Radiation hardness of 24 GeV proton and mixed irradiated LGAD sensors

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4TH DRD3 WEEK, CERN

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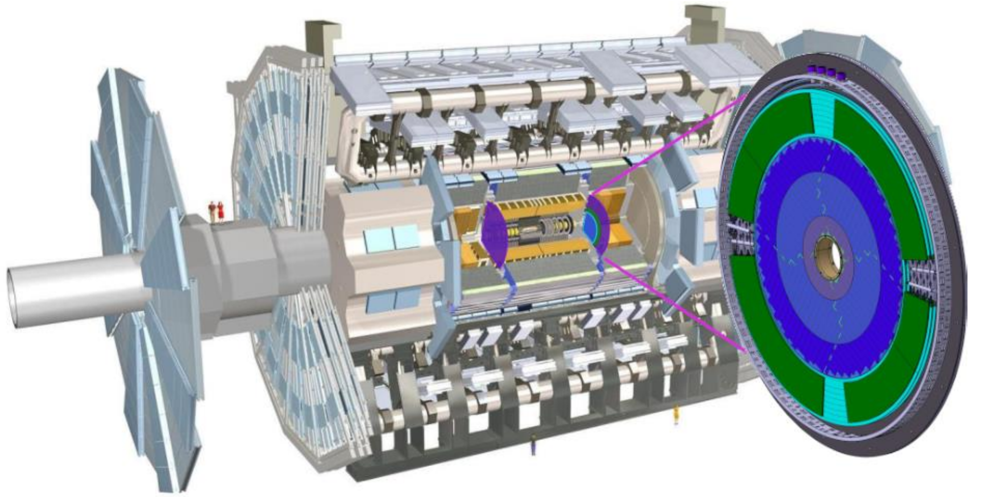
ATLAS-HGTD and LGAD sensors

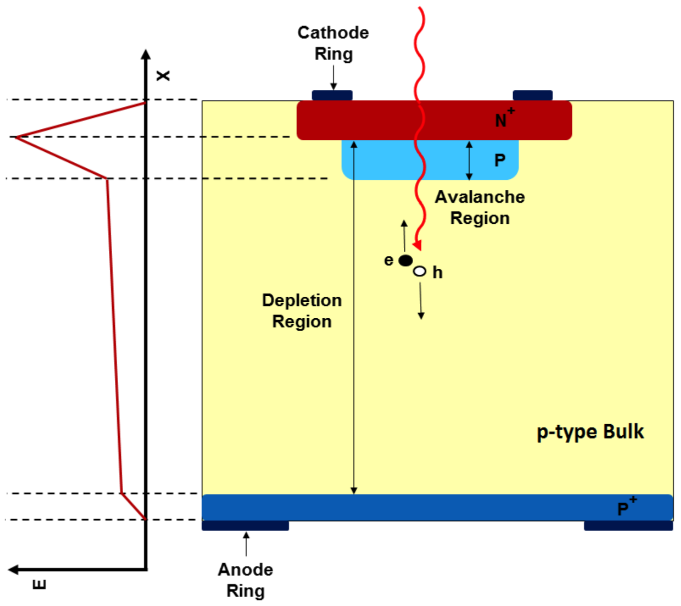


HGTD TDR

- ATLAS High Granularity Timing Detector (HGTD) for HL-LHC upgrade
  - Pile-up mitigation in the forward region $2.4 < |\eta| < 4.0$
  - 50 ps track time resolution
  - Luminosity measurement (1 % resolution)
  - Radiation hardness requirements before replacements: 2.5×10^{15} n_{eq} cm^{-2}, 2 MGy

Rapidity coverage	$2.4 < \|\eta\| < 4.0$
Position in z	± 3.5 m
Number of channels	3.6 M
Pad size	1.3 mm × 1.3 mm
Operating T	–30 °C (CO_2)
Track time resolution	≤ 50 ps

- Low Gain Avalanche Diode (LGAD) sensors
  - p^+ gain layer with high electric field
  - Internal gain by impact ionization, high S/N ratio
  - Ongoing HGTD sensor production
    - Two designs (IHEP-IME, USTC-IME), ≈ 1000 wafers
    - First 5 % (preproduction) completed
  - Wafer-level production quality control irradiation tests ongoing at JSI (neutron irradiations), arxiv



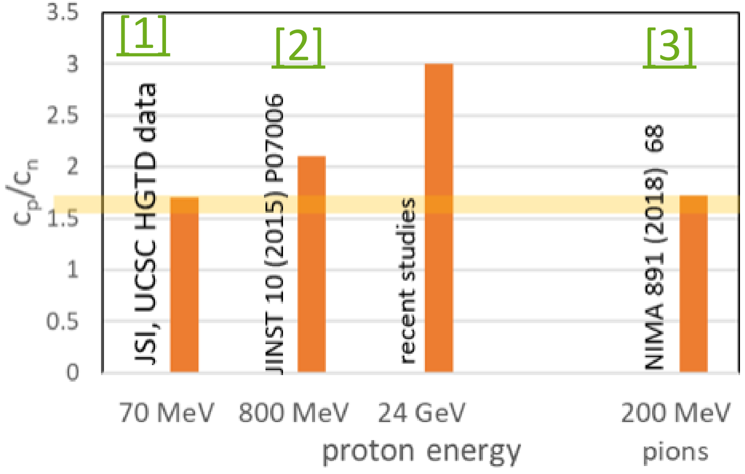
$$E_{gl} \approx \frac{V_{gl}}{w_{gl}} + \frac{V_{bias} - V_{fd}}{d}$$

