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

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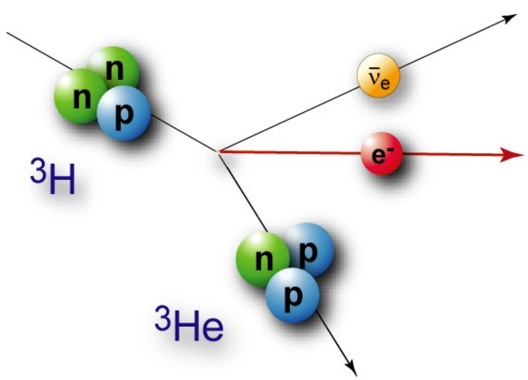
- Introduction
- Experimental setup
- Wire electrode
- Status and outlook

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

Introduction (1/3): 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

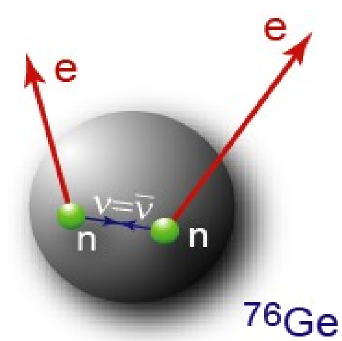


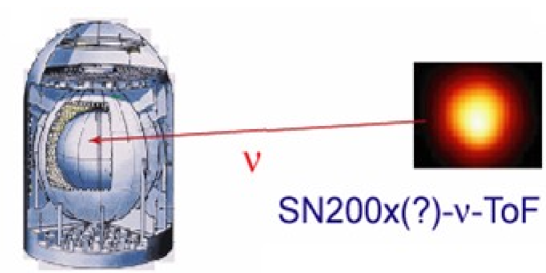
neutrino mass measurements

m_β

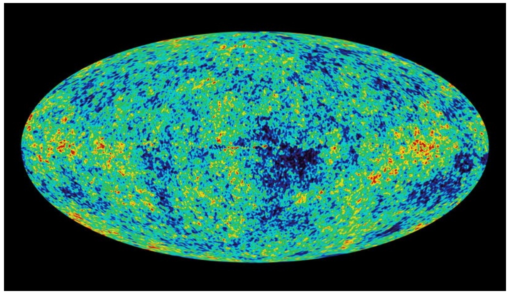
m_{ee}

Σm_i





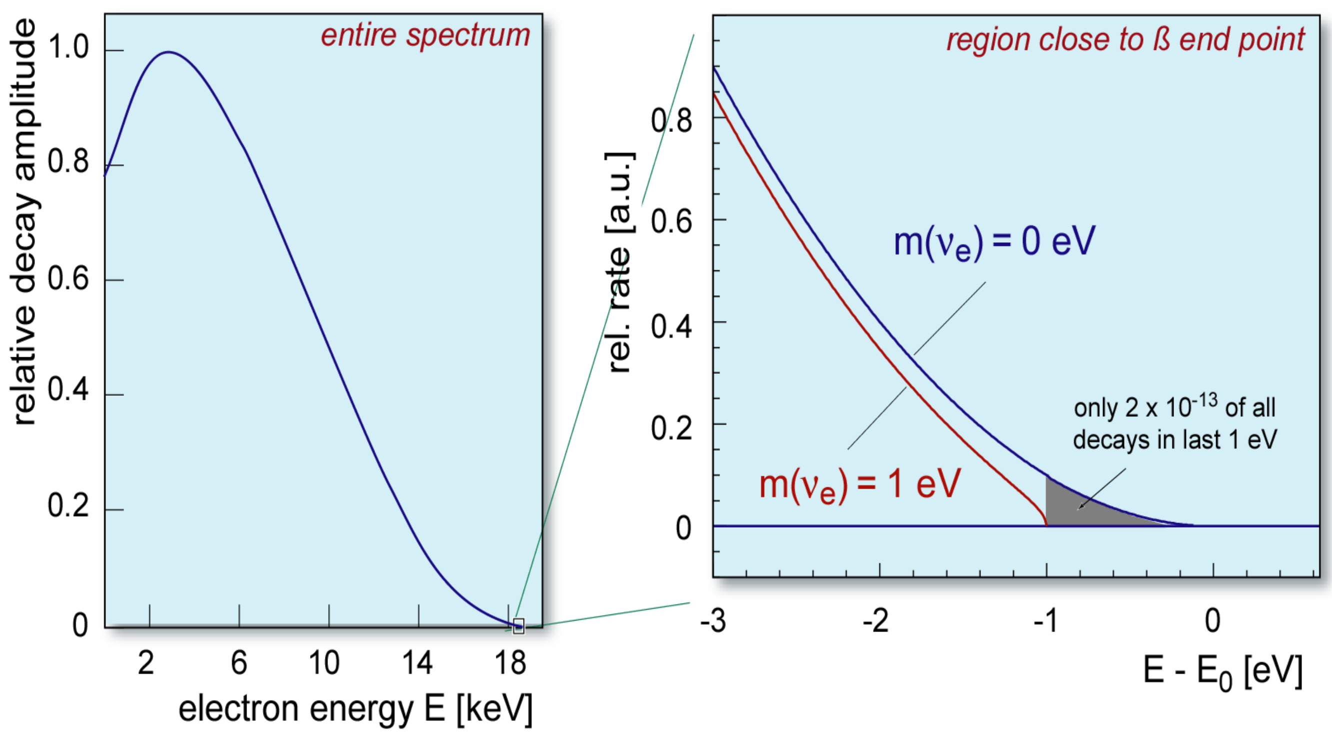
cosmology: ν hot dark matter Ω_ν
model dependent, analysis of LSS data
status: $m_\nu < 0.7$ eV
potential: $m_\nu < 0.07$ eV
e.g.: WMAP, SDSS, LSST, Planck



Introduction (2/3): kinematic determination of $m(\nu_e)$

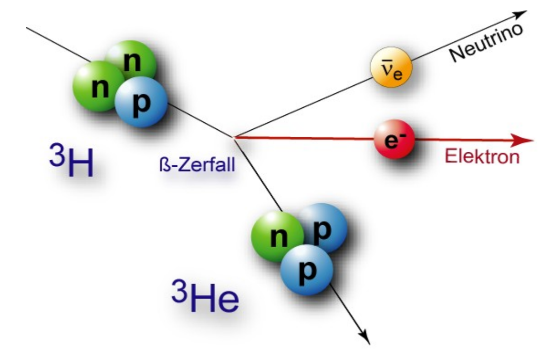
Simplified form of the β spectrum:

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



Tritium: ideal β emitter for this purpose

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



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

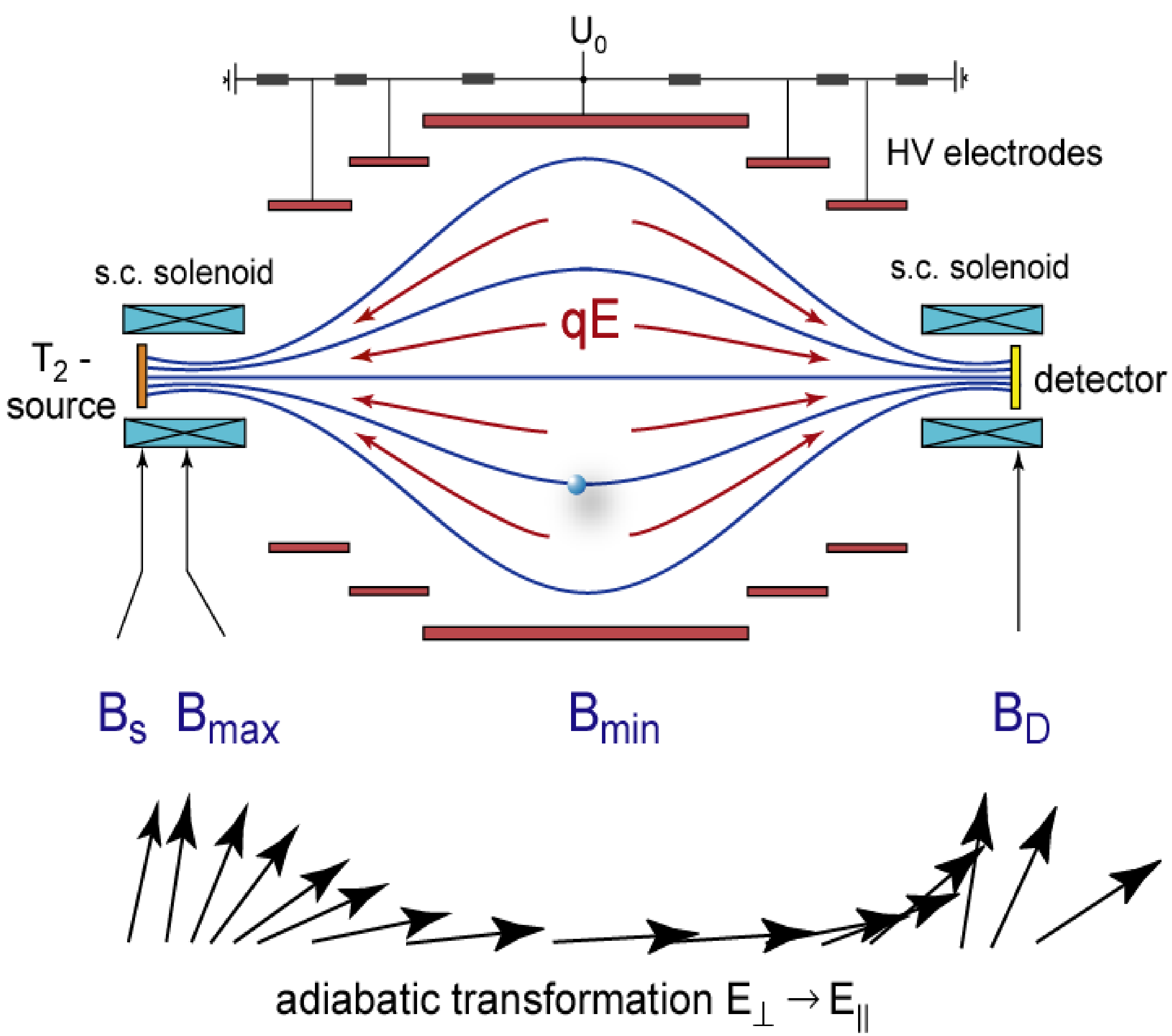
Requirements:

- high energy resolution
- large solid angle ($\Delta\Omega \sim 2\pi$)
- low background rate

→ **use MAC-E filter**

Introduction (3/3): 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 (1/4): experiment overview

Windowless Gaseous Tritium Source (WGTS)

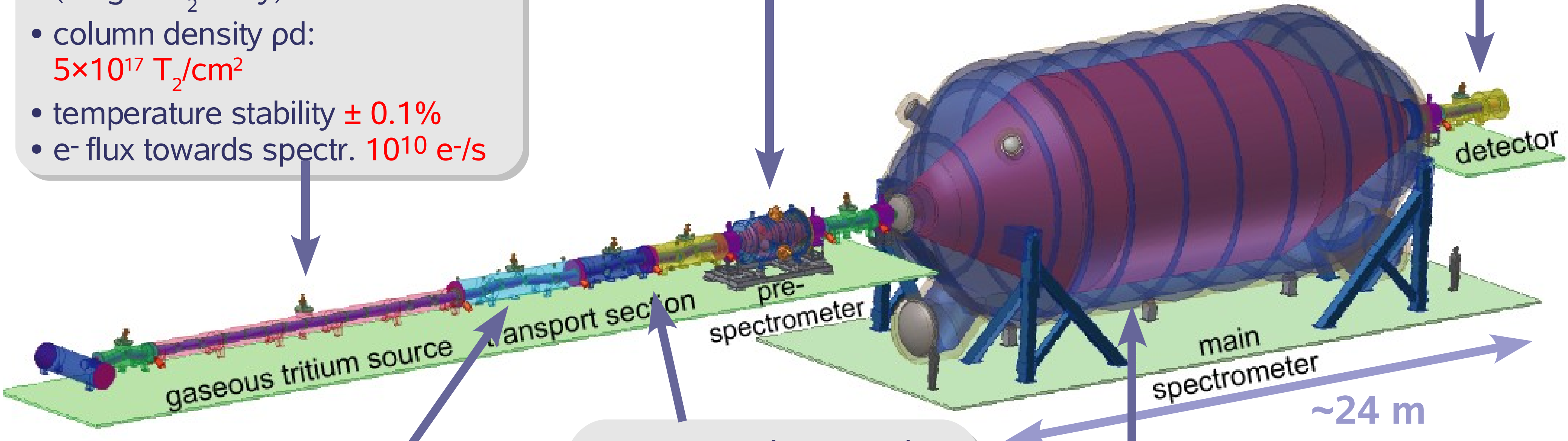
- Tritium flow rate of 5×10^{19} molecules/s (40 g of T_2 / day)
- column density ρd: 5×10^{17} T_2/cm^2
- temperature stability ± 0.1%
- e- flux towards spectr. 10^{10} e-/s

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
- T_2 reduction by 10^{14} (DPS+CPS)

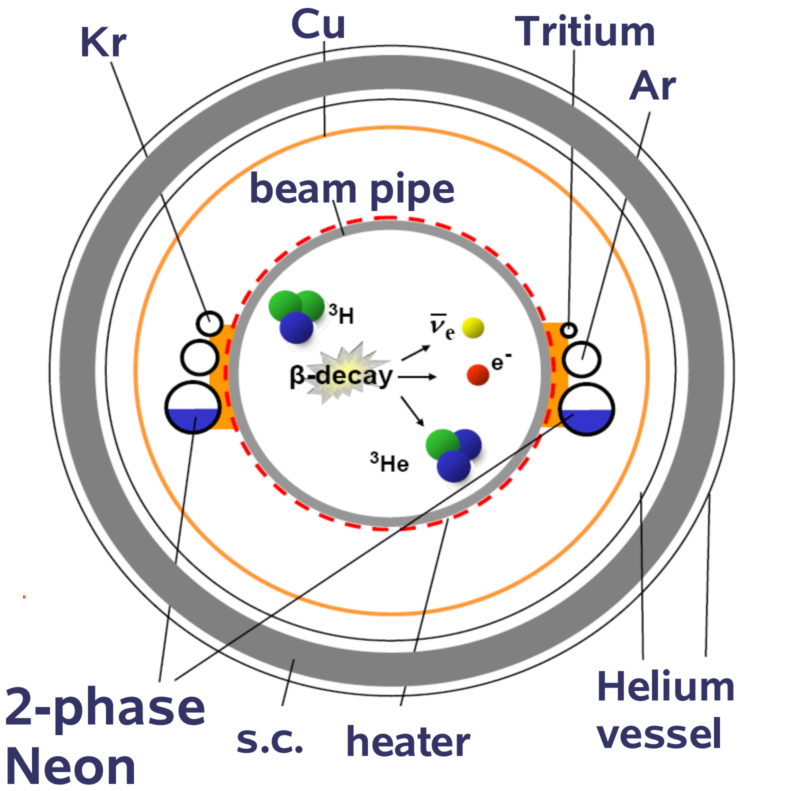
Main-Spectrometer (MAC-E)

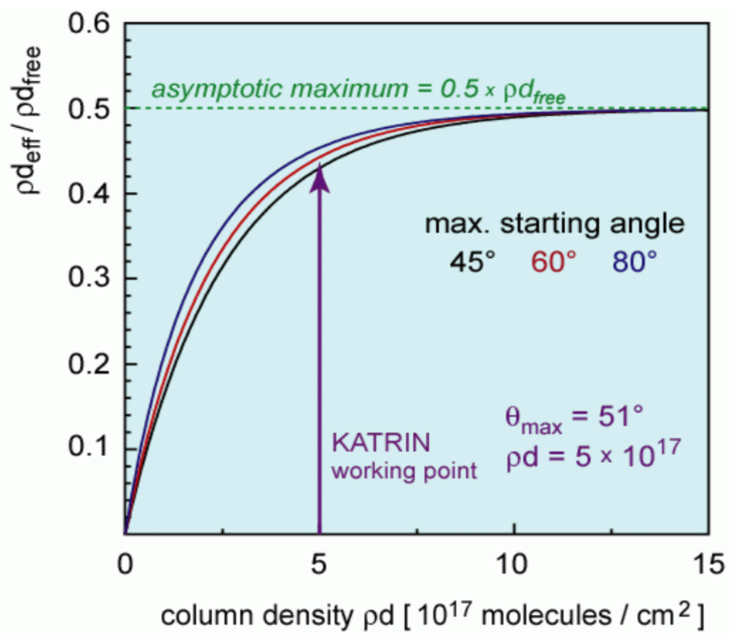
- @ 18.6 keV (endpoint)
- 1 eV resolution
- p < 10^{-11} mbar

1000 days of data → 0.2 eV at 90% CL

(KATRIN design report 2004, FZKA 7090)

The KATRIN experiment (2/4): 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 (3/4): Tritium Laboratory Karlsruhe

