MAX PLANCK
SEMICONDUCTOR
LABORATORY

TRISTAN SDD

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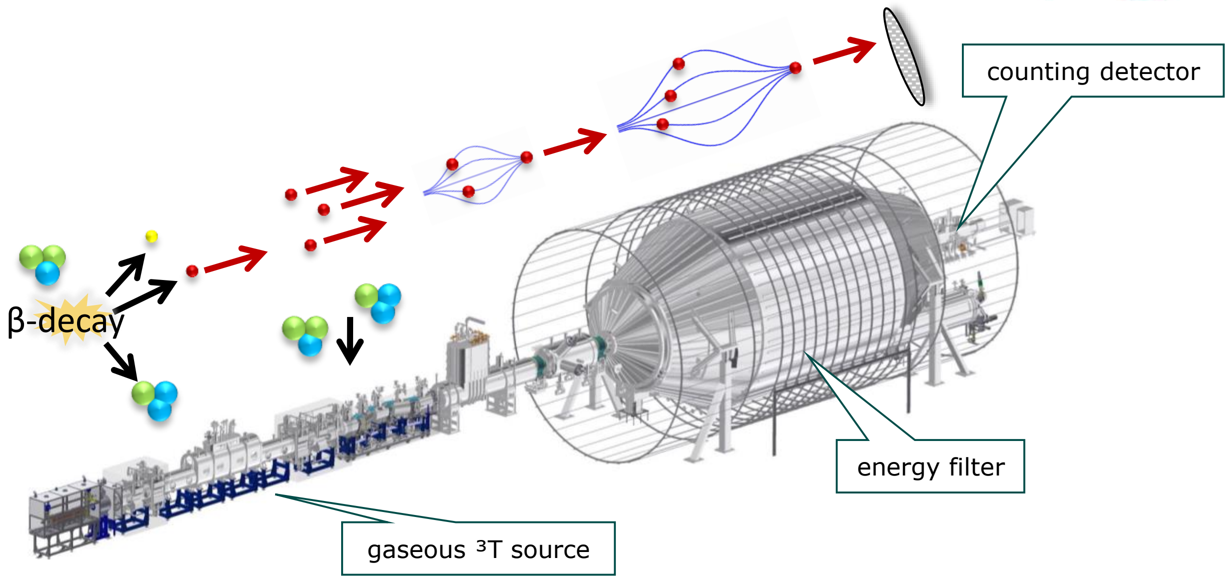
DePFET Workshop, Tutzing, 24.05.2023

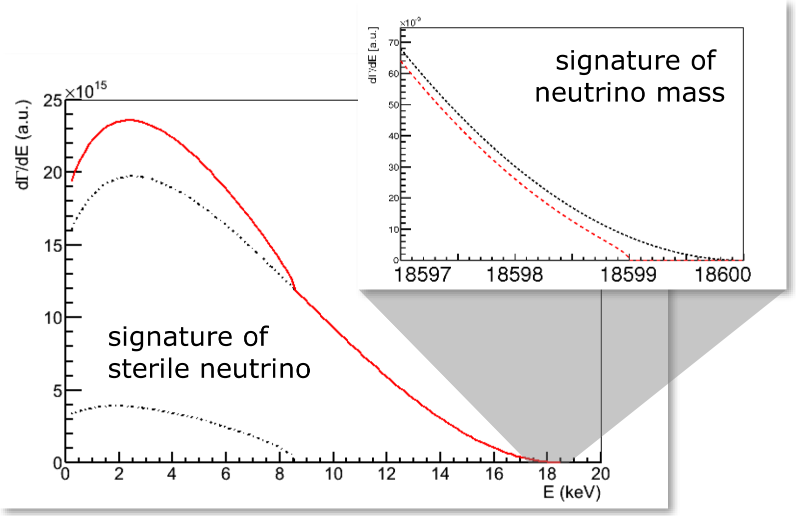
TRISTAN (TRItium STerile Anti-Neutrino)

- KATRIN (KArlsruhe TRItium Neutrino experiment) @ KIT Karlsruhe
  - ▷ measurement of neutrino mass by β-spectrum end point
  - ▷ spectrometer filters electron energy by retarding field
    - only electrons with energy > filter potential reach the detector
    - electron counting detector, event rate ~ 2 el / day
    - required statistics in 5 years, momentary $m_\nu \leq 0.8$ eV/c^2

- TRISTAN
  - ▷ search for "sterile neutrino" ≡ dark matter candidate
    - expected mass ~ 10 keV
    - visible as tiny kink ($\sigma \sim 10^{-6}$) in β-decay continuum
  - ▷ use of KATRIN facility without energy filter
    - energy-dispersive measurement of full β-spectrum
    - count rate 10^8 … 10^9 el / sec

→ **new detector required**

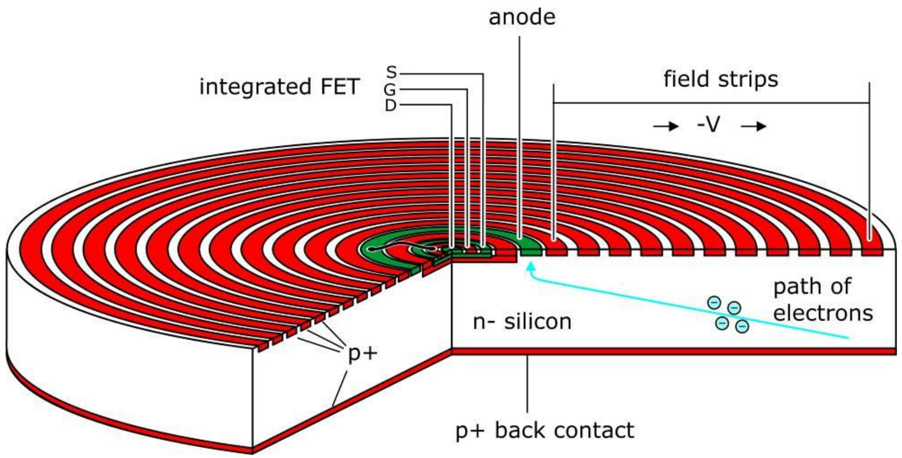


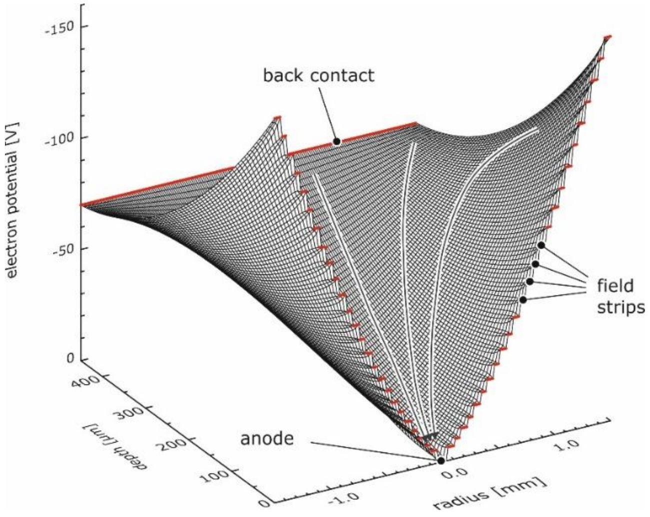


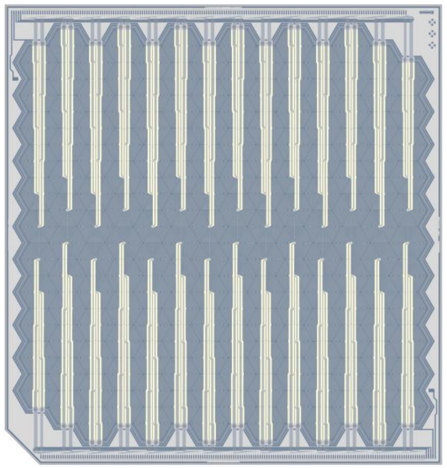
TRISTAN

- requirements
  - ▷ spectroscopy → good energy resolution < 300 eV FWHM @ 20 keV (25 el. ENC)
  - ▷ minimal energy loss → thin entrance window < 100 nm dead layer
  - ▷ beam dimension → large area coverage Ø ~ 20 cm focal plane, ~ 300 cm²
  - ▷ high count rate → segmentation Ø ~ mm cell size, ~ 1.000 cells

- detector choice: Silicon Drift Detector SDD
  - ▷ small capacitance & large cell area
  - ▷ multi-channel option

