Systematics and background suppression in the KATRIN Experiment

- Introduction
- KATRIN – overview of the setup
- Requirements on background suppression, statistics and systematics
- Status & outlook

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Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

SUSY 07

How can we fix the absolute ν mass scale?

→ talk by G. Drexlin on Tuesday

β decay: absolute ν mass
- model independent, kinematics

status: $m_\beta < 2.3$ eV (Mainz, Troitsk)

potential: $m_\beta < 0.2$ eV

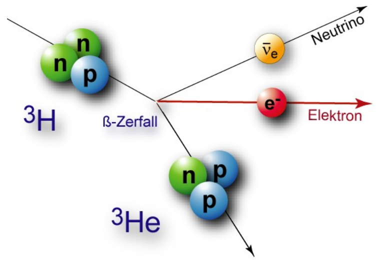
e.g.: KATRIN, MARE

0νββ decay: effective Majorana ν mass
- ν-nature (CP), peak at E_0

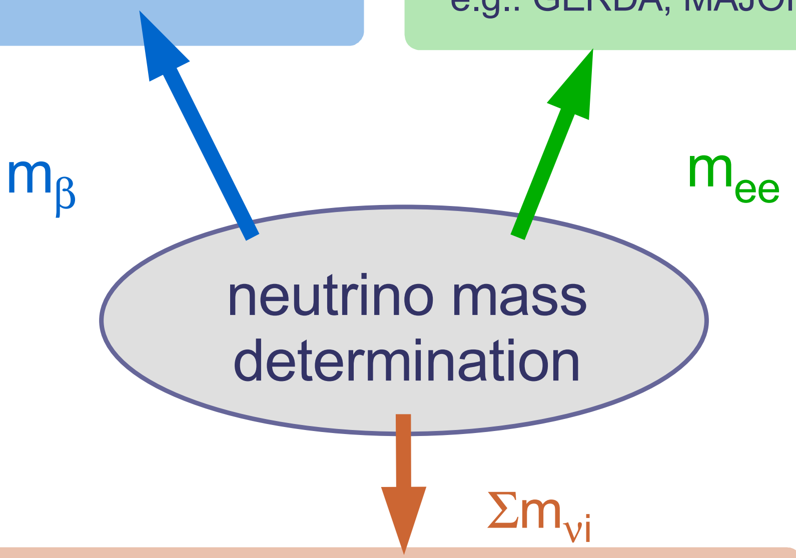
status: $m_{ee} < 0.35$ eV

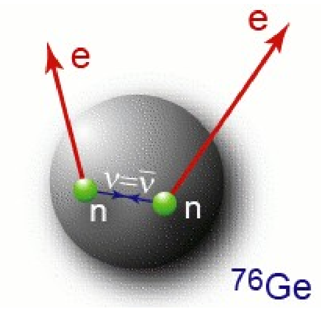
potential: $m_{ee} < 0.03$ eV

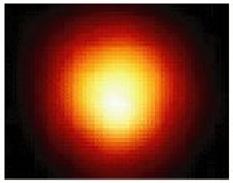
e.g.: GERDA, MAJORANA, EXO, CUORE, COBRA, NEMO3



$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$







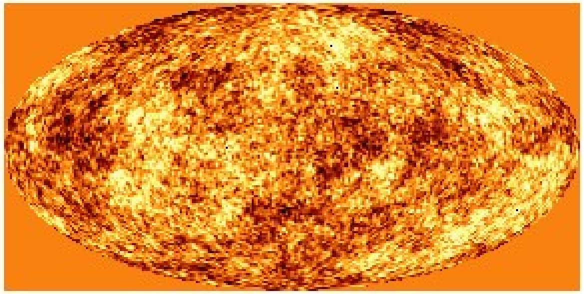
SN20xx

cosmology: ν hot dark matter Ω_ν
- model dependent, analysis of LSS data

status: $\Sigma m_{\nu i} < 0.7$ eV

potential: $\Sigma m_{\nu i} < 0.07$ eV

e.g.: WMAP, SDSS, LSST, PLANCK



CMBR

Direct determination of $m(\nu_e)$ from β decay

$(A, Z) \rightarrow (A, Z+1)^+ + e^- + \bar{\nu}_e$

$E_0 = E_e + E_\nu$

measure β electron energy spectrum:

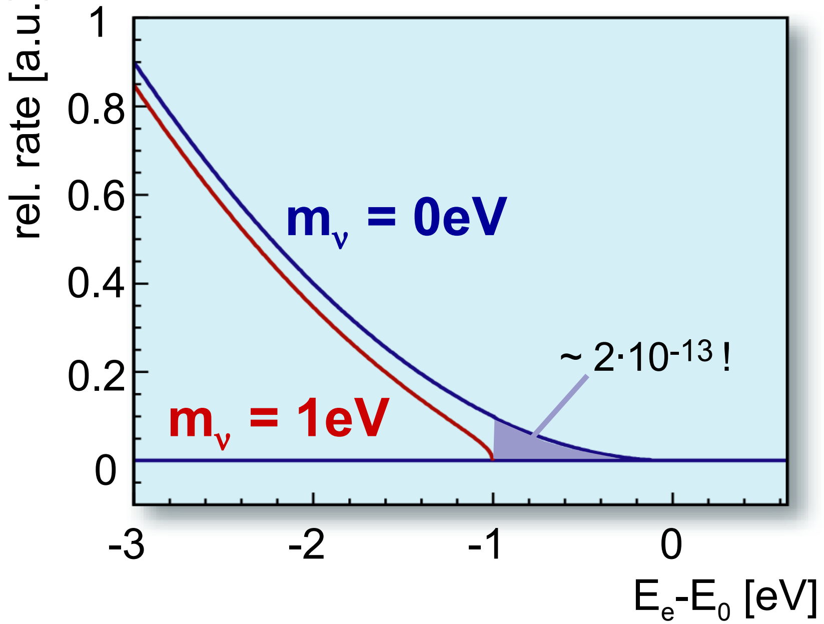
$$\frac{dN}{dE} = K\cdot F(Z,E)\cdot p\cdot(E_e+m_e c^2)(E_0-E_e)\cdot\sum_i |U_{ei}|^2\sqrt{(E_0-E_e)^2-m^2(\nu_i)c^4}$$

(modified by electronic final states, recoil corrections, radiative corrections)

experimental observable:

$m^2(\nu_e) := \sum |U_{ei}|^2\, m(\nu_i)^2$

theoretical β spectrum near endpoint



requirements:

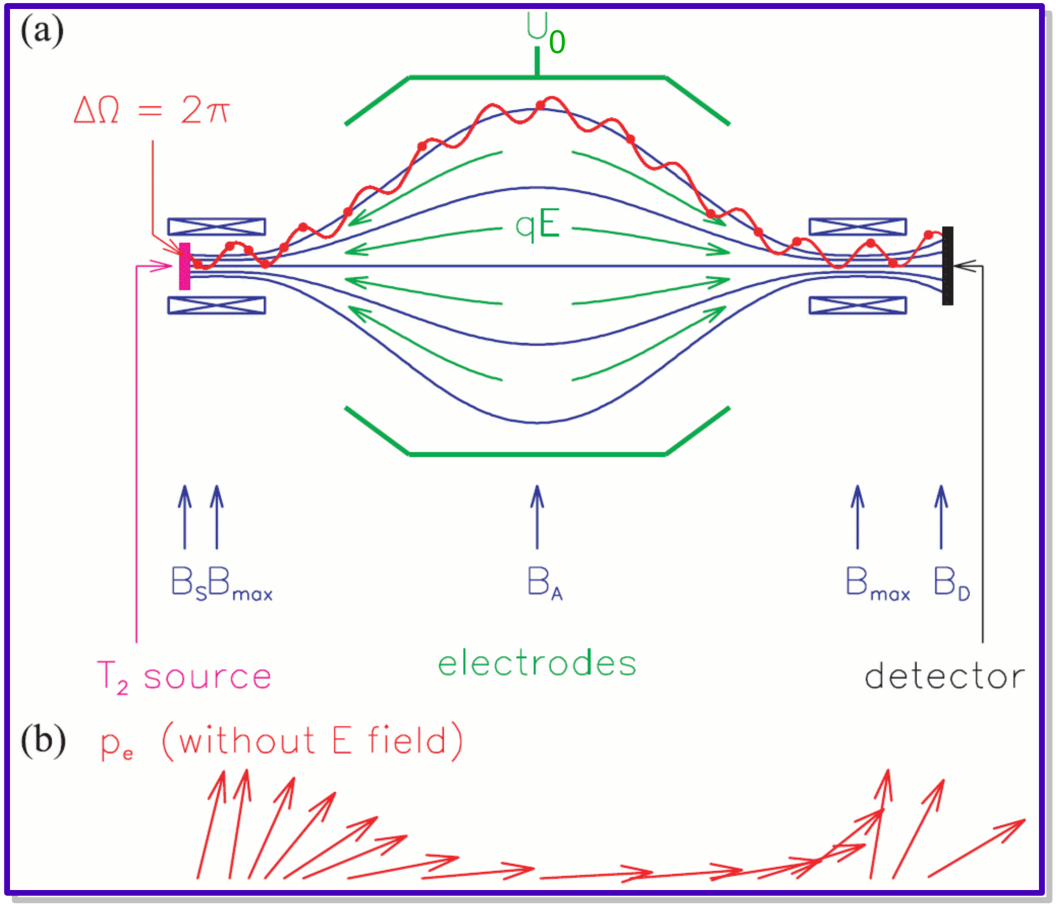
- strong source (high count rate near E_0)
- small endpoint energy E_0 → ^{3}H (^{187}Re)
- very good energy resolution
- long term stability
- low background rate