- former focus on fusion resarch for ITER (development of T_2 fuel cycle)
- area : ca. 1000 m^2
- current T_2 inventory: 25 g
- will house all T_2 carrying components of the KATRIN experiment

Westfälische Wilhelms-Universität Münster

The KATRIN experiment (4/4): arrival of the main-spectrometer

KATRIN
Karlsruhe Tritium Neutrino Experiment

25.11.2006

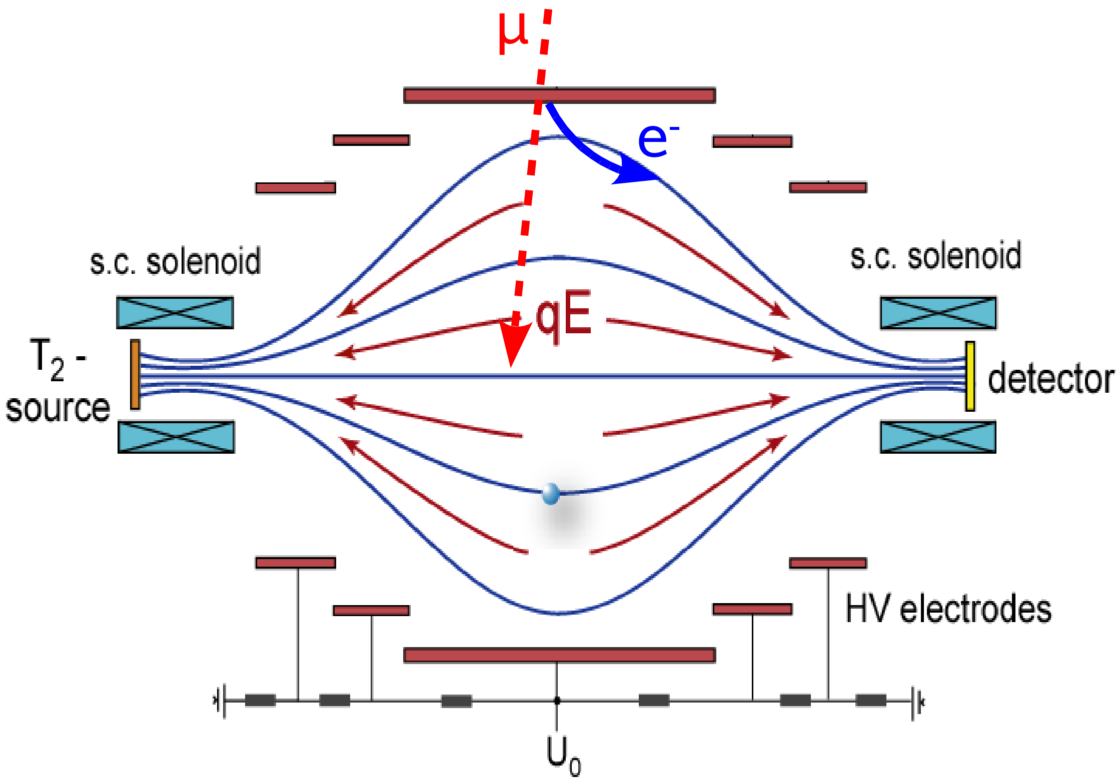
Design parameters:

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

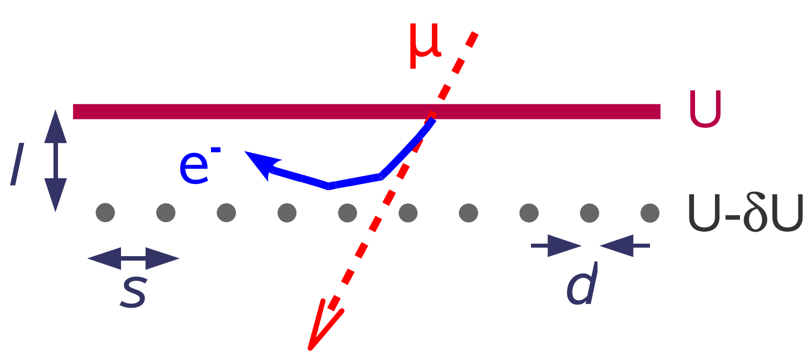
First vacuum tests:

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

KATRIN wire electrode (1/2): screening of background electrons



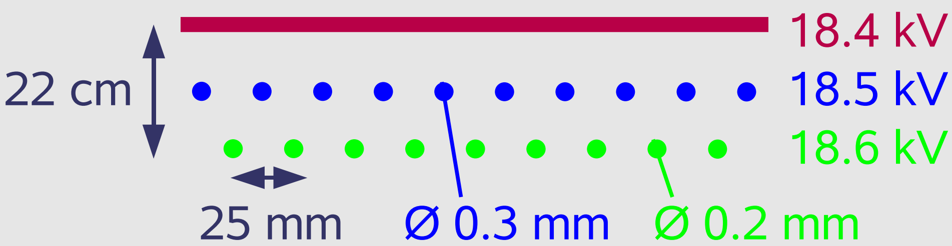
- Cosmics and radioactive contamination can mimic e^- in endpoint energy region
- $650 m^2$ surface of main spectrometer
  → ca. 10^5 μ / s + contamination
- Reduction due to B-field: factor 10^5-10^6
- Real signal rate in the mHz region
- **Additional reduction necessary**



- 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

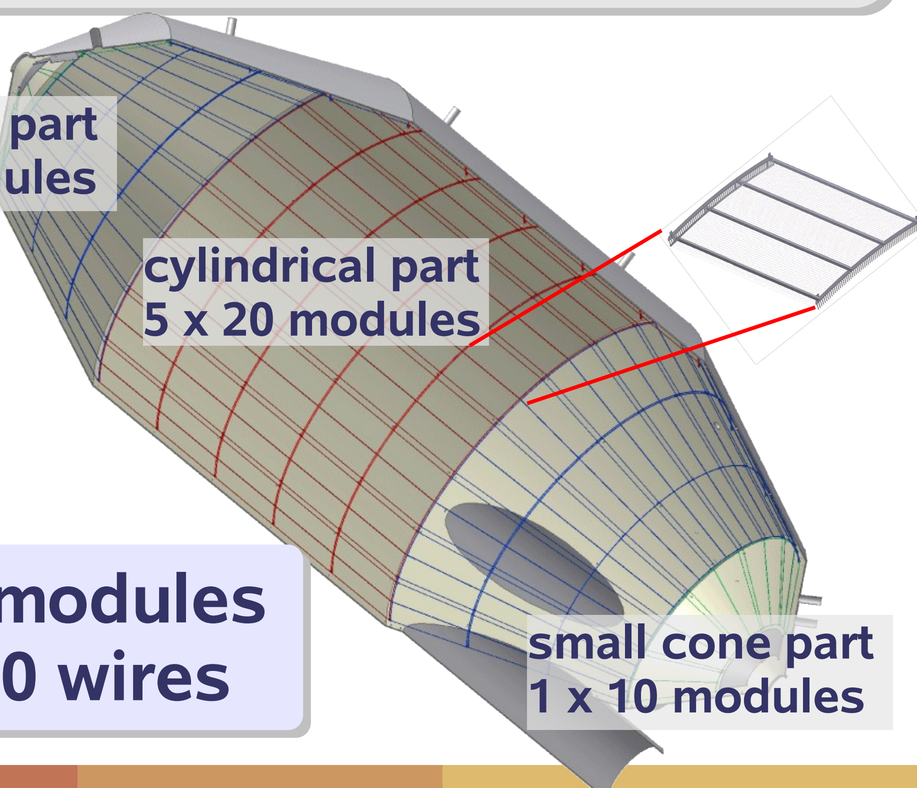
KATRIN wire electrode (2/2): technical design and quality assurance

KATRIN: double layer electrode

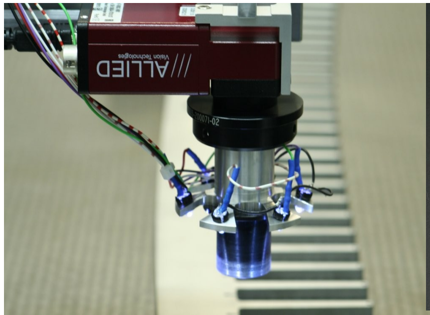


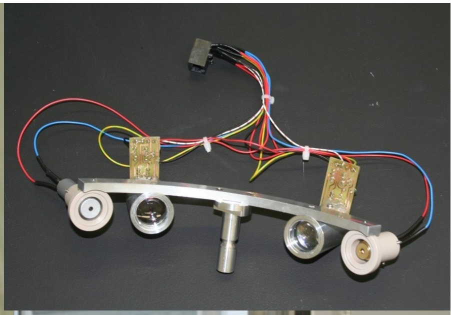
- improved shielding and electric field homogeneity