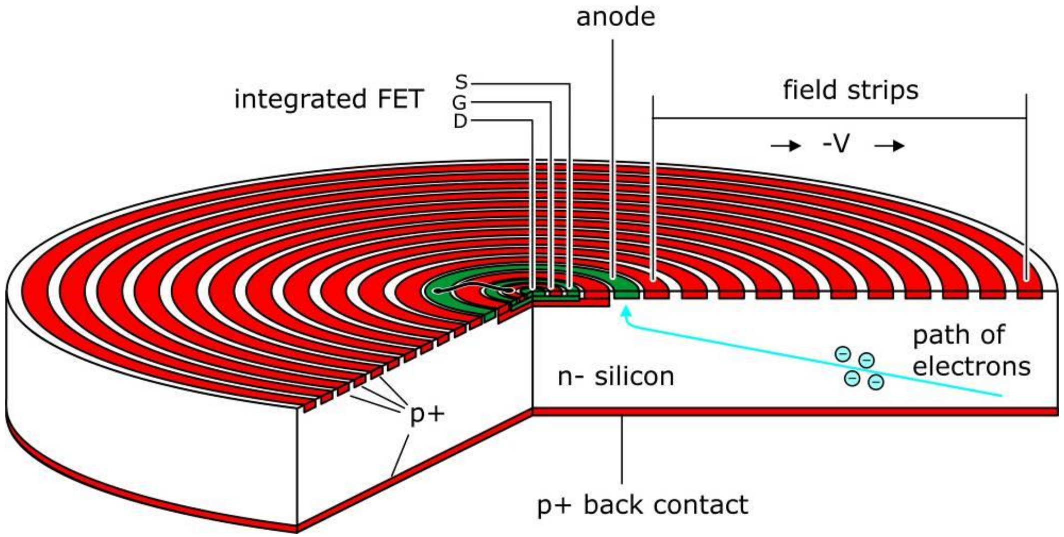


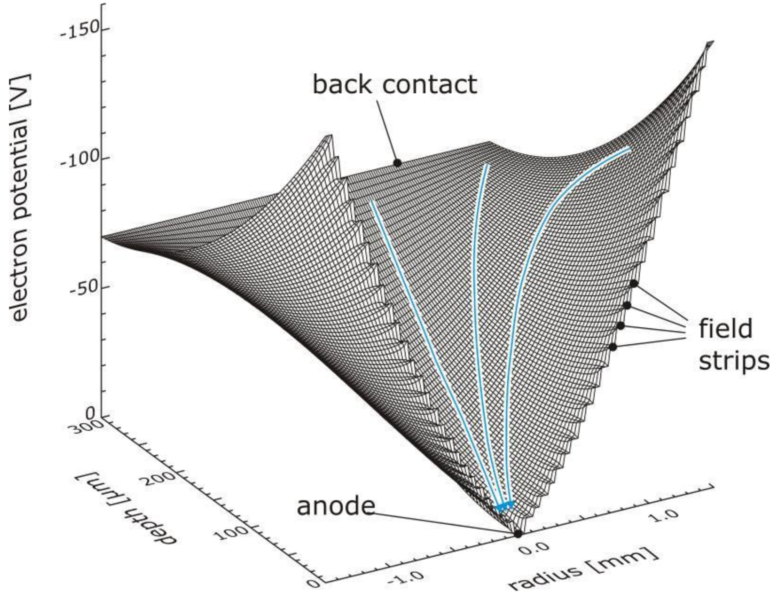




SILICON DRIFT DETECTOR (SDD)

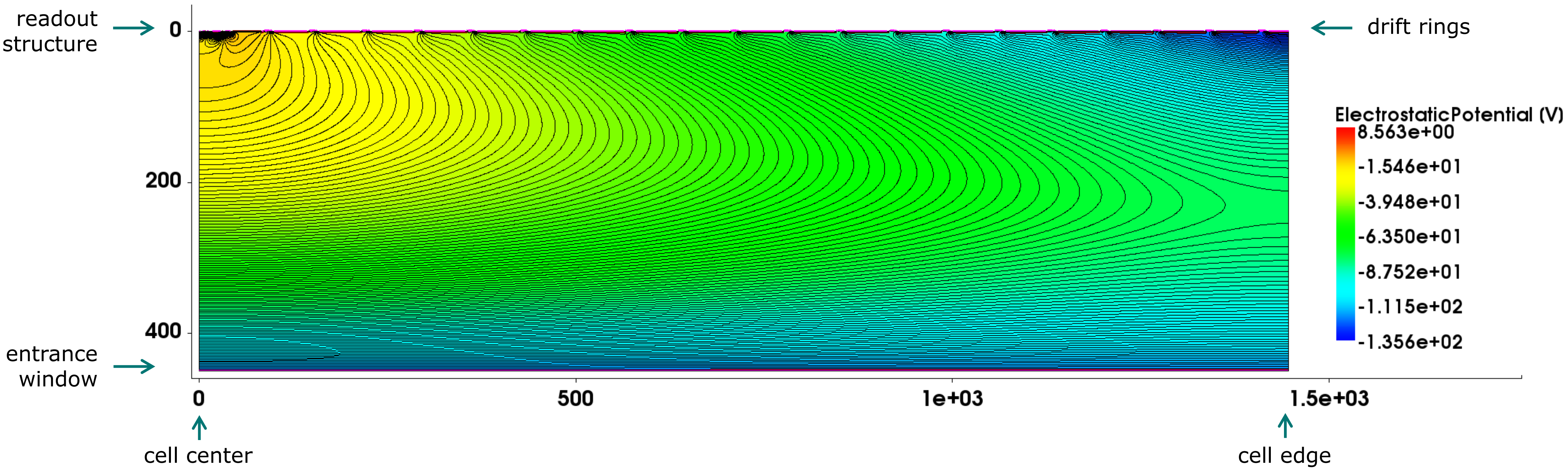
- principle
  - signal charge collection on small readout node by internal static electric field
  - X-ray & particle spectroscopy
- large area
  - 5 mm² … 1 cm² (… wafer scale)
- small capacitance
  - low noise, high count rates
- fully depleted and sensitive
  - efficiency @ high energies
- backside illuminated, uniform thin window
  - efficiency @ low energies
  - peak/background ratio
- integration of 1st amplifying FET
  - further capacitance reduction
  - no pickup, no microphonic noise





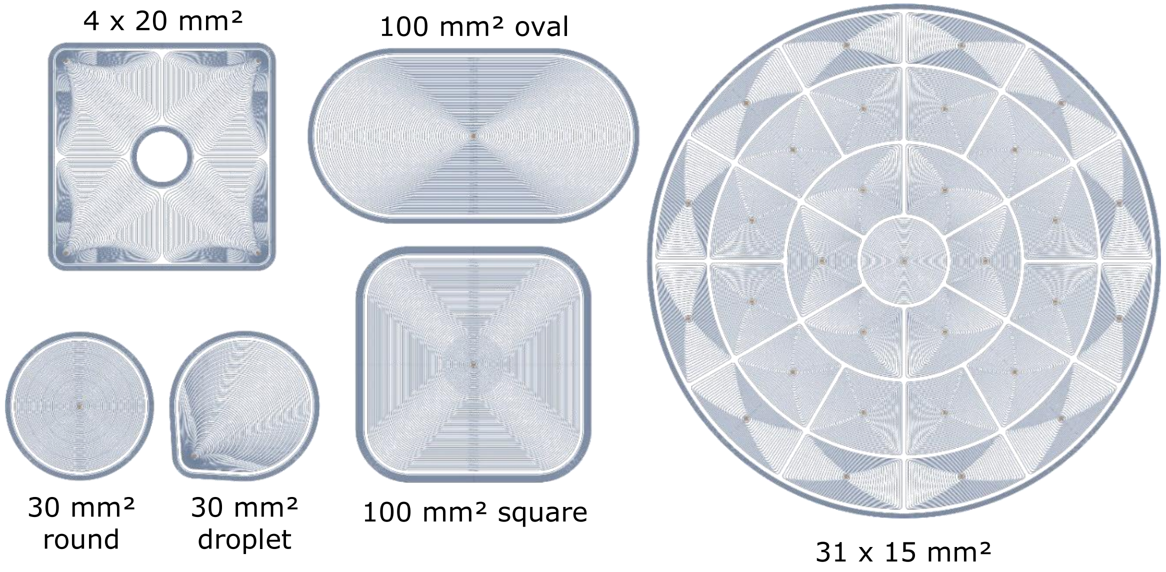
SILICON DRIFT DETECTOR (SDD)

- simulated electrostatic potential
  - ▷ equipotential lines ΔV ≈ 1V
  - ▷ strong E-field ⊥ surface, weak E-field || surface
    - → fast vertical drift to 1D potential minimum
    - → 'slow' horizontal drift to readout structure
  - ▷ two saddle points (vertical minimum & horizontal maximum)
    - – cell edge
    - – barrier of readout structure
      - → "field-free" regions

