Active pixel sensors in ams H18/H35 HV-CMOS technology for the ATLAS HL-LHC upgrade

10th International "Hiroshima" Symposium
Xi'an, China

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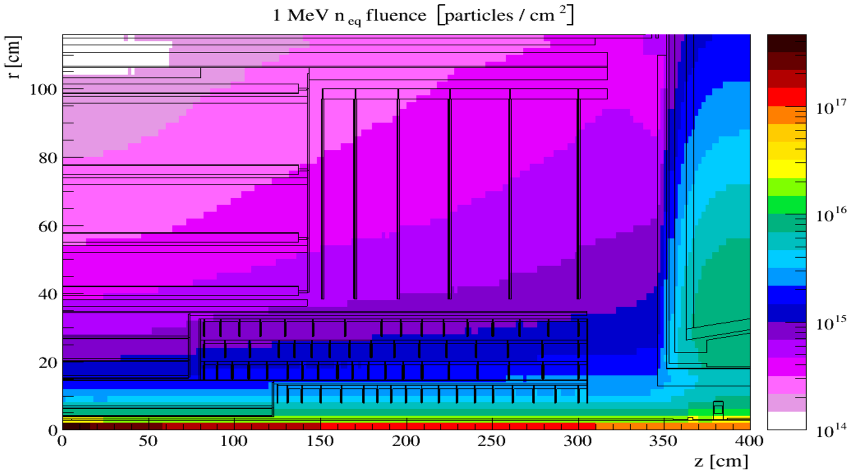
CERN / Université de Genève

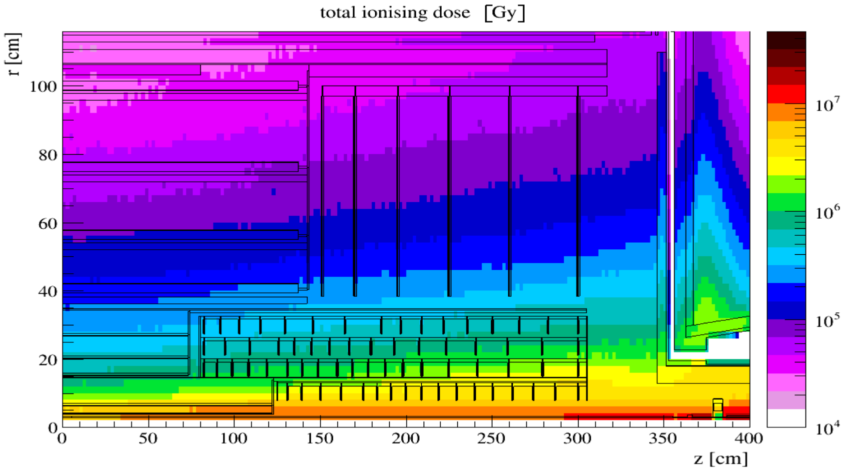
On behalf of the ATLAS HVCMOS R&D Collaboration

v1.1

LHC Upgrade

- LHC upgrade to higher luminosities planned for 202x
  - Integrated luminosity: 300 fb^{-1} → 3000 fb^{-1}
- Hybrid detectors proven to be rad-hard enough
- Main drawback: Price
  - Bump bonding expensive due to special processes
  - Sensor processes non-standard + on small wafers
  - ITk requires ~100-200m^2 of silicon → price matters





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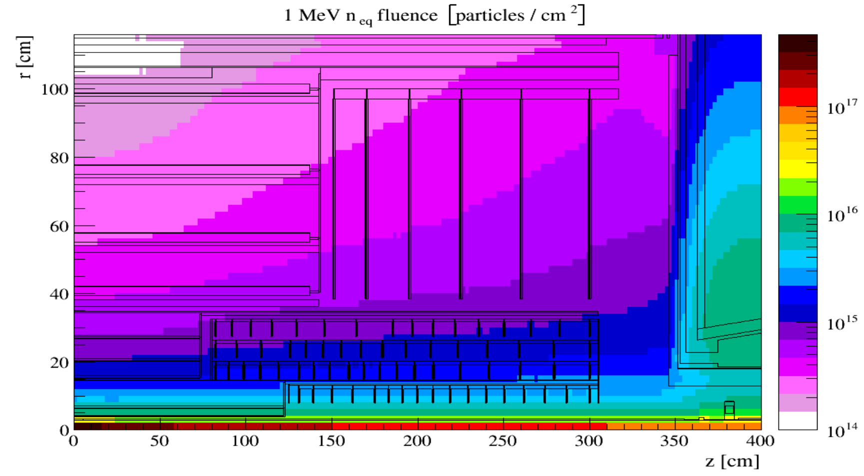
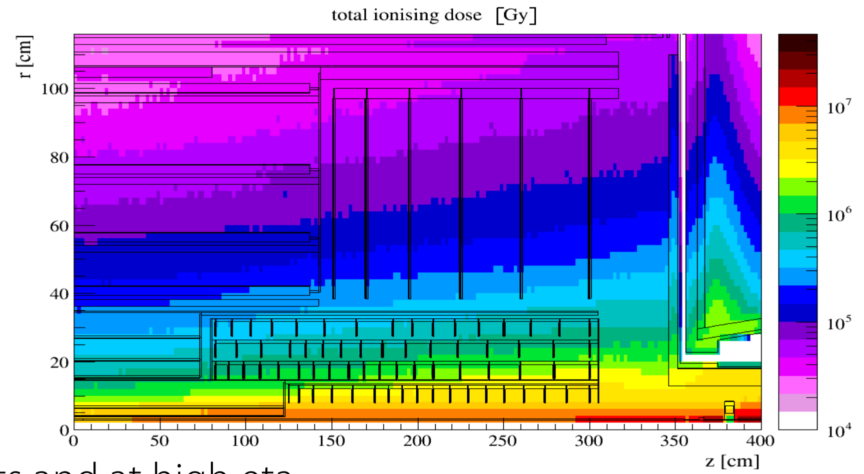


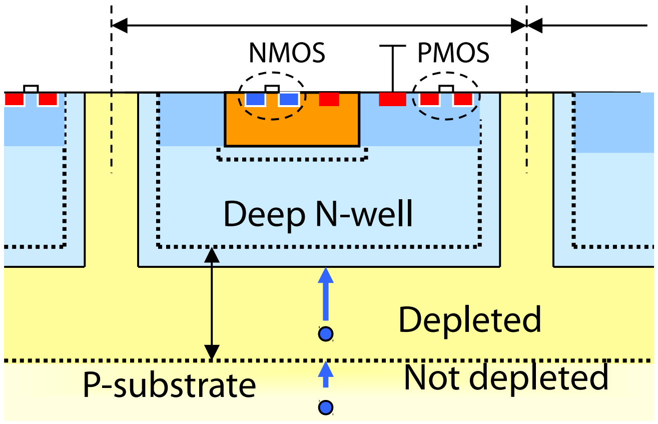
→ Possible solution: Industrialized processes
  - … and interconnection technologies
  - Commercially available by variety of foundries
    - Large volumes, multiple vendors
  - 8" to 12" wafers
    - Low cost per area, wafer thinning quite standard
  - usually p-type Cz silicon
    - Thin active layer, helpful to disentangle tracks in boosted jets and at high eta
      - Requires low capacitance → small pixels

