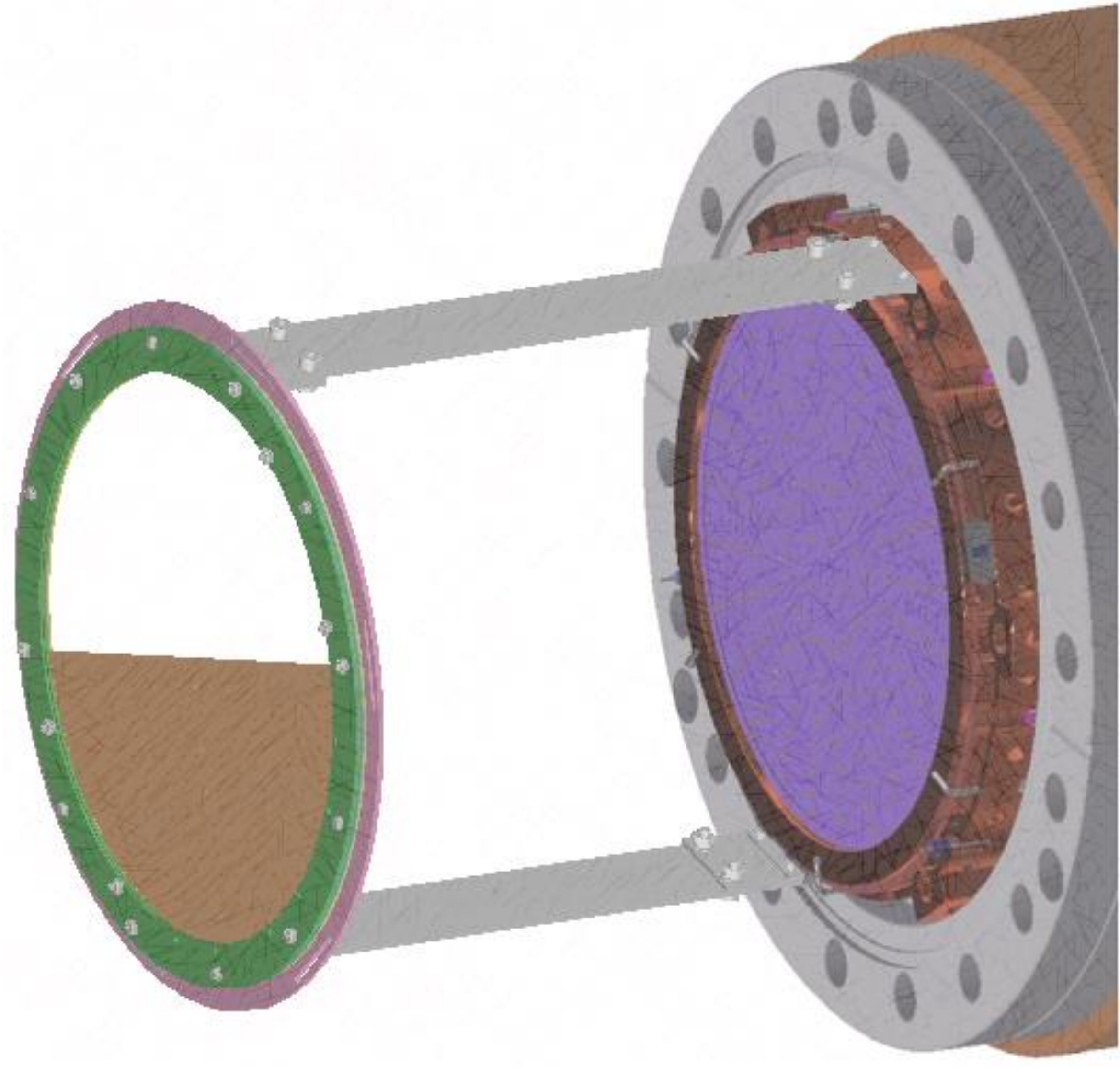
Background investigations at the KATRIN experiment using a transverse energy filter

Dominic Hinz

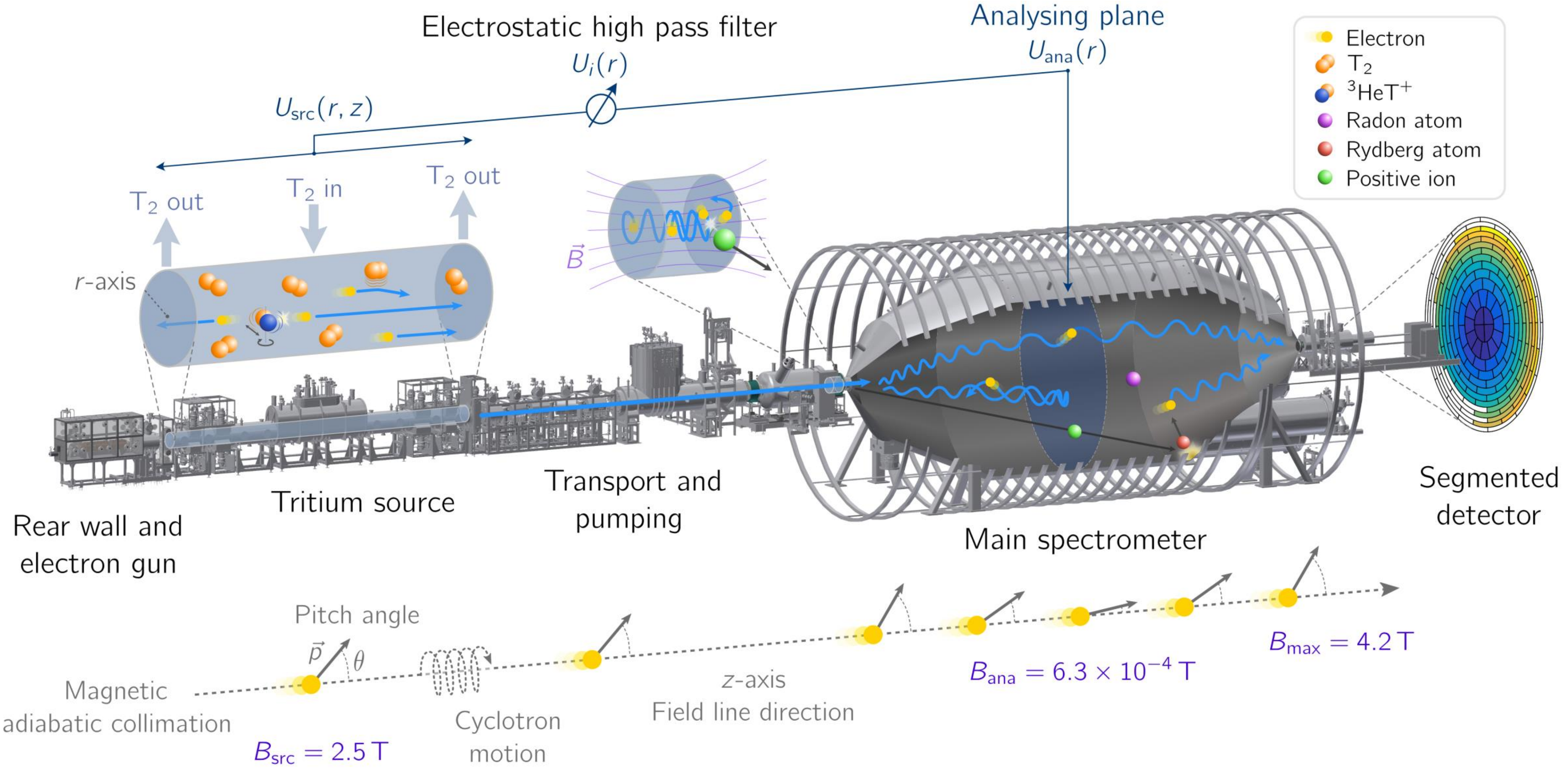
9th KSETA Plenary Workshop 2022 (14-16 March 2022)

Outline

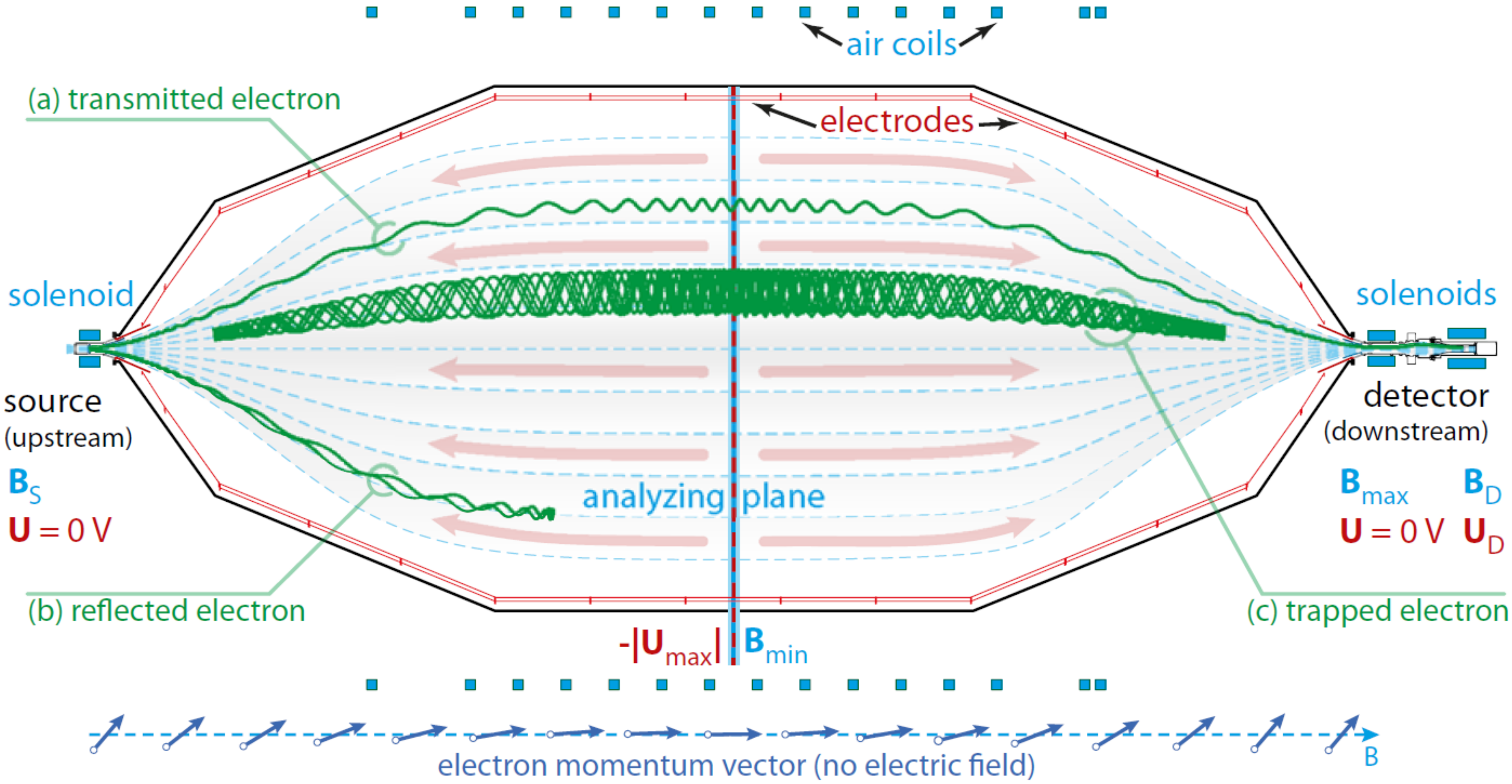
- KATRIN: Experimental overview
  - MAC-E-filter principle
- Present background model
- **p**assive **T**ransverse **E**nergy **F**ilter (pTEF)
  - What is that?
  - Why is its use of interest?
- Transmission studies with Kassiopeia
- Measurement configurations
- Preliminary results
- Summary



