Development of an active Transverse Energy Filter (aTEF) with angular-dependent electron detection for background reduction at the KATRIN experiment

Sonja Schneidewind for the KATRIN Collaboration
University of Münster, Germany
TIPP conference Cape Town, 07-09-2023

Team:

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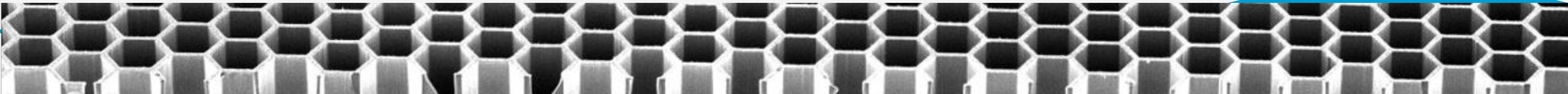
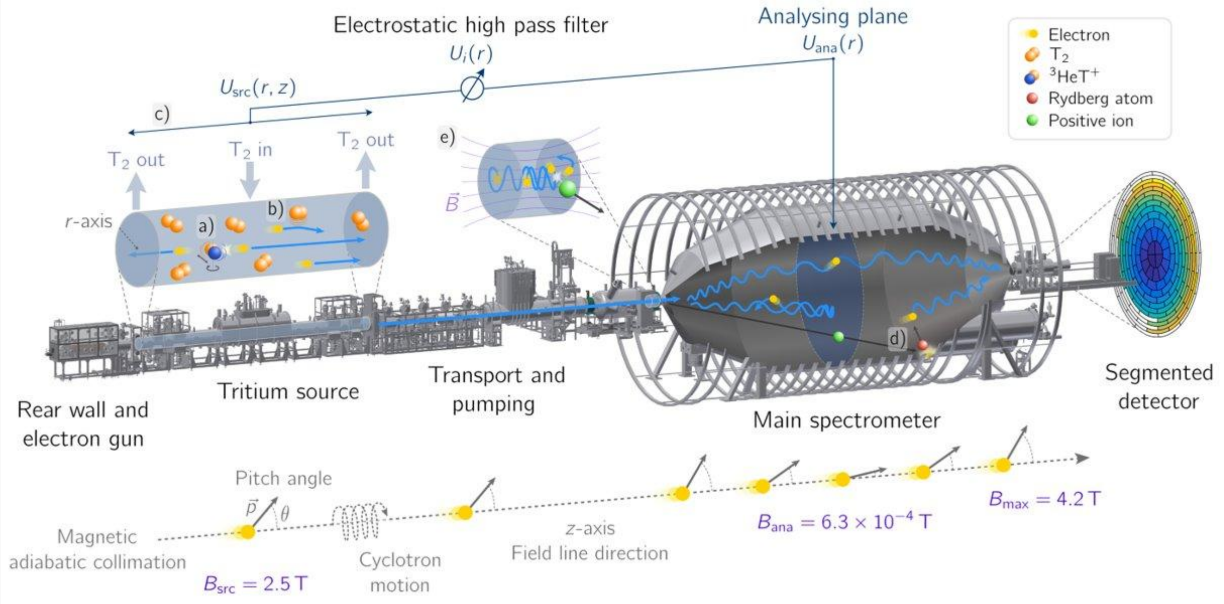
with help from Wolfram Pernice (PI / CeNTech / KIP Heidelberg), Maik Stappers (PI / CeNTech Münster), Norbert Wermes (PI Bonn)



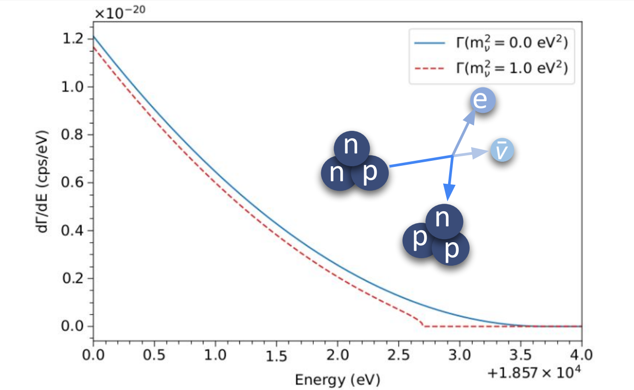
KATRIN Experiment

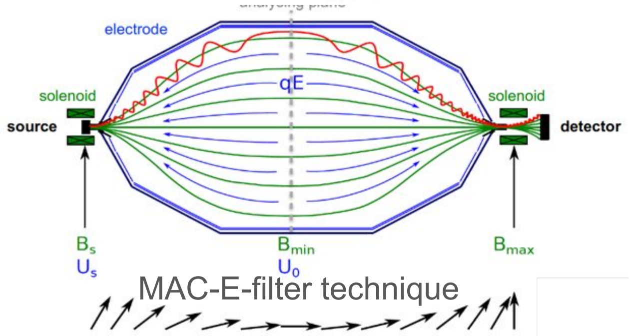
See talk #144 by Frank Edzards

- Goal: Measurement of incoherent sum of neutrino masses $m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$
- Approach: Precision spectroscopy of kinetic tritium β–decay spectrum in endpoint region



[Nature Physics volume 18, pp. 160–166 (2022)]





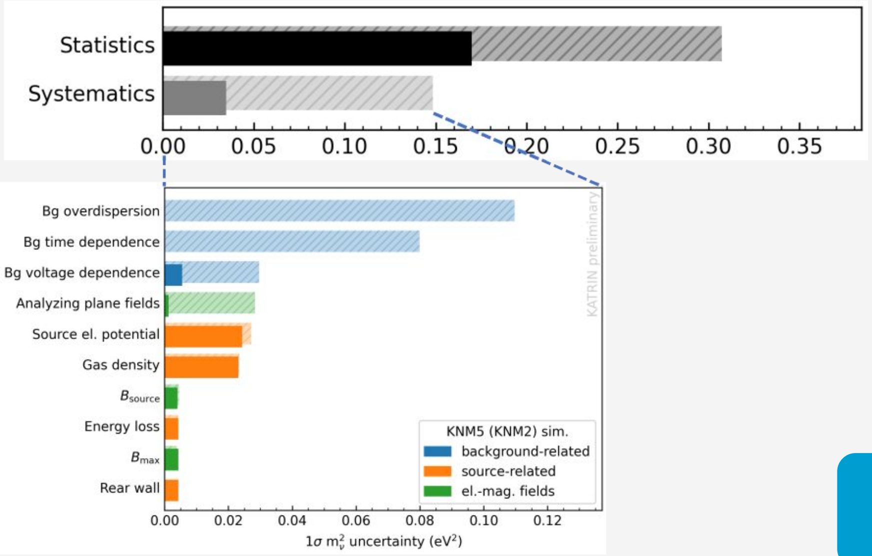
MAC-E-filter technique

Current mass limit:
$m_\nu < 0.8$ eV/c² (90% C.L.)