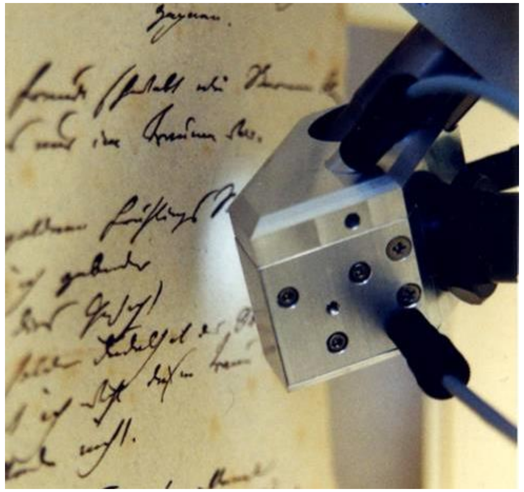


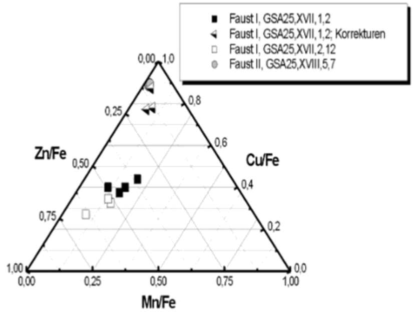
SILICON DRIFT DETECTOR (SDD)

- flexible size & shape
  - cell sizing by number & width of field strips
  - cell shaping by bended field strips
  - any 2D geometry
  - multi-cell option



- numerous fields of application
  - commercial products
  - scientific experiments
  - main applications
    - electron microscope EDX
    - X-ray fluorescence XRF

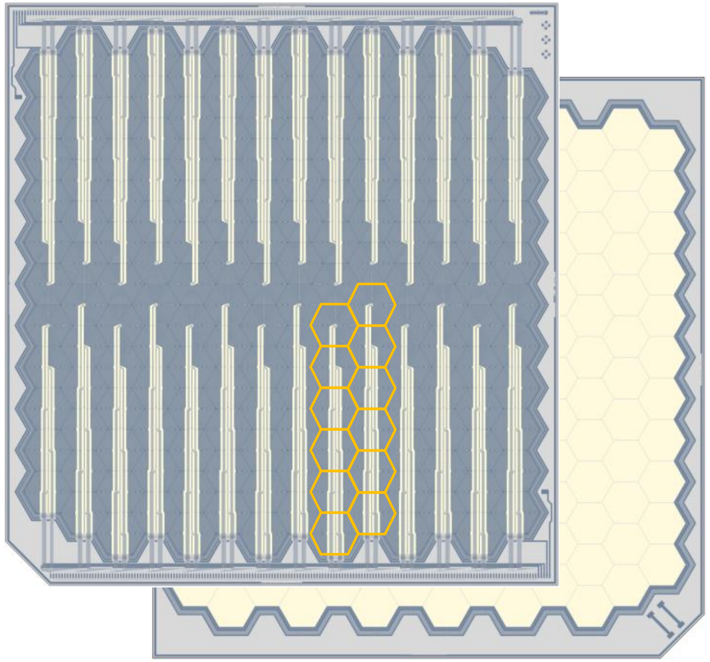




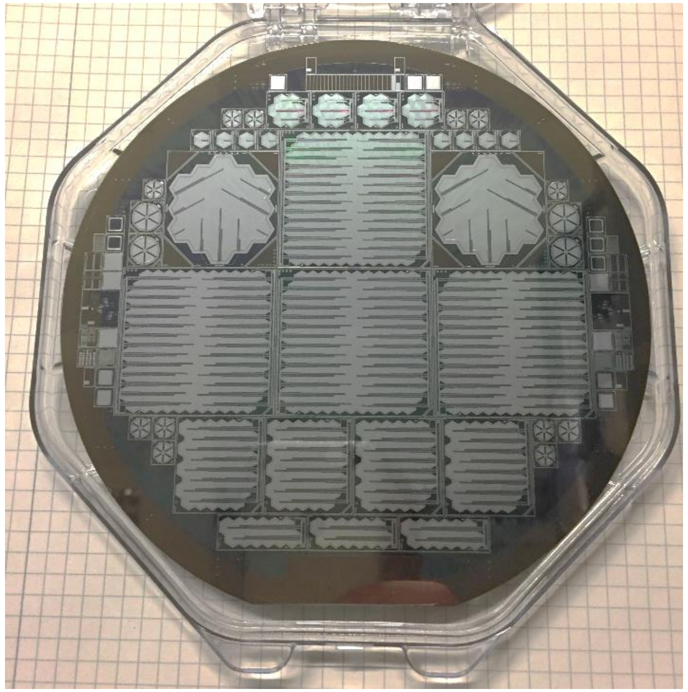
ink analysis of Goethe's original manuscript of Faust II (BAM)

TRISTAN SDD

- prototype production SDD33
  - volume 6 (+2) wafers
  - SDD with integrated FET
  - 166 cell device (~ 14 x 12 array)
    - 120 "full" cells
    - 46 edge cells for event reconstruction
  - hexagonal SDD cell Ø ≈ 3 mm, A ≈ 7 mm²
  - chip format 38 x 40 mm²
  - organized in 14 groups of 12 (11) cells
  - 2 rows of ~ 180 bond pads
  - cut corner for back side bonds
  - smaller formats 8 x 6 cells
    2 x 6 cells
    7 cells
    1 cell



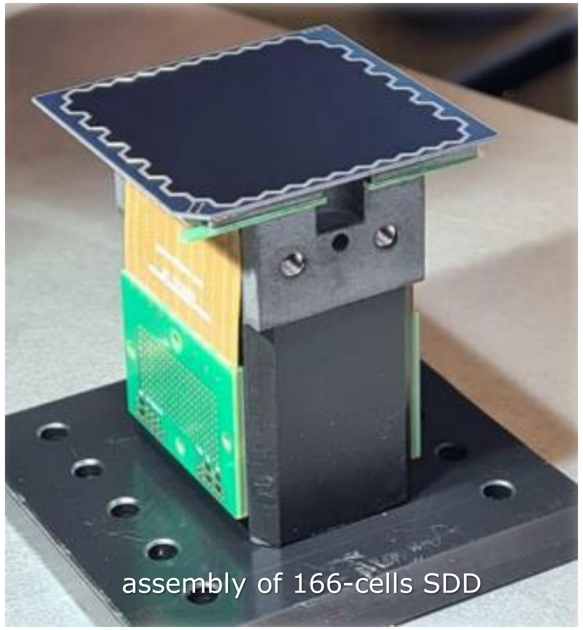
layout of 166 cells TRISTAN SDD

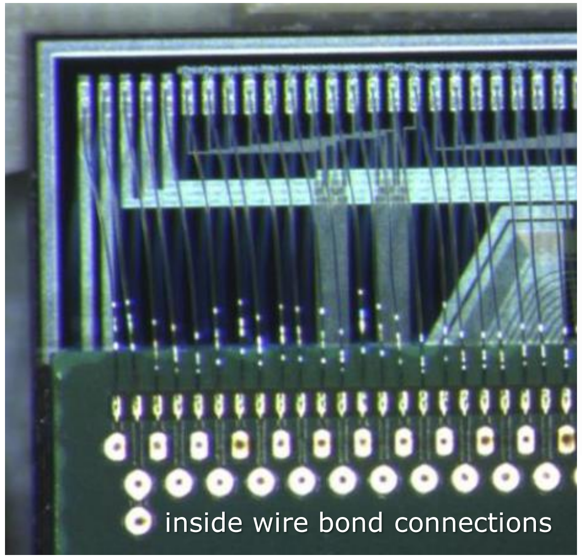


SDD33 wafer

TRISTAN SDD

- module concept
  - ▷ 4-side buttable
  - ▷ perpendicular orientation of
    - – thermal & mechanical connection
      - ▪ CeSiC cooling adapter
        glued to SDD readout side
      - ▪ Cu column
    - – signal & supply lines
      - ▪ C-shaped pcb & flex lead
      - ▪ spring contact matrix
      - ▪ electronics board
        7 x 12-channel ETTORE readout
        ASIC (XGLab Milan)
      - ▪ flex lead to vacuum flange

