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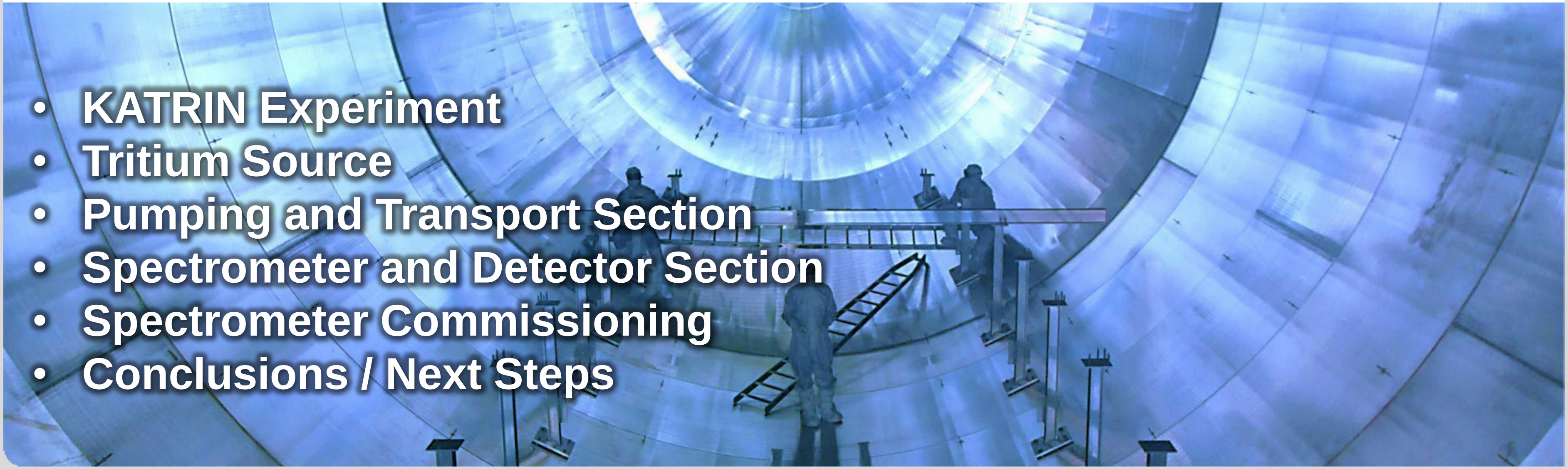
The Vacuum System of the KATRIN Experiment

Joachim Wolf

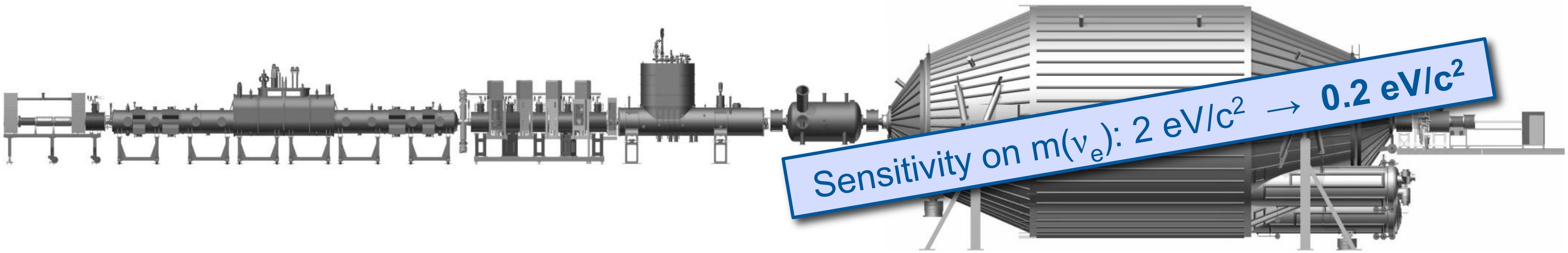
Institute of Experimental Nuclear Physics

Grenoble, 02.12.2014



- 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**

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Westfälische Wilhelms-Universität Münster
Bergische Universität Wuppertal
universität mainz
universität bonn
Hochschule Fulda University of Applied Sciences
The University of North Carolina at Chapel Hill
University of Washington 1861
MIT
Berkeley Lab
UCSB
Max-Planck-Institut für Kernphysik
Universidad Complutense Madrid
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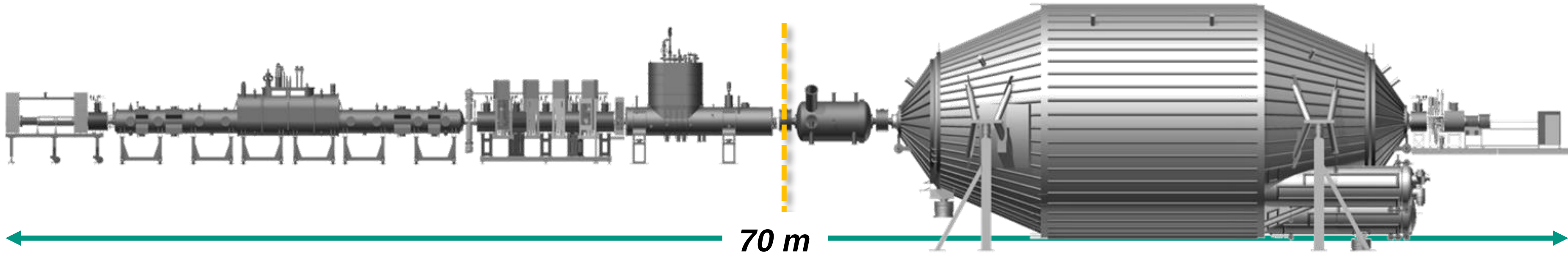
The KArlsruhe TRItium Neutrino Experiment