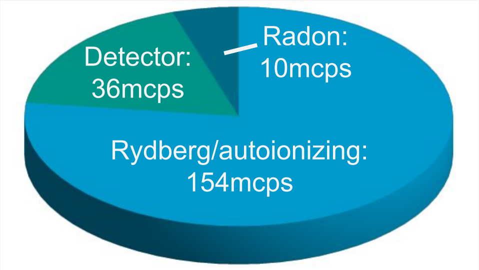
KATRIN sensitivity & background

- Strong reduction of systematics contributions from 2nd to 5th measurement campaign
- Statistical sensitivity diminished by background level of ~140mcps
  → Currently predicted final sensitivity on *m*: *O*(300meV/c²) > 200meV/c² (design goal)

[KATRIN design report (2005)]



Contributions to neutrino-mass uncertainty

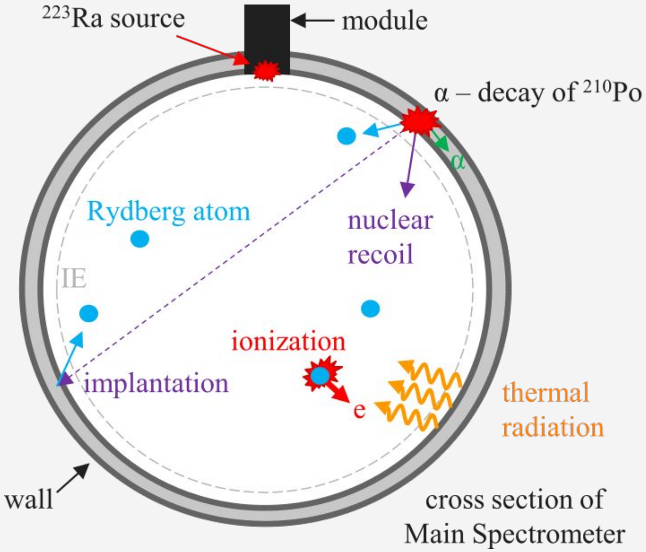


Background composition during KATRIN's 2nd measurement campaign

Background level limits KATRIN's final neutrino-mass sensitivity

Rydberg background

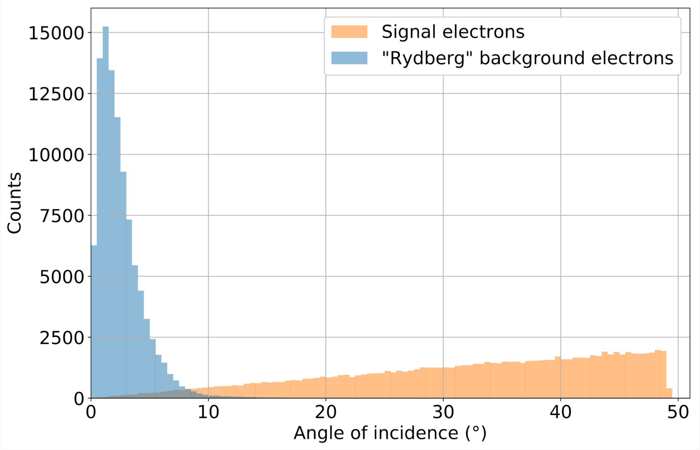
Generation of Rydberg background electrons



[Astroparticle Physics 138 (2022) 102686]

- Proportional to fiducial volume
- Indistinguishable from signal electrons by energy
- **Narrow angular distribution around 0°, in contrast to signal electrons**

Simulated angular distribution of signal & background electrons at Focal Plane Detector



[K. Gauda, S. Schneidewind et al., Eur. Phys. J. C 82, 922 (2022)]

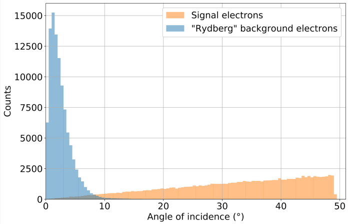
Can specific angular distribution of background be used for background suppression?

active Transverse Energy Filter

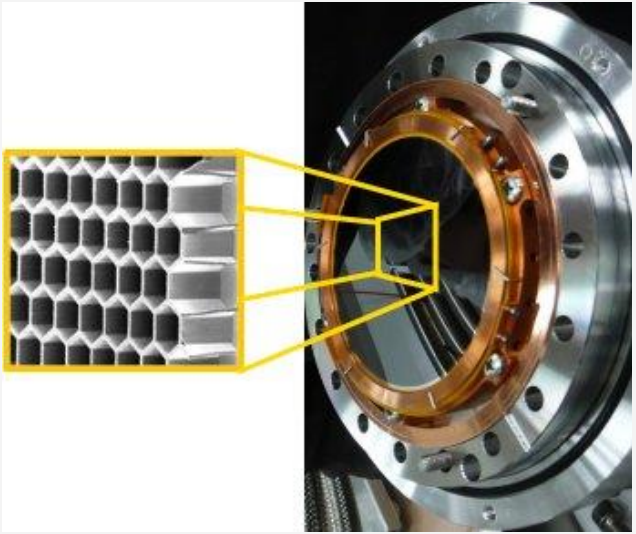
Background removal strategy: Make profit from **small angular distribution** of background: angular selective electron detection with **active Transverse Energy Filters (aTEF)**

→ Preferred detection of electrons with large incidence angles (signal electrons)

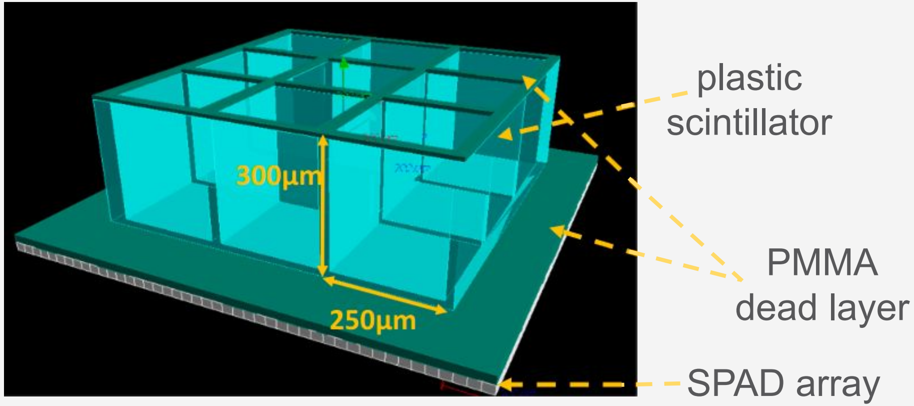
[aTEF idea paper: K. Gauda, S. Schneidewind et al., Eur. Phys. J. C 82, 922 (2022)]