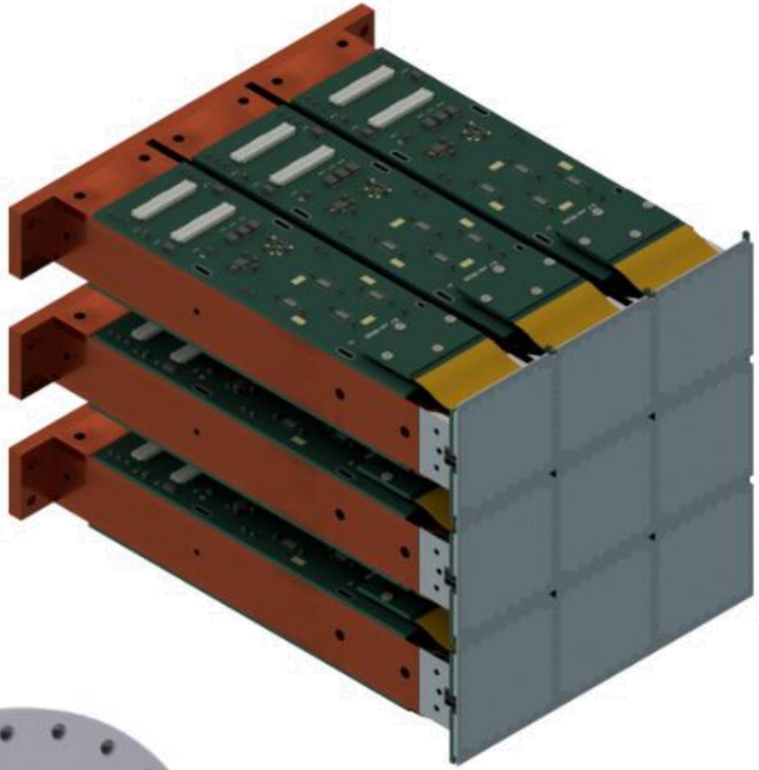

assembly of 166-cells SDD


inside wire bond connections


TRISTAN
166-cells
SDD module

TRISTAN SDD

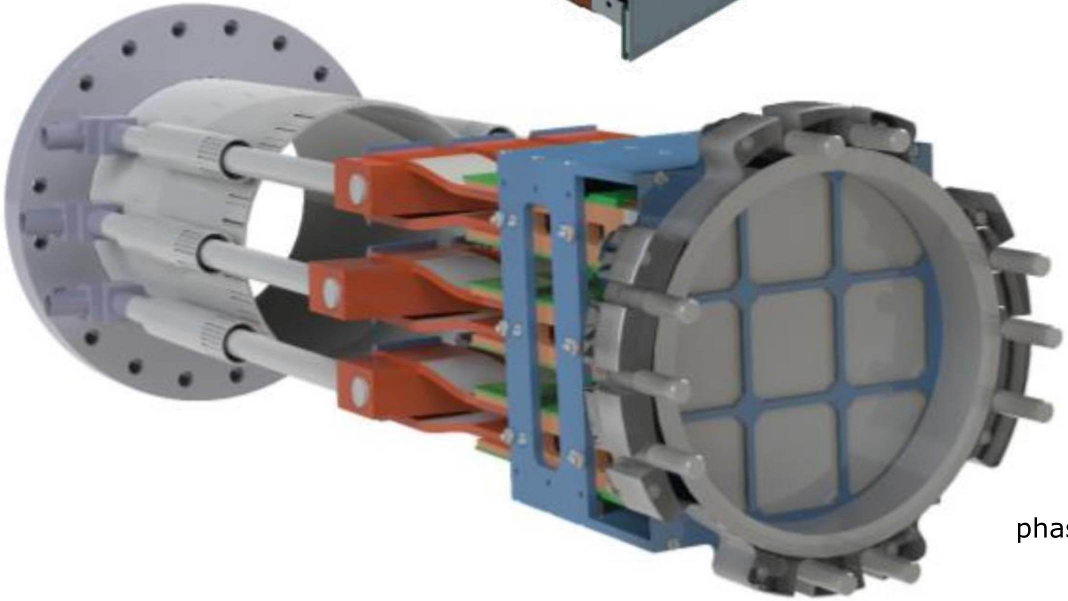
- phase 1 detector plane
  - 3 x 3 array of SDD modules



phase 1 detector plane

3 x 3 modules array
~ 1500 SDD cells

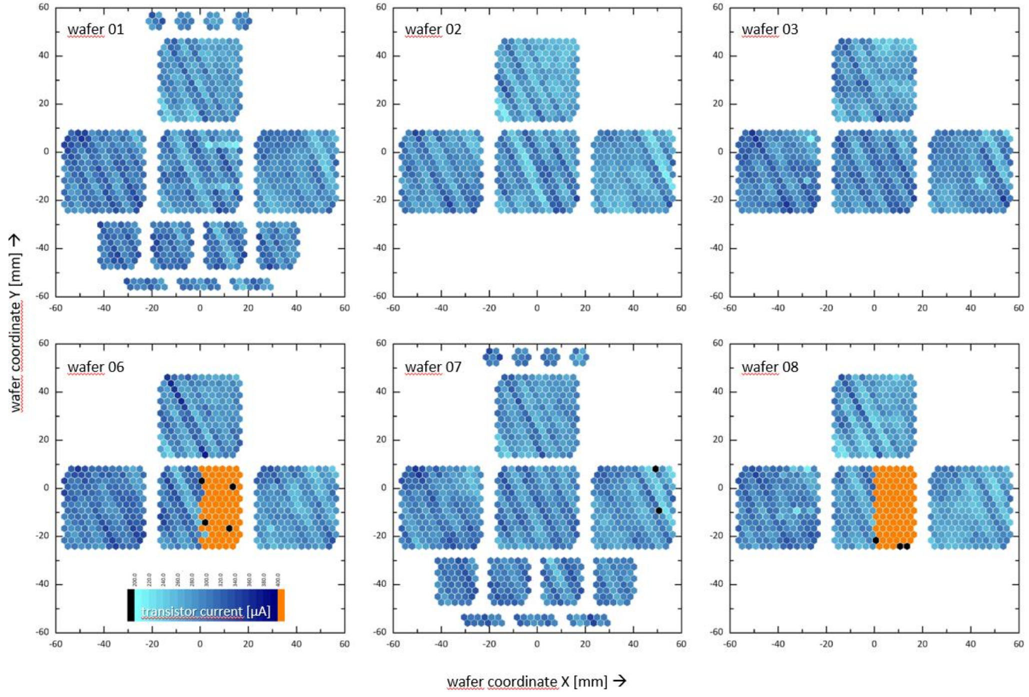
- phase 2
  - optional expansion to 21 sensors