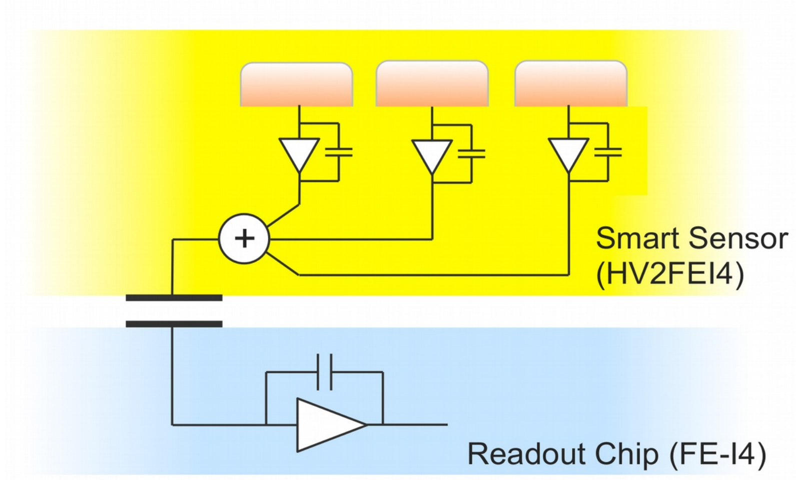


HV-CMOS sensors in ams technology

Austria Micro Systems offers HV-CMOS processes with 180nm and 350nm feature size

- Several substrate resistivities O(10 - 1000)Ωcm
  → $N_{eff} > 10^{11}...10^{14}/cm^3$
- Collecting electrode and HV isolation → Deep N-Well
- Biasing of substrate to ~60-100V(H18) ~150V (H35)
- Depletion depth theoretically in the order of 10 - 100µm
  → Drift signal ~500...O(1000)e^-
- On-sensor amplification possible - and necessary for good S/N
  - Key: small pixel sizes → low capacitance → low noise
- Additional circuits, e.g. discriminator
  - Adjustable high output signal
  - Capacitive coupling (CCPDs)
  - Sub-pixel encoding (small pixels)
- Hybridization by gluing using flip chip machines
  - Glue thicknesses of several µm reached
  - Below 1 µm precise alignment





A short story of ams CCPDs for ATLAS

The HV2FEI4 CCPD family
Idea and most designs by
Ivan Peric

ams H18 → **2012: H18CCPDv1** → **2013: H18CCPDv2** → **2013: H18CCPDv3** → **2014: H18CCPDv4** → **2015: H18CCPDv5** → **H18Demo**

2012: H18CCPDv1
- Proof of principle
- Standard lib components
  → Non radiation hard
- Chessboard structure

2013: H18CCPDv2
- Radiation hardened design
  - Circular transistors
- Several pixel flavours
- Irradiated to 830MRad and $1\times10^{16} n_{eq} cm^{-2}$

2013: H18CCPDv3
- CLICpix focused
- New amplifiers
- One diode w/o electronics directly accessible

2014: H18CCPDv4
- Lower noise amplifiers
- New pixel type STime:
  - time encoding
- Linear sub pixel arrangement
- Analogue pixels

2015: H18CCPDv5
- Timewalk compensating discriminators
- Optimization towards higher bias voltage stability

ams H35 → **2013: H35CCPDv1** → **2015: H35CCPDv2** → **2015/16: Demonstrator**

2013: H35CCPDv1
- Purely analogue (no discriminators)
- Two pixel types containing one or two stage amplifiers

2015: H35CCPDv2
- Timewalk compensating discriminators
- HV optimizations

2015/16: Demonstrator
- Submission on the way
- More information later

ams H35 → **Striplike Sensors**

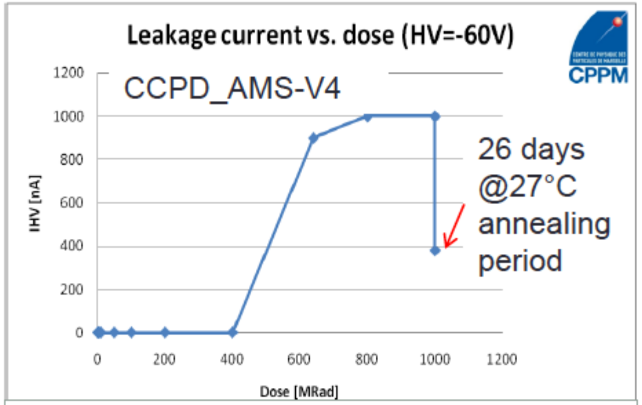
→ see Zhijun Liang's poster

Irradiation of H18CCPDv4 samples

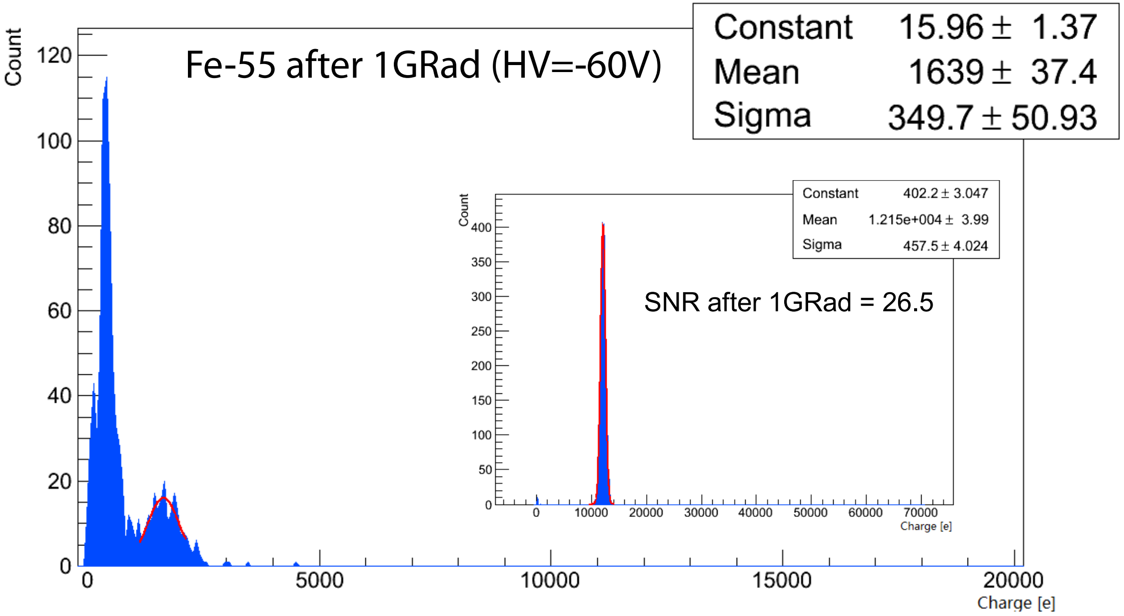
CPPM

X-Ray irradiation up to 1000MRad (158.4MRad/day): stand alone CCPD V4, powered

- Increase of leakage current after 400 MRad
  - Drops to 380 nA after 26 days of annealing at room temperature
    → High temperature annealing not necessary
- Amplifier with linear and circular feed back transistor investigated
  - Linear FB transistor shows noise after 100MRad
  - Circular FB transistor remains quiet up to 1GRad → Fe-55 peak clearly visible



After 26 days @27°C (annealing period), the leakage current reduces from 1000nA to 380nA.



