UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Section de physique

STREAM

Characterization of HV-CMOS pixel sensor prototypes

Ettore Zaffaroni

STREAM Final Conference, 17/09/2019

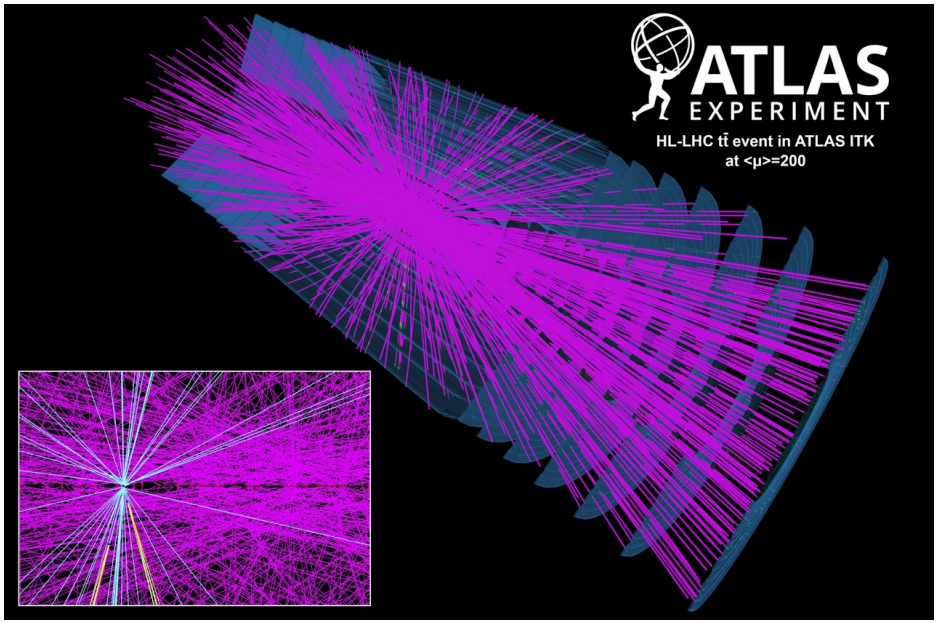
Smart Sensor Technologies and Training for Radiation Enhanced Applications and Measurements (STREAM) is a project funded by the European Commission under the Horizon2020 Framework Program under the Grant Agreement no 675587. STREAM began in January 2016 and will run for 4 years.

Outline

- Introduction
- The characterized sensors
- TCT (Transient Current Technique) measurements and results
- Testbeam measurements and results

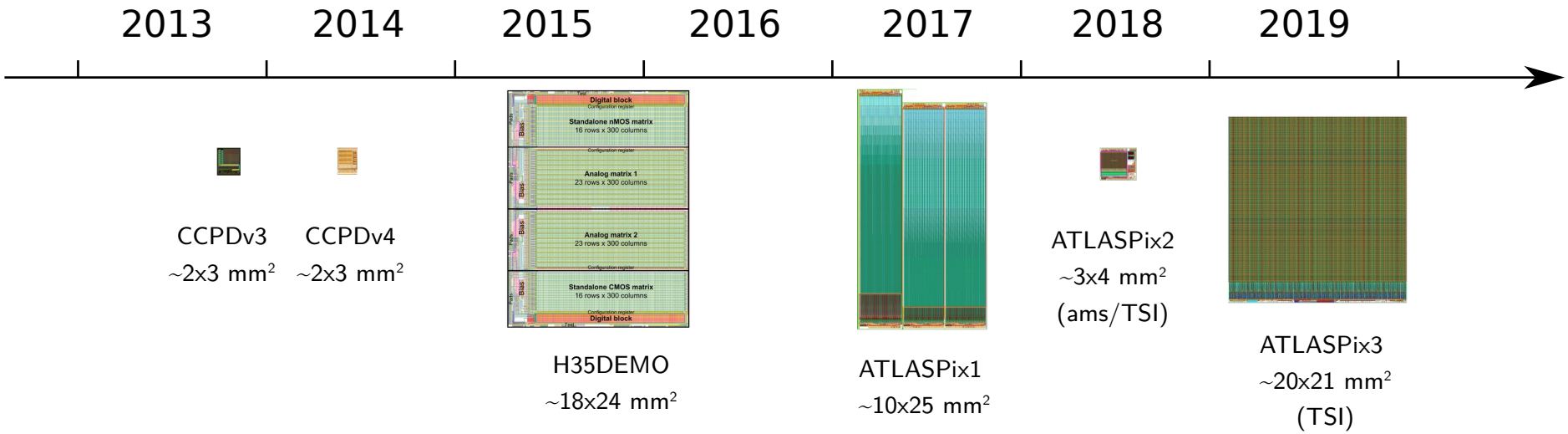
Introduction

- ATLAS will upgrade its inner tracker for HL-LHC
  - ITk, ~190 m^2 of silicon, ~15 m^2 of pixel detectors
  - High occupancy and radiation damage
- HV-CMOS developed as a possible replacement for the outermost pixel layer



Technical Design Report for the ATLAS Inner Tracker Pixel Detector", CERN-LHCC-2017-021 (2018). https://cds.cern.ch/record/2285585

ams development timeline



- CCPDv3, CCPDv4 (ams 180 nm) small prototypes, capacitively coupled to front-end ASICs
- H35DEMO (ams 350 nm), first full scale prototype, with monolithic parts
- ATLASPix1 (ams 180 nm), fully monolithic, 3 pixel matrices
- ATLASPix2 (ams/TSI 180 nm), small scale prototype, focus on periphery and SEU tolerant memory
- ATLASPix3 (TSI 180 nm), full scale prototype, single pixel matrix

H35DEMO chip

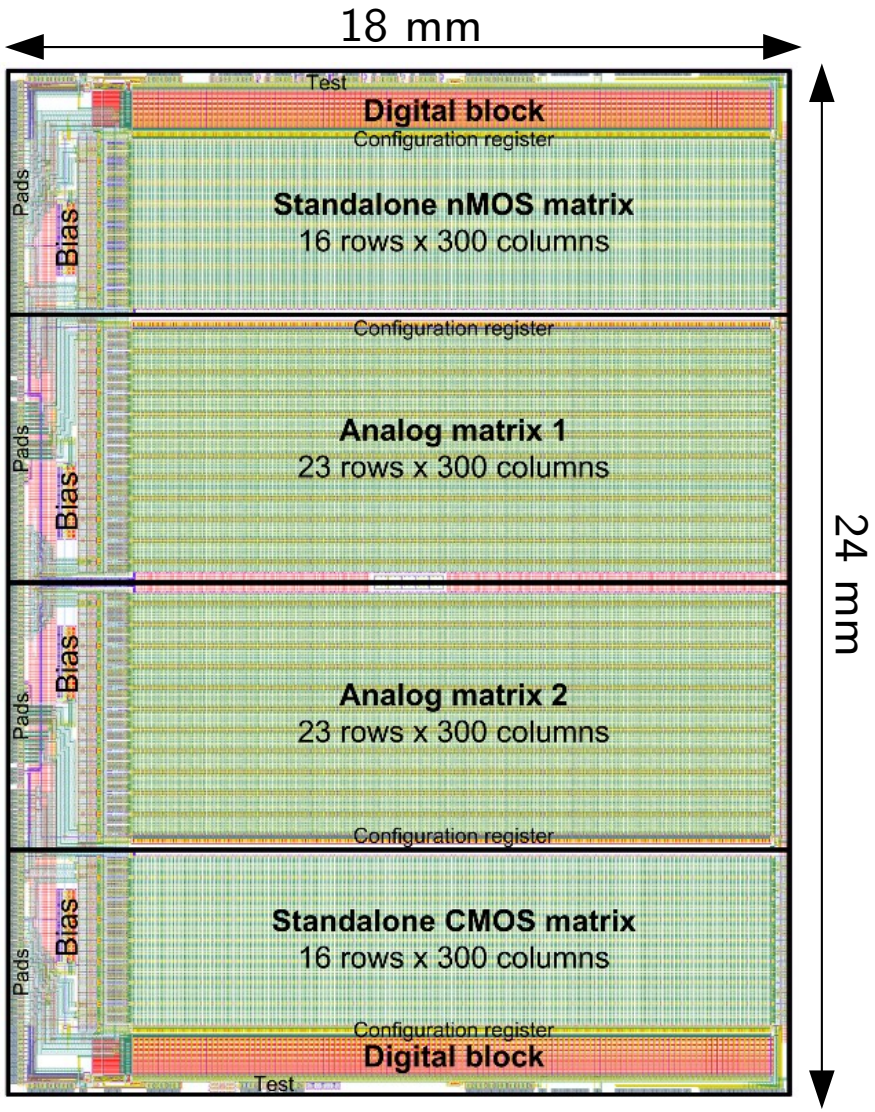
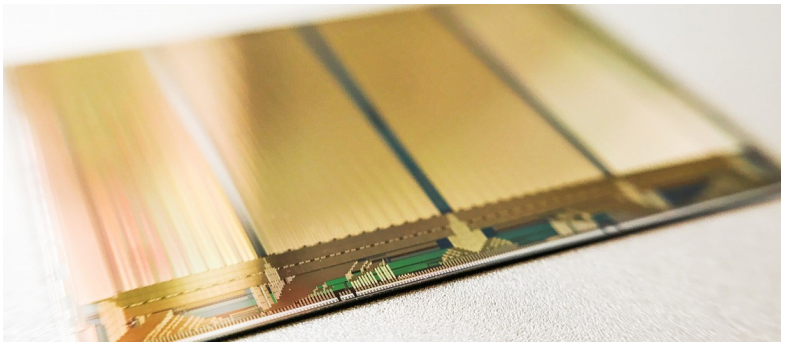


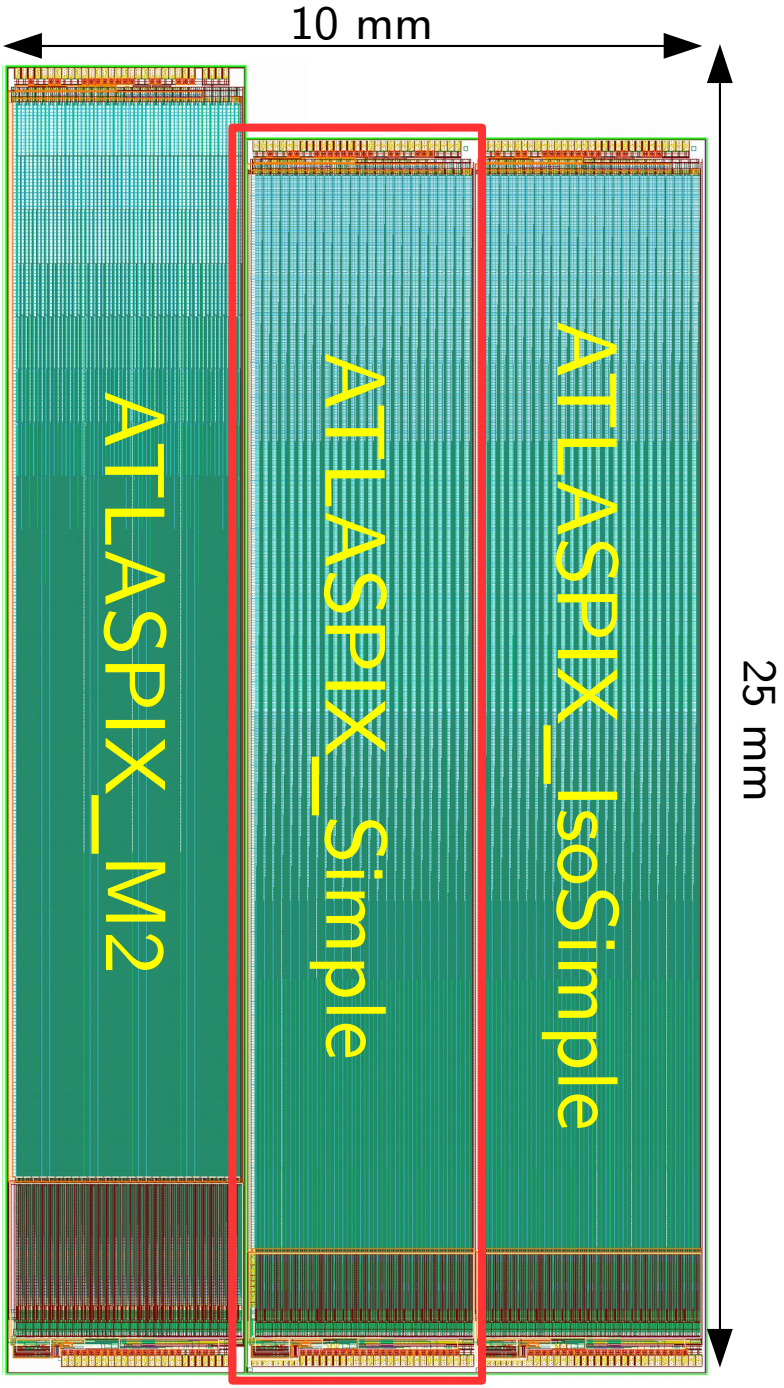
Image from:
http://dx.doi.org/10.1088/1748-0221/11/01/C01012