Si-aTEF @ University of Münster

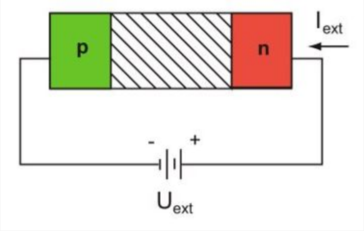


Scint-aTEF @ KIT Karlsruhe, Germany



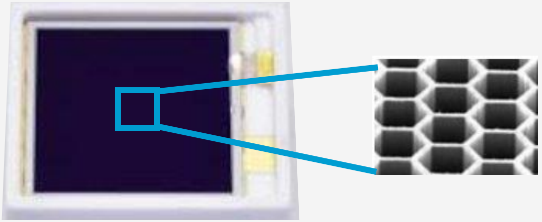
Si-aTEF working principle I

- KATRIN Focal Plane Detector (FPD): pixelated Si-PIN diode (9cm diameter)
- **Si-aTEF idea:** Microstructuring of FPD to function as aTEF:
  - Active channel walls:
    Charge collection from electrons with large pitch angles
  - Passive channel grounds:
    Absorption of electrons with small pitch angles
- **Requirement:** Production of microstructured Si-PIN detector

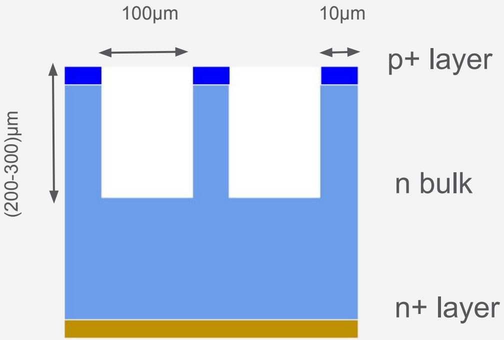


PIN-diode
[Kolanoski, Wermes, 2015]

Test samples: Microstructured PIN diodes



Hamamatsu S3590, 10x10mm², 300µm

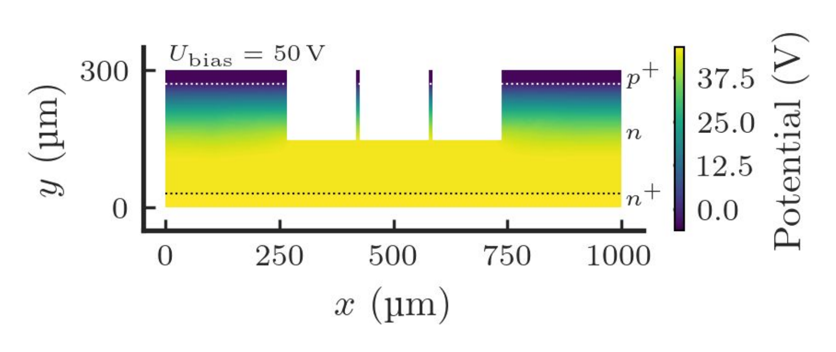


Si-aTEF working principle II

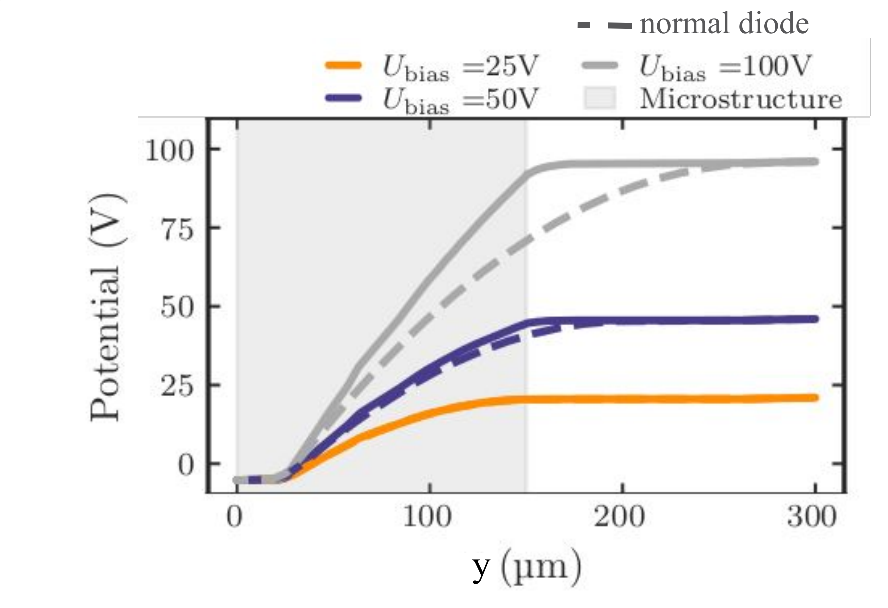
- Dependence of depletion layer depth on reverse bias voltage (normal PIN-diode):

$$d \approx \sqrt{\frac{2\varepsilon_0 \varepsilon_r}{e N_D} U_{bias}}$$

- Formation of depletion layer from p+ side to n+ side
- Potential gradient only in channel walls
  → **Active** channel walls
  → **Passive** channel grounds



2D semiconductor simulations via COMSOL® Multiphysics (*K. Gauda*)

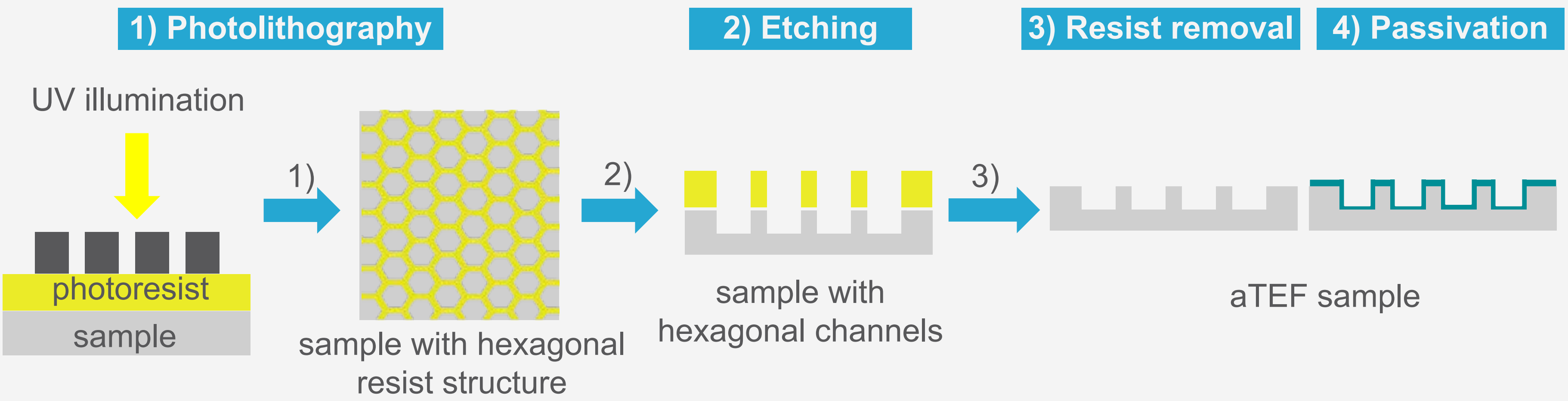


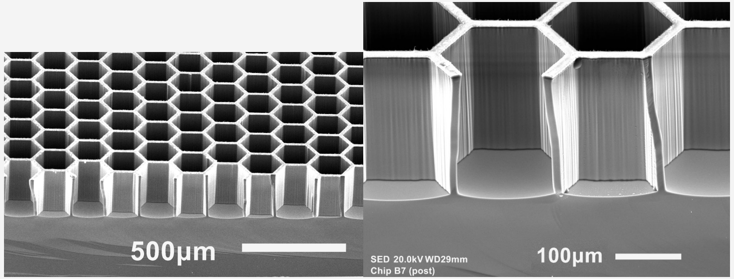
Potential gradient in 1D-cut through aTEF-channel (*K. Gauda*)