KATRIN experiment



MAC-E-filter principle

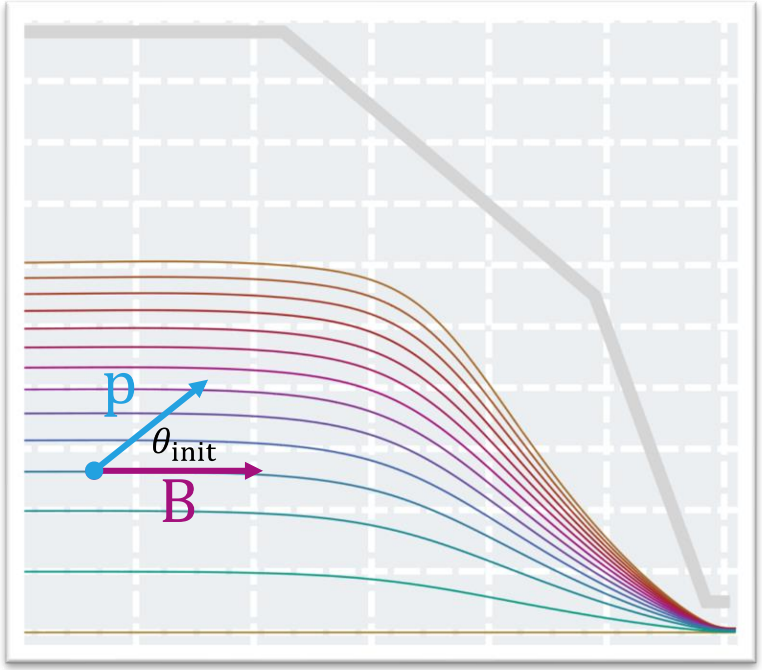


- Retarding potential U
- Magnetic fields B
- Transmission condition
- $\theta_{\max} = \arcsin\left(\sqrt{\frac{B_S}{B_{\max}}}\right)$
- Adiabatic motion
- Orbital magnetic moment $\mu = \frac{E_t}{B} = \text{const.}$
- E_t transverse kinetic energy

Transmission condition of background electrons

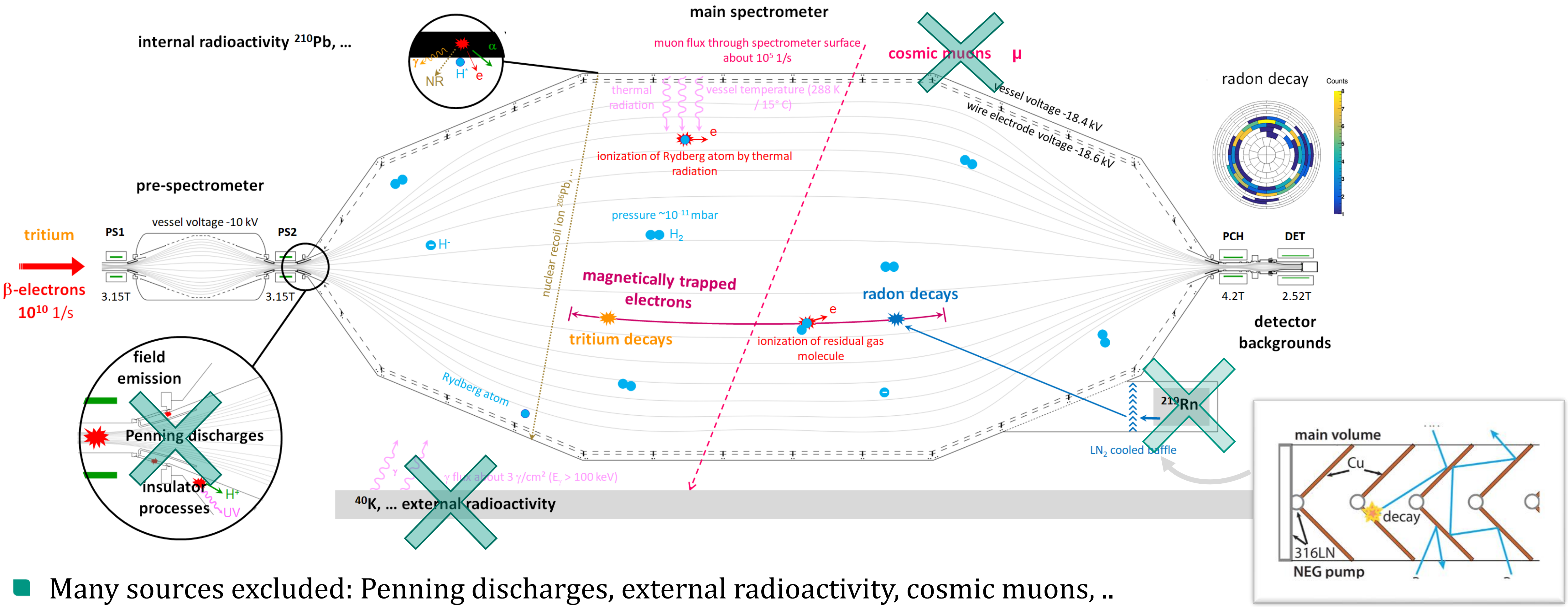
- Beta electrons: $\theta_{\max} = \arcsin\left(\sqrt{\frac{B_S}{B_{\max}}}\right)$

- Background electrons: $\mu = \frac{E_t}{B}$ conserved
  - $\mu_{\text{init}} = \frac{E_{\text{init}} \cdot \sin(\theta_{\text{init}})^2}{B_{\text{init}}} \equiv \frac{E_{\text{final}} \cdot \sin(\theta_{\text{final}})^2}{B_{\text{final}}} = \mu_{\text{final}}$
  - $\theta_{\text{final}} = \arcsin\left(\underbrace{\sqrt{\frac{E_{\text{i}}}{E_{\text{f}}} \cdot \frac{B_{\text{f}}}{B_{\text{i}}} \cdot \sin^2(\theta_{\text{i}})}}_{\leq 1}\right) \rightarrow E_t \leq \frac{B_{\text{i}}}{B_{\text{f}}} \cdot E_{\text{f}}$



  - If the condition is not fullfilled electrons get reflected at the pinch magnet and magnetically trapped

Present background model

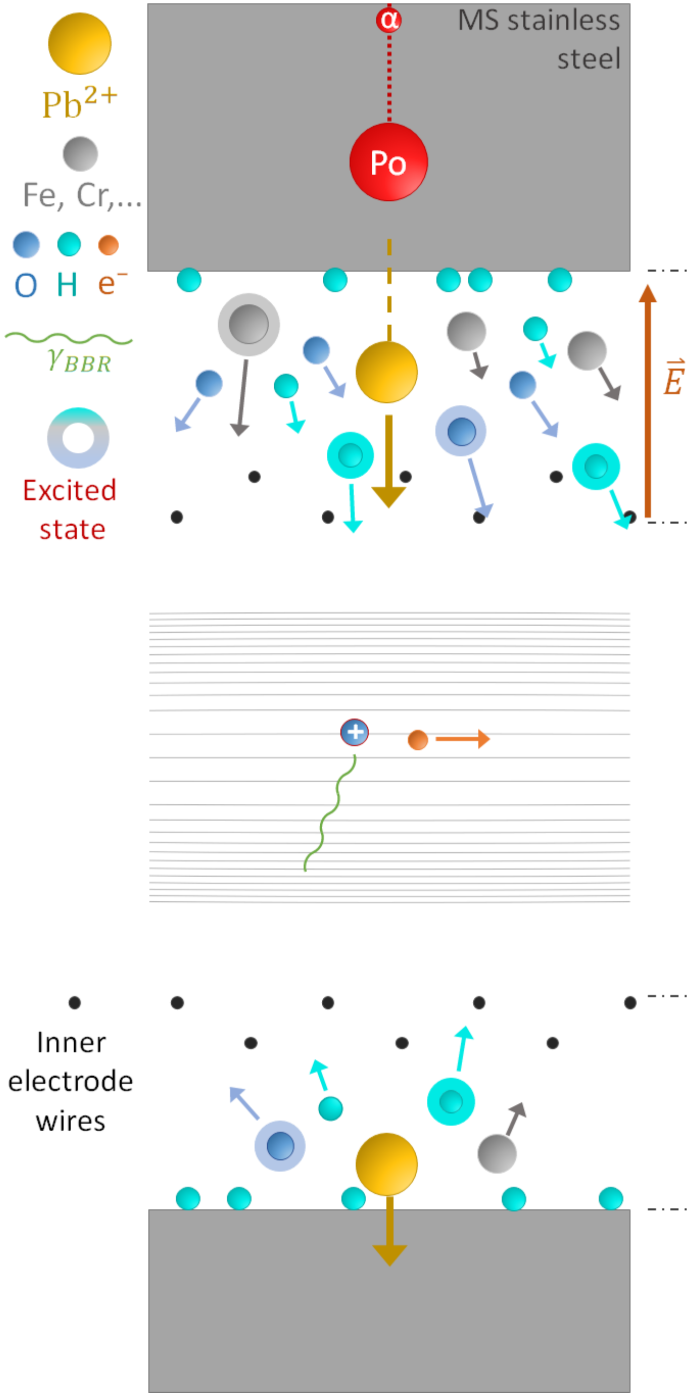


- Many sources excluded: Penning discharges, external radioactivity, cosmic muons, ..
- Remaining: Radon-induced, detector background and Rydberg background
  - Rydberg background: Neutral particle mediated background - highest contribution to total budget

Present background model:
Rydberg background hypothesis

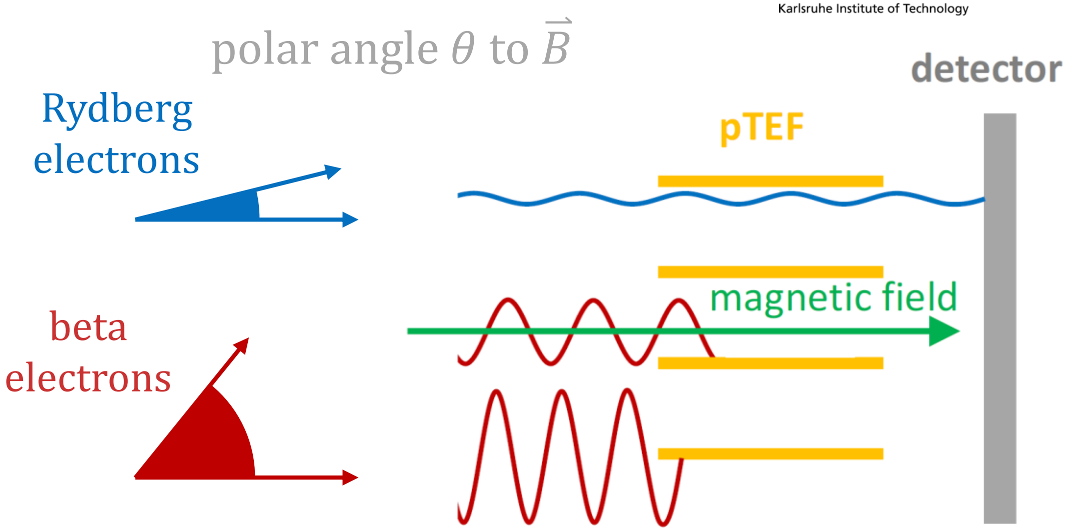
- Intrinsic radioactive contamination of ^{210}Pb
  - Half-life of 22 years
  - Resulting α-decay $^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb}$
  - Sputtering of atoms from vessel surface
- Neutral particles (atoms) as electron carrier
- Excited atoms: binding energy $E_{\mathrm{bind}} \propto \frac{1}{\mathrm{n}^2}$
  - High n: very low energy
  - Black-body radiation photons ~ 70 meV
  - Enough energy to ionise