- H35 technology by ams
  - 350 nm HV-CMOS
- 4 pixel matrices and test structures
- 250x50 μm² pixels
- 4 different resistivities
  - 20, 80, 200, 1000 Ω · cm



ATLASPIX1 chip

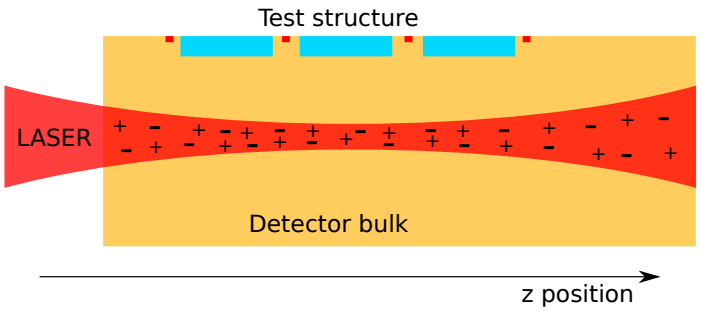
- aH18 technology by ams
  - 180 nm HV-CMOS
- Fully monolithic
- Same resistivities as H35DEMO
- ATLASPIX_Simple matrix tested
  - 130x40 μm² pixels
  - 25x400 matrix
  - Column-drain readout, triggerless



Transient Current Technique

TCT (Transient Current Technique)

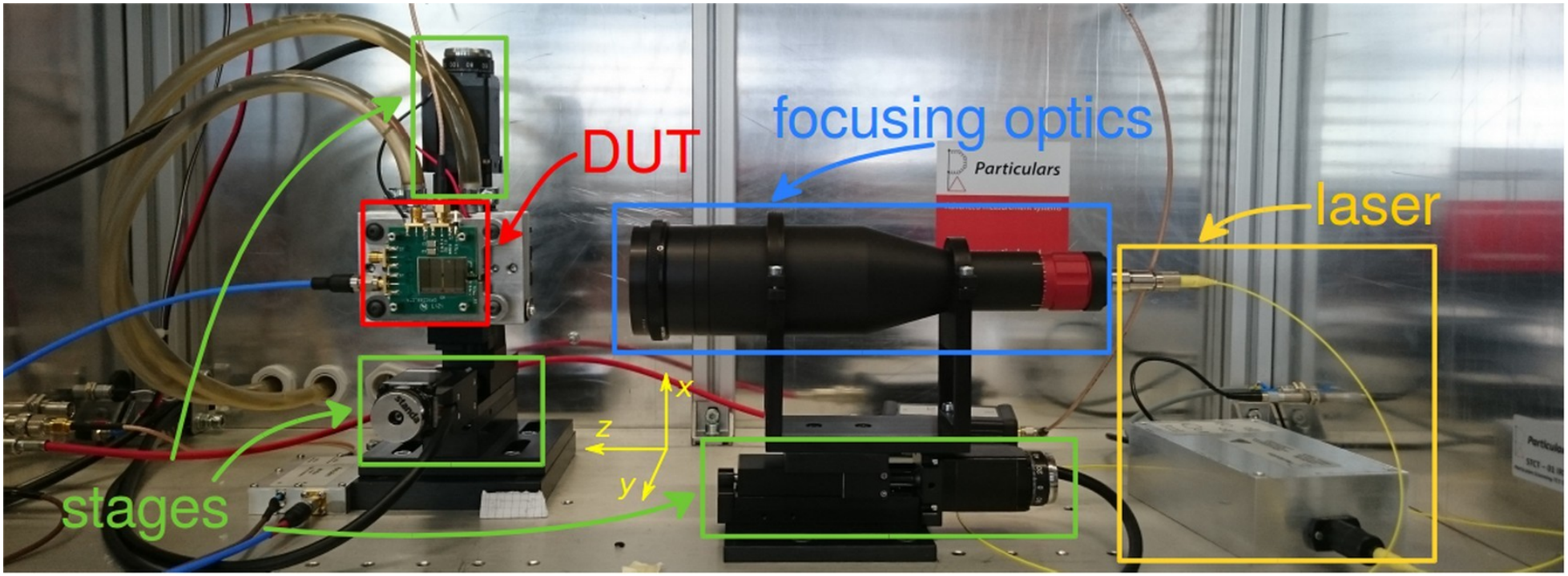
- Generation of carriers using a laser
  - Precise location
- Carriers move under electric field, generating a current
- Current signal amplified with a RF amplifier



- TCT allows to study the space charge region
  - Depletion depth, N_{eff}, etc.

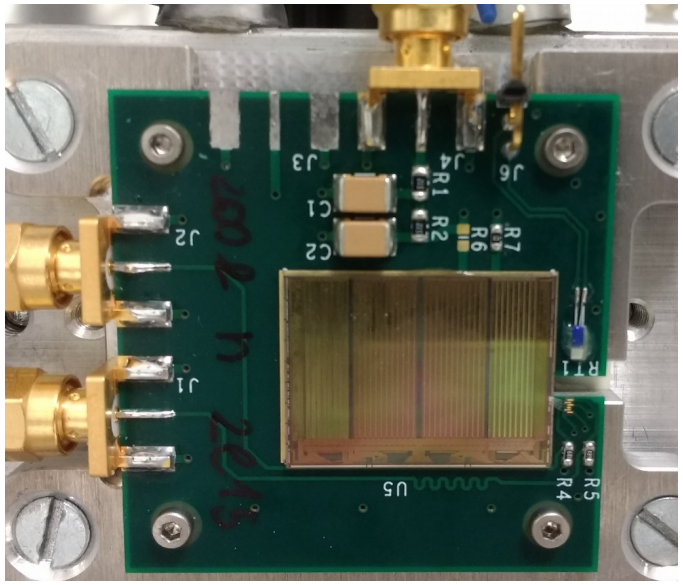
TCT setup

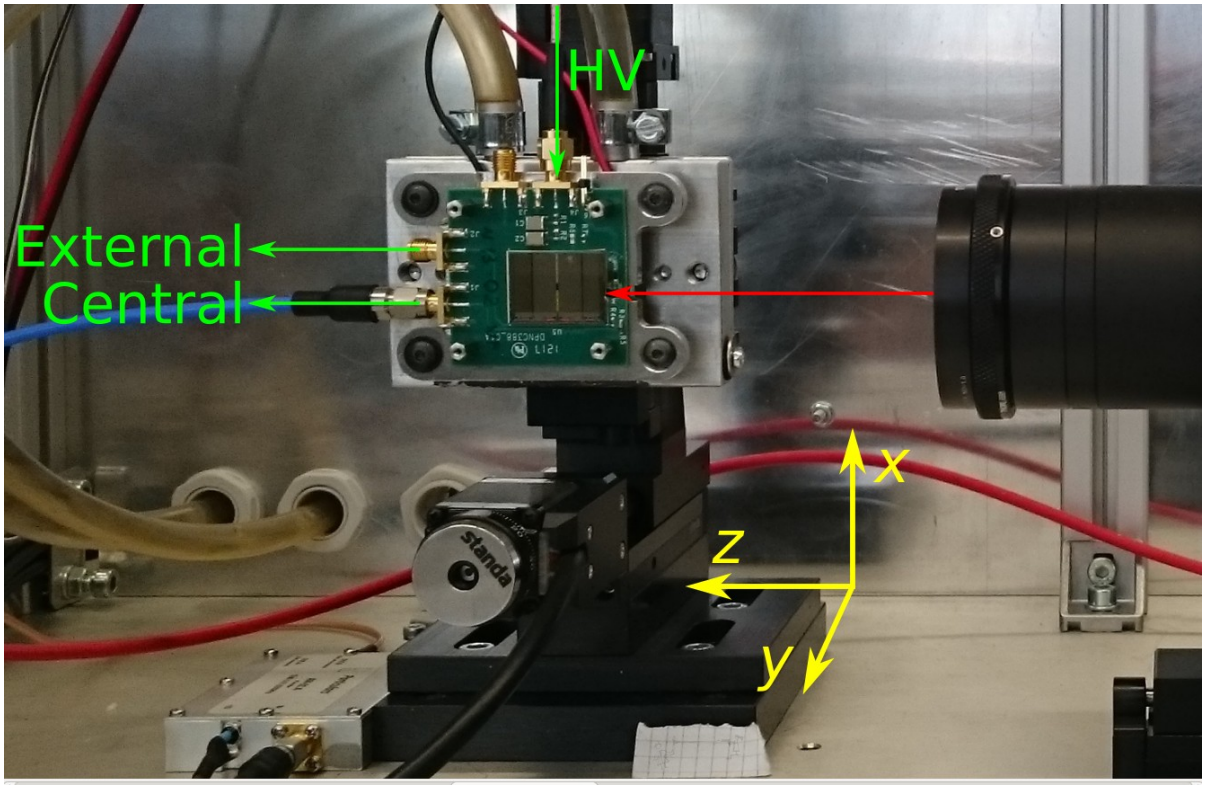
- Pulsed IR laser (1064 nm) with FWHM of 12 µm
- Detector at –27 °C using Peltier
- 1 µm step size in all axes



