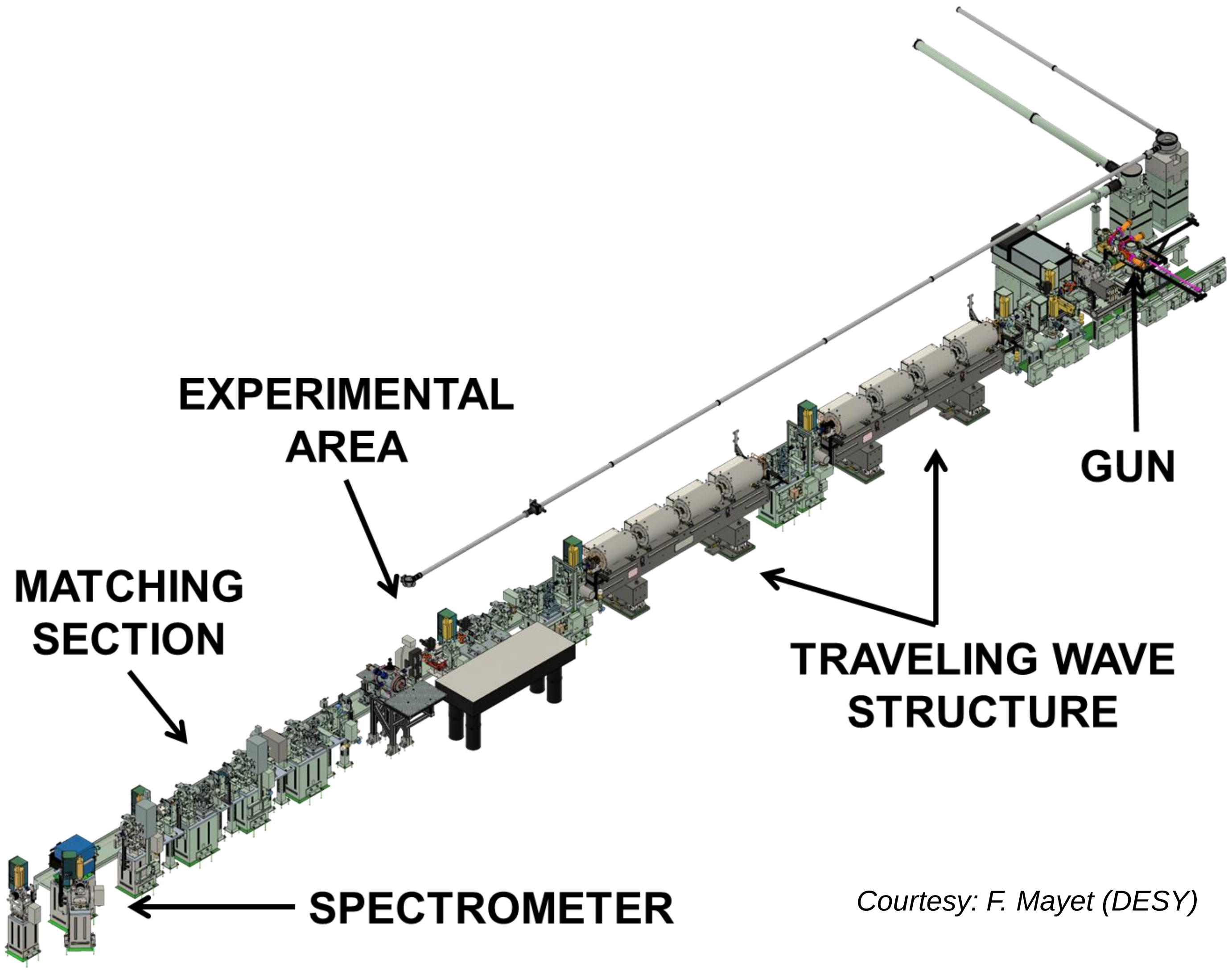
Development of a Beam Profile Monitor based on Silicon Strip Sensors for Low-Charge Electron Beams at ARES

STRIDENAS - a Silicon Strip Detector for Novel Accelerators at SINBAD

Sonja Jaster-Merz (DESY)
Elba, 19.09.2019

Introduction

See talk:
B. Marchetti “SINBAD-ARES - A Photo-Injector for external Injection Experiments in novel Accelerators at DESY”



Courtesy: F. Mayet (DESY)

- Injection into novel accelerators
- Spectrometer setup to measure energy
- Special beam profile monitor for low-charge beams

ARES parameter	
Bunch duration	fs to sub-fs
Energy	52 MeV – 155 MeV
Charge	0.3 pC – 30 pC
Repetition rate	50 Hz

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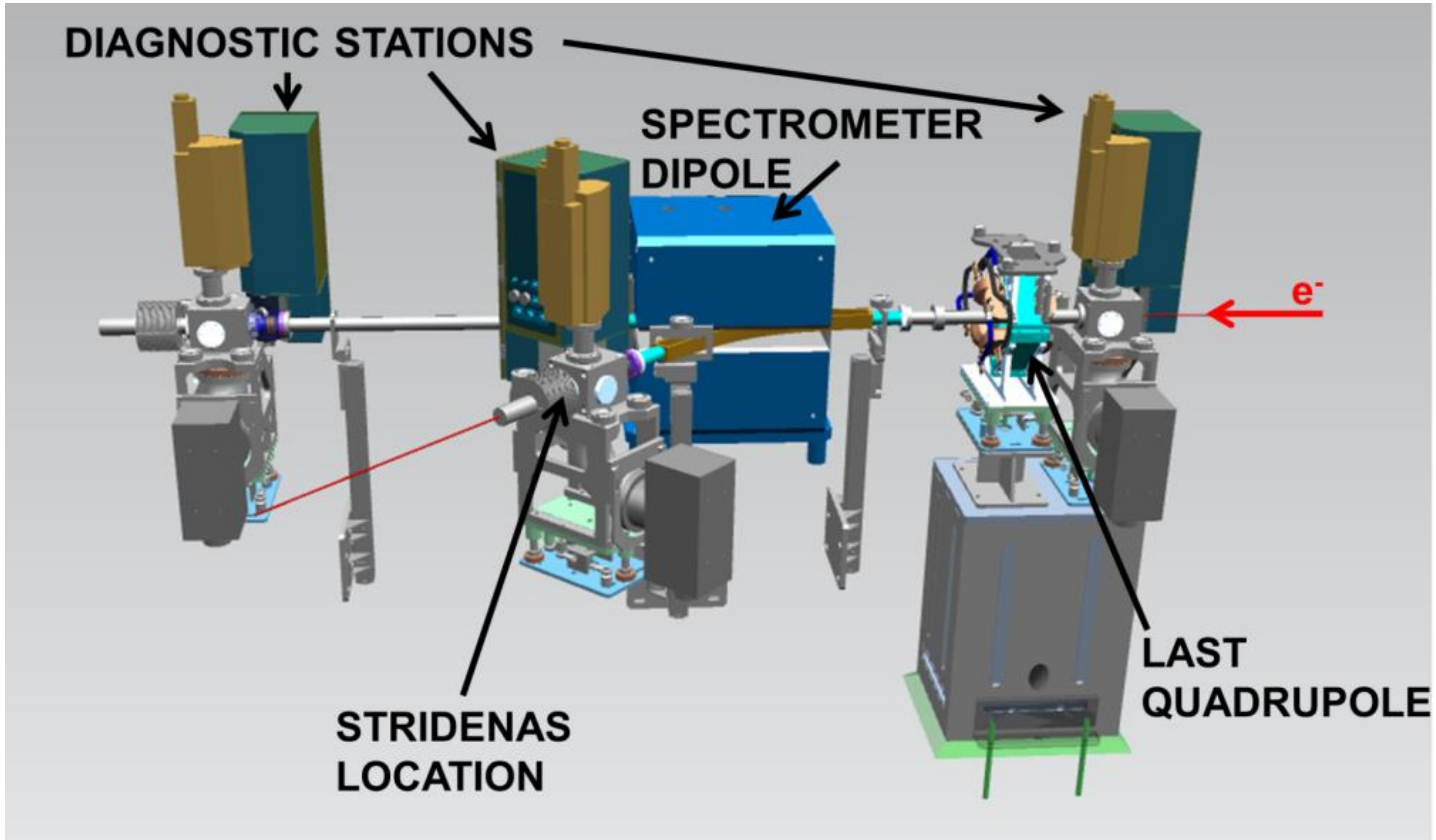

Courtesy: J. Hauser (DESY)

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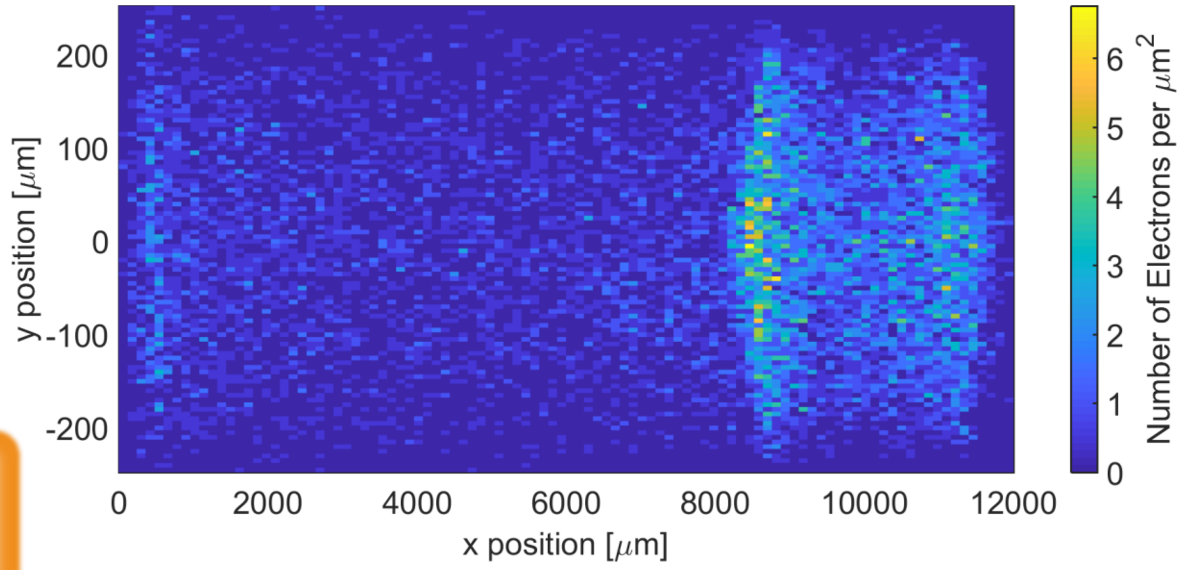
Possible Electron Distribution

