The Vacuum System of the KATRIN Experiment

Joachim Wolf

KATRIN Experiment
Tritium Source
Pumping and Transport Section
Spectrometer and Detector Section
Spectrometer Commissioning
Conclusions / Next Steps
The KArlsruhe TRItium Neutrino Experiment

- Goal: measure the effective neutrino mass
- International KATRIN collaboration:
  - about 130 members
  - 5 countries (GER, US, CZ, RUS, ES)
  - 15 institutions

Sensitivity on $m(\nu_e)$: $2 \text{ eV/c}^2 \rightarrow 0.2 \text{ eV/c}^2$
The KArlsruhe TRItium Neutrino Experiment

Source & Transport Section (STS)

Spectrometer & Detector Section (SDS)

3H: super-allowed

<table>
<thead>
<tr>
<th>E₀</th>
<th>18.6 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>t₁/₂</td>
<td>12.3 y</td>
</tr>
</tbody>
</table>

ideal β-emitter

\[ ^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e \]

The MAC-E Filter

Magnetic Adiabatic Collimation with Electrostatic Filter

A. Picard et al., NIM B 63 (1992)

isotropically emitted tritium $\beta$-electrons

adiabatically collimated by magnetic field

electrons filtered by electric potential

remaining electrons counted after filtering

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Magnetic field & electrostatic potential

F. Glück, Prog. in Electromagnetics Research B, 32 (2011) 351-388 & 319-350

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KATRIN – benchmark parameters

tritium source: \(10^{11}\) β-decays/s

total background: \(10^{-2}\) cps

Experimental challenges:
- \(10^{-3}\) stability of tritium source column density
- \(10^{-3}\) isotope content in source
- \(10^{-5}\) non-adiabaticity in electron transport
- \(10^{-6}\) monitoring of HV-fluctuations
- \(10^{-8}\) remaining ions after source
- \(10^{-11}\) mbar in Main Spectrometer
- \(10^{-14}\) remaining flux of molecular tritium

Many benchmark parameters reached or exceeded.
Source: Tritium Loop and Retention

- Tritium Loop and Retention
- DPS1-R
- WGTS
- DPS1-F
- DPS2-F
- CPS
- 99% inner loop to controlled T₂ injection
- 95% outer loop
- 1% inner loop
- 1% outer loop
- T₂ processing isotope separation
- T₂ recycled: 10 kg/a
- every 60 days (<1 Ci)
- T₂ retention
- existing TLK infrastructure

T₂ recycles: 10 kg/a

- column density
- electron gun
- activity
- X-ray detector
- gas injection pressure stabl.
- isotopic content
- Raman spectr.
- beam tube Temp
- 2-phase neon
- ion diagnosst.
- FT-ICR
- beam size
- Si PIN det.
Windowless Gaseous Tritium Source

Beam tube temperature

Challenge
- temperature stability on $10^{-3}$ level

Technological development
- novel 2-phase neon cooling system
- required: $\Delta T = \pm 30 \text{ mK (1 h)}$
- achieved: $\Delta T = \pm 1.5 \text{ mK (1 h)}$

→ stability surpassing specifications
Windowless Gaseous Tritium Source

Raman spectroscopy

**Challenge**
- measure isotopic source content with $10^{-3}$ accuracy in 100 s

**Technological development**
- calibrated Laser-Raman system for all 6 hydrogen isotopologues
- achieved: $< 10^{-3}$ accuracy in 60 s
Tritium Retention Techniques
Suppress tritium flow from source to spectrometer by factor $> 10^{14}$

$T_2$ injection $\rightarrow$ tritium bearing components $\rightarrow$ tritium free

Tritium flow rate [mbar $\ell$/s]

$10^1$ $10^{-1}$ $10^{-2}$ $10^{-3}$ $10^{-4}$ $10^{-5}$ $10^{-6}$ $10^{-7}$ $10^{-8}$ $10^{-9}$ $10^{-10}$ $10^{-11}$ $10^{-12}$ $10^{-13}$ $10^{-14}$ $10^{-15}$ $10^{-16}$ $10^{-17}$

differential $\&$ cryo-pumping
Transport and Pumping Sections

Differential Pumping Section (DPS)
- active pumping: 6+8+4 TMPs
- Tritium retention: $10^7$
- magnetic field: 5.6 T
- built at KIT, commissioning 2015

Cryogenic Pumping Section (CPS)
- based on by cryo-sorption
- Tritium retention: $>10^7$
- magnetic field: 5.6 T
- delivery, commissioning: 2015

O. Kazachenko et al., NIM A 587 (2008) 136
F. Eichelhardt et al, Fusion Science and Technology 54 (2008) 615
Hazardous operating conditions for TMPs?