Irradiation of H18CCPDv4 samples

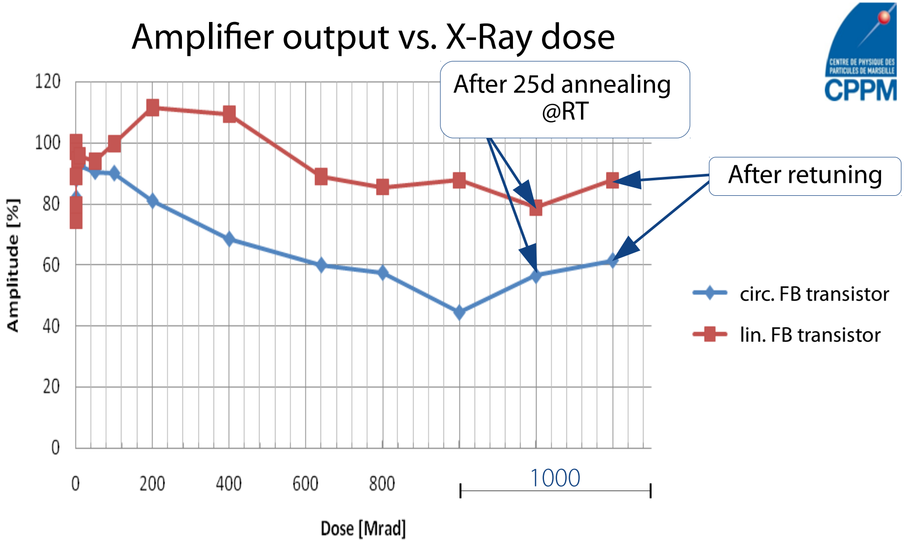
CPPM

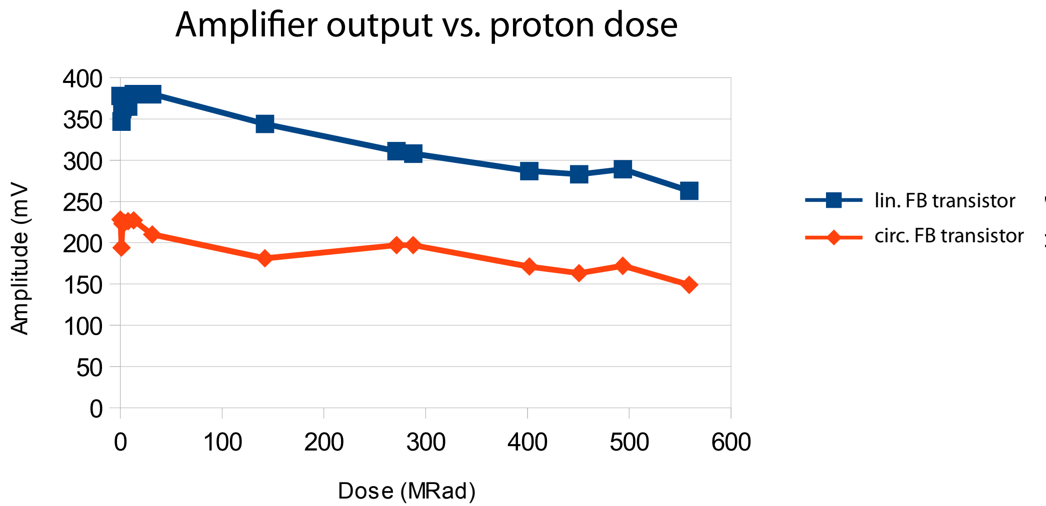
X-Ray irradiation up to 1000MRad: stand alone CCPD V4, powered

- Amplifier output signal recovered by annealing at room temperature and retuning
  - Relative amplitude of linear FB transistor: 88%, but noisy
  - Relative amplitude of cicrular FB transistor: 62%

Proton irradiation up to 560MRad:stand alone CCPD V4, powered

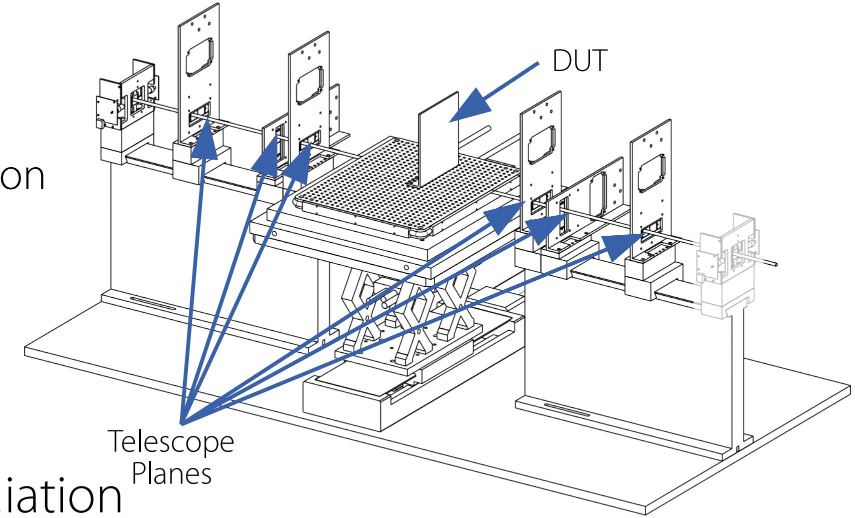
- No annealing or retuning performed
  - Relative amplitude of linear FB transistor: 75%, but noisy
  - Relative amplitude of cicrular FB transistor: 63%
- Investigation ongoing



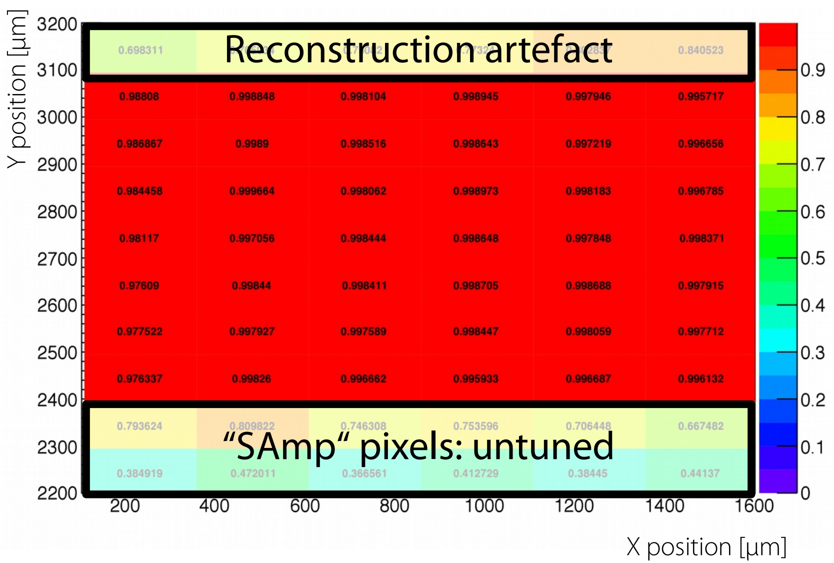


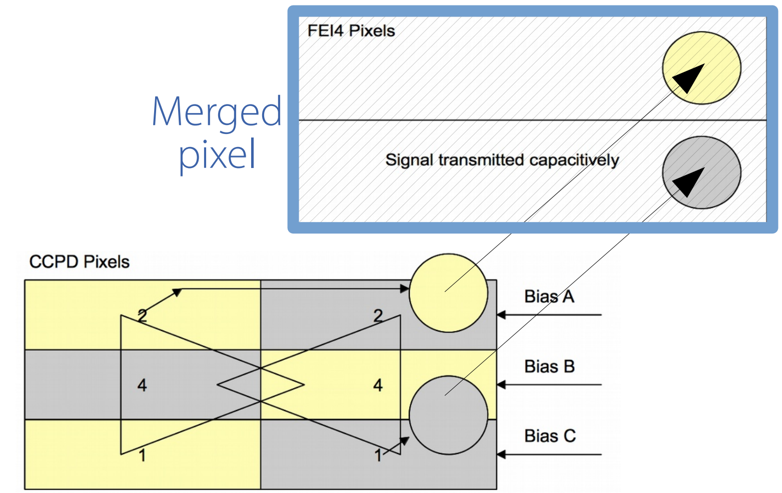
Testbeam results on H18CCPDv4 samples

- Multiple testbeam periods during last 1.5 years
- Performed using new FEI4 based telescope
  - Resolution at DUT ~8/12um for typical telescope configuration
- Two H18CCPDv4 samples tested
  - 402: unirradiated and 404: $1\times10^{15} n_{eq} cm^{-2}$
  - Subpixel encoding not tested → FE-I4 pixel pairs merged