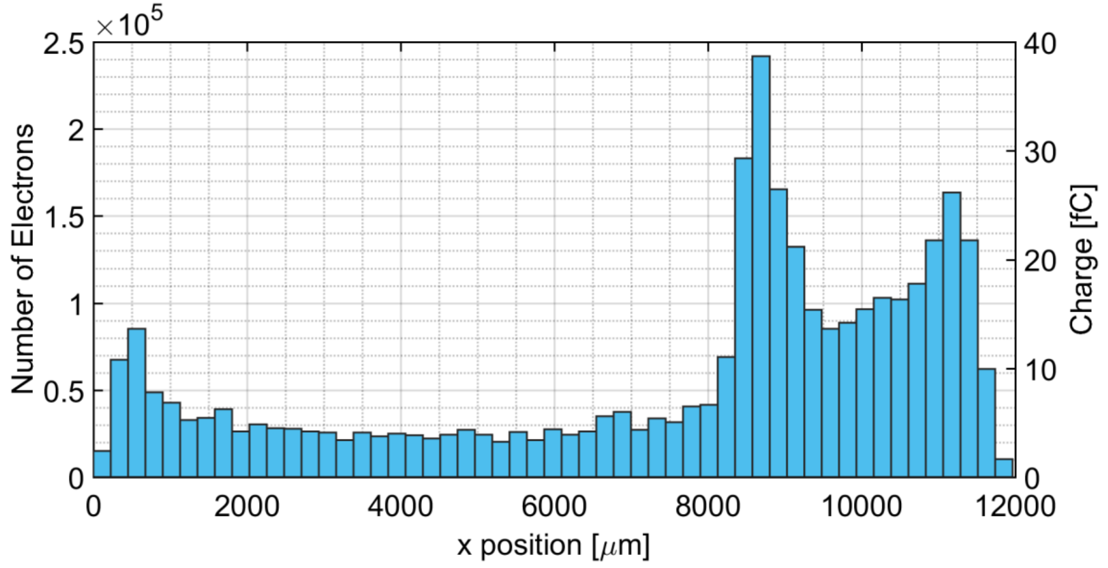
At spectrometer screen

- Small apertures → low charge (< 0.5 pC)
- For a possible ACHIP working point:
  Less than 7 electrons per µm²

Parameter	Unit	Value
Charge	pC	0.5
Energy	MeV	52
Full Bunch Duration	ps	5.6
σ_t	ps	1.2
Full Width on Screen Δx	mm	12
σ_x	mm	3.4
Full Height on Screen Δy	mm	0.5
σ_y	mm	0.1

See poster:
F. Mayet "Status report on the dielectric laser acceleration experiments at the SINBAD/ARES linac"





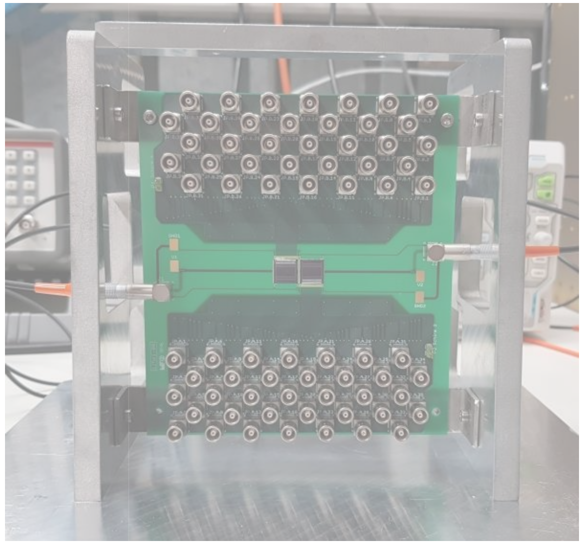
STRIDENAS
dedicated beam profile monitor for low-charge beams

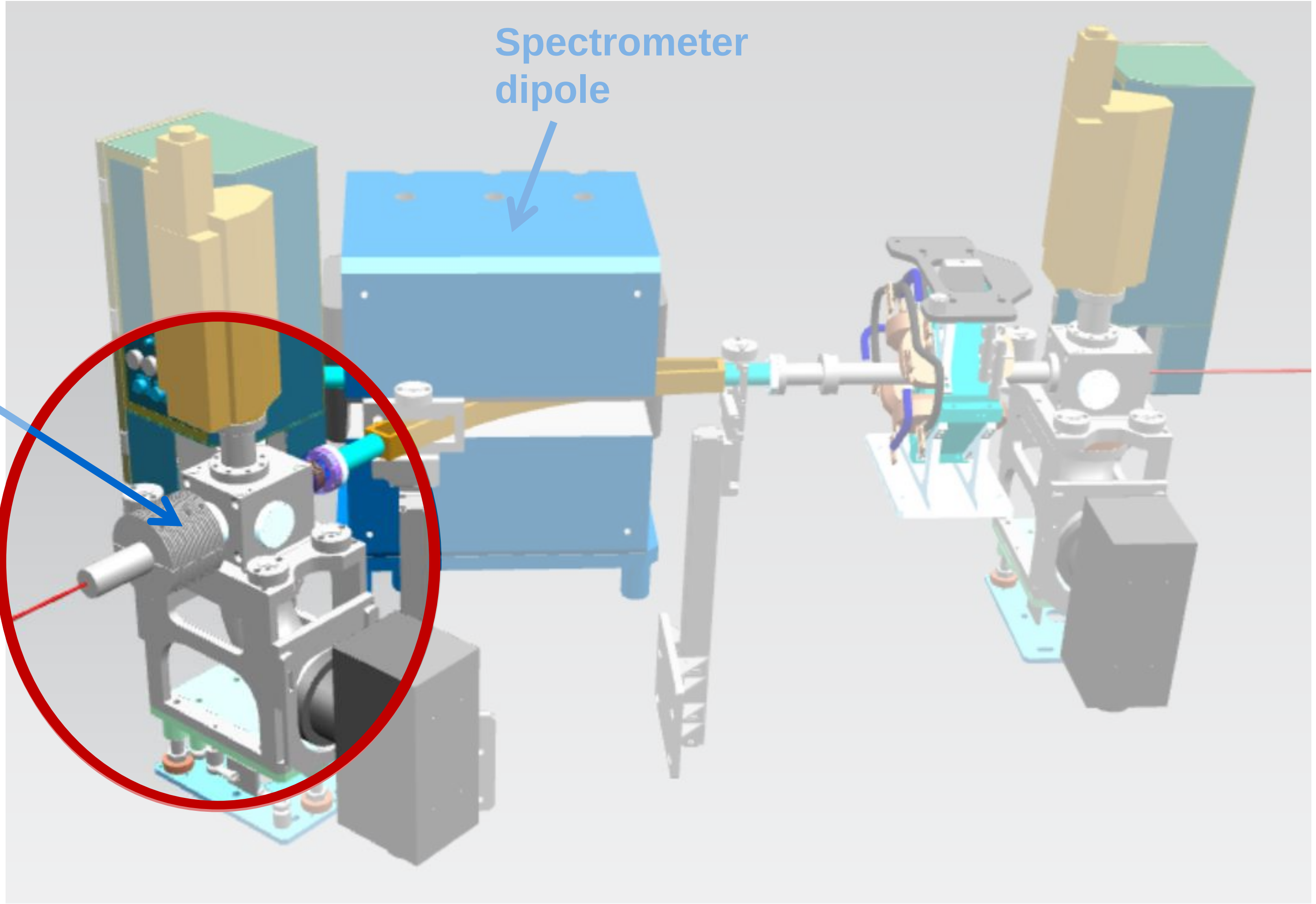
Courtesy: F. Mayet (DESY)

STRIDENAS

A Silicon Strip Detector for Novel Accelerators at SINBAD

Location of
detector





DESY Collaboration (MPY-1 and FH-ATLAS)

MPY-1

Sonja Jaster-Merz

Florian Burkart

FH-ATLAS / FLC

Marcel Stanitzki

Jan Dreyling-Eschweiler,
Uwe Kraemer, Lennart Huth

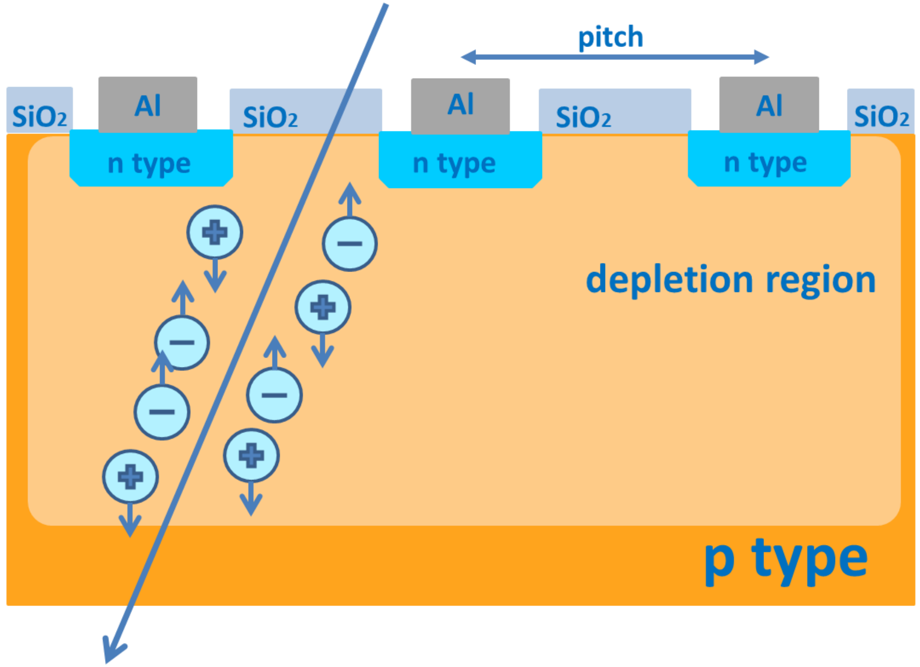
Further support from DESY technical groups

University of Hamburg
Detector development group of Erika Garutti

Silicon Strip Sensors

Theory

- Working principle: pn-junction
- To gain spatial resolution: segmented electrodes
  p-type bulk and n-type implants
- Electrons and photons interact with the sensor material and deposit energy, follows a Landau distribution for MIPs
- Production of electron-hole pairs (~80 per µm and MIP)
- Under reversed bias charge carriers drift towards the electrodes and start the signal current
- Geometric resolution: $\boldsymbol{\sigma} = \frac{\textbf{pitch}}{\sqrt{\mathbf{12}}}$
- Transverse signal spread due to
  - Thermal diffusion
  - Plasma effect (for high charge carrier densities)



$$w \sim \sqrt{V_{ext}}$$

w – depletion width (asymetrirally doped)
V_{ext} – external potential

STRIDENAS Challenges

LOW CHARGE DENSITIES AT ARES → USE SILICON SENSORS FROM HEP EXPERIMENTS?