Endurance test for TMP with tritium
- tritium can affect non-metal parts of pump
- TMP type: Leybold MAG-W 2800
- tested at Tritium Laboratory Karlsruhe (TLK)
- one year operation with tritium

TMP in a magnetic field
- eddy currents can over-heat rotor
- high mag. field can slow down rotor
- failure of magnetic bearing
- test setup built at KIT for large TMPs
- math. model developed for prediction


R. Größle et al., Vacuum 86 (2012) 985-989
Results of TMP tritium runs

- total runtime of MAG W2800 at TriToP: **398 days**
- total throughput: **1106 g tritium**
- equivalent to approx. **one year of KATRIN operation**
- RGA spectrum compatible with H, D, T, N, O and hydrocarbons
- **no traces of HF, TF** found in Raman spectrum of process gas

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**Diagrams:**

- Left: Partial pressure (mbar) vs. Mass (amu) after 0 days. Key species: HT, DT, T₂.
- Right: Partial pressure (mbar) vs. Mass (amu) after 85 days. Key species: T, 18, 19, 20, TO, THO, T₂O.

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Complete dismantling of a MAG W 2800

- parts were highly contaminated with tritium, but
- parts looked like new, no indication of wear, cables and O-rings ok

no indications of damages or imminent failure
TMP in a magnetic field

- Helmholtz coils: radius = 60 cm
- B-field: 0 – 50 mT
- coils can be turned by 90°
- pyrometer used for rotor temperature
- gas flow possible
Model 1: fit of parameters $k_1 \ldots k_6$

Leybold MAG W 2800

$T_R$ (measured)

$T_R$ (fit)

B-field [mT]

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Model 1: maximum temperature

Leybold MAG W 2800

critical rotor temperature

Rotor temperature also depends on cooling temperature!
Model 1 test:
Rotor temperature in a pulsed mag. field

Leybold MAG W 2800

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Influence of magnetic field on TMP

parallel field:
- failure of magn. bearing (PZ12)
  - for $B \uparrow$ at 12.6 mT
  - for $B \downarrow$ at 21.5 mT
- no heating of the rotor

perpendicular field:
- heating of the rotor (eddy current) < 5 mT
- reduction of rotation speed at 8 - 10 mT
- bearing stable up to 40 mT

controller in magnetic field:
- fan fails at 6.5 mT
- pump shut down at 11 mT

 TMPs need magnetic shielding at WGTS and DPS

(magnetic field values valid for MAG W 2200 and 2800)
KATRIN Main Spectrometer

- **MAC-E Filter** principle → precise electron energy measurement
  - Vacuum vessel & electrodes on
    - **variable retarding potential** (18.6 kV)
  - Magnetic guiding field: 0.3 mT – 6 T
  - High resolution: $\Delta E = 0.93$ eV @ 18.6 keV

- **Stainless steel** (~200 to, 316LN)

- **Dimensions:**
  - diameter: 10 m
  - Length: 23 m
  - volume: 1240 m³
  - inner surface: 1240 m² (including wire electrodes)
**Requirements:**

- **Low pressure** ($< 10^{-11}$ mbar)
  - tritium partial pressure $< 10^{-21}$ mbar
  - few radon decays per day
  - outgassing rate $< 10^{-12}$ mbar·ℓ/s·cm²
  - total leak rate $< 5 \cdot 10^{-9}$ mbar·ℓ/s
- **Bakable at 350°C (NEG activation)**
- **Stable operation at 20°C**
- **Vacuum components operated in**
  - Magnetic field: 0.3 mT – 6 T
  - Electric potential: 18.6 kV
KATRIN Main Spectrometer (Deggendorf)
KATRIN Main Spectrometer Journey to KIT