V_{gl} … depletion voltage of the gain layer (≈ 25 V)
V_{fd} … depletion voltage of the gain layer + bulk
w_{gl} … gain layer thickness (≈ 1 µm)
d … active thickness (≈ 50 µm)

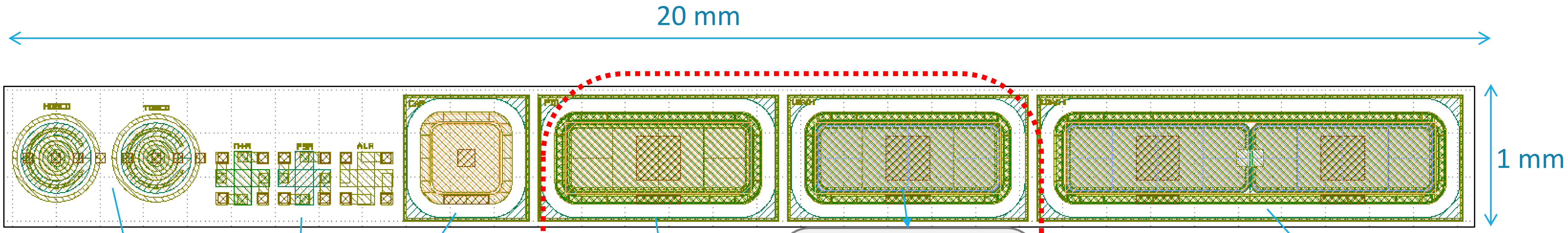
Motivation

- LGAD performance degrades with irradiation due to **acceptor removal in the gain layer:** $V_{gl} = V_{gl,0} \times e^{-c\emptyset}$
- Acceptor removal depends on particle type (neutrons vs. charged hadrons)
  - Charged hadrons generally more damaging than neutrons $c_p > c_n$, consistent between many manufacturers, energy dependence
  - In ATLAS: at η = 2.4 ratio **n**:**h** = 90:10, at η = 4 ratio **n**:**h** = 50:50
- Verification required that proton and neutron damaged are cumulative (no interplay of defects)
  - First proton irradiation test with HGTD (pre)production sensors in this study
  - Irradiations on samples from a single early preproduction wafer (IHEP-IME V1R5)

- **Neutron irradiation** campaign at JSI TRIGA reactor
  - 7 samples, fluences: 1.5e15 n_{eq}/cm^2, 2.5e15 n_{eq}/cm^2, 3e15 n_{eq}/cm^2
- **Proton irradiation** campaign with CERN IRRAD 24 GeV protons (June 2024)
  - 11 irradiated samples, Target fluences: 2x 4e14 p/cm^2, 2x 8e14 p/cm^2, 7x 12e14 p/cm^2 (1 p/cm^2 = 0.62 1 MeV n_{eq}/cm^2)
- **Mixed irradiation**:
  - 3 of the proton irradiated samples additionally irradiated with neutrons
    - 4e14p + 5e14n
    - 8e14p + 5e14n
    - 12e14p + 8e14n



Quality Control Test Structure (QC-TS)



Gate controlled diodes

MOS Capacitor
SiO_2 thickness monitoring

Van der Pauw structures
Implant resistivity measurements

PIN diode
Bulk properties, dosimetry

1 × 1 LGAD
Charge collection, time resolution, acceptor removal

1 × 2 LGAD
Same + interpad region

Main test structure for QC-IT

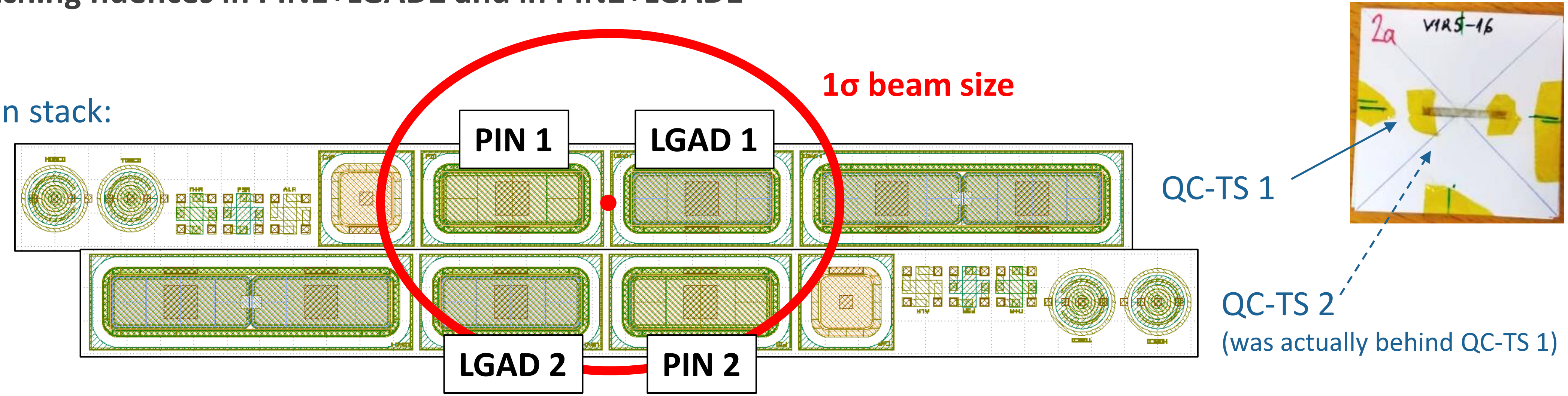
PIN and LGADs have the size of 2.1 mm × 0.65 mm and have the same area (geometric capacitance) as pads on the main sensor

