- Introduction
- $\beta$-spectroscopy with MAC-E-filters
- KATRIN components
- Results of 2014/15 SDS campaigns
- First Light measurements 2016 & beyond
- Conclusions
KATRIN experiment

- Karlsruhe Tritium Neutrino Experiment
  - direct $\nu$–mass experiment at Tritium Laboratory (TLK) of KIT
  - international collaboration: ~130 members
  - from 6 countries: D, US, CZ, RUS, F, ES

- 18 institutions:

  - KIT
  - MIT
  - Universität Bonn
  - Université Côte d'Azur
  - TU München
  - TU München
  - Berkeley Lab
  - University of North Carolina at Chapel Hill
  - Johannes Gutenberg Universität Mainz
  - Jülich Forschungszentrum
  - Westfälische Wilhelms-Universität Münster
  - UCSB
  - Bergische Universität Wuppertal
  - University of Washington
  - Universidad Complutense Madrid
  - Hochschule Fulda
  - University of Applied Sciences
KATRIN experiment – science case

**physics programme**
- model-independent effective electron (anti-)neutrino mass: \( m(\nu_e) = 200 \text{ meV} \) (90% CL)
- search for light… heavy sterile neutrinos: sub-eV … keV mass scale
- constrain local relic-\( \nu \) density, search for Lorentz violation, exotic currents, BSM physics …
KATRIN overview: 70 m long beamline

diagnostics

cryogenic pumping

tritium source

differential pumping

integral energy analysis

electron counting

G. Drexlin – KATRIN
Project milestones 2015 - CPS

July 30: delivery of CPS cryostat
Sept. 10: delivery of WGTS cryostat
KATRIN overview: challenges-I

ITER (>2030)

- Largest ever tritium throughput ~ 10 kg/a

LHC
154 m³

- Largest ever UHV recipient (<10⁻¹¹ mbar)

1250 m³
KATRIN overview: challenges-II

tritium source: $10^{11}$ β-decays/s

(≡ LHC particle production)

total background: $10^{-2}$ cps

(≡ low level @ 1 mwe)
MAC-E principle: high-intensity tritium $\beta$-spectroscopy

- **Magnetic Adiabatic Collimation & Electrostatic Filter**: scan high-intensity T2 source

![Diagram showing tritium decay and electron detection](image_url)

- Large acceptance angle

$5 \cdot 10^{10}$ electrons/s

0.5 - 100 electrons/s

$\theta_{\text{max}} = \arcsin \left( \frac{B_s}{B_{\text{max}}} \right)$

High voltage

Electron energy (keV)

Integrated rate (cps)

Retarding potential (V)
MAC-E principle: high-resolution tritium $\beta$-spectroscopy

- **Magnetic Adiabatic Collimation & Electrostatic Filter:** adiabatic conversion $E_\perp \rightarrow E_\parallel$

$$\mu = \frac{E_\perp}{B} = \text{const.}$$

Electron from source

Electrode

Solenoid

Detector

Cyclotron path

Electron

Magnetic field line $B$

Electrostatic Filter: adiabatic conversion $E_\perp \rightarrow E_\parallel$

$B_s$, $U_s$

$B_{\text{min}}$, $U_0$

$B_{\text{max}}$
MAC-E principle: high-resolution tritium β-spectroscopy

- **Magnetic Adiabatic Collimation & Electrostatic Filter:** analytic transmission function $T$

![Diagram showing the MAC-E principle](image)

**isotropic source**

- electrode
- solenoid

\[
\Delta E / E = \frac{B_{\text{min}}}{B_{\text{max}}} \times 3 \times 10^{-4} \quad \text{T} / \text{6 T}
\]

\[
\Delta E = 0.93 \text{ eV} \quad @18.6 \text{ keV}
\]

- $T(B_{\text{min}}, B_{\text{max}}, U_0)$: no Gaussian tails but: $U_0$ on ppm-scale for sub-eV $m(\nu_e)$!
MAC-E principle: integrated $\beta$-spectrum close to $E_0$

- **MAC-E filter**: count all $\beta$-decay electrons with $E > U_0$ in focal plane detector
  - requires excellent source stability (and diagnostics), **R&D on differential read-out ongoing**

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**differential** tritium $\beta$-spectrum

**integrated** count rate after MAC-E filter
MAC-E principle: $B$ and $U_0$ from source to detector

field layout & particle tracking by

ultra-high precision

$B_{\text{max}}$ and $B_{\text{min}}$ from source to detector

RS        WGTS        DPS        CPS        PS        FPD
KATRIN components
Rear Section for diagnostics

- **Rear Section**: an indispensable tool for diagnostics of source & spectrometer
  - **angular selective photoelectron gun**: spectrometer transmission & energy losses in source
  - **Rear Wall**: definition of source potential, neutralization of cold WGTS tritium plasma, online monitoring of tritium β-decay activity via X-rays (BIXS)
WGTS – source cryostat