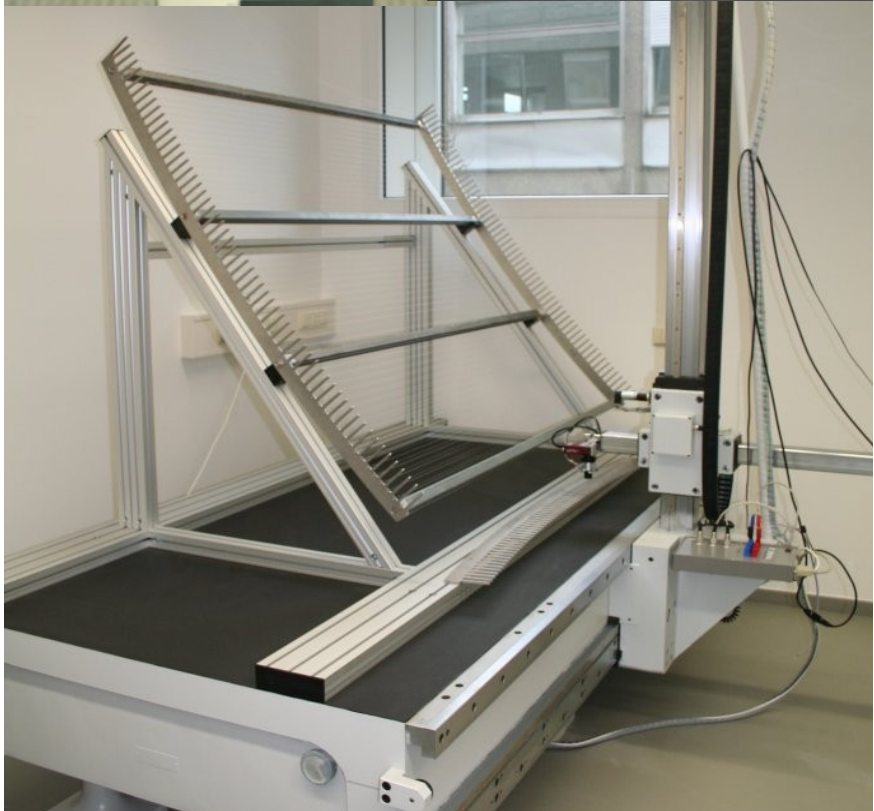
  → **expected background reduction by 10 - 100**



Σ = 240 modules
23000 wires







3D measurement table in Münster clean-room

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
- **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

The KATRIN collaboration

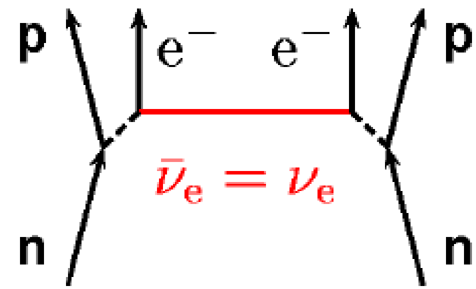
- ≈100 scientists
- 5 countries
- 14 institutions

Backup sheets

Neutrinoless double β-decay

Weak interaction: left-handed fermions $\Psi_L = (1-\gamma_5)/2\ \Psi$ couple to charge current

$0\nu\beta\beta$: decay rate is proportional to fraction of positive helicity state within Ψ_L



$$\begin{aligned}
\Gamma \sim u_2^{+} u_L &= W'(\mathcal{H} = +1) \\
&= \frac{1}{2}(1-\beta_\nu) \\
&= \frac{1}{2}\left(1 - \frac{p_\nu\, c}{E_\nu}\right) = \frac{1}{2}\left(\frac{E_\nu - p_\nu\, c}{E_\nu}\right) \\
&= \frac{1}{2}\,\frac{\sqrt{p_\nu^2 c^2 + m_\nu^2 c^4} - p_\nu c}{E_\nu} \\
&= \underbrace{\frac{p_\nu c}{2E_\nu}}_{\approx\frac{1}{2}}\left(\sqrt{1 + \frac{m_\nu^2 c^2}{p_\nu^2}} - 1\right) \\
&= \frac{1}{2}\left(1 + \frac{m_\nu^2 c^2}{2p_\nu^2} - 1\right) \sim m_\nu^2
\end{aligned}$$

more complete

decay rate $\propto m^2_{ee}(\nu)$:

$m_{ee}(\nu) = |\ \Sigma\ |U_{ei}{}^2|\ e^{i\alpha(i)}\, m(\nu_i)|$

(coherent sum over all neutrino mass eigenstates contributing to the electron neutrino)

$\Rightarrow$ partial cancelation possible

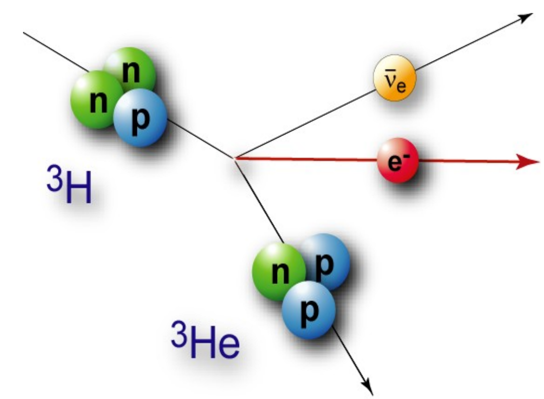
Kinematic determination of $m(\nu_e)$

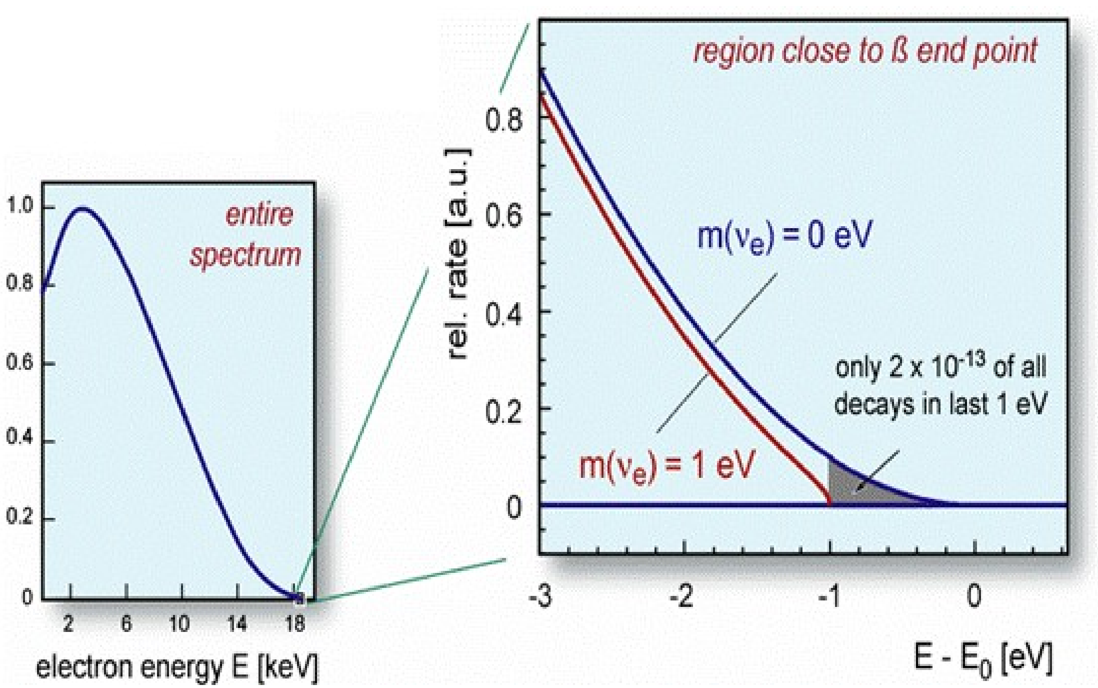
$$\frac{d\Gamma}{dE} = C\, p\, (E + m_e)\, (E_0 - E)\, \sqrt{(E_0 - E)^2 - m_{\nu_e}^2}\, F(E)\, \theta(E_0 - E - m_{\nu_e})$$

$$C = G_F^2 \frac{m_e^5}{2\,\pi^3} \cos^2\theta_C\, |M|^2$$

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

experimentally observable





Stability and Neutrino mass

- 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 $m_\nu^2 = 0$: $$\frac{dN}{dE_\beta} \propto (E_0-E)^2-\frac{1}{2}m_\nu^2$$