Quality Control Test Structures (QC-TS) main devices in radiation hardness testing

Irradiation strategy

- **Neutron irradiation:**
  - Straightforward, uniform neutron flux over the entire sample
  - Fluence uncertainty ± 10 % peak-to-peak
- **Proton irradiation:**
  - Gaussian shaped beam with σ = 3-4 mm – non uniform fluence
  - Beam centered between PIN and 1x1 LGAD on the QC-TS
  - Samples irradiated in pairs with PIN of one device overlapping with 1x1 LGAD from the other device
  - **Matching fluences in PIN1+LGAD2 and in PIN2+LGAD1**

Proton irradiation stack:



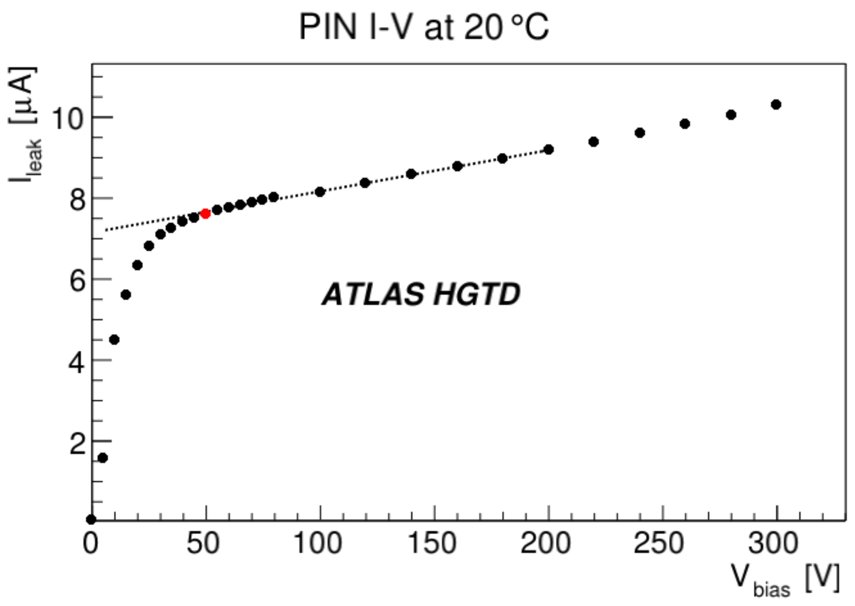
Dosimetry

- Equivalent fluence in the PIN calculated from the leakage current (NIEL hypothesis)

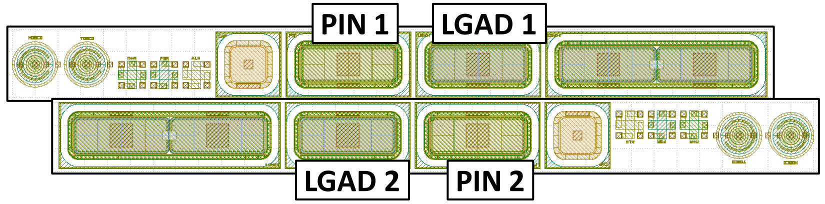
$$\varnothing_{\mathbf{eq}} = \underbrace{\frac{\mathbf{1}}{\boldsymbol{\alpha S d}}}_{2.94\text{e-}14\ n_{eq}/\text{cm}^2/\mu\text{A}} \times \boldsymbol{I}\ (\boldsymbol{T} = \mathbf{20°C})$$

$\alpha = 4 \times 10^{-17}\text{cm}^{-1}$, $S = 2.1 \times 0.8\ \text{mm}^2$, $d = 50\ \mu\text{m}$