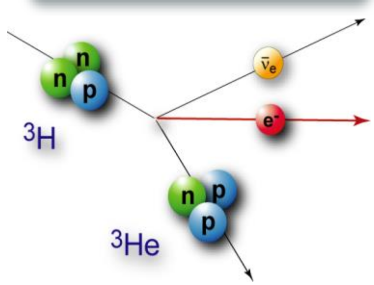


Source & Transport Section (STS) | **Spectrometer & Detector Section (SDS)**

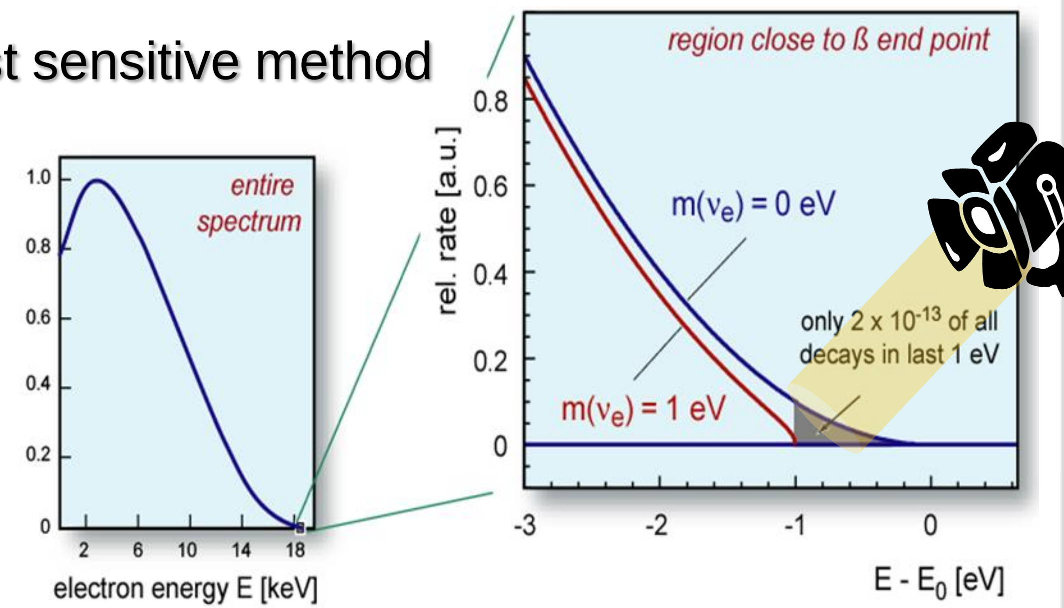
ideal β-emitter

^3H: super-allowed	
E_0	**18.6 keV**
$t_{1/2}$	**12.3 y**

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



most sensitive method

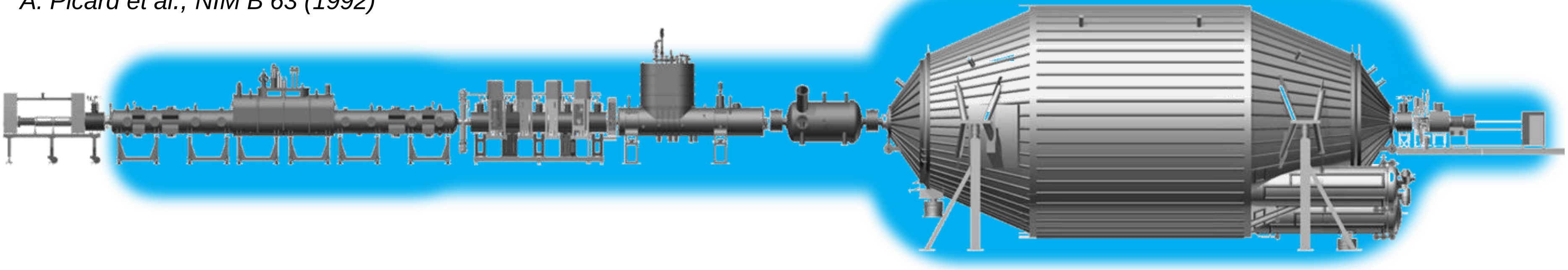


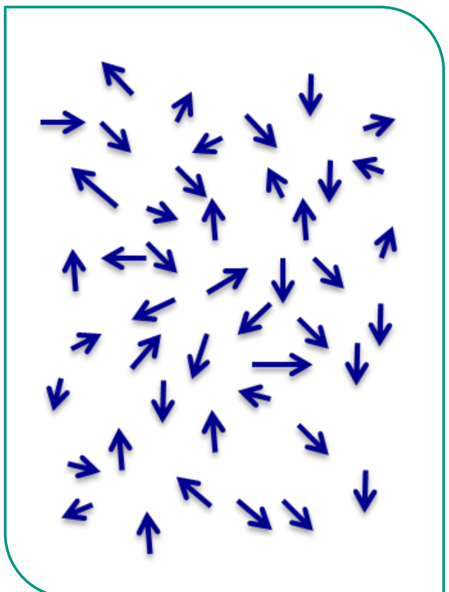
G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, ***Current Direct Neutrino Mass Experiments (Review)***
Advances In High Energy Physics (2013) 293986

The MAC-E Filter

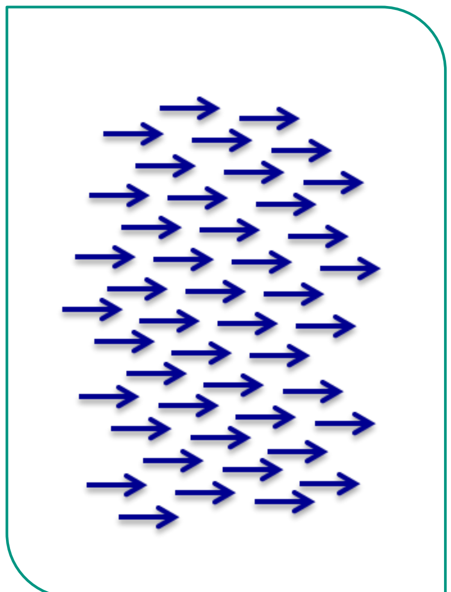
Magnetic Adiabatic Collimation with Electrostatic Filter