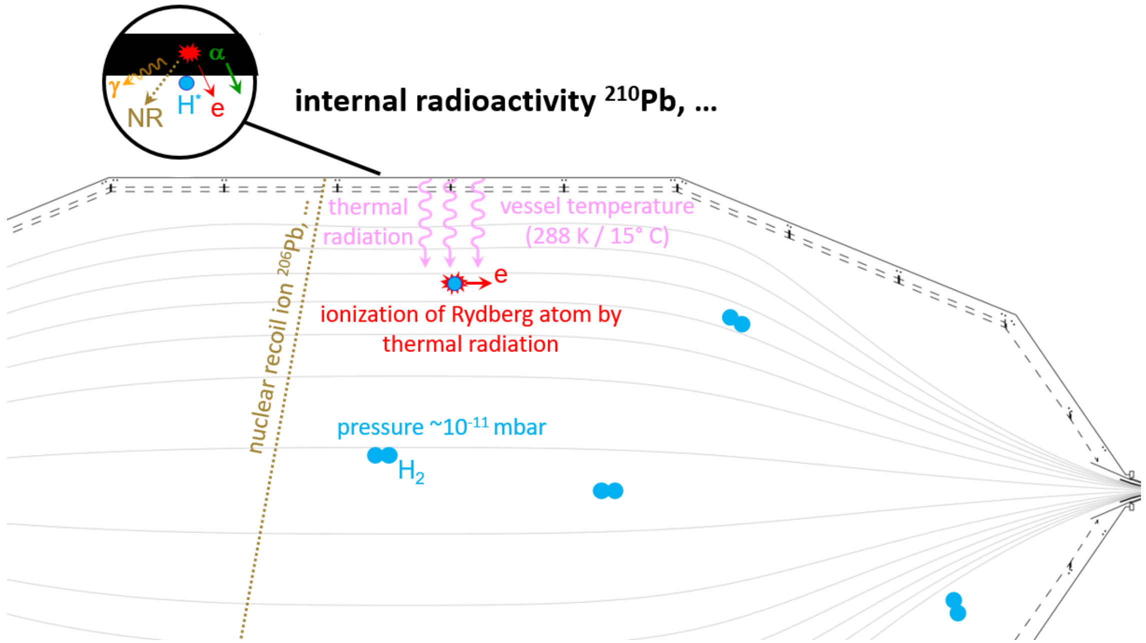
- Background electrons with small meV energies
  - Guided to detector by electro-magnetic field
  - No distinguishability of background and beta electrons at detector



What is meant by a pTEF? What was our aim?

- **p**assive **T**ransverse **E**nergy **F**ilter
  - Micro-structured unit
  - Blocking of electrons which interact with the filter
  - Not useful for neutrino mass measurements
  - Background investigations only





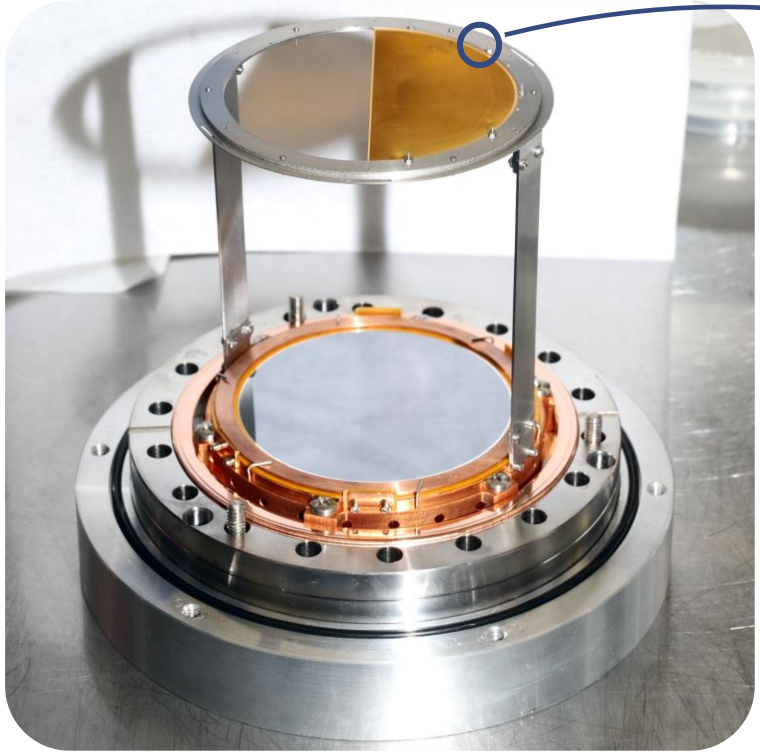
- What is the aim of investigations with a pTEF?
  - Proof of concept for such a type of filtering device
    - Future silicon or scintilliating aTEF concepts
  - Probing the Rydberg background scenario
    - Polar angular distribution
    - Transmission as a function of U_0 and B-field
    - → Energy of background electrons
  - Are there eV electrons ? (deduced by former PhD students)

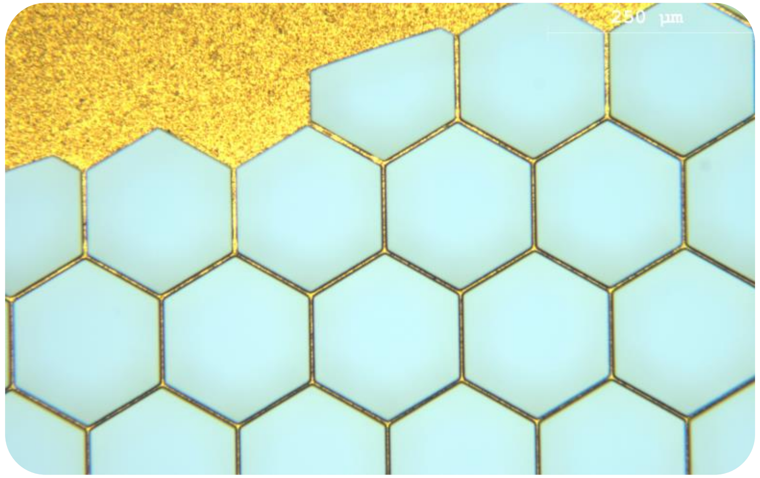
pTEF installation

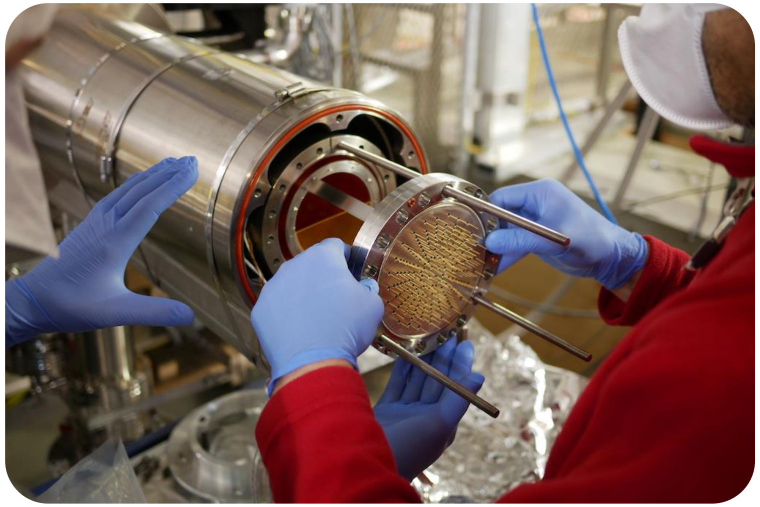
- Gold plate with microscale honeycomb structure
  - Side length 100µm
  - Wall thickness 8µm
  - Depth 250µm
  - Open-area-ratio (OAR) 91.4%

- Specific holding structure mounted directly on FPD wafer flange
- Distance to FPD ~11cm
  - pTEF placed at center of detector magnet
  - homogeneous, well-defined field B_{det}
  - Smallest impact of possible misalignment of pTEF with respect to magnetic field lines

- Measurement phase Dec ’21 to Jan ‘22

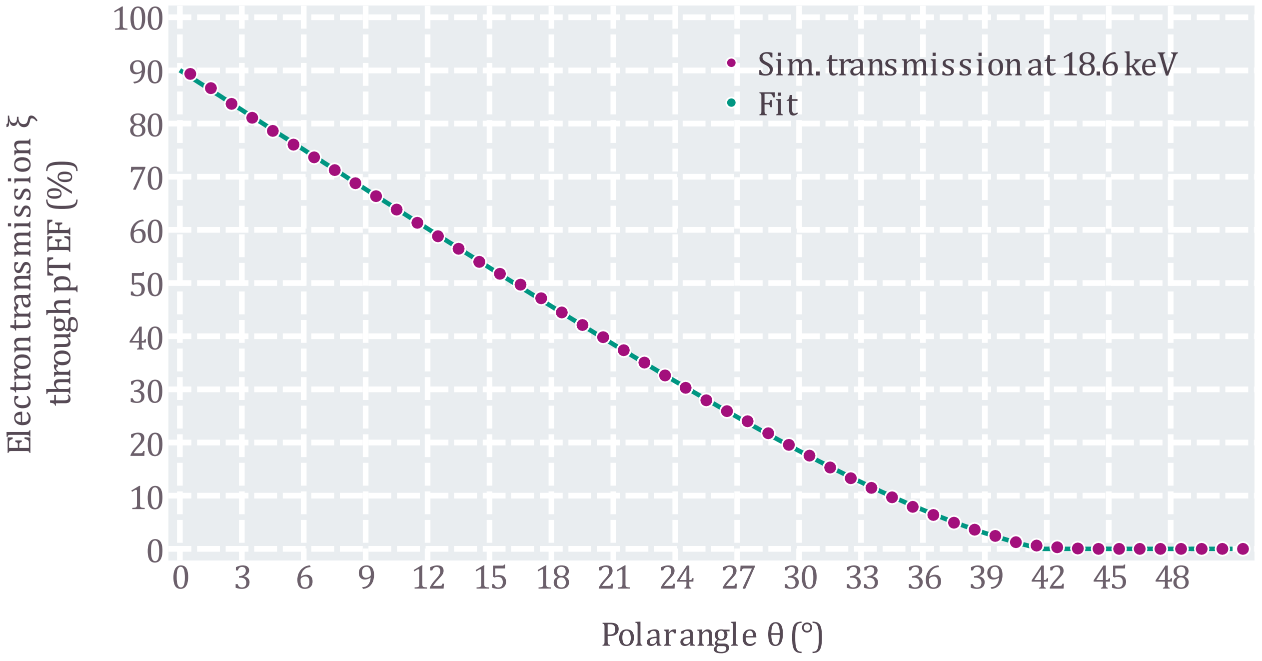






Transmission studies with Kassiopeia

- Honeycomb structure implemented in Kassiopeia
- Simulation of electrons with varying polar angle θ relative to $\vec{B}$
  - Determine final positions of track: a) front surface, b) within hexagons or c) behind
  - Different electron energies (12.1, 18.6 and 34.1 keV)
- Final polar angle at pTEF/detector θ_{final} as function of of B_{i}, B_{f}, E_{i} and E_{f} :
  - Using the invariance of the magnetic moment
  - $\theta_{\mathrm{final}} = \arcsin\left(\sqrt{\frac{E_{\mathrm{i}}}{E_{\mathrm{f}}} \cdot \frac{B_{\mathrm{f}}}{B_{\mathrm{i}}} \cdot \sin^2(\theta_{\mathrm{i}})}\right)$
- Transmission ξ through pTEF
  - Nearly linear with θ_{final}
  - $\xi = 0$ for $\theta > 43°$
  - $\xi < 1$ due to OAR
  - Most important quantity for transmission analysis