- Distance: 340 km
- Distance: 8800 km
- Roughing pump: 640 m³/h screw-pump
- 6 turbo-molecular pumps (Leybold MAG-W 2800): 10 000 ℓ/s (H₂)
- Fore-vacuum: 300 ℓ/s TMP and scroll pump (30 m³/h)
- 3 NEG-pumps (3000 m SAES St707 getter strips): ~10⁶ ℓ/s (H₂)
- 3 cryogenic LN₂ baffles (radon): ~170 000 ℓ/s (Rn)
Flanges and Gaskets:

**UHV:**
- CF flanges up to 250 mm
- HTMS double gaskets:
  - 500 mm flanges at ground-electrodes
  - 1700 mm flanges at pump ports
- all gaskets bakable at 350°C

**intermediate vacuum:**
- CF flanges

**fore-vacuum:**
- KF flanges (Viton O-rings)
- ISO K for pump-down and venting
Radon as background source (problem)

- $^{219}$Rn emanation from St707 NEG getter strips (3000 m) in pump ports
- $^{220}$Rn emanation from stainless steel walls/weldings
- electrons trapped in B field for hours
- they produce secondary electrons by ionization

F.M. Fränkle et al., Astropart. Phys. 35 (2011) 128
S. Mertens et al., Astropart. Phys. 41 (2013) 52
Radon as background source (solution)

- passive background reduction: LN2-cooled baffles to cryo-sorb $^{219}$Rn

- reduction of effective NEG pumping speed: 40%
- reduction of Rn flow into main volume: $\sim 0.4\%$
- pumping speed for Rn from walls: 170 000 ℓ/s
KATRIN Main Spectrometer and Detector Commissioning 2013

Date: March 7, 2014
Time: 9:00 – 13:00
Venue: Room 142, IP, Building 242

Parcels:
- SDS phase II commissioning
  - preparation meeting

- SDS system
  - new TG leader

- SDS schedule and shift operation
  - T. Thümmler

- SDS discussion and adjourn
  - all

10-11 mbar
6 weeks baking,
T_{max} = 300 \, °C
low background,
148 pixel

UHV conditions

- angular selective electron gun
- MAC-E filter, energy analysis
- vessel on HV, wire electrode
- Si-PIN detector

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2008 – 2012: Wire Electrode Installation

- 248 wire electrodes on the inner surface
  - 23,440 insulated wires
  - 120,000 individual parts
- Installed under cleanroom conditions
2012: All Components Installed

- Electrode installation completed
- Vacuum system installed
- Successful leak test
- Commissioning of heating and vacuum control system (PCS7)
Spectrometer Commissioning: Bake-out

- PT100 temp. sensor
- Extractor pump port (P3)
- Extractor vessel (F9)

- Several short circuits
- First short circuit
- Short circuit disappeared
- Air leak
- Differentially pumped vacuum sleeve

Temperature (°C) vs. Time (01.01.2013 to 31.01.2013)

Pressure (mbar, N₂) vs. Time (01.01.2013 to 31.01.2013)
Baking of the Main Spectrometer

- Duration of baking: 4 weeks
- 24/7 shifts
- Max. temperature: 300°C
- Heating rate: 1°C – 5°C/h
- Thermal expansion during bake-out: ~ 10 cm
Vacuum status after bake-out

- Before baking: $6.4 \times 10^{-8}$ mbar
- After baking: $3.5 \times 10^{-11}$ mbar

**Graph:**
- **H$_2$O**
- **CO / N$_2$**
- **CO$_2$**

**Axes:**
- **Pressure in mbar** (N$_2$ cal.)
- **RGA mass (amu)**

**Legend:**
- Yellow: before baking
- Red: after baking

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NEG activation

- Indicator for NEG activation:
  - pressure ratio between vessel and pump port

![Graph showing pressure ratio and MolFlow+ simulation results](image)

- MolFlow+ simulation
- Measured ratio after activation
- H₂

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NEG activation

- Indicator for NEG activation:
  - pressure ratio between vessel and pump port
  - first indication for NEG pumping at 200°C

