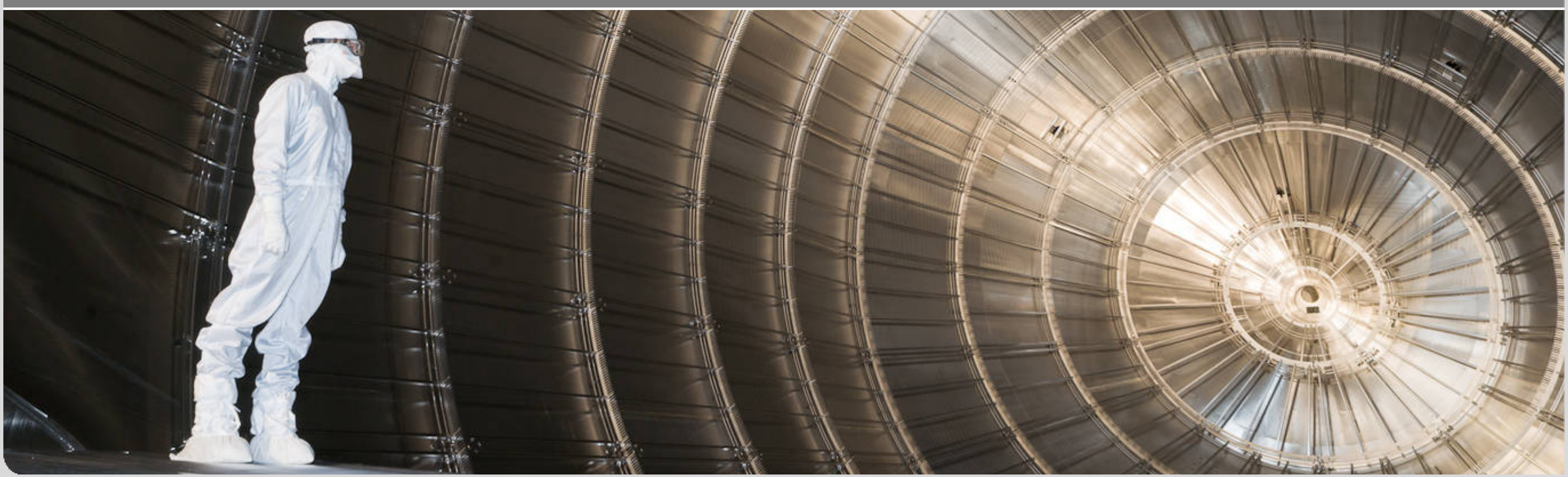
“Vacuum performance of the KATRIN experiment”

- Florian Fränkle for the KATRIN collaboration -

Institute for Nuclear Physics (IKP), Karlsruhe Institute of Technology (KIT)

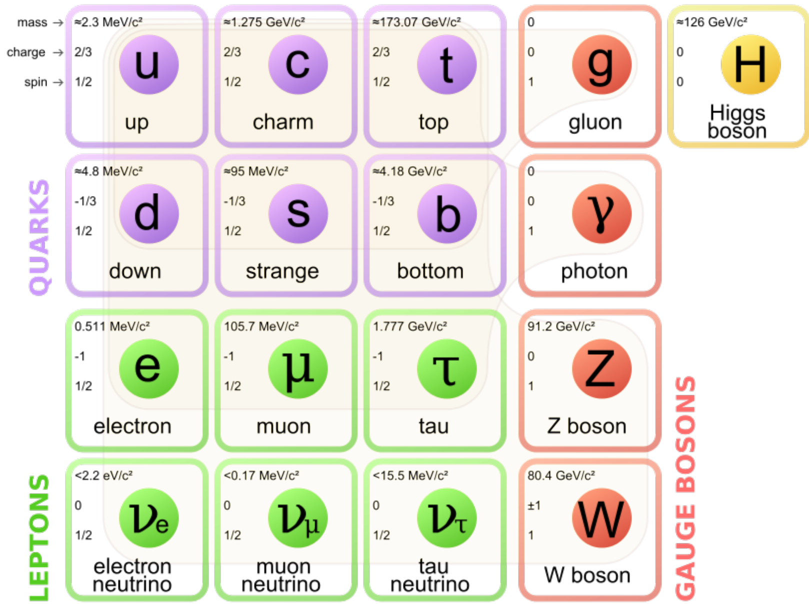


outline

- neutrino physics
- the KATRIN experiment
- vacuum performance of the KATRIN main spectrometer
- summary & outlook