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

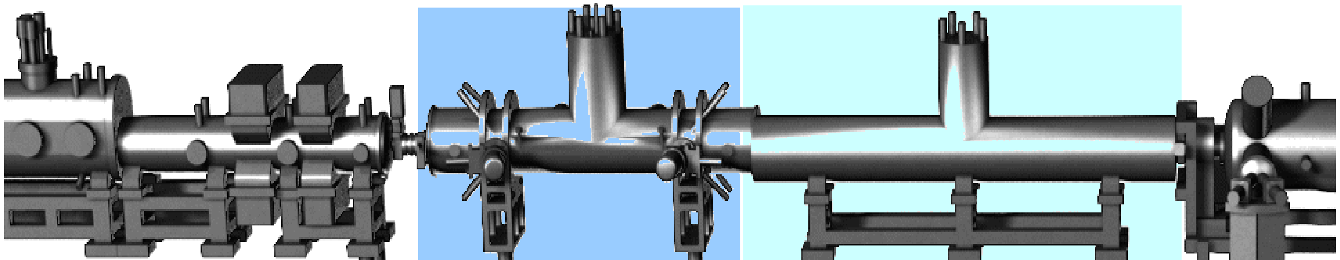
➜ **fluctuation σ^2 causes a downward shift in m_ν^2**

<u>Example:</u> $\Delta m_\nu^2 < 0{,}007\ eV^2 \Leftrightarrow \sigma < 60\ meV$

$$\frac{\Delta U}{U} = \frac{0.06}{18575} \approx 3\cdot 10^{-6}$$ $\Rightarrow$ 3 ppm long term stability required

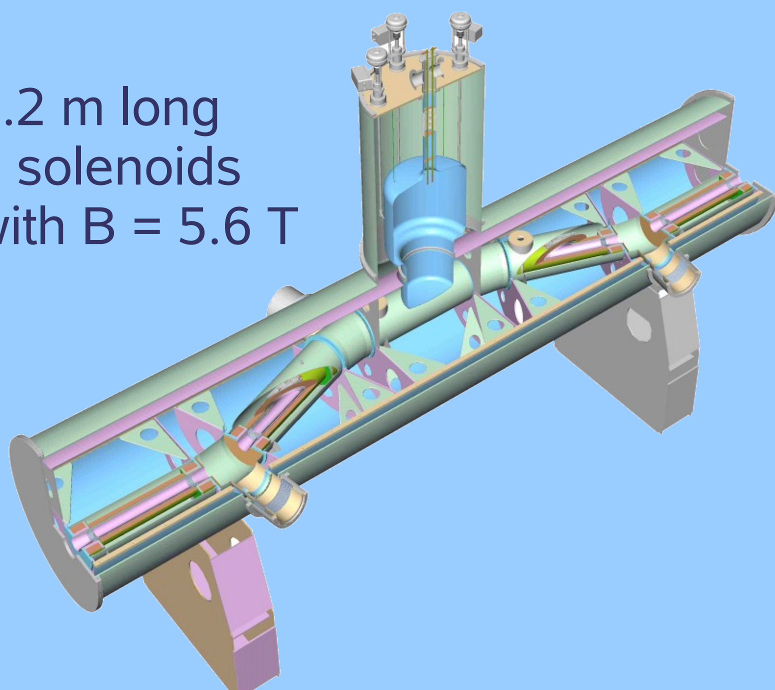
Transport of the main spectrometer

The KATRIN experiment (4/8): differential and cryo pumping sections



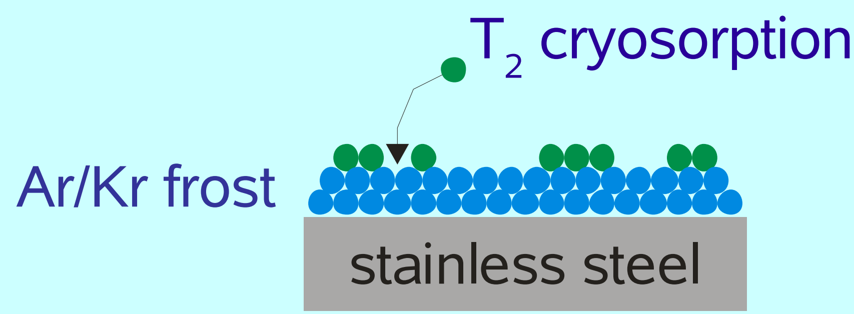
DPS: differential pumping of T_2 using TMPs (2000 l/s)

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



→ T_2 reduction by 10^7

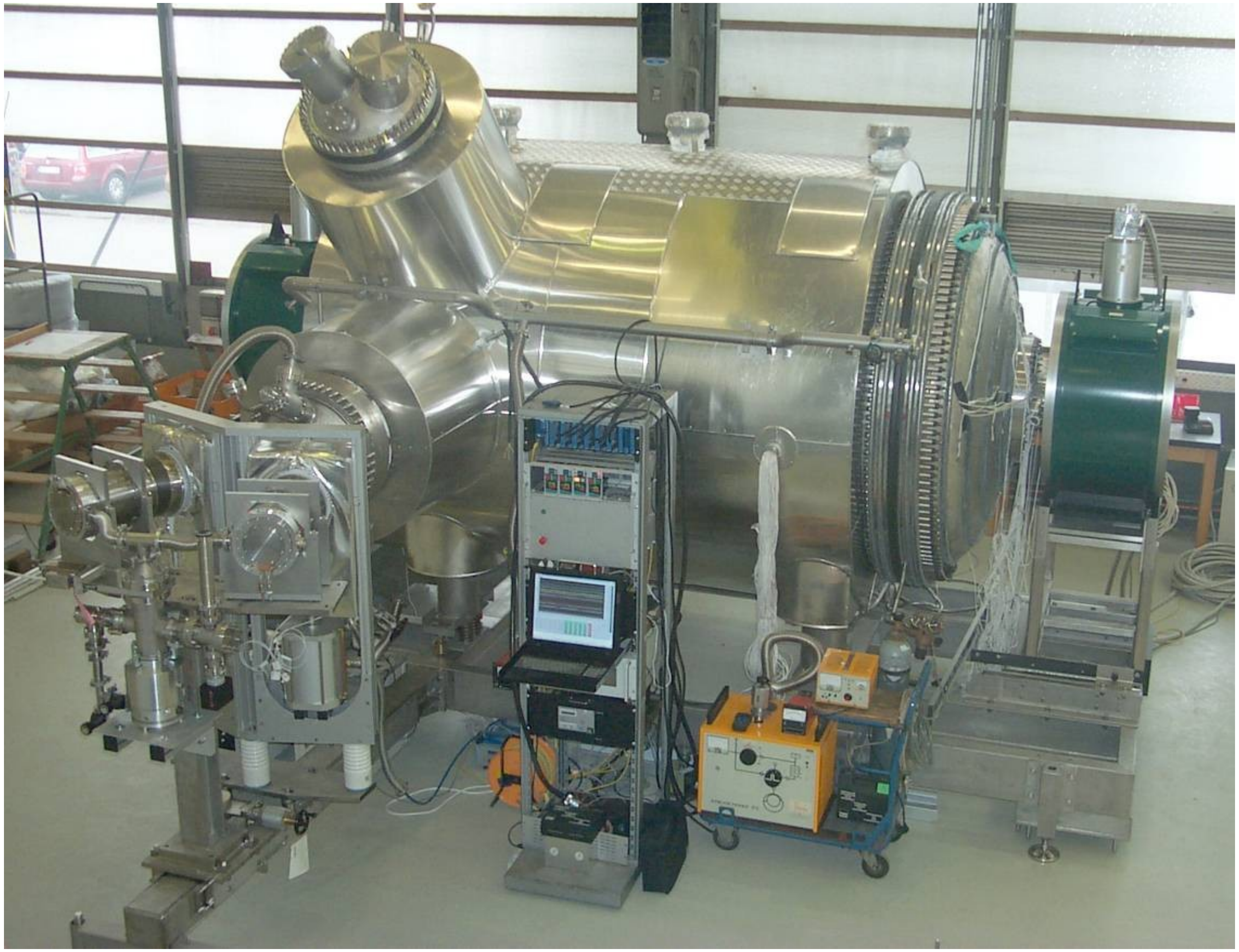
CPS: cryosorption of tritium on Ar/Kr frost at 3 – 4.5 K



- 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 (5/8): 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
- $p < 10^{-11}$ 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 (8/8): detector