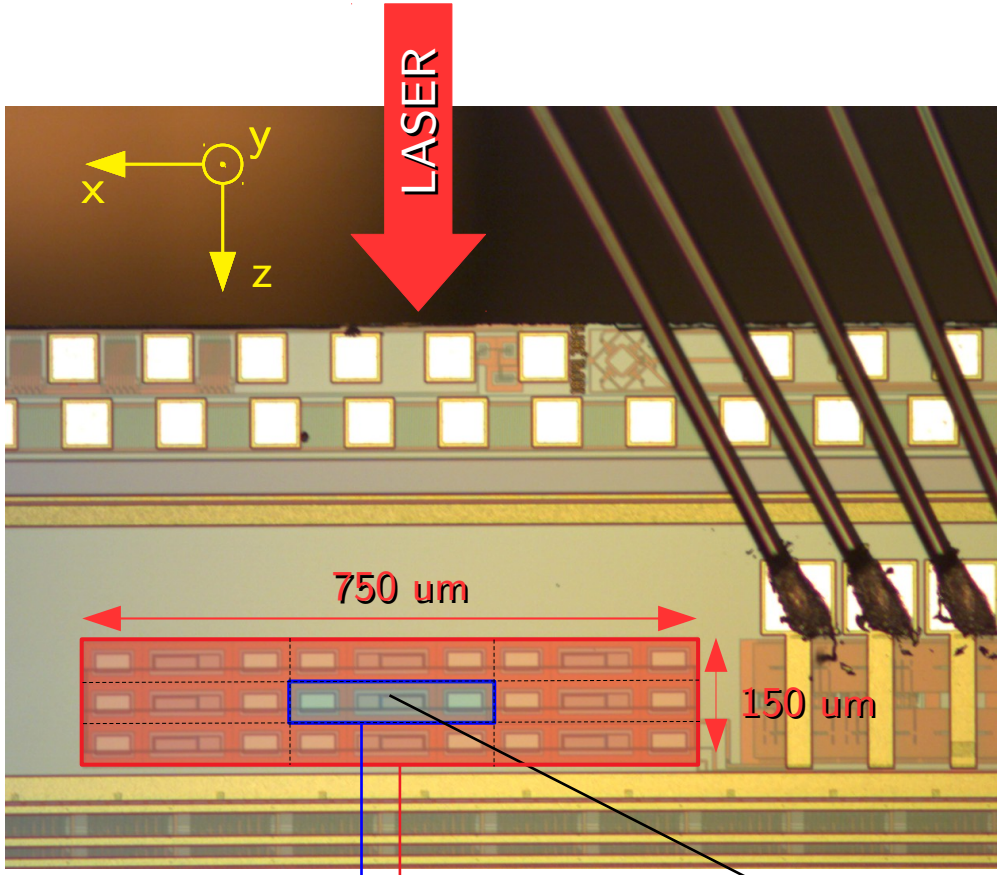
TCT setup

- DUT mounted vertically to reduce effects of swinging stages
- PCB with controlled impedance traces and correct termination to remove signal reflections

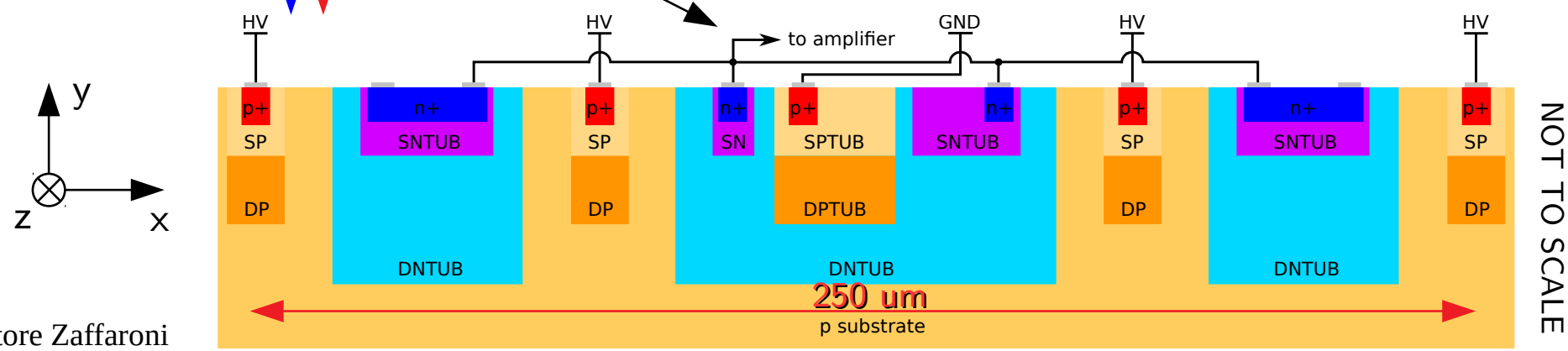




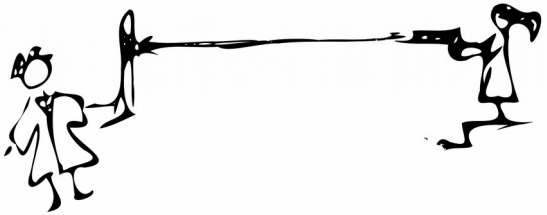
H35DEMO test structures



- In the periphery of the chip
- 3x3 pixel matrix (just the sensor diodes)
- Outermost pixel cathodes are connected together
  - 2 channels (central and external)
- Top bias

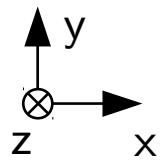


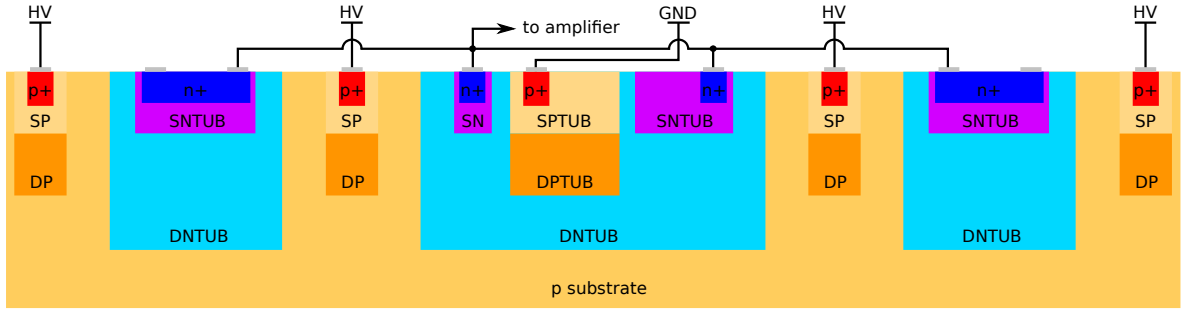
Irradiation campaigns



- Neutrons
  - TRIGA reactor in Ljubljana
    - One irradiation step per sample
  - Annealing
- Protons (measurements at Uni. Bern and Uni. Geneva)
  - BERN Inselspital cyclotron (16.7 MeV)
    - Multiple irradiation steps per sample
  - PS IRRAD (24 GeV)
    - One irradiation step per sample

eTCT scans



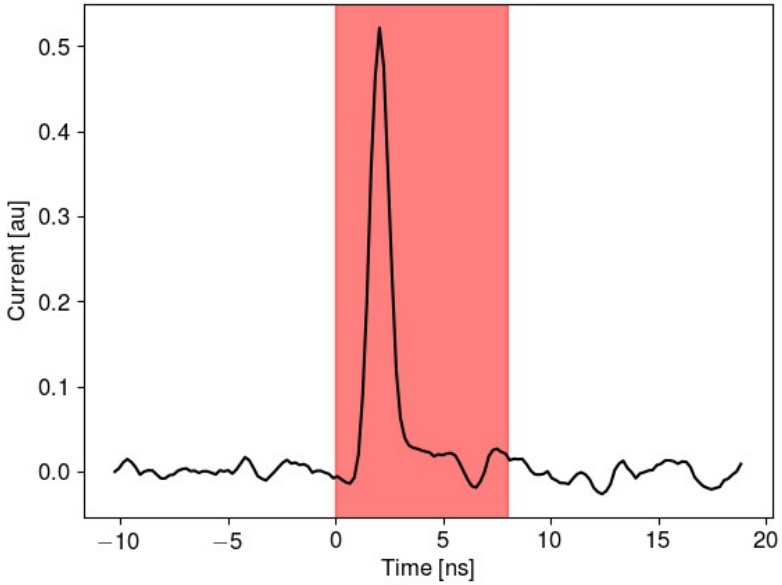


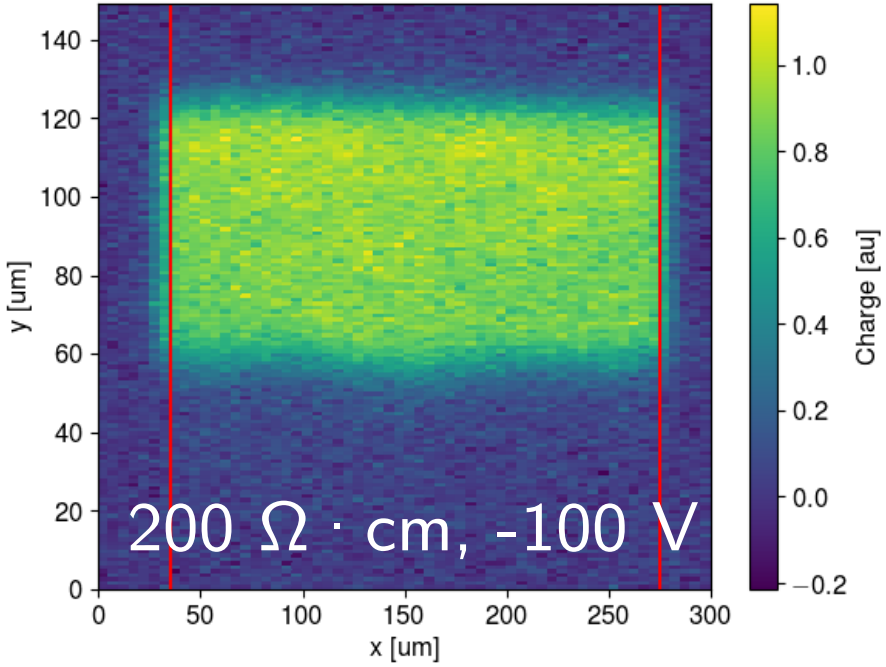
- Edge TCT scans perfomed
- ~150-300x 1 µm steps in y, ~70x 5 µm steps in x
- Several voltage steps (10 to 12 normally)
  - From 0 V to -100 or -165 V
- At each step the signal is averaged 40 times
  - To reduce noise
- All results shown for central pixel