neutrinos

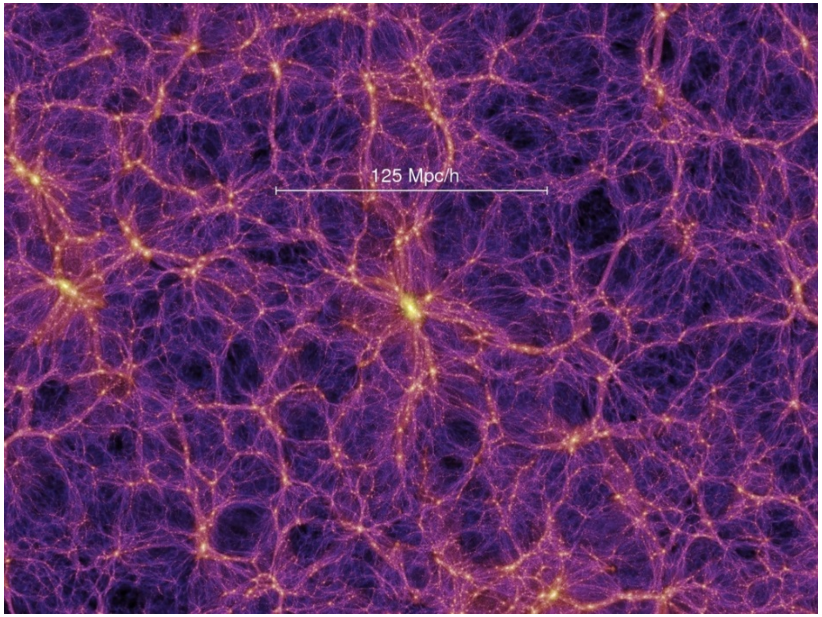
particle physics



Wikipedia.org

- neutrinos are neutral elementary particles
- their mass is still unknown

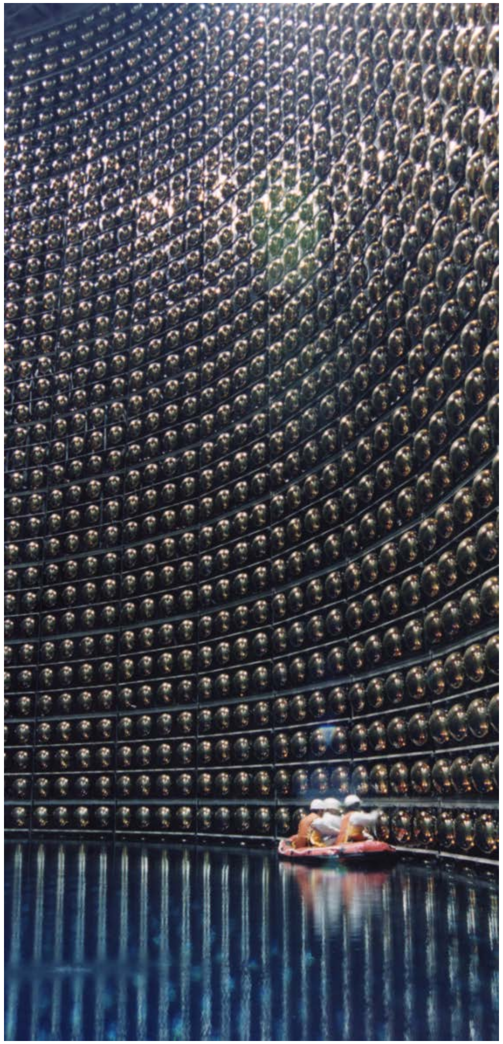
cosmology



The Millennium Simulation Project, Max-Planck-Institut für Astrophysik

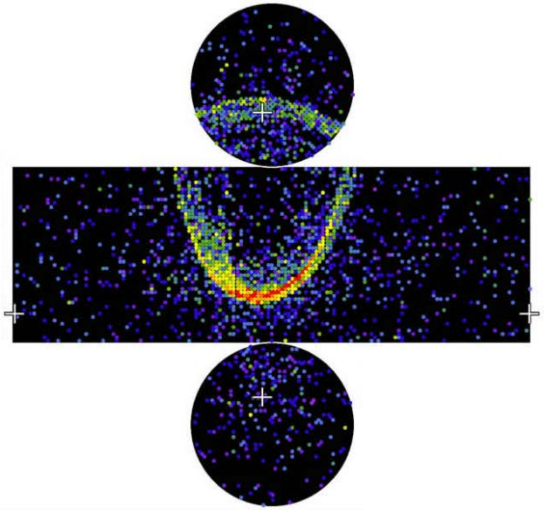
- neutrinos are among the most abundant particles in the universe
- even with a small mass they influence structure formation

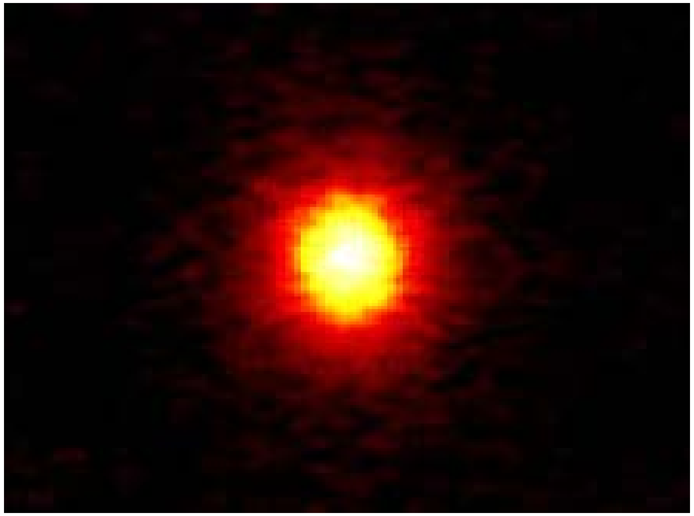
Super-Kamiokande neutrino detector



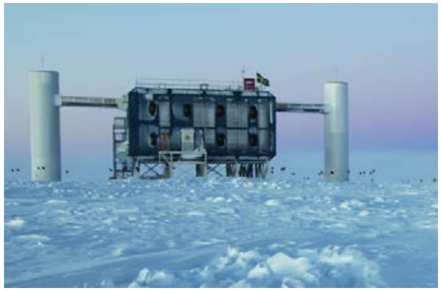
Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

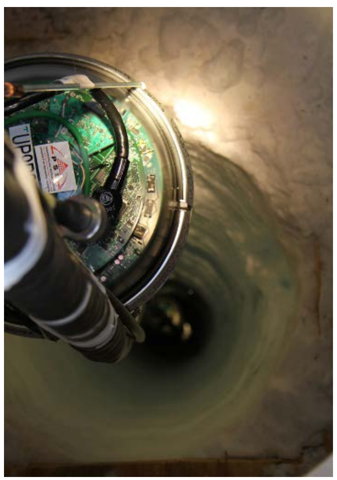
- Super-Kamiokande detector is located in an underground laboratory in Japan
- 50 000 t of pure water
- about 11 100 photomultiplier tubes (20”)
- in operation since April 1996
- noble prize in physics 2015 (Takaaki Kajita)