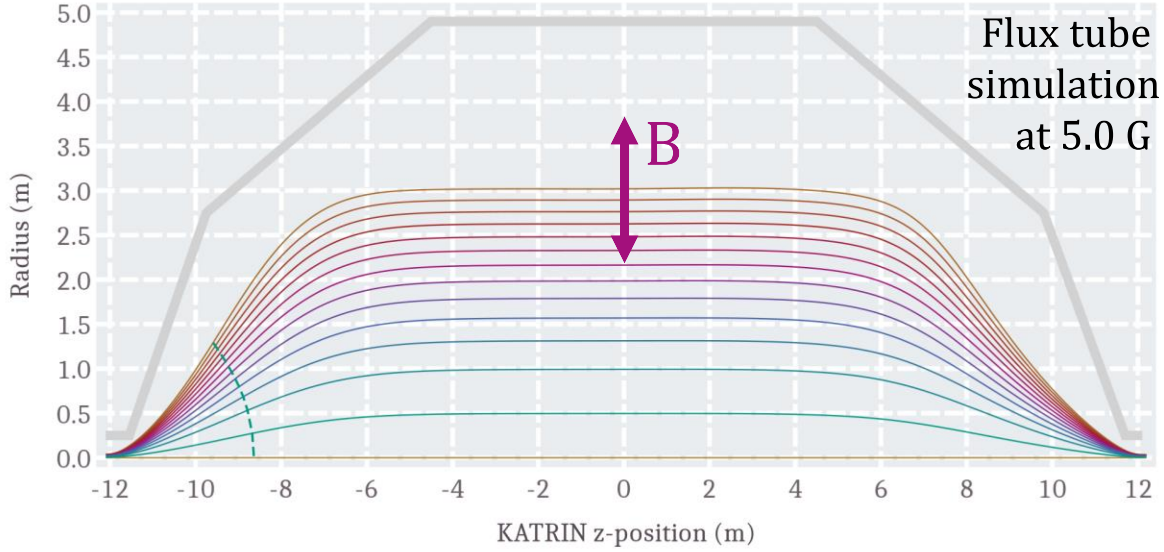


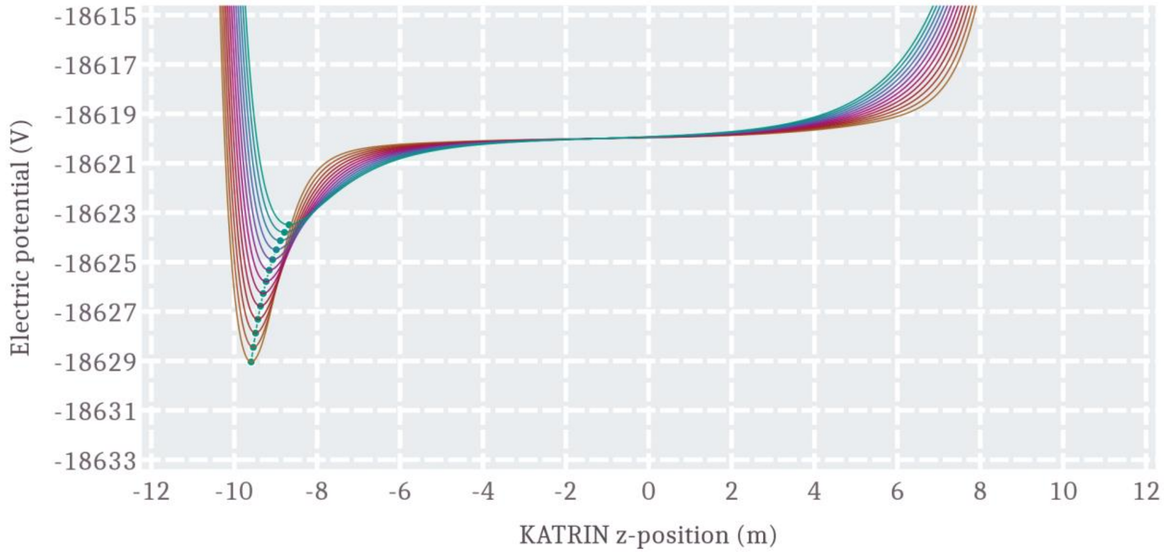
Measurement configurations

- $\theta_{\text{final}} = \arcsin\left(\sqrt{\frac{E_\text{i}}{E_\text{f}} \cdot \frac{B_\text{f}}{B_\text{i}} \cdot \sin^2(\theta_\text{i})}\right)$

- Investigation of background for different electro-magnetic fields
  - 2.7, 5.0, 8.0, 12.0, 17.0 G with non-centered potential
    - Beneficial for background investigation
    - Maximal rate: nearly whole flux tube mapped
    - Larger magnetic field → smaller flux tube volume
    - Variation of B_i
  - 5.0G central potential (NAP) and standard SAP
  - Retarding potential U_0: -12.1kV, -18.6 kV and -34.1 kV
    - Variation of E_f

- Further special measurements

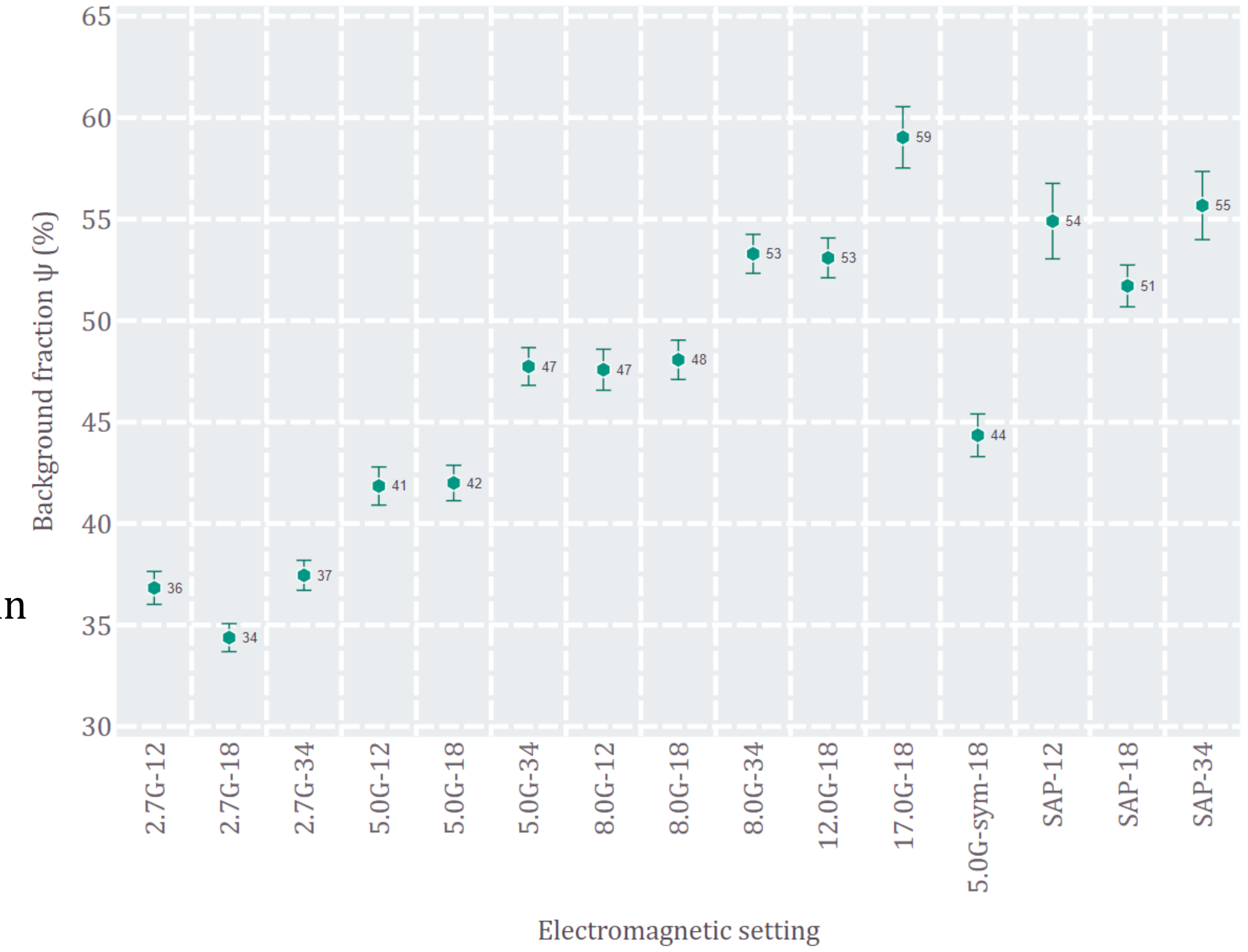




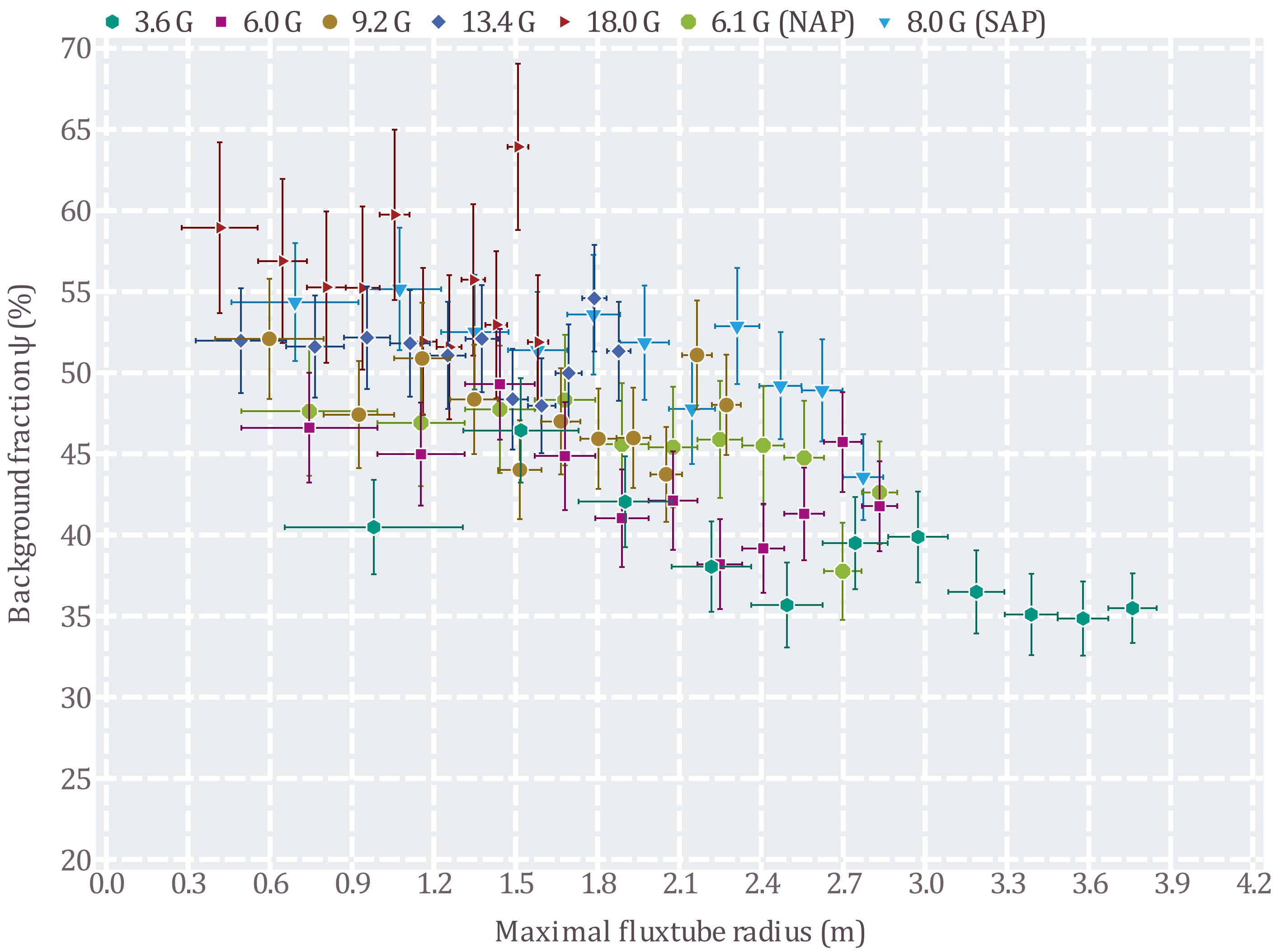
Results: Measured background fraction

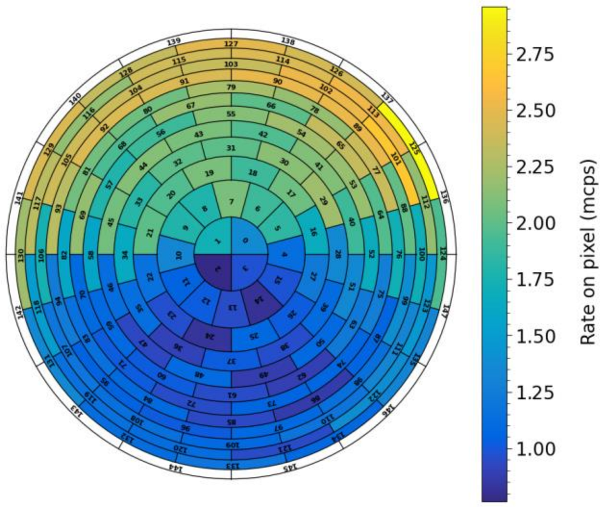
- Value of interest: transmitted background fraction $\psi = \frac{R_{\text{behind pTEF}}}{R_{\text{before pTEF}}}$
- directly depends on θ_{final} which is connected to $\overrightarrow{B_i}$ and U_0 via E_f