Challenges

- Sensors usually used for **single particle detection**
- At ARES an **intensity ~10^5 times** higher is expected
  - Regime where sensor behaviour is not well studied
  - HEP signal amplification done with an ASIC - not designed for such intensities
  - ASIC not ultra-high vacuum compatible

Approach

SENSOR
from HEP experiments

+

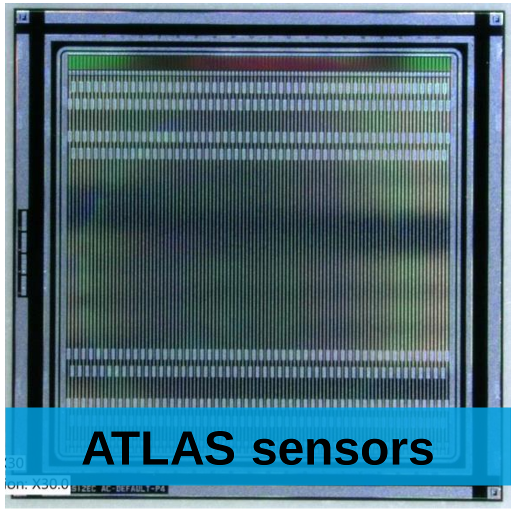
READOUT ELECTRONICS
for higher charges

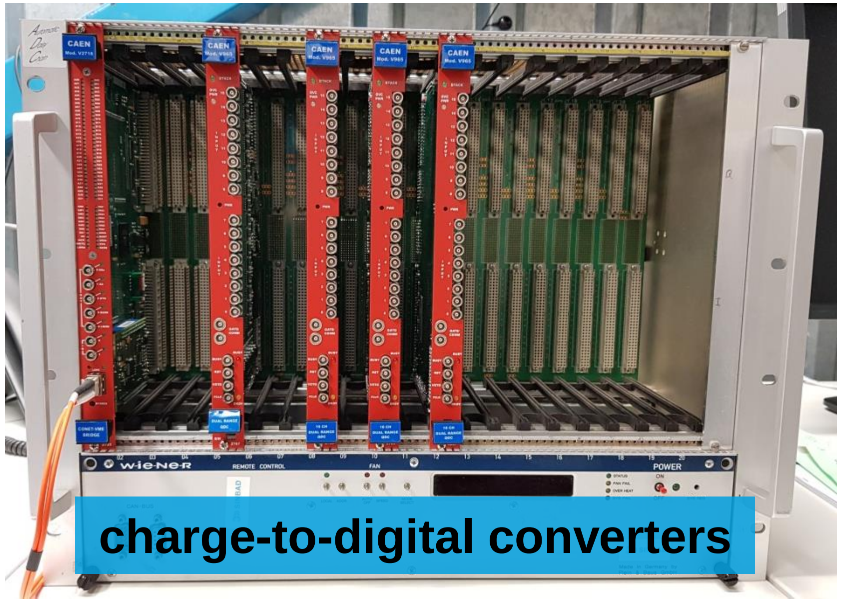
STRIDENAS Specifications

Requirements

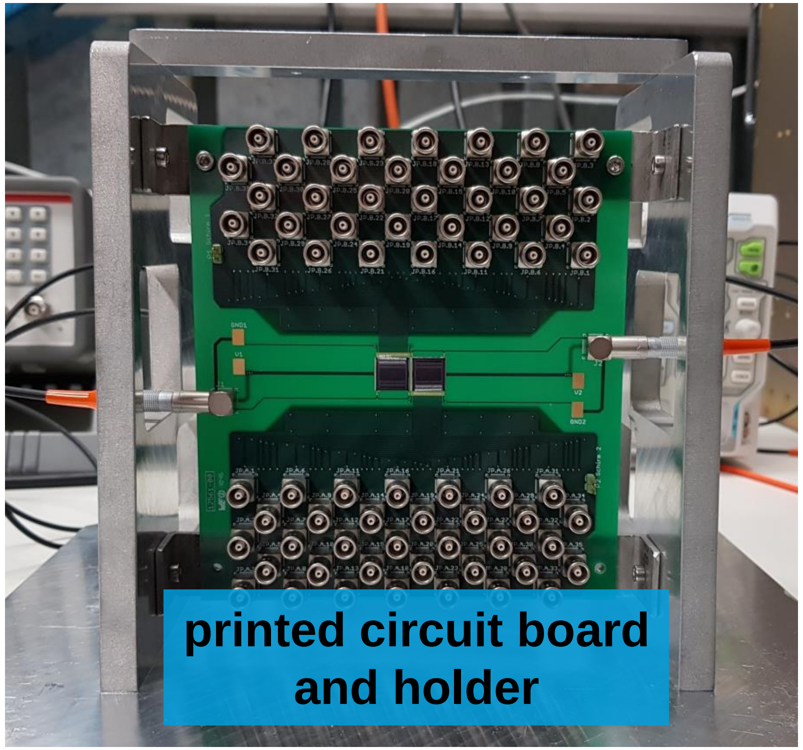
- Spatial resolution in the 100 µm range
- Dynamic charge range after the spectrometer dipole between ~1 fC and ~40 fC per readout channel
- Needs to withstand ~10^6 electrons per shot
- Compact and shielded from ambient light
- Remotely controllable and ultra-high vacuum compatible final setup

- **First:**
  Prototype outside vacuum
  + test of the components
- **Then:**
  Vacuum compatible design