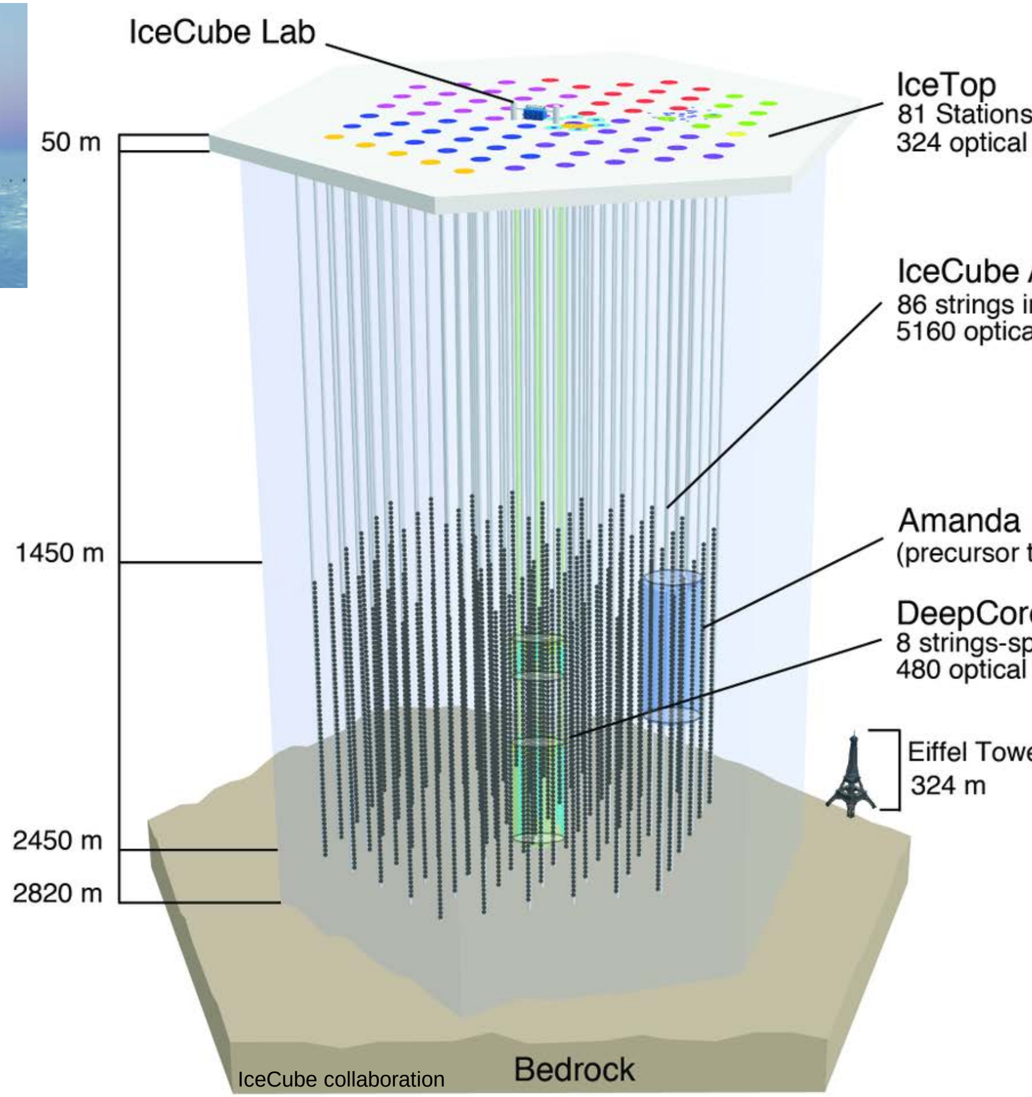


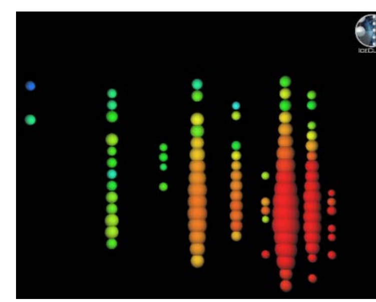


IceCube neutrino detector

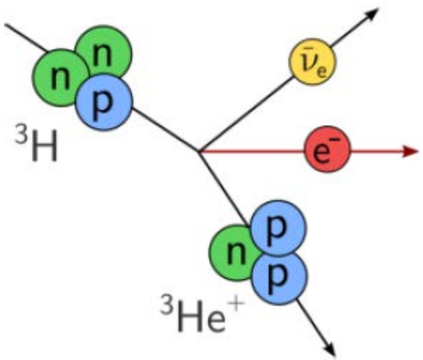








Neutrino mass and single β-decay



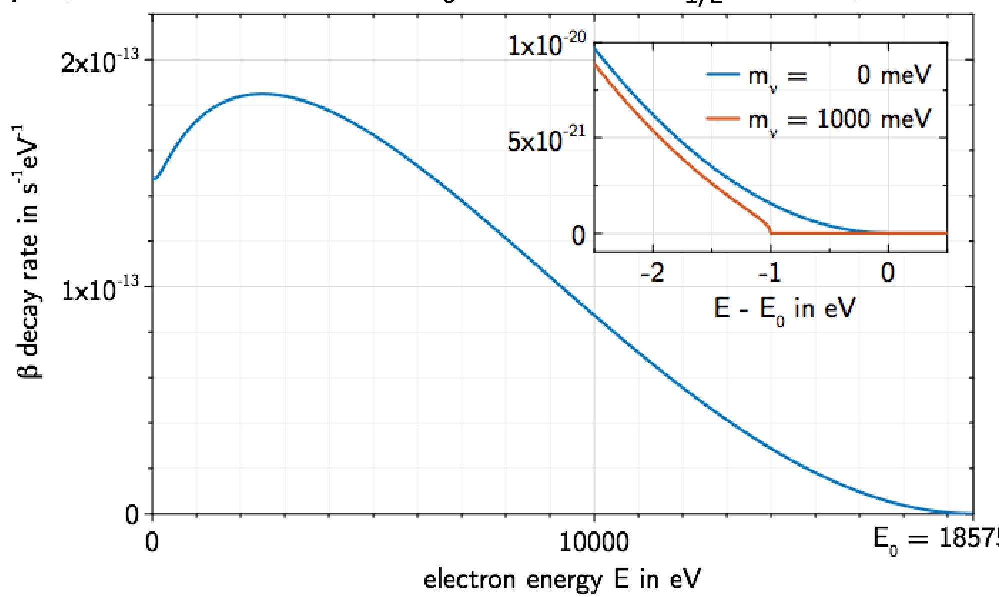
- β-decay: $n \rightarrow p + e^- + \overline{\nu}_e$
- Neutrino mass influences energy spectrum of β-decay electrons
- Neutrino mass determination via precise measurement of the spectral shape close to the endpoint

Fermi theory of β-decay:

$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot p(E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

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

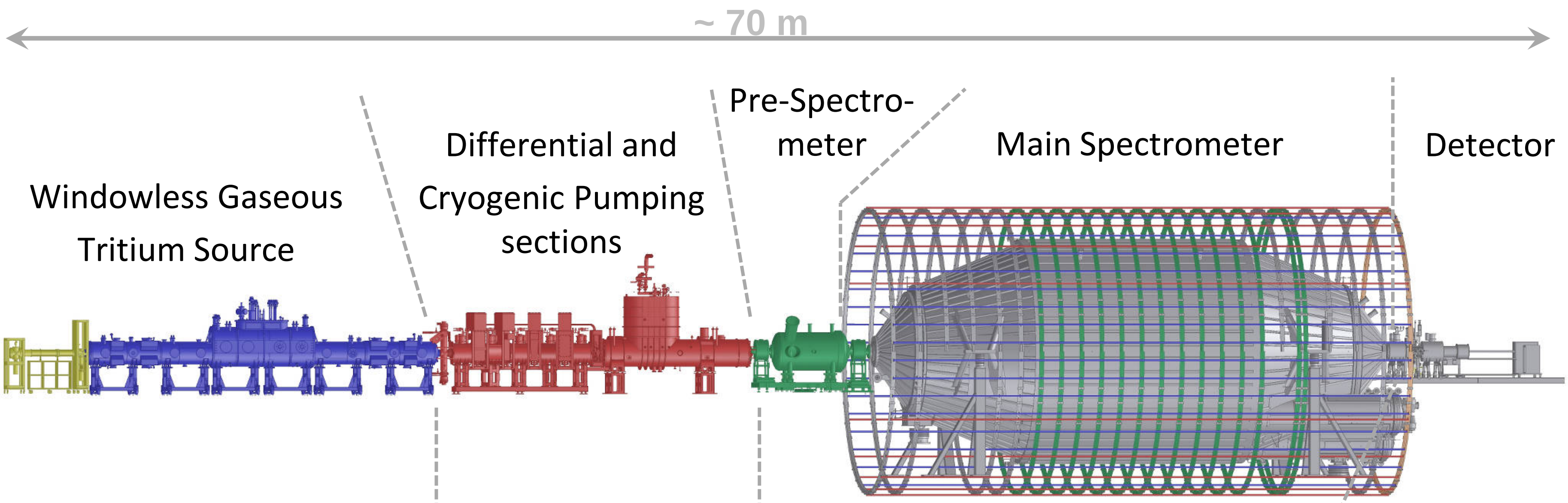
β-spectrum for tritium (E_0 = 18.6 keV, $T_{1/2}$ = 12.3 y):




KATRIN
Karlsruhe Tritium Neutrino Experiment

The KATRIN experiment

- **KA**rlsruhe **TRI**tium **N**eutrino experiment
- Goal: Measure neutrino mass with a sensitivity of **200 meV/c²** (0.000 000 000 000 000 000 000 000 000 000 000 000 36 kg)



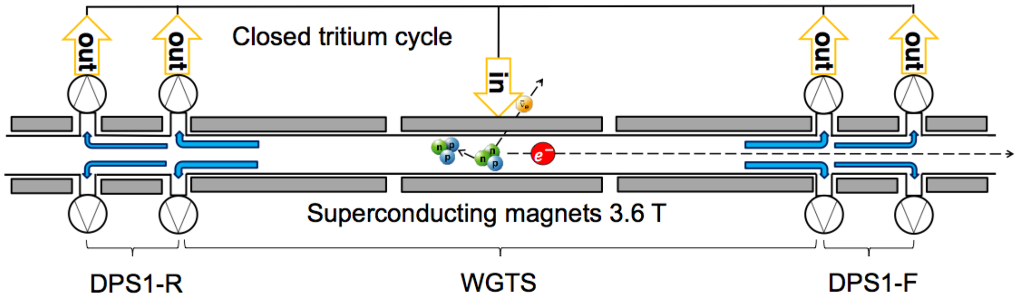
- tritium β-decay
- decay rate: 10^{11} 1/s
- T_2 pressure: 10^{-3} to 10^{-6} mbar

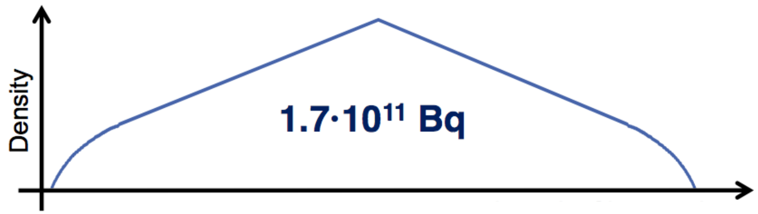
- β-electron transport
- tritium retention (factor > 10^{12})

- energy analysis of β-electrons
- resolution 0.93 eV @ 18.6 keV
- pressure < 10^{-10} mbar