MAC-E type spectrometer
(or cryo-bolometer for ^{187}Re)

The MAC-E filter

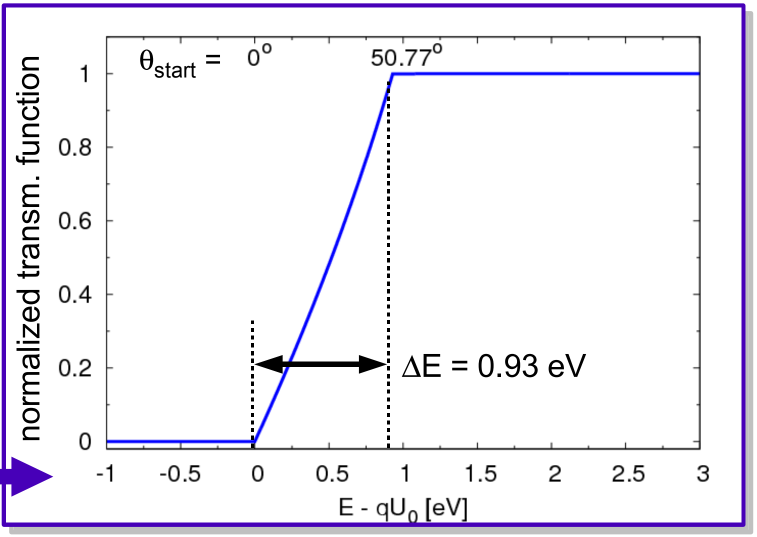
Magnetic Adiabatic Collimation with Electrostatic Filter

A. Picard et al., Nucl. Instr. Meth. B 63 (1992)



- adiabatic magnetic guiding of e$^-$
- energy analysis by electrostatic field:
  only e$^-$ with $E_{||} > qU$ transmitted
- $\mu = E_\perp / B = \text{const.}$
  $\Rightarrow \quad E_\perp \rightarrow E_{||}$ in inhomog. B field
- energy resolution at 18.6 keV:
  $\Delta E = E \cdot B_{min}/B_{max} \approx 5$ eV (Mainz), ≈ 1 eV (KATRIN)

analytical transmission function without tails



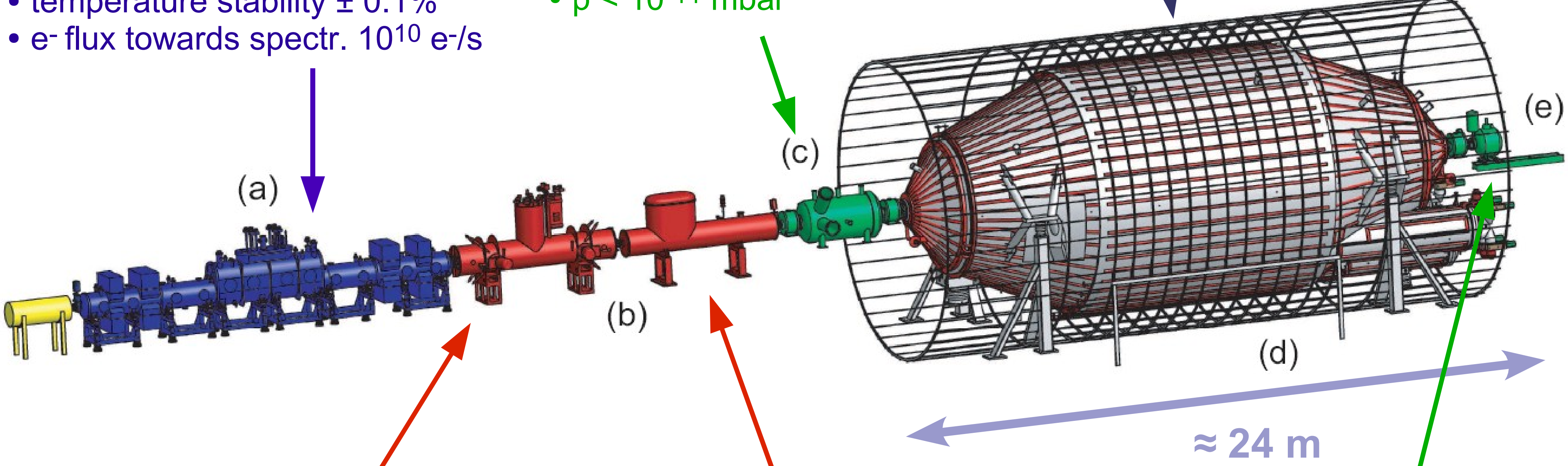
The **KA**rlsruhe **TRI**tium **N**eutrino experiment: overview of the setup

`http://www-ik.fzk.de/katrin`
`→ Technical Design Report`

Windowless Gaseous Tritium Source (WGTS)
- Tritium flow rate: 5×10^{19} molecules/s (40 g of T_2 / day)
- column density: $\rho d = 5 \times 10^{17}\ T_2/\mathrm{cm}^2$
- temperature stability ± 0.1%
- e^- flux towards spectr. $10^{10}\ e^-/s$

Pre-Spectrometer (MAC-E)
- retardation voltage 18.3 kV
- reduce flux to $10^3\ e^-/s$
- $p < 10^{-11}$ mbar

Main-Spectrometer (MAC-E)
- 1 eV resolution at 18.6 keV (β endpoint)
- $p < 10^{-11}$ mbar
- 24 m length, 10 m diameter



Differential pumping section
- e^- guided along beamline by strong magnetic fields
- T_2 removed by TMPs in kinks

Cryo pumping section
- T = 4K
- Argon frost as cryo pump
- B = 5.6 T

Electron detector
- segmented
- ≈ 1 keV resolution
- veto shield

Sensitivity requirements for KATRIN

Physics aim: improvement of sensitivity on m(ν): **2.3 eV → 0.2 eV**
i.e. **2 orders of magnitude** in the observable **$m^2(\nu)$**!

$$A_{analys} = \boxed{\frac{E}{\Delta E}} \cdot \boxed{A_{source,eff}}$$

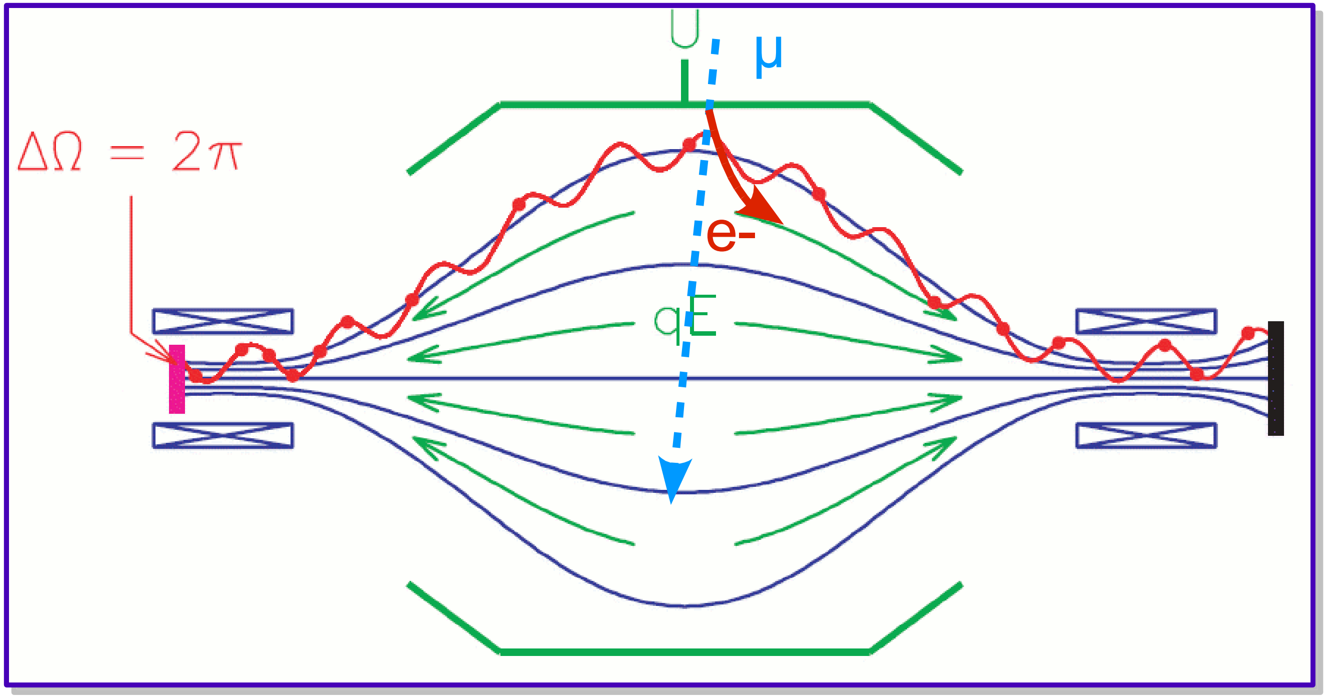
- **higher energy resolution:** $\boxed{\Delta E \approx 1 eV}$
- **good statistics:**
  - ▸ stronger $\boxed{T_2 \text{ source}}$
  - ▸ longer measurement time: 100 d → 1000 d and optimised measurement point distribution