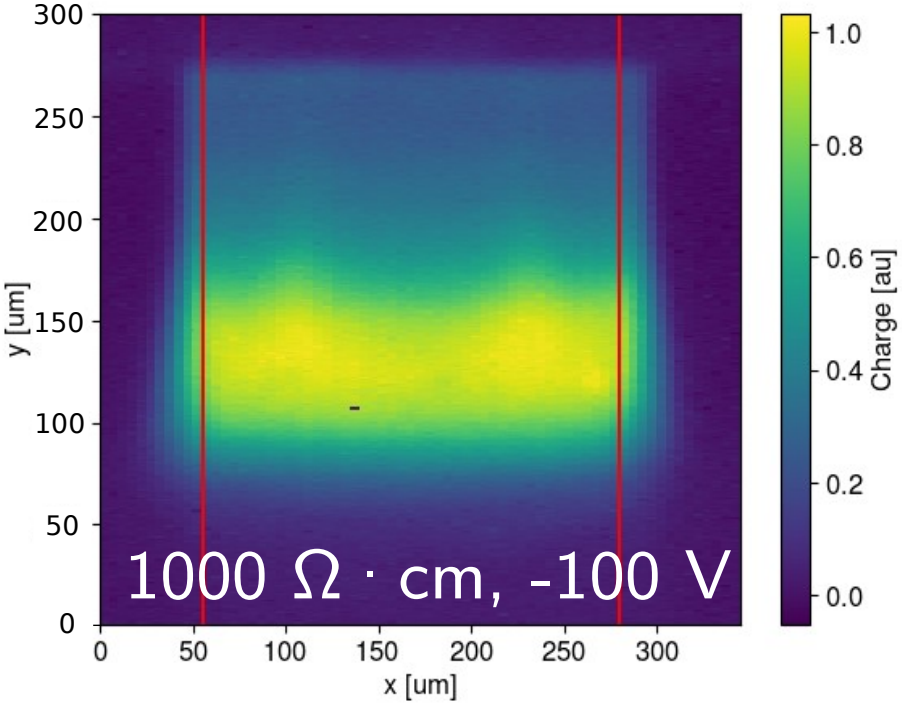
DOI: 10.1088/1748-0221/13/10/p10004

Data analysis - depletion

- Integration of current signal to get the charge
- Selection of the region

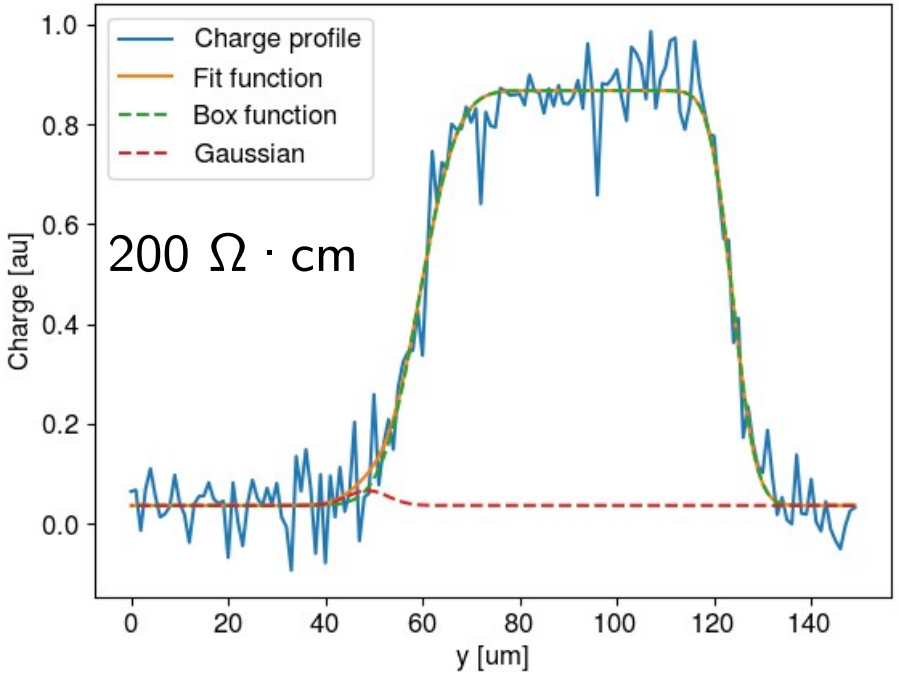


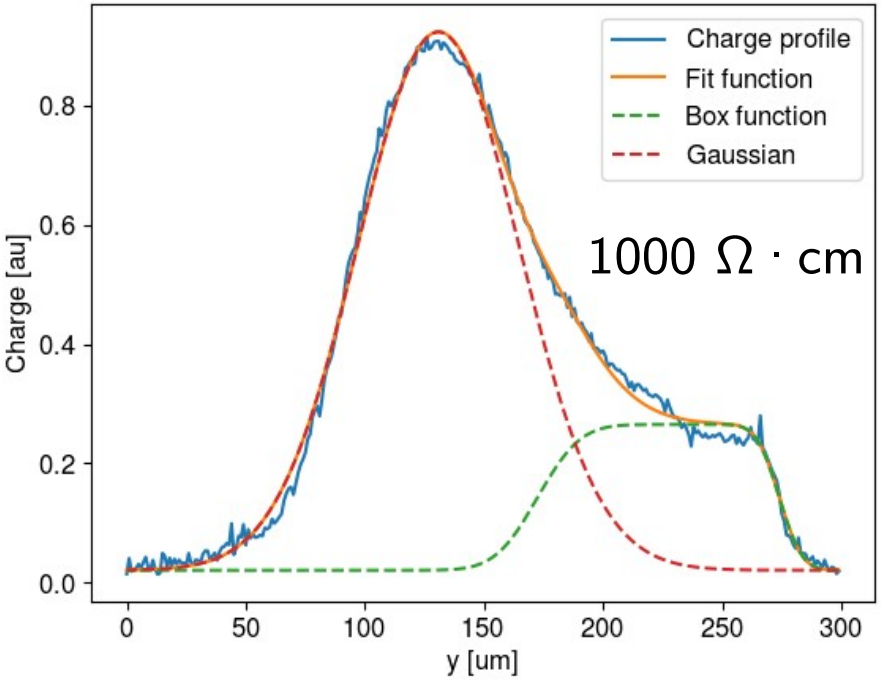




Data analysis - depletion

- Fit of the charge profiles
  - One fit per profile in the ROI
- Two contributions:
  - Smeared box function
  - Gaussian, to model the charge sharing
- Calculation of the FWHM
  - Max of the box function considered

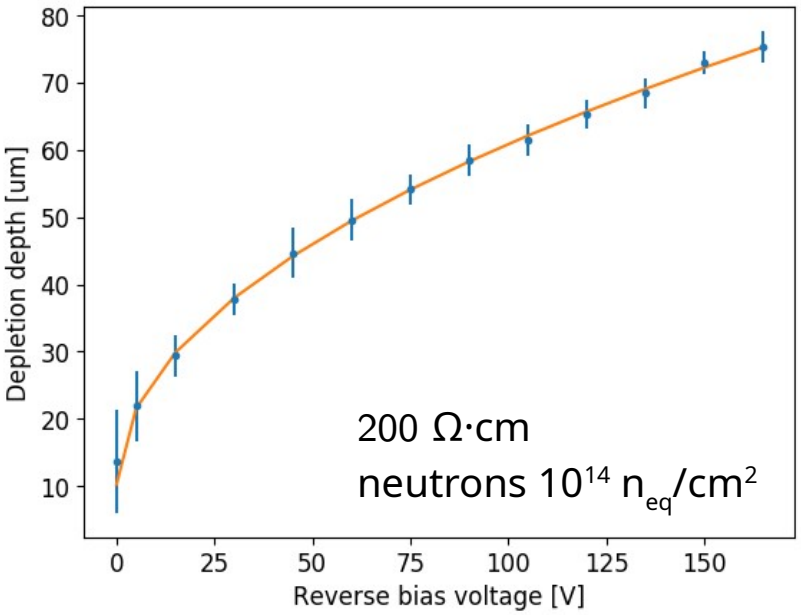




Data analysis - N_{eff}

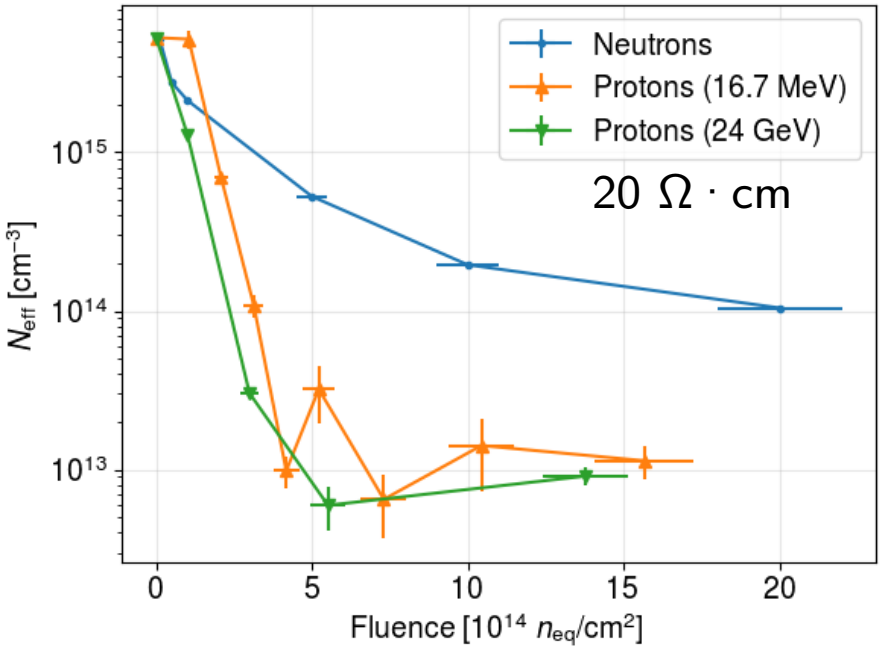
- N_{eff} (effective doping concentration) is calculated by fitting the depletion vs voltage data with:

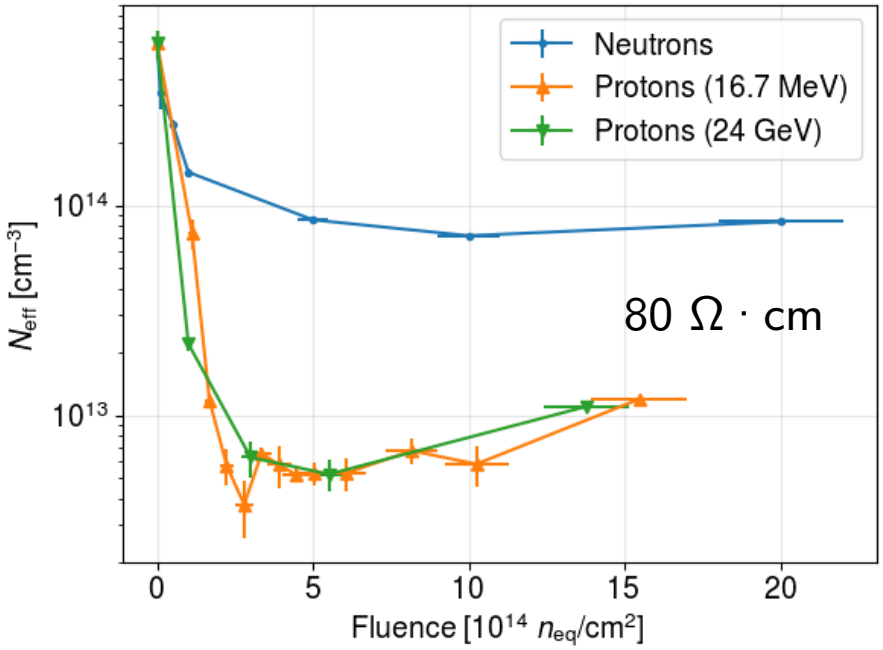
$$d = d_0 + \sqrt{\frac{2\epsilon}{e N_{eff}} V}$$