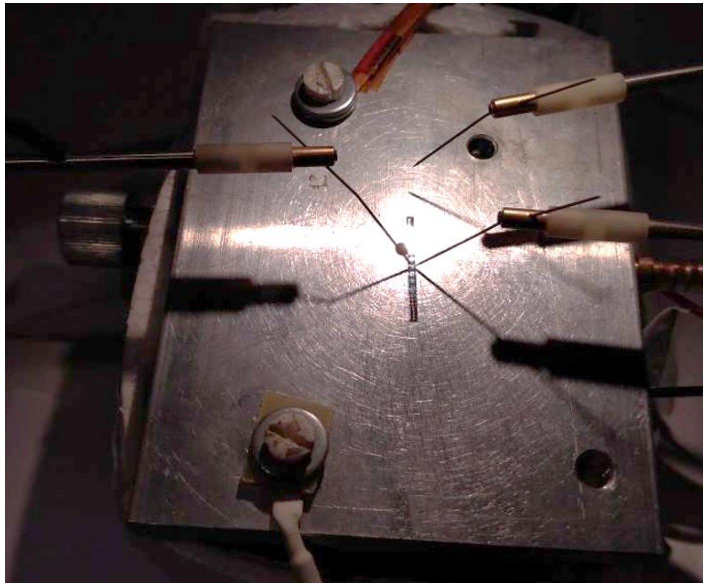
I is the current at $V_{fd} + 20$ V

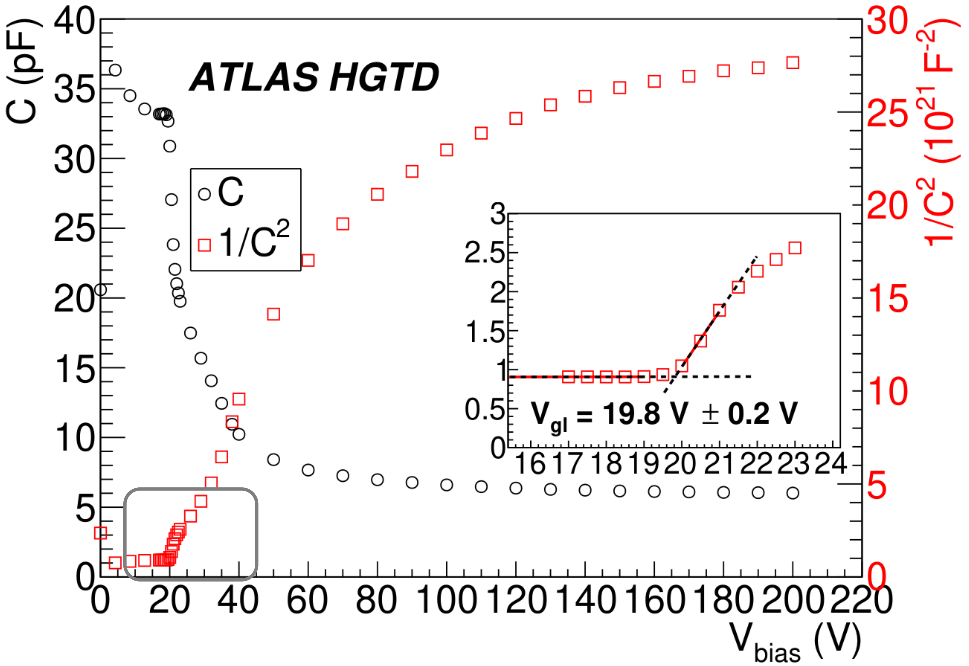


- **Neutrons:** $\phi_{LGAD} = \phi_{PIN}$
- **Protons:** $\phi_{LGAD2} = \phi_{PIN1}$ and vice versa
- **Protons + neutrons:** $\phi_{LGAD2} = \underbrace{\phi_{PIN1,p}}_{\boldsymbol{\phi_p}} + \underbrace{(\phi_{PIN2,p+n} - \phi_{PIN2,p})}_{\boldsymbol{\phi_n}}$



C-V test method

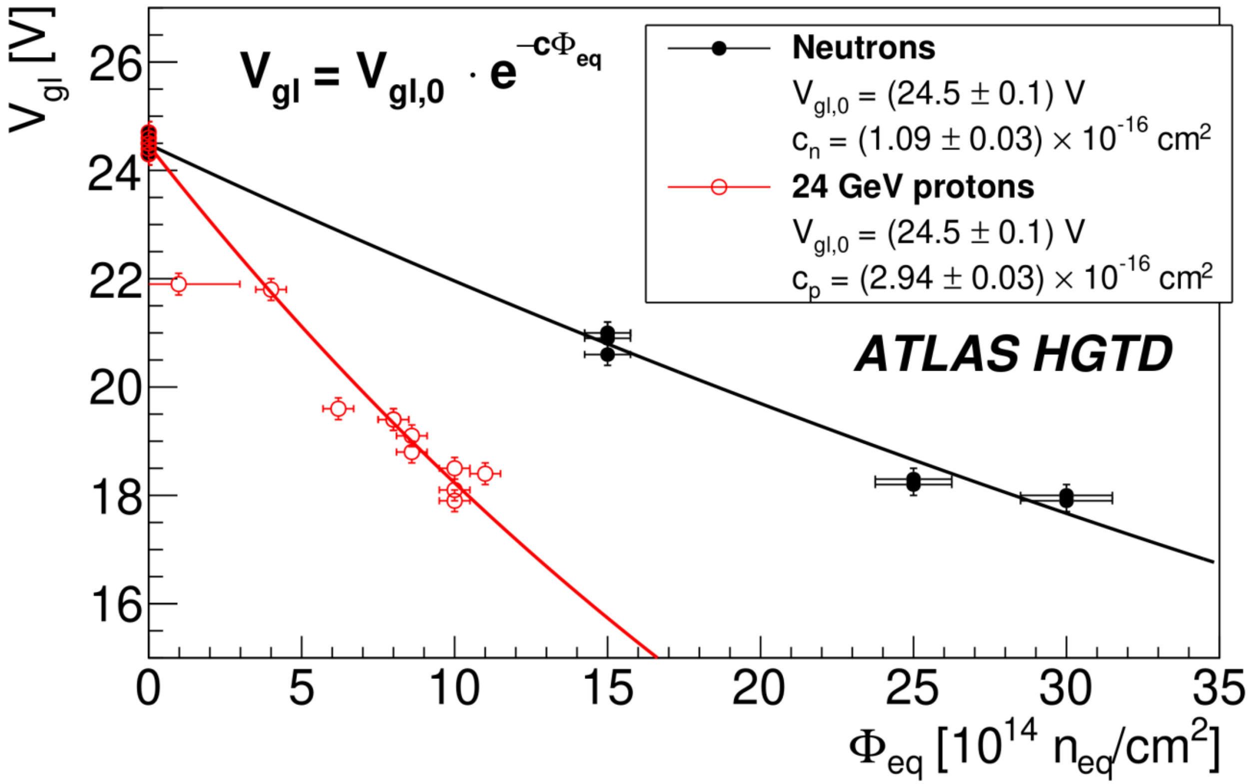




V_{gl} extracted from intersection of linear fits in $1/C^2$ vs. V_{bias}

- LGAD contacted with a probe needle
- Capacitance-Voltage (10 kHz, 0.5 V, Cp-Rp) measurement to extract V_{gl}
  - When biasing for the first time after irradiation V_{gl} is lower, then stabilizes
  - All results shown after second biasing