![](chart.png)
NEG activation

- Indicator for NEG activation:
  - pressure ratio between vessel and pump port
  - after baking: $p_{P3}/p_{F9} = 0.41 \Rightarrow S_{NEG} \approx 290 \text{ m}^3/\text{s}$

**Graph:**
- Maximum: $156 \text{ m}^3/\text{s}$ for $\alpha = 100\%$
- Expected: $125 \text{ m}^3/\text{s}$ for $\alpha = 2.9\%$
- Measured: $96 \text{ m}^3/\text{s}$ for $\alpha = 1.1\%$

- Expected outgassing rate: $10^{-12} \text{ mbar} \cdot \text{l/s} \cdot \text{cm}^2$
- Surface (vessel & electrodes): $1240 \text{ m}^2$
- Effective pumping speed: $375 \text{ m}^3/\text{s}$
- **Expected pressure in vessel**: $3.3 \cdot 10^{-11} \text{ mbar}$
- **Actual H}_2\text{ pressure in vessel**: $5.7 \cdot 10^{-11} \text{ mbar}$
- Actual H}_2\text{ outgassing rate: $1.4 \cdot 10^{-12} \text{ mbar} \cdot \text{l/s} \cdot \text{cm}^2$
Coupling of Spectrometer and Detector

- Detector de-coupled during bake-out
- Requires valve inside magnet bore
- O-ring partly slipped out during baking
- **Challenge:** attach detector without saturation of the activated NEG-pump
Coupling of Spectrometer and Detector

- **Solution:** replacing the O-ring under inert gas atmosphere (Ar)
- Gas quality N9.0 required to prevent contamination of NEG

- ✓ O-ring exchanged in Ar atmosphere
- ✓ beam-line valve now leak tight
- ✓ detector section attached

**XENON 1t**

gas purification system (SAES NEG)
Vacuum status after venting with argon

- After baking: 3.5E-11 mbar
- After venting: 3.3E-11 mbar

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KATRIN Schedule

- spectrometer upgrade for low background (0.01 cps)  Q1/2015
- tritium retention units DPS and CPS functional  Q2/2015
- tritium source WGTS final mounting completed  mid-2015
- spectrometer upgrade completed  Q3/2015
- all source elements & tritium loops integrated  Q4/2015
- first tritium in source, ramp up to nominal $\rho_d$  Q1-Q2/2016
- first tritium data with entire beam line  mid-2016
Conclusions

- Source and Transport Section still under construction
- Spectrometer and Detector Section commissioned
- Various smaller experiments investigate specific questions
  - TMPs in magnetic fields
  - Tritium compatibility of TMPs
  - Outgassing rates
  - ...
Thank you for your attention
Backup slides
The KATRIN Setup - Overview

Tritium source

- $^{3}\text{H}$
  - $^{\beta}\text{decay}$
  - $10^{11}$ $\text{e}^{-}/\text{s}$
  - $E = 18.6$ keV

Transport section

- $^{3}\text{He}$
  - $10^{10}$ $\text{e}^{-}/\text{s}$

Pre spectrometer

- $E > 18.3$ keV
  - $10^{3}$ $\text{e}^{-}/\text{s}$

Spectrometer

- $\Delta E = 0.93$ eV

Detector

- $1$ $\text{e}^{-}/\text{s}$

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KATRIN experiment – overview

KATRIN (2015)
- Large tritium throughput
  ~ 10 kg/a

ITER (2027)

1240 m³
- One of largest UHV-recipient (<10⁻¹¹ mbar)

LHC
- 154 m³

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**DPS 2-F – differential pumping section**

- **DPS**: active differential pumping by 4 main TMPs - retention factor $10^5$

subsections tilted by 20°
CPS – cryogenic pumping section

- **CPS**: passive cryotrap

**cryogenic pumping**
- 3 K beam tubes with Ar frost
- tritium retention factor > $10^7$

**adiabatic guiding of electrons**
- 7 s.c. solenoids ($B = 5.6$ T)

**Port instrumentation**
- vertical access port for condensed $^{83\text{m}}\text{Kr}$ source
- horizontal port for monitoring