Microstructuring from p+-side results in e^- detection in channels only

Silicon microstructuring process

Cooperation with Prof. Pernice and M. Stappers from PI / CeNTech / MNF Münster, Germany



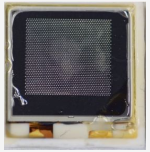


SEM pictures of Si wafer samples

[K. Gauda, S. Schneidewind et al., Eur. Phys. J. C 82, 922 (2022)]

Si-aTEF fabrication

- Application of Si-microstructuring process examined for Si chips to Hamamatsu Si-PIN diodes
- Challenges:
  - coverage of electrodes
  - ceramic housing by manufacturer
    → achievement of desired wall thickness of 10µm

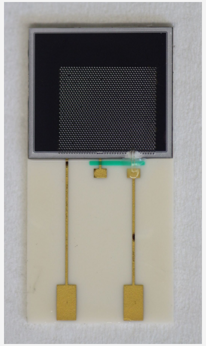


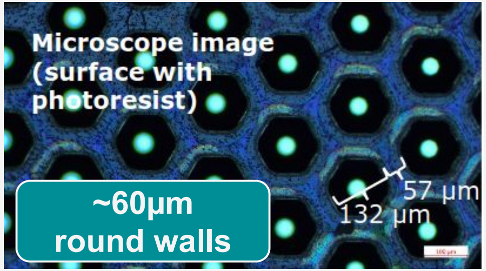
S3590 with regular housing

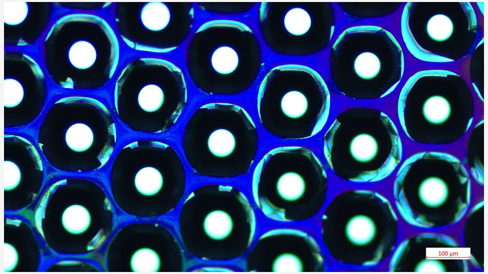
optimisation of photolithography and diode geometry

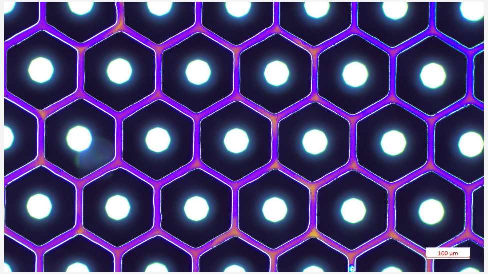
S3590 with flat housing

~15µm hexagonal walls



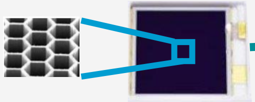




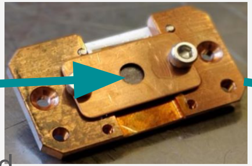


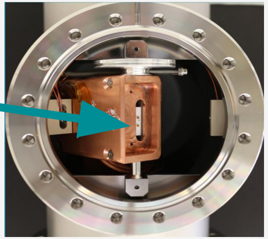
Microstructured geometries close to target - final geometry will be fabricated by institute in the Fraunhofer-Gesellschaft, a world's leading applied research organization in Germany

aTEF test setup Münster



Test samples: Microstructured PIN diodes

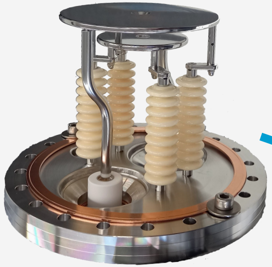


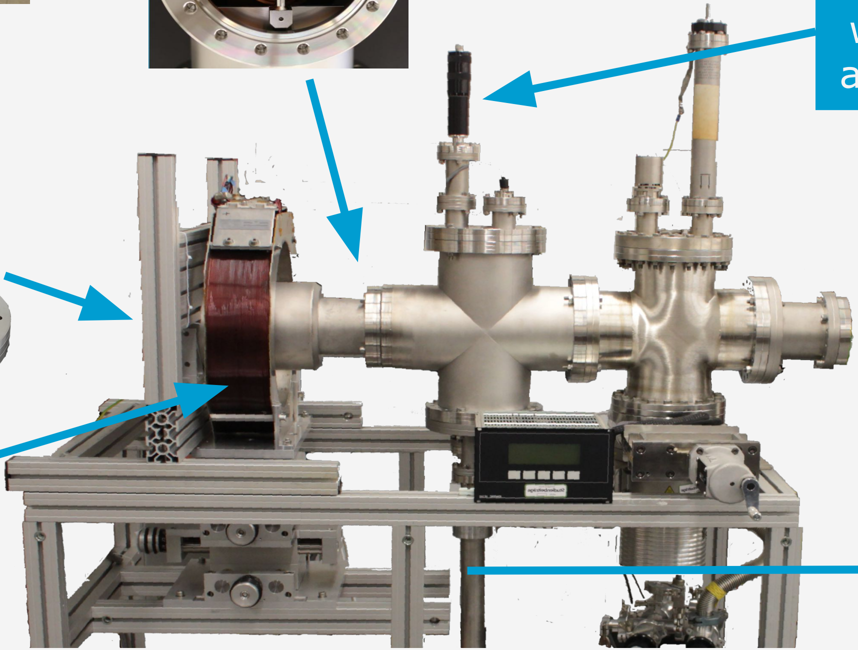


detector holder and preamplifier (rotatable)

linear feedthrough with bowden cable, angles -40° to +33°

photoelectron source, fixed angle, up to 23keV





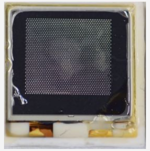
adjustable coil, ~20mT field

LN_2 cooling finger, down to -110°C

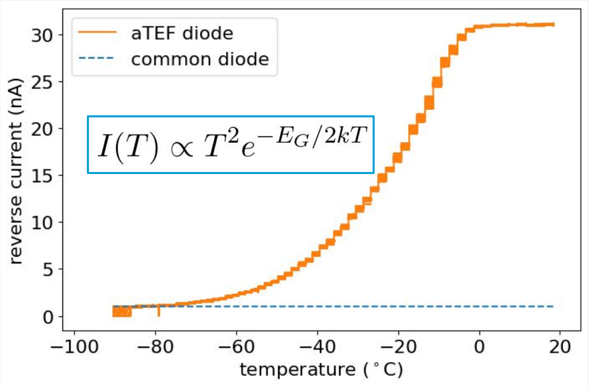
Performance of aTEF prototypes

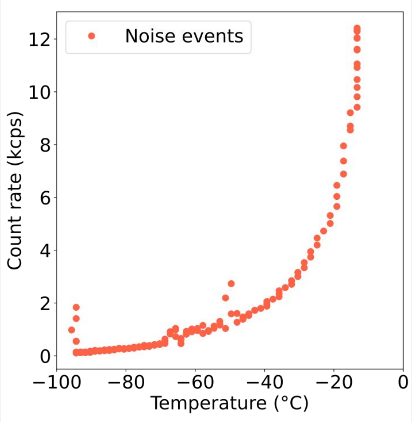
Enlarged **reverse current and noise** characteristics after microstructuring:

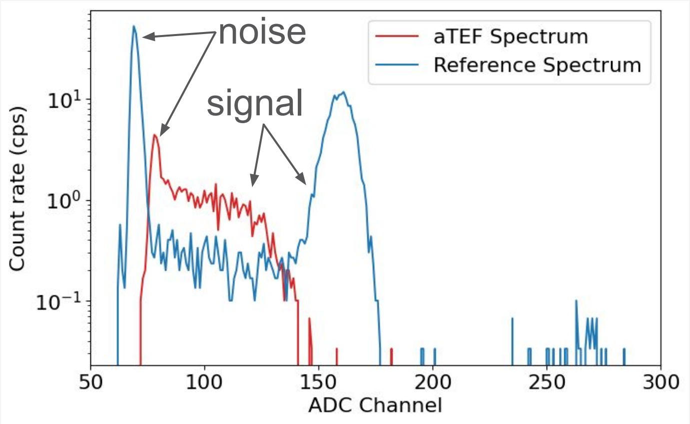
- unstructured diodes: typically (1-3) nA @ room temperature
- microstructured diodes: shortcut current @ room temperature
- T↓ → noise level↓ & charge collection efficiency↑
  → **Cooling necessary!**



Microstructured Hamamatsu diode

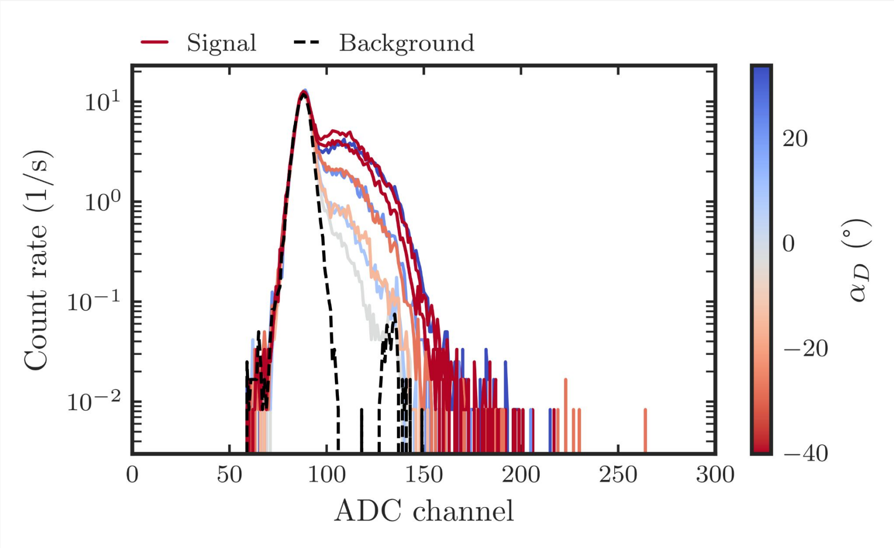




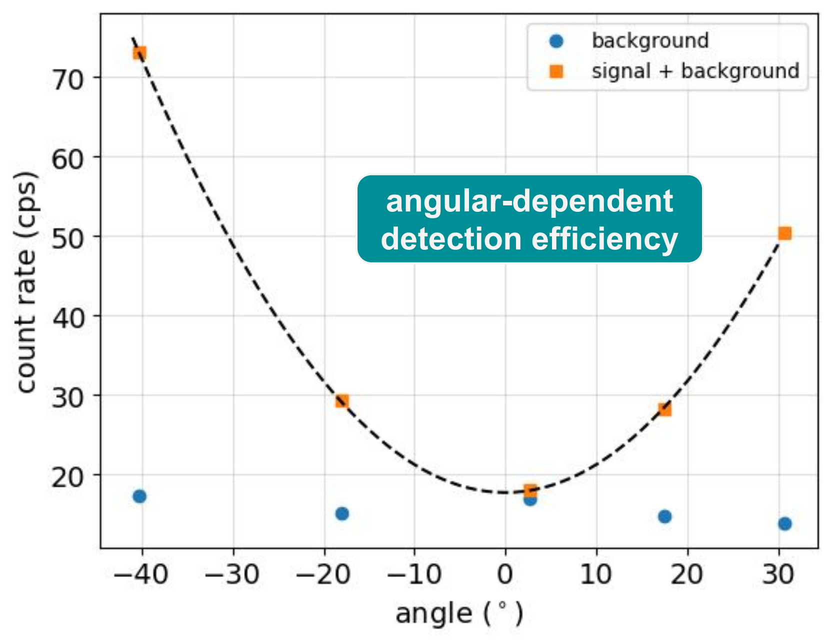


Typical aTEF operation temperature without passivation currently ~-100°C

Performance of aTEF prototypes



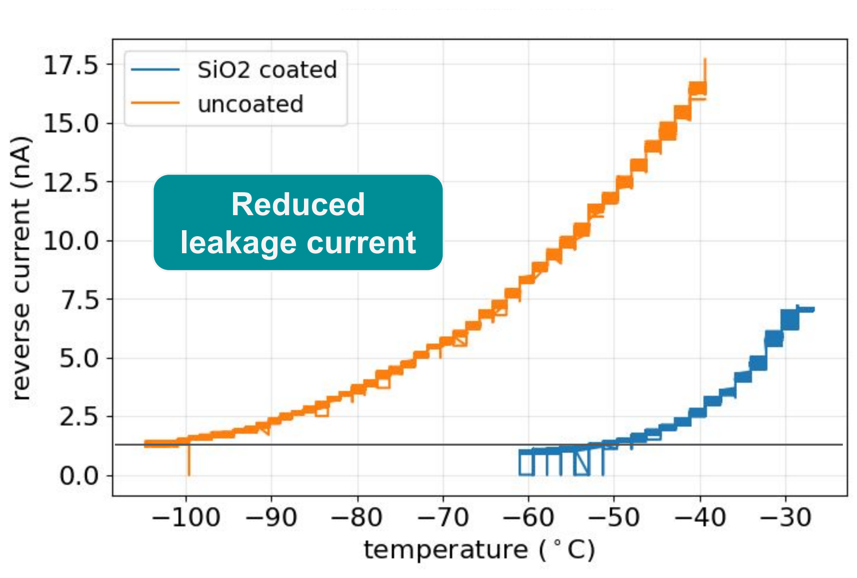
K. Gauda

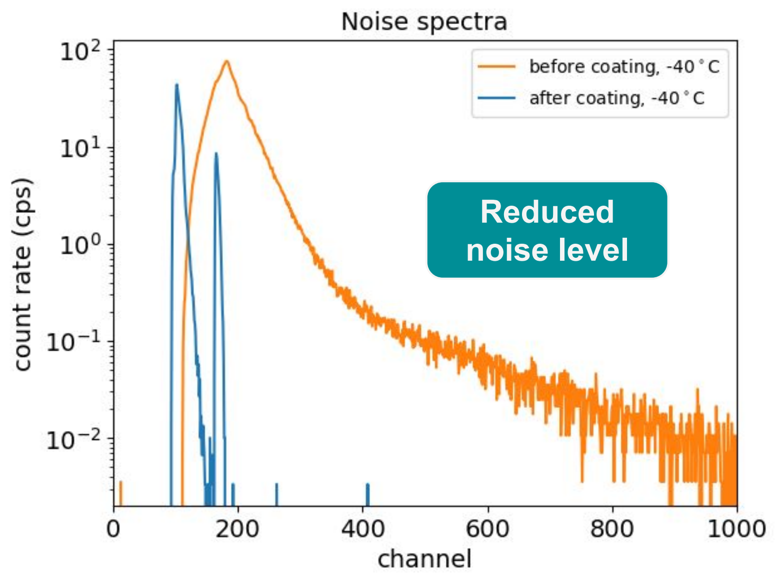


Open challenge:
Operation temperature @ FPD around -40°C instead of -100°C

Performance improvement by passivation layer

Deposition of SiO_2 passivation layer via thermal Physical Vapor Deposition (PVD)

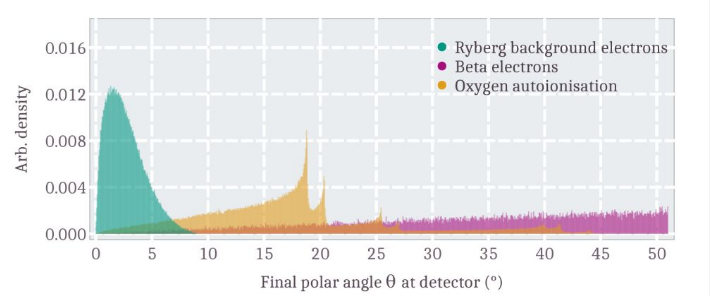




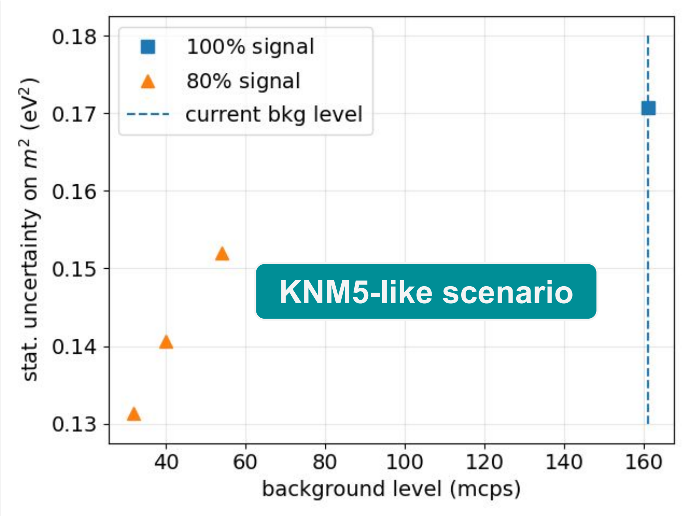
enhancement of operation temperature from -100°C to -50°C / -40°C by passivation layer