- Background fraction increases
  - with magnetic field
  - (with high voltage)
  - SAP compatible to 8G to 12G fields
- Measured transmission significantly smaller than in original Rydberg hypothesis
  - meV-scale electrons would be transmitted by 70 – 85 % !!
  - $\psi \sim 35\% \ - 60\%$
  - Do we have higher energetic electrons ?
    - If yes, where do they come from ?
    - If no, what diminishes the transmission ?



Results: Ringwise background fraction

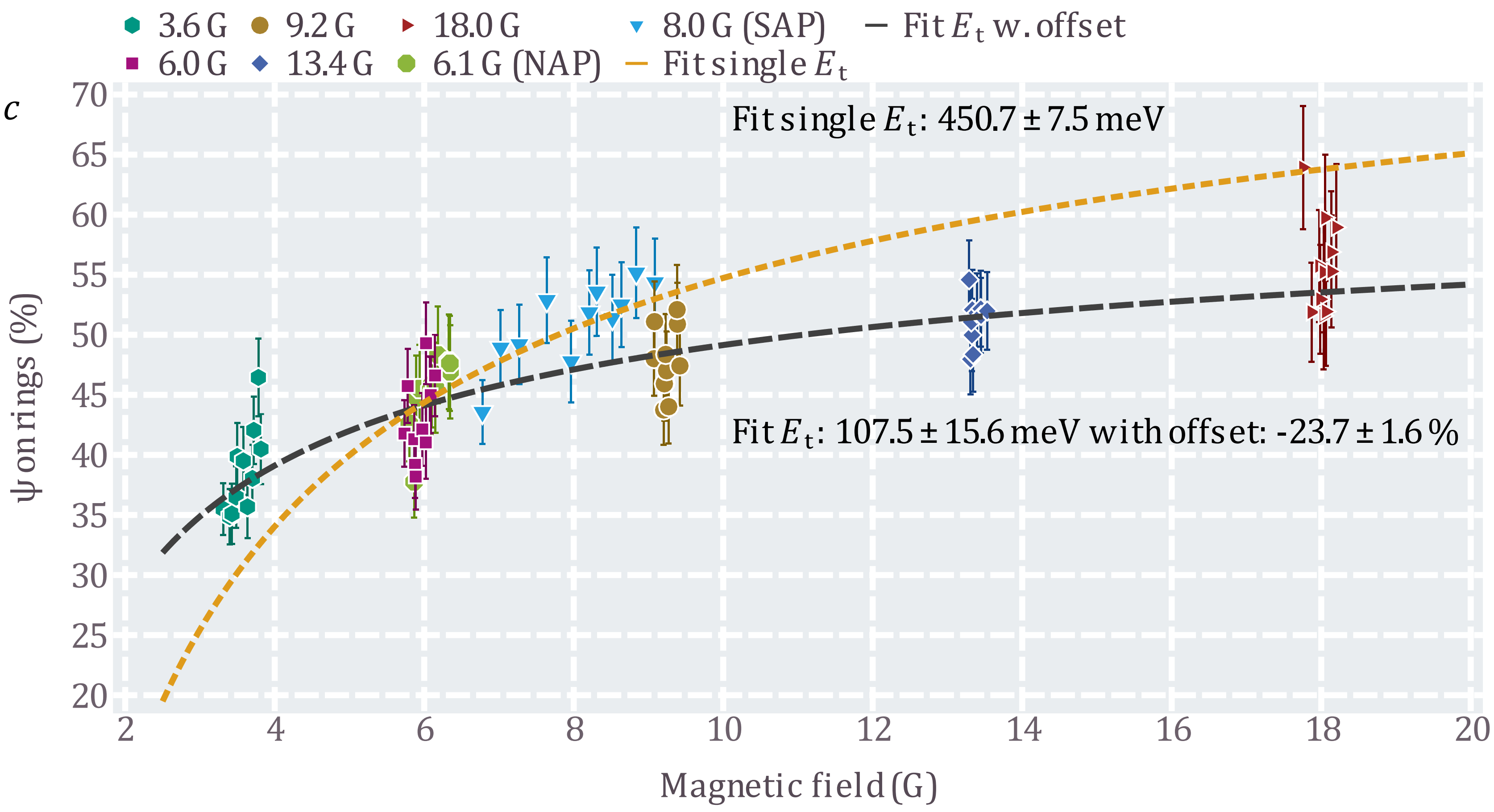




- Combine pixel in rings for radial effects:
  - Different generation mechanism of electrons
- Statistical variations on the ringwise representation
- Compatible with flat transmission over whole flux tube
  - → This does not reflect the radial background rate dependence!
  - Hint to at least 2 electron generation mechanisms
    - Classical Rydberg meV electrons
    - Others: higher energetic to explain the measured background fraction

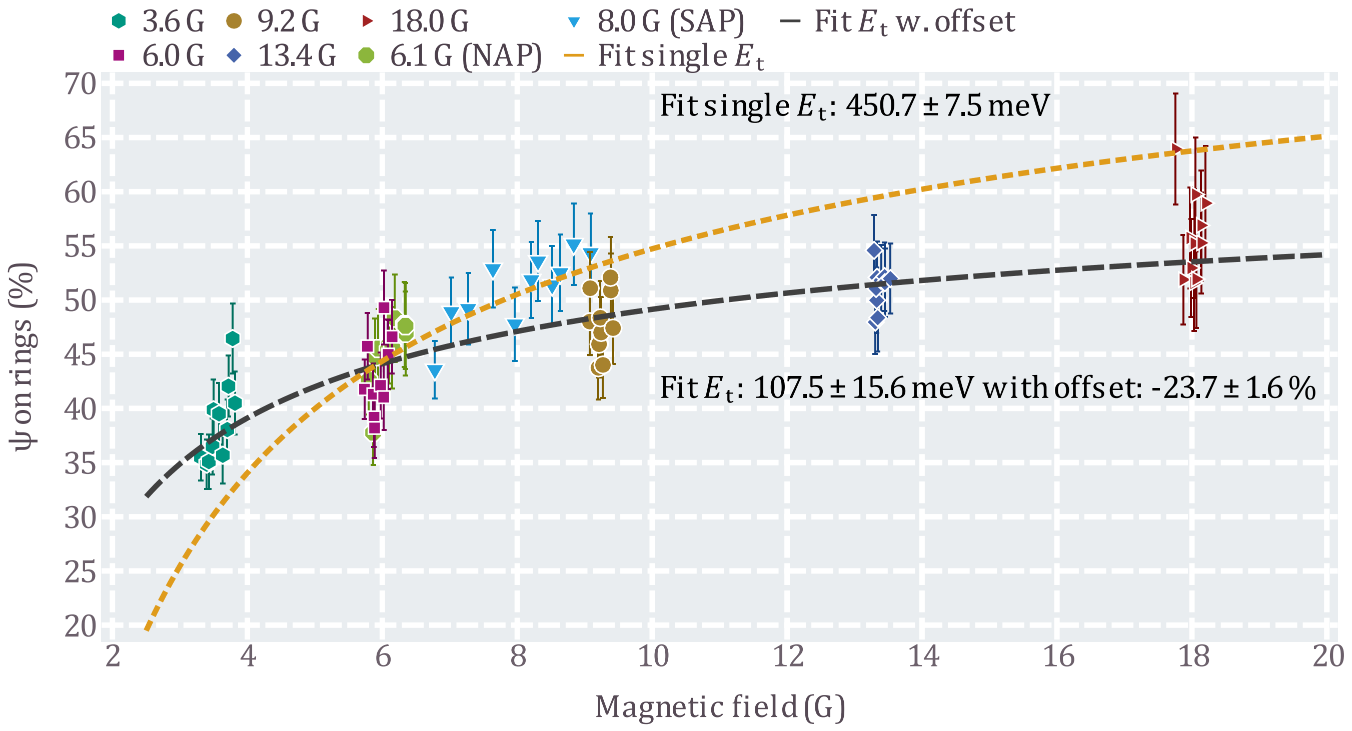
Results: Background fraction over magnetic field

- Combine transmission probability ξ with θ_{final} to perform a fit with transverse energy as parameter
  - $\psi(E_t; c) = \xi(\theta_{\text{final}}(B_i, B_f, E_t, E_f)) + c$
  - $\theta_{\text{final}} = \arcsin\left(\sqrt{\frac{E_t}{E_f} \cdot \frac{B_f}{B_i}}\right)$
- $E_t = E_i \cdot \sin^2(\theta_i)$
- B_f = 2.5 T (fix)
- B_i = ring-wise fields from simulation
- E_f = 18600 eV (fix)



Results: Background fraction over magnetic field

- Fit delivers transverse energy of ~450 meV
  - Isotropic directions: mean($\sin^2(\theta_i)$) ≈ 0.66
  - → initial Energy: ~680 meV
- velocity of generated electrons may not be isotropically distributed
  - If electrons start in direction of atom
  - mean($\sin^2(\theta_i)$) ≈ 0.80
  - → initial energy: ~560 meV
  - Depends on model & simulations
- Data also compatible with smaller transverse energies ~100 meV with offset to lower transmission
  - Mechanism of reduction needs to be investigated
  - Maybe backscattering from detector explains this observation
  - Combination of low and higher energetic e^-
- Several hundred meV are also not described by <u>classical Rydberg model</u>