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The MAC-E Filter

A. Picard et al., NIM B 63 (1992)

- **Collimation:** \( \mu = E_\perp / B = \text{const.} \Rightarrow E_\perp \rightarrow E_\parallel \) for \( B = 6 \text{ T} \rightarrow 3 \text{ mT} \)
- **Energy Analysis:** transmission condition: \( E_\parallel > eU_0 \) (retarding potential)
- **Energy Resolution:** \( \Delta E = E \cdot \frac{B_{\text{min}}}{B_{\text{max}}} = 18.6 \text{ keV} \cdot 0.3 \text{ mT} / 6 \text{ T} = 0.93 \text{ eV} \)
Vacuum conditioning for the MAC-E-filter test measurements

- Plan: baking of the M.S. at 350°C (cleaning and activation of NEG)
- Goal: reach UHV conditions with $p \approx 10^{-11}$ mbar
- Bake-out in January 2013

Problems during bake-out (partly solved)

- Short circuit between current leads to electrodes @ 200°C – 300°C
  - Reduced baking temperature (300°C) to avoid further damage
- Leakage in CF flange at 50°C
  - Differentially pumped vacuum sleeve
  - Another leakage after Ar venting
- Leakage in beam-line valve
  - Ar venting for repair

Detector and e-gun connected

Start of MAC-E-filter tests

temperature map
detailed transmission and background studies

- sharpest transmission function ever measured with MAC-E filter
- background from $^{219}\text{Rn}/^{220}\text{Rn}$ emanation eliminated

- will be improved during 2014 commissioning runs
Two short measurements

Background strongly reduced

Proof of principle: baffles work as expected

Long-term performance will be tested in 2014/2015
Vacuum scheme of the Main Spectrometer
Wire defines electrostatic filter:
- 248 modules, 23440 wires
- precision requirement 0.2 mm
- compatible to UHV

K. Valerius et al., Particle and Nuclear Physics, Volume 64, Issue 2, April 2010
**KATRIN Main Spectrometer**

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Temp.</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Spectrometer vacuum vessel</td>
<td>316LN</td>
<td>20°C</td>
<td>690.0 m²</td>
</tr>
<tr>
<td>Wires (23440 wires with a total length of 42400 m)</td>
<td>316L</td>
<td>20°C</td>
<td>33.6 m²</td>
</tr>
<tr>
<td>Electrode frames (248 modules)</td>
<td>316L</td>
<td>20°C</td>
<td>436.8 m²</td>
</tr>
<tr>
<td>Electrode rail system</td>
<td>316LN</td>
<td>20°C</td>
<td>58.0 m²</td>
</tr>
<tr>
<td>Feedtrough flanges</td>
<td>316LN</td>
<td>20°C</td>
<td>2.0 m²</td>
</tr>
<tr>
<td>Small components (frame NEG-pumps, etc.)</td>
<td>316L</td>
<td>20°C</td>
<td>1.5 m²</td>
</tr>
<tr>
<td><strong>Σ stainless steel</strong></td>
<td>316L(N)</td>
<td>20°C</td>
<td>1221.9 m²</td>
</tr>
<tr>
<td><strong>Σ ceramic insulators</strong></td>
<td>Al₂O₃</td>
<td>20°C</td>
<td>5.8 m²</td>
</tr>
<tr>
<td><strong>Σ anti-penning electrodes</strong></td>
<td>Ti</td>
<td>20°C</td>
<td>11.0 m²</td>
</tr>
<tr>
<td><strong>Σ ground electrodes</strong></td>
<td>Al</td>
<td>20°C</td>
<td>1.3 m²</td>
</tr>
<tr>
<td><strong>Σ surfaces at room temperature</strong></td>
<td></td>
<td>20°C</td>
<td>1240 m²</td>
</tr>
<tr>
<td><strong>Σ cryogenic baffles</strong></td>
<td>Cu</td>
<td>77 K</td>
<td>31 m²</td>
</tr>
<tr>
<td><strong>Σ NEG-strips</strong></td>
<td>St707</td>
<td>20°C</td>
<td>180 m²</td>
</tr>
</tbody>
</table>