ATLAS sensors



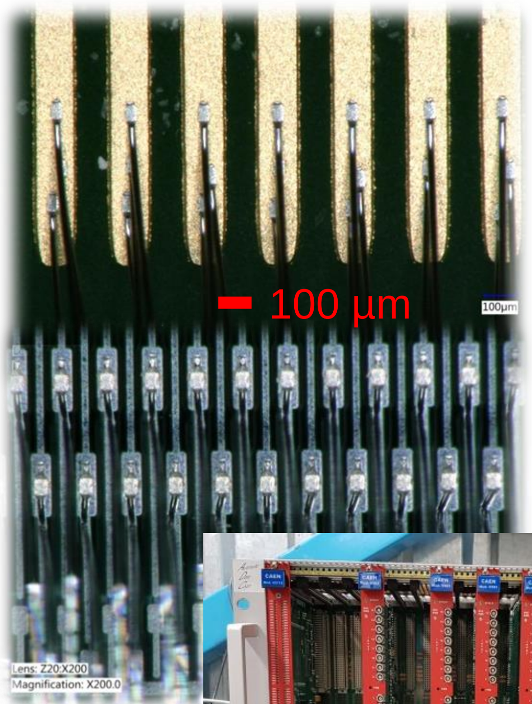
charge-to-digital converters

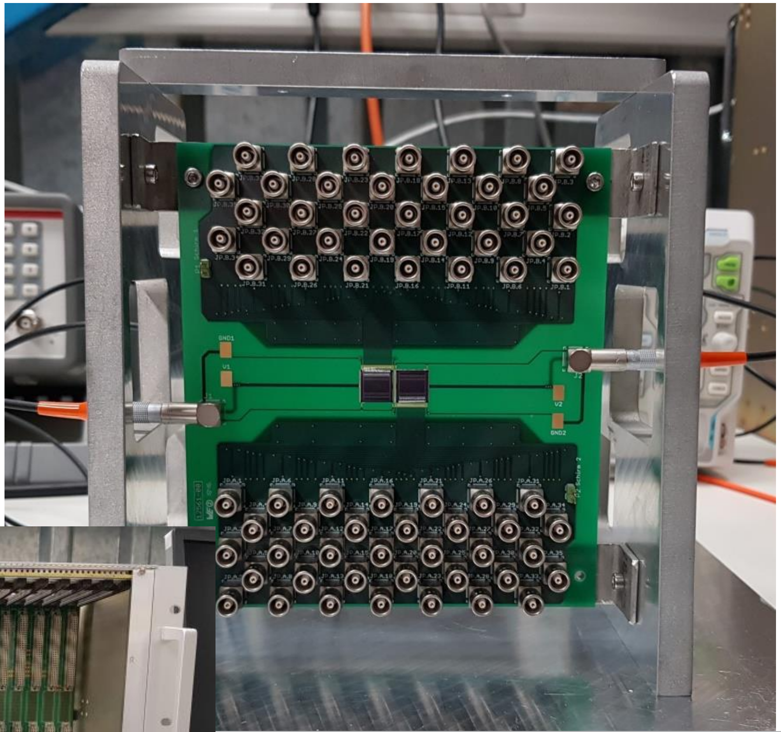

printed circuit board and holder

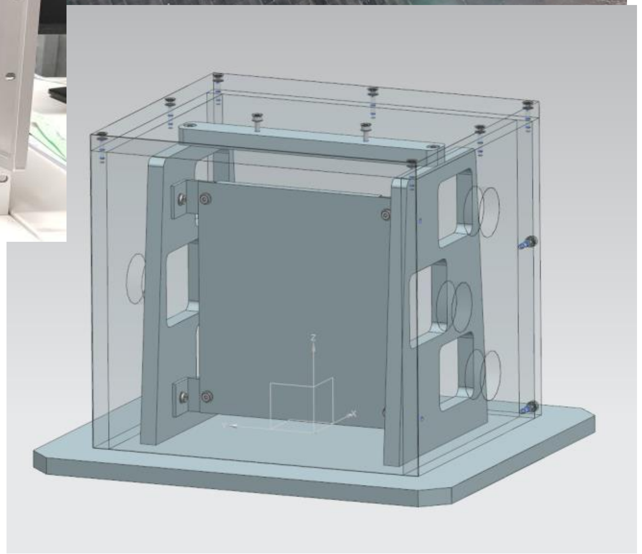
STRIDENAS

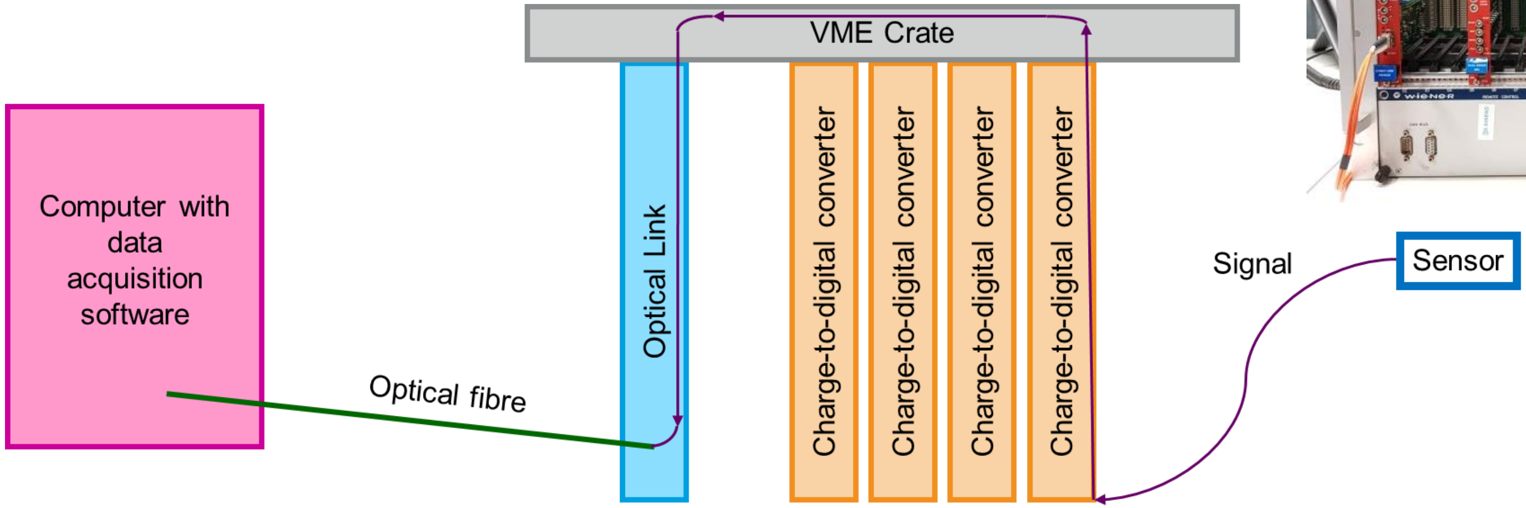
Components

- PCB with 64 readout channels
- Sensors glued and bonded to PCB
- PCB can be placed in a dedicated holder
- CAEN charge-to-digital converters
  - Dynamic range: 0 – 900 pC
  - Dual range: 25 fC and 200 fC resolution









Courtesy: J. Stein (DESY)

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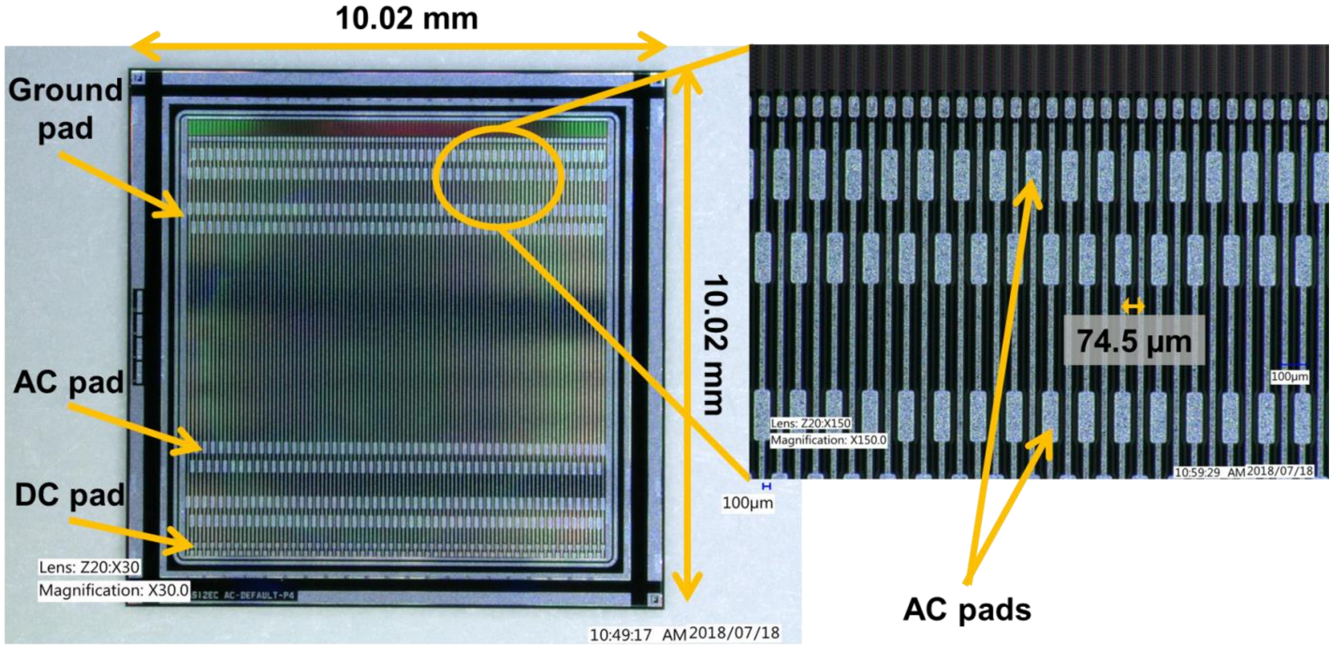
ATLAS12EC Silicon Sensors

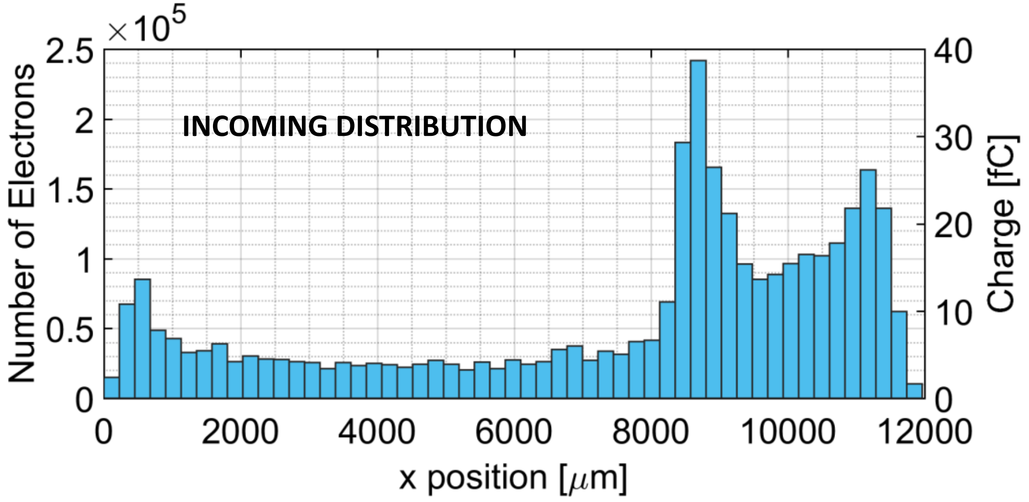
- Test structures developed for the High Luminosity LHC ATLAS inner tracker upgrade
- 1 x 1 cm², 310 µm thick, 103 strips, 74.5 µm pitch
- Punch through protection

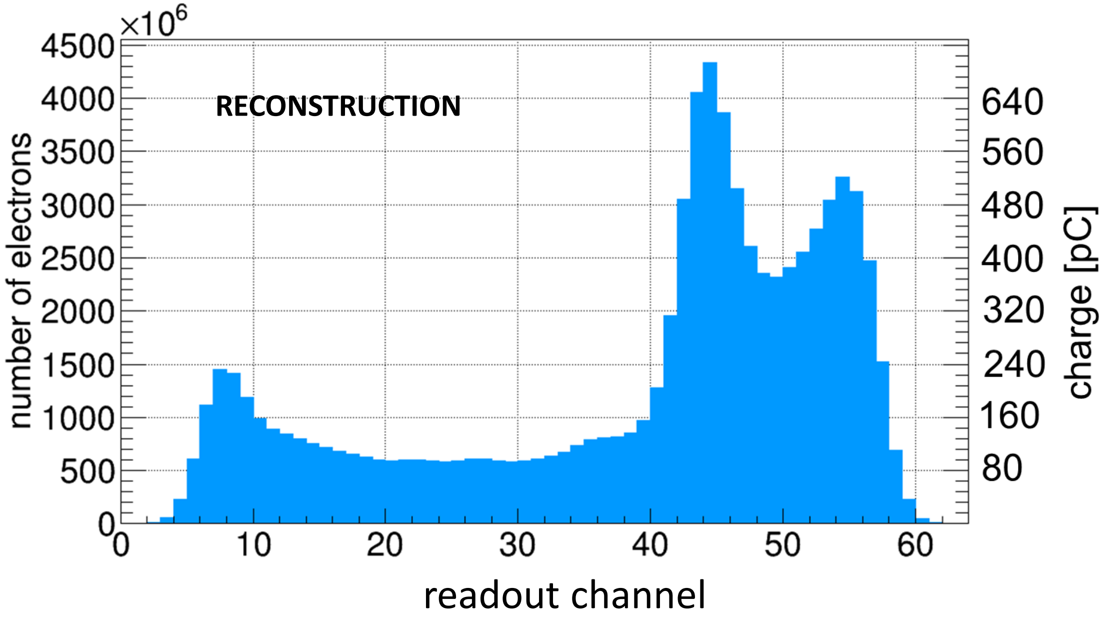


- IV measurement:
  - Determine leakage current
  - Check breakdown of sensors
- CV measurement:
  - Determine the depletion voltage
- Uniform behaviour of all sensors
- Agree with measurements performed by ATLAS