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

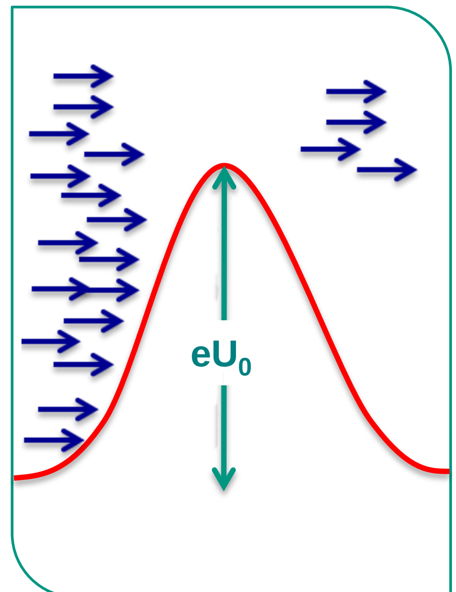




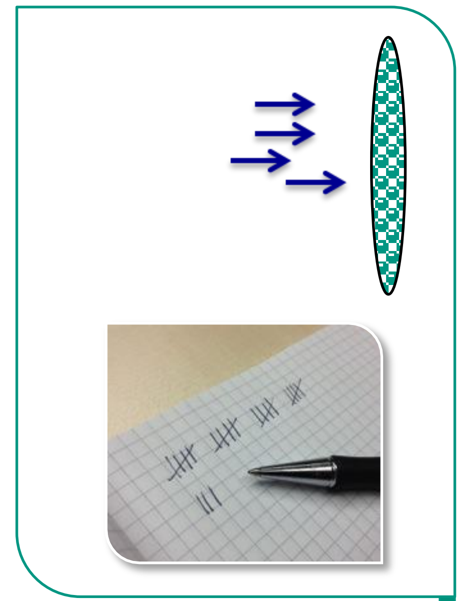
isotropically emitted tritium β-electrons