- High efficiency of **99.7%** before and 96.2% after irradiation

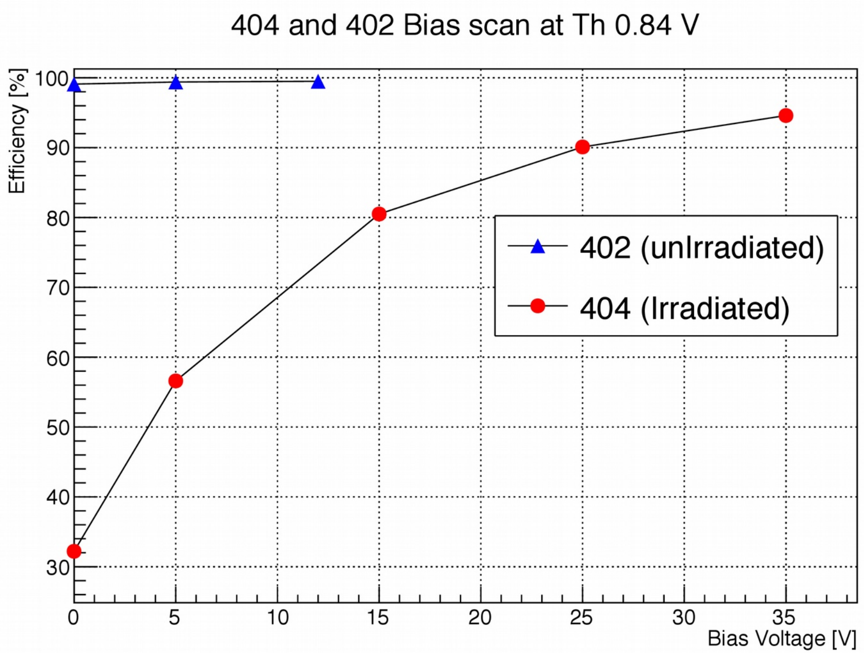


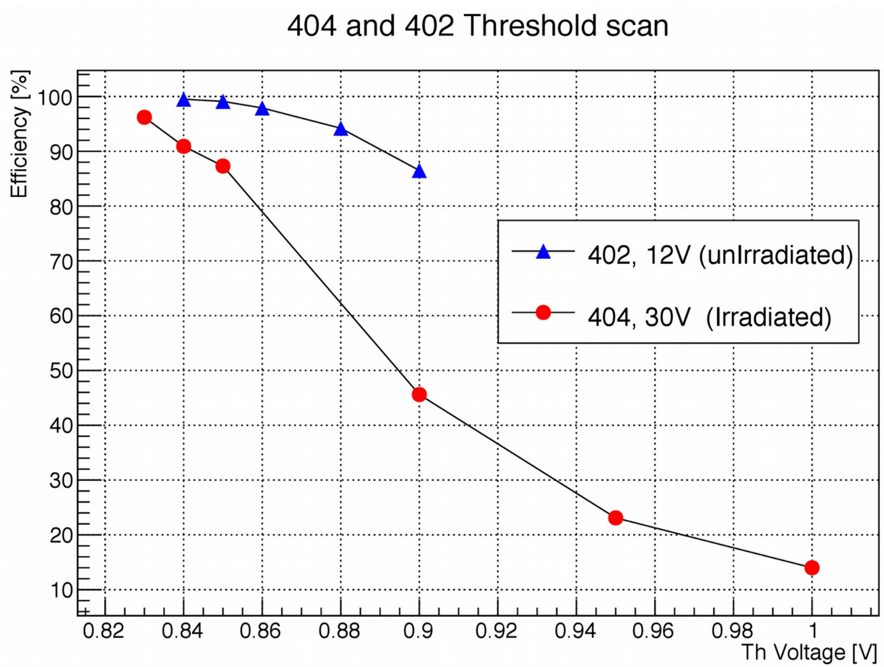


Bias and threshold Scans

- Bias scan from 0V to breakdown voltage performed
  - Diffusion contributes significantly to signal in unirradiated case
  - Early breakdown prevented optimal performance (especially in case of irradiated sample)
  - H18v4 samples can be biased up to ~95V → New data expected this year

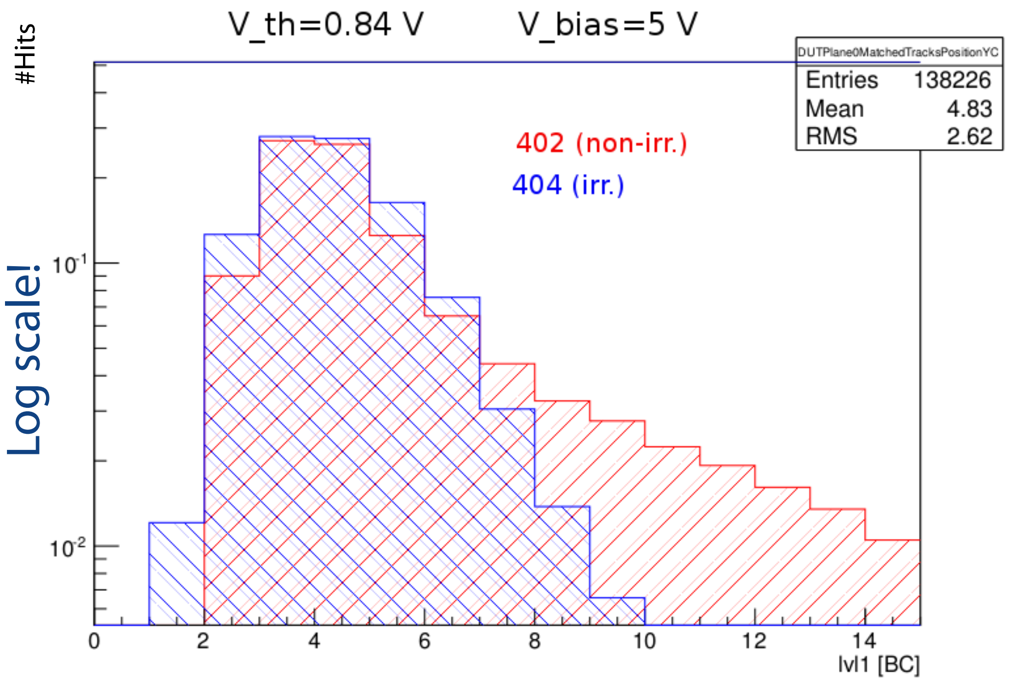
- Threshold scan from close to the noise edge to up to several thousand electrons performed
  - Detection efficiency depends highly on properly tuned sample (if not biased with high voltages)