**Volume Main Spectrometer**

1240 m³
Simulations of the Main Spectrometer

- simplified model of the main spectrometer created (optimized discretization for Molflow)
- simulate pressure ratio $p_{p3} / p_{F9}$ of pressure gauges
three possible gas sources for hydrogen and radon:
- complete stainless steel tank
- NEG strips in pump ports
- diagonal virtual area in one pump port (cross section between port and vessel) for determination of pumping speeds

three possible pump variations:
- NEG pumps hydrogen with $\alpha_{\text{NEG}}$ between 0.5% and 3.5% (2.9% expected)
- TMPs for hydrogen or radon with their respective $\alpha_{\text{TMP}}$
- baffles with $\alpha_{\text{baffle}}$ between 0% and 100% for radon

aims:
- find correlations between $\alpha_{\text{baffle}}$, $\alpha_{\text{NEG}}$ and pressure ratios
- simulation of effective pumping speed of NEG, TMPs and baffles
- comparison with experimental ratios $\Rightarrow$ effective pumping speed
- simulate radon suppression factor
Simulation of the Main Spectrometer (MoIFlow+)

- main components:
  - CF 200 ports on main vessel
  - Baffles
  - NEG strips
  - Vacuum gauges
  - TMPs

Source:
S. Görhardt: Background Reduction Methods and Vacuum Technology at the KATRIN spectrometers, PhD thesis, Karlsruhe 2014
Simulation of an effective pumping speed

- Simulate pump as surface with an adsorption probability $\alpha$
- Determine pumping probability: $w = \frac{N_{ads}}{N_{des}}$
- Calculate the effective pumping speed: $S(M) = \frac{1}{4} \bar{c}_M \cdot A_{port} \cdot w$

$\bar{c}$: mean molecular speed for mass $M$

$\bar{c} = \sqrt{\frac{8k_B T}{\pi M}}$

$A_{port}$: desorption area (virtual area)

$N_{ads}$: number of adsorptions in pump

$N_{des}$: total desorption number

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TMP simulation

- Determine pumping speed of TMP for mass of gas particle (Malyshev model)
- Simulate pumping probability $w = \frac{N_{ads}}{N_{des}}$
- Effective pumping speed: $S(M_2) = \frac{1}{4} \bar{c}_{M_2} \cdot A_{port} \cdot w$

Malyshev model:


\[
\frac{S(M_1)}{S(M_2)} \approx \frac{\sqrt{M_2}}{\sqrt{M_1}} \cdot \frac{\ln M_1}{\ln M_2}
\]

Pumping speed of TMP:

\[
S(M_2) = \frac{1}{4} \bar{c}_{M_2} \cdot A_{TM P} \cdot \alpha_{TM P}
\]

Graph showing TMP pumping speed vs. mass (amu) with points for $N_2(28): 2650 \text{ l/s}$, $H_2(2): 2060 \text{ l/s}$, and $\text{Rn}(220): 1530 \text{ l/s}$.
NEG-pump simulation (without baffle)

maximum: 545 m$^3$/s for $\alpha = 100$

expected: 309 m$^3$/s for $\alpha = 2.9$

NEG pump no baffle
NEG-pump simulation (with baffle)

- Maximum: 156 m$^3$/s for $\alpha = 100$
- Expected: 125 m$^3$/s for $\alpha = 2.9$

Graph showing NEG pumping speed (m$^3$/s) vs. NEG sticking coefficient $\alpha$. The line shows the expected speed with a baffle, peaking at 156 m$^3$/s at 100% sticking coefficient.
Simulation results for the NECs as primary pumps

- ratio of hit numbers in vacuum gauges $\approx$ ratio of pressures: $p_{PP3} / p_{F9}$
- gas: hydrogen

![Graph showing extractor gauge ratio $p_{PP3}/p_{F9}$ vs NEG sticking coefficient $\alpha$]

- measured ratio after activation
- wall desorption
- NEG desorption

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Simulation results for the NEGs as primary pumps

- calculation of the NEG pumping speed:  \[ S = \frac{1}{4} \cdot \bar{c} \cdot A \cdot \frac{N_{\text{NEG}}}{N_{\text{des}}} \]
- gas: hydrogen

Graph:
- Maximum: 156 m³/s for \( \alpha = 100\% \)
- Expected: 125 m³/s for \( \alpha = 2.9\% \)
- Measured: 96 m³/s for \( \alpha = 1.1\% \)