adiabatically collimated by magnetic field

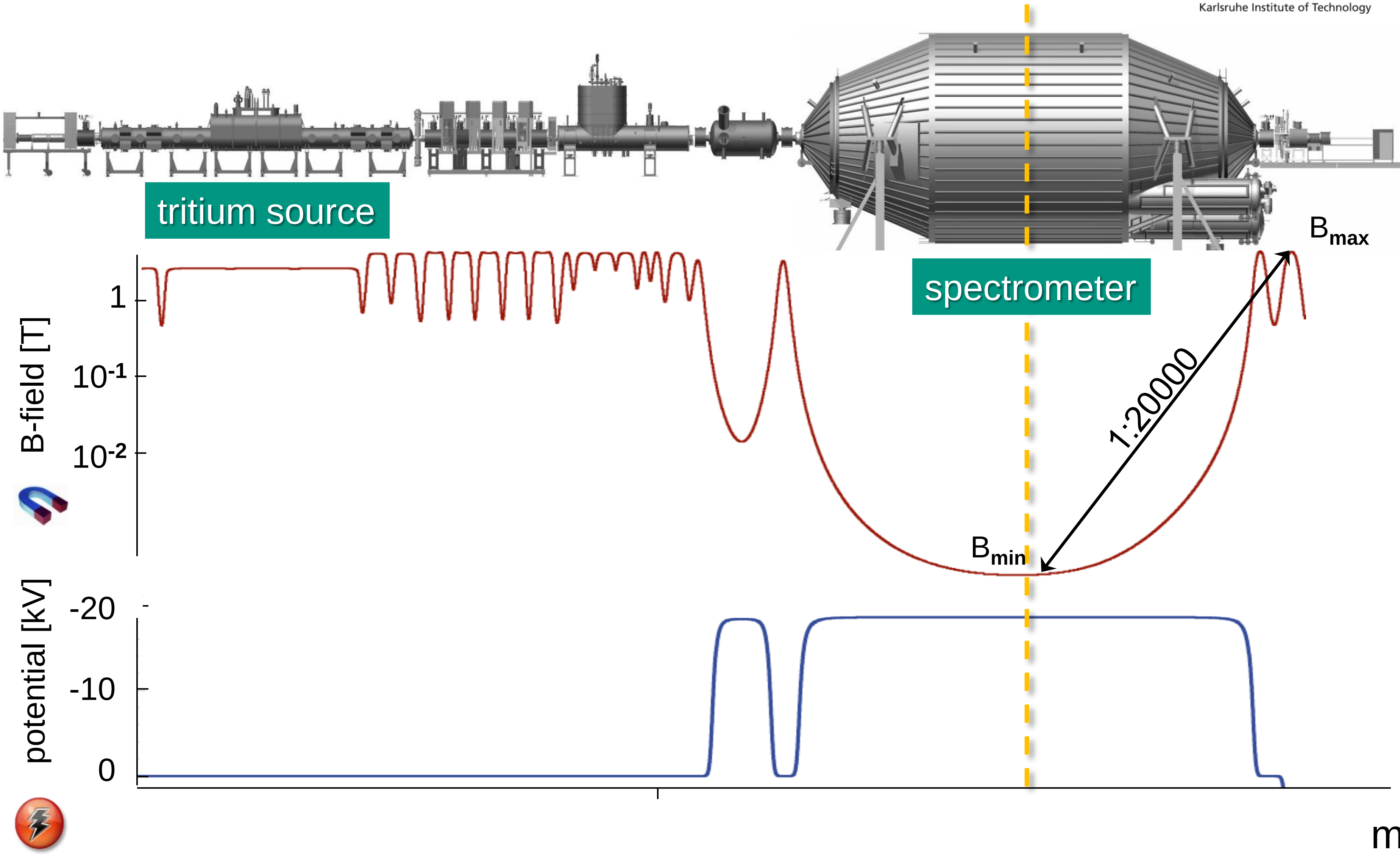


electrons filtered by electric potential



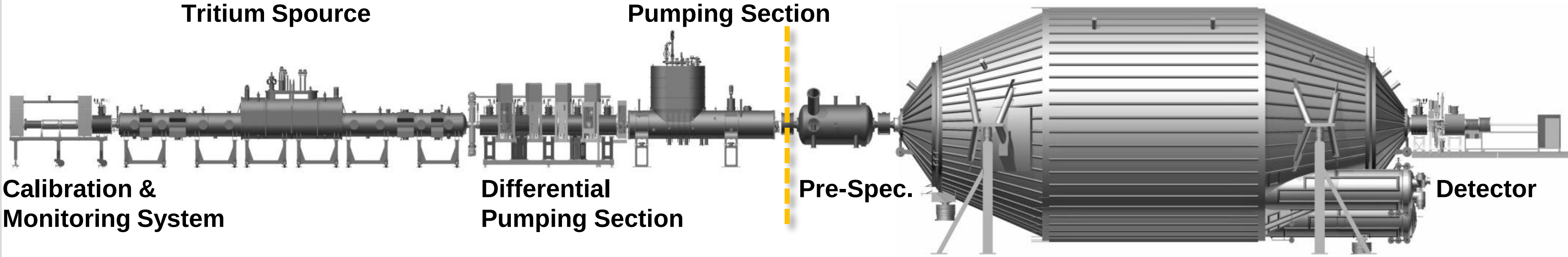
remaining electrons counted after filtering

Magnetic field & electrostatic potential



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

KATRIN – benchmark parameters



Source & Transport Section (STS)

tritium source: 10^{11} β-decays/s

Spectrometer & Detector Section (SDS)