STRIDENAS

Simulation of Charge Sharing

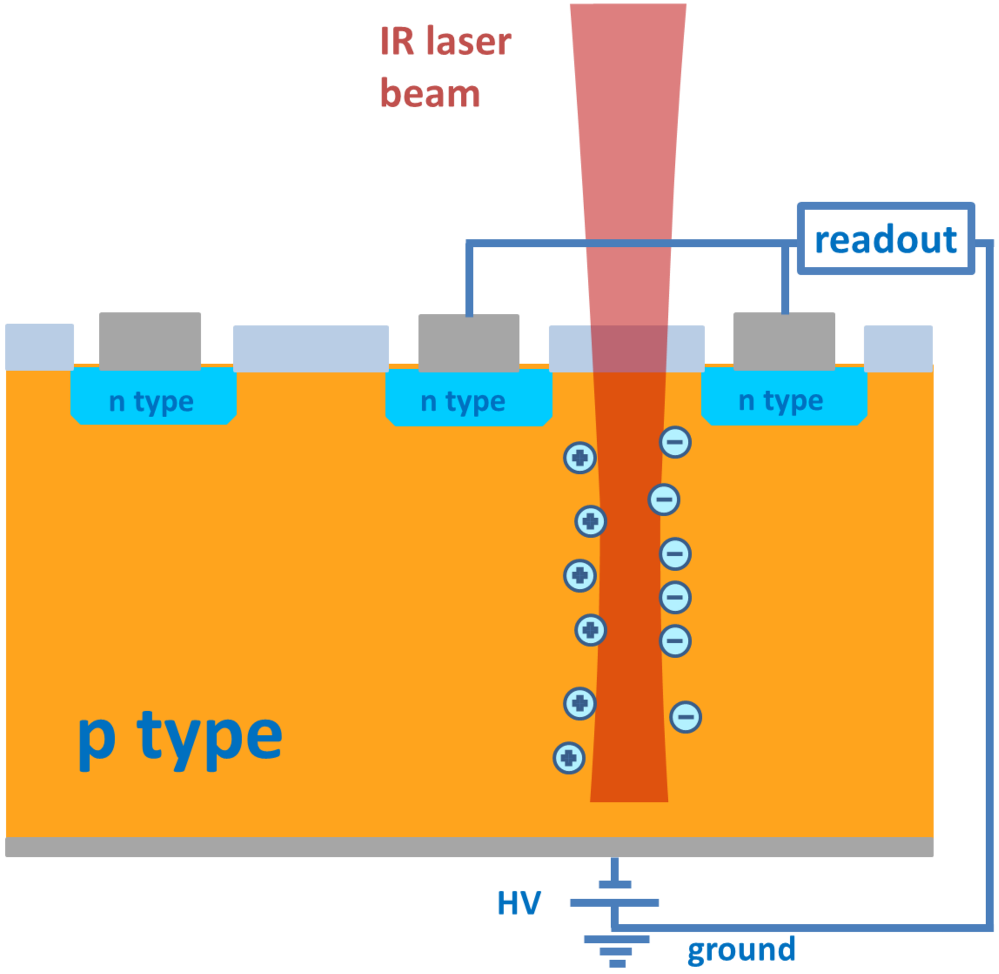


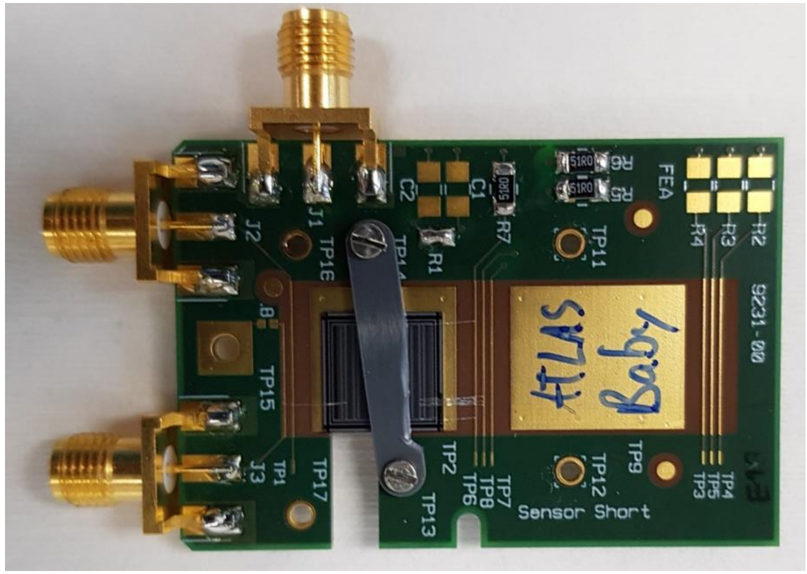


- Estimate the behaviour of the sensor for a 0.5 pC ACHIP working point
- ROOT simulation
  - Assuming incoming particles are MIPs
  - Sensor thickness: 310 µm
  - 64 readout channels with 223.5 µm pitch
  - Gaussian transverse spread with a σ of 300 µm
- Beam features of interest well resolved

Sensor Characterization

Transient-Current Technique Measurements

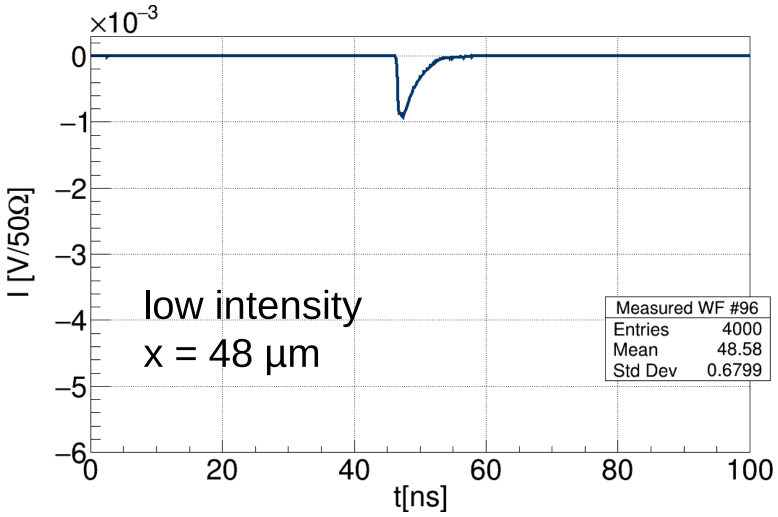


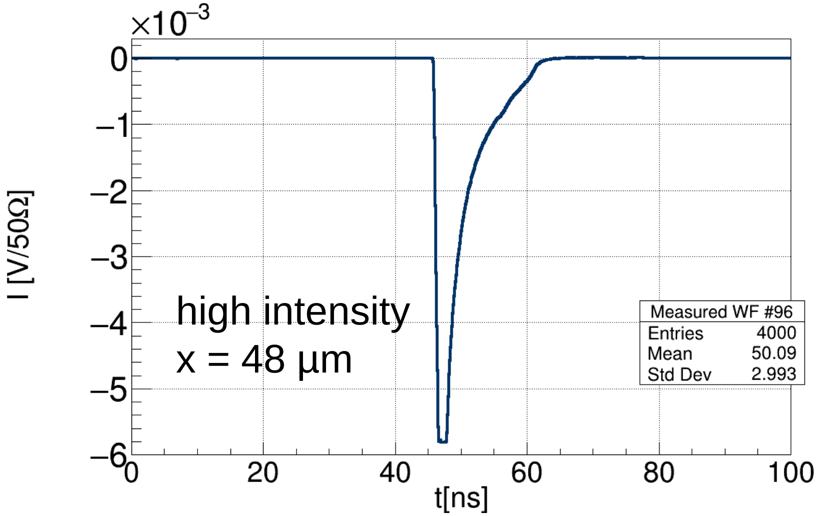


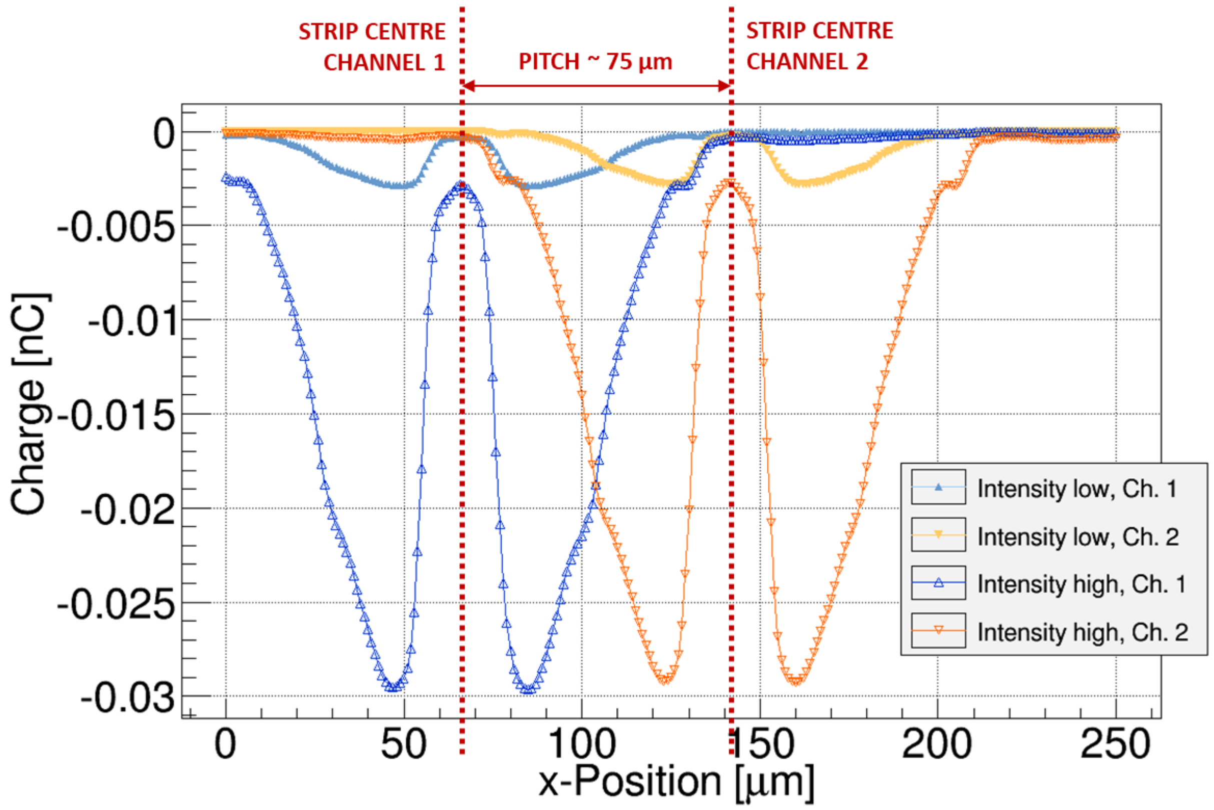
- Transient-current technique uses laser light instead of electrons
- Also production of electron-hole pairs
- Investigate **signal length**, **transverse spread**, plasma effect, correlation between applied bias voltage and produced charge in the sensor
- Measurements with **red** and **infrared** light