→ Development of new (extended) model of background electron generation

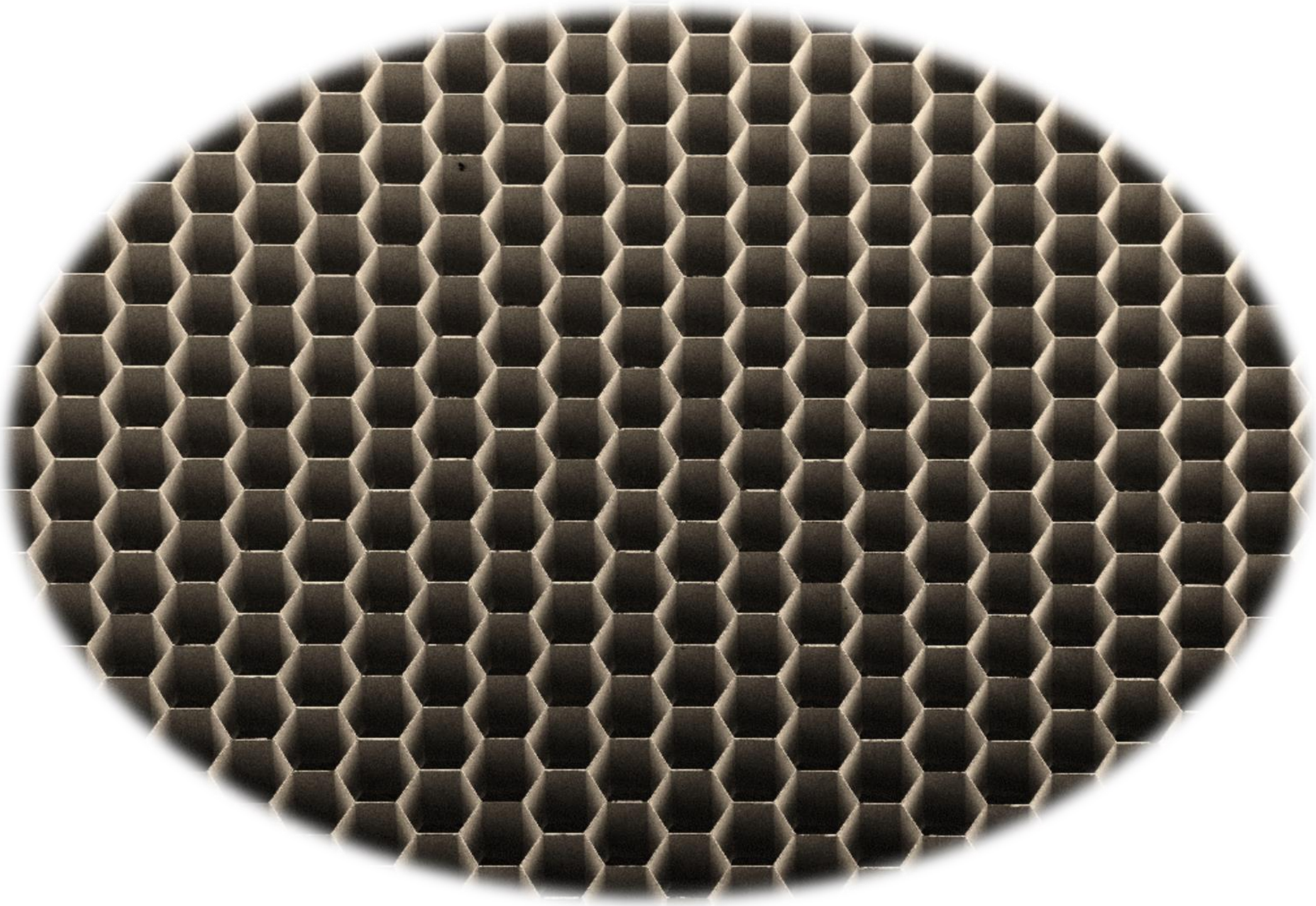
Summary

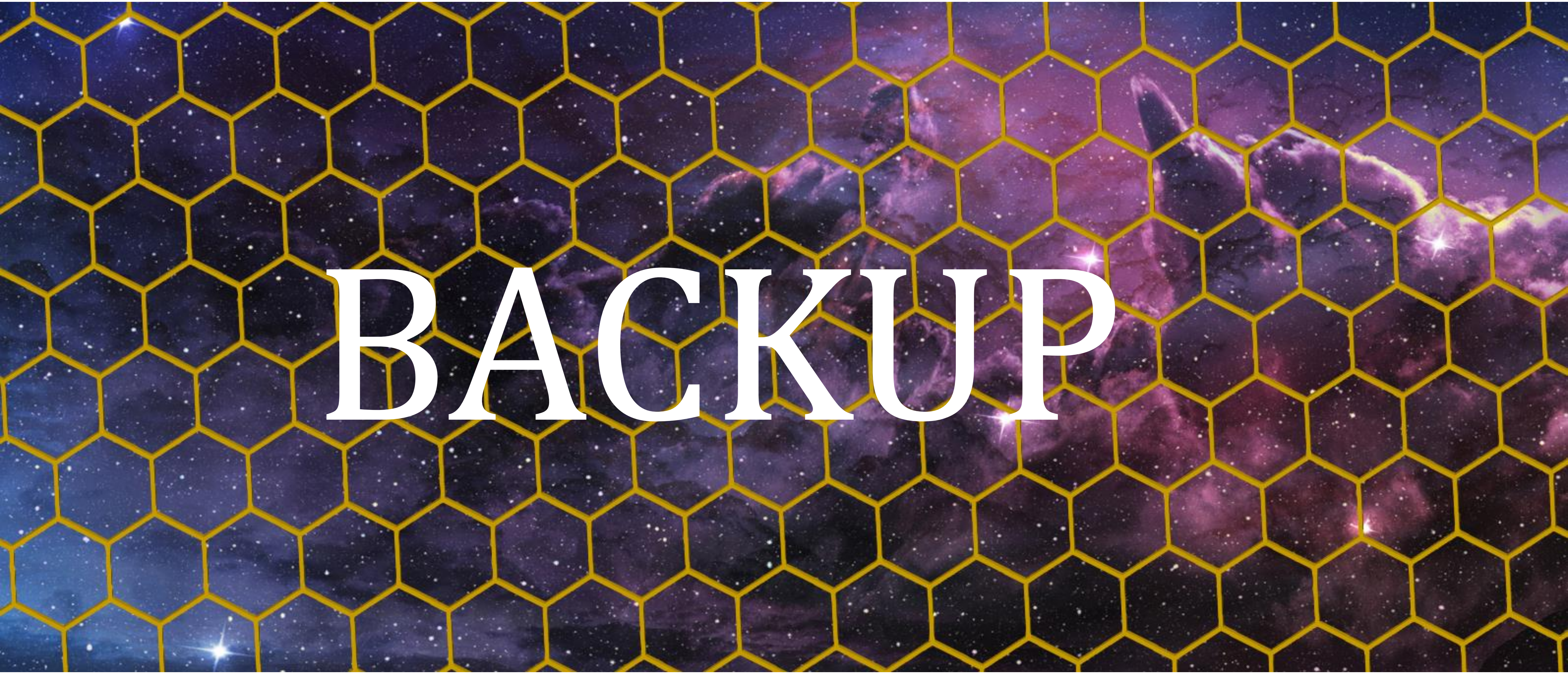
- Analysis of the pTEF Campaign is still ongoing
  - Detector background and alignment is taken into account
  - Alignment problematic since pTEF itself hinders investigation directly
  - -12.1 & -34.1 kV measurements and simulation – work in progress

- Fit of data at -18.6 kV reveals best fit electrons with $E_\mathrm{t} \sim 450$ meV
  - Fit $\psi(E_\mathrm{t}; c)$ is applicable to describe the data
  - Consider different than isotropic directions
- Data also compatible with electrons of $\sim$100 meV with reduced transmission due to unknown reason
  - Backscattering effects as possible candidate

- Extension on Rydberg background model
  - How can higher energetic electrons be generated in agreement with our observations?
    - Electromagnetic fields, pressure, temperature, …
    - Doppler effect due to atoms motion
  - Beyond H-atom like description of ionisation by BBR
    - Excited oxygen atoms
    - Doubly-excited states
    - Autoionisation