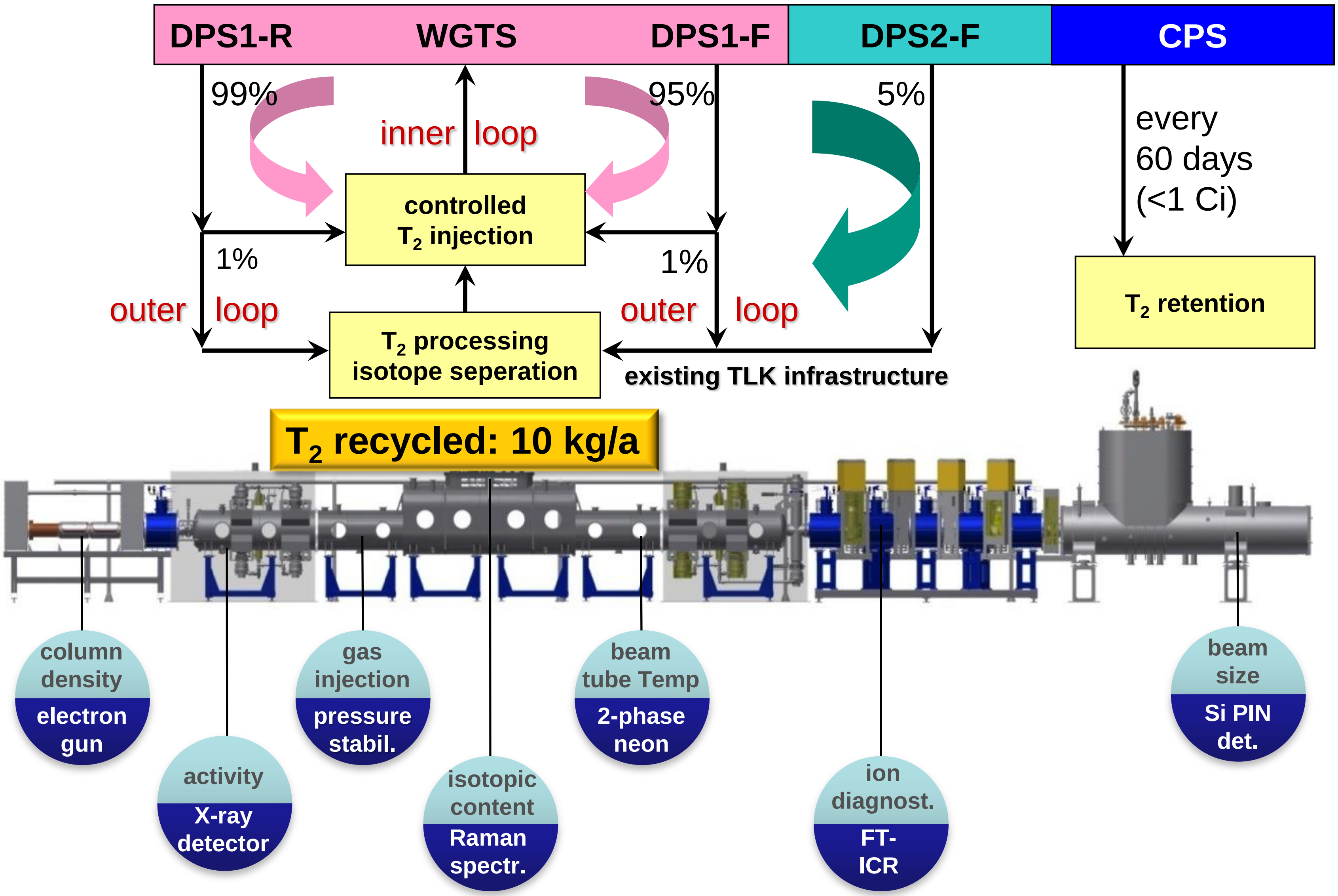
total background: 10^{-2} cps

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

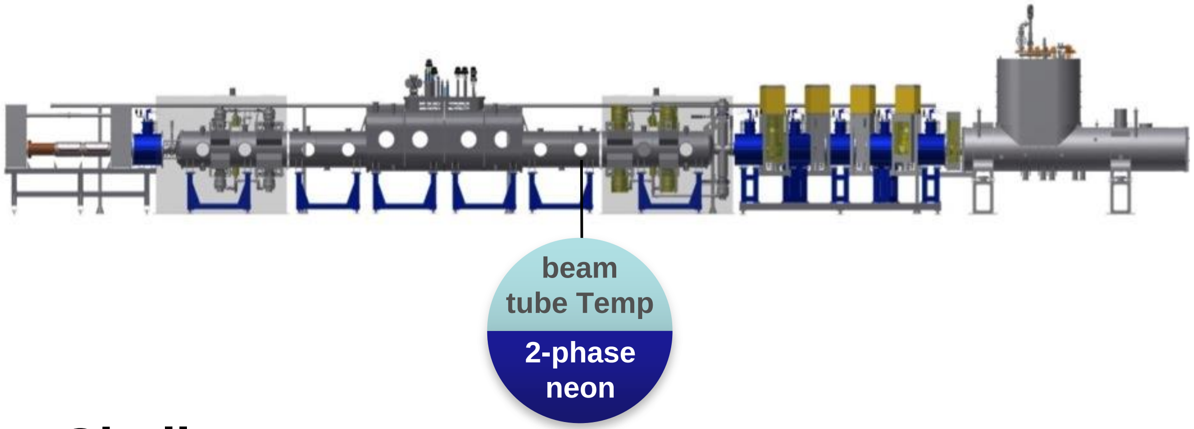
many benchmark parameters reached or exceeded

Source: Tritium Loop and Retention



Windowless Gaseous Tritium Source

Beam tube temperature



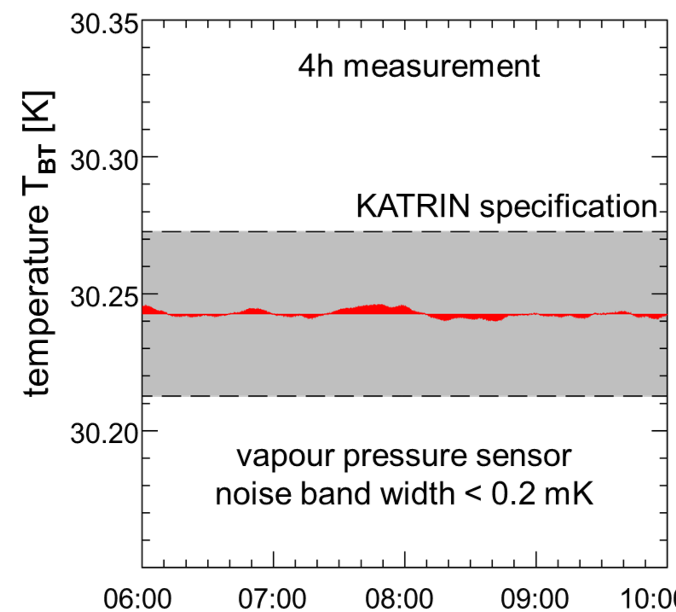
Challenge

- temperature stability on 10^{-3} level

Technological development

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

→ **stability surpassing specifications**



Windowless Gaseous Tritium Source

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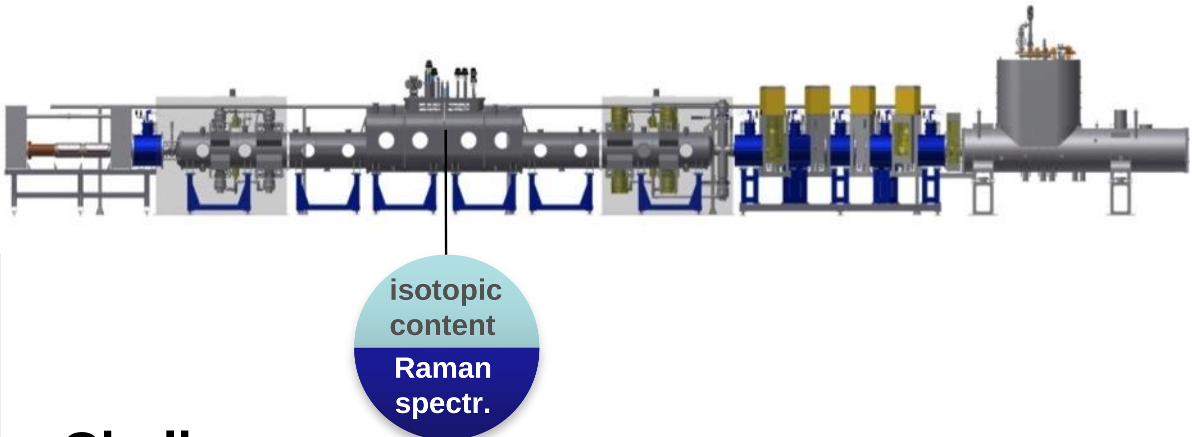
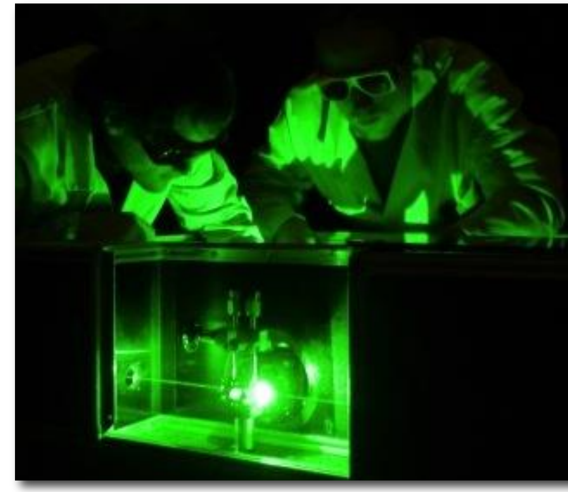
Raman spectroscopy