Possible sensitivity improvement of KATRIN by aTEF

[D. Hinz, Background systematics and extensions to the KATRIN background model, PhD thesis, 2022]



- Expected signal detection efficiency of an aTEF: ≈ 80% of current KATRIN detector
- Expected background reduction depending on background composition: ≈ (67 - 80)%
- Simulation of possible sensitivity improvement with aTEF with KATRIN's recent KNM5 measurement campaign as example

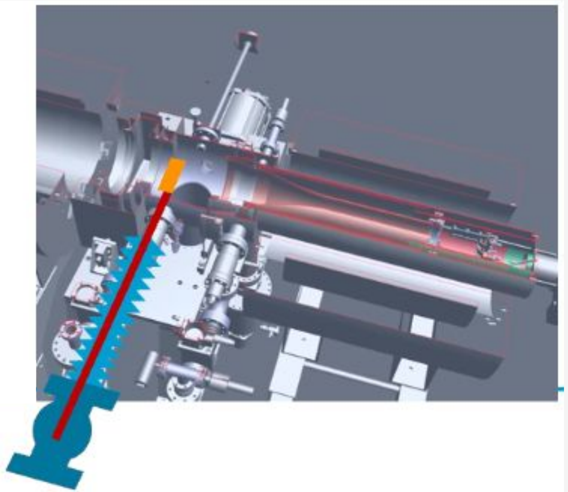


Example KNM5: 11% - 23% better statistical uncertainty on squared neutrino mass m^2 with aTEF

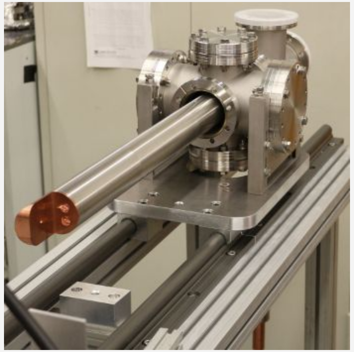
Outlook: Next steps for an aTEF at KATRIN

Test setup for aTEF testing in KATRIN beamline:

- to be installed in KATRIN detector section
- features easily accessible test platform without breaking detector UHV

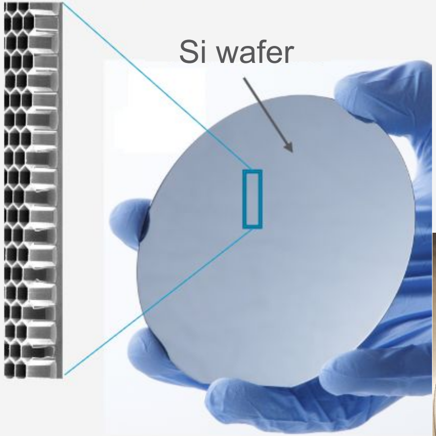


side-access for detector testing

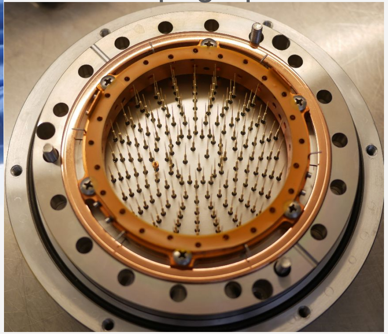


Upcoming stability test:

4” test wafer being produced by Fraunhofer institute for applied sciences IZM



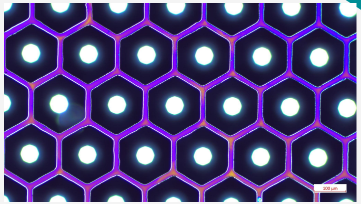
detector holder with pogo pins

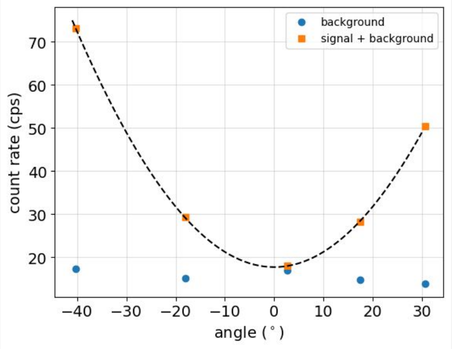


Summary & Outlook

Supported by BMBF Germany under contract number 05A20PMA & 05A23PMA & GRK2149

- Final KATRIN sensitivity with current background m_ν < 300meV/c² at 90% C.L. → larger than design goal
- active Transverse Energy Filter as possible concept for background reduction at KATRIN based on angular-selective electron detection
- Si-PIN diodes microstructured via Si etching show promising results towards angular-selective electron detection at KATRIN
- 11% - 23% improvement in stat. sensitivity on m_ν^2 expected with aTEF + Improvement of robustness of KATRIN result due to increased signal-to-background ratio



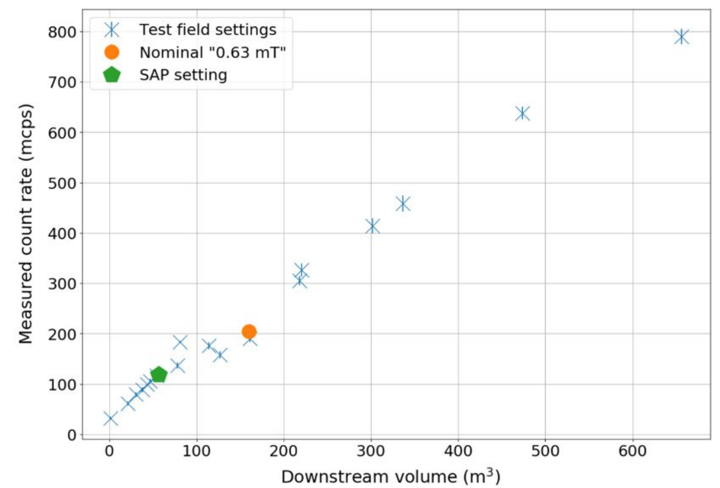


Backup Slides

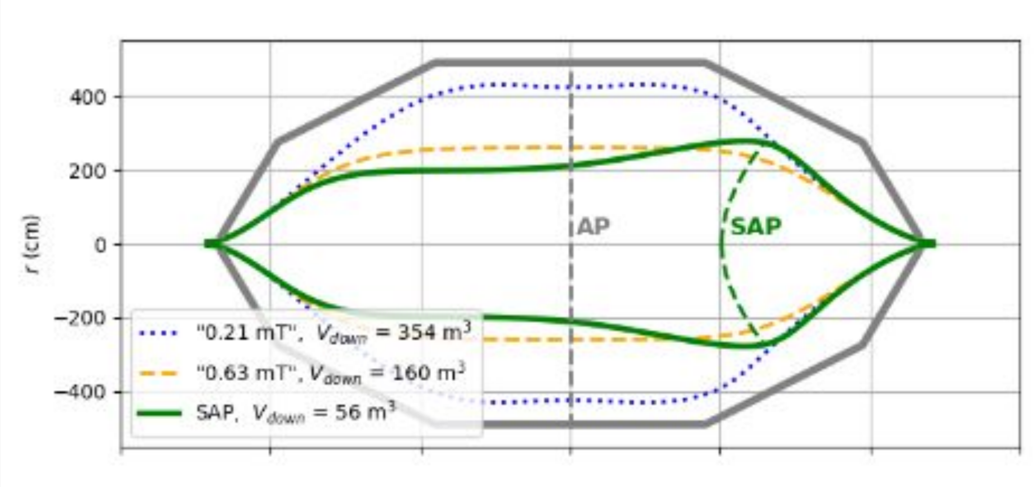
Background removal strategies

Making profit from **volume dependence** of background:

Shifted Analyzing Plane (SAP)



Background rate in dependence of downstream volume



SAP field configuration

[Eur. Phys. J. C (2022) 82: 258]

Background reduction by factor 2 already achieved with SAP configuration

Proof-of-principle of MCP-aTEFs/pTEFs

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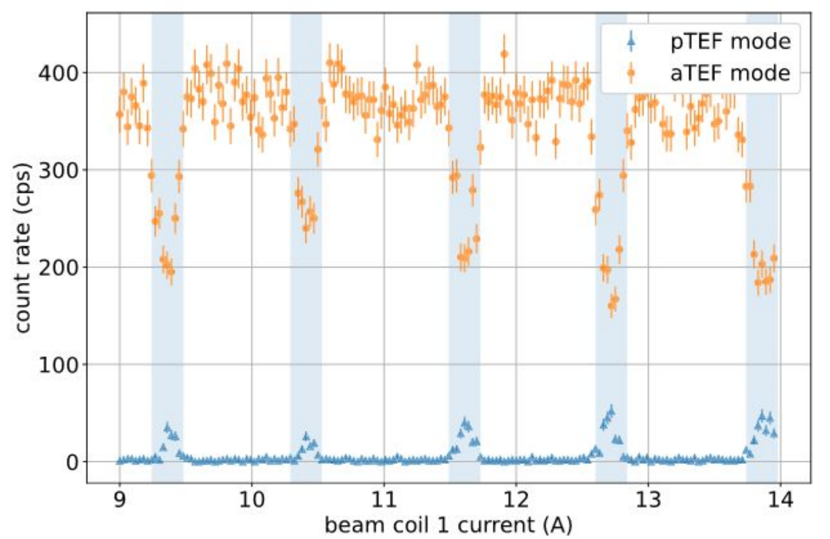
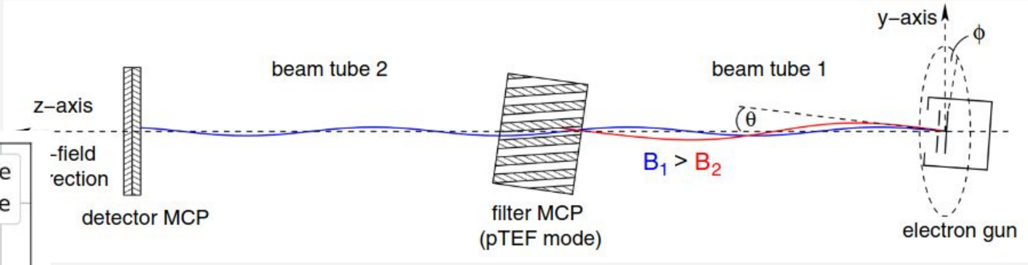
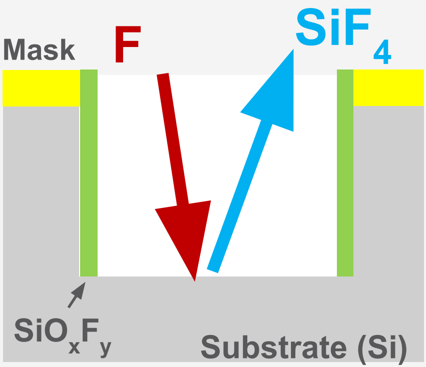