C-V: acceptor removal for neutrons and protons



Data fitted with an exponential function:

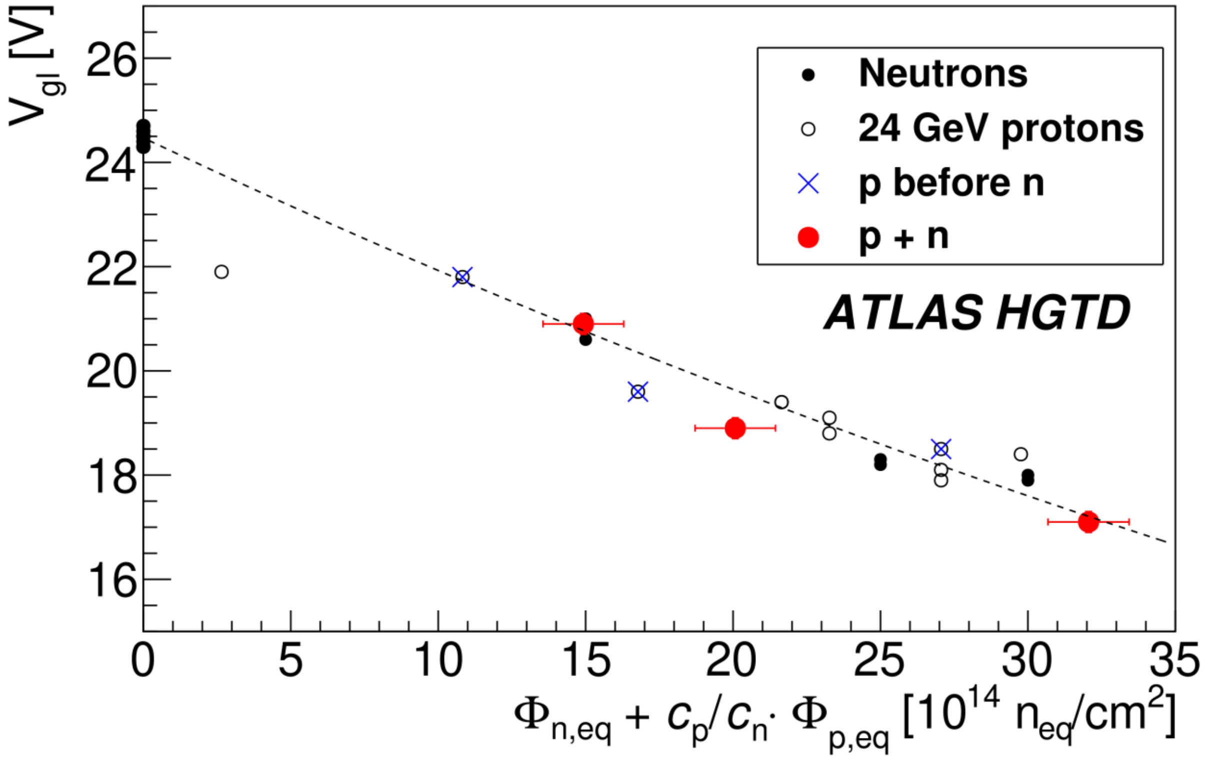
$$V_{gl} = V_{gl,0} \times e^{-c\emptyset}$$

$$c_n = 1.1 \times 10^{-16} \mathrm{cm}^2$$
$$c_p = 2.9 \times 10^{-16} \mathrm{cm}^2$$

$$c_p/c_n = 2.7$$

- $V_{gl,0}$ = 24.5 V slightly smaller than typical production sensors (25.5 V), probably slight process difference
- c_n = 1.1e-16 cm^2 is similar to the value for preproduction wafers (1.2e-16 cm^2)

C-V: Rescaled fluence and mixed irradiation



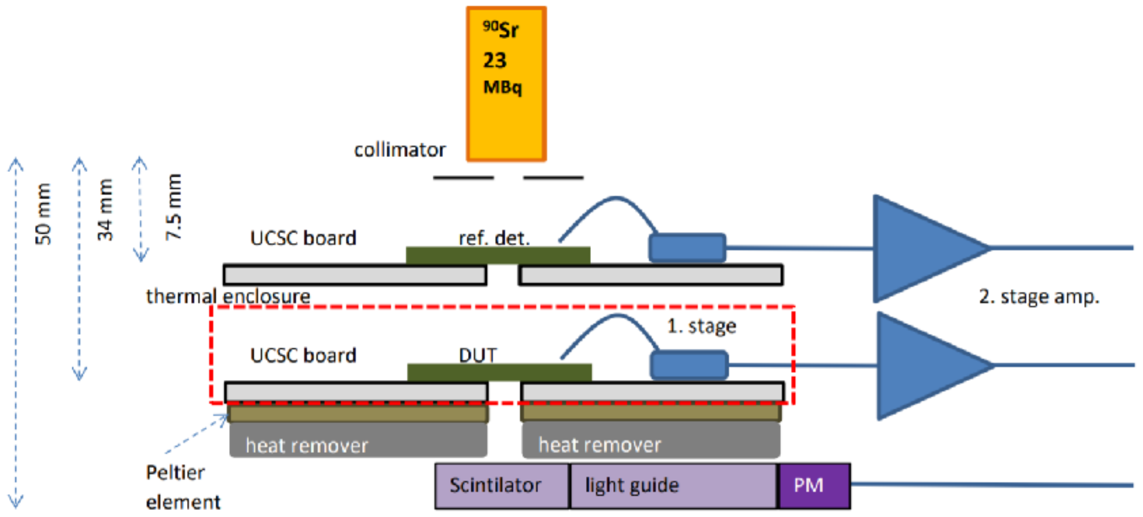
- Rescaling to effective fluence for acceptor removal:

$$\phi_{\mathrm{scaled}} = \phi_{\mathrm{n}} + \frac{c_{\mathrm{p}}}{c_{\mathrm{n}}}\phi_{\mathrm{p}}$$