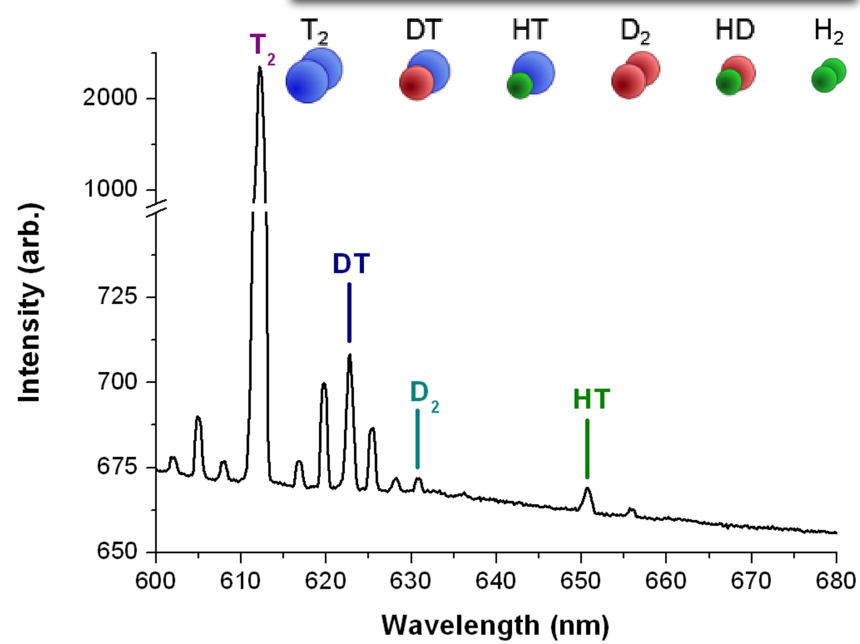


Challenge

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

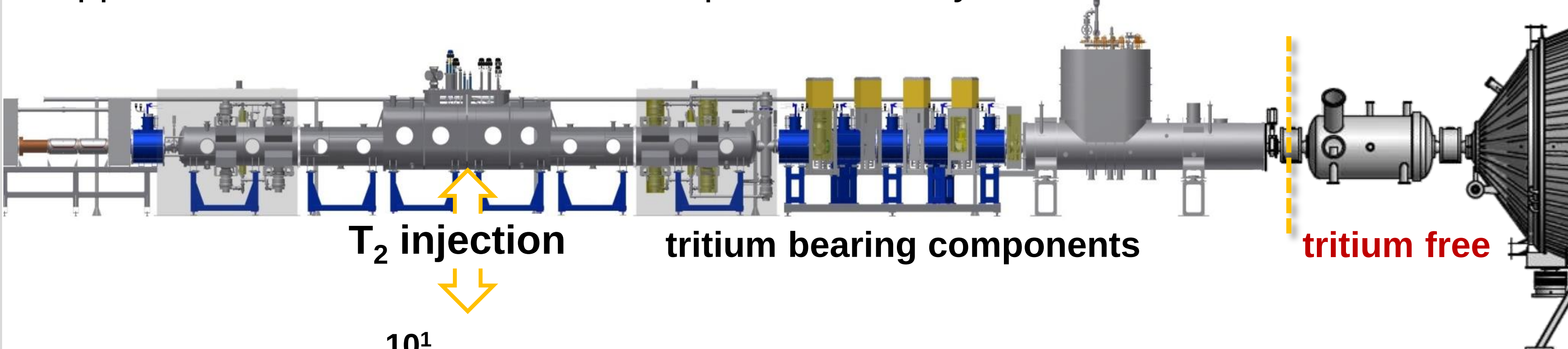
Technological development

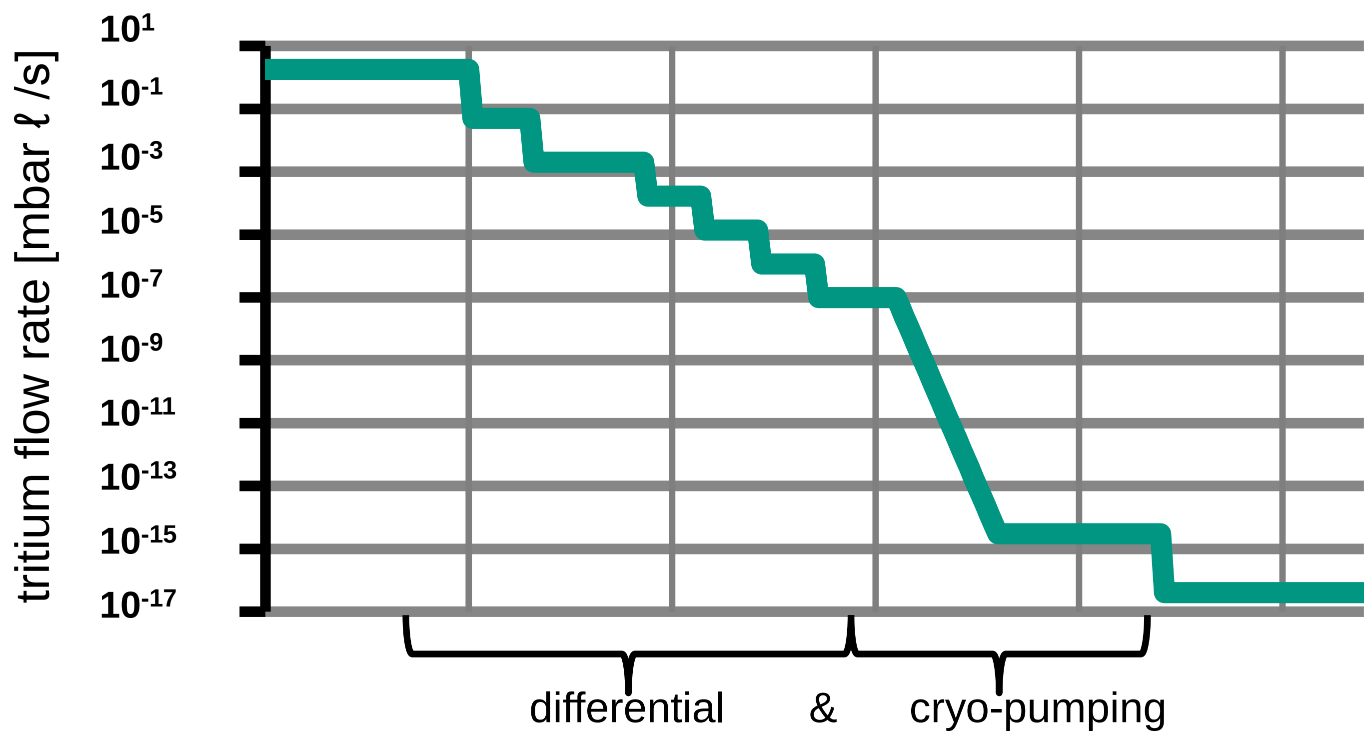
- calibrated Laser-Raman system for all 6 hydrogen isotopologues
- achieved: < 10^{-3} accuracy in 60 s