Angular-selectivite electron detection concept verified

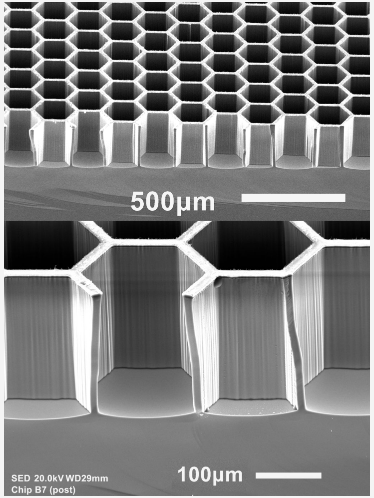
ICP-RIE Si Deep-Cryo plasma etching

- Highly-directional chemical etching via flourine radicals
- **Process gases:**
  - $SF_6 \rightarrow SF_x + F_y$
  - $O_2 \rightarrow O$
- **Etch product:**
  - $Si + F \rightarrow SiF_4$
- **Sidewall passivation:**
  - $Si + F + O \rightarrow SiO_xF_y$
  - SiO_xF_y sticks on the walls at -90°C to -140°C, volatile at room temperature



Satisfying Si microstructures achieved: 10µm channel thickness & 360µm depth

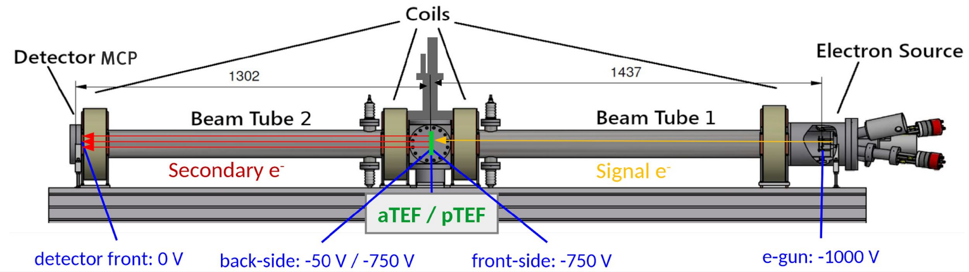
SEM pictures of Si samples

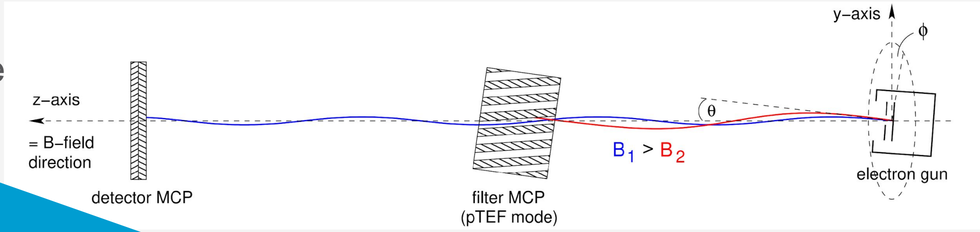


[K. Gauda, S. Schneidewind et al., Eur. Phys. J. C 82, Art. Nr. 922, 2022]

MCP-aTEF proof-of-principle

- **MCP-aTEF:** Angular selective electron detection with commercial Multi-Channel-Plate detectors
- Test setup at IKP, University of Münster with
  - Angular-selective photoelectron source *[Eur. Phys. J. C (2017) 77: 410]*
  - Guiding magnetic field along beamline
  - Filter MCP in middle
    - In active mode with acceleration voltage betwe front and back
    - In passive mode without acceleration vol
- Detector MCP signal depending on e$^-$ interaction in filter MCP





Electron differentiation by incidence angle with aTEF MCPs was shown *[arXiv:2203.06085]*

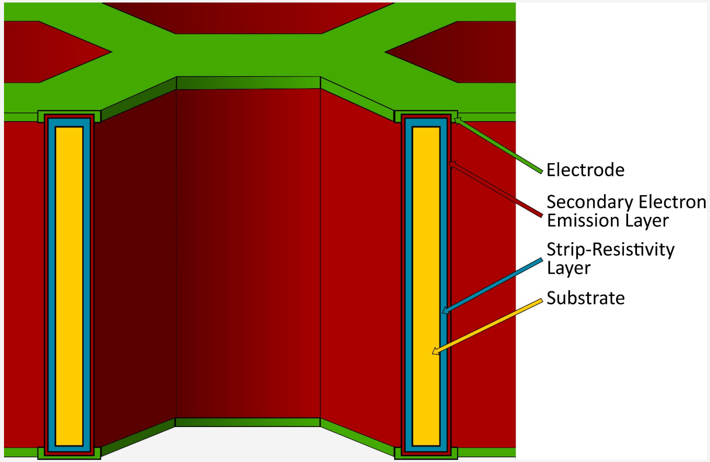
Commercial MCPs not suitable for KATRIN: OAR too low, channel diameter too small, no zero-angle w.r.t. B-field, background too high

Requirements for an MCP-aTEF at KATRIN

See poster by Christian Gönner

- Low intrinsic background - *O*(mcps/cm^2)
- Small aspect ratio - ≈3-4:1
- Large channel diameter - 50 µm to 100 µm
- Open-Area-Ratio of ≈90 % for high efficiency
- FPD compatibility by low gain (<<10^3)

Requirements not fulfilled by commercial MCPs



MCP-aTEF at KATRIN technically extremely challenging

Outlook: Challenges for an aTEF implementation at KATRIN

Basic functionality:

- Operation temperature ~ -40°C
- **Stability with regard to mechanical load due to pogo pins**
- **Passivation of channel grounds due to n-p doping of FPD**

Performance:

- Intrinsic background level like current FPD - O(10mcps)
- Minimum signal efficiency (75-80)%
- Background suppression of >=3
- Reasonable charge collection efficiency
- Comparable energy and time resolution to current FPD
- Homogeneity of detection properties over whole detector
- Control of backscattering effects