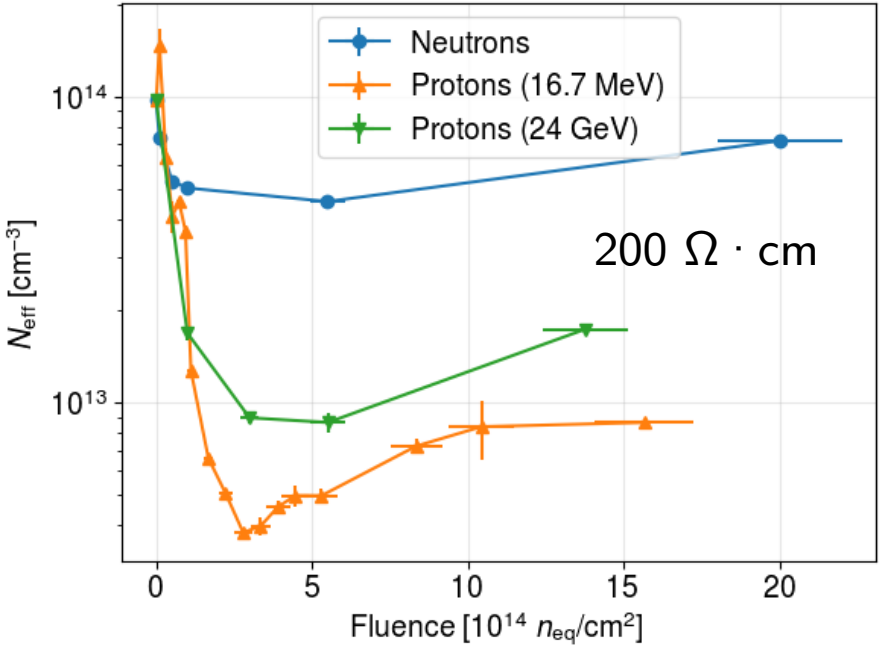


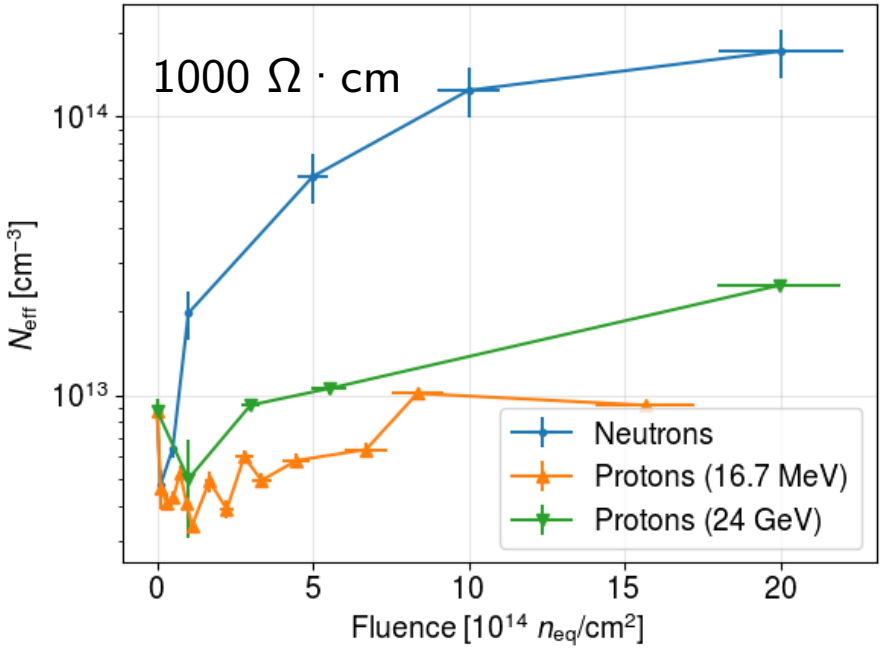
- d_0 and N_{eff} free parameters
  - e electron charge
  - ε silicon dielectric constant
- d_0: sensitive region depth at 0 V bias (due to built-in voltage and n-well finite depth)

Results - N_{eff}







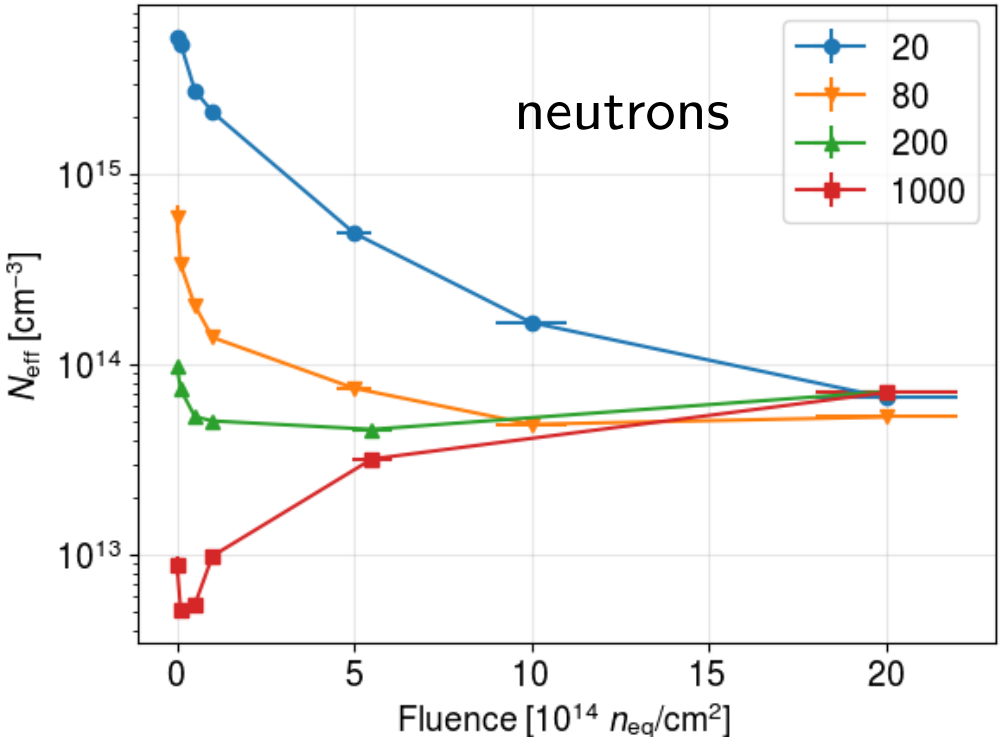


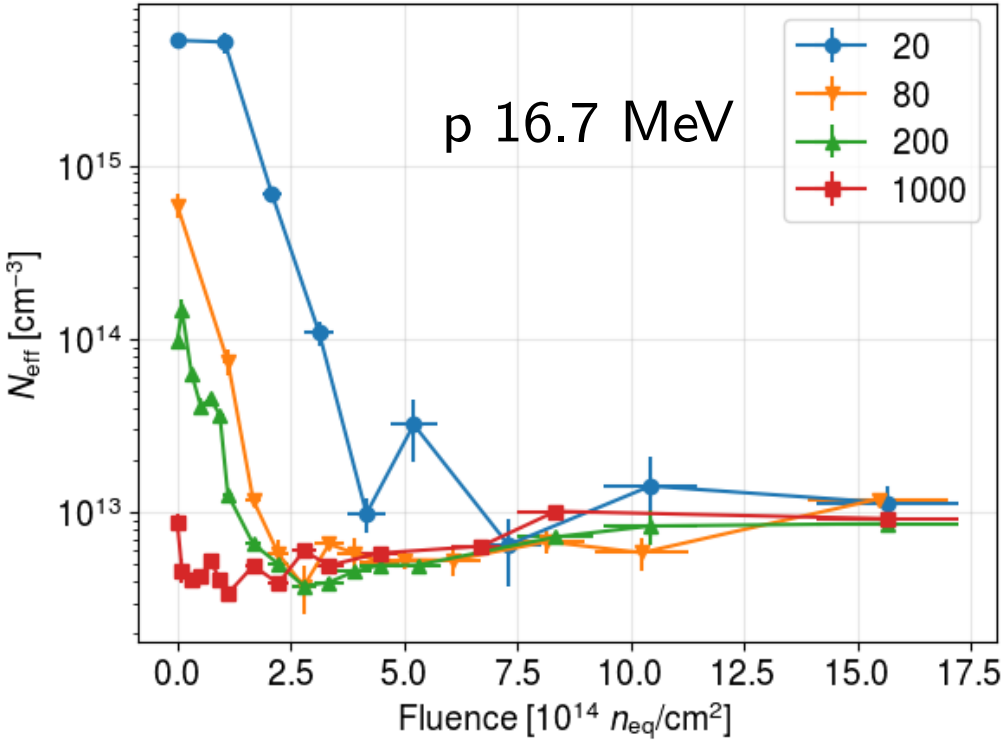
Results - N_{eff}

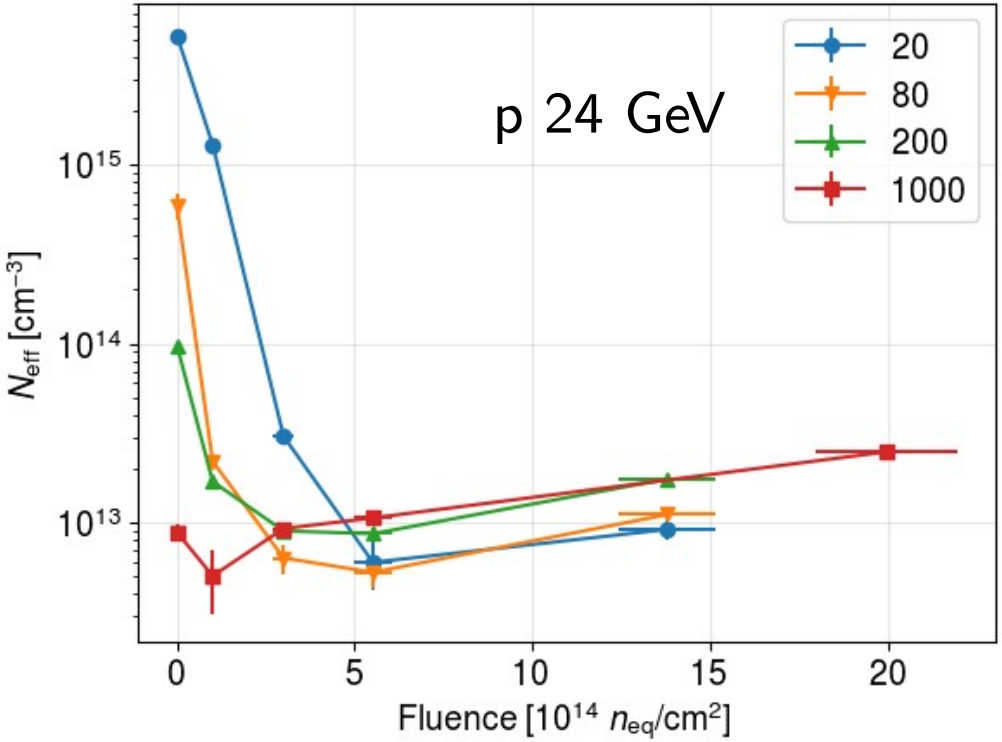
- Significant differences between protons and neutrons and between resistivities
- Initial increase of N_{eff} at very low fluences ($<$1e14 n_{eq}/cm^2, protons) for the 200 $\Omega \cdot$ cm sample
  - Effect competing with initial acceptor removal?
  - Not observed in 1000 $\Omega \cdot$ cm, data not available for 20 and 80 $\Omega \cdot$ cm

Results – N_{eff}

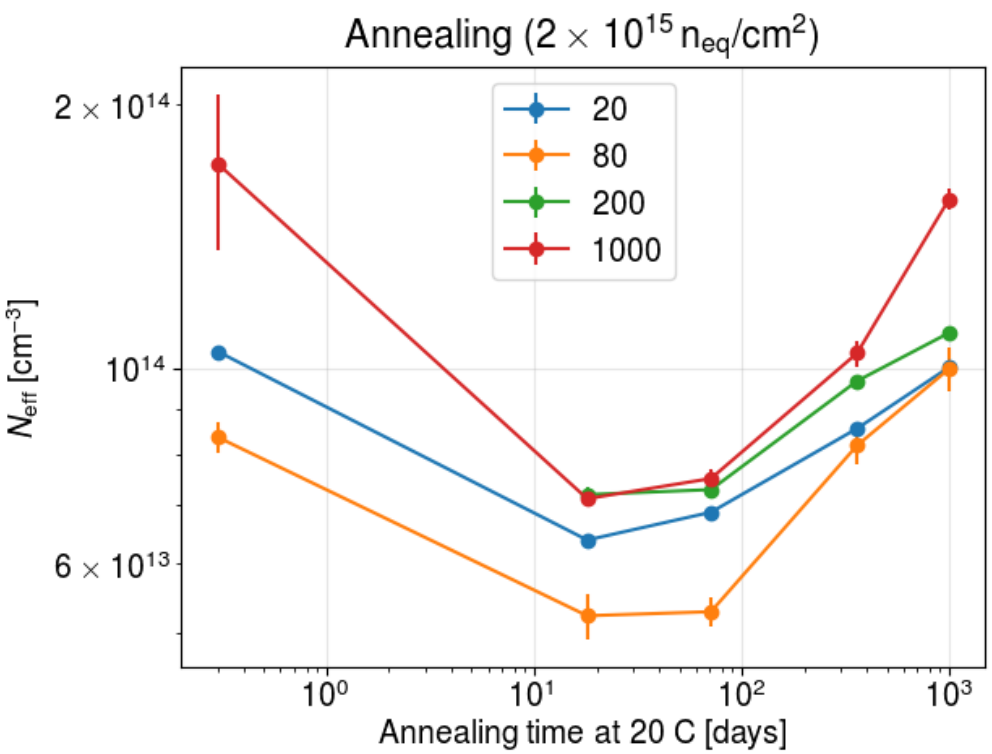
- Plots combined by particle type, for different initial resisitivities
- Tend to the same N_{eff} value







