermediate voltages
  - ➢ **Reduction of $\mu_{e,h}(E)$ with E**
  - ➢ SCR grows marginally, increasing resistivity

HPTM simulation @ 243 K, 0.1 V reverse bias

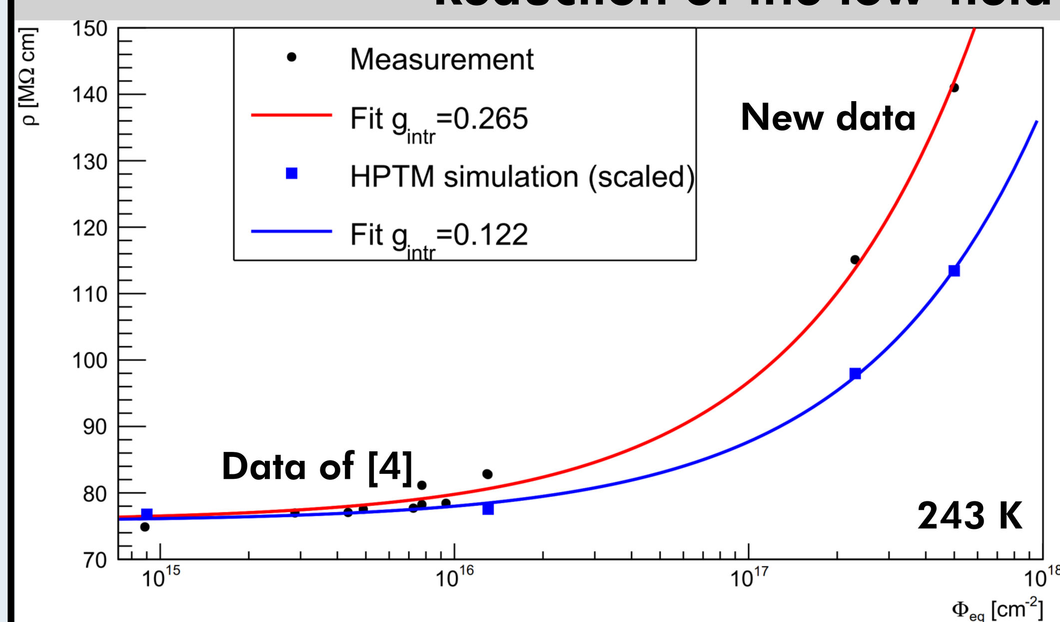


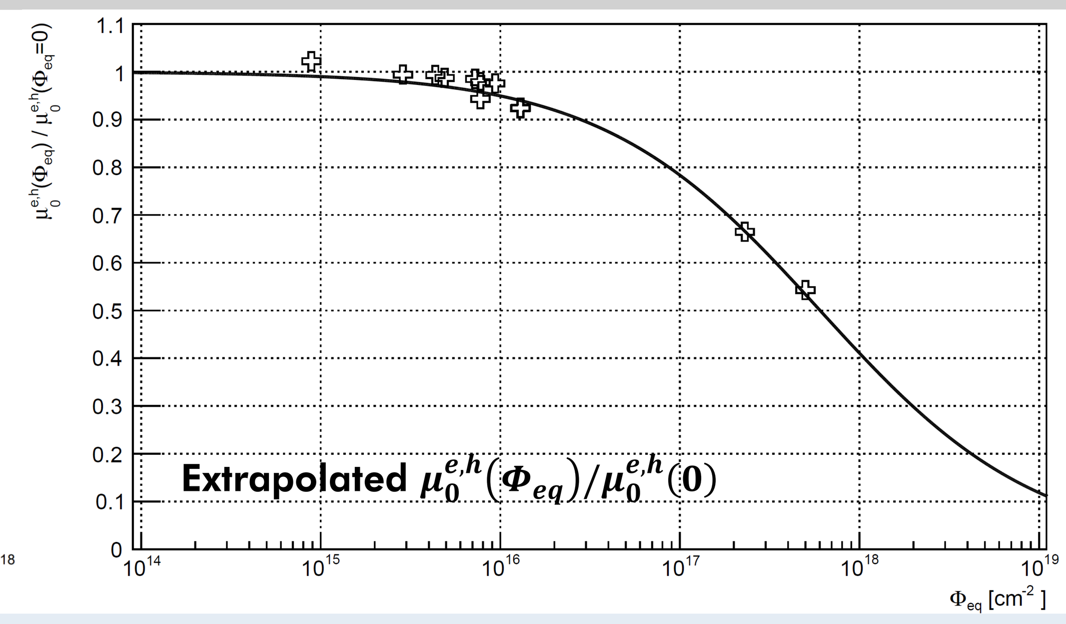


Fluence [cm⁻²]	5×10^{17}	2.3×10^{17}	1.3×10^{16}	9×10^{14}
μ_e [Vs/cm²]	1361	1651.5	2249.1	2369
μ_h [Vs/cm²]	534.9	602.8	724.5	743.5
n [10^7 cm⁻³]	1.89	1.88	1.88	1.77
p [10^7 cm⁻³]	7.53	7.55	7.57	8.02
J [10^{-4} A/m²]	3.54	4.10	5.18	5.23
n_i/n_e	2.00	2.00	2.01	2.13
n_i/n_h	0.501	0.499	0.498	0.470

- Naïve resistor expectation $J_e(x) = J_h(x) = const$ not fulfilled, but:
  - ➢ **Current densities** in the bulk are **constant**
  - ➢ ***n*, *p* in the bulk independent of the fluence**

Reduction of the low-field mobilities with the fluence





- We don't need to know true steady-state bulk carrier concentrations, assuming n, p are independent of Φ_{eq} and $\mu_0^{e,h}(\Phi_{eq})$ scale equally for e, h
- ➢ Approximate empirical Masetti formula [5] to scale $\mu_0^{e,h}(\Phi_{eq})$, using $N_{ref} = 1.6\text{e}17$ cm⁻³ and $\alpha = 0.715$:

$$\rho(\Phi_{eq}) = \frac{1 + \left(\frac{g_{intr}\cdot\Phi_{eq}}{N_{ref}}\right)^{\alpha}}{e(n\mu_0^e + p\mu_0^h)}$$

[1] cds.cern.ch/record/2651300
[2] doi.org/10.1109/NSSMIC.2018.8824412
[3] doi.org/10.1016/j.nima.2022.167180 Fig. 1
[4] bib-pubdb1.desy.de/record/410589
[5] doi.org/10.1109/T-ED.1983.21207