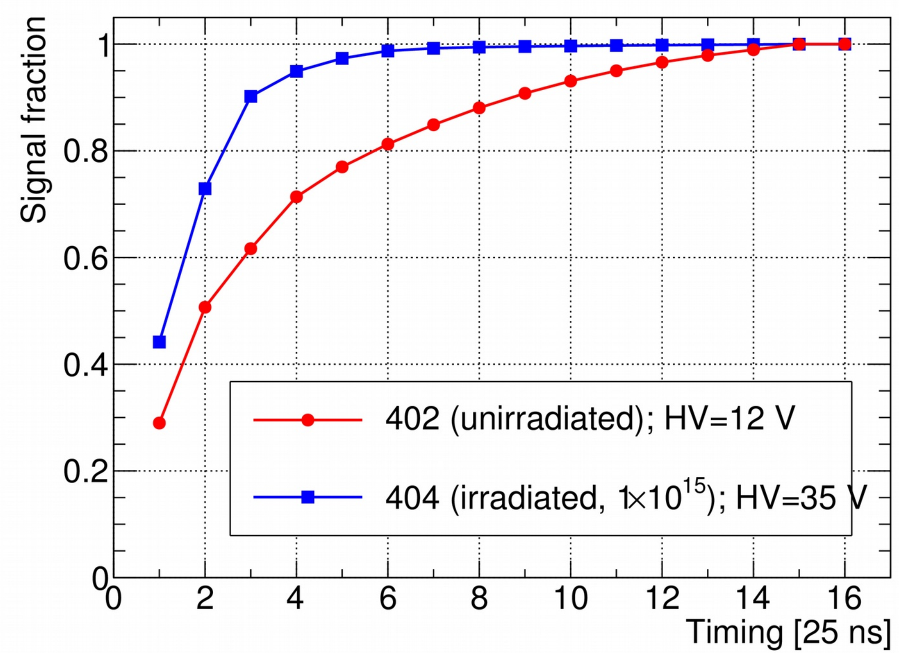




Timing comparison

- Output signal shows broad timing distribution of several bunch crossings
- Slow signal/tail suppressed after irradiation hinting on trapping of diffusion component
  - Improvement of timing can be reached by higher bias voltages → higher drift fraction of signal
- ATLAS requires signal generation in one bunch crossing
  → Time walk compensation in H18v5

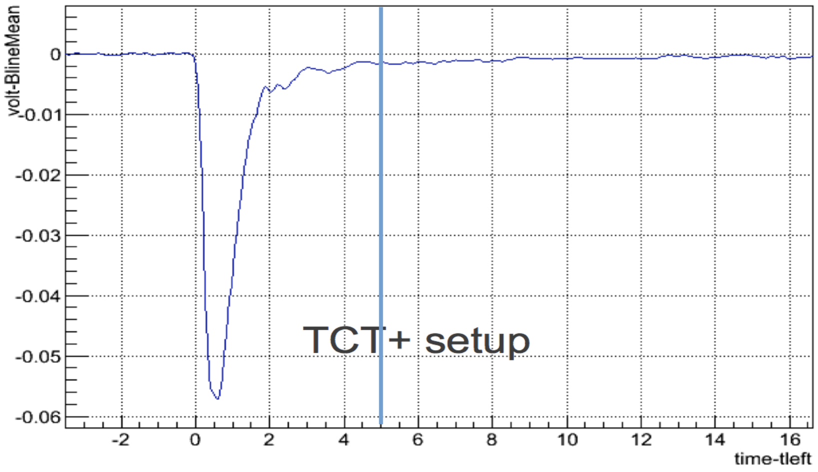




(Edge) Transient Current Technique

TCT (Transient Current Technique): record time-resolved charge collection

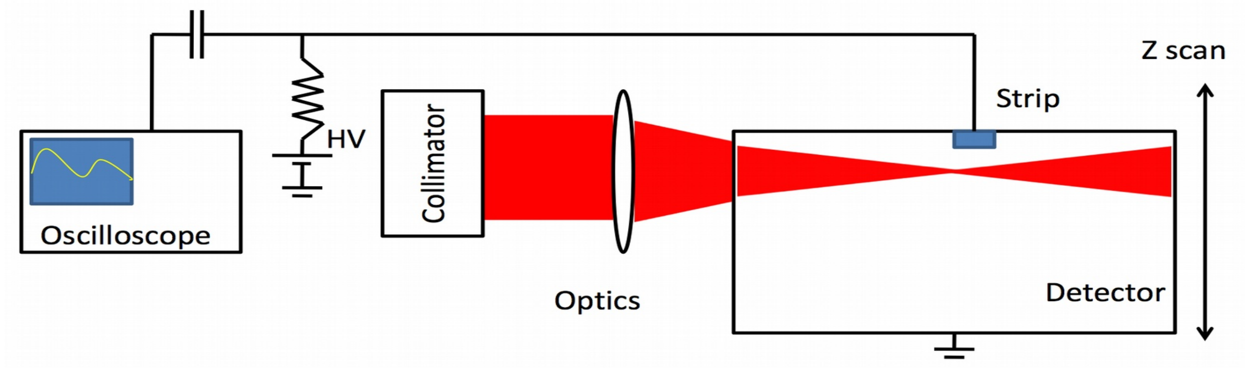
- Charges usually generated via infrared laser, shot into the bulk of sensor
  - Constant charge deposition per pulse → averaging over many pulses cancels noise
- Observables: Transient current (charge movement)
  Integrals (collected charge)
- Fast signals (~ns) → External amplification, fast readout with scopes
- Edge TCT: shooting in through the side-wall of the sensor with a IR laser
  - Can study the charge collection at different depths → depletion?



Why E-TCT?

- Expected depletion depth for 10 Ohm*cm around 10 µm → 500-600e for a MIP
- Observed: ~1500-1900 e⁻ (~1200 e⁻ after irradiation) from in-pixel charge-sensitive amplifiers
  - Origin of discrepancy unclear

Christian Gallrapp
CERN / PH-DT-DD

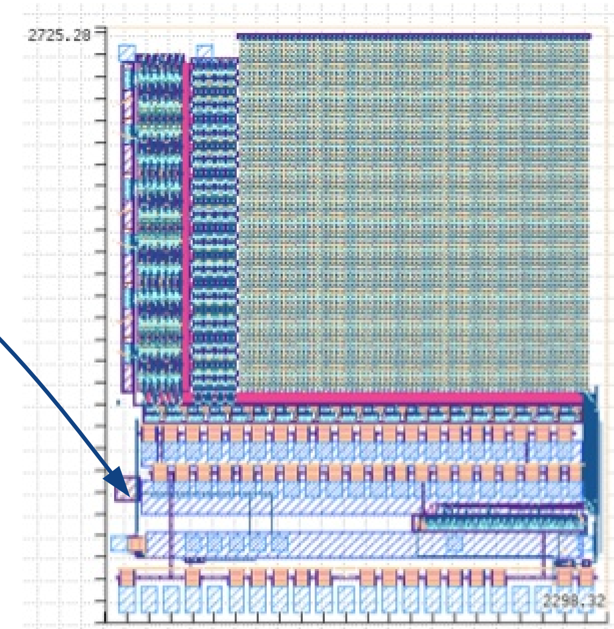


E-TCT on ams samples

Measurements on H18CCPDv3 samples

- 10Ωcm substrate, max. ~90V bias
- One dedicated passive 100 x 100 μm^2 diode accessible
- No neigbours → possible edge effects

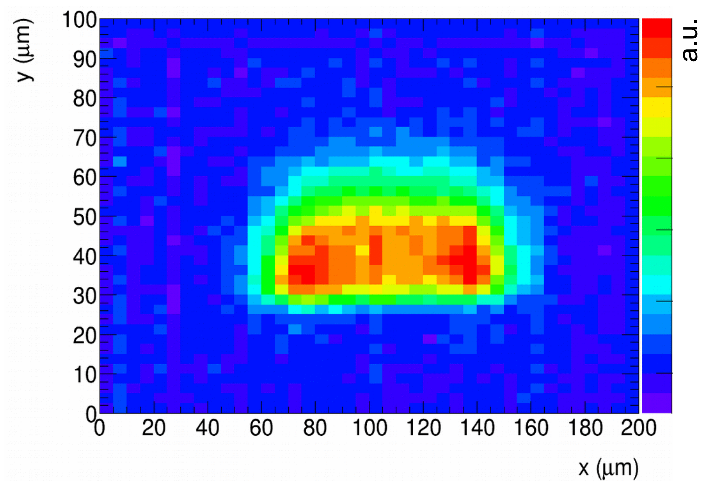
- Irradiation at CERN PS (Irrad 1) without biasing
  - Fluences: 2.3, 6 and 11.1x10^{15} p/cm^2 (1.42, 3.72 and 6.9x10^{15} n$_{eq}$/cm^2)
  - p-irradiated samples cooled to 0 degrees for measurement
- Irradiation at JSI Ljubljana, Slovenia
  - Fluences: 1, 7, 20x10^{15} n$_{eq}$/cm^2
- Collected charge obtained as integral over 5ns