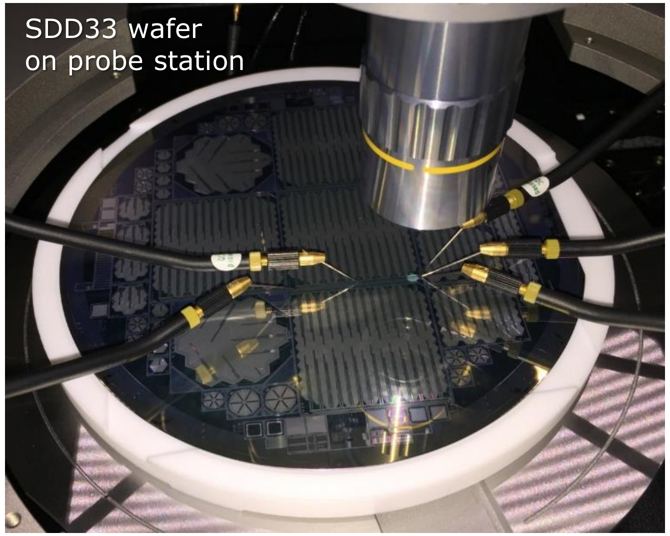
phase 1 detector chamber

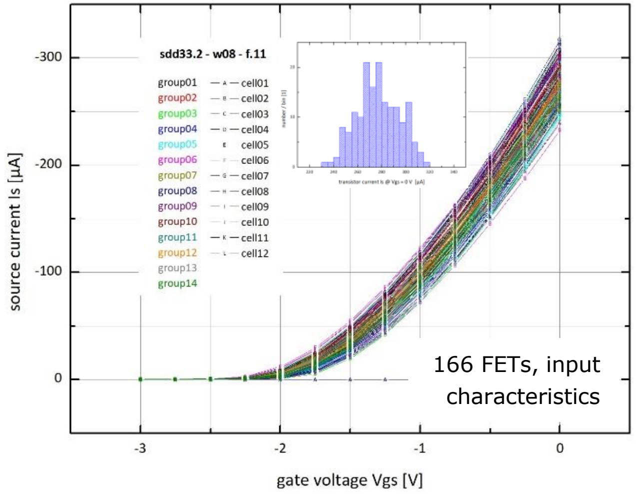
TRISTAN SDD

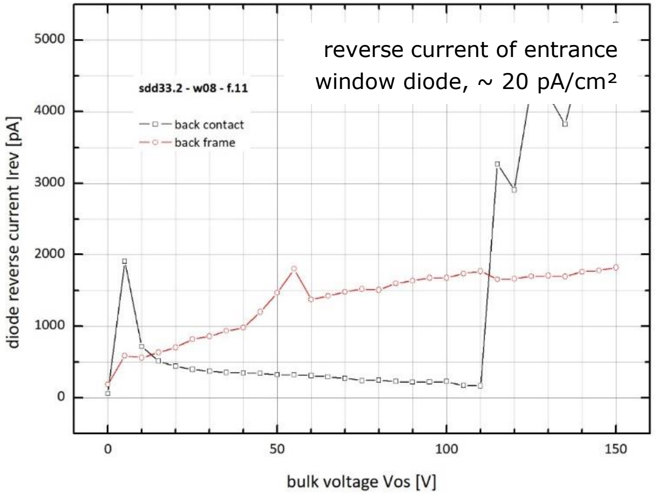
- wafer & die level test of prototypes
  - ▷ semi-automatic stepping & test function
    - – stability of diodes
    - – integrity of insulating layers
    - – characteristics of integrated voltage divider
    - – characteristics of integrated FET
    - – leakage current
  - ▷ high yield, expected performance figures



wafer maps of FET currents

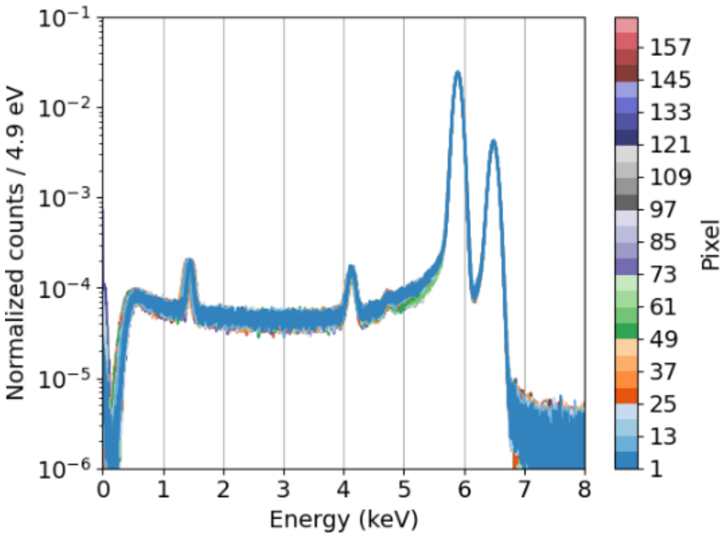






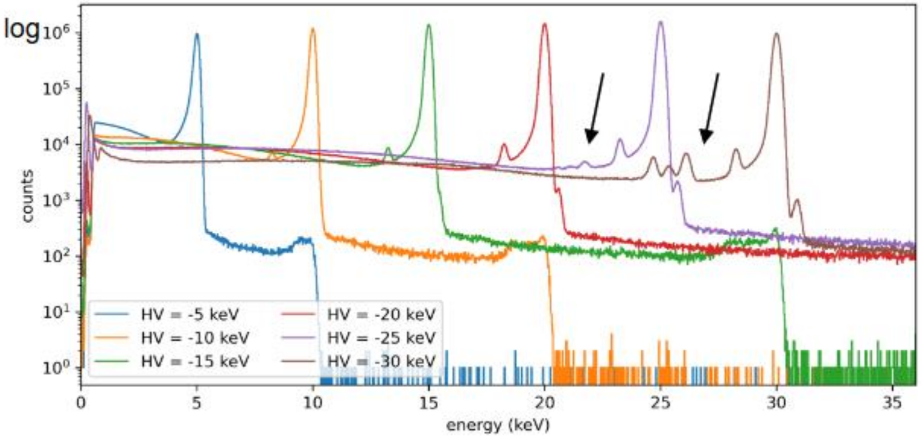
TRISTAN SDD

- performance
  - X-ray spectroscopy
    - ΔE = 150 eV FWHM @ 5.9 keV
    - T = -30 °C, τ = 1 μsec

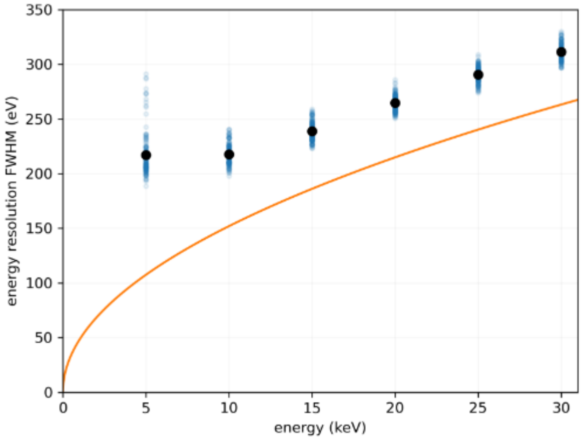


spectra of a ^{55}Fe source recorded by TRISTAN 166-cells SDD

  - electron spectroscopy
    - monoenergetic electrons by electron gun
    - ΔE « 300 eV FWHM @ 20 keV
    - fake peaks by HV instabilities



spectra of monoenergetic electrons

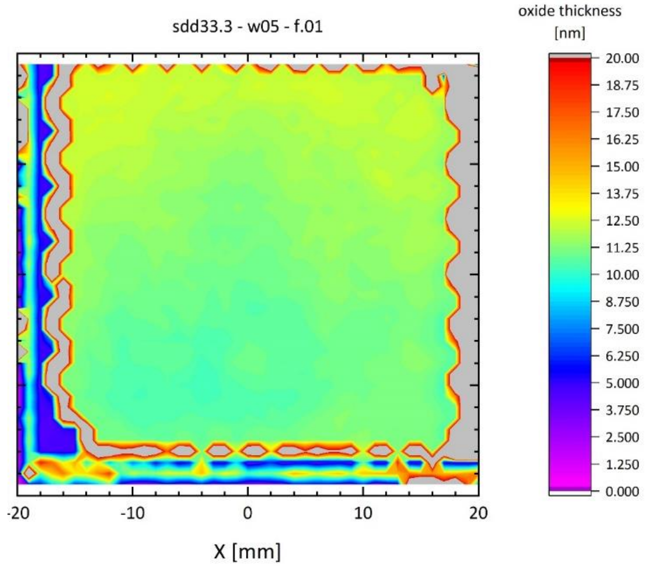


FWHM resolution vs. electron energy

plots by D. Siegmann, K. Urban (MPP & TUM)