- Three p samples (×) additionally irradiated with neutrons
- Acceptor removal (V_{gl} change) in mixed irradiation samples consistent with the overall behavior
- **Indication that damage from different particles is additive**

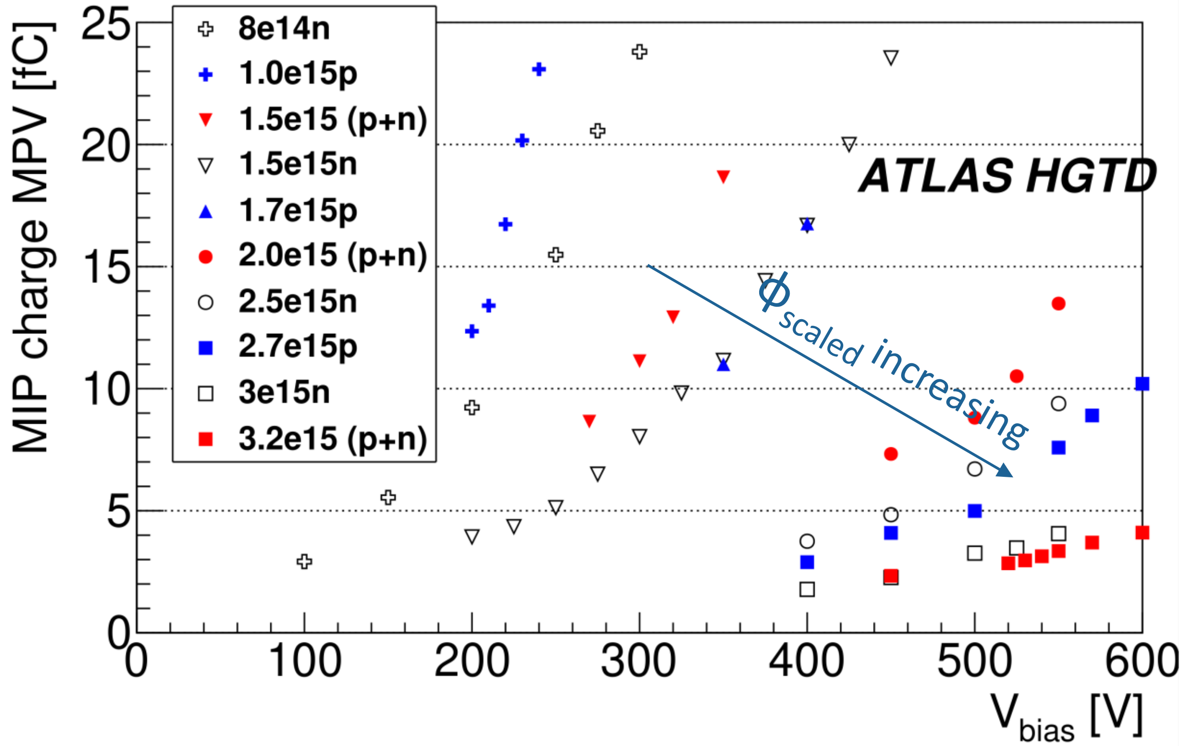
^{90}Sr charge collection setup

- ^{90}Sr Charge collection/Time resolution measurements
  - Readout based on UCSC boards
  - Trigger on PMT + reference LGAD (30 ps)
  - DUT cooled to –30°C, not part of the trigger
  - 5000 events per setting, geometric track acceptance in DUT 10 %
- Measured charge is 20 % more than MIP expectation
  - 10 % more ionization (2 MeV beta electron not exactly a MIP)
  - 10 % comes from more multiple scattering → wider charge cloud → less gain loss due to smaller E-field screening