Measurements on H35 samples (CHESS1)

- 20Ωcm substrate, max. 120V bias
- 100 x 45 μm^2 diodes forming an array accessible

- Irradiation at JSI Ljubljana, Slovenia
  - Fluences: 0.2, 0.5, 1, 2, 5, 10x10^{15} n$_{eq}$/cm^2
- Collected charge obtained as integral over 25ns (!)



E-TCT results of ams H18 Samples

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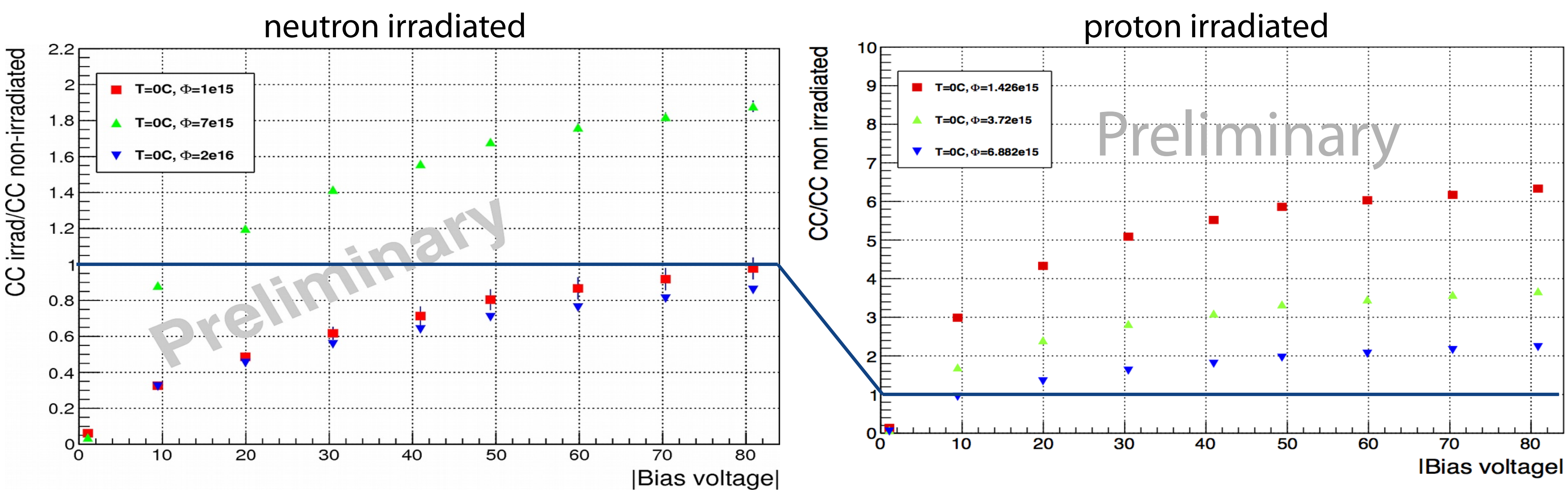
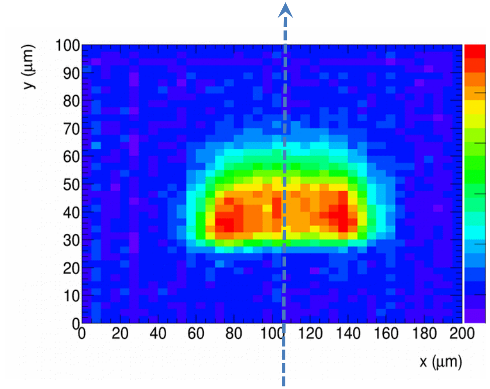
- Relative charge collection (CC) after neutron irradiation
  - CC at 0V after 1x10^{15} n$_{eq}$/cm^{2} near 0 → Diffusion component degraded by trapping
  - Can be recovered to 85% even after 2x10^{16} n$_{eq}$/cm^{2}
  - Collected charge doubled in case of 7x10^{15} n$_{eq}$/cm^{2} → Acceptor removal effect → Deeper depletion zone
- ….and after proton irradiation
  - CC exceeds unirradiated case at below 10V
  - Largest collection after 1.42x10^{15} n$_{eq}$/cm^{2} (p irradiation) reaches relative CC of up to 6 at 80V
    → Acceptor removal for protons much stronger than for neutrons at that fluence
  - Comparable after 7x10^{15} n$_{eq}$/cm^{2}: 1.9 (n) vs. 2.2 (p) at 80V



Depletion depth on H18 and H35 samples

- Depletion depths obtained as FWHM of scanning over y
- H18 and H35 samples yield comparable results
  - 1×10^{15} n_{eq}/cm^2 inconclusive: Precise knowledge of fluence crucial
- Results confirm charge collection measurements
  - Discrepancy between proton and neutron irradiation
  - Equal charge collection for $\sim7\times10^{15}$ n_{eq}/cm^2



Scan direction

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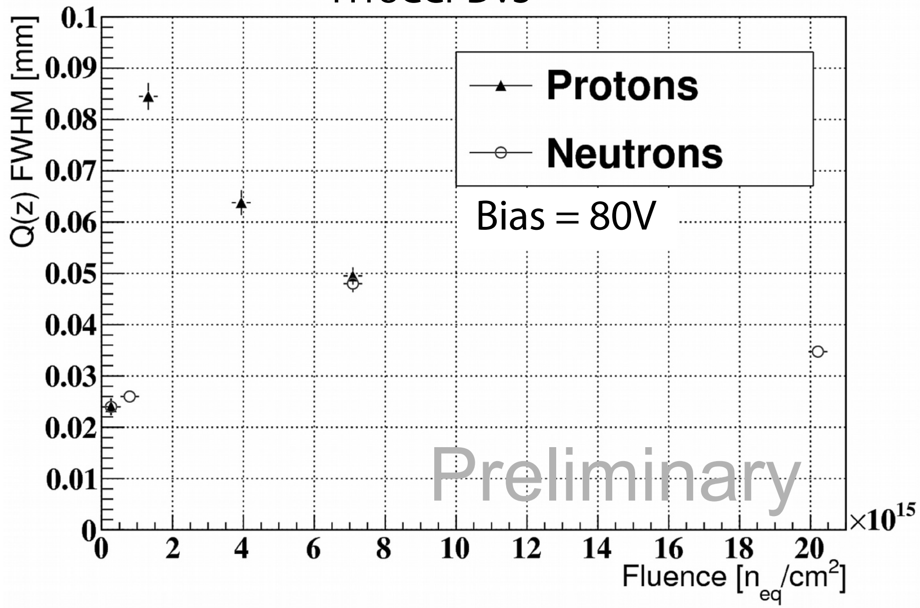
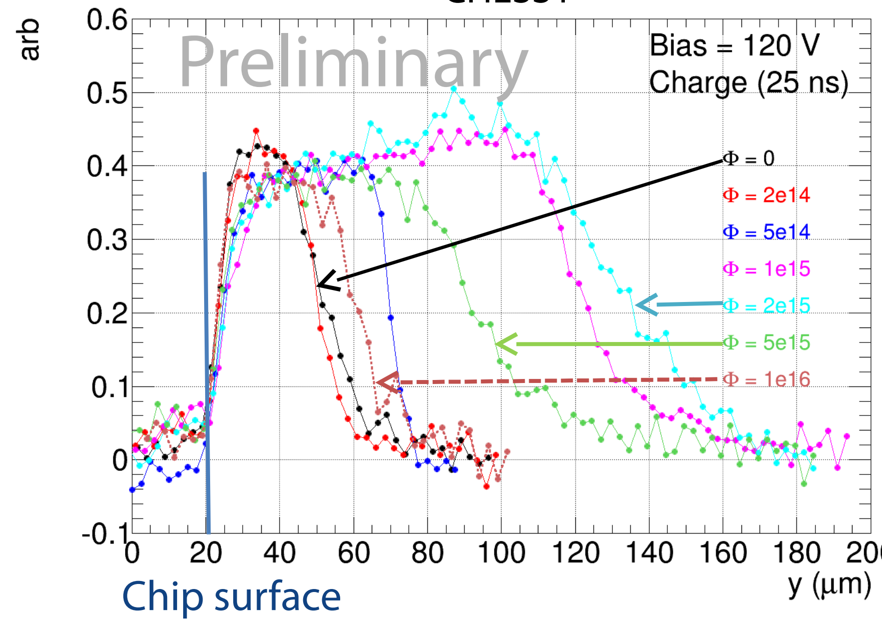
JSI Ljubljana