Task

- detection of electrons passing the main spectrometer

Requirements

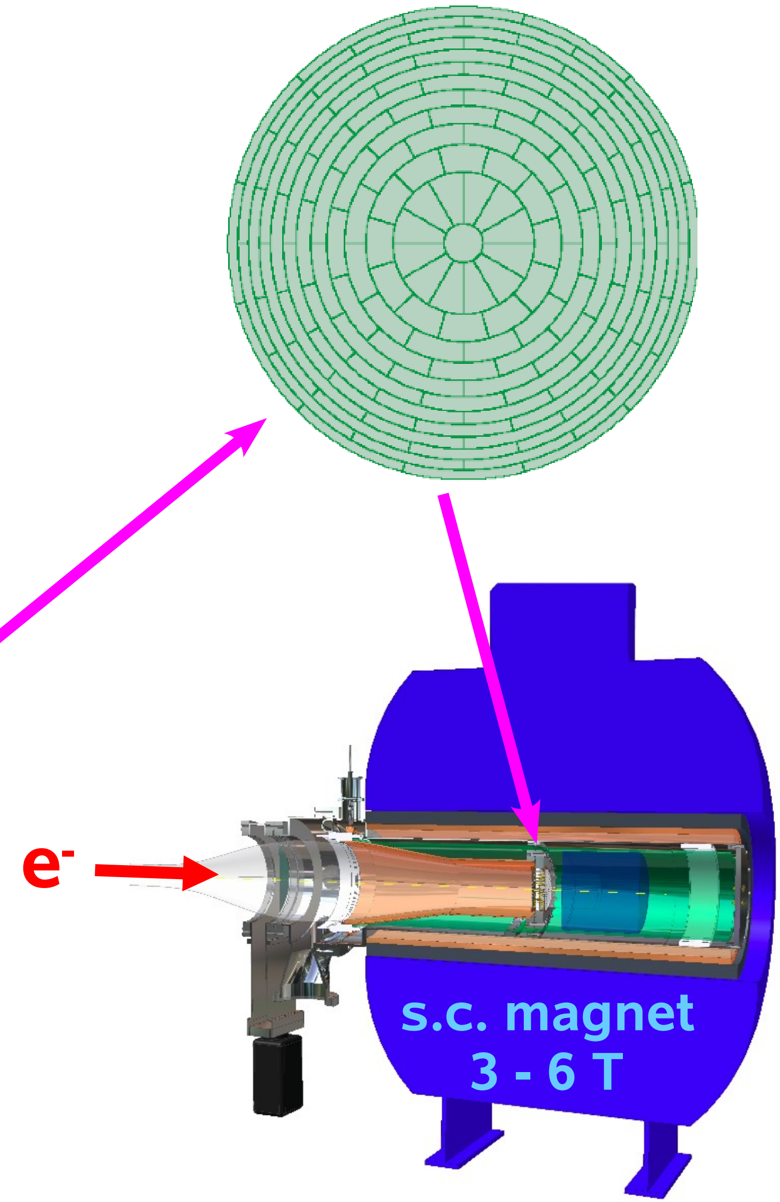
- high efficiency (> 90%)
- low background (< 1 mHz)
- good energy resolution (< 600 eV)

Properties

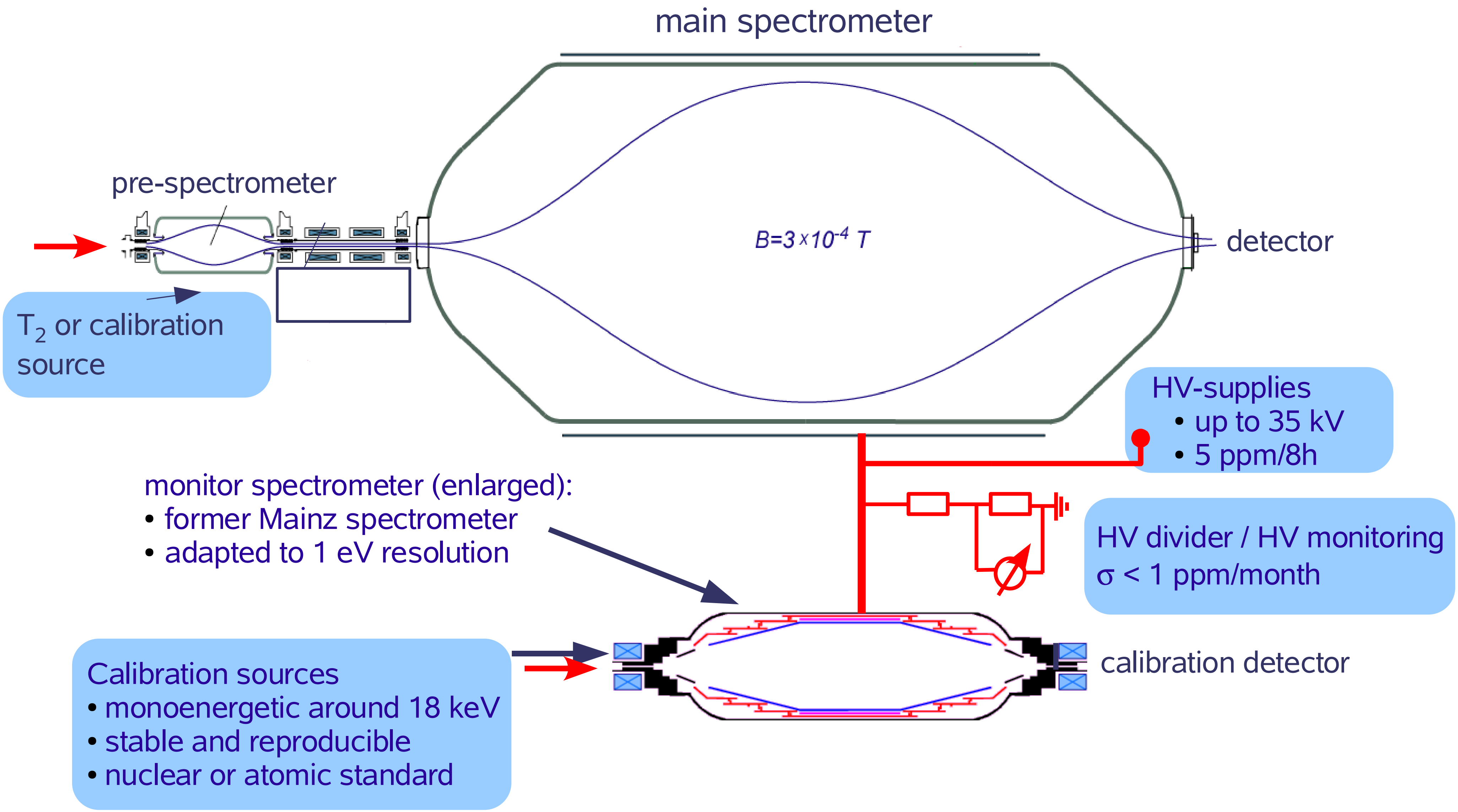
- silicon PIN diodes
- thin entry window (50nm)
- segmented wafer (150 pixels)
- post acceleration (30kV)

Status

- 2007: design report (FZK, Seattle, MIT)
- 2009: commissioning



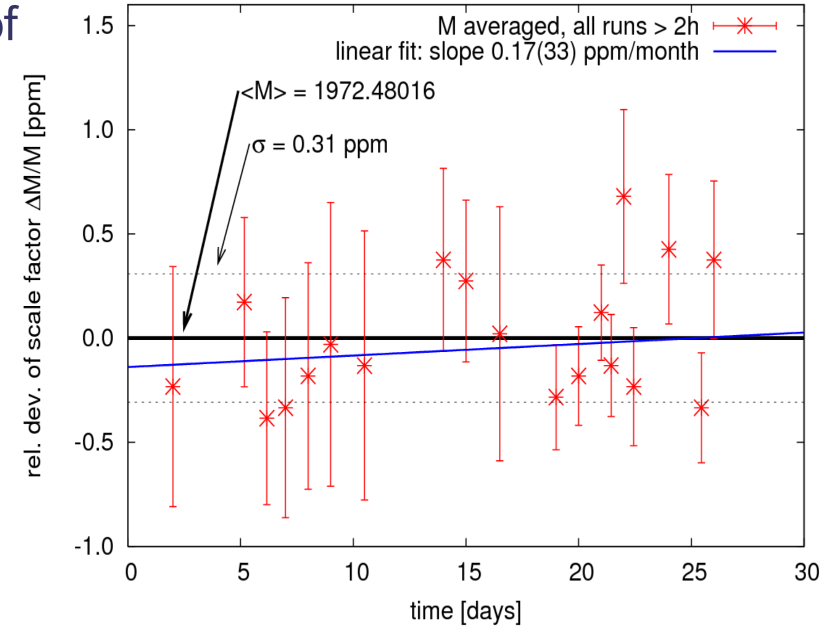
Calibration and monitoring (1/3):