- counting of transmitted β-electrons

Windowless Gaseous Tritium Source

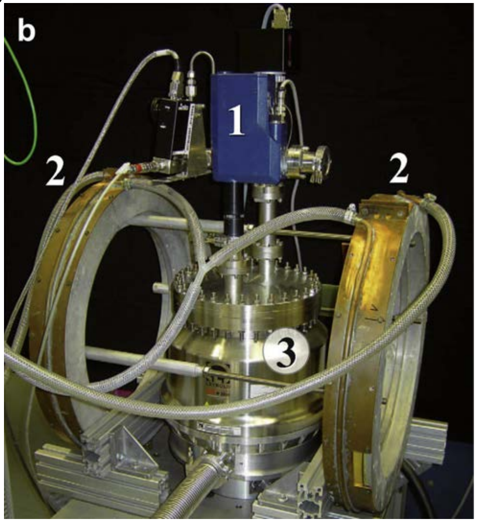




- Stability of T_2 density profile of **10^{-3}** (function of T_2 injection rate, purity, beamtube temperature T_B stability and homogeneity, pump rate)
- T_B stability in prototype experiment 10× better than specified*
- Tritium loop processes 1.4×10^{16} Bq tritium / day (same scale as ITER)
- Operation of TMPs in magnetic stray field of superconducting magnets

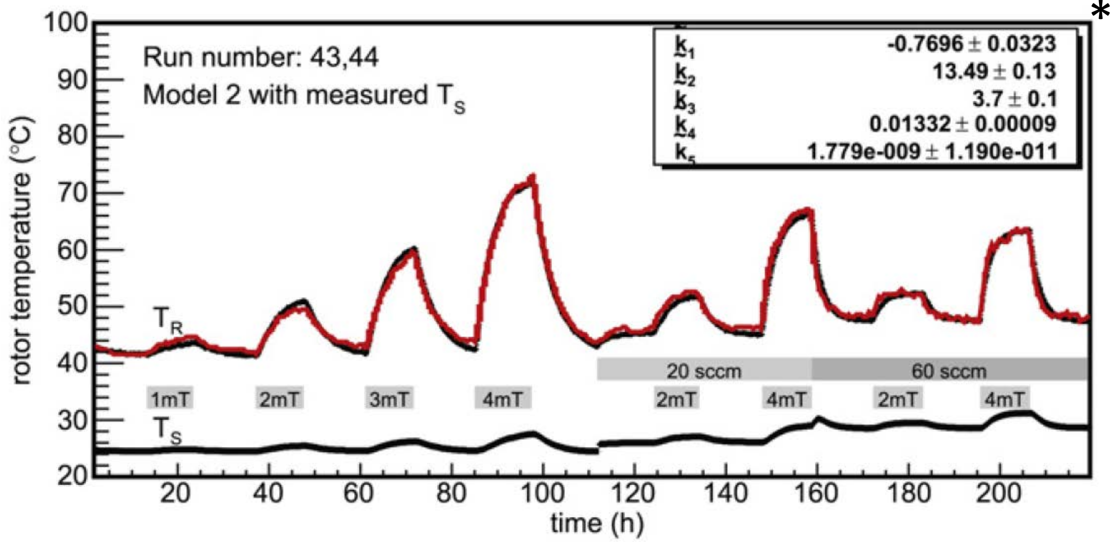
* S. Grohmann et al. “The thermal behaviour of the tritium source in KATRIN”, Cryogenics, V. 55–56, 2013, p. 5–11, DOI: 10.1016/j.cryogenics.2013.01.001

TMPs in strong magnetic fields

*


*

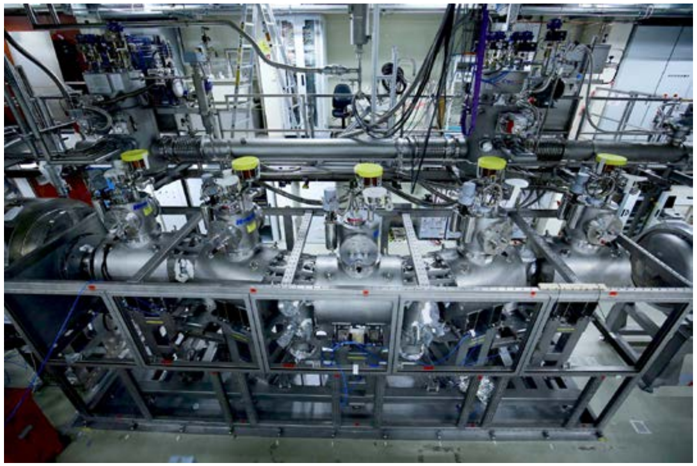

- heating of fast moving TMP rotor by eddy currents
- test setup to monitor rotor temperature for different magnetic fields and gas loads
- developed model to predict rotor temperature over time

*


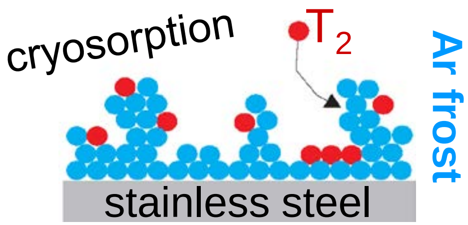
* J. Wolf et al. “Investigation of turbo-molecular pumps in strong magnetic fields”, Vacuum, V. 86, 2011, p. 361–369, DOI: 10.1016/j.vacuum.2011.07.063

Pumping sections

Differential pumping



Cryogenic pumping



- T_2 partial pressure reduction (10^5) via differential pumping
- Magnetic guiding of β-electrons
- Removal of positive ions

- T_2 partial pressure reduction (10^7) via cryosorption of T_2 on argon frost
- Concept successfully tested*
- Magnet system successfully tested

* F. Eichelhardt et al. "First Tritium Results of the KATRIN Test Experiment Trap" Fusion Science and Technology 54 (2008), Nr. 2, p. 615-618

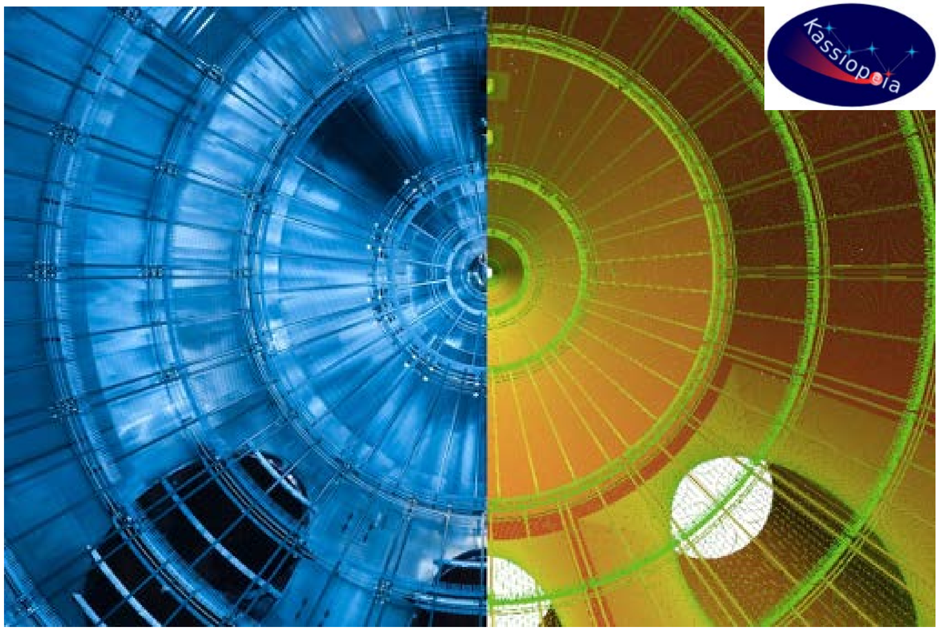
Main Spectrometer

purpose: energy analysis

properties:

- MAC-E filter (integrating high pass filter)
- energy resolution 0.93 eV @ 18.6 keV
- stable HV system (1 ppm @ -18.6 kV)
- volume: 1240 m^3, surface: 689.6 m^2
- inner wire electrode system (532 m^2)
- variable voltage to scan E_0 region

view inside main spectrometer



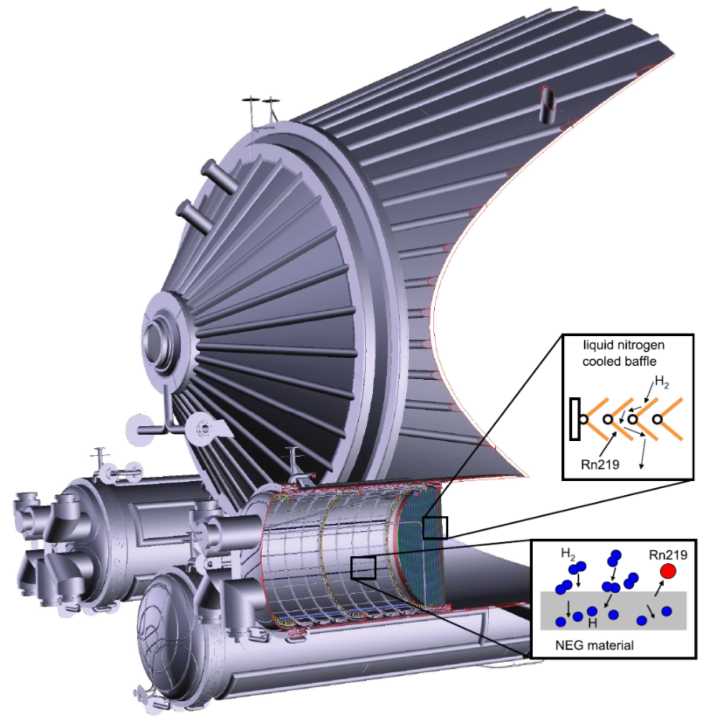
status:

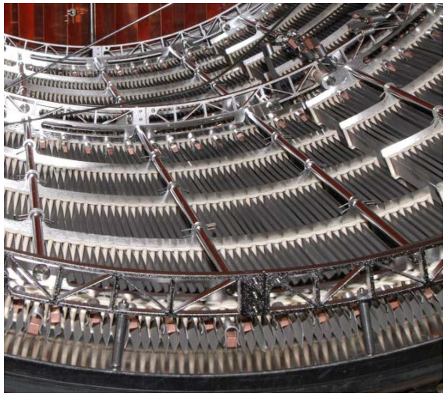
- 2^{nd} commissioning measurement phase completed
- Preparations for final commissioning phase ongoing

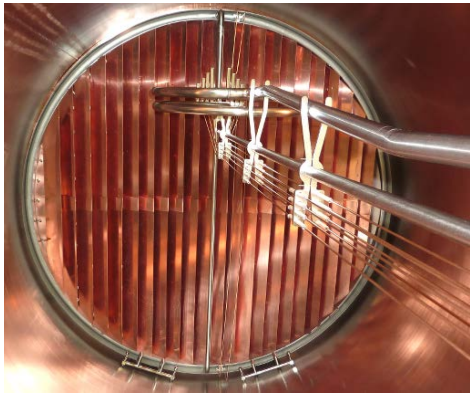
- Detailed 3D model for electric and magnetic field calculation (particle tracking)
- Kassiopeia software package developed in-house

Vacuum system

- 3 NEG-pumps (3000 m SAES ST707 getter strips) ~ 1000 m³/s (H_2)
- Getter material emanates ^{219}Rn
- ^{219}Rn decays in the spectrometer volume and generates a background 50 times above the design goal (0.01 cps)
- LN2-cooled baffles to cryo-sorb ^{219}Rn ~ 170 m³/s (Rn)
- Rn suppression successfully tested (efficiency ~ 97 %)
- Conductance of baffles reduces NEG pumping speed to 375 m³/s