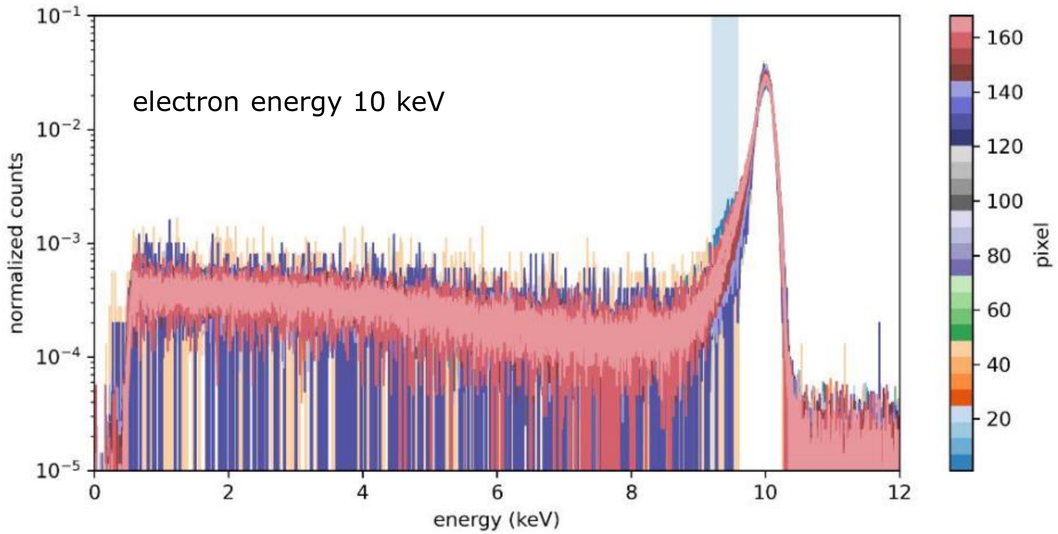
TRISTAN SDD

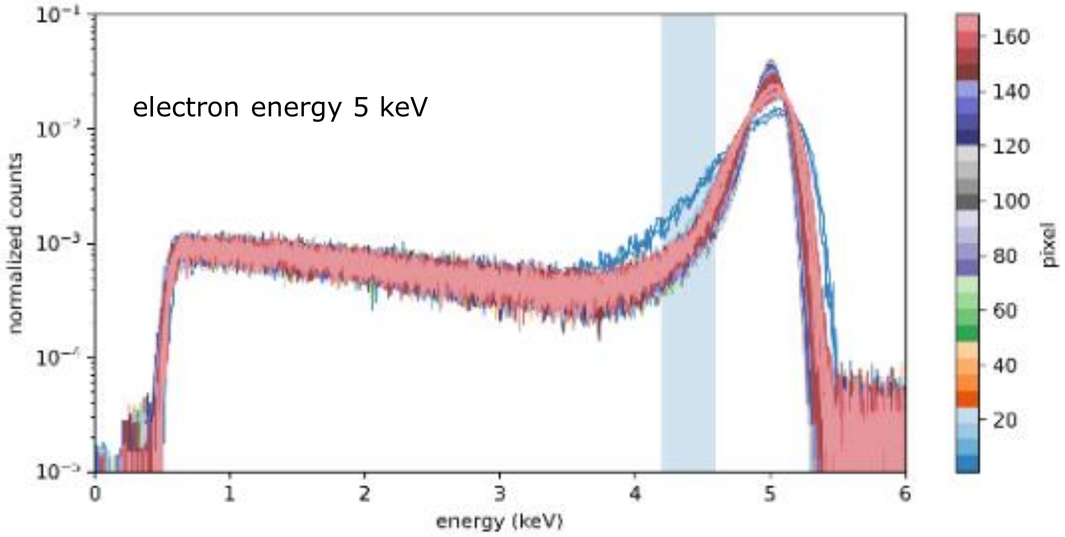
- entrance window
  - ▷ contamination by thin covering layer
    - – distortion of low energy electron spectra
    - – local phenomenon
    - – removed / redistributed by solvent cleaning
  - ▷ occurs in mounting, storage, transport, operation, …
  - ▷ origin unknown, work in progress



entrance window ellipsometry

d_{SiO2} = 11 nm ± 1 nm





TRISTAN SDD

- lessons

  ▷ drain series resistance

  – polySi replaced by metal

  ▷ contact resistance

  – additional shallow n-implantation

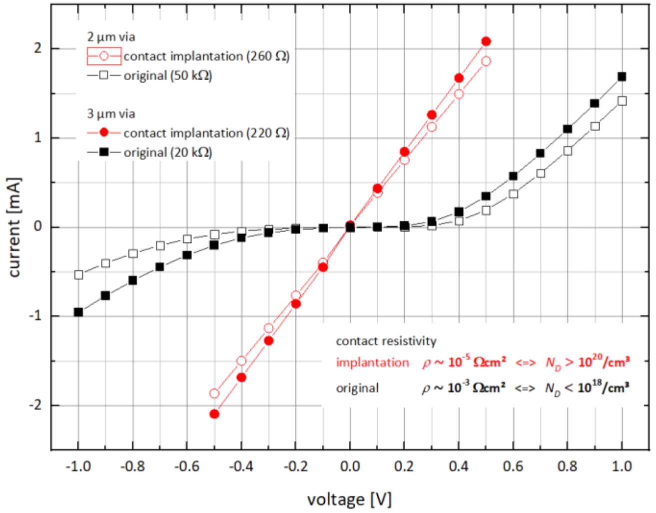
  – reduction 1/100

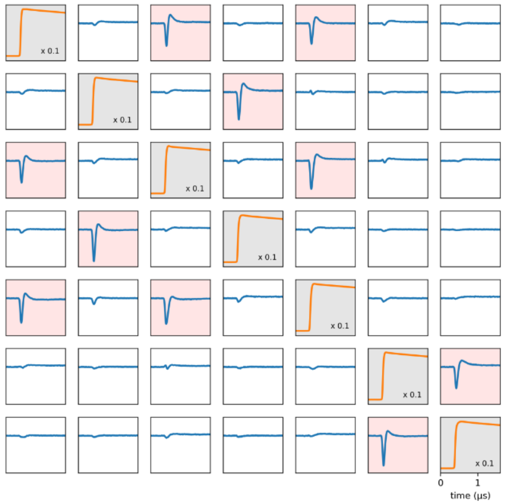
  ▷ cell-to-cell cross talk

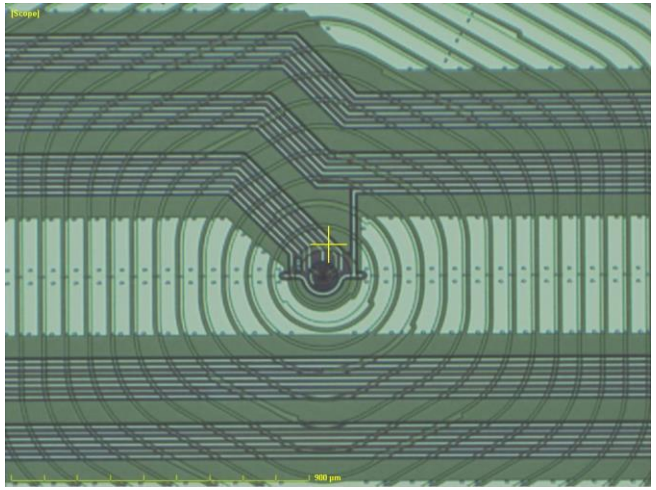
  – modified routing: line width & spacing

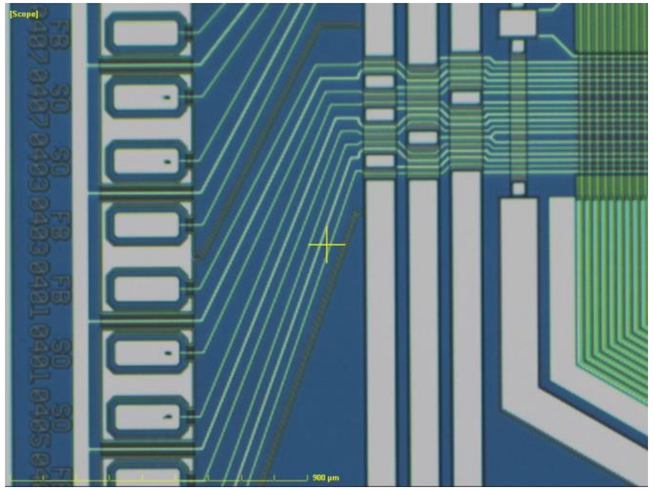
  – insulator thickness x 3.5

  – ground plane



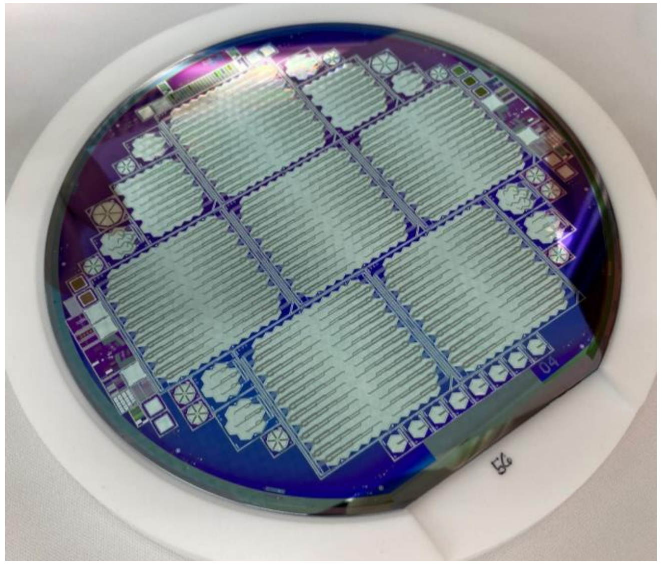




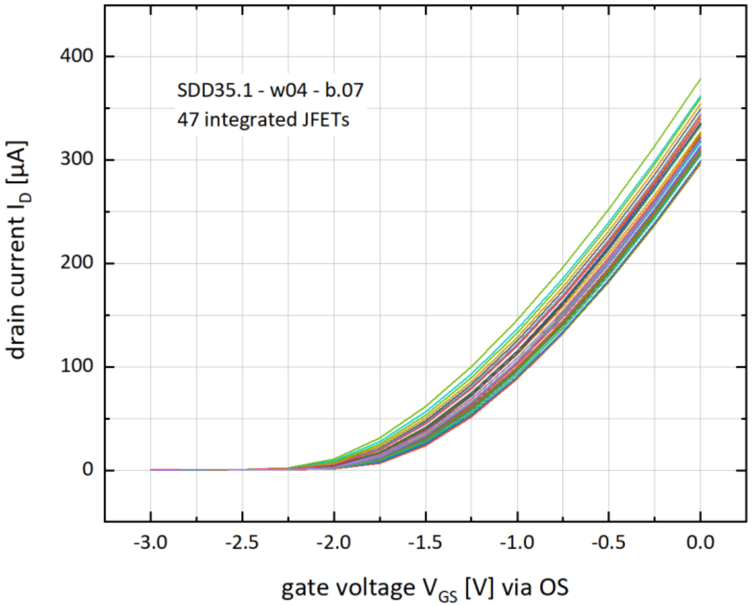


TRISTAN SDD

- final production SDD35
  - volume 10 wafers
  - chip count 6 x 166 cells
    2 x 47 cells
    8 x 7 cells
  - e.t.a. summer 2023 (7 wafers)
  - inline yield tests nominal
  - integration @ KATRIN ~ end 2024