Windowless Gaseous Tritium Source cryostat
WGTS – source cryostat

- **complex tritium source cryostat**: 16 m length, 27 t total weight, ~ 40,000 pieces
  - 7 s.c. solenoids for adiabatic guiding of β-decay electrons (3.6 – 5.6 T)
  - 7 cryogenic fluids for tritium operation (BT: 30-120K) & liquid He bath for magnets (4 K)
  - tritium beam tube @30K with stability and homogeneity of 0.1%
  - extensive instrumentations: >800 sensors (B, T, p, level, flow, …)
source-related challenges - overview

1. injection pressure (± 0.1%)
2. isotopic content (0.1% in < 60 s)
   (also: add $^{83m}$Kr)
3. beamtube temperature (27-125 K)
4. source potential (mV-scale)
5. plasma properties ($10^{11}$ T-ions/s)
6. tritium retention (12 TMPs)
source challenges: injection & gas flow calculation

- Injection pressure (± 0.1%): 3 μbar

δ(z) = \frac{R \cdot ρ(z)}{\mu \cdot v_m} \cdot k_B T

- Hydrodynamical regime: \(δ \gg 1\)
  - Navier-Stokes equations

- Rarefied flow parameter \(δ\)

- Transitional regime: \(δ \sim 1\)
  - Boltzmann equations

- Free molecular flow: \(δ \ll 1\)
  - Only wall interactions

- ToF(T2): ~ 1s

- \(P_{ex} = 0.05 P_{in}\)
**differential pumping - DPS**

- **differential pumping section DPS2-F:**
  - serial pumping with TMPs $\rightarrow 10^5$ reduction
  - ion elimination with $E \times B \rightarrow 10^7$ reduction

- **DPS instrumentation for ions:**
  - FT-ICR (ion diagnostics)
  - dipoles (ion elimination)
  - ring electrode (ion blocking)
cryogenic pumping - CPS

- cryogenic pumping section CPS:
  - 3K section with Ar-frost layer \( \rightarrow >10^7 \) reduction of T2

- CPS instrumentation:
  - condensed \(^{83}\)Kr-source (calibration)
  - forward beam monitor (ß-activity)
electrostatic spectrometers & detector

- **tandem spectrometer:**
  - sub-eV precision energy filtering at $E_0$

**pre-filter option**
- *fixed* retarding potential
  - $U_0 = 0 \text{ V} \ldots -18.3 \text{ kV}$
  - $\Delta E \sim 100 \text{ eV}$

- **precision filter - scanning**
  - *variable* retarding potential
    - $U_0 = -18.4 \ldots -18.6 \text{ kV (ppm-scale)}$
    - $\Delta E = 0.93 \text{ eV (100\% transmission)}$
a large Helmholtz coil system for fine-shaping of low-B-field region

LFCS
low-field fine-tuning

EMCS
earth field compensation

Ø = 12.7 m
inner electrode system
(24,000 wires)
mounting precision: 200 µm!
Focal Plane Detector system

- Detection of transmitted electrons with **Si-PIN detector array**
  - 148 pixels ($A = 44 \text{ mm}^2$ each) with ~ 100 nm top deadlayer in 500 µm wafer
  - 12 rings, each consisting of 12 pixels each, central 4-pixel bullseye
  - active scintillator µ-veto & passive (Pb, Cu) shielding, PAE: $+10 \text{ kV}$

position resolution over entire flux tube (radius, azimuth)
SDS measurements
spectrometer commissioning measurements 2013-15

- **over 12 months of continuous spectrometer measurements** to verify:
  - functionality of all components: UHV, HV, B-fields, SC, DAQ,…
  - MAC-E filter characteristics via egun transmission studies
  - refine background model & optimisation of bg-reduction methods
Main spectrometer: MAC-E characteristics

- Main spectrometer works as high-resolution MAC-filter:
  - sharp transmission function for 18.6 keV electrons from egun, HV precision on 10 mV scale

![Graph showing residuals normalised e-rate (a.u.) vs. electron surplus energy (eV)](image_url)

18.6 keV egun: \( \sigma \sim 200 \text{ meV} \)

Width still limited by finite egun emission energy spectrum
Radon-induced background

- **main spectrometer** background:
  - no contributions observed from
    - $\mu$-induced secondaries
    - environmental $\gamma$'s

- Background stems only from neutral, unstable atoms in UHV

- $^{219}$Rn atoms emanate from large surface of NEG pumps (2 km strips)
  - eV…keV electrons from $\alpha$-decay
  - corresponding bg-rate: ~0.5 cps