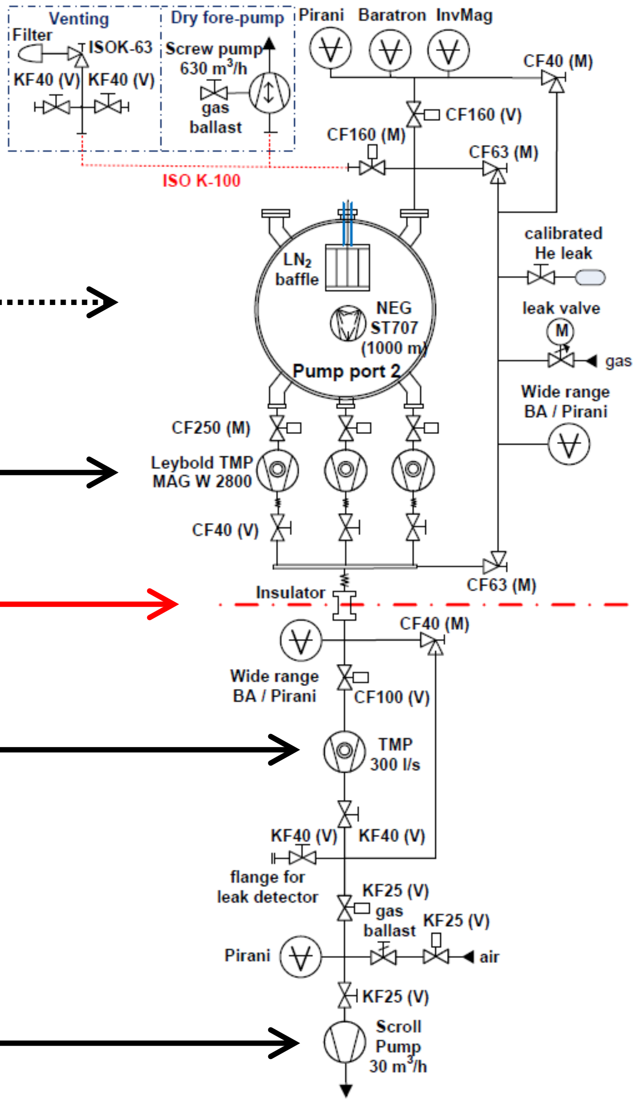




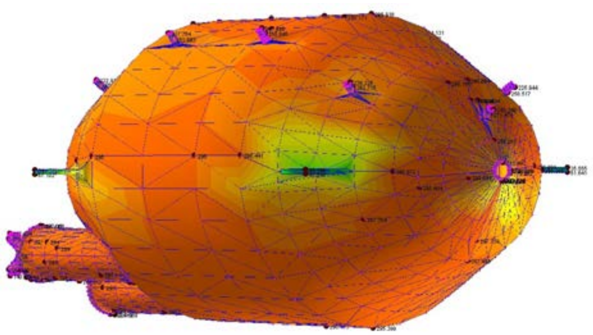


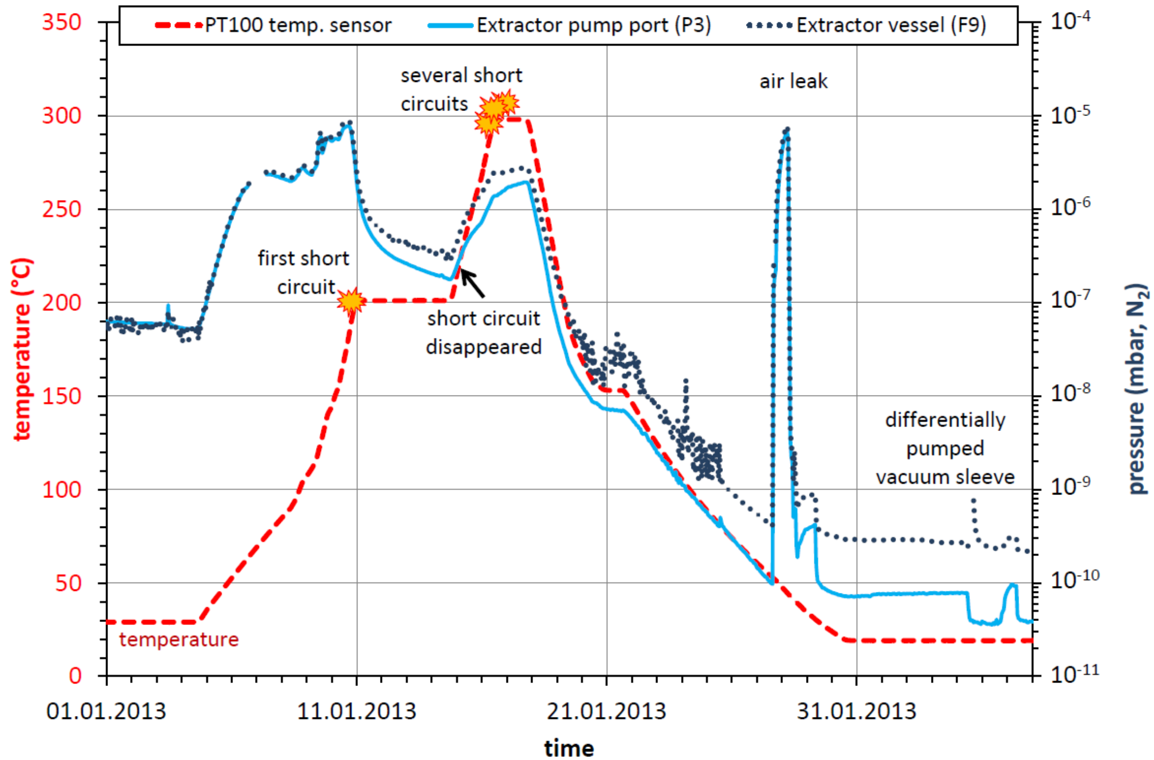
Vacuum system

- Initial pump down screw pump 630 m³/h
- Filter for venting spectrometer with air
- Vacuum gauges, leak valve, RGA, …
- 1st stage TMPs Leybold MAG W 2800 (6x total)
- High voltage separation
- 2nd stage TMP 300 l/s (2x total)
- Scroll pump 30 m³/h (2x total)



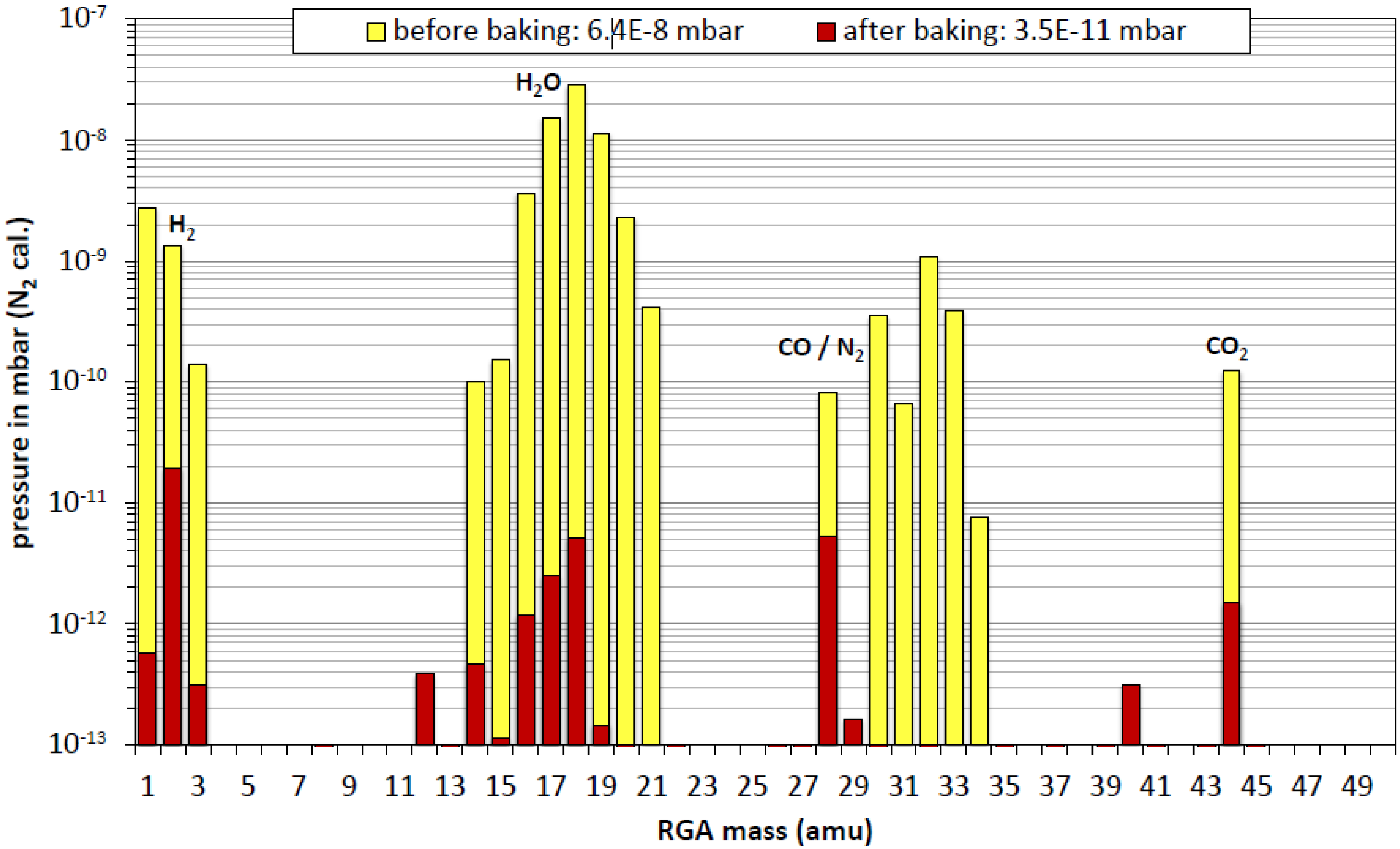
Spectrometer bake-out





- bake-out removes water and allows for NEG pump activation
- duration of bake-out about 4 weeks, maximum temperature 300 °C
- thermal expansion of spectrometer during bake-out about 10 cm