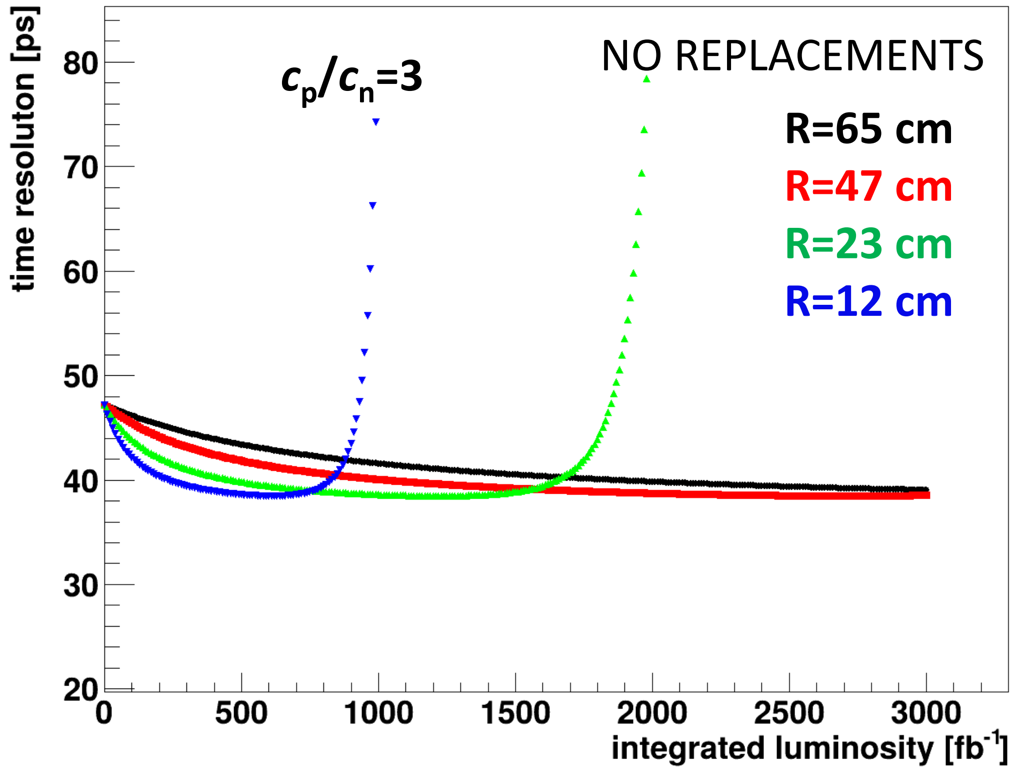
^{90}Sr: collected charge

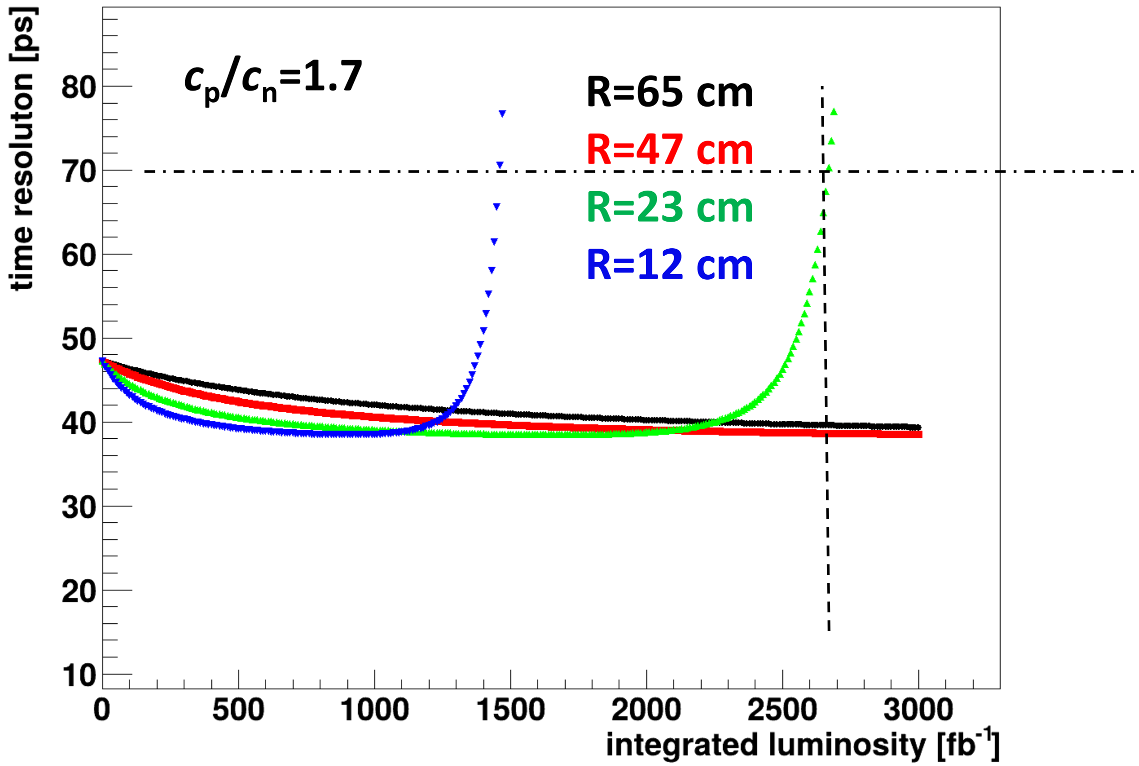
$$\emptyset_{\text{scaled}} = \emptyset_{\text{n}} + \frac{c_{\text{p}}}{c_{\text{n}}}\emptyset_{\text{p}}$$



- ^{90}Sr charge measurement using ϕ_{scaled}
  - **Neutron** only
  - **Proton** only
  - Mixed
- Collected charge reducing consistently with ϕ_{scaled}
- **Scaled fluence from different particles is additive**

Estimated HGTD performance over the lifetime (3000 fb^{-1})





- HGTD performance simulation using particle composition at HL-LHC
- Significant dependence on charged hadron damage factor c_p/c_n
- Indication that 3000 fb^{-1} (including safety factor 1.5) can be withstood with 1-2 replacements of the inner part (default plan is two replacements), etc.