H18CCPDv3



CHESS1



Presented at the ITK Week
Sep 2015 by Igor Mandic

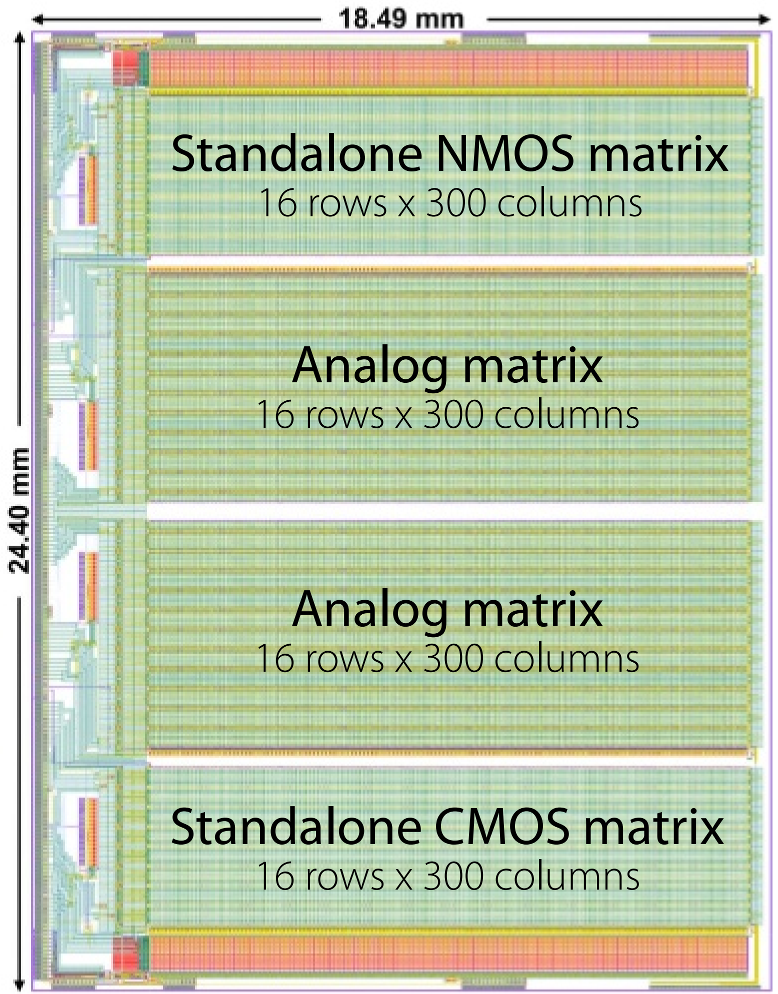
The AMS H35 Demonstrator

IFAE | KIT
University of Liverpool

- Engineering run, proving feasibility of full reticle size sensors
- Built in AMS H35 350nm HV-CMOS process
- Substrate resistivities: 20, 80, 200, 1000Ωcm
- Submission on-going

Floorplan

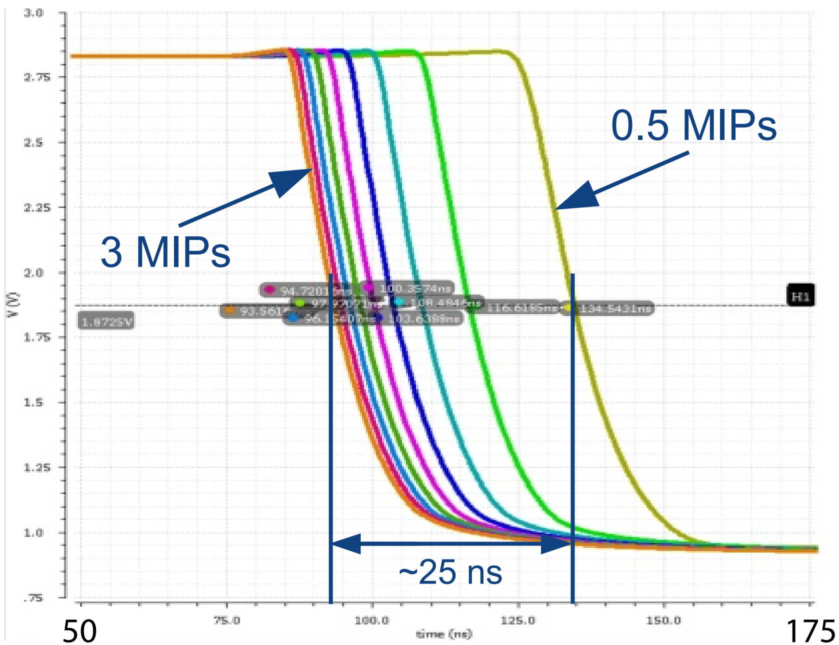
- Analog pixels (only amplifiers) for FEI4 coupling
  - 3 flavours optimized for gain and/or speed
- Standalone NMOS matrix
  - Different in-pixel amplifiers and discriminators
  - Read out by FE-I4 or an FE-I3 like digital structure at periphery
- Standalone CMOS matrix
  - Different in-pixel amplifiers
  - Can be read out by FE-I4
  - CMOS discriminators at periphery and FE-I3 like digital structure at periphery