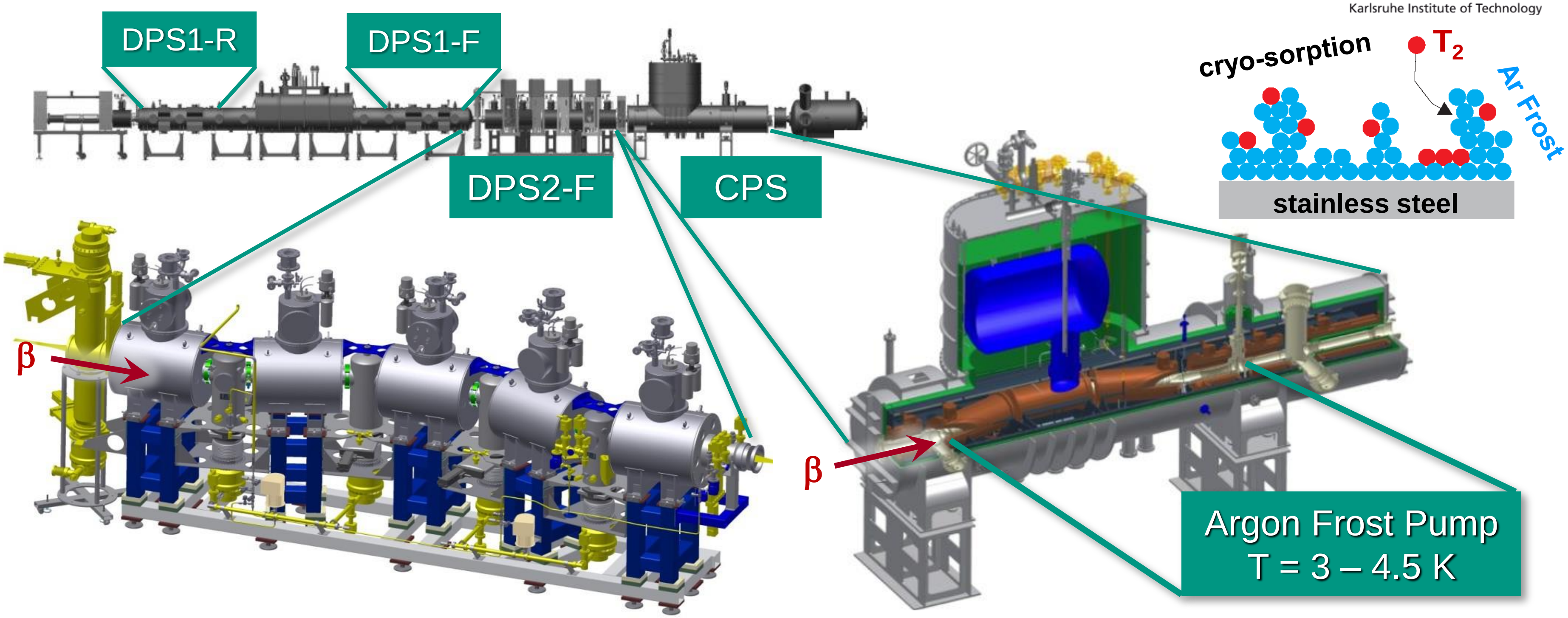
Tritium Retention Techniques

Suppress tritium flow from source to spectrometer by factor > 10^{14}





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

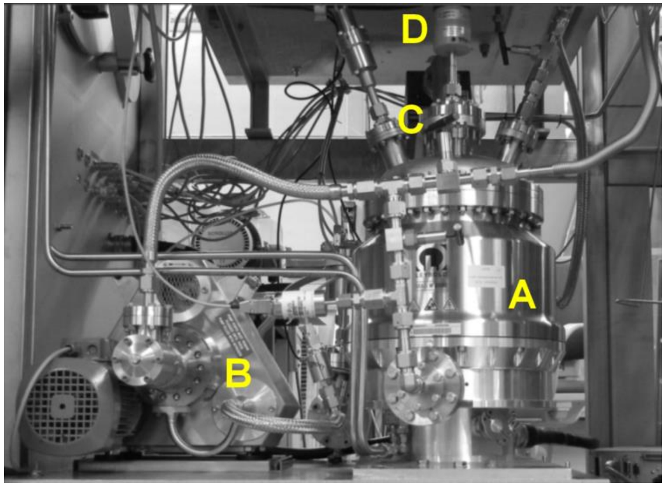
O. Kazachenko et al., NIM A 587 (2008) 136

F. Eichelhardt et al, Fusion Science and Technology 54 (2008) 615

Hazaradous operating conditions for TMPs?