Conclusion

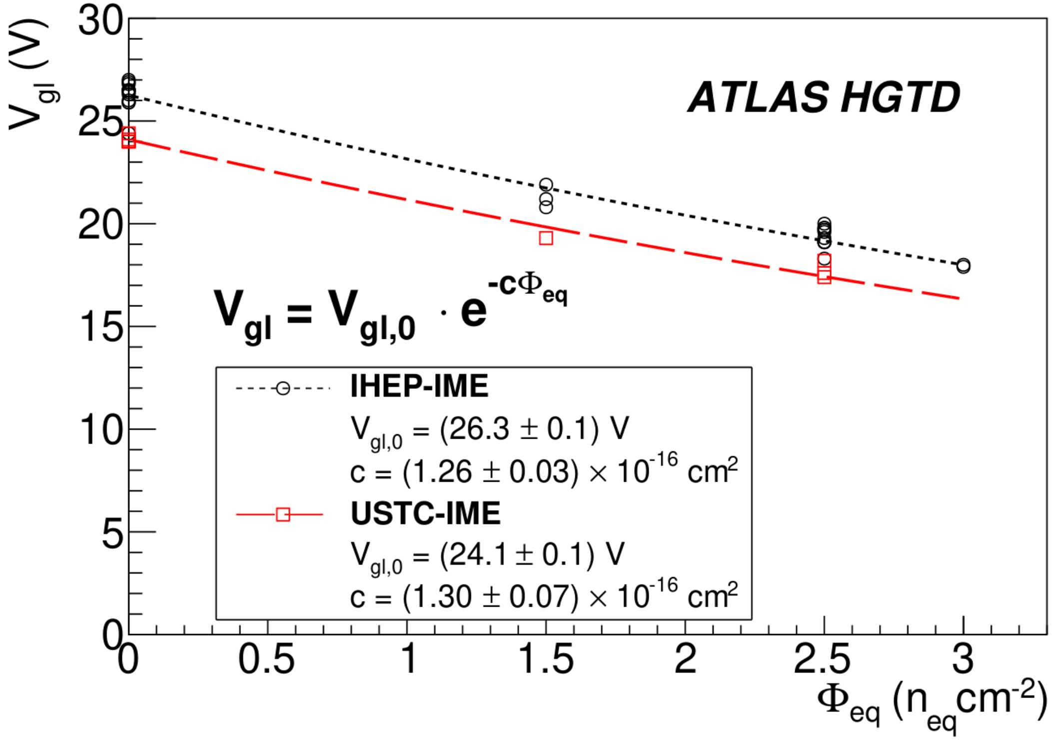
- Neutron, 24 GeV proton and mixed p + n irradiations with QCTS from the same ATLAS-HGTD early preproduction wafer V1R5
- Characterization with CV (V_{gl}, c) and ^{90}Sr (collected charge)
- $\boldsymbol{c_{\mathrm{n}} = 1.1 \times 10^{-16}\mathrm{cm}^2}$
- $\boldsymbol{c_{\mathrm{p,24\ GeV}} = 2.9 \times 10^{-16}\mathrm{cm}^2}$
- $\boldsymbol{c_{\mathrm{p}}/c_{\mathrm{n}} = 2.7}$
- Damage from different particle types is cumulative (no interplay of defects)
- Charge collection can be well modelled using fluence scaled by damage factor

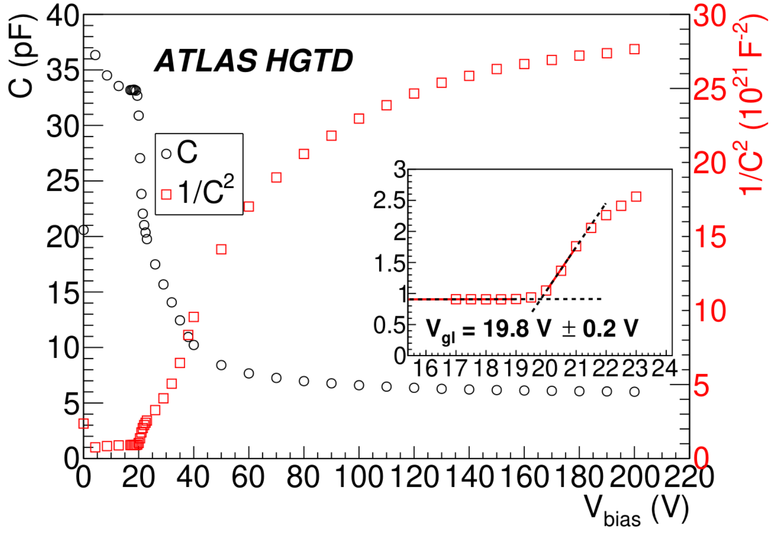
$$\emptyset_{\mathbf{scaled}} = \emptyset_{\mathbf{n}} + \frac{\boldsymbol{c_{\mathrm{p}}}}{\boldsymbol{c_{\mathrm{n}}}}\emptyset_{\mathbf{p}}$$

- Faster removal rate with charged hadrons not expected to critically impact HGTD performance

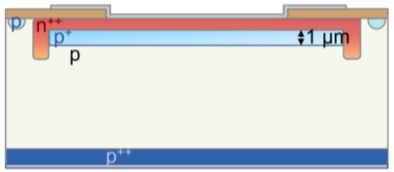
Backup

CV/IV acceptor removal with neutrons (HGTD preproduction)





V_{gl} extracted from intersection of linear fits in $1/C^2$ vs. V_{bias}



- HGTD preproduction samples irradiated with neutrons
- **Extracted c = 1.3 × 10^{-16} cm^2 indicates good radiation hardness of both designs**
- Difference in $V_{gl,0}$ between IHEP-IME and USTC-IME due to gain layer design – no direct implications on radiation hardness (*c* is similar)