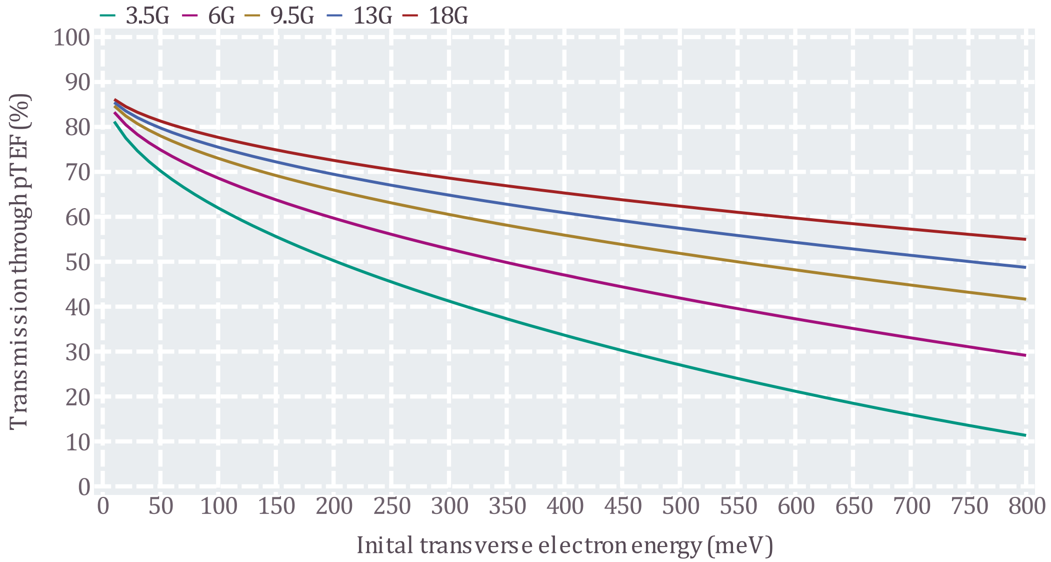
Thank you for your attention

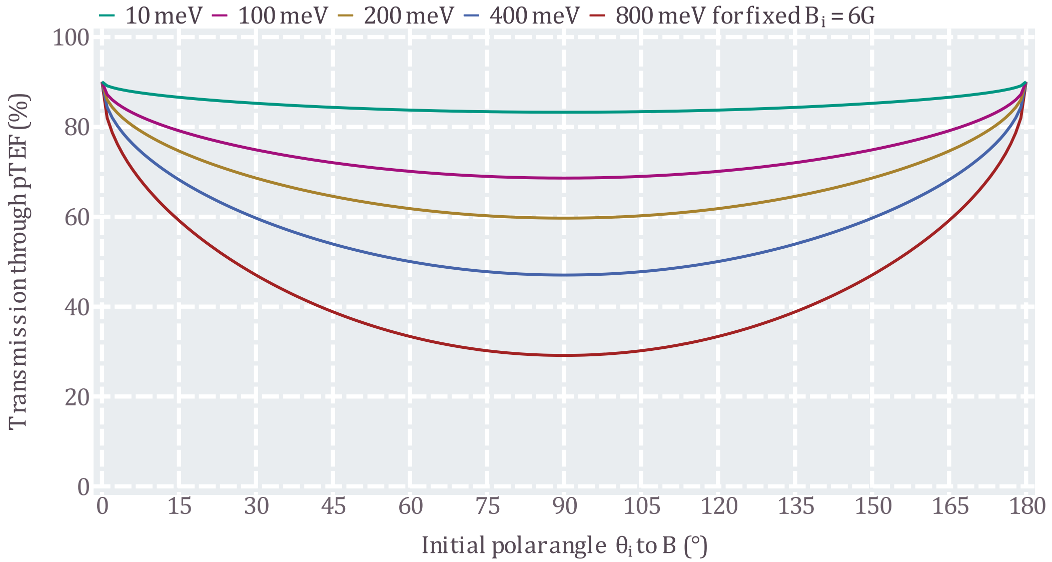


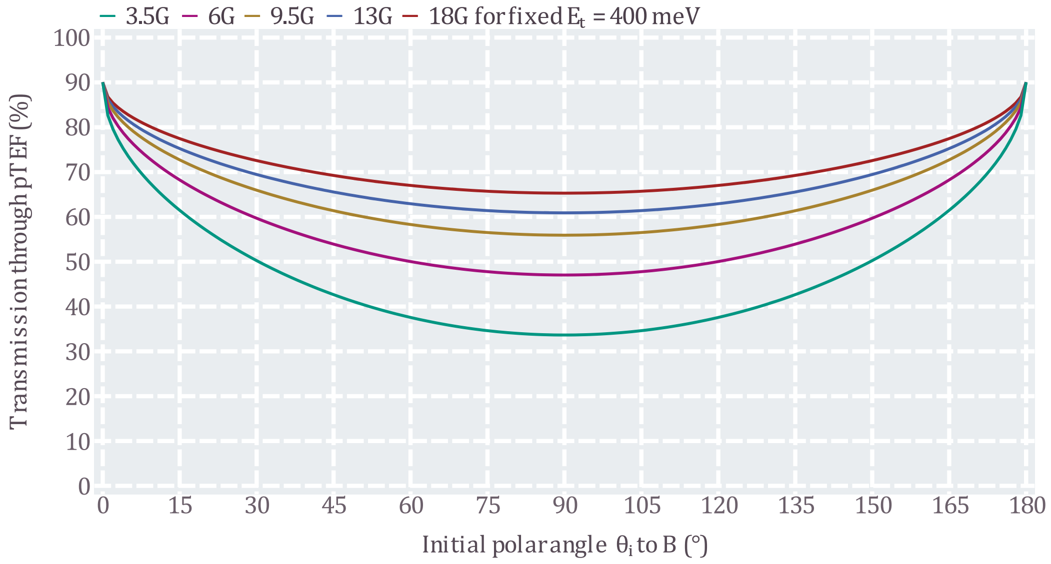


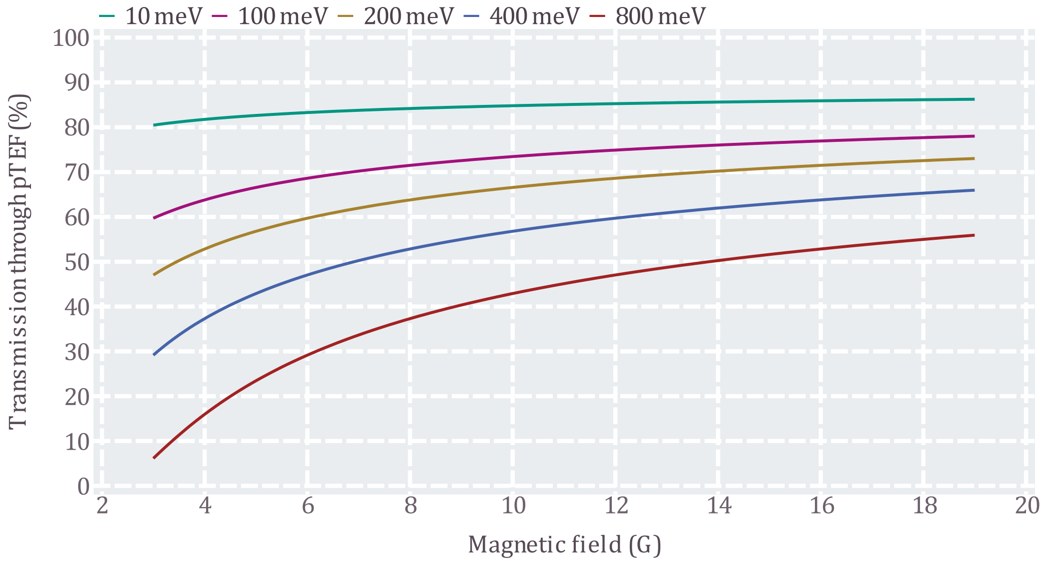
BACKUP

Some dependencies of transmission probability



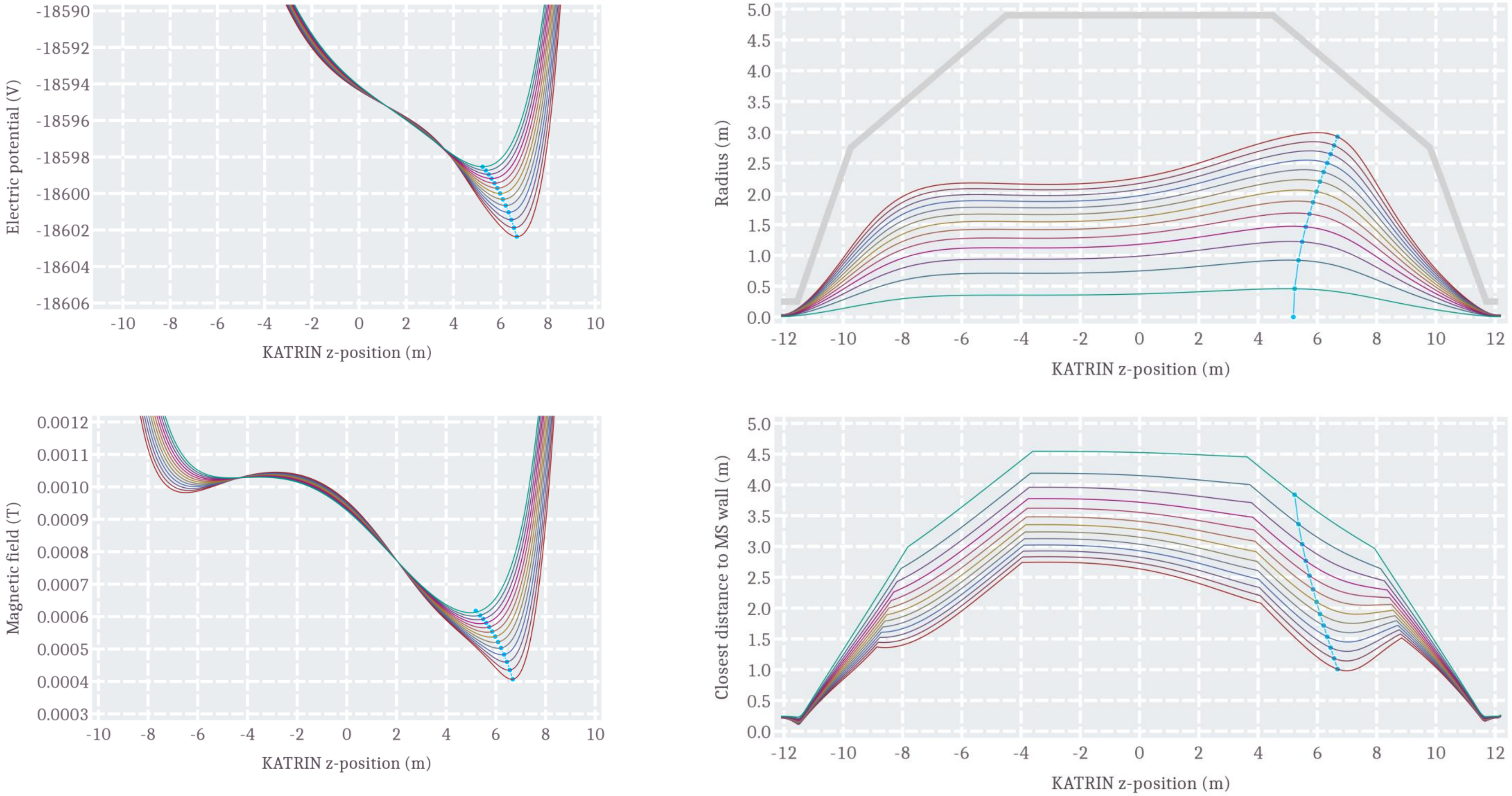




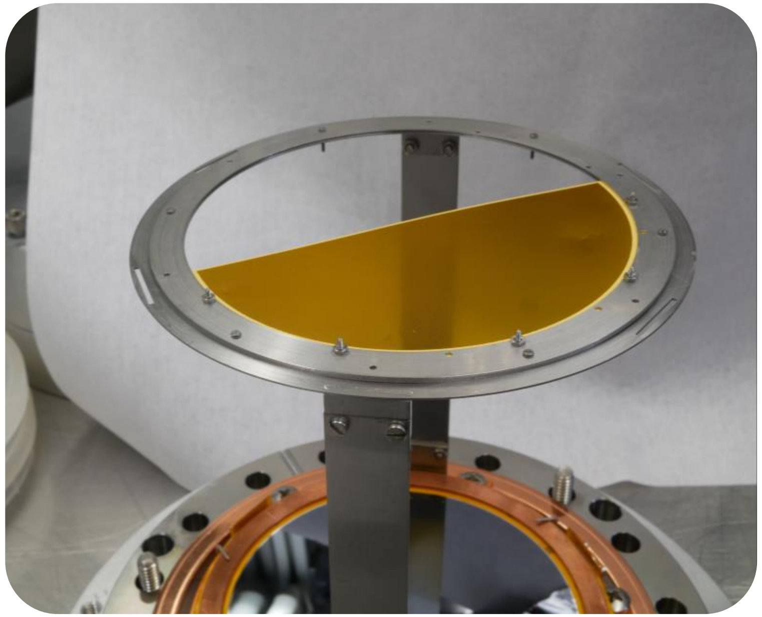


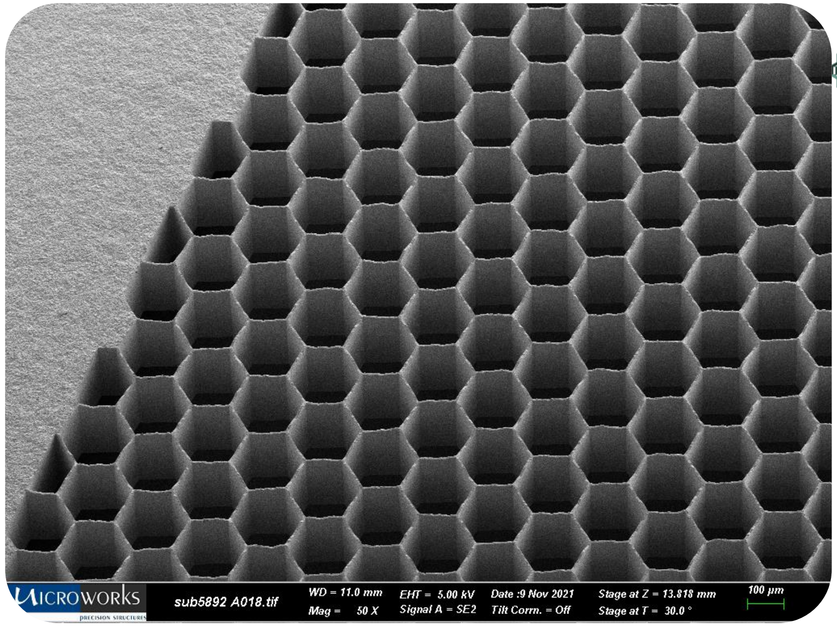
SAP setting

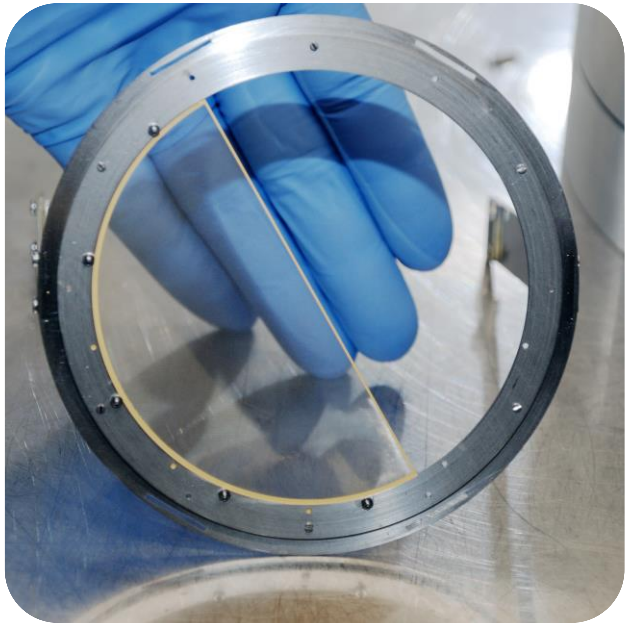
- Reduced background due to smaller flux tube volume
- Magnetic and electric inhomogeneities