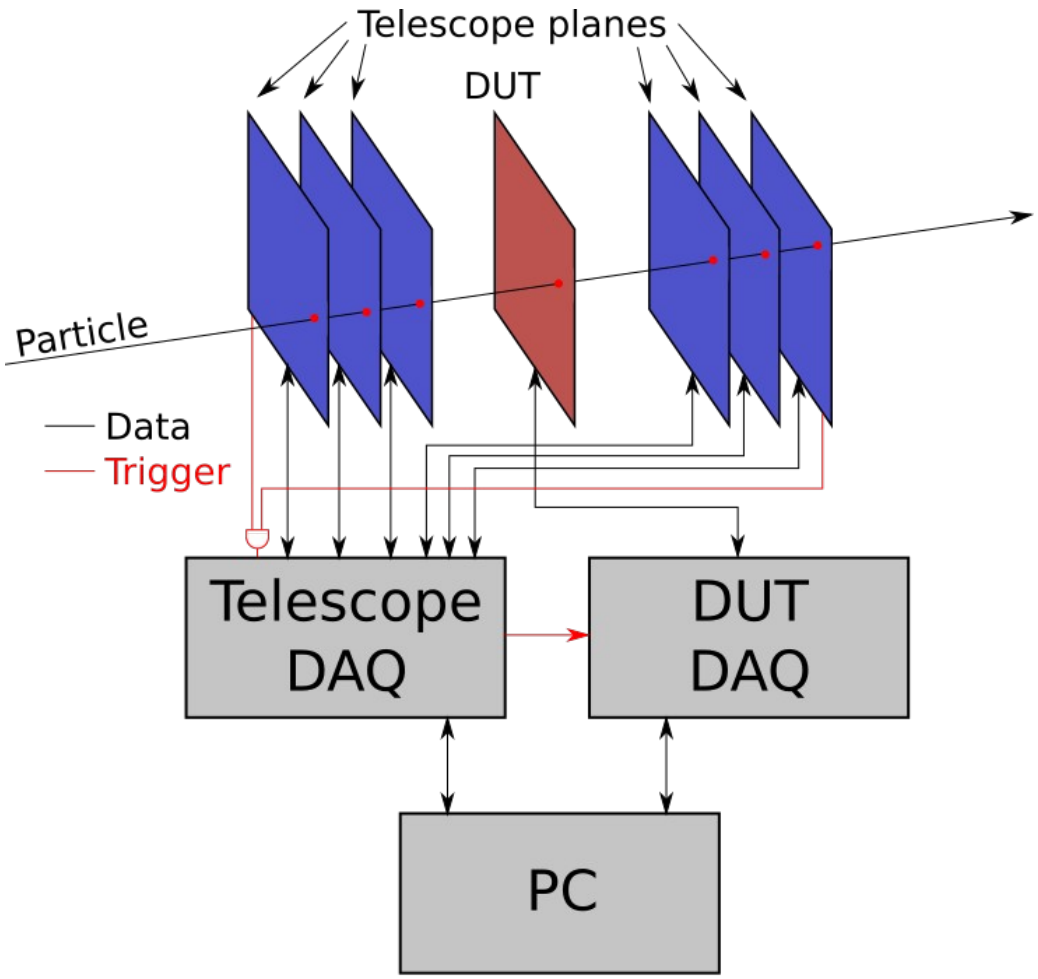
Results - annealing



- Measured on neutron irradiated samples
- Initial beneficial annealing, then reverse annealing
- Measurement will be performed on proton irradiated samples for comparison

Testbeams

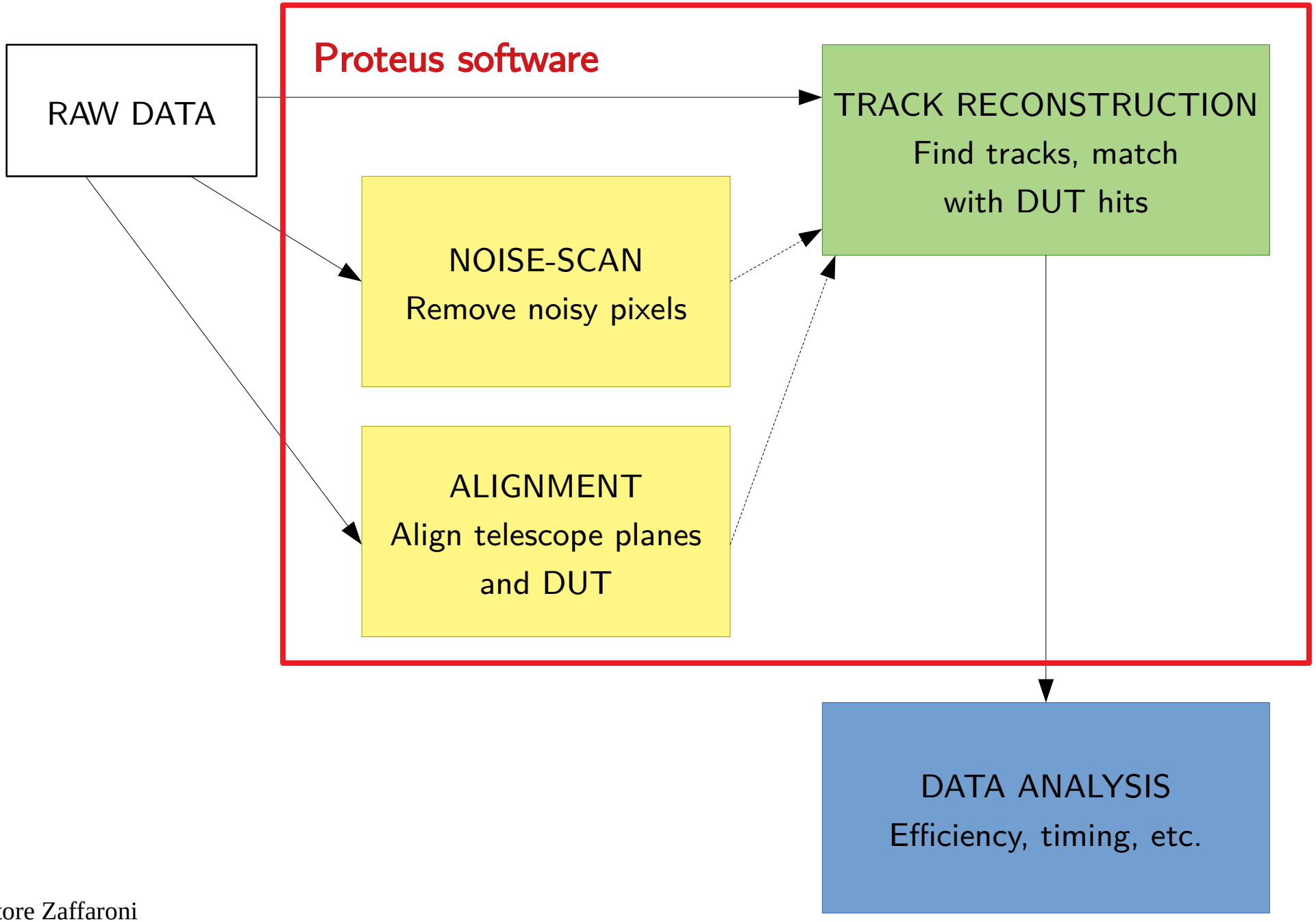
Testbeams



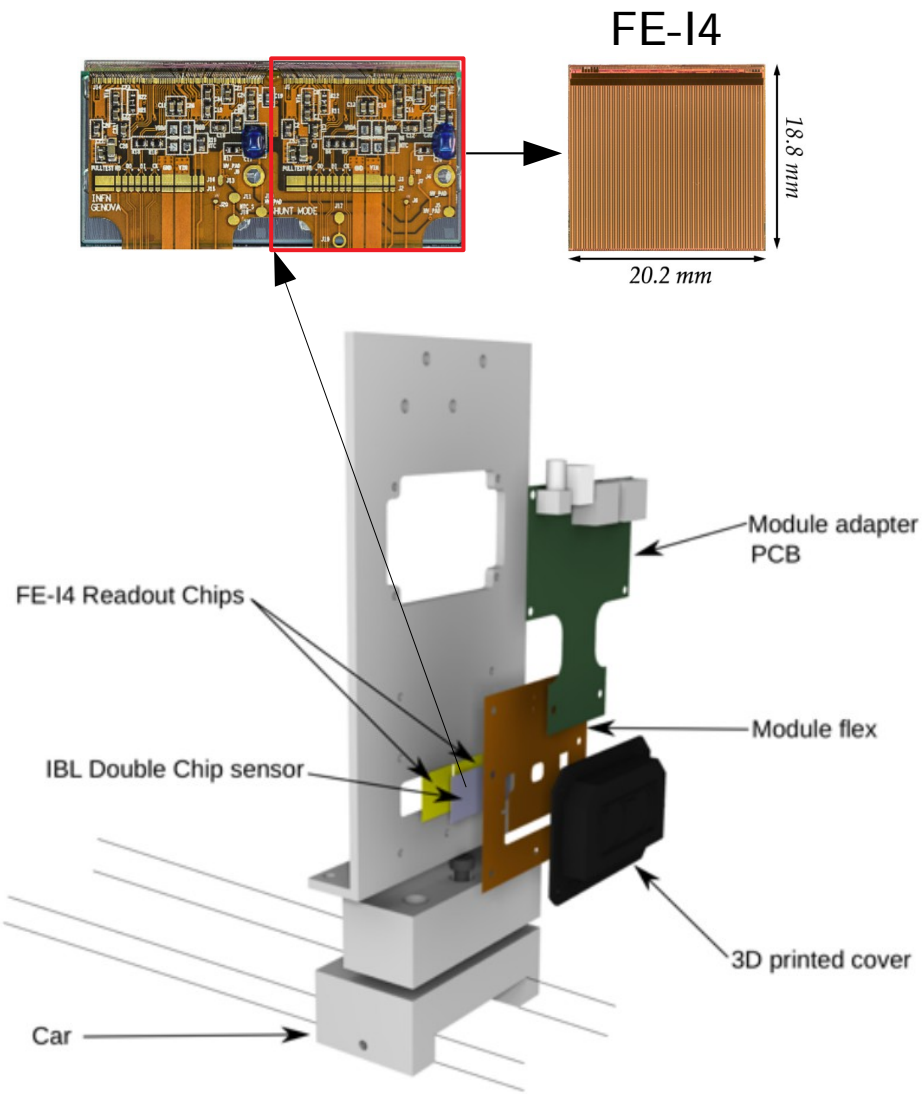
DCS (power, HV, cooling...) not represented

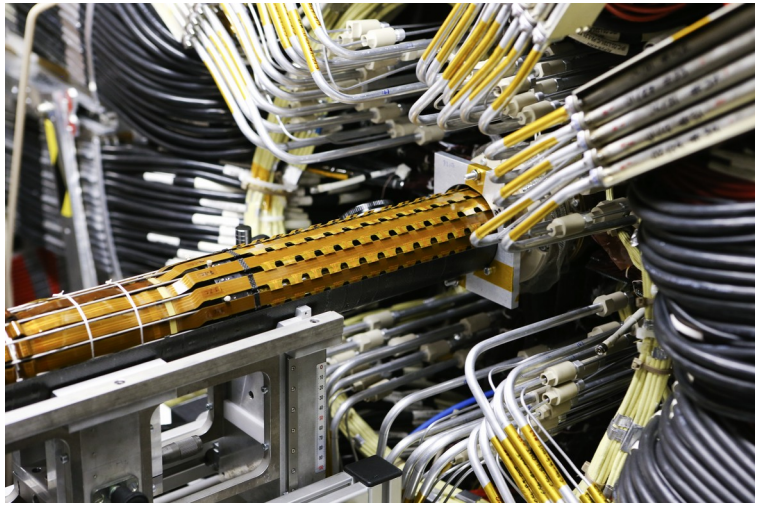
- Telescope: pixel sensors used to measure tracks and generate trigger
- DUT read out at the same time
- Reconstruction and analysis