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

Calibration and monitoring (2/3): 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 N2 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

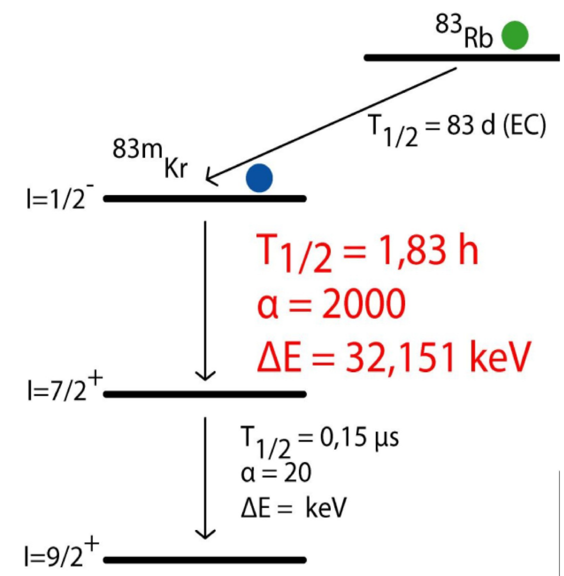
preliminary

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

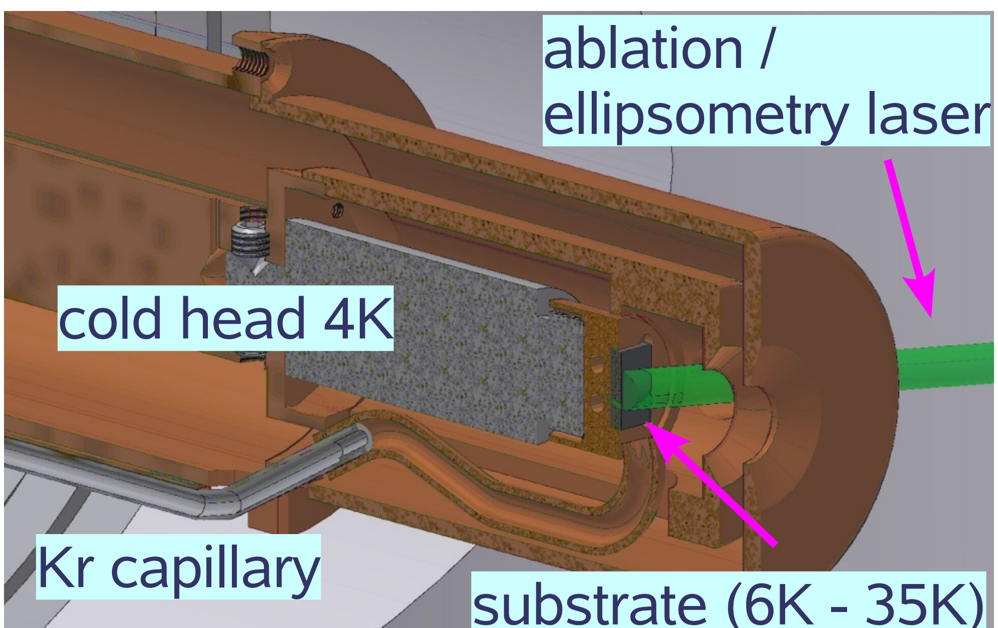
preliminary: 0,6ppm/Monat

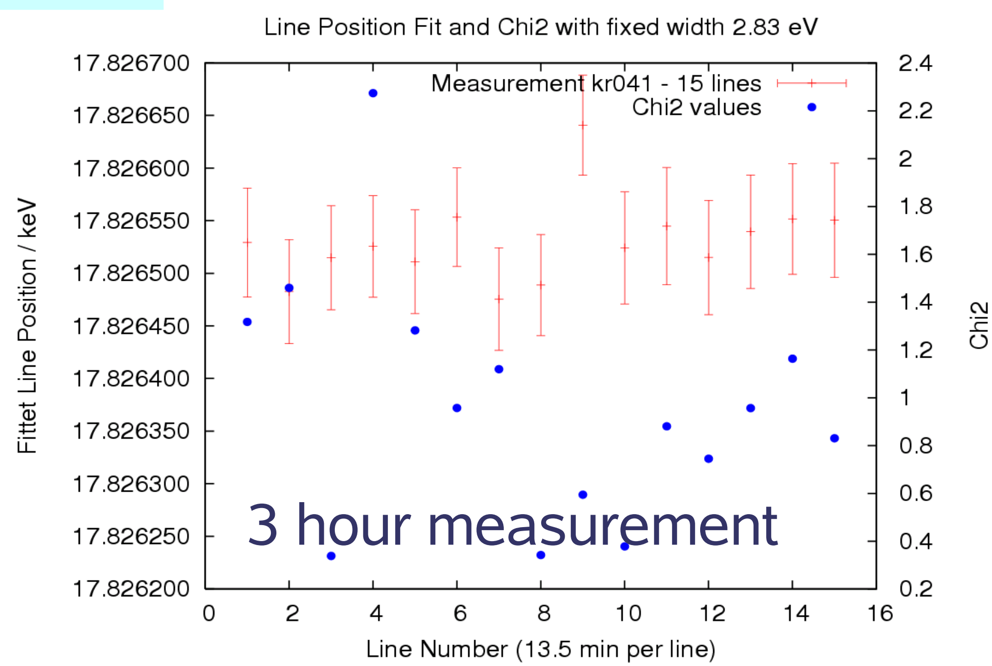
Calibration and monitoring (3/3): condensed Krypton source

- Natural standard via conversion electrons from ^{83m}Kr decay
- Production via ^{81}Br(α,2n)^{83}Rb at the Uni-Bonn cyclotron
- Measurement at Mainz: 17826.529 eV ± 10.2 meV
- over 3 hours: σ = 39.5 meV
- over weeks with pre-plating: σ = 56 meV