Sensor Characterization

Transient-Current Technique Measurements





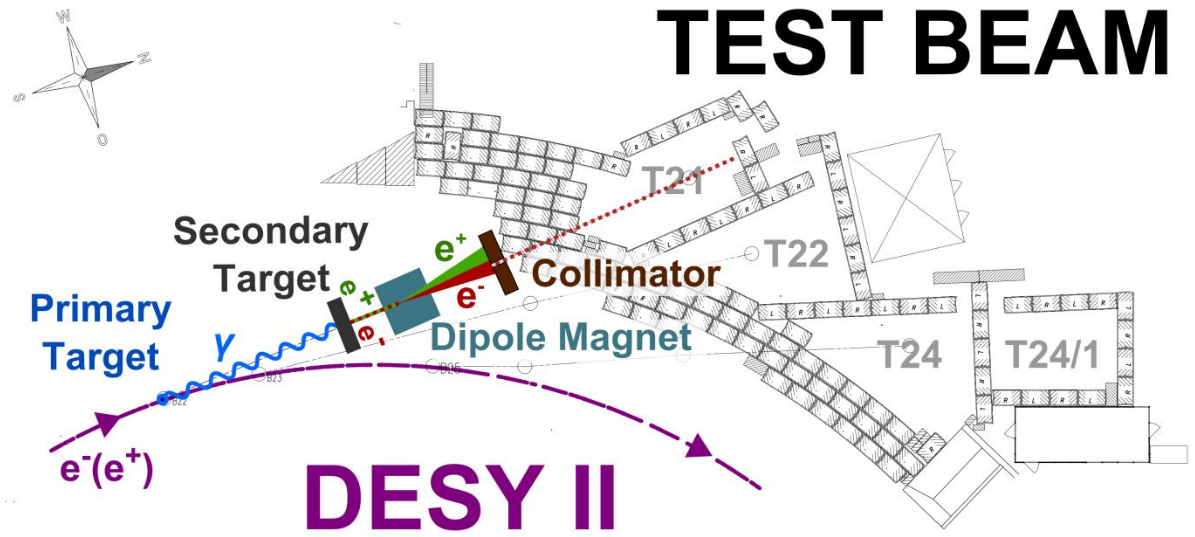


- Position scan to investigate signal spread
- For maximum charge: no problems expected (7298 ± 691 MIPs)

STRIDENAS Functionality Tests

DESY II Test Beam Facility

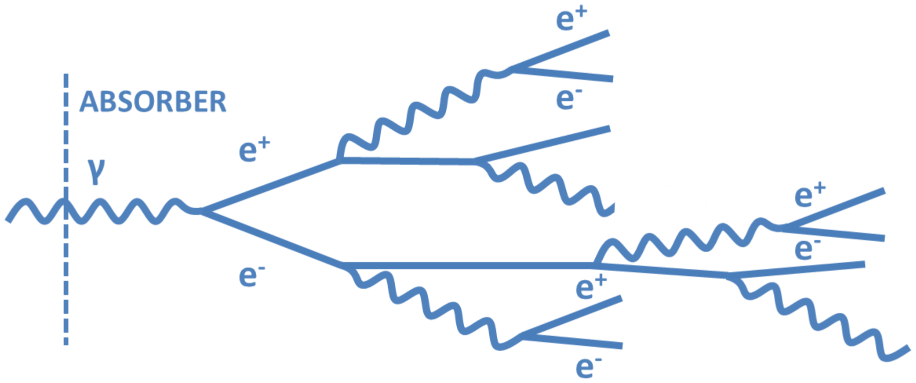
- DESY II Test Beam facility generates particles with a double conversion setup
- Electron energies: 1 – 6 GeV
- Single electrons needed for detector tests
- Particle rate up to ~ 40 kHz
- Provides infrastructure for experiments
- Due to single electrons: Individual tests of the STRIDENAS components
  - Readout electronics tests with a photomultiplier signal from the test beam telescope
  - Tests of the STRIDENAS detector
  - Tests with the sensor bonded for the TCT measurements

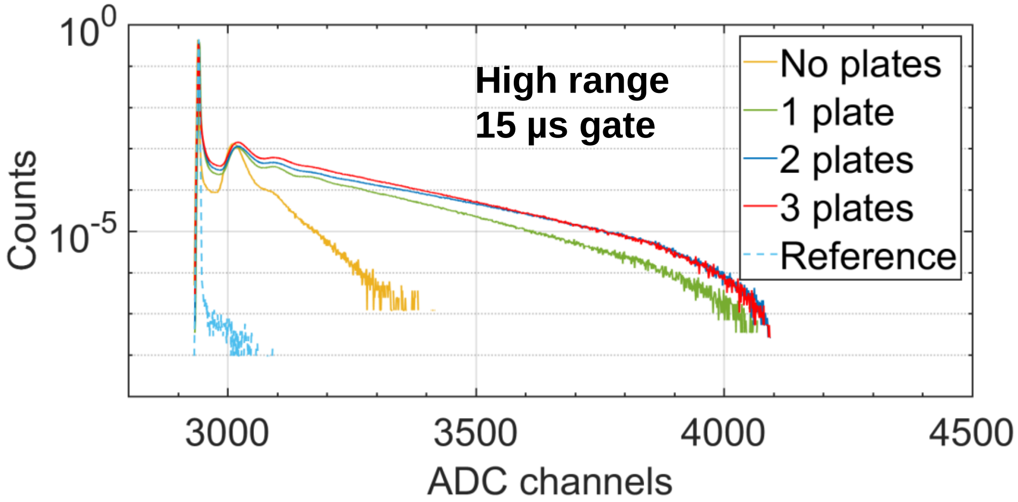


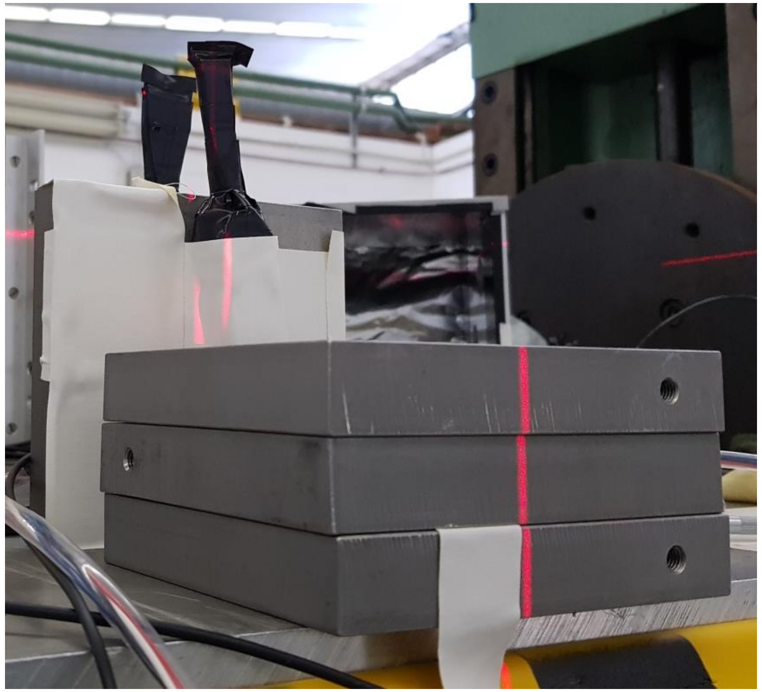
STRIDENAS Functionality Tests

Readout Electronics Test with Photomultiplier Signals

- Different charge integration gates
- Use of iron plates to produce particle showers and increase the number of incoming particles
- Example measurements with a 15 µs gate signal







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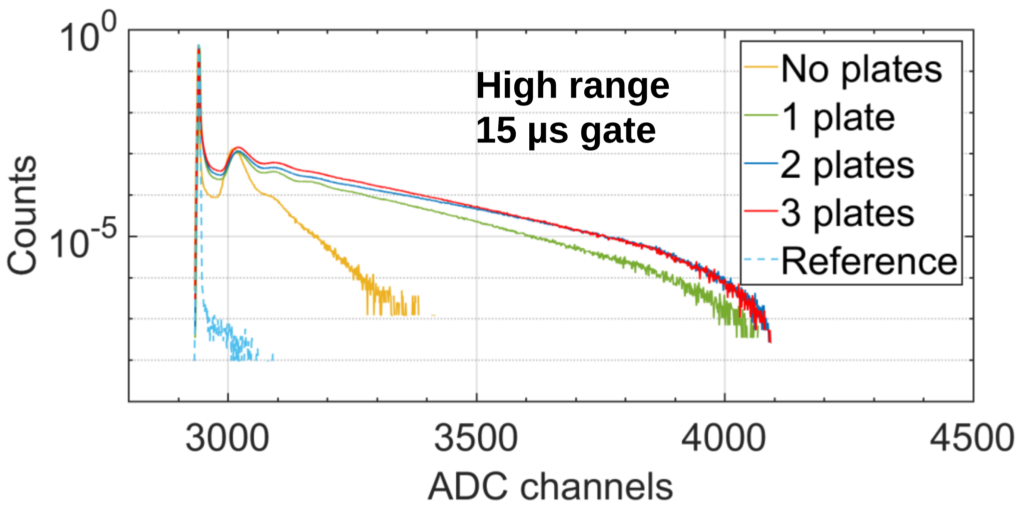
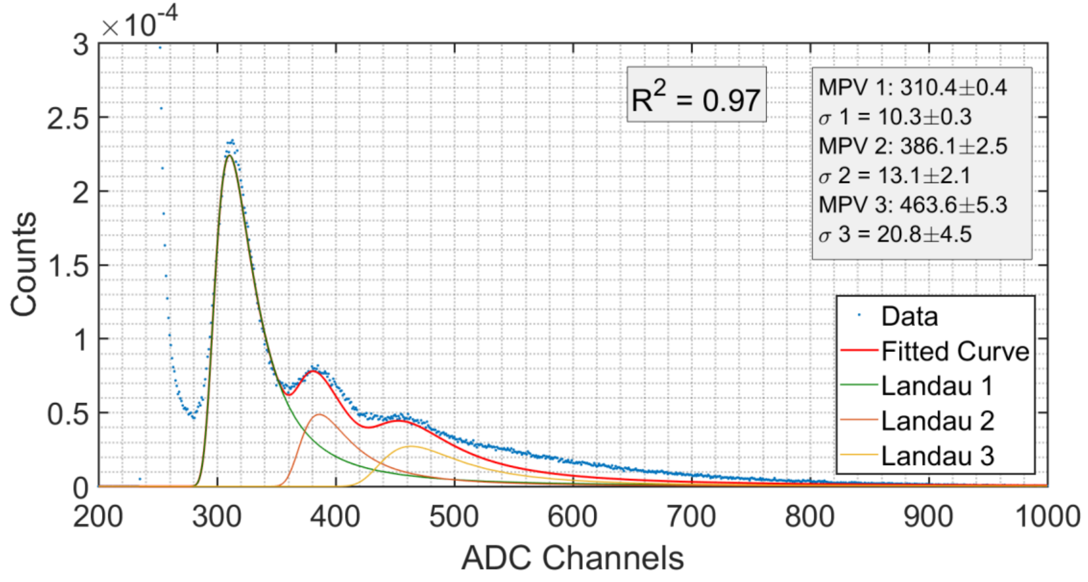