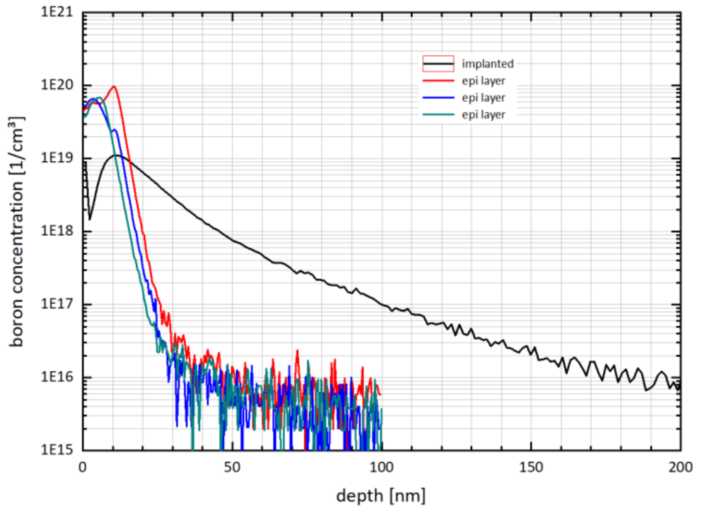
SDD35 wafer



inline test of 47 integrated nJFETs $I_D(V_{GS})$

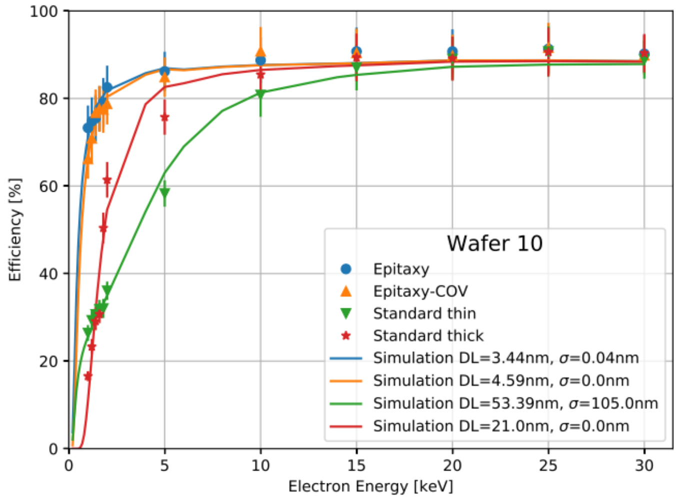
TRISTAN SDD

- entrance window
  - implanted diode
    - minimum energy & dose
    - min 'dead layer' thickness limited by profile diffusion @ thermal treatment for B activation
  - molecular beam epitaxy (MBE)
    - growth of B-doped Si
    - shallow profiles
    - external service by partner lab
    - tested on diode level
    - confirmed by e-beam current measurements
    - 3 SDD35 wafers with MBE window in production



SIMS measured boron profiles

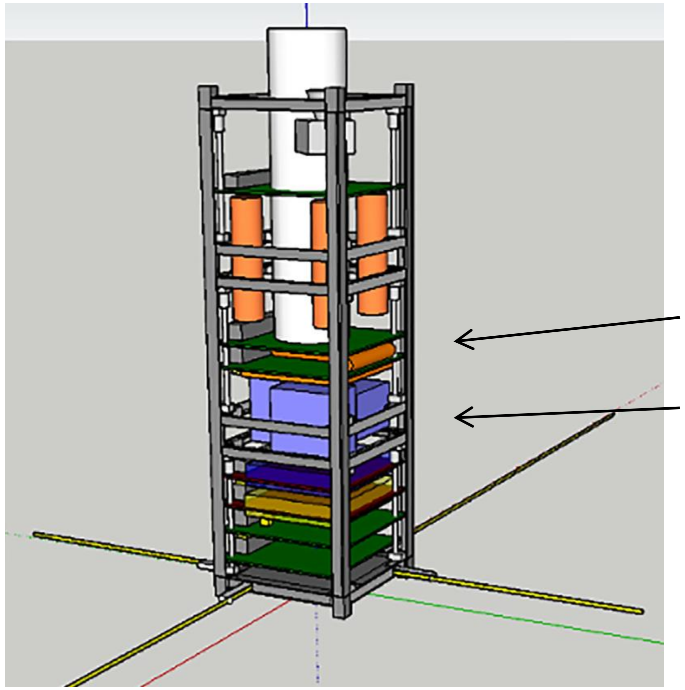
- implanted entrance window
- epitaxial grown layer(s)



charge collection efficiency by monoenergetic electron beam current (thesis M. Lebert)

COMPOL (COMPTON POLARIMETRY)

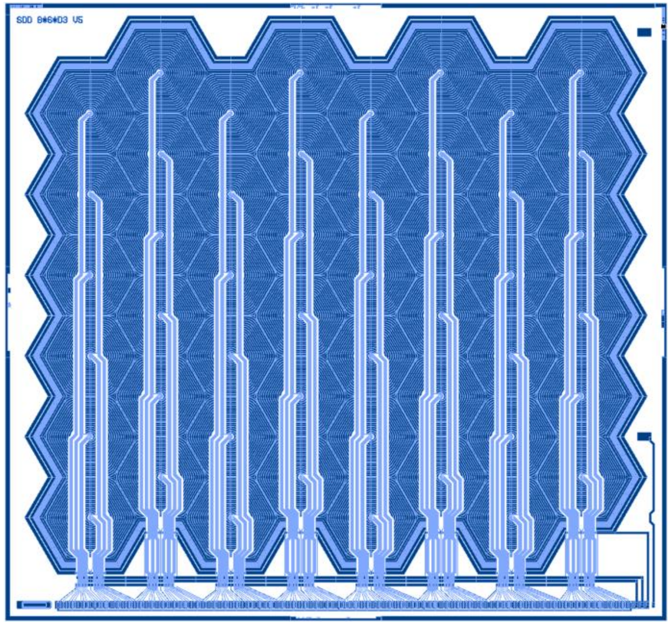
- Compton camera
  - 48-cells SDD
    - → scattering detector: interaction position & electron energy
  - $CeBr_3$ scintillator & SiPM matrix
    - → calorimeter: angle & energy of scattered photon
- CubeSat mission
  - standardised platform, 3 units
  - launch ~ 2025, 1 year, low earth orbit ~ 500 km
  - target: generation mechanism of black hole binary X-rays
    - – synchrotron emission (polarised)
    - – inverse Compton scattering (unpolarised)
  - hard X-ray polarimetry (Cygnus X1)
- precursor experiment on ISS
  - smaller sensor format
  - launch 2023?