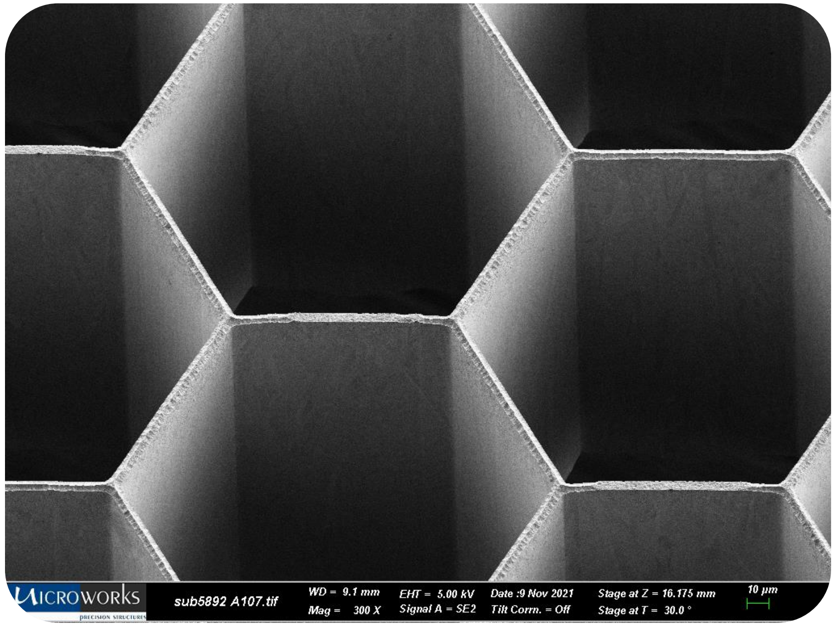


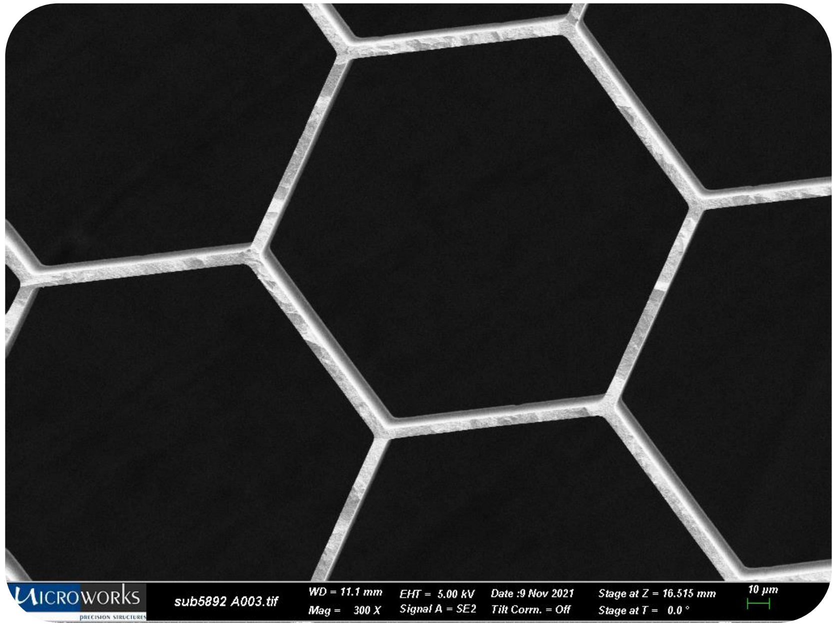
pTEF




MICROWORKS
PRECISION STRUCTURES
sub5892 A018.tif
WD = 11.0 mm
Mag = 50 X
EHT = 5.00 kV
Signal A = SE2
Date :9 Nov 2021
Tilt Corrn. = Off
Stage at Z = 13.818 mm
Stage at T = 30.0 °
100 µm




MICROWORKS
PRECISION STRUCTURES
sub5892 A107.tif
WD = 9.1 mm
Mag = 300 X
EHT = 5.00 kV
Signal A = SE2
Date :9 Nov 2021
Tilt Corrn. = Off
Stage at Z = 16.175 mm
Stage at T = 30.0 °
10 µm

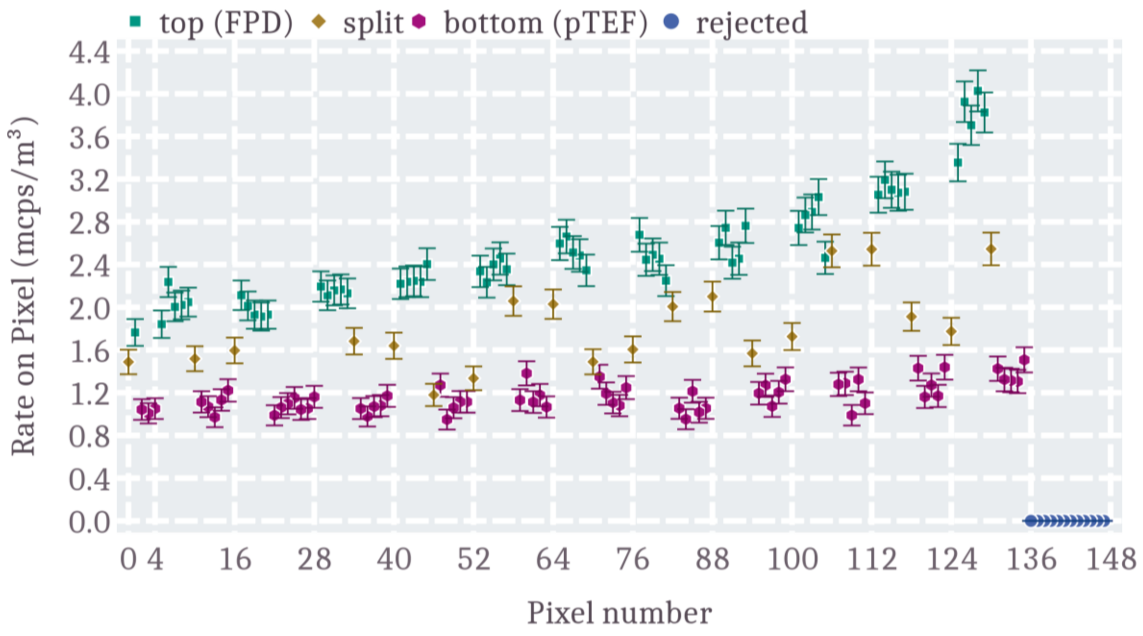

MICROWORKS
PRECISION STRUCTURES
sub5892 A003.tif
WD = 11.1 mm
Mag = 300 X
EHT = 5.00 kV
Signal A = SE2
Date :9 Nov 2021
Tilt Corrn. = Off
Stage at Z = 16.515 mm
Stage at T = 0.0 °
10 µm

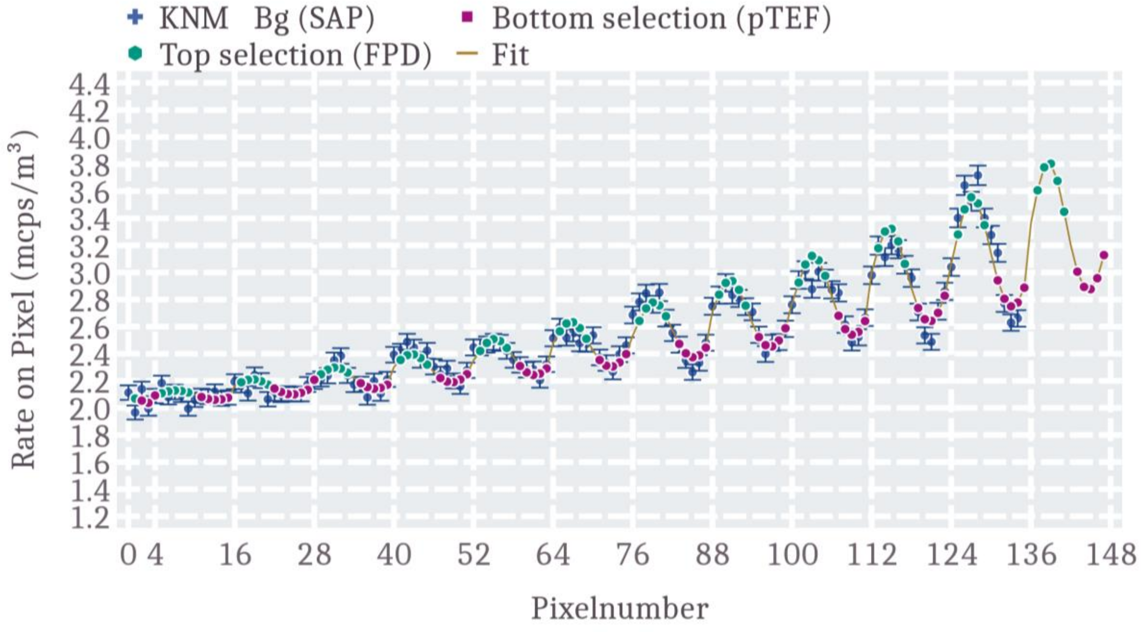
Alignement problematic

- Misalignment can be seen in pixelwise rate distribution.
- No misalignment each pixel per Ring sees same rate (step-like)
- In pTEF Campaign misalignment hidden due to pTEF

- Compare to KNM Background data
  - Sinusodial effect on rate on pixel in ring
  - Due to lateral shifts of detector on the mm-range

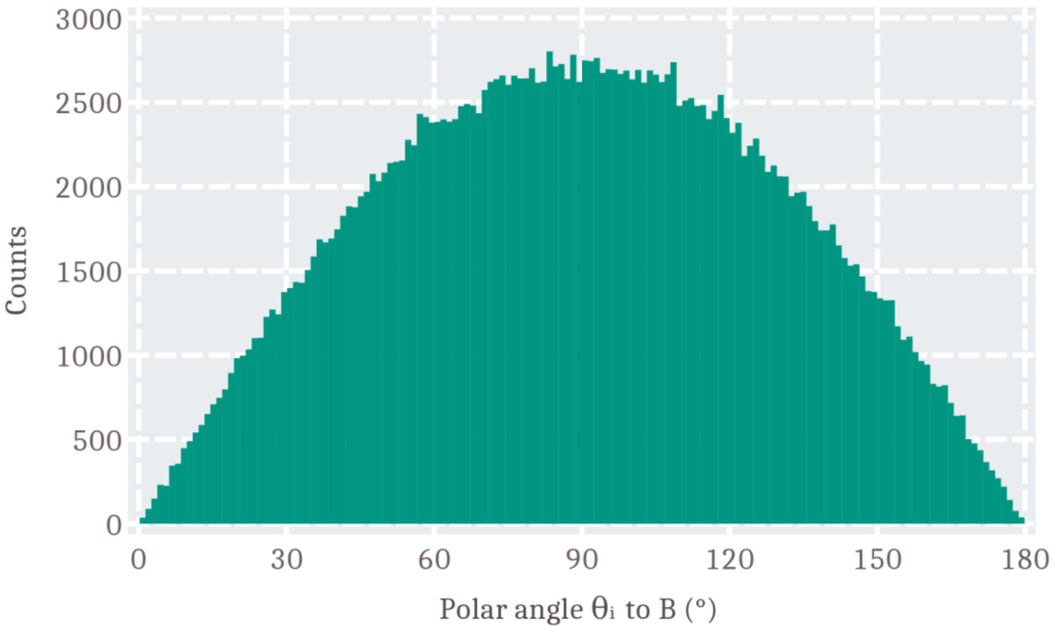
- For FPD/pTEF pixel selection
  - Strong differences on rate per ring observable
  - Down to 80% of rate on pTEF pixels in ring
  - Need to correct that, based on former measurements





Polar angle distributions of starting positions (5.0G asym.)

- Isotropic directions
- → $\text{mean}(\sin^2(\theta_\text{i})) \approx 0.66$



- From Rydberg paths simulation
- Atoms starting from surface crossing sensitive fluxtube
- Mean polar angle within ring volume
- → $\text{mean}(\sin^2(\theta_\text{i})) \approx 0.80$