- Triple Landau fit
  - Equally spaced peak-to-peak distance corresponding to ~15 pC
  - Agrees well with expected value from photomultiplier

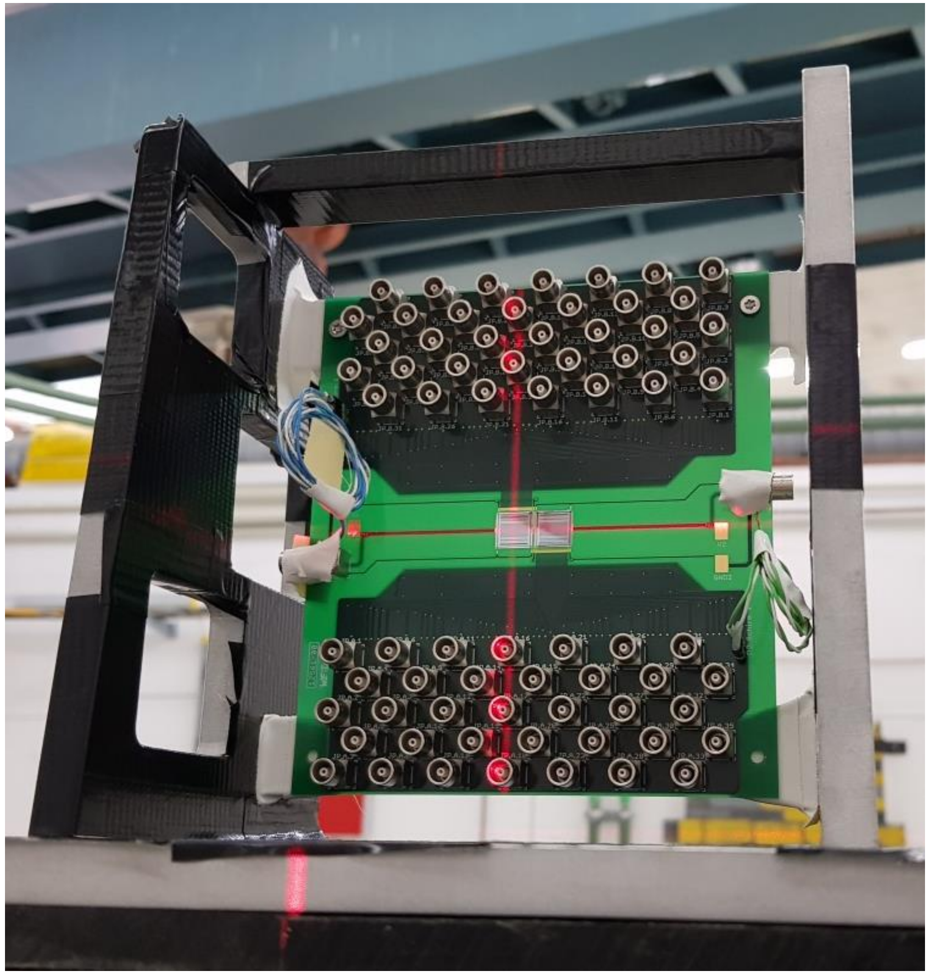


STRIDENAS Functionality Tests

Test Measurements with the STRIDENAS detector

- Different test measurements with STRIDENAS detector
  - ➢ Measurements unsuccessful due to early breakdown of the sensors

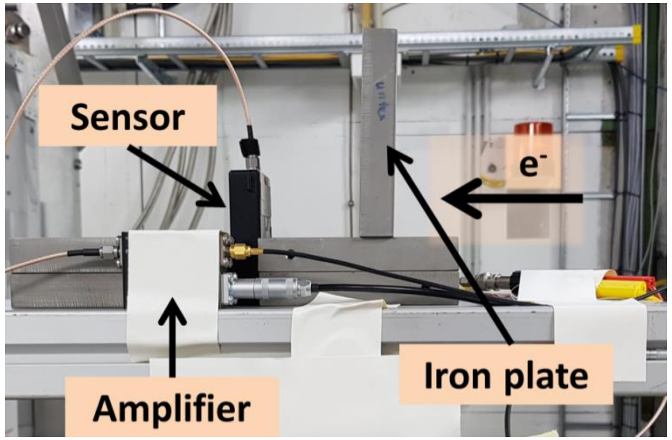
- Investigate with new sensor if it is in principle possible to observe single electrons
- No visible signal from the Test Beam (single electrons)
  - ➢ Produced signals were too small to be detected
  - ➢ **Higher charge carrier density** or **amplification** is needed

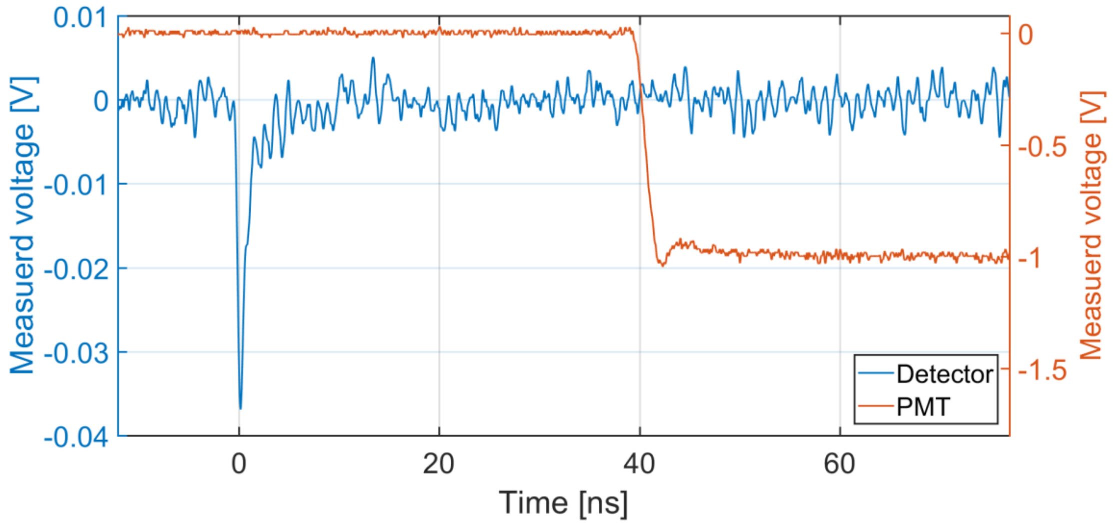


STRIDENAS Functionality Tests

Sensor Tests with Amplifier

- Measurements with sensor from the TCT measurements and a 40 dB amplifier
- Signal connected to an oscilloscope
- Area under the signal is proportional to the produced charge inside the sensor
- Varies according to the Landau distribution





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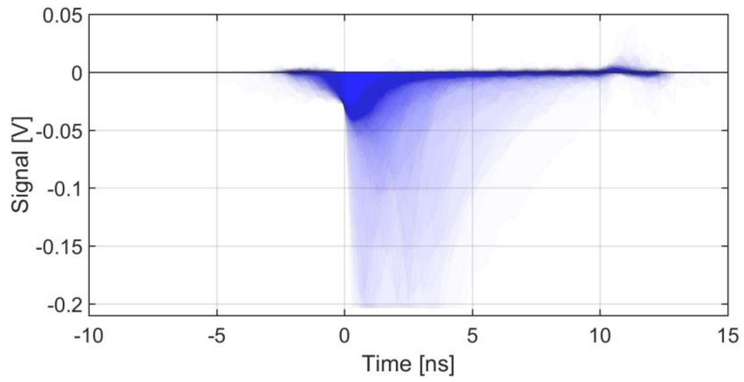
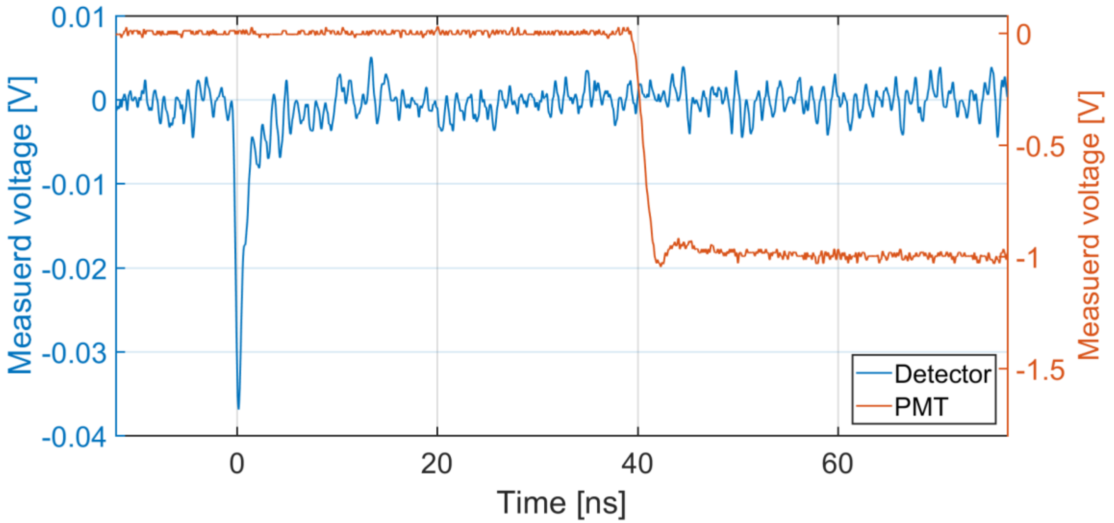
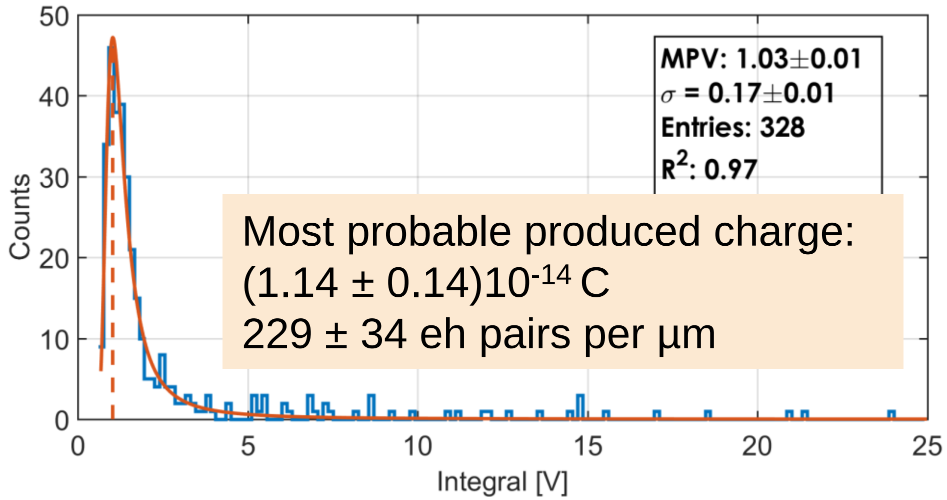