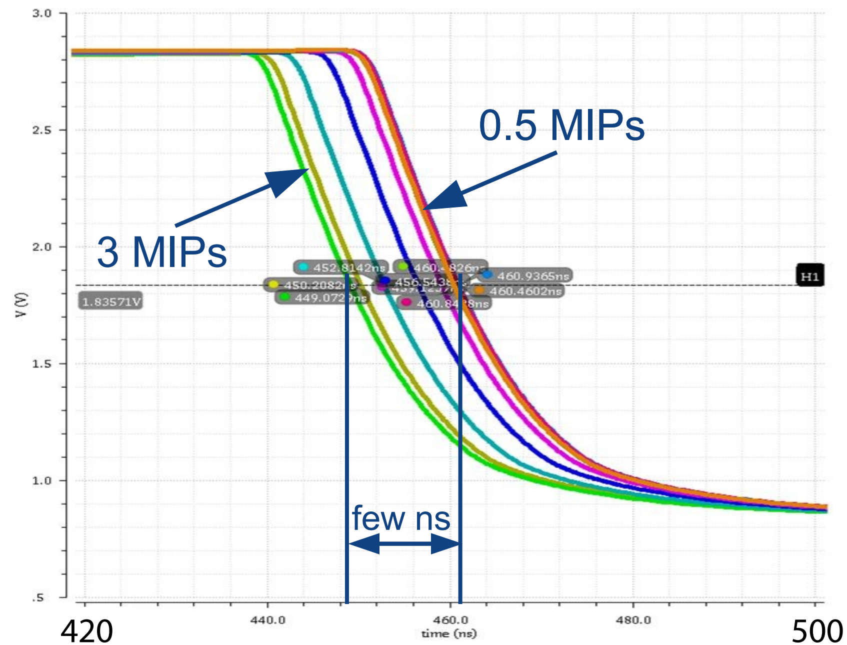


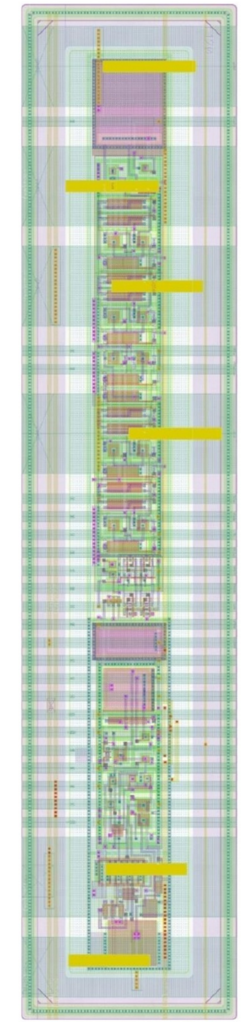
The AMS H35 Demonstrator

IFAE | KIT
University of Liverpool

- Timewalk has been addressed by a timewalk compensating discriminator
- Post design simulation reveals significant improvement especially for low charges
- Higher substrate resistivities will yield higher signals, further mitigating this issue
  - Possible backside implant for HV biasing → homogenious E-field through bulk







Summary and outlook

- HV-CMOS sensors are promising sensor candidates for the upgrade of the ATLAS Inner Tracker
  - Very good detection performance and radiation hardness
  - Cost efficient (standard processes and gluing instead of bump bonding)
  - Offered by various vendors and in big volumes
- Testbeam measurements yield detection efficiencies of up to 99.7% for irradiated and 96.2% for $1x10^{15} n_{eq} cm^{-2}$ irradiated samples under non-optimal conditions
- Deteorioration of Amplifier signals after irradiation with ionizing particles can be mitigated by room temperature annealing and retuning
- Timewalk issue has been identified and addressed by improved comparator design
- Edge TCT measurements show improved charge collection for irradiated sensors due to the acceptor removal effect
  - Up to 6 times (2 times for neutron irradiation) the initial charge collected for 1...2x1015neqcm-2

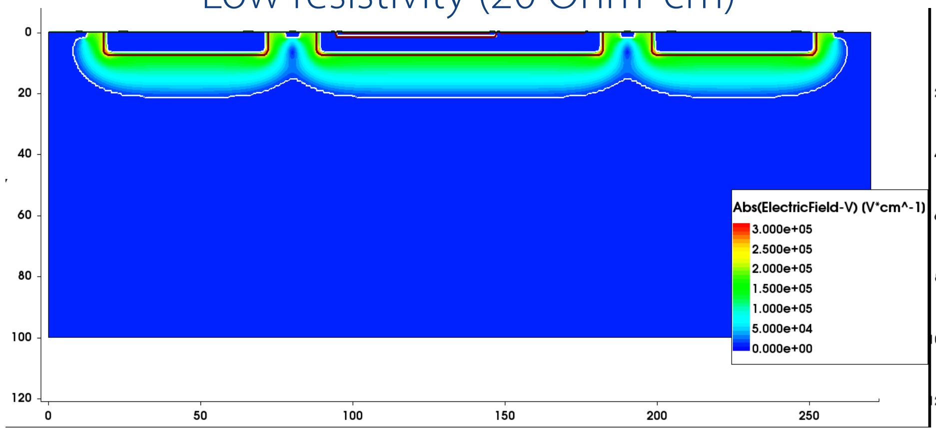
- Full size demonstrator design in H35 technology prepared
  - Production on several (high) bulk resistivities for improved SNR
  - Back side metallization by ams possible
- Mu3e tracker will be built as HV-CMOS MAPS → Implementation for ATLAS conceivable

Backup

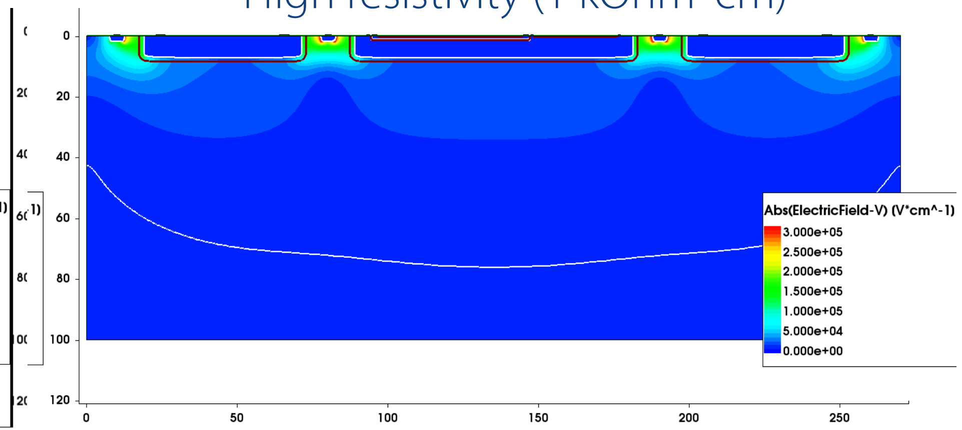
HV Biasing - bulk resistivity and contact position

E-Field distribution - Top Side bias

Low resistivity (20 Ohm*cm)

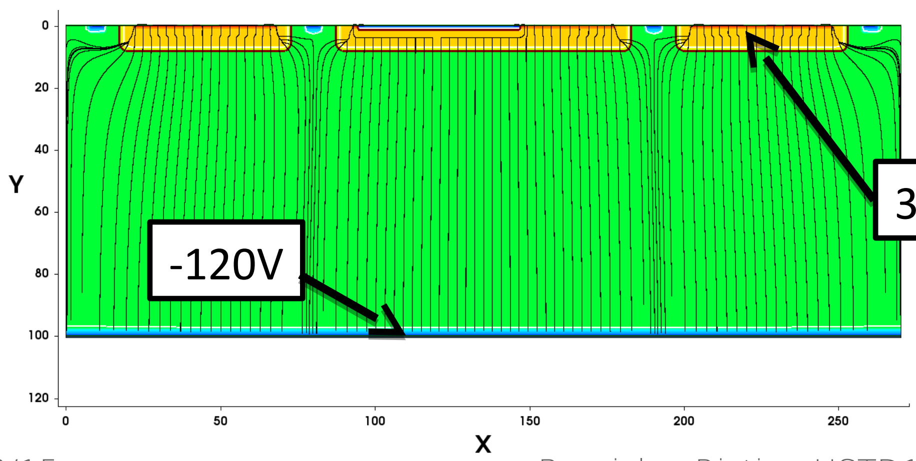


High resistivity (1 kOhm*cm)



E-Field Lines - High resistivity (1 kOhm*cm)

Back Side bias



Top Side bias