Reconstruction and analysis



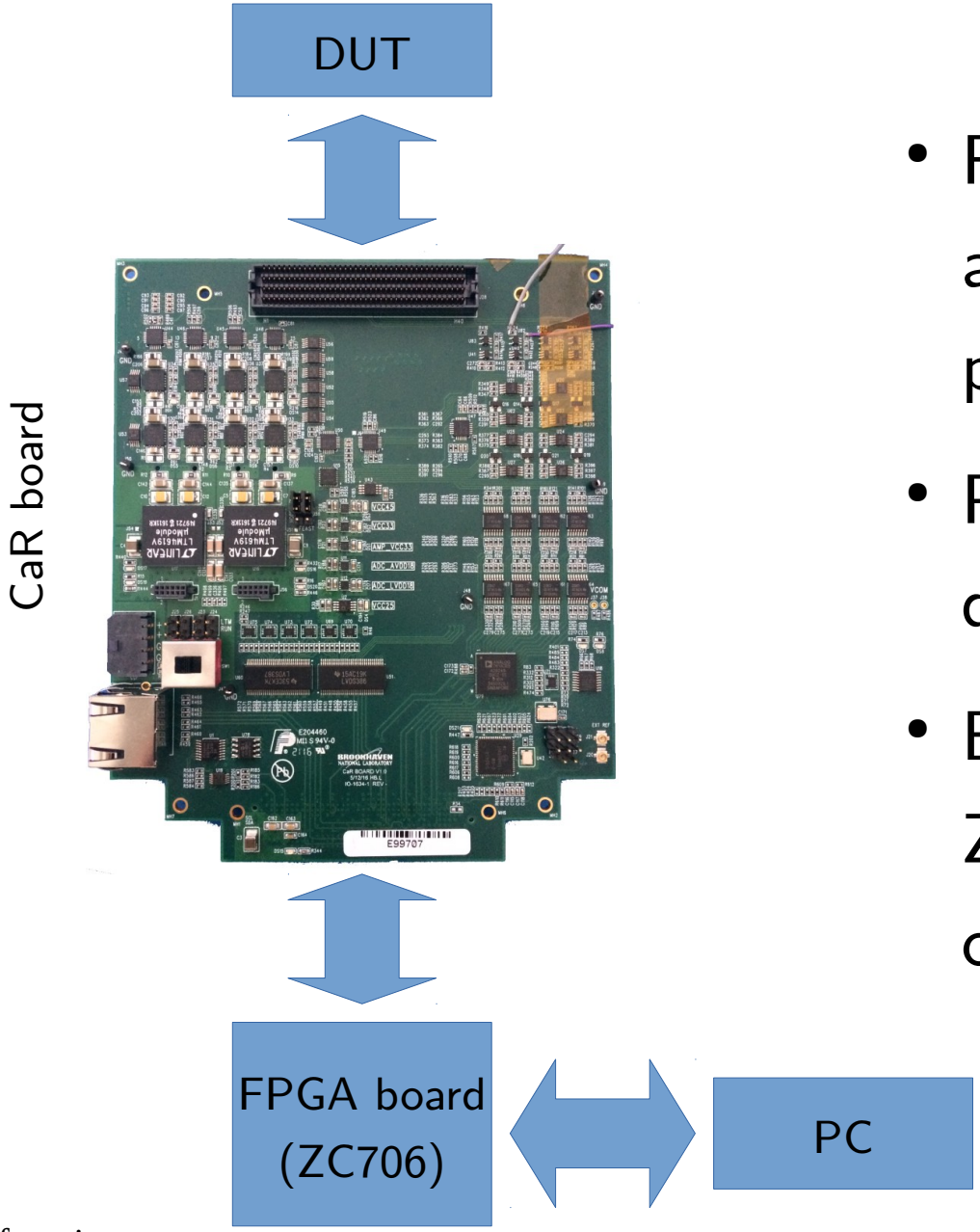
Telescope modules





- Planar modules from IBL
  - Innermost pixel layer in ATLAS
  - Planar silicon pixel sensor
- Read out by the FE-I4 ASIC
  - 50x250 μm² pixels
  - 80 columns, 336 rows

DAQ: CaRIBOu system

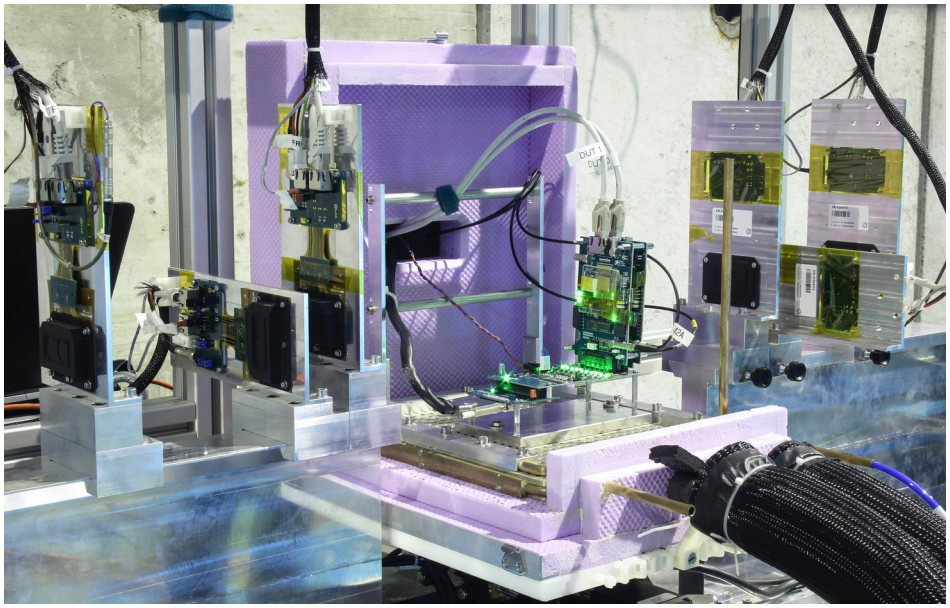


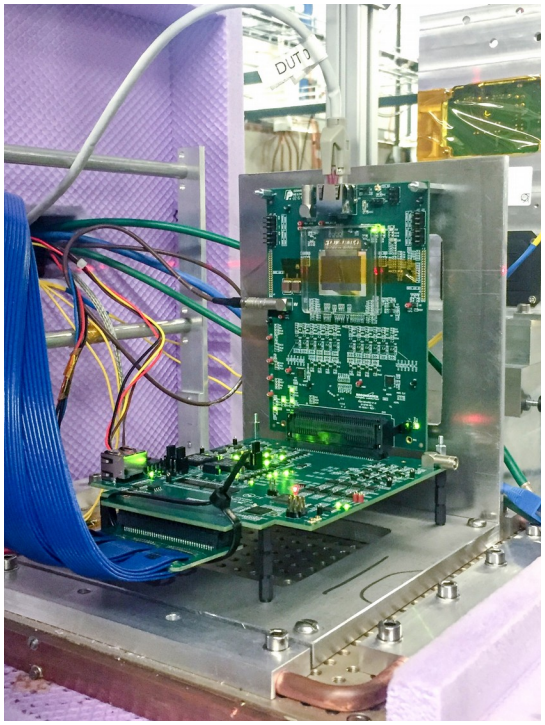
- Read-out system for ITk and CLIC sensor prototypes
- Provides power, HV and data links
- Based on a PC, a Zynq-7000 FPGA and a custom DUT board

DOI: 10.1088/1748-0221/12/01/P01008

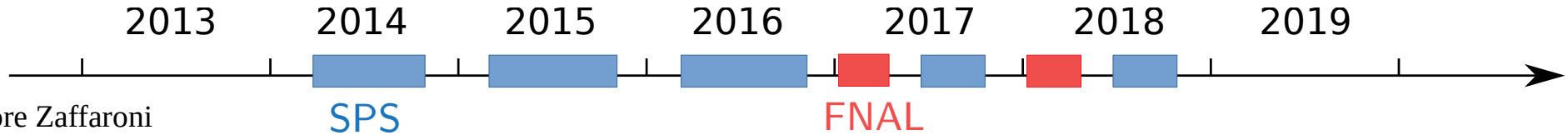
Telescope

- 6 FE-I4 modules
  - Spatial resolution 8x12 um
- Trigger rate up to 4 kHz
- Cold DUT box (down to -20 °C)
- Successfully used in various campaigns (SPS, FNAL) since 2014