Spectrometer bake-out



- bake-out reduced water by more than 3 orders of magnitude

Vacuum performance

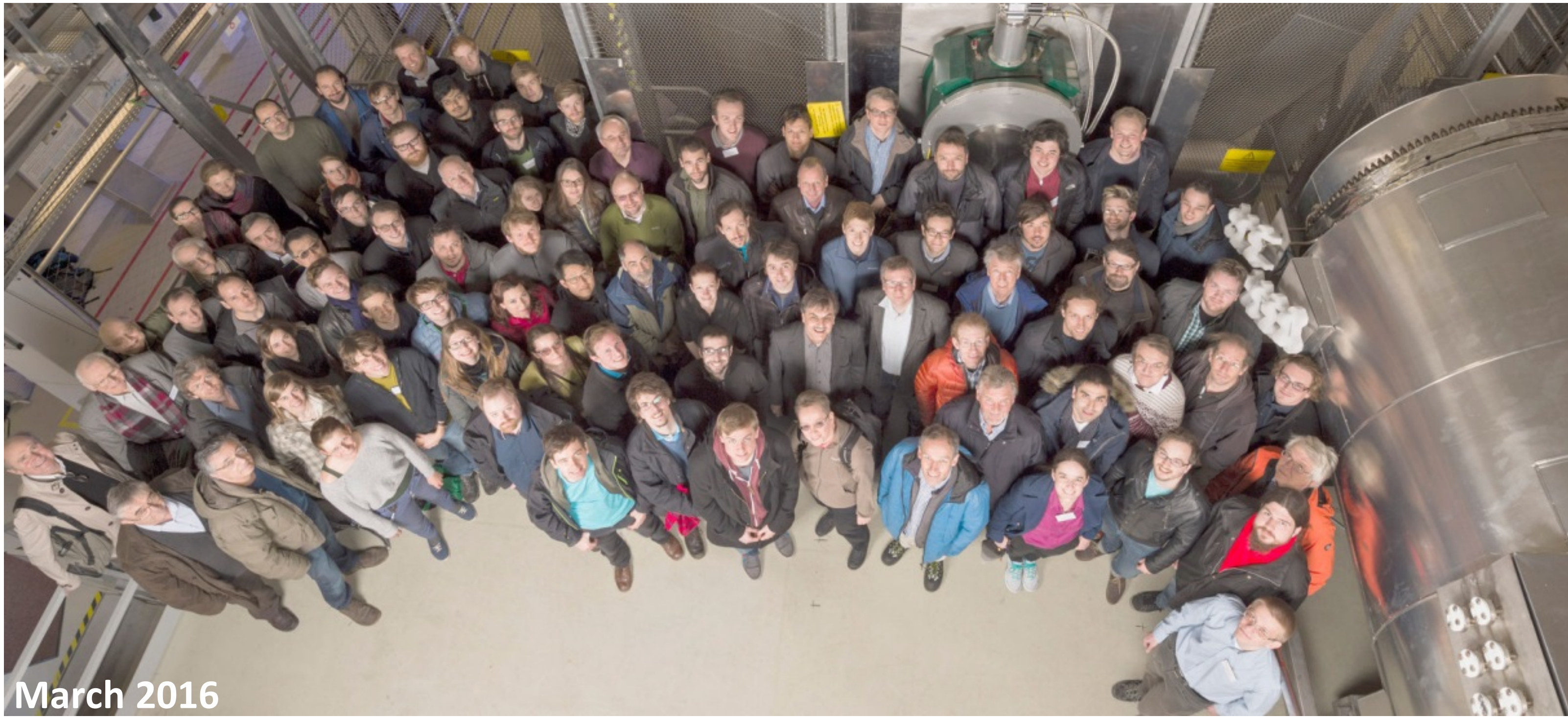
- Main spectrometer volume: 1240 m^3, surface: 1222 m^2
- NEG pump effective pumping speed (activation at 300 °C for 28 h): **300 m^3/s**
- outgassing rate stainless steel wall: **1.4 – 2.5 × 10^{-12} mbar l/(s cm^2)**
- pressure inside spectrometer: **10^{-10} mbar**
- Residual gas composition dominated by **hydrogen (90 %)**

M. Arenz et al. “Commissioning of the vacuum system of the KATRIN Main Spectrometer" Journal of Instrumentation 11 (2016), Nr. 4, DOI: 10.1088/1748-0221/11/04/P04011

Summary & outlook

- The neutrino mass is one of the big open questions in particle physics, astrophysics and cosmology
- The KATRIN experiment aims to measure the neutrino mass with a sensitivity of **200 meV/c²**
- The KATRIN main spectrometer reached a pressure of about **10^{-10} mbar** with a combination of different techniques
- KATRIN is in the final commissioning phase and measurements will start in **2017**

KATRIN collaboration



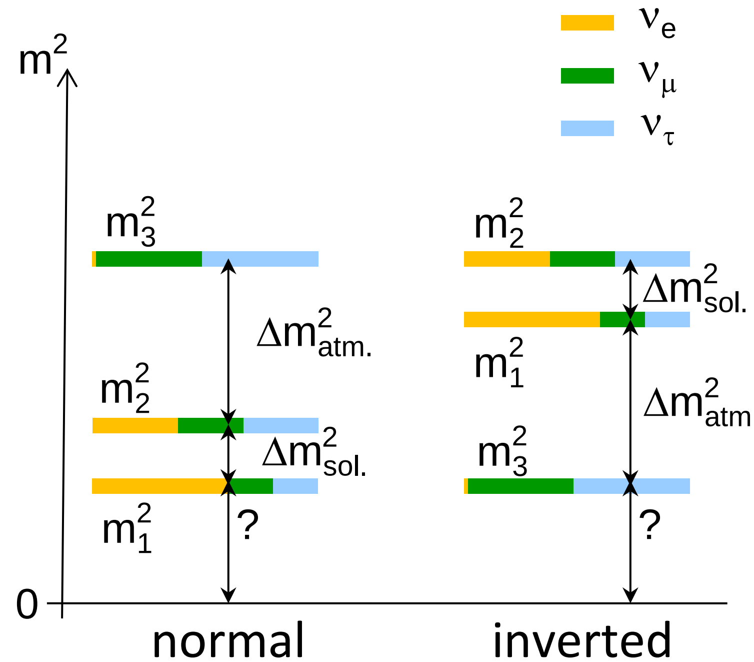
Backup

Neutrino masses

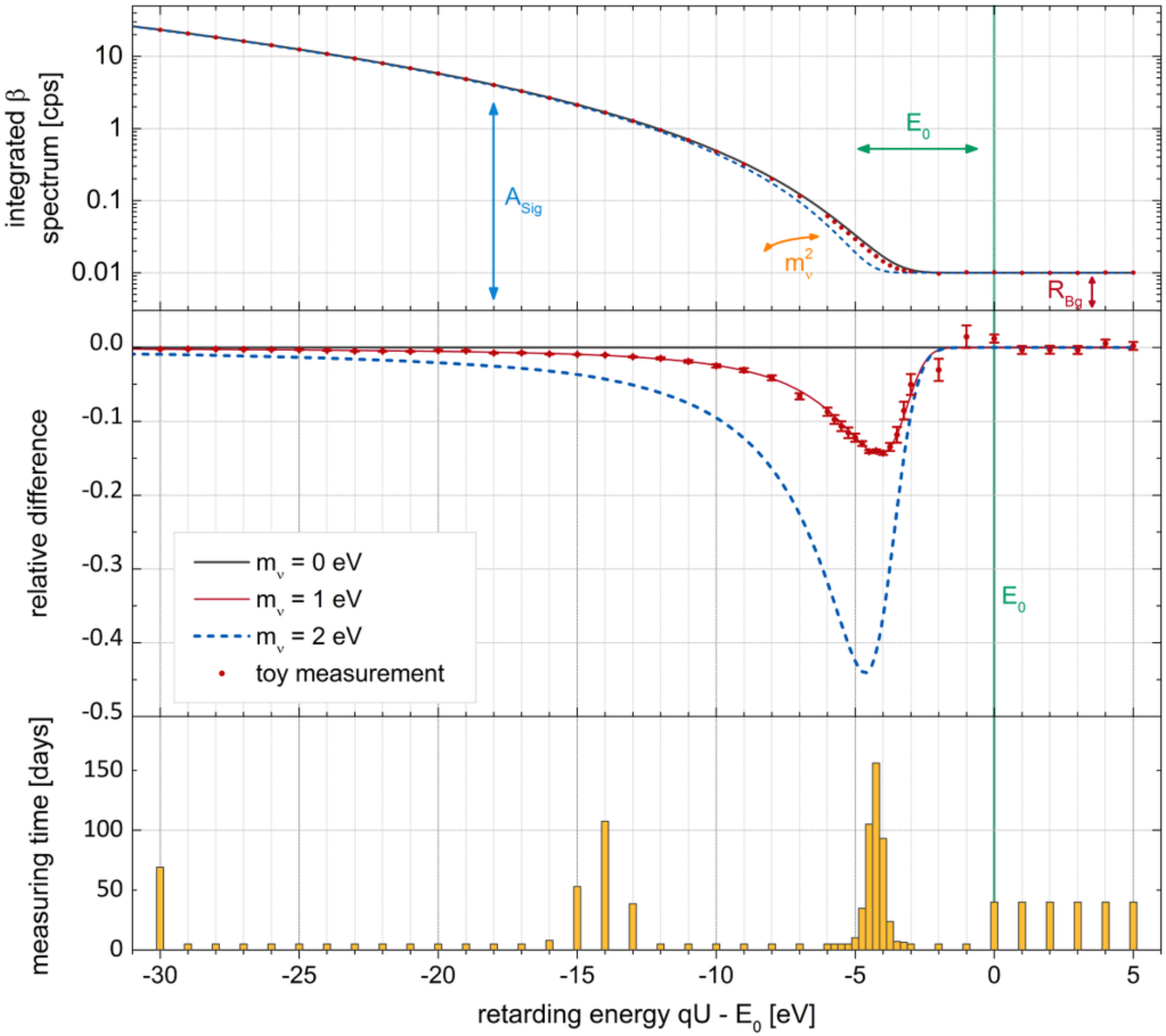
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