NEG pump with baffle

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Simulation results for the TMPs as primary pumps

- ratio of hit numbers in vacuum gauges \(\approx\) ratio of pressures: \(p_{P3} / p_{F9}\)
- gas: radon

![Graph showing suppression of radon from NEG in vessel](image)
Simulation results for the TMPs as primary pumps

- calculation of the pumping speed (TMP + Baffle): \( S = \frac{1}{4} \cdot \bar{c} \cdot A \cdot \frac{N_{\text{TMP}} + N_{\text{Baffle}}}{N_{\text{des}}} \)
- gas: radon
NEG simulation with baffle (MolFlow+)

- Expected outgassing rate: $10^{-12}$ mbar·ℓ/s·cm²
- Surface (vessel & electrodes): 1240 m²
- Effective pumping speed: 375 m³/s
- Expected pressure in vessel: $3.3 \cdot 10^{-11}$ mbar

- Maximum: 156 m³/s for $\alpha = 100$
- Expected: 125 m³/s for $\alpha = 2.9$

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Baffle simulation for Radon (MolFlow+)

- $\alpha_{\text{Rn}} \approx 80\%$ estimated from Pre-Spectromter results
- **Suppression factor** for radon emanating from NEG: $\approx 250$

- Effective pumping speed for 6 TMPs: 3400 ℓ/s
- Effective pumping speed for 3 baffles: $\approx 170,000$ ℓ/s
Hydrogen outgassing and pressure at 20°C

- **Fit of** $p_{P3}$ versus $p_{F9}$
  - NEG pumping speed from $p_{P3}/p_{F9}$: $290$ m$^3$/s ($\alpha = 1.1\%$)
  - Offset of Extractor gauge F9: $1.8 \cdot 10^{-10}$ mbar

- **Fit of** $p_{F9} \cdot \sqrt{T/293K}$ versus $1/T$
  - Desorption enthalpy of $H_2$ on st. steel: $53$ kJ/mol = $0.55$ eV/$H_2$
  - Extrapolated pressure at $20°C$: $2.6 \cdot 10^{-11}$ mbar (gas corr. $H_2$: $5.7 \cdot 10^{-11}$ mbar)

- Outgassing rate $j_{H_2} = p(20°C) \cdot S_{eff}/A = 1.4 \cdot 10^{-12}$ mbar·ℓ/s·cm$^2$

**Graphs:**

- **Graph a:** NEG activation
  - $y = 0.412x - 7.56 \cdot 10^{-11}$
  - Offset $p(F9)$: $1.83 \cdot 10^{-10}$ mbar

- **Graph b:**
  - $p_{F9} \cdot \sqrt{T/293K} = a_0 \cdot e^{-\frac{a_1}{T}}$
  - 80°C
  - $y = 0.079e^{6393x}$
  - $p(20°C) = 2.6 \cdot 10^{-11}$ mbar
  - Pressure at 20°C

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Vacuum status with cold baffles

![Graph showing vacuum status with cold baffles. The graph displays the pressure in mbar for various RGA mass (amu) values, with different species indicated by bars. The labels include \(H_2\), \(H_2O\), \(CO/N_2\), \(Ar\), and \(CO_2\). The legend indicates 'after venting: 3.2E-11 mbar' and 'cold baffle: 2.5E-11 mbar'.]
RGA spectrum after venting

![Graph showing RGA spectrum after venting. The graph includes various gases such as H2, H2O, N2, Ar, and the RGA(sum). The x-axis represents dates from 21.05.2013 to 18.09.2013, and the y-axis represents pressure in mbar ranging from 1E-13 to 1E-04.]
KATRIN Main Detector

- Si-PIN diode
- detection of transmitted β’s (mHz to kHz)
- low background for $T_2$ endpoint investigation
- high energy resolution:
  \[ \Delta E = 1.48(1) \text{ keV (FWHM)} \text{ at } 18.6 \text{ keV} \]
- 12 rings with 30° segmentation + 4-fold center = 148 pixels
  - minimize bg, investigate systematic effects
  - compensate field inhomogeneities of spectrometer’s analyzing plane.

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