- countermeasure (factor 20):
  - 3 LN2-cooled Cu-baffles in front of NEG
  - cryotrap eliminates $^{219}$Rn-propagation
  - remaining bg level: ~0.5 cps
A highly excited H-atoms (Rydberg states) produced by Pb-206 recoils

- Long-term forced ventilation of spectrometer, $^{222}$Rn $\alpha$-decays results in $^{210}$Pb implantation
- Single $^{206}$Pb recoil ions generate large clouds of H-Rydberg states, which propagate in UHV
- Small number of H*-atoms is ionized in UHV by thermal BBR from spectrometer
- Isotropic generation of low-energy (<1 eV) electrons in active flux tube volume (0.5 cps)
Rydberg-background: mitigation strategies

- **Extended bake-out phase of MS:**
  ~3 weeks of bake-out at 470-500 K reduce number of H2O & H-atoms on inner spectrometer surface to reduce number of H-Rydberg states (already successful in SDS2 in 2015)

- **Intense extended UV-illumination of MS:**
  UV-induced desorption of H2O & H-atoms from inner spectrometer walls to reduce number of H-Rydberg states
KATRIN
first light & future
Source and Transport System – STS

- **Commissioning of source components:**
  - **RS:** assembly of egun, preparing for „First Light“ via UV-illumination of Rear Wall
  - **WGTS:** active cool-down, ongoing preparations for tests of s.c. magnet system (4 K today!!) & long-term tests of 2-phase BT cooling system
  - **DPS:** magnet filling with LHe & pumping of BT-vacuum, test of instrumentation
  - **CPS:** successful cryogenic & magnet commissioning, full thermal cycle RT → 3K → RT
  - **Loops:** ongoing manufacture of piping & PCS7 control

**October 2016:** all STS components ready for „First Light“ measurements

T<sub>BT</sub> = 180 K (today)

T<sub>BT</sub> = 100 K (today)
KATRIN First Light: Alignment & Ion Systematics

- **Alignment Measurements**: collisionless & adiabatic transport of low-energy electrons in flux-tube of 191 T cm² (start: Oct, 14 2016)

- **Ion systematics**: low-energy pencil beam of deuterium ions to study ion blocking & ion removal via E × B drift
KATRIN future: tritium loops in Q1-Q2/2017

Loop installation works (KATRIN – TLK connection) completed March, 8 2017 ⇒ commissioning with D2, then T2 by mid-2017
**KATRIN - reference neutrino mass sensitivity**

- **KATRIN reference \( \nu \)-mass sensitivity** for 3 `full beam´ (5 calendar) years:

  - Analysis for nominal bg-level of 10 mcps

  - Sensitivity \( m(\nu_e) = 0.2 \text{ eV} \) (90% CL)

  - 0.35 eV (5\( \sigma \))

- Very moderate impact of an enhanced background level due to shape analysis and specific countermeasures:
  - Optimized scanning strategy
  - Range of spectral analysis
  - Reduced flux tube volume

  - For bg-level of 2015 with 0.5 cps: \( m(\nu_e) = 0.24 \text{ eV} \) (90%) CL

expect further bg-reduction!
KATRIN: Upgrade plans to improve sensitivity for $m(\nu_e)$

- KATRIN sensitivity of $m(\nu_e) = 200$ meV can be improved substantially to push for $m(\nu_e) \sim 100$ meV and below, on-going R&D for
  - differential read-out (encouraging 1st measurements!)
    via ToF-technique & also other methods
  → aim: bg-free scanning of tritium spectrum
- novel source concepts
  (atomic tritium source,…)
KATRIN: Upgrade plans to hunt for keV-scale ν’s

- β-decay shape modification by **keV-mass sterile neutrinos** with mass $m_s$
- TRISTAN: a novel Si-pixel detector array to cover entire T phase space
  
- $\frac{dN}{dE} \approx \sin^2 \theta$
  
- $\frac{dN}{dE} = \cos^2 \theta \cdot \frac{dN}{dE} (m_\nu) + \sin^2 \theta \cdot \frac{dN}{dE} (m_s)$

- ~$10^4$ Si-pixels to detect more than $10^{10}$ e-$/s$
- ongoing R&D programme (S. Mertens et al.)

*see following presentation by Thierry Lasserre*
Conclusions & Outlook

**experimental status:**
- all source components on-site, smooth on-going cool-down phase
- spectrometer: excellent MAC-E filter characteristics, ongoing mitigation plans against remaining bg-level

**near future:**
- „first light“ measurements mid-October 2016
- final commissioning until mid-2017
- first tritium runs in Q3-2017: best limits on kev-scale sterile ν́s (~10^{-3} level and below)

**mid-term future:**
- few months of tritium runs: sub-eV result (end of 2017)

**long-term future:**
- upgrades for keV-scale sterile ν́s, push down to 100 meV…
grazie