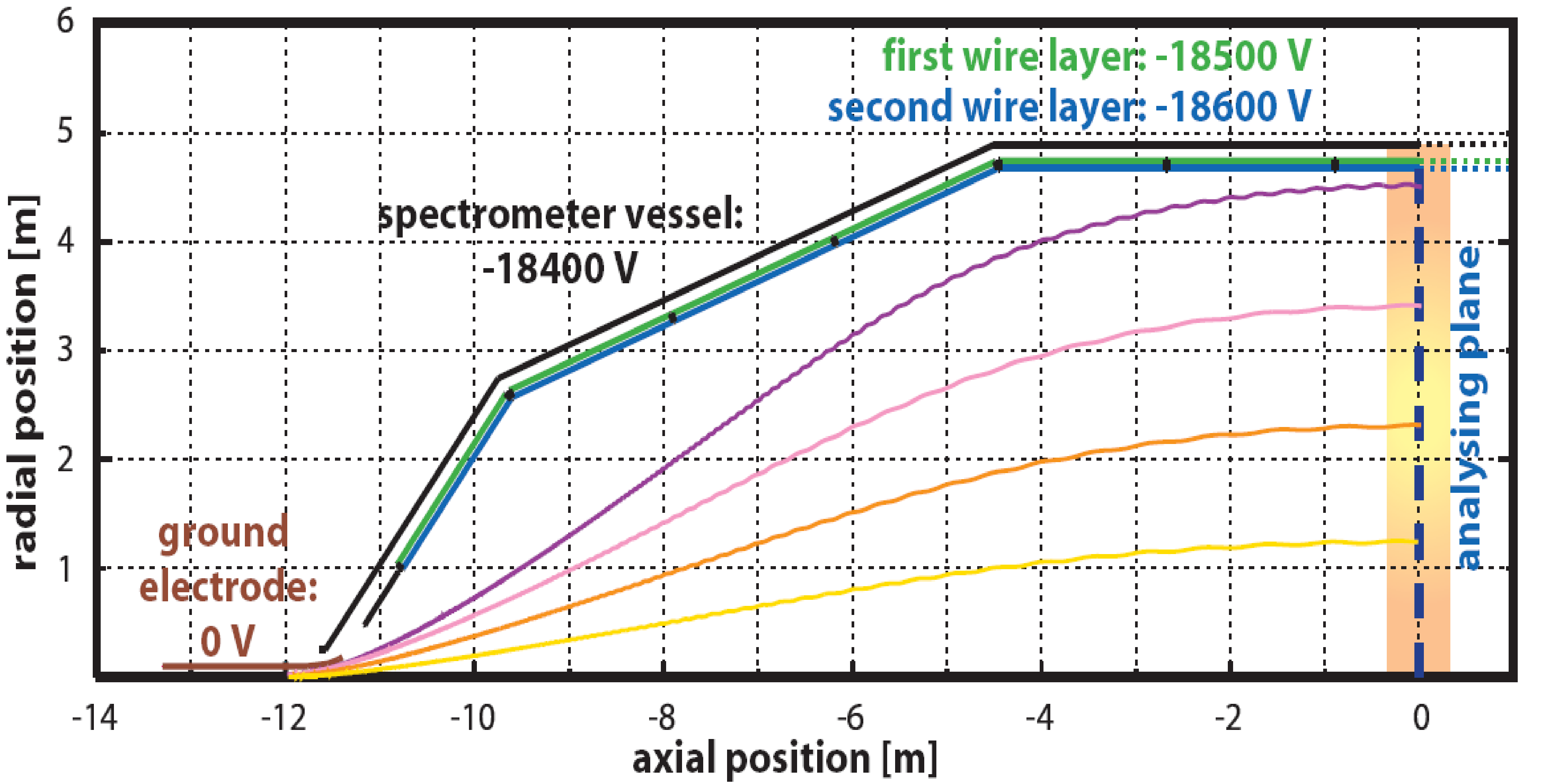


graphite substrate pre-plated with stable Kr





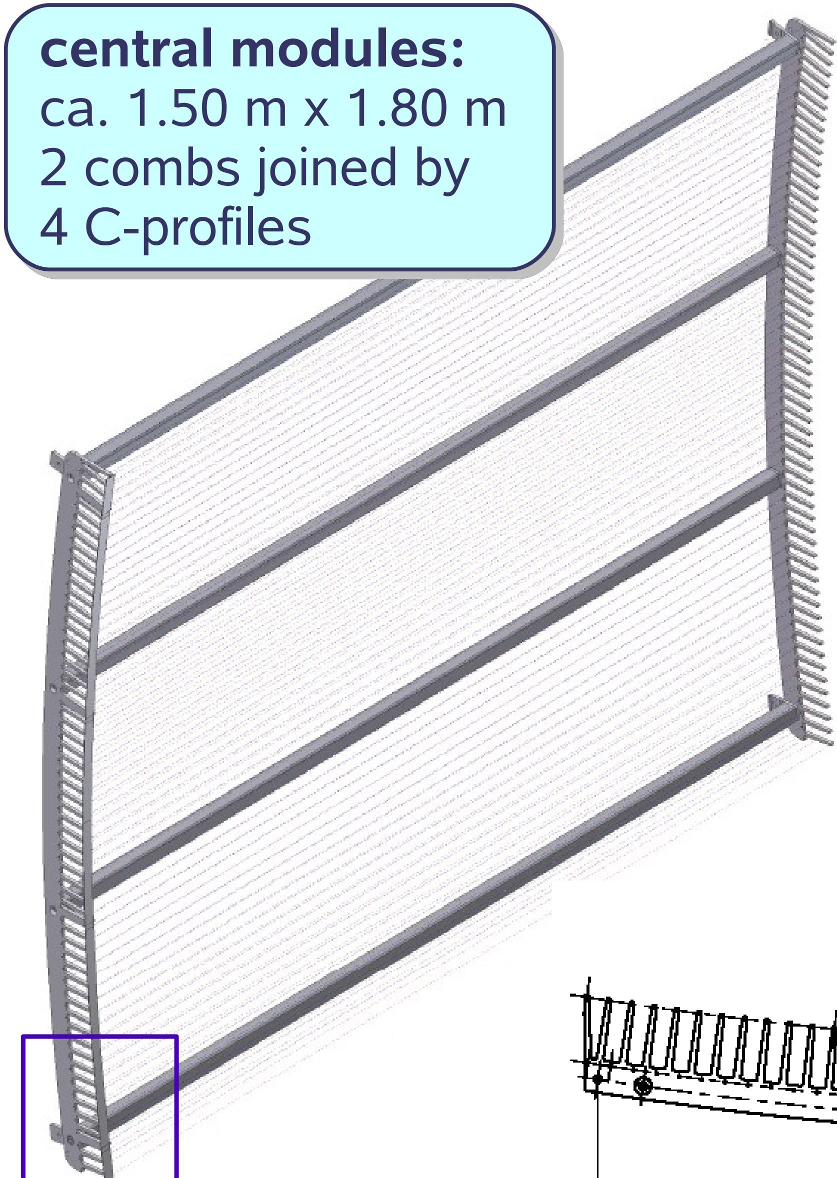
Electrode design (1/3): schematic view / modular setup



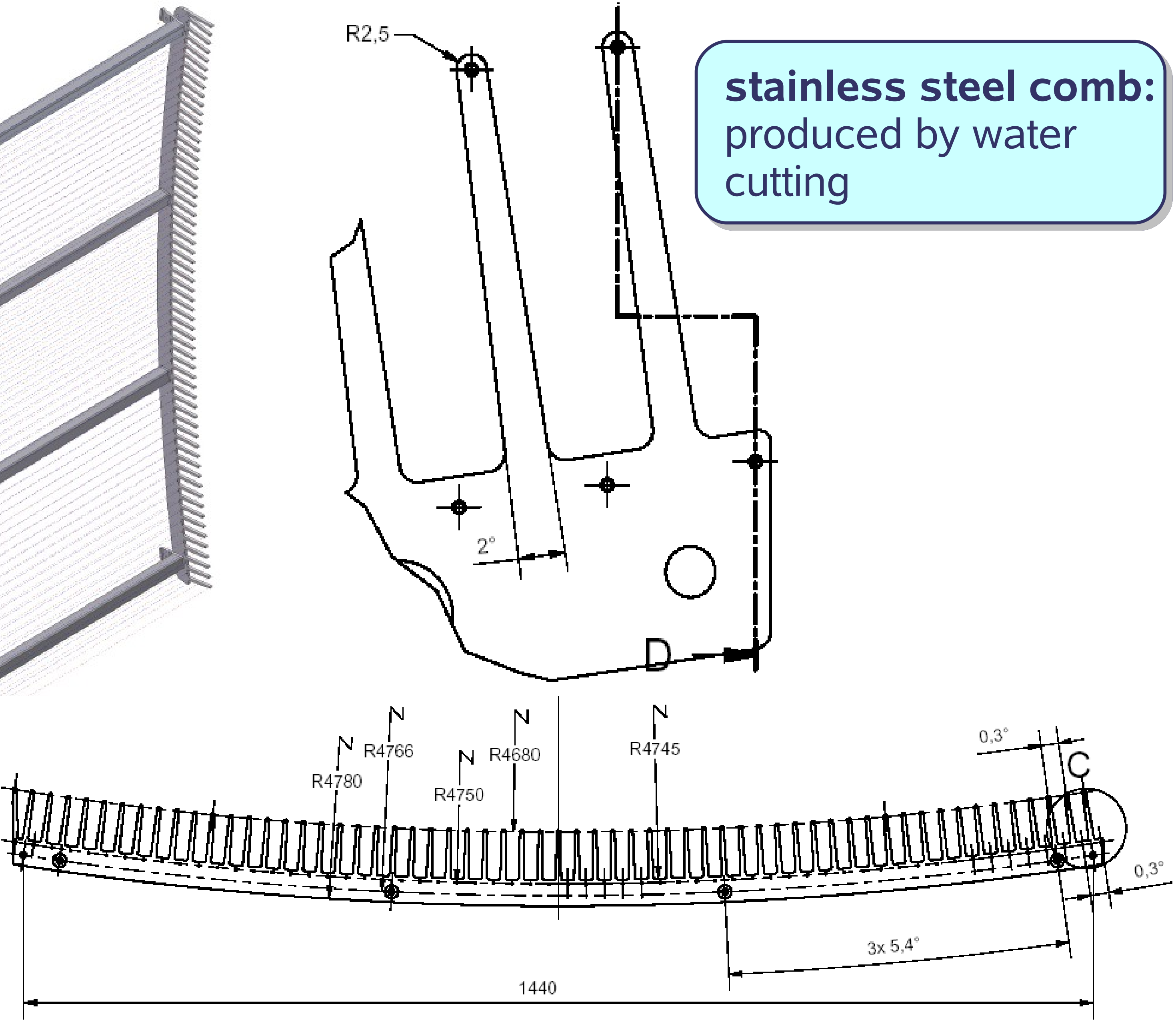
overview: electrode system of the main spectrometer

Background suppression (3/3): wire electrode modular design

central modules:
ca. 1.50 m x 1.80 m
2 combs joined by
4 C-profiles



stainless steel comb:
produced by water cutting



H.-W. Ortjohann