- Neutrino flavour eigenstates are related to neutrino mass eigenstates by the lepton mixing matrix (PMNS)
- Neutrino oscillations are sensitive to the differences between the squares of neutrino masses
- Two mass ordering scenarios possible
- The value of the lightest neutrino mass is unknown

mass ordering

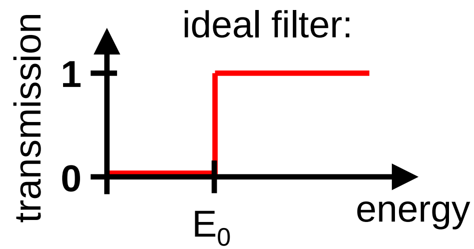


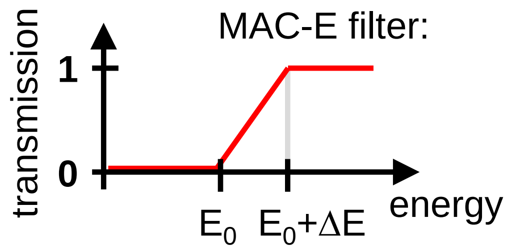
KATRIN measurement



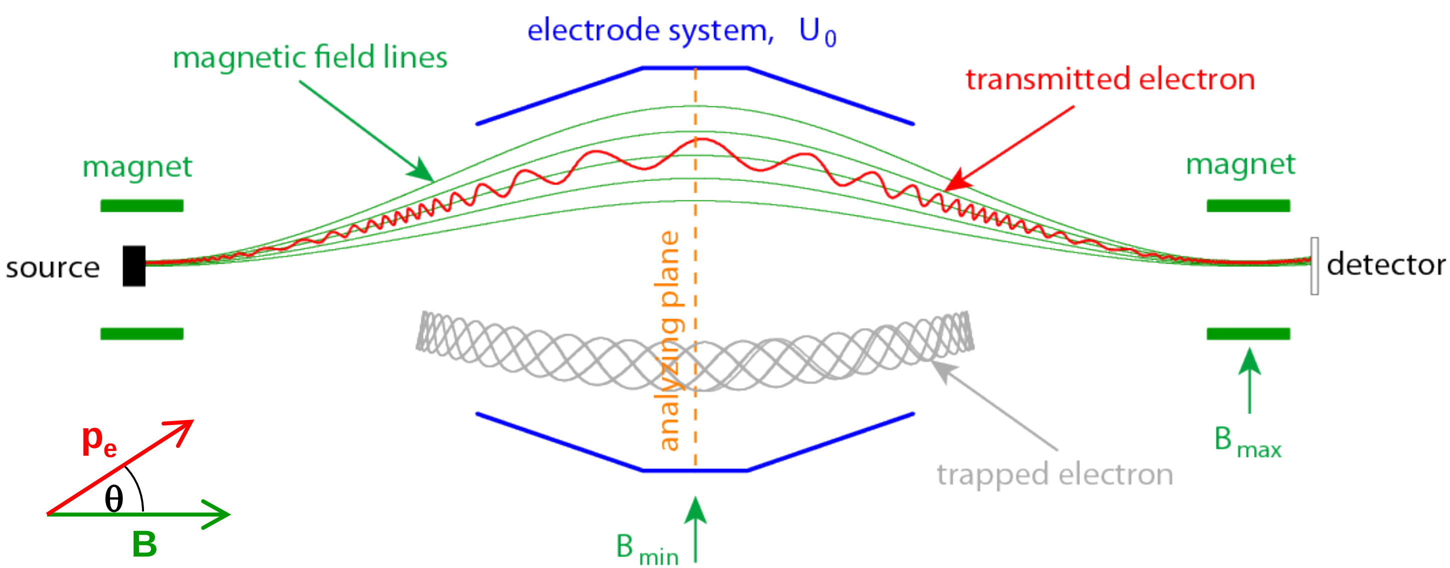
- KATRIN will measure the integrated β-spectrum close to the T_2 endpoint E_0
- The influence of m_ν is most pronounced a few eV below E_0
- Optimized measurement time distribution to increase sensitivity

MAC-E filter





- **M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter
- Technique used by Mainz and Troitsk neutrino mass experiments, current best upper limit $m_\nu < 2\ eV/c^2$



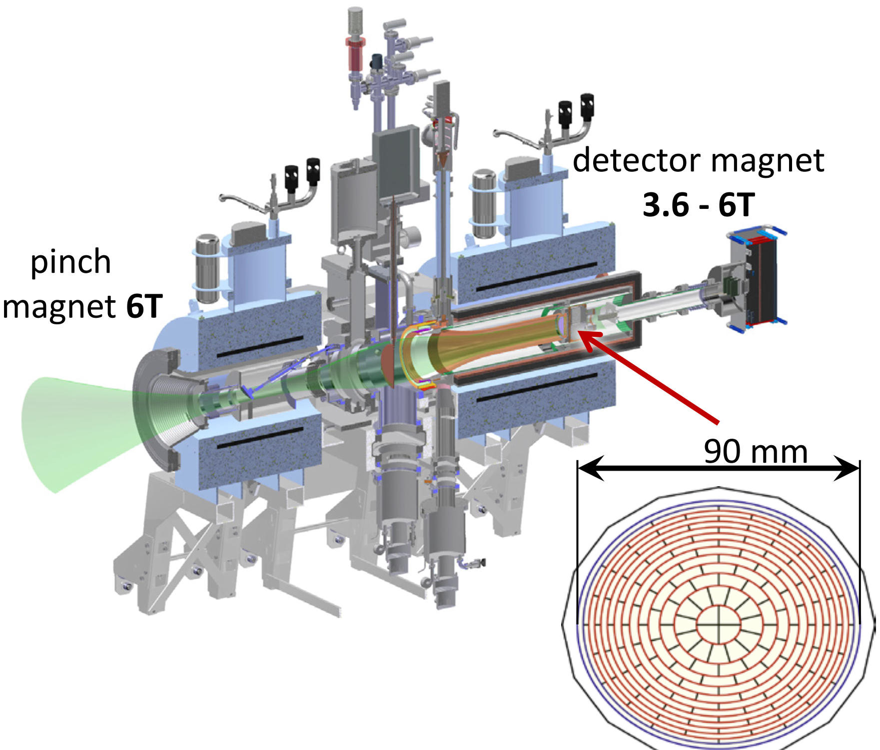
magnetic moment:

$$\mu = \frac{E_t}{B} = const$$

energy resolution:

$$\Delta E = \frac{B_A}{B_{max}} E_0$$

Detector system



purpose: counting transmitted β-decay electrons

properties:

- segmented monolithic Silicon PIN Diode
- 148 pixels, area ~ 50 mm² each
- dead layer ~ 100 nm
- post acceleration (up to +10 kV)
- muon veto system
- energy resolution 1.4 keV (FWHM)
- intrinsic background 1.2 mcps / keV

status:

- system successfully commissioned
- maintenance phase ongoing