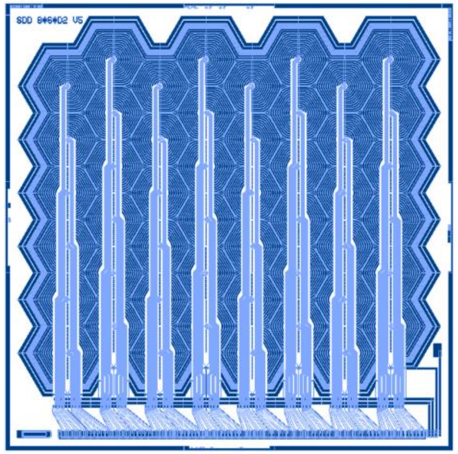


SDD

$CeBr_3$ calorimeter

CAD model of CubeSat ComPol

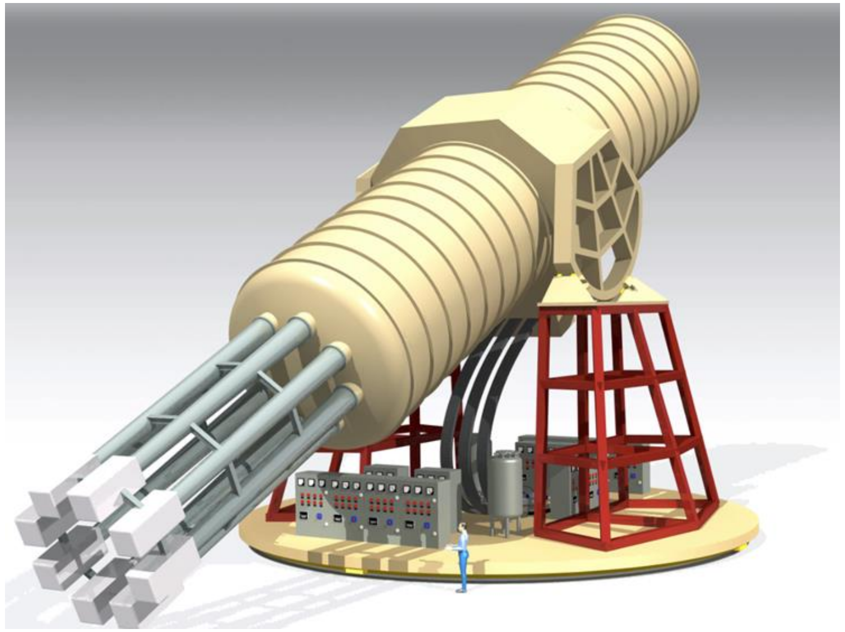




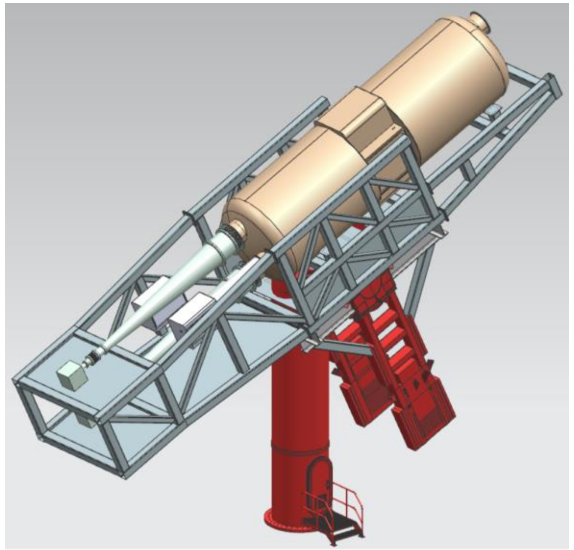
layout plots of 48-cells SDD
Ø = 3 mm, 2 mm

IAXO (INTENATIONAL AXION OBSERVATORY)

- solar axion search
  - ▷ predicted particle, dark matter candidate
  - ▷ conversion to X-ray in strong magnetic field
- IAXO telescope @ CERN
  - ▷ CAST successor
  - ▷ magnet 2.5 T
  - ▷ eight telescopes
    - X-ray mirror optics
    - X-ray sensors (3 competing proposals)
  - ▷ underground lab
  - ▷ pointing to the sun
- BabyIAXO demonstrator @ DESY
  - ▷ commissioning in 2024



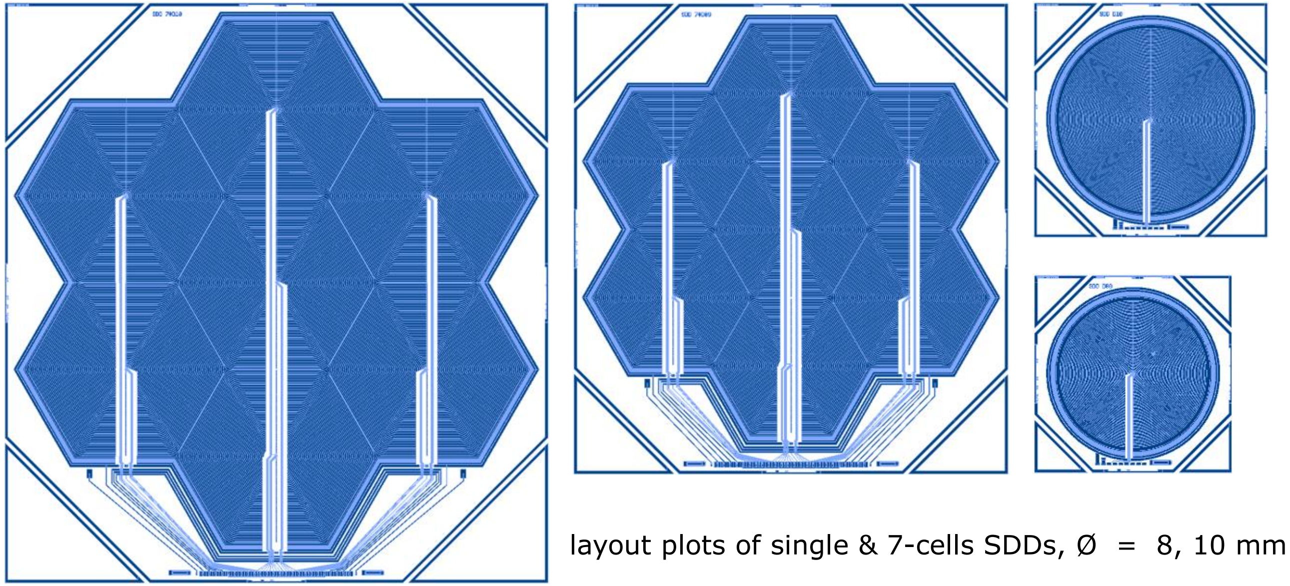
IAXO telescope @ CERN



BabyIAXO @ DESY

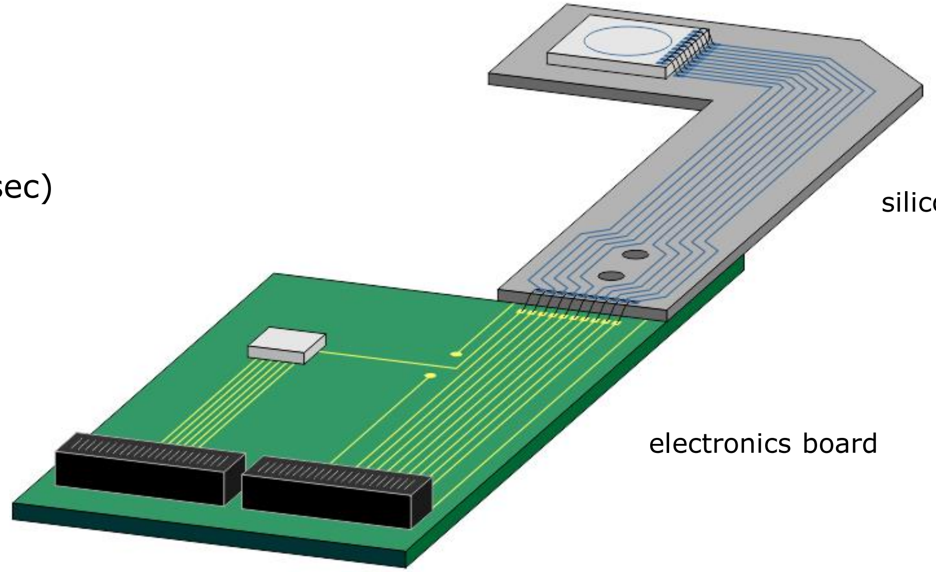
IAXO (Intenational AXion Observatory)

- IAXO detector
  - requirements
    - detection threshold 1 keV
    - efficiency interval 1 … 10 keV
  - single cell & seven cells SDDs
  - cell diameter 8 mm & 10 mm



layout plots of single & 7-cells SDDs, Ø = 8, 10 mm

- low countrate experiment
  - radiopurity requirement: 10^{-8} - 10^{-7} counts/(keV · cm^2 · sec)
  - silicon adapter in fabrication
  - optional active Ge shield



SUMMARY

- Silicon Drift Detector
  - SDD topology
    - → large area, low noise, high count rate
  - integrated FET
    - → less noise, higher count rates
    - → no pickup, no microphonic noise
  - elaborate process technology
    - → low leakage current, moderate cooling
  - numerous applications
    - → X-ray spectroscopy, particle spectroscopy