Endurance test for TMP with tritium

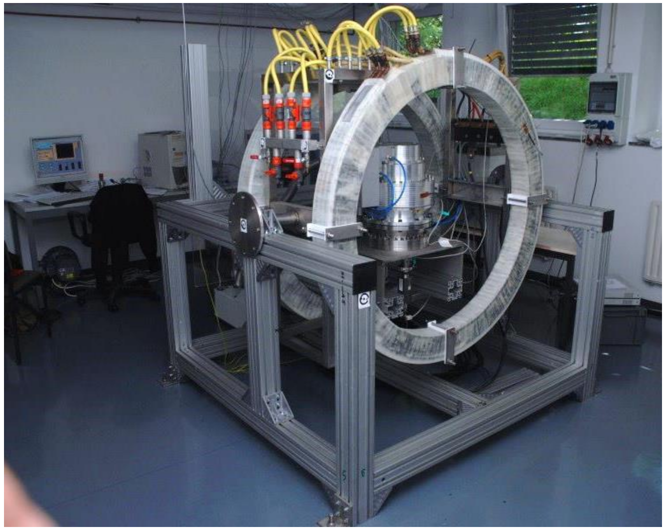
- tritium can affect non-metal parts of pump
- TMP type: Leybold MAG-W 2800
- tested at Tritium Laboratory Karlsruhe (TLK)
- one year operation with tritium



F. Priester, PhD thesis at KIT (2013), http://www.katrin.kit.edu/375.php

TMP in a magnetic field

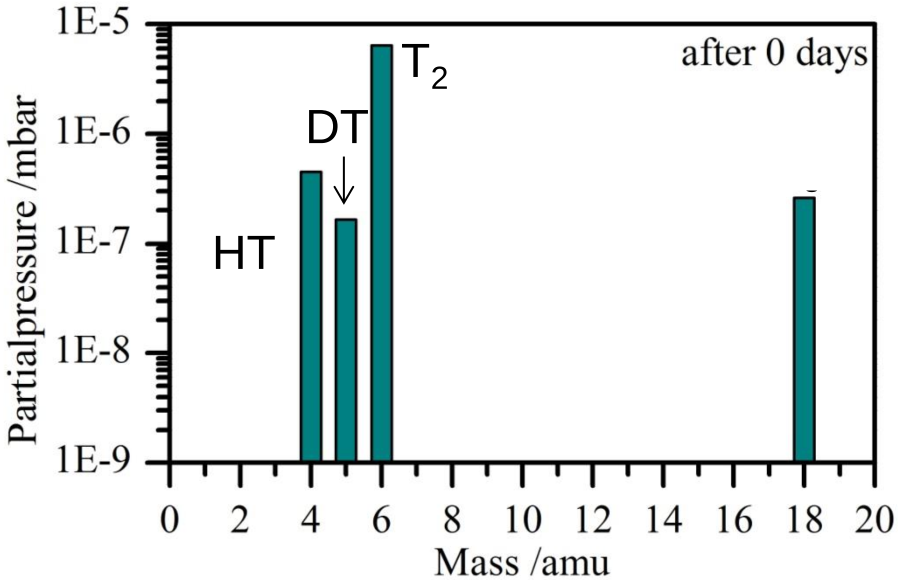
- eddy currents can over-heat rotor
- high mag. field can slow down rotor
- failure of magnetic bearing
- test setup built at KIT for large TMPs
- math. model developed for prediction

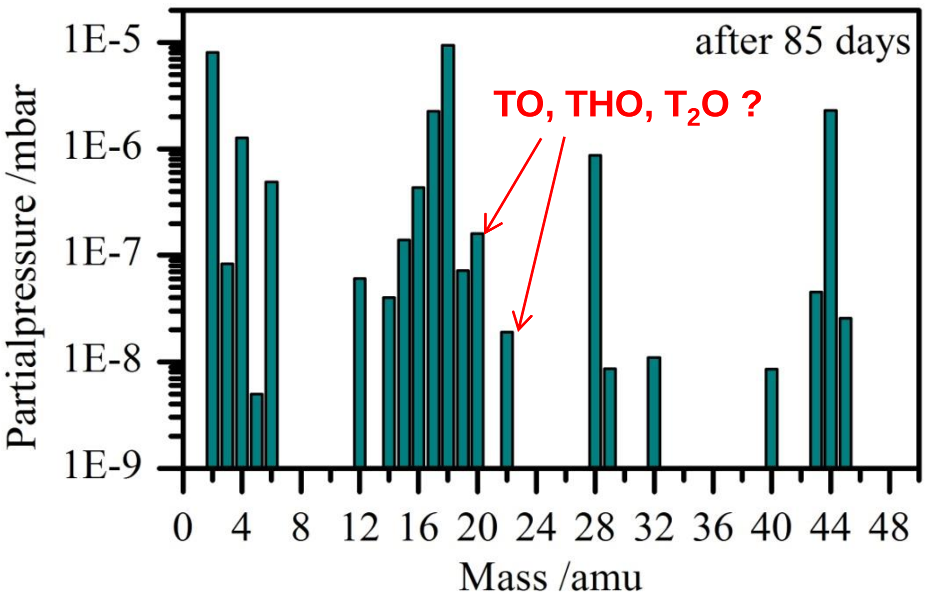


R. Größle et al., Vacuum 86 (2012) 985-989

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





Complete dismantling of a MAG W 2800

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