DOI: 10.1088/1748-0221/13/02/p02011, 10.1088/1748-0221/13/12/p12009

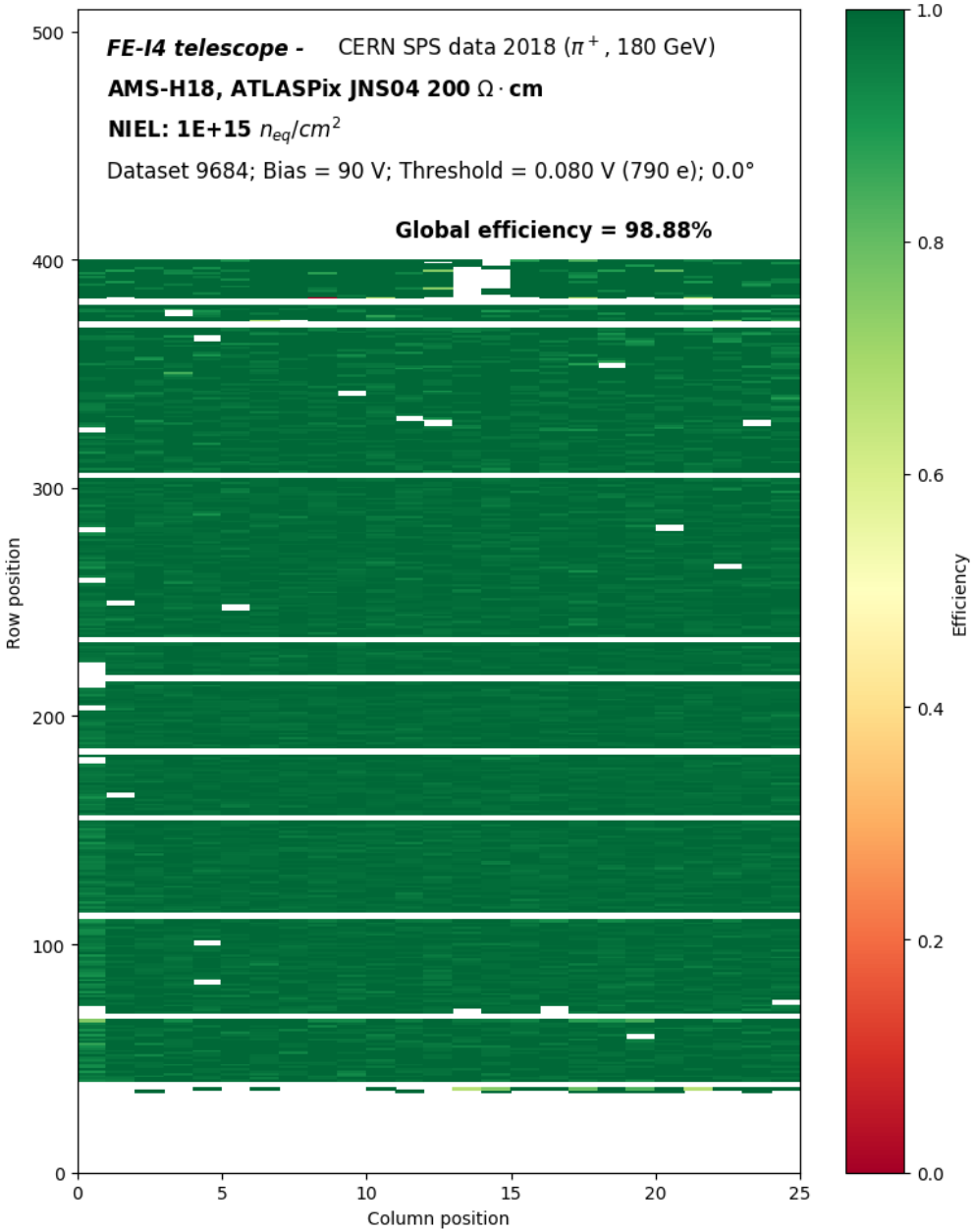


Measurement campaign

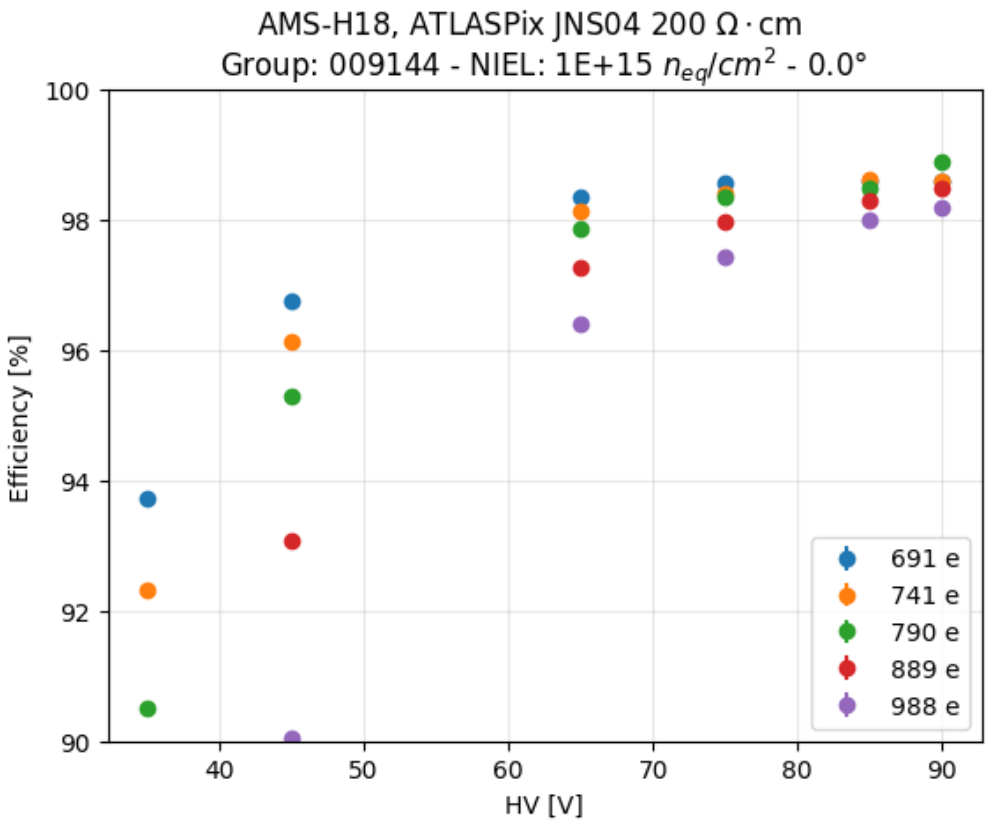
- Data acquisition at CERN SPS (06-10/2018)
- Simple matrix of ATLASPIX1
- Bias voltage and threshold scans
- Different irradiations
  - Protons (while operating the sensor)
  - Neutrons

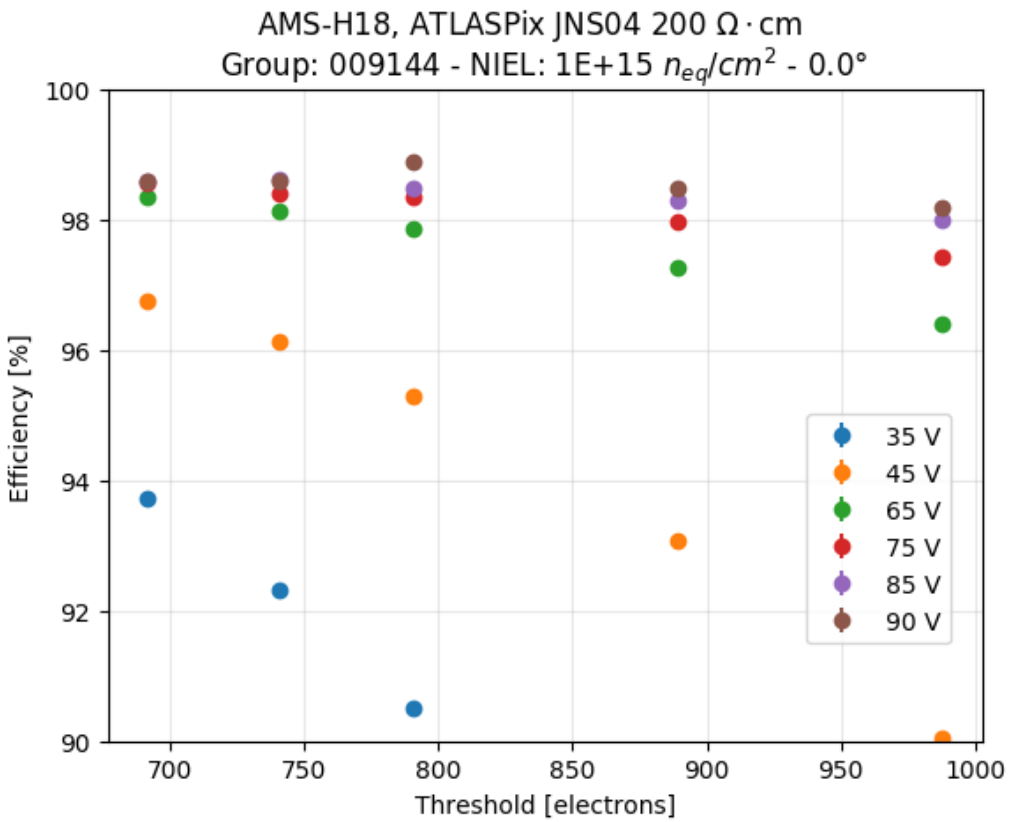
Testbeam results

- High efficiency after irradiation
- Noisy pixels and neighbors masked
- Lines masked due to issues in row circuitry
  - Identified and solved in subsequent prototype submission



Testbeam results

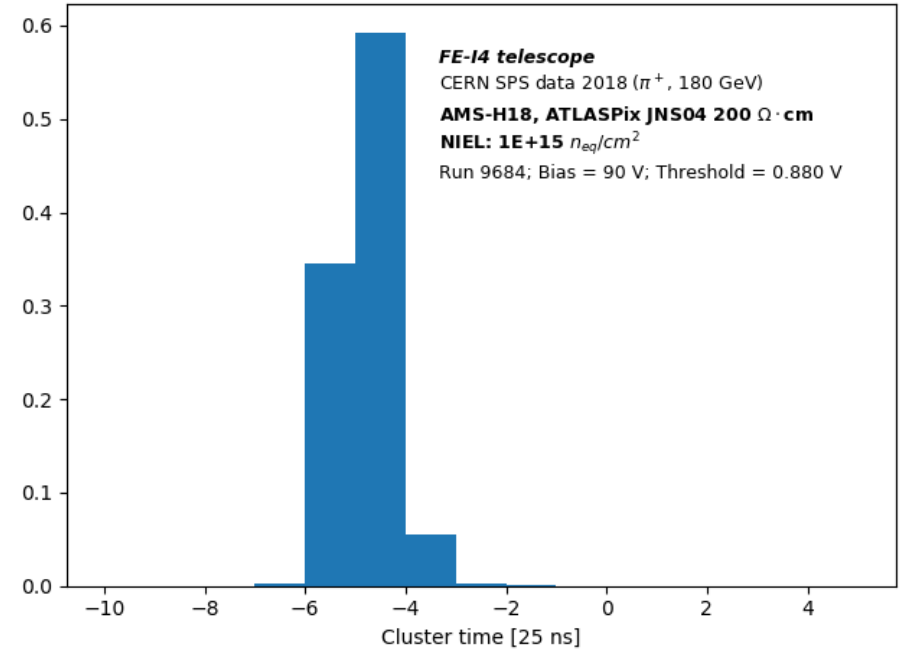


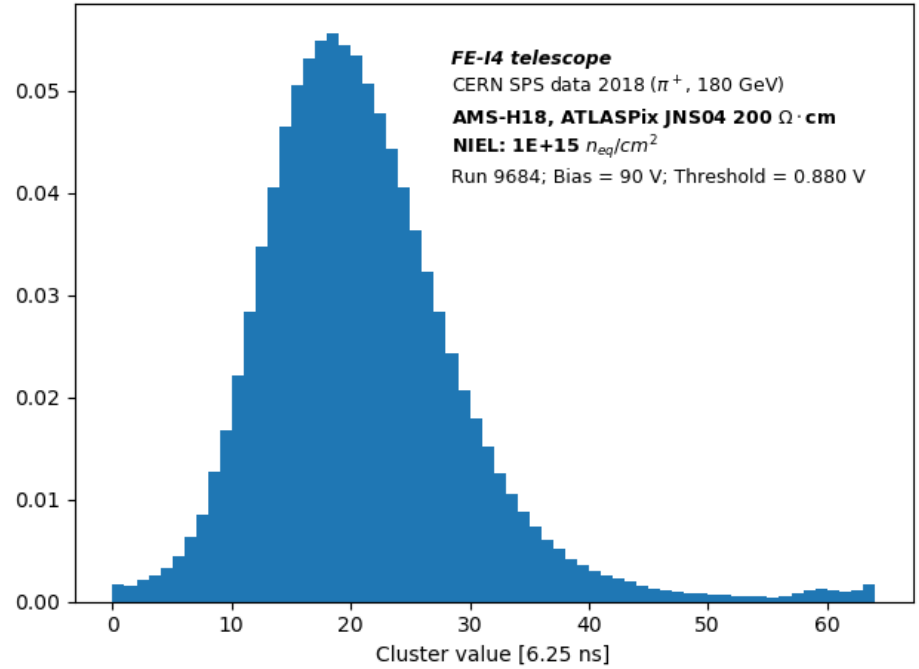


- Efficiency vs bias voltage (left) and threshold (right)
- Above 98% for a wide range of parameters

Testbeam results

- Cluster time: difference between trigger time (telescope) and cluster time (DUT)
  - 1 bin spread given by the telescope
- Cluster value: time over threshold





Comments

- Testbeams show excellent performance of ATLASPix1 before and after irradiation
  - Efficiency up to ~99% after 10^{15} n_{eq}/cm^2
  - Excellent timing performances
- Identified issues in the circuitry, feedback provided to the designers

Conclusions

- TCT measurements
  - Initial acceptor removal observed after proton and neutron irradiation
  - Beneficial and reverse annealing observed for neutrons
  - Significant differences between neutron and protons effects
- Testbeams
  - High, uniform efficiency over a large pixel matrix after irradiation
  - Very good timing performances
- Excellent results for fully monolithic pixel sensors!

Thank you!