  $\Rightarrow$ **$\sigma_{stat}(m_\nu^2) = 0.018\ eV^2$** for interval $[E_0 - 30\ eV, E_0 + 5\ eV]$
- **systematic uncertainties:** need to be very small!

  total error budget **$\sigma_{syst,tot}(m_\nu^2) = 0.017\ eV^2$** (see following slides!)
- **low background:** largest background source: e^- from spectrometer (Mainz exp.) but KATRIN spectrometer is much bigger!

  ⇒ ***need something new***

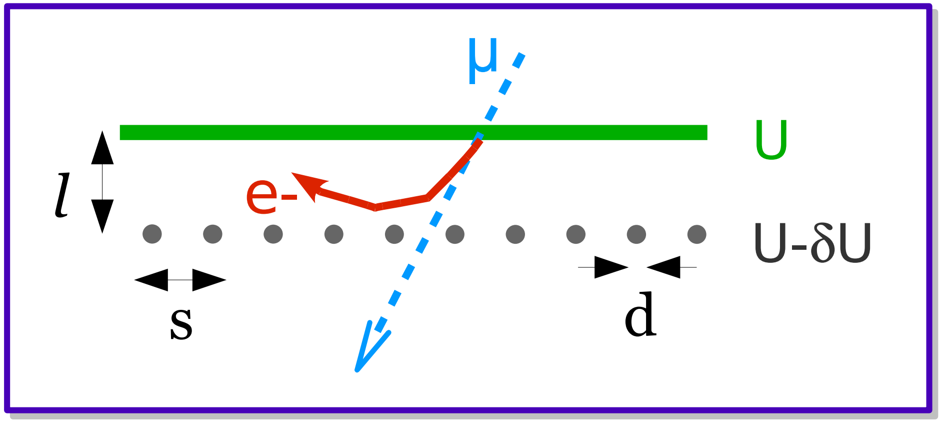
KATRIN wire electrode: screening of background electrons



- cosmics and radioactive contamination can mimic e^- in endpoint energy region
- 650 m^2 surface of main spectrometer ⟶ ≈ 10^5 μ / s + contamination
- reduction due to B-field: factor 10^5 - 10^6
- BUT: real signal rate in the mHz region

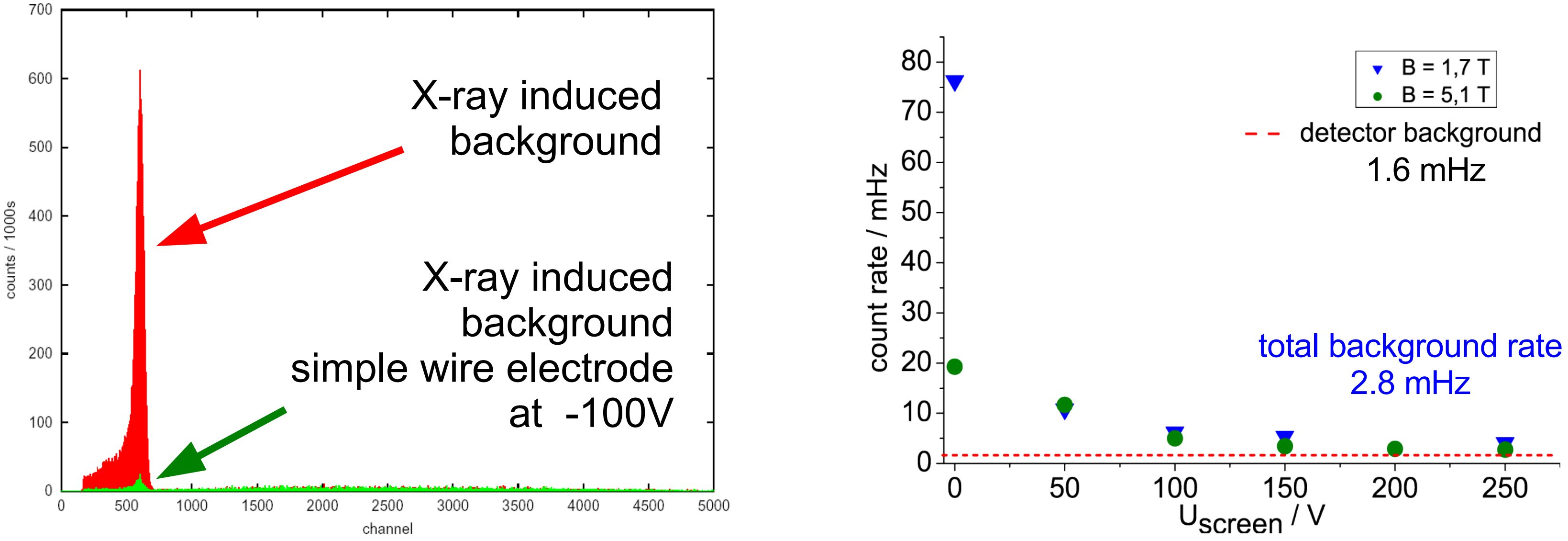
⇒ ***additional reduction necessary!***

KATRIN wire electrode: screening of background electrons



- screening of background electrons by wire grid on more negative potential
- proof of principle at Mainz MAC-E filter

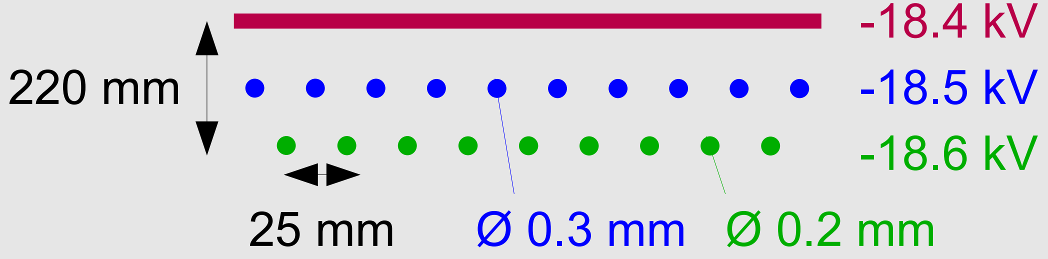
  → at 200 V shielding potential:
  reduction of background rate **by a factor 10**
  with a single layer electrode
- further tests at *KATRIN pre-spectrometer*



Dipl. thesis B. Ostrick (U Mainz, 2002), PhD thesis B. Flatt (U Mainz, 2004)

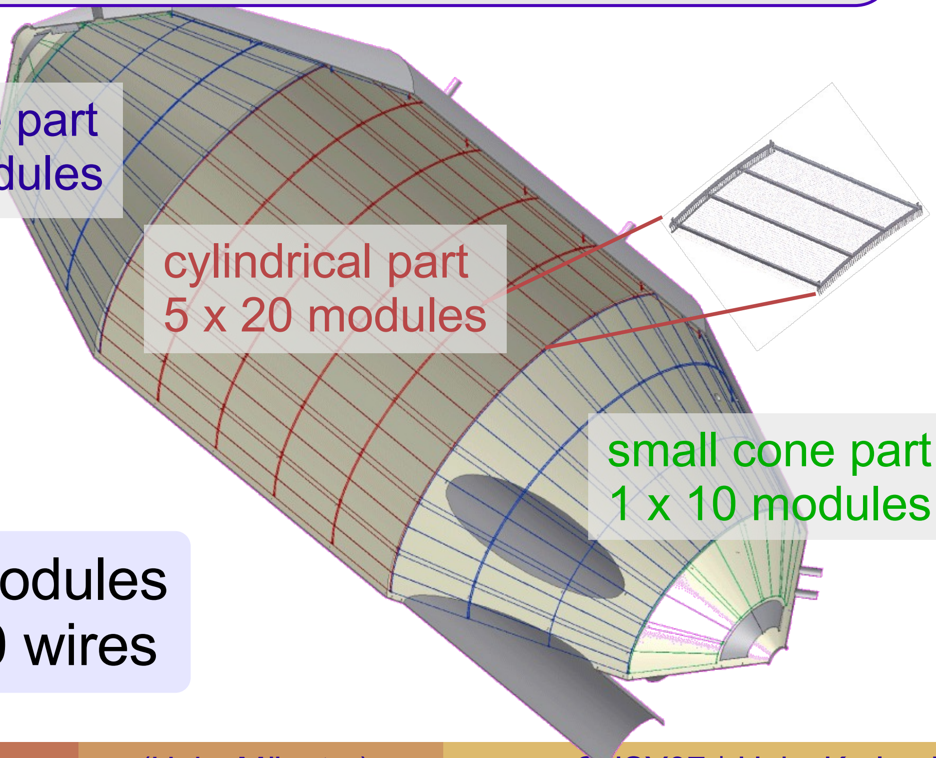
KATRIN wire electrode:
technical design and quality assurance

KATRIN: double layer electrode



improved shielding and electric field homogeneity

→ **expected background reduction by 10 - 100**

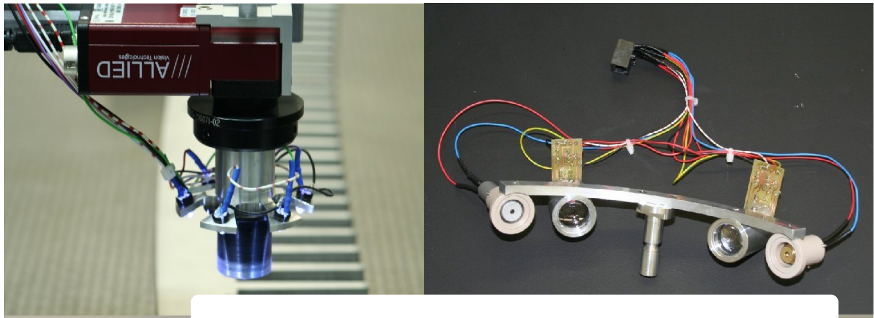


large cone part
3 x 20 modules

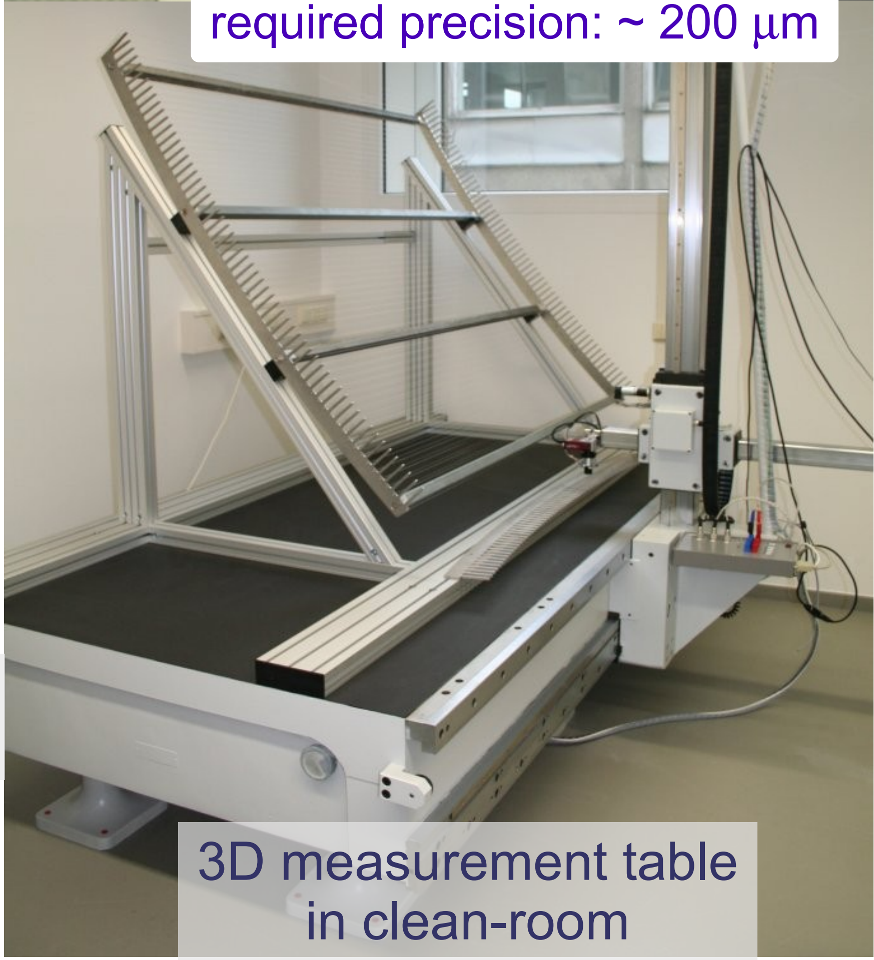
cylindrical part
5 x 20 modules

small cone part
1 x 10 modules

Σ = 240 modules
23000 wires



required precision: ~ 200 µm



3D measurement table
in clean-room

Systematic uncertainties

1. inelastic scattering of e^- inside WGTS
   - requires dedicated e-gun measurements, deconvolution techniques for response fct.
2. fluctuations of WGTS column density (required < 0.1%)
   - rear detector, Laser-Raman spectroscopy, T=30 K stabilisation, e-gun measurements
3. transmission function
   - e-gun scans with high spatial resolution, multi-pixel detector
4. HV stability of retarding potential on ~3 ppm level required
   - precision HV divider (PTB), monitor spectrometer beamline
5. WGTS charging due to remaining ions (MC: $\phi < 20$ mV)
   - inject low energy meV electrons from rear side, diagnostic tools available
6. electronic final state distribution of daughter molecules
   - reliable quantum chem. calculations

a few contributions with $\sigma(m_\nu^2) \leq 0.007$ eV^2 each

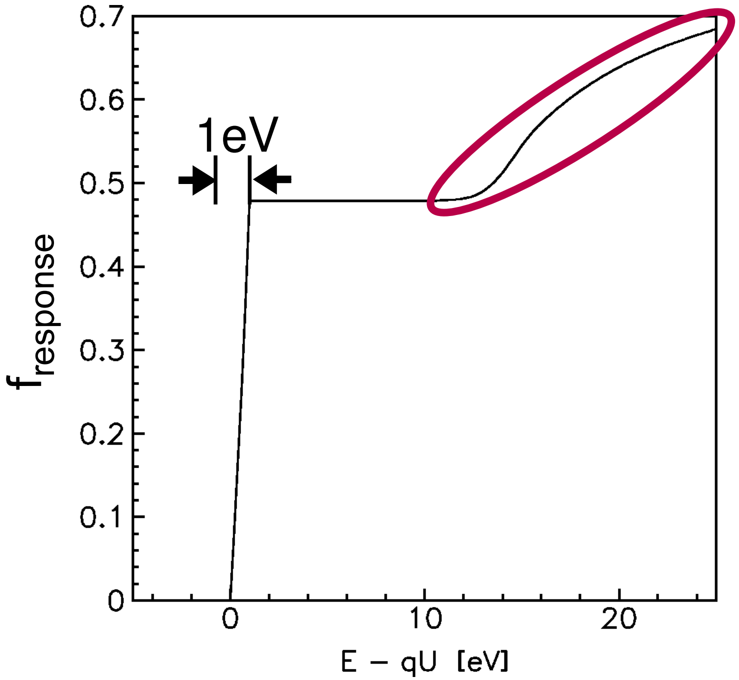
↓

total systematic uncertainty $\sigma_{\text{syst, tot}} = 0.017$ eV^2

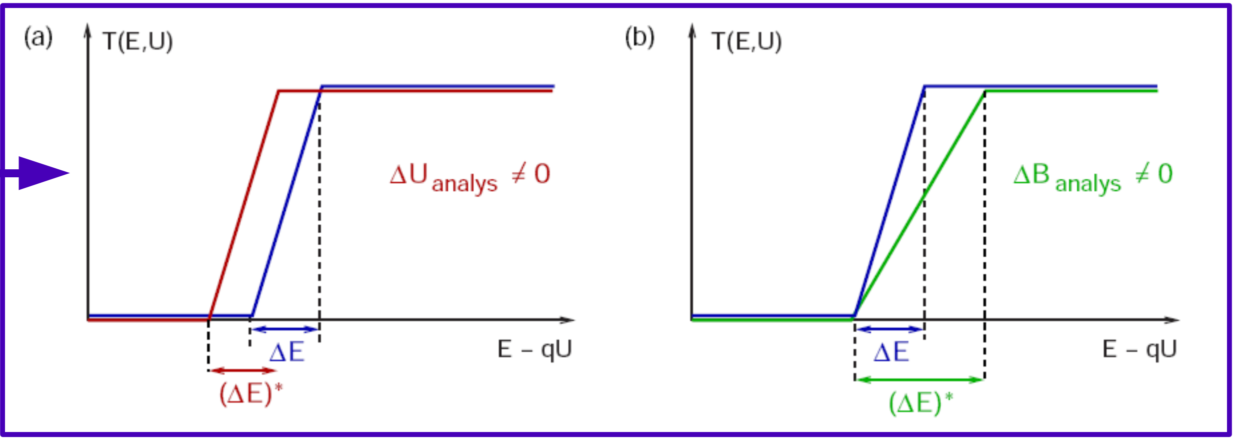
Systematic uncertainties

for smaller m(ν) ⇒ *smaller region of interest below endpoint* E_0

- excited electronic final states do not play a role (ΔE_{exc} > 27 eV)
- inelastic scattering in T_2 is small (ΔE_{inel} > 12 eV)
- rotational-vibrational excitations ($\Delta E_{exc,\ mean}$ = 1.7 eV) of the ground state must be accounted for: can be calculated to good accuracy

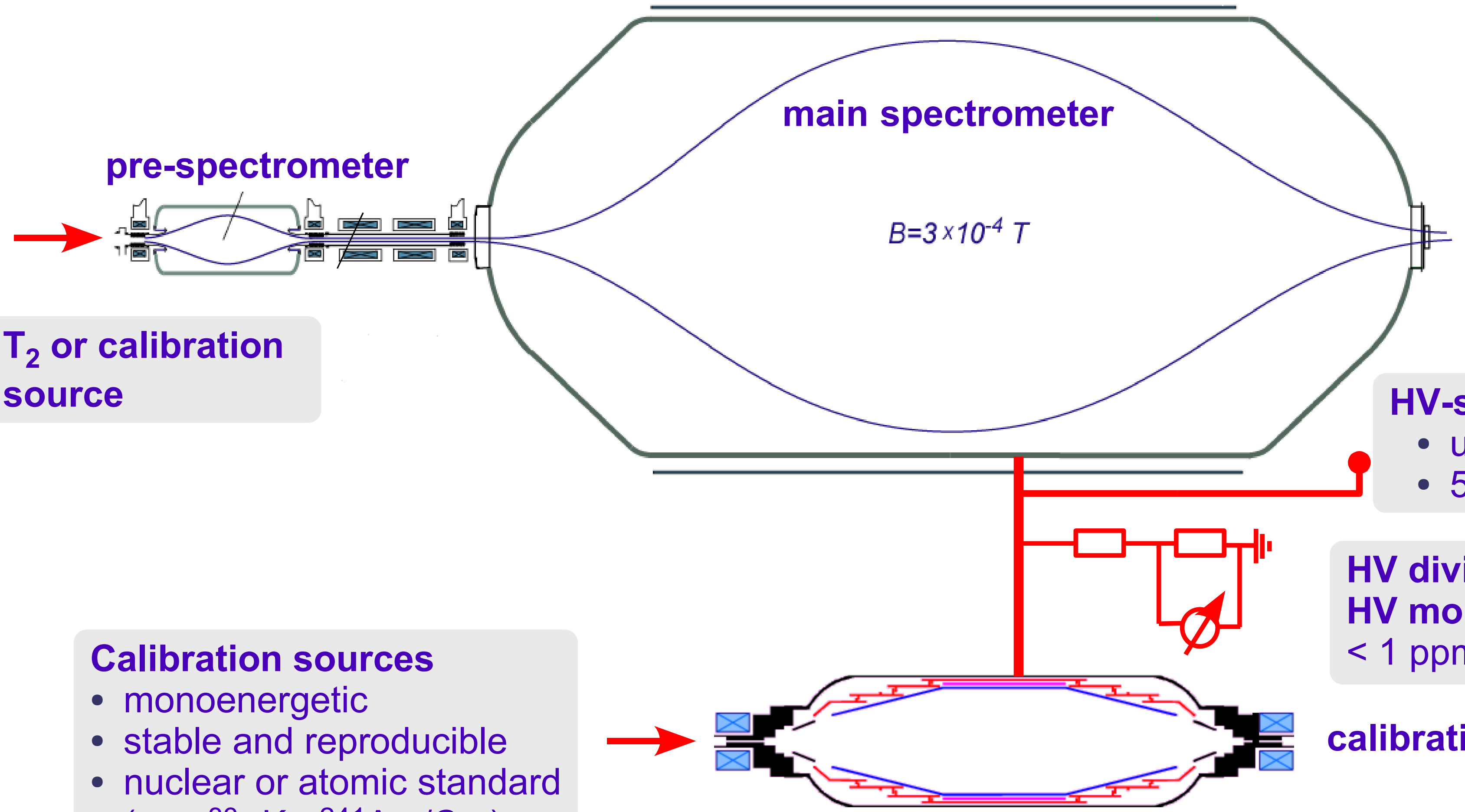


inhomogeneity of electrostatic (ΔU) and magnetic field (ΔB) across analysing plane can cause distortions of the transmission function



⇒ need
a) highly segmented detector
b) precise measurement of transm. fct.
pixel by pixel

Calibration and monitoring of the retarding potential: concept



pre-spectrometer

main spectrometer

detector

T_2 or calibration source

HV-supplies
- up to 35 kV
- 5 ppm/8h

HV divider / HV monitoring
< 1 ppm/month

calibration detector

Calibration sources
- monoenergetic
- stable and reproducible
- nuclear or atomic standard (e.g. ^{83m}Kr, ^{241}Am/Co)

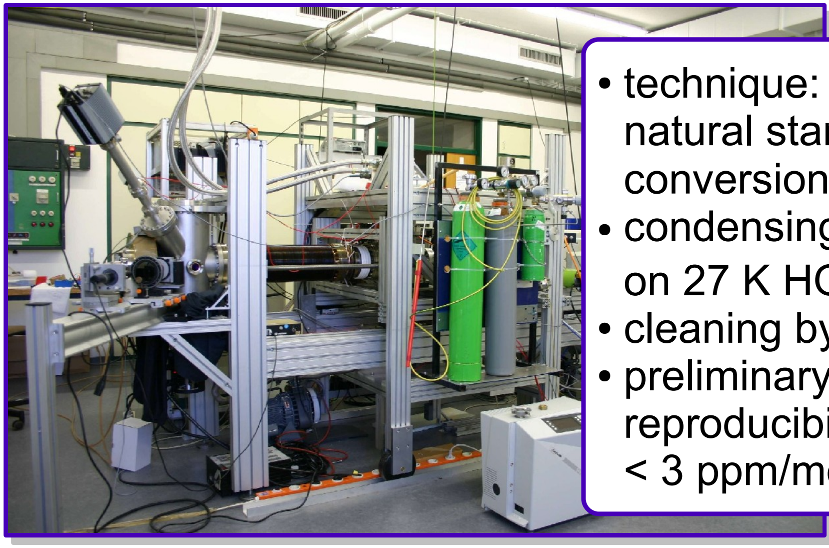
monitor spectrometer (enlarged):
- former Mainz spectrometer
- adapted to 1 eV resolution

$\Delta m_\nu^2 = -2\,\sigma^2$

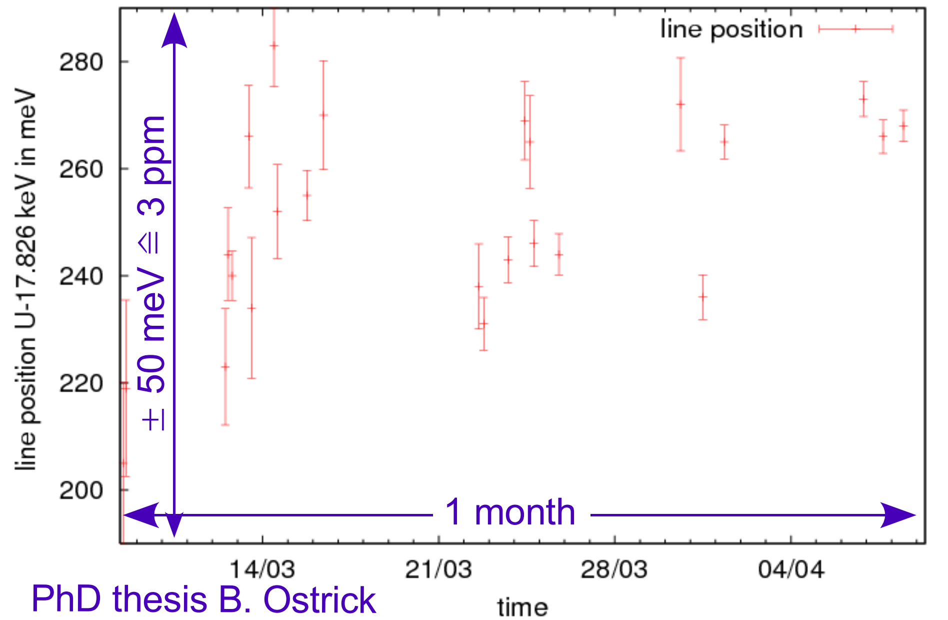
error budget: $\Delta m_\nu^2 \leq 0.007\ \text{eV}^2 \;\Rightarrow\; \sigma < 60\ \text{meV} \;\Rightarrow$ 3 ppm stability over 2 month run

Calibration and monitoring of the retarding potential

e.g.: condensed ^{83m}Kr calibration source



- technique:
  natural standard:
  conversion e⁻ from ^{83m}Kr
- condensing Kr ($T_{1/2}$ = 1.83 h) on 27 K HOPG
- cleaning by laser ablation
- preliminary:
  reproducibility within
  < 3 ppm/month



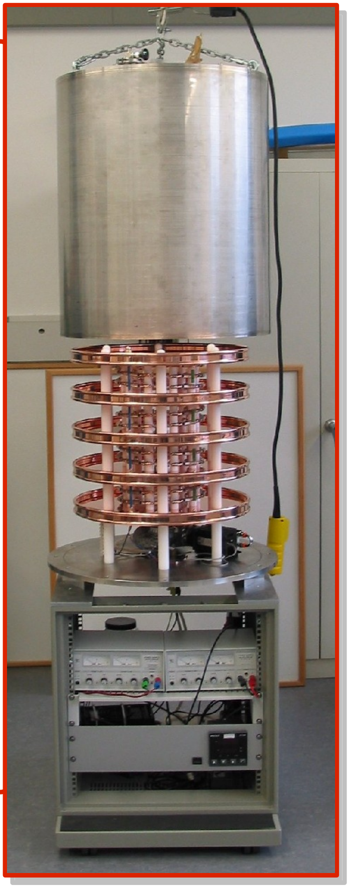
PhD thesis B. Ostrick

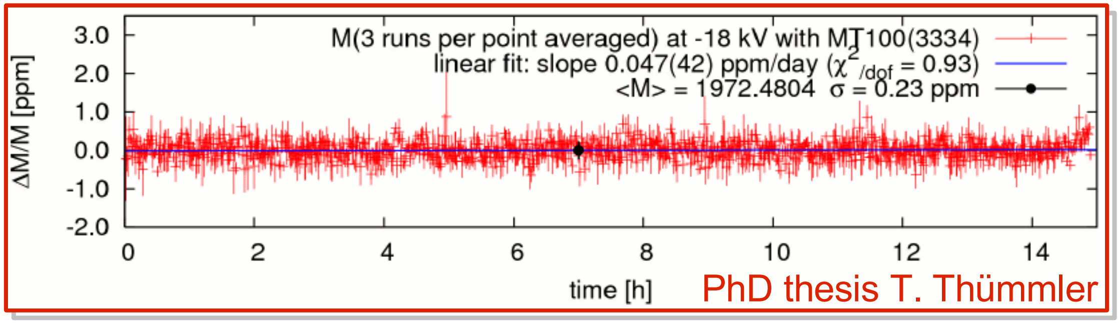
high-precision HV divider

- developed and tested in cooperation with PTB (Braunschweig)
- technique:
  bulk metal foil resistors,
  184 MΩ total resistance

prelim. divider properties:

- TCR of divider < 0.2 ppm/K
  (+ temp. stabiliz. to ± 0.1 K)
- reproducibility < 0.3 ppm
- long-term stability
  0.6 ppm/month
- voltage dependence
  < 1 ppm/kV (range: 8-32 kV)





PhD thesis T. Thümmler

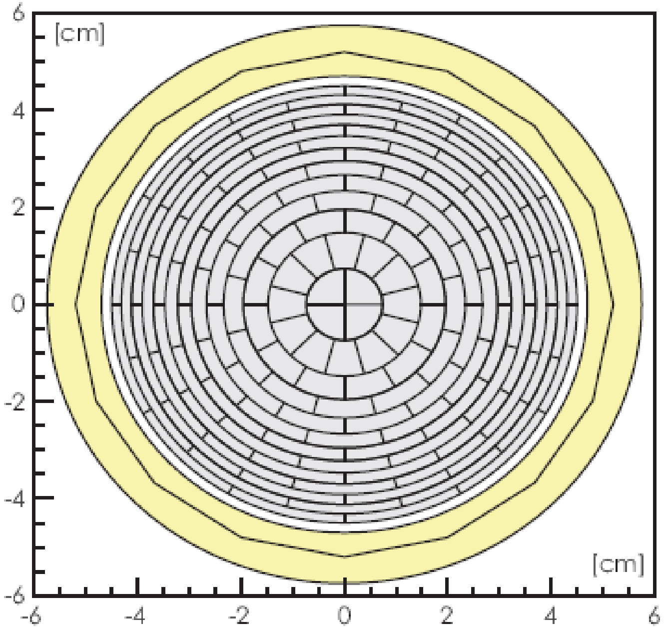
The detector

task: **detection** of transmitted β-decay electrons (≈1 keV energy resolution & high efficiency), record **radial profile of flux tube**

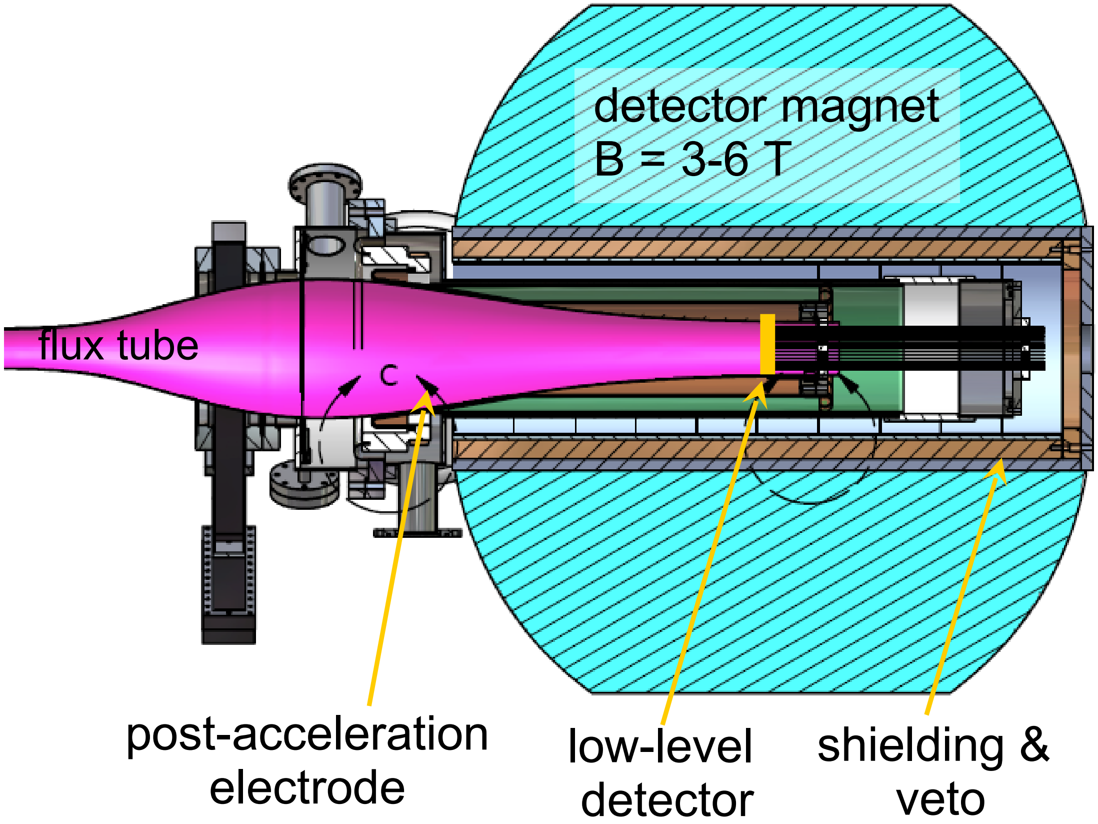
aim: minimise background & reduce systematics by **post-acceleration (~ 30 kV)**

↑ shift signal window to lower background

↑ smaller backscattering probability



design: segmented Si-PIN diode array
~150 pixels with A=100 cm²



Status & Outlook

- **KATRIN main components**
  pre- and main-spectrometer: set up
  tritium source, differential pumping section: under construction at external companies
  test experiments are running (TILO, TRAP, calibration sources)

- **Main spectrometer**
  installation of full vacuum system
  in summer 2007,
  now: test of heating/cooling system

  production of **inner wire electrode**
  started June '07,
  → installation of modules early 2008

- **Start of KATRIN measurements:** 2010,
  expected data taking 5-6 years
  for 3 years effective meas. time

- **Sensitivity:**
  5σ significance for $m(\nu) = 0.35$ eV
  3σ significance for $m(\nu) = 0.30$ eV
  or upper limit of 0.2 eV with 90% C.L.

Nov. 29, 2006

Backup transparencies

simplified form of the β-spectrum:

$$\frac{dN}{dE_\beta} \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2 c^4}$$

gaussian fluctuation:

$$\frac{dN}{dE_\beta}(m_\nu^2 = 0) \otimes e^{\left(\frac{-\Delta E^2}{2\sigma^2}\right)} \propto (E_0 - E)^2 + \sigma^2$$

Taylor series around $m_\nu^2 = 0$:

$$\frac{dN}{dE_\beta} \propto (E_0 - E)^2 - \frac{1}{2} m_\nu^2$$

$$\Rightarrow \Delta m_\nu^2 = -2\sigma^2$$

→ fluctuation σ^2 causes a downward shift in m_ν^2

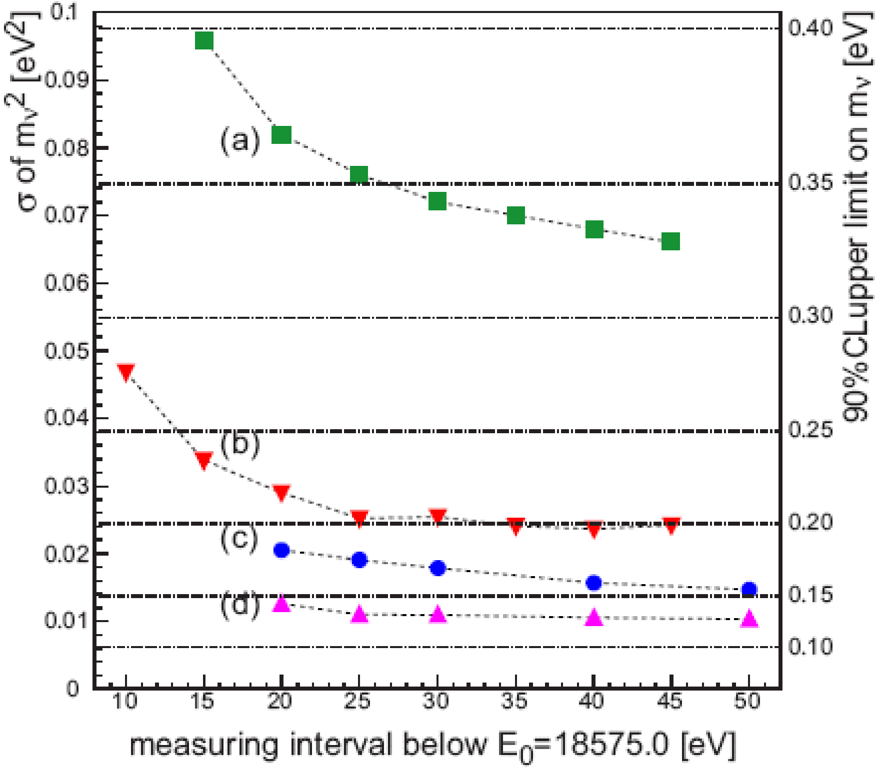
Example:

$\Delta m_\nu^2 < 0{,}007\ \mathrm{eV}^2 \Leftrightarrow \sigma < 60\ \mathrm{meV}$

$$\frac{\Delta U}{U} = \frac{0.06}{18575} \approx 3 \cdot 10^{-6}$$

⇒ 3 ppm long term stability required

Statistical uncertainty



design optimisation 2001-2003

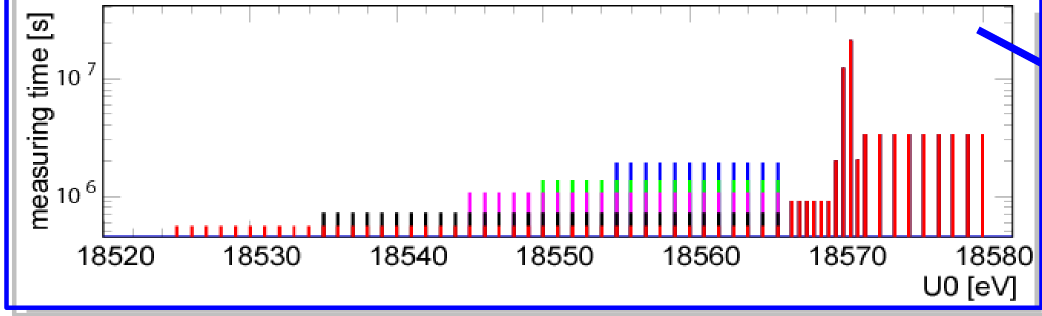
(a) KATRIN Letter of Intent, 2001
(Ø 7 m main spectrometer)

(b) improved T_2 purity;
stronger gaseous source
(Ø 75 mm → 90 mm)
requires Ø 10 m main spectrometer

(c) optimised measurement time
accounting for better signal/background ratio
a few eV below endpoint
→ 40-50 % improvement on σ
compared to uniform distribution

(d) background rate 10 mHz → 1 mHz

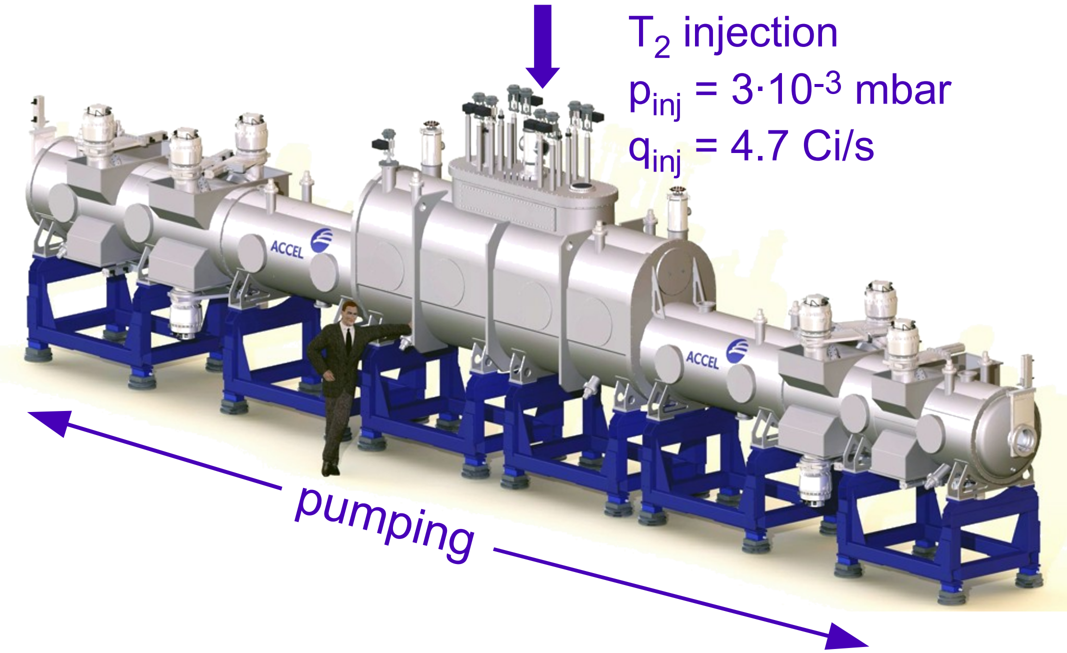
improved measurement point distrib.
⇒ generate MC data for β spectrum



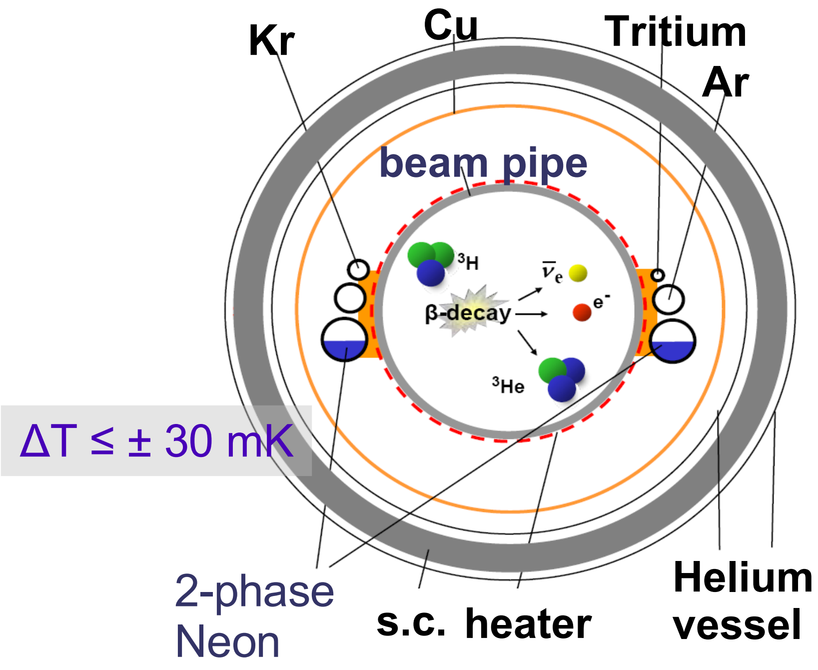
KATRIN "reference configuration",
interval [E_0 – 30 eV, E_0 + 5 eV]:

σ_{stat} = 0.018 eV²

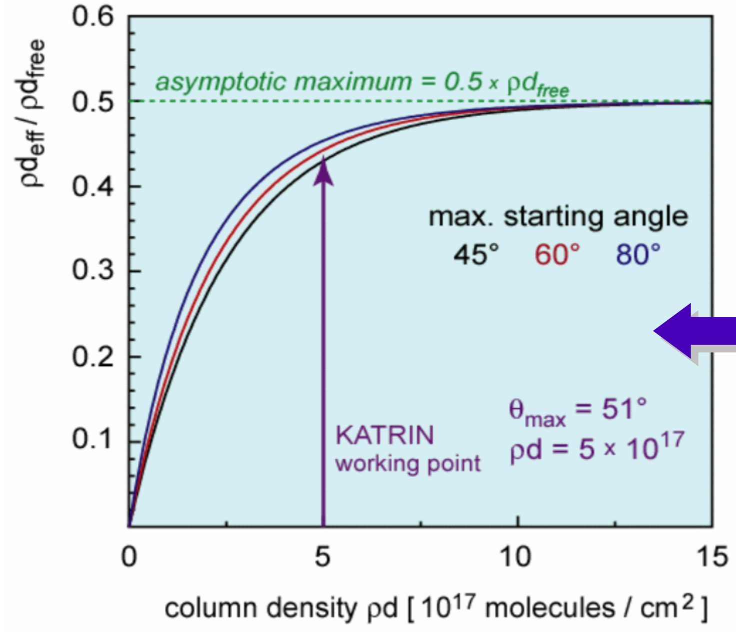
The windowless gaseous tritium source



T_2 injection
$p_{inj} = 3 \cdot 10^{-3}$ mbar
$q_{inj} = 4.7$ Ci/s



ΔT ≤ ± 30 mK

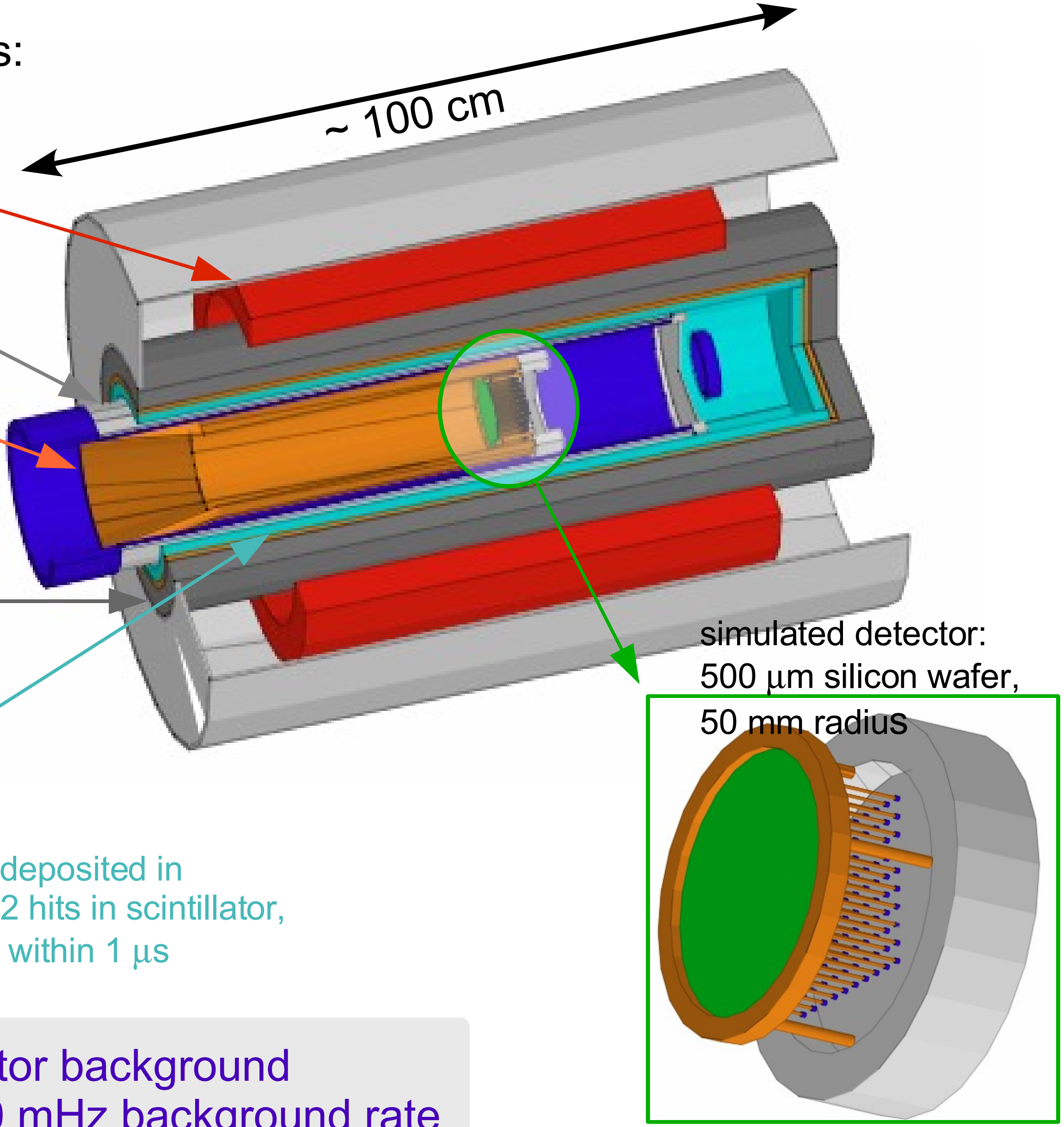


WGTS design:

- tube in long superconducting solenoids
  ∅ 9 cm, length: 10 m, T = 30 K
- near to max. count rate
  while keeping systematic uncertainties small:
  ⇨ working point at $\rho d = 5 \cdot 10^{17}/\mathrm{cm}^2$
- temperature stability of ± 0.1%
  achieved by 2 phase Neon cooling

Reduction of detector background

input model for GEANT4 simulations:



s.c. magnet coil

stainless steel vacuum tube, beam line

post-acceleration electrode
⇒ move away from common γ lines

ceramics HV insulator

passive shielding
outer shield (lead, 3 cm) and inner shield (copper, 1 cm)
⇒ reduce bg from outside sources

active veto shield
(plastic scintillator, 1 cm)
⇒ tag unwanted cosmic ray events and secondary particles

veto cuts:
E > 2 MeV deposited in scintillator, 2 hits in scintillator, detector hit within 1 μs

simulated detector:
500 μm silicon wafer,
50 mm radius

goal: achieve 1 mHz detector background
as contribution to overall 10 mHz background rate

M. Leber, UW Seattle