- Histogram of waveform integrals with Landau fit
- $Q = \frac{L_C}{A\,R}\int_{t_s}^{t_f} U dt \sim \frac{L_C}{A\,R}\, I_M\, \Delta t$

L_C = signal loss compensation
A = amplification factor
R = impedance of system
U = measured voltage
t_s, t_f = starting and final time boundaries
I_M = MATLAB integral
Δt = actual data spacing

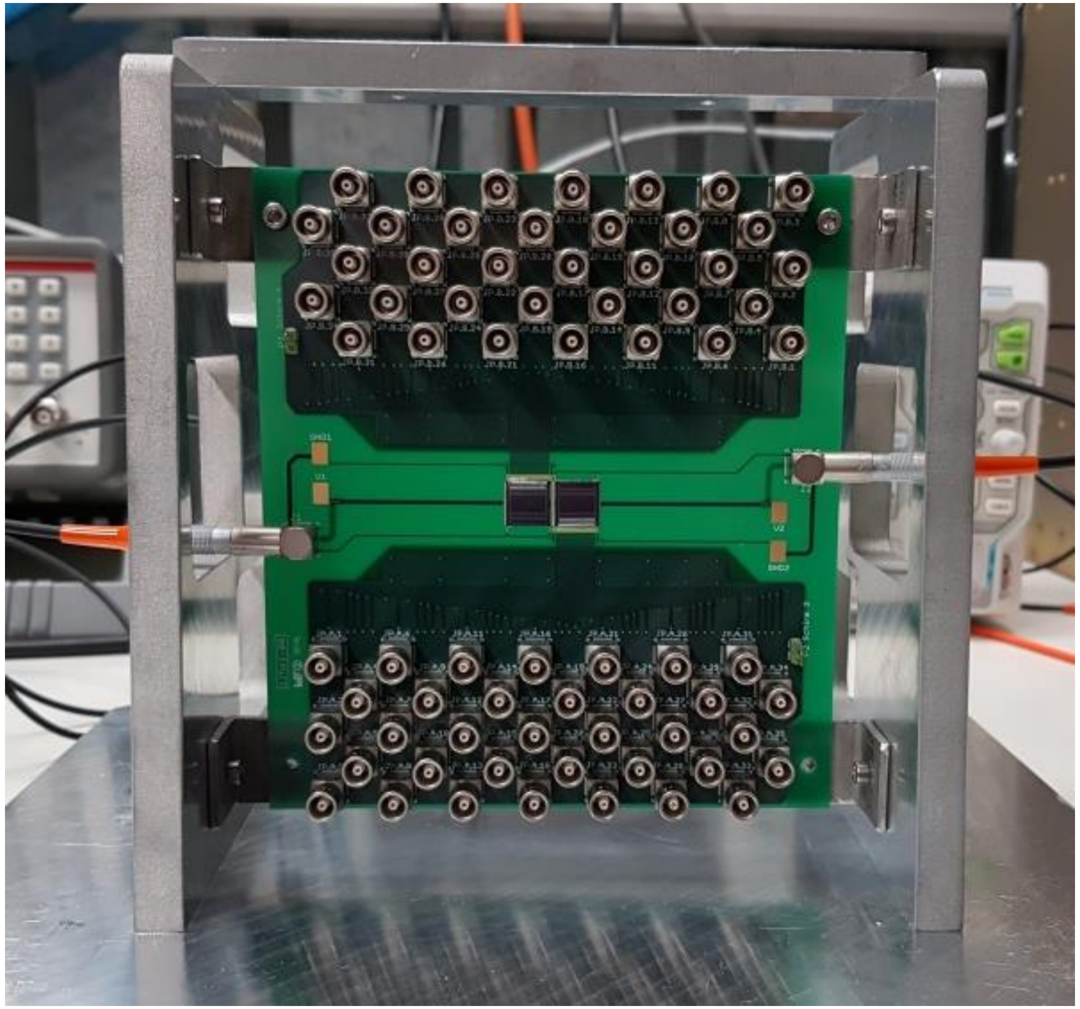




Most probable produced charge:
$(1.14 \pm 0.14)10^{-14}$ C
229 ± 34 eh pairs per µm

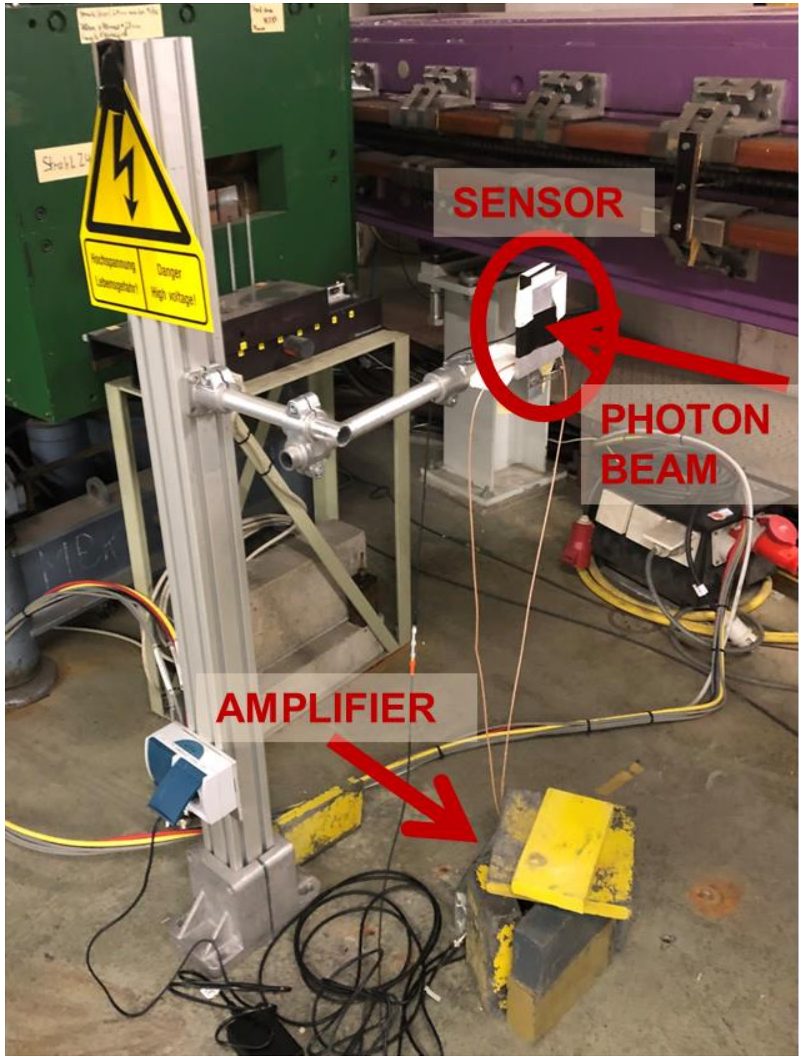
Conclusion

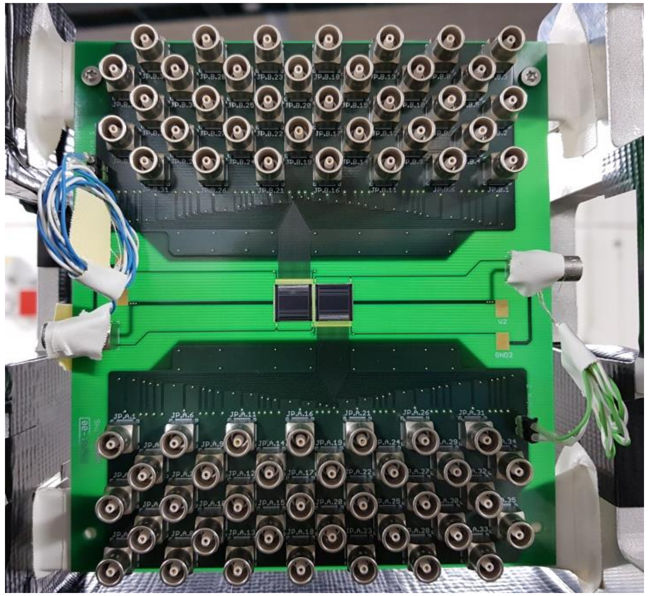
- ✓ Successfully detected single electrons
- ✓ Successful sensor tests with a high electron intensity simulated with laser beam
- ✓ Readout electronics tested successfully for high intensities with signals from photomultipliers
- ✓ Amplifier needed to reduce noise introduced by meter long cables



Outlook

- Repeat high intensity measurements with incoming electrons
- Development of suited signal amplification
- Build vacuum compatible setup
  First discussions with the DESY vacuum group are ongoing
- Implementation at the ARES spectrometer





MADE POSSIBLE WITH THE HELP OF:

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