The KATRIN experiment - a direct ν mass measurement with sub-eV sensitivity

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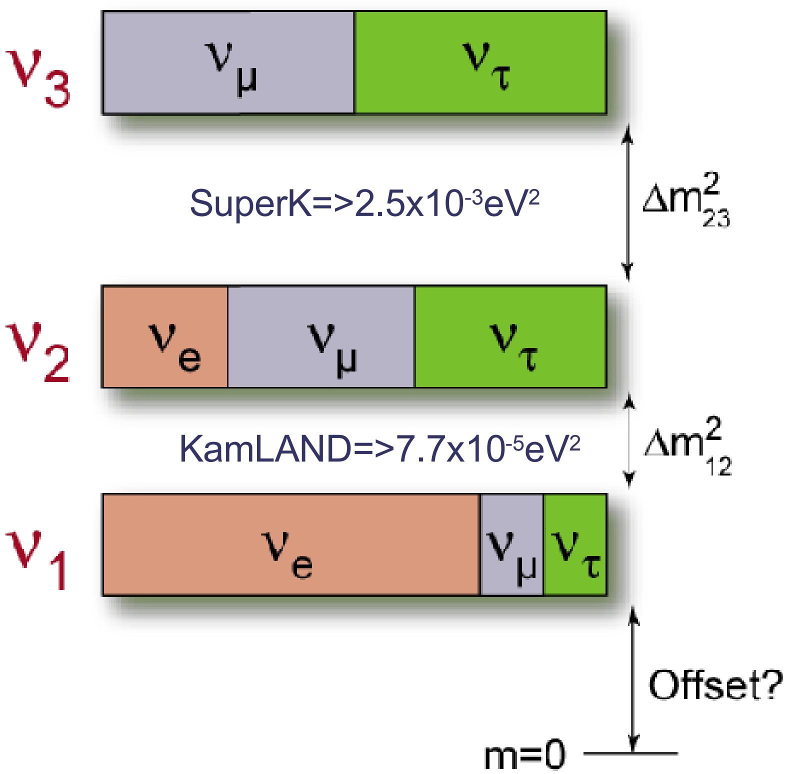
- Introduction
- Experimental setup
- Background suppression
- Calibration and monitoring
- Status and outlook

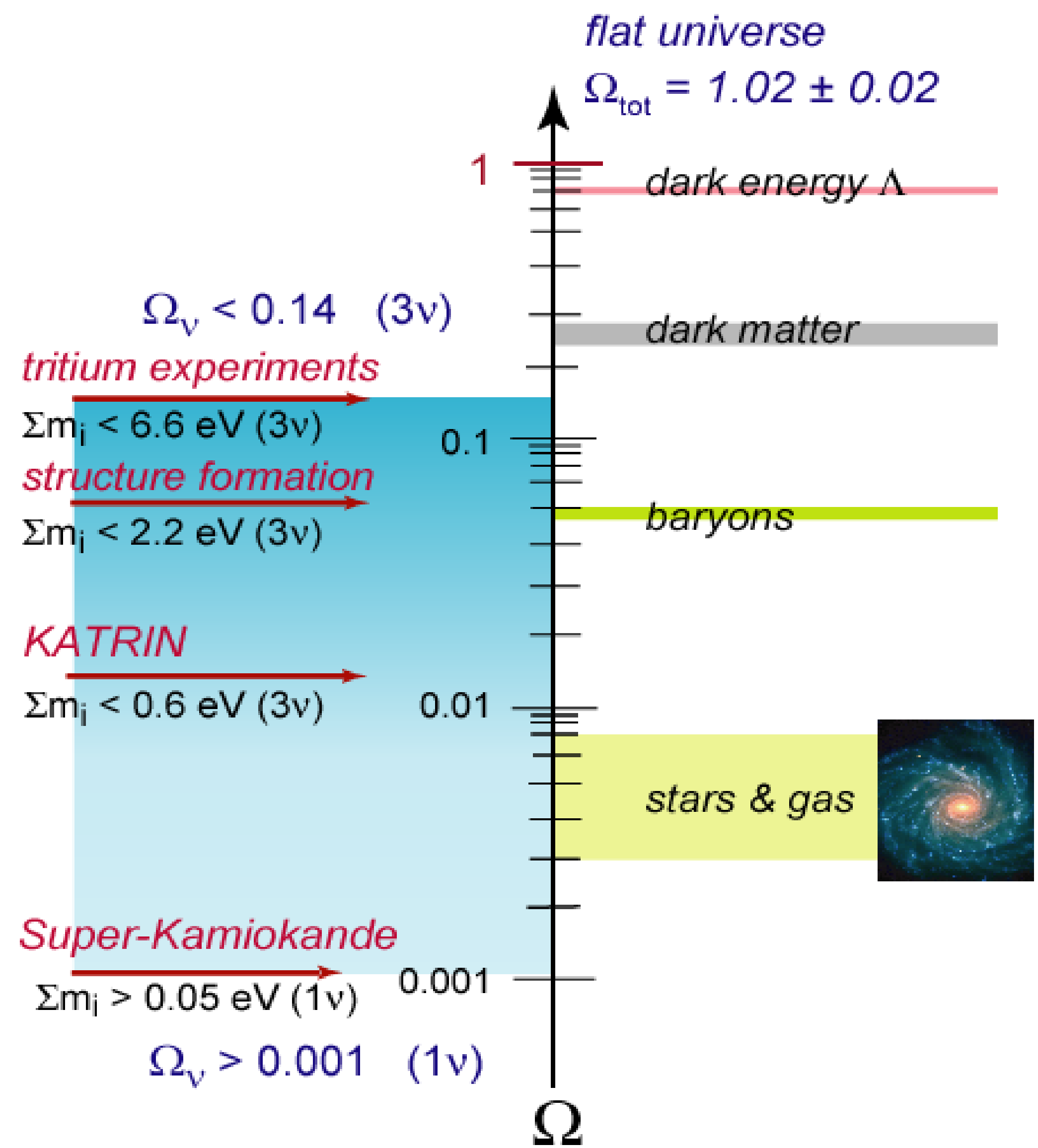
bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

Introduction: neutrino mass in particle and astrophysics

oscillation experiments
measure $\Delta m^2 = (m_i^2 - m_j^2)$



$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$



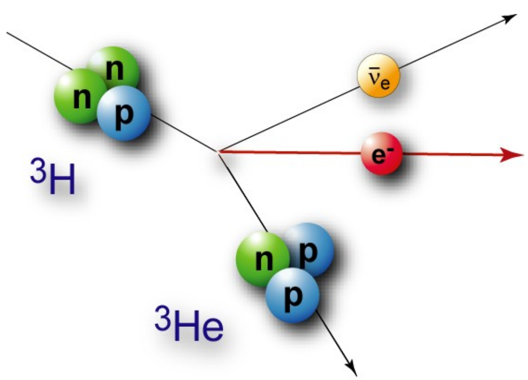
Introduction: methods and upper limits

β-decay: absolute ν-mass
model independent, kinematics
status: $m_\nu < 2.3$ eV
potential: $m_\nu < 0.2$ eV
e.g.: KATRIN, MARE

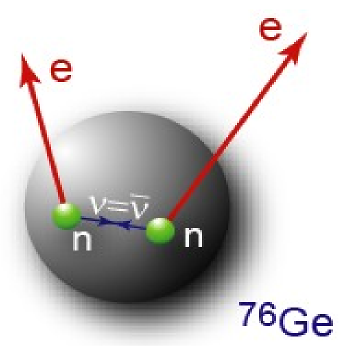
0νββ-decay: eff. Majorana mass
ν-nature (CP), peak at E0
status: $m_\nu < 0.35$ eV
potential: $m_\nu < 0.03$ eV
e.g.: CUORE, EXO, GERDA, Majorana, Nemo 3

m_β

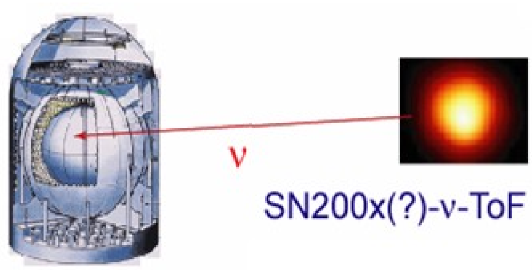
m_{ee}



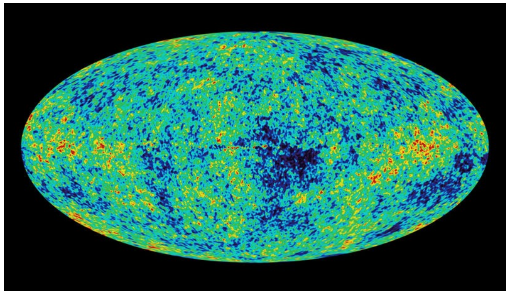
neutrino mass measurements



Σm_i



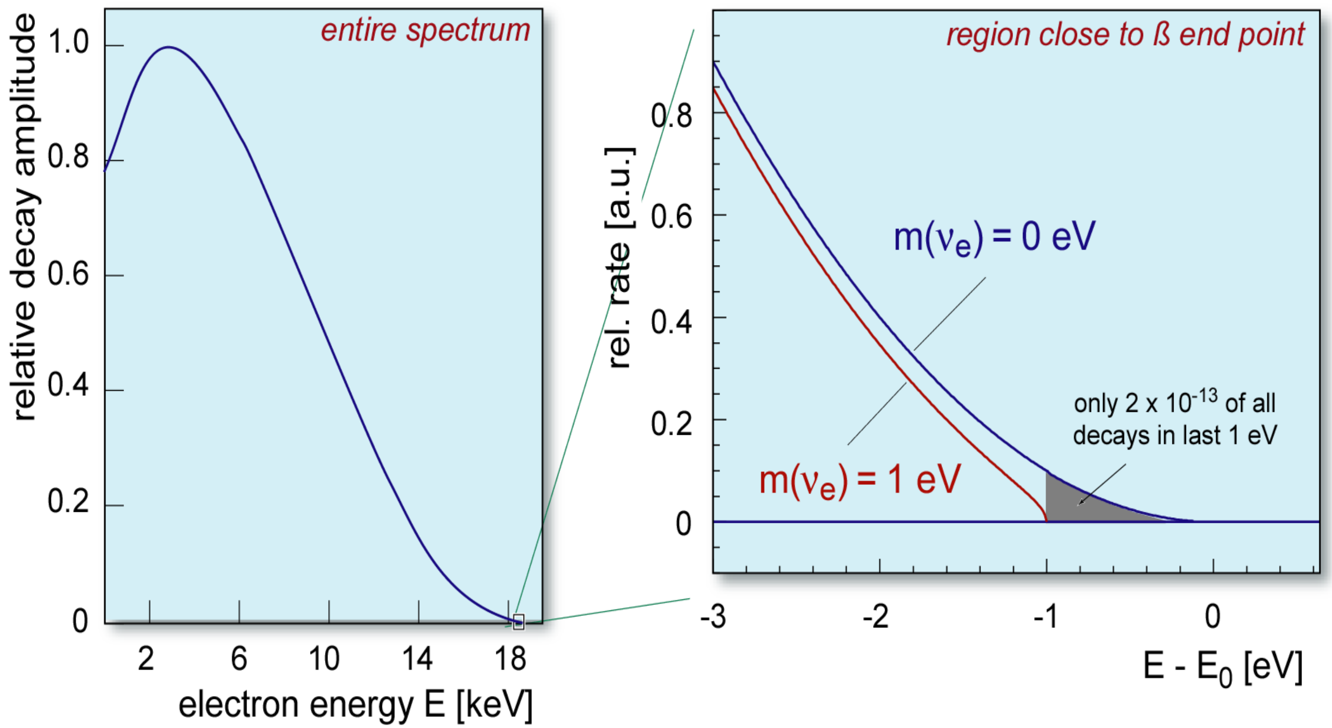
cosmology: ν hot dark matter Ω_ν
model dependent, analysis of LSS data
status: $m_\nu < 0.7$ eV
potential: $m_\nu < 0.07$ eV
e.g.: WMAP, SDSS, LSST, Planck



Introduction: kinematic determination of $m(\nu_e)$

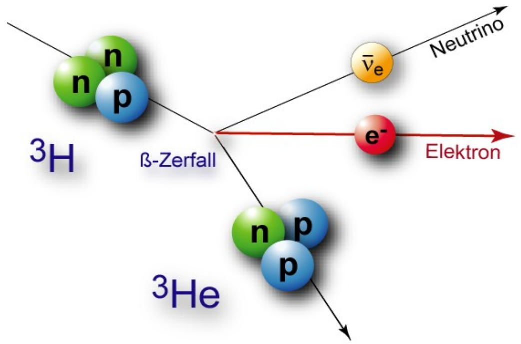
Simplified form of the β spectrum:

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



Tritium: ideal β emitter for this purpose

- E_0 = 18.6 keV
- $T_{1/2}$ = 12.3 a



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

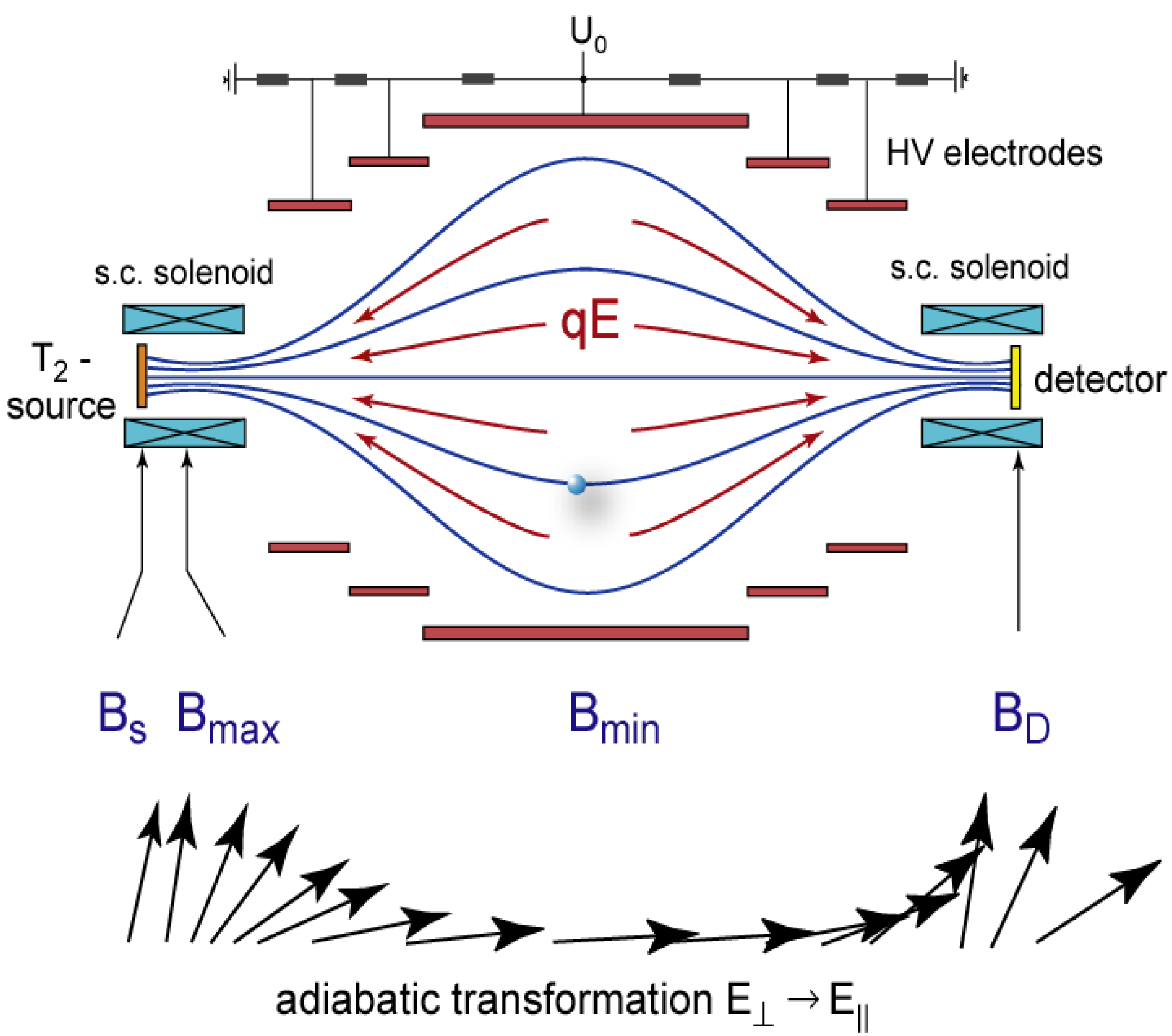
Requirements:

- high energy resolution
- large solid angle (ΔΩ ~ 2π)
- low background rate

→ **use MAC-E filter**

Introduction: MAC-E filter concept

Magnetic Adiabatic Collimation with Electrostatic Filter



- electrons gyrate around magnetic field lines
- only electrons with $E_{||} > eU_0$ can pass the MAC-E filter

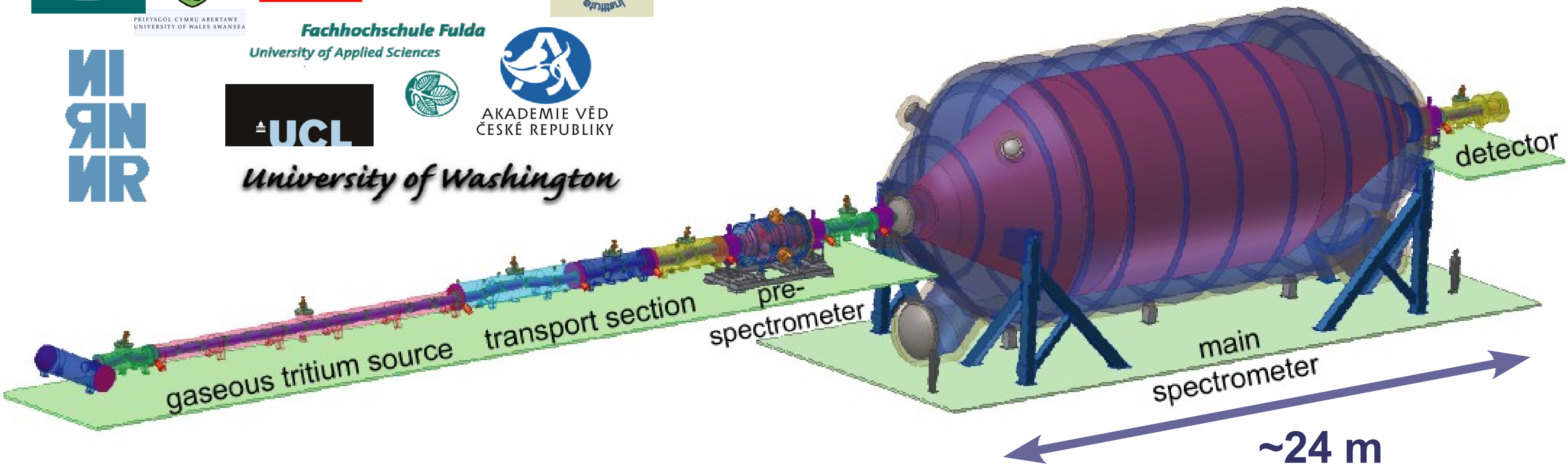
  $\longrightarrow$ **Energy resolution depends on ΔU_0 and on $E_\perp$**
- B drops by a factor 20000 from solenoid to analyzing plane,

  $\mu = E_\perp / B = \text{const.} \longrightarrow E_\perp \rightarrow E_{||}$
- **$\Delta E = E * B_{min} / B_{max} \approx 1$ eV**
- MAC-E filter acts as a high pass filter with a sharp transition function

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

The KATRIN experiment: collaboration

- 100 scientists
- 5 countries
- 14 institutions



Aim: improve the current upper limit by at least one order of magnitude

1000 days of data → 0.2 eV at 90% CL

(KATRIN design report 2004, FZKA 7090)

The KATRIN experiment: experiment overview

Windowless Gaseous Tritium Source (WGTS)

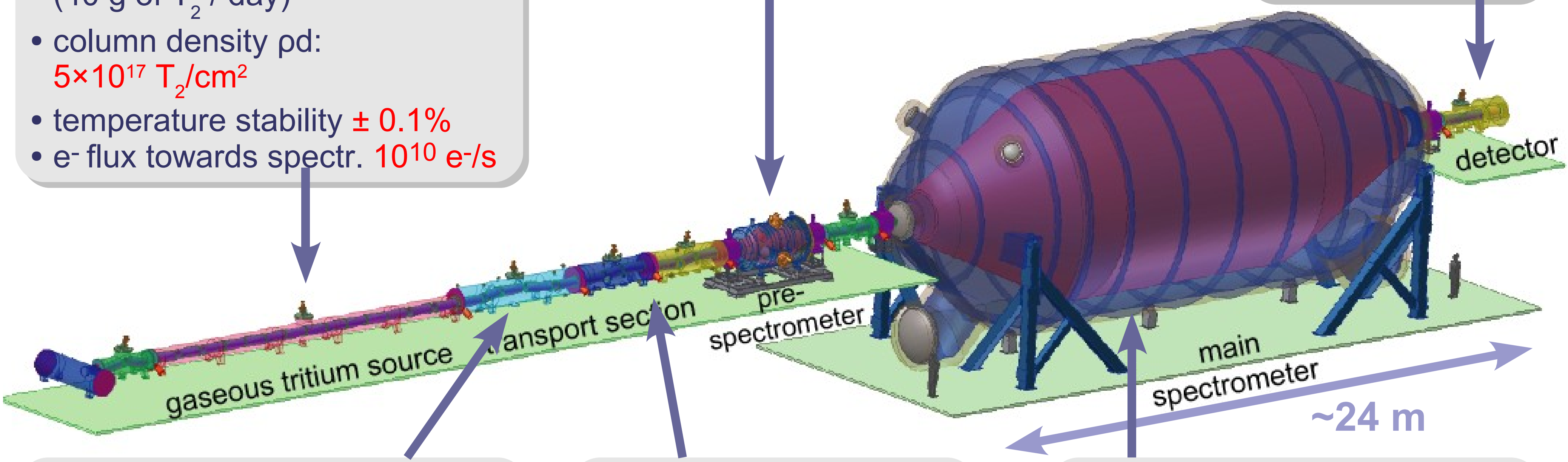
- Tritium flow rate of 5×10^{19} molecules/s (40 g of T_2 / day)
- column density ρd: 5×10^{17} T_2/cm^2
- temperature stability ± 0.1%
- e^- flux towards spectr. 10^{10} e^-/s

Pre-Spectrometer (MAC-E)

- retardation voltage 18.3 kV
- reduce flux to 10^3 e^-/s
- $p < 10^{-11}$ mbar

Electron detector

- segmented
- ≈ 1 keV resolution
- B = 5.6 T
- veto shield



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

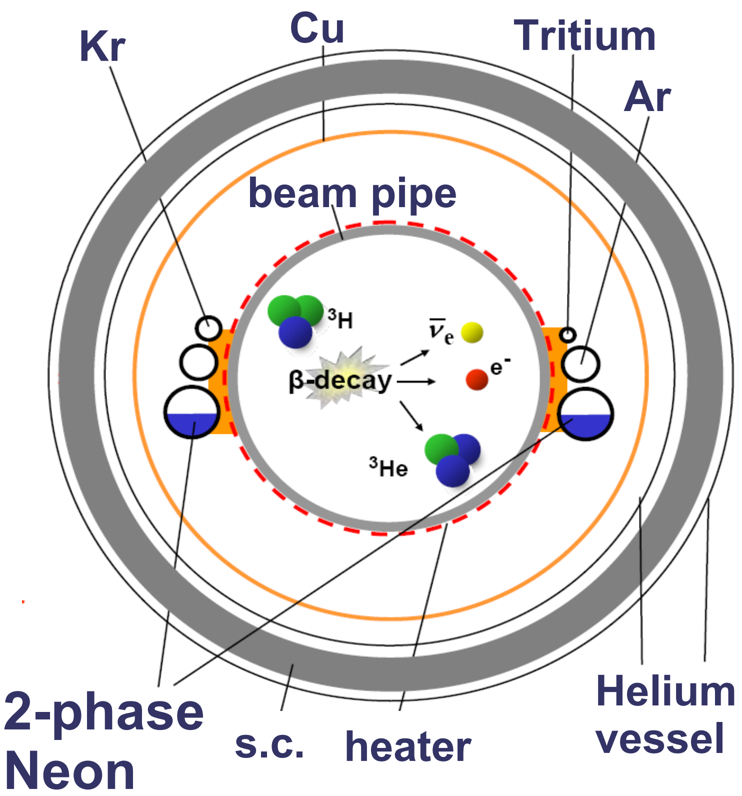
Main-Spectrometer (MAC-E)

- @ 18.6 keV (endpoint)
- 1 eV resolution
- $p < 10^{-11}$ mbar

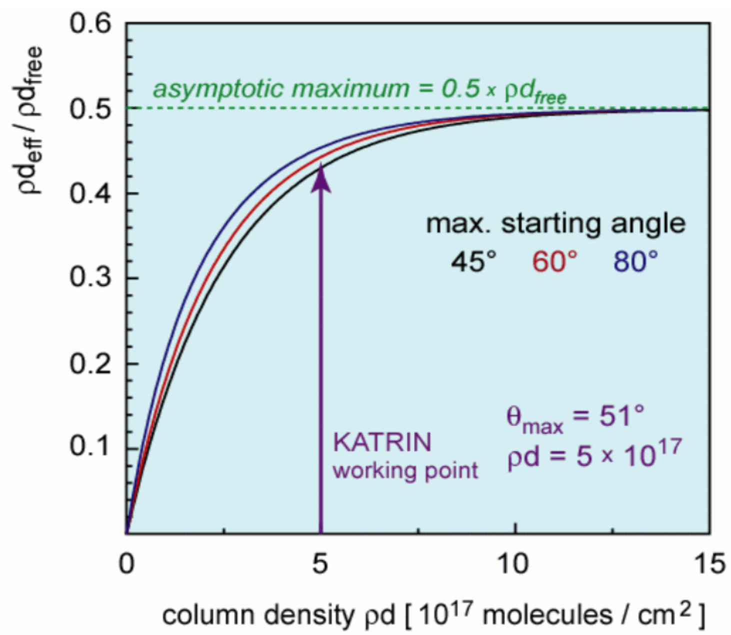
Tritium laboratory Karlsruhe (TLK)

KATRIN spectrometer hall

The KATRIN experiment: windowless gaseous tritium source



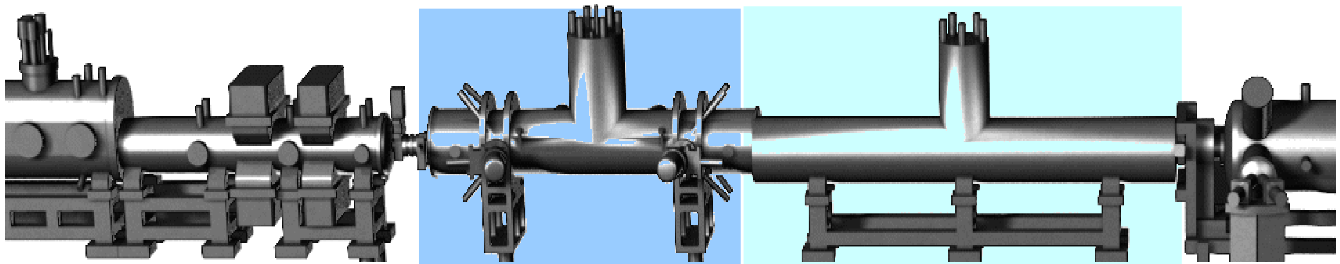
ΔT ≤ ± 30 mK



WGTS design:

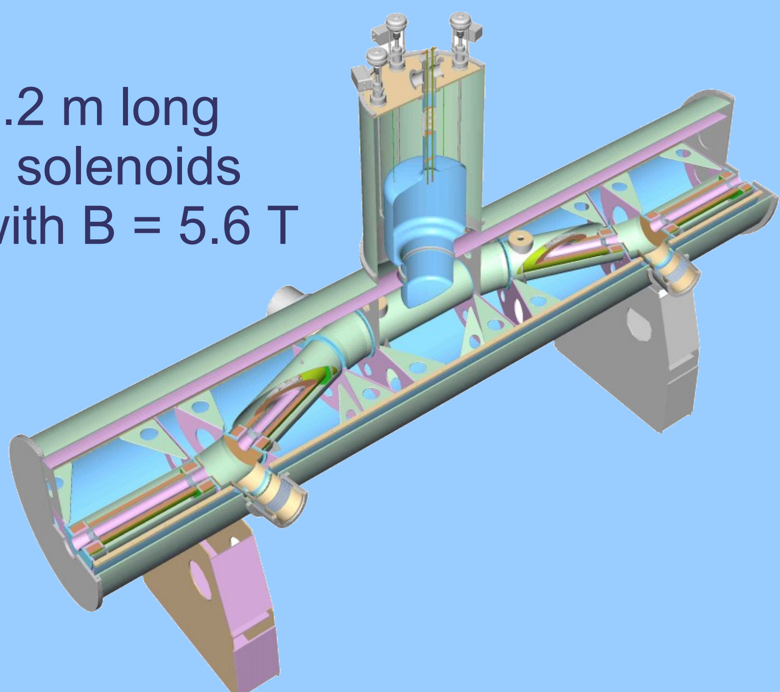
- tube in long superconducting solenoids
  ∅ 9cm, length: 10m, T = 30 K
- near optimal working point @ $\rho d = 5 \cdot 10^{17}/cm^2$
- temperature stability of ± 0.1%
  achieved by 2 phase Neon cooling

The KATRIN experiment: differential and cryo pumping sections



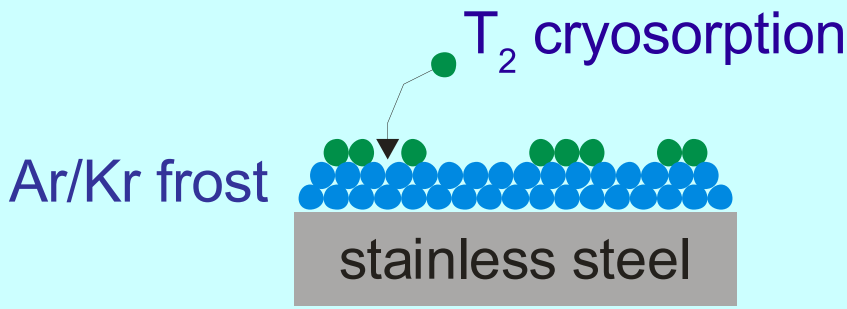
DPS: differential pumping of T_2 using TMPs (2000 l/s)

- 6.2 m long
- 5 solenoids
- with B = 5.6 T



→ T_2 reduction by **≥ 10^7**

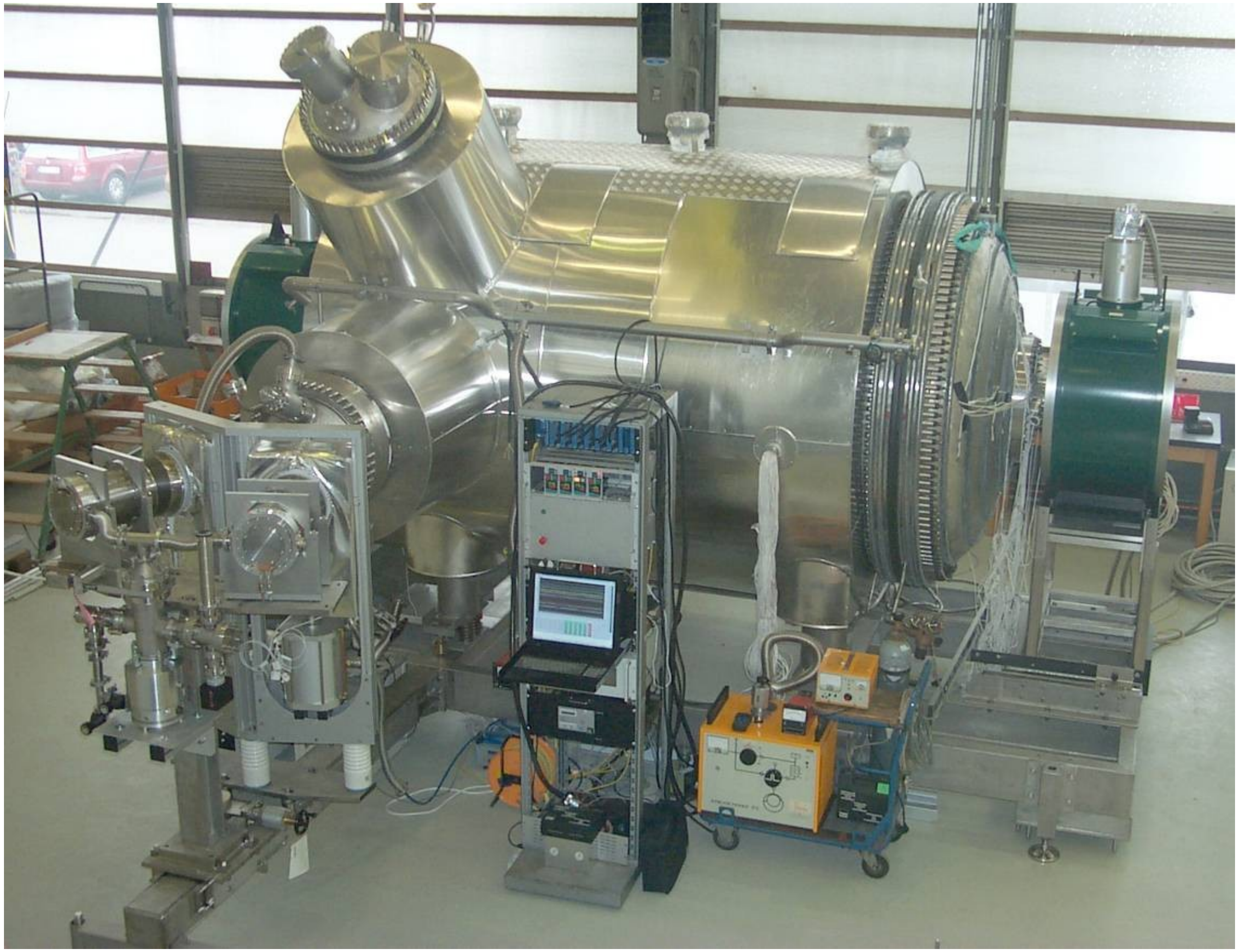
CPS: cryosorption of tritium on Ar/Kr frost at 3 – 4.5 K



- maximum allowed tritium flow into the pre-spectrometer: 10^{-14} mbar l/s
- last tritium retention stage before the spectrometers
- tritium suppression factor **≥ 10^7**

The KATRIN experiment: pre-spectrometer

- **Pre-filter** with a fixed potential: $E = 18.3$ keV
  $\Delta E \approx 100$ eV
- **Test-bed** for the main spectrometer technology



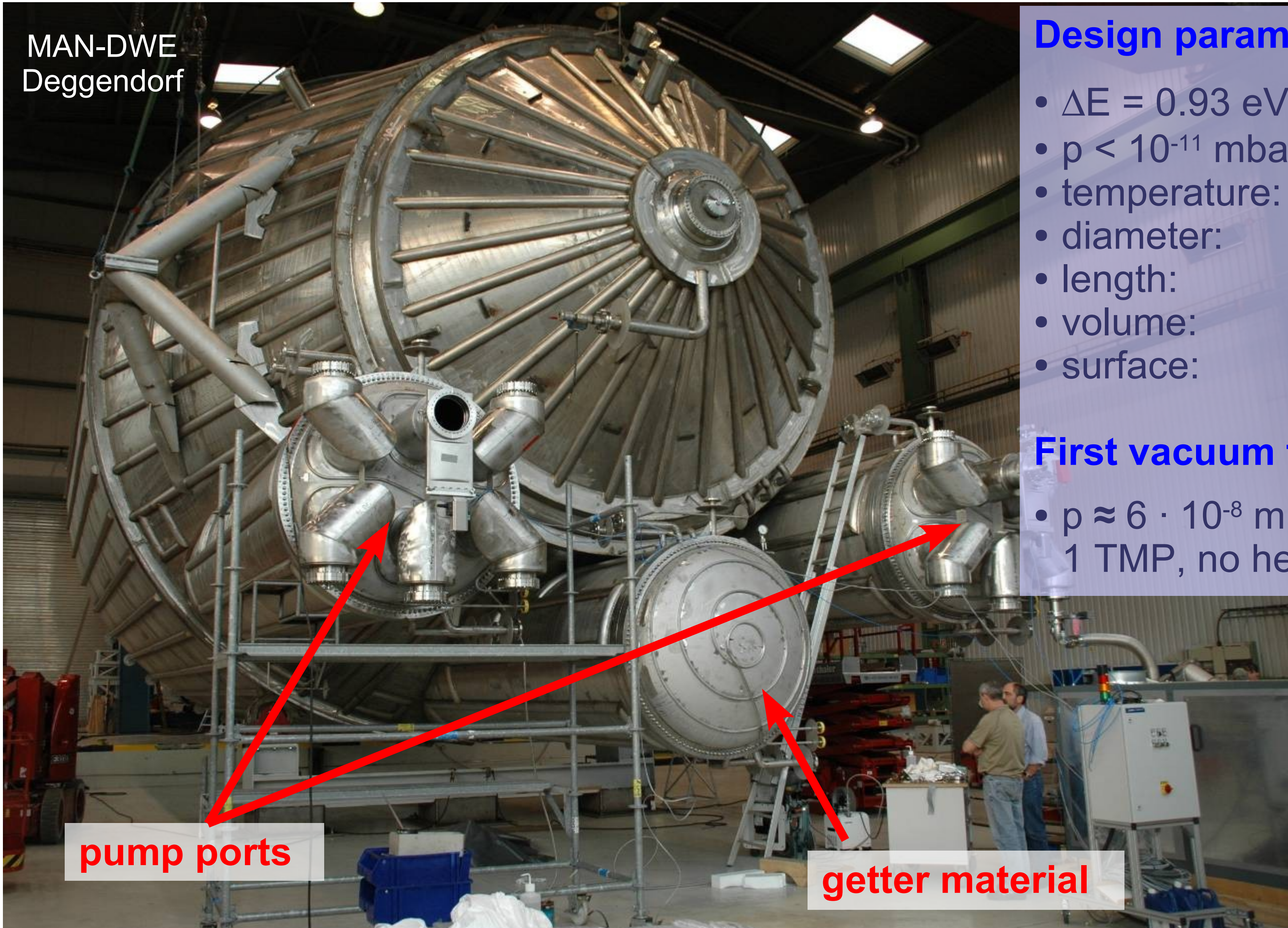
Vacuum tests:

- turbo-molecular pumps
- NEG pumps (getter)
- outgassing rate:
  $< 10^{-12}$ mbar l/cm^2 s
- $p < 10^{-11}$ mbar
- heating/cooling

Electro-magnetic tests:

- test of el.-mag. design
- high voltage on outer vessel
- inner wire electrode
- electrical insulators
- s.c. magnets

The KATRIN experiment: main-spectrometer



Design parameters:

- $\Delta E = 0.93$ eV
- $p < 10^{-11}$ mbar
- temperature: 10...350°C
- diameter: 10 m
- length: 23.3 m
- volume: 1258 m^3
- surface: 650 m^2

First vacuum tests:

- $p \approx 6 \cdot 10^{-8}$ mbar with 1 TMP, no heating

The KATRIN experiment: main-spectrometer transport

8800 km

The KATRIN experiment: installation in experimental hall

The KATRIN experiment: detector

Task

- detection of electrons passing the main spectrometer

Requirements

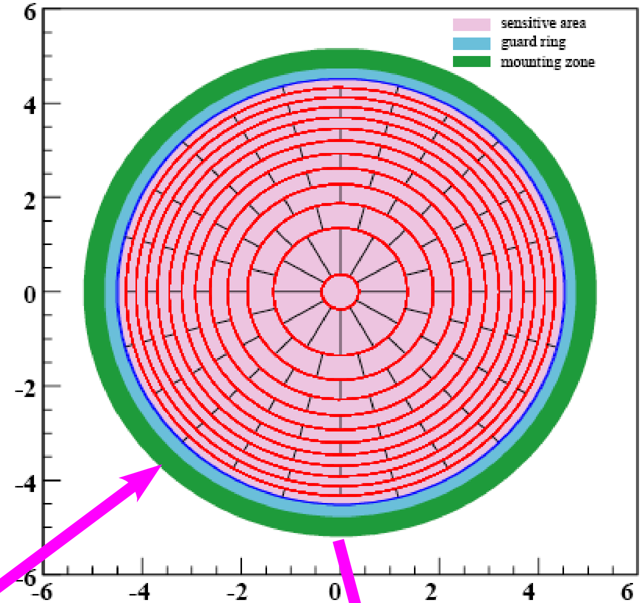
- high efficiency (> 90%)
- low background (< 1 mHz) (passive and active shielding)
- good energy resolution (< 1 keV)

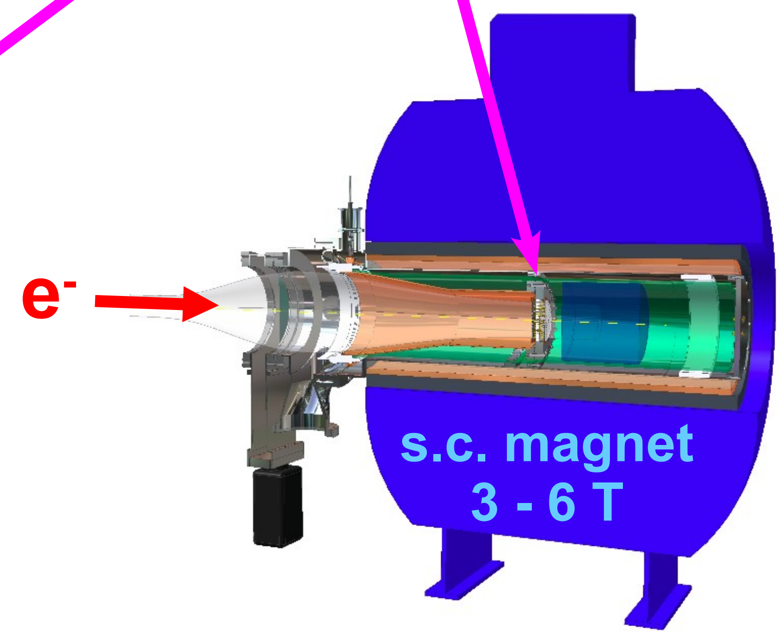
Properties

- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- segmented wafer (145 pixels)
- post acceleration (30kV) (to lower background in signal region)

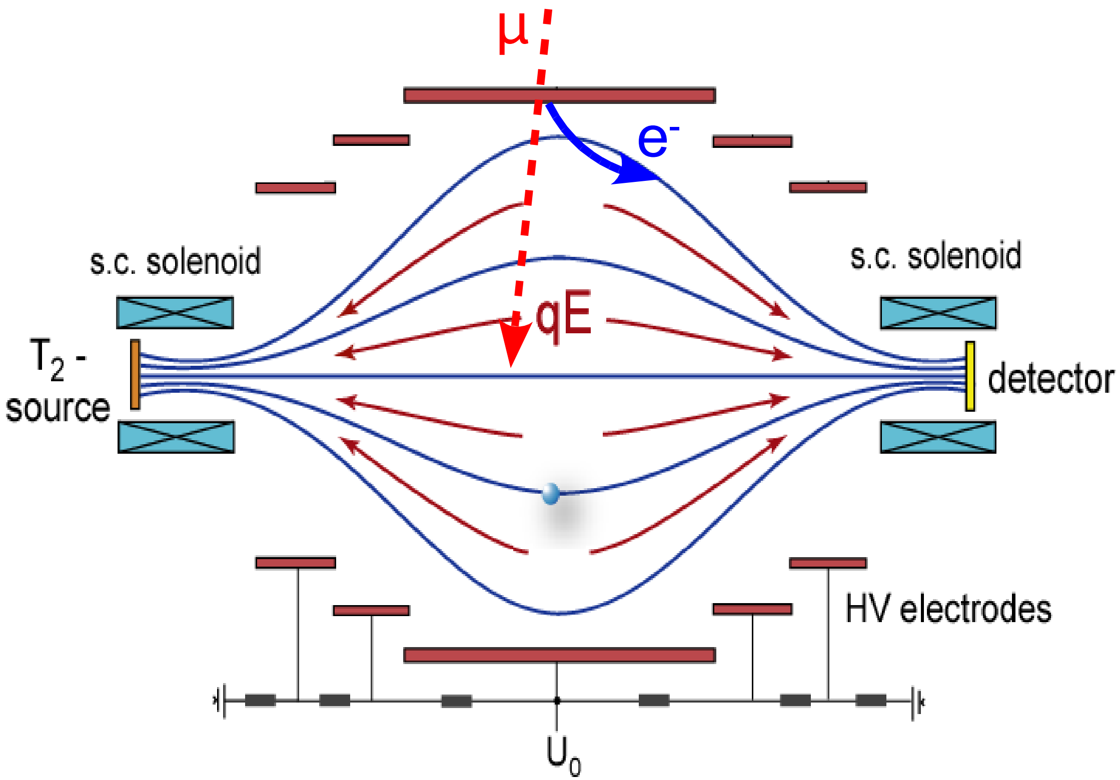
Status

- 2007: design report (FZK, Seattle, MIT)
- 2010: commissioning

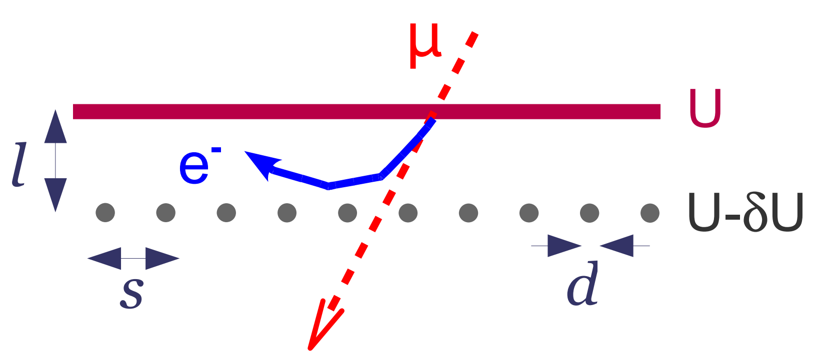




KATRIN wire electrode: screening of background electrons



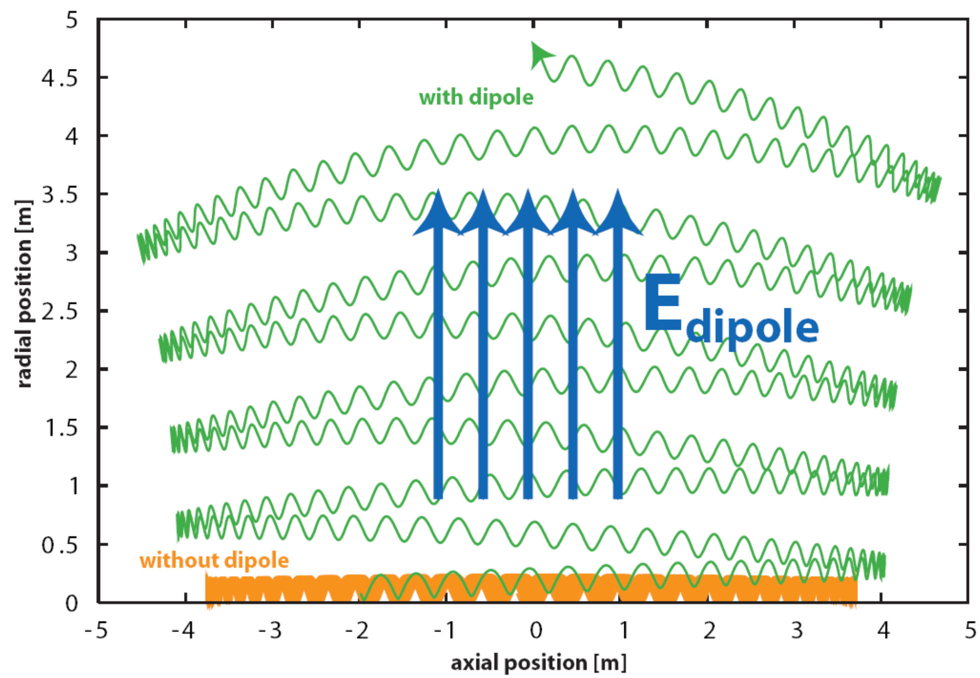
- Cosmics and radioactive contamination can mimic e⁻ in endpoint energy region
- 650m² surface of main spectrometer
  → ca. 10^5 μ / s + contamination
- Reduction due to B-field: factor 10^5-10^6
- Real signal rate in the mHz region
- **Additional reduction necessary**



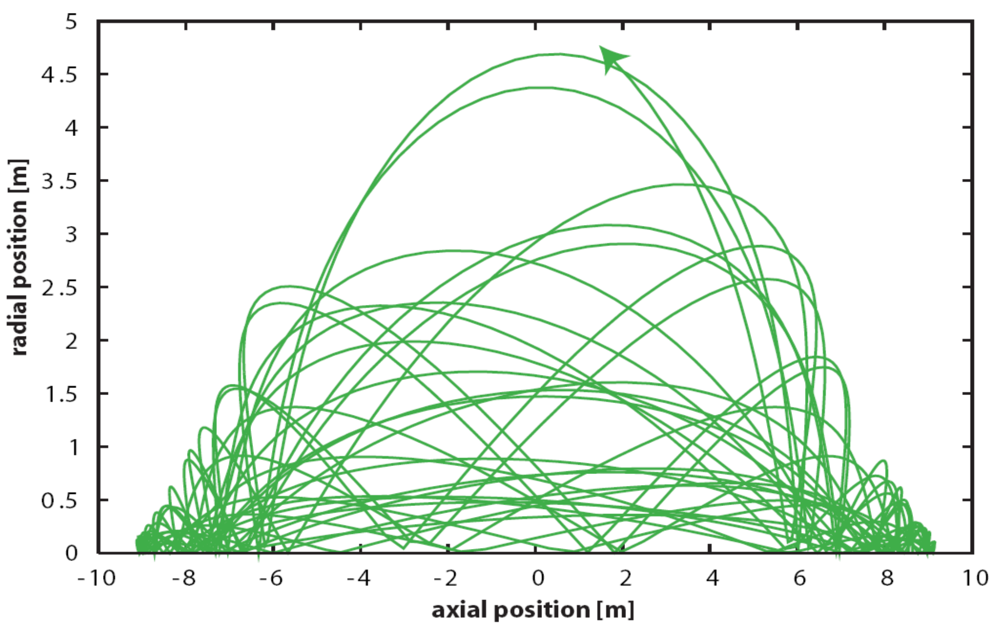
- Screening of background electrons with a wire grid on a negative potential
- Proof of principle at Mainz MAC-E filter
  → at 200 V shielding potential the background rate was **reduced by a factor 10** with a single layer electrode

KATRIN wire electrode: removal of trapped particles

- combined electrostatic and magnetic fields can trap charged particles inside the main spectrometer
- ionization of residual gas molecules → creation of secondary electrons increasing background



trapped electron (orange), electric dipole field causes radial drift motion out of sensitive spectrometer region (green)



trapped proton, remains stored inside central volume for many cycles of reflection

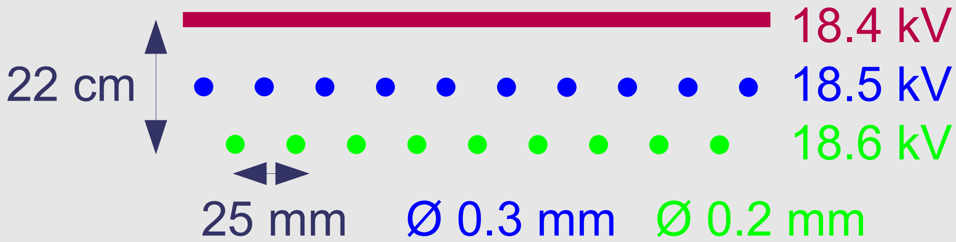
'dipole mode' of wire electrode:

- trapped particles are driven towards vessel wall by E x B drift
- removed from sensitive volume by absorption or neutralization

$$v_{drift} = (E \times B) / |B|^2$$

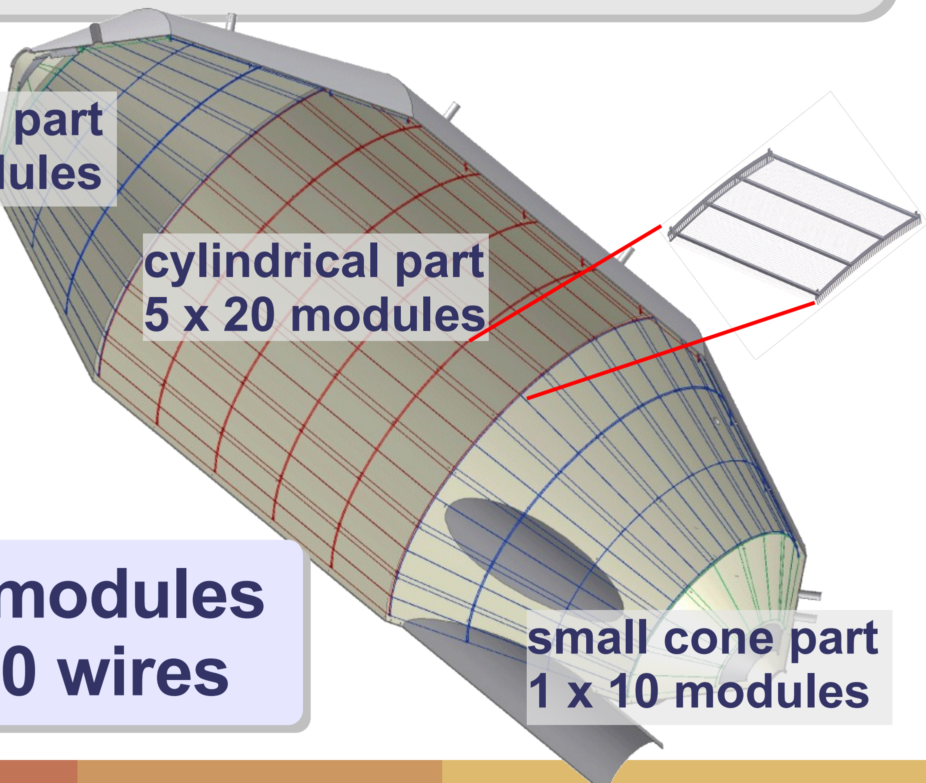
KATRIN wire electrode: technical design and quality assurance

KATRIN: double layer electrode

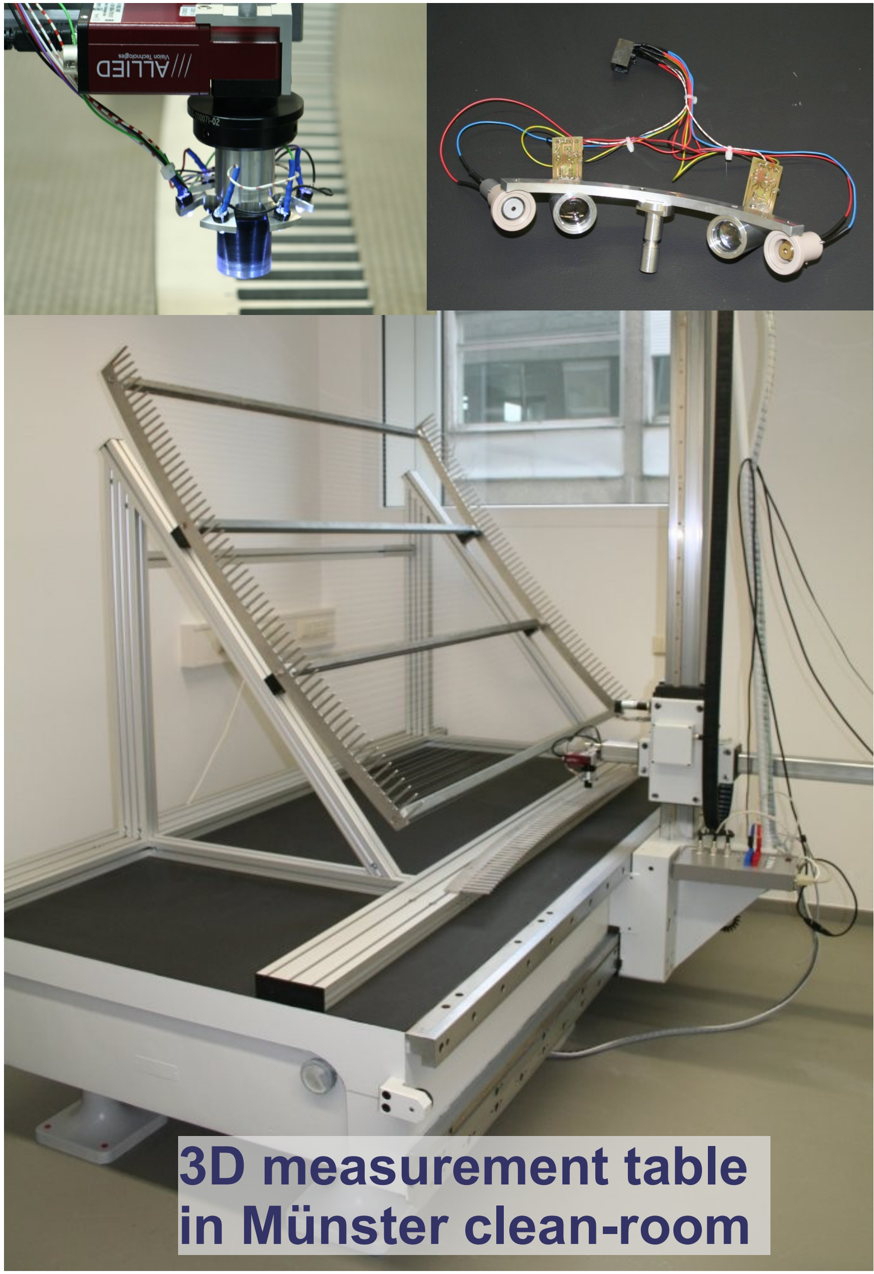


- improved shielding and electric field homogeneity

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

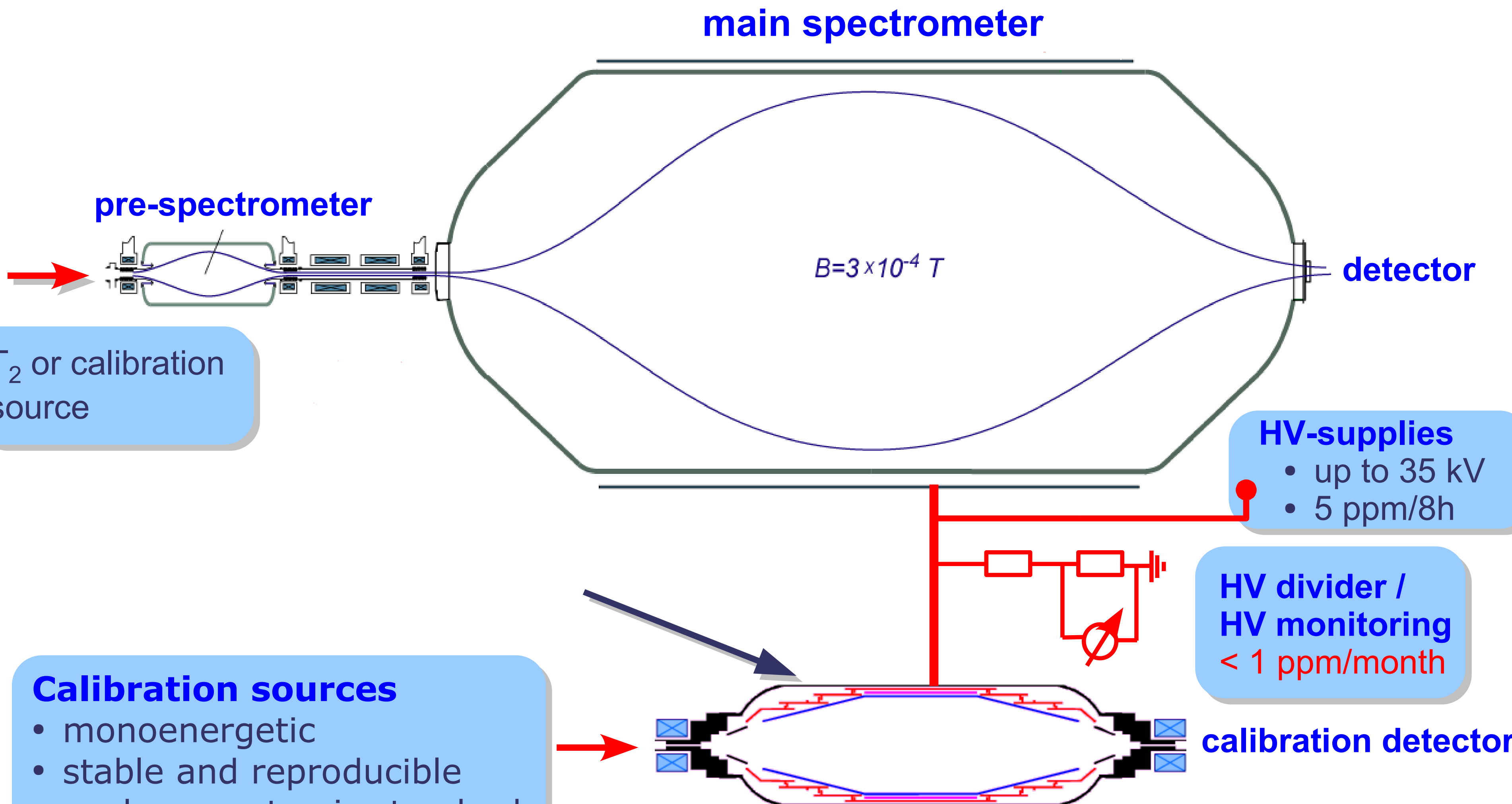


Σ = 240 modules
23000 wires



3D measurement table in Münster clean-room

Calibration and monitoring: monitor spectrometer concept



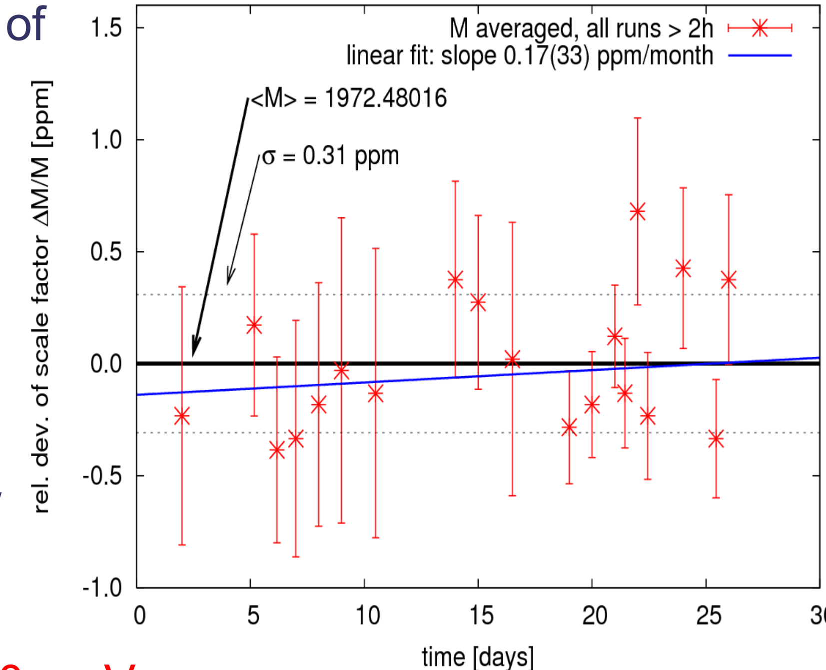
Calibration sources
- monoenergetic
- stable and reproducible
- nuclear or atomic standard

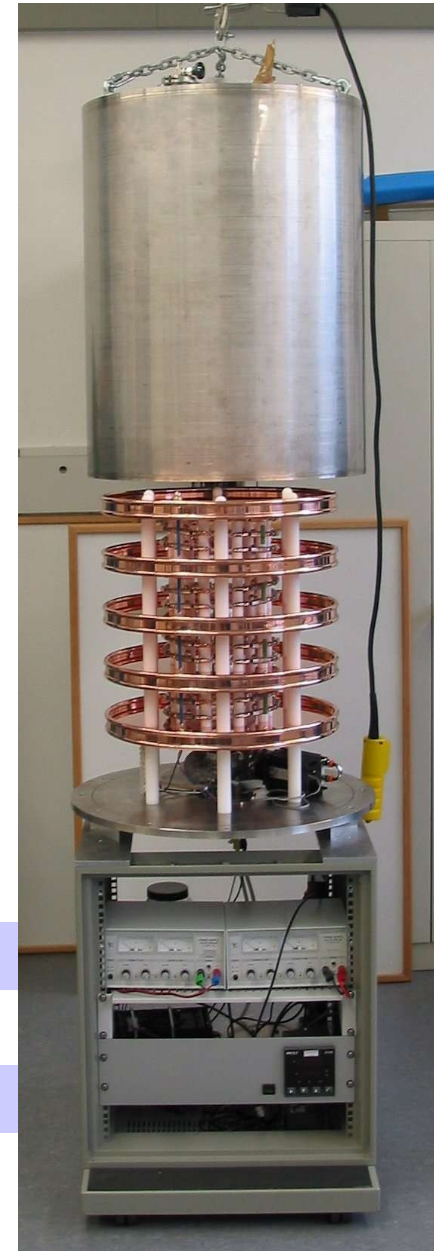
monitor spectrometer (enlarged):
- former Mainz spectrometer
- adapted to 1 eV resolution

error budget: $\Delta m_\nu^2 \leq 0.007\ eV^2 \Rightarrow \sigma < 60\ meV \Rightarrow$ 3 ppm long term stability

Calibration and monitoring: precision high voltage divider

- Precision HV divider for monitoring of KATRIN retardation voltage
- 100 Vishay bulk metal foil resistors with a total resistance of R = 184 MΩ, **TCR < 2 ppm / K**
- divider ratios 1:3944 / 1:1972
- Temperature regulated with N_2 flow to T = 25 °C with ΔT < 0.1 °C
- KATRIN stability requirement σ < 60 meV
  → long term stability of < 1 ppm/month required





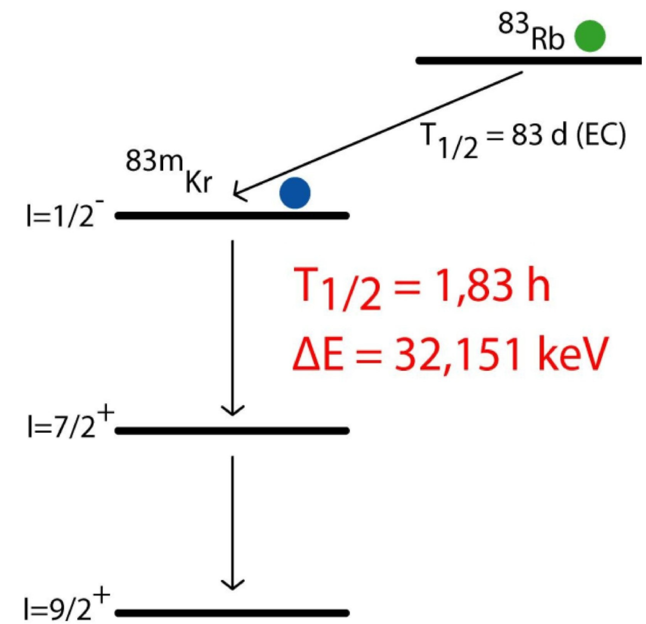
scale factors	**1972,48016(61) : 1**	**3944,95973(138) : 1**
rel. standard deviation	**0,31 ppm**	**0,35 ppm**
long term stability (Sept. 2005)	**3,0(1,0) ppm/month**	**1,6(7) ppm/month**
long term stability (Okt. 2006)	**0,17(33) ppm/month**	**0,25(59) ppm/month**
long term stability 2005 - 2006	**0,604(53) ppm/month**	**0,564(52) ppm/month**

preliminary

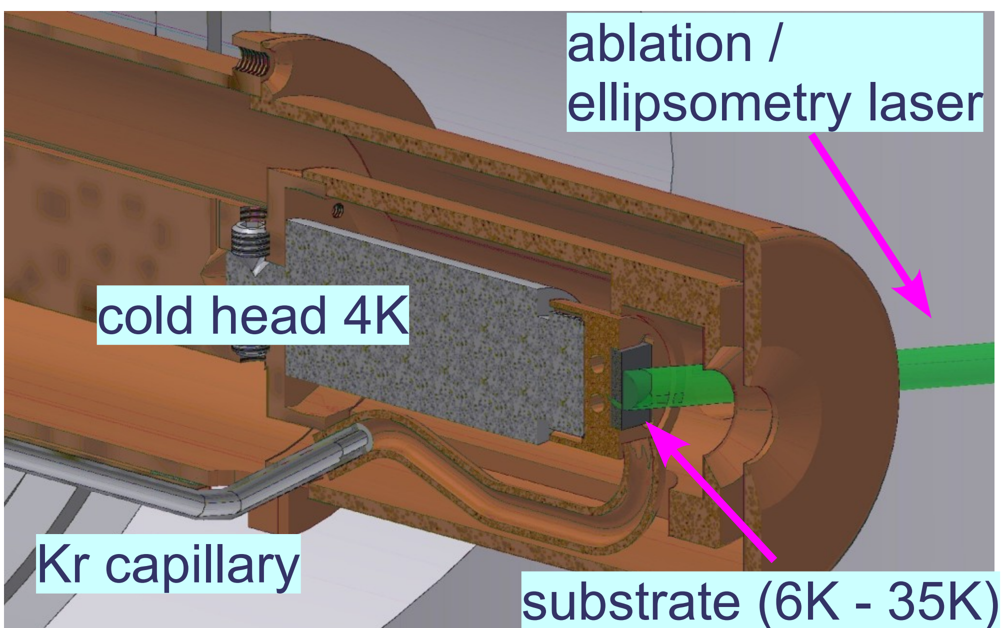
T. Thümmler with support from Dr. K. Schon und R. Marx, PTB Braunschweig.

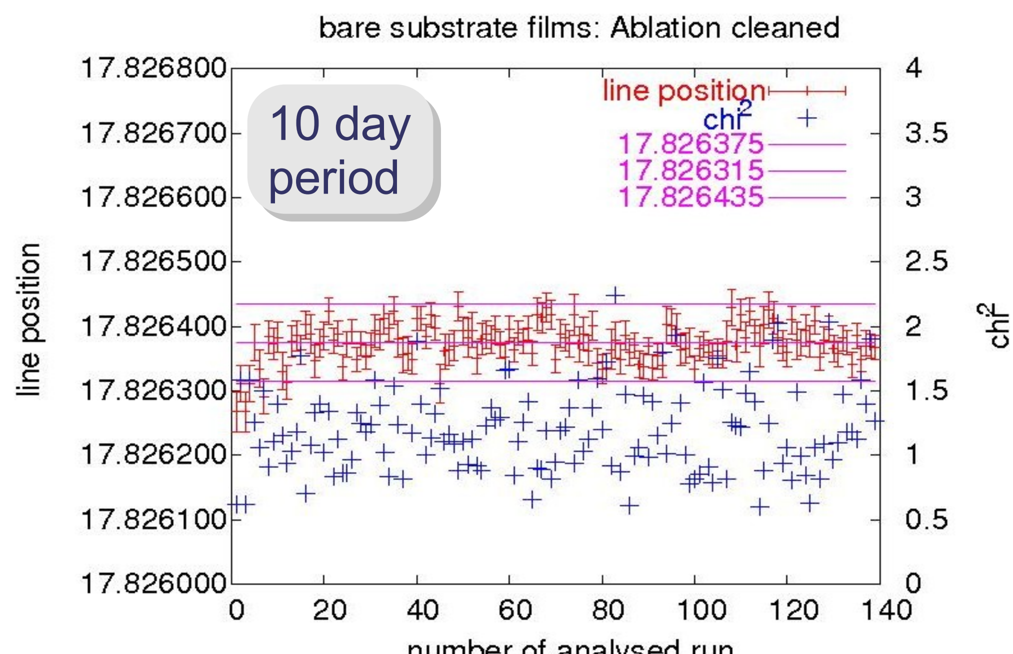
Calibration and monitoring: condensed Krypton source

- Natural standard via 17.8 keV conversion electrons from ^{83m}Kr decay (additional L_3-32 line at 30.5 keV)
- Production via ^{81}Br(α,2n)^{83}Rb at the Uni-Bonn cyclotron
- stability with pre-plated substrate: σ = 56 meV



graphite substrate pre-plated with stable Kr





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KATRIN experiment: status and outlook

- **KATRIN main components** are either set up (e.g. pre-spectrometer, main-spectrometer vessel) or under construction (e.g. WGTS, DPS); test experiments are running (TILO, TRAP, calibration sources)

- **Main spectrometer:** installation of full vacuum system and test of heating cooling system summer 2007;
  Production of **inner wire electrode** starts June 2007,
  installation of wire electrode beginning of 2008

- **CkrS:** automation and final tests summer 2007;
  HV divider: first divider successfully built and tested,
  second (redundant) divider under construction

- **Begin of KATRIN measurements:** 2010,
  expected measurement time 5-6 years for 3 years worth of data

- **Sensitivity:** upper limit of 0.2 eV with 90% C.L. ;
  a neutrino mass of 0.35 eV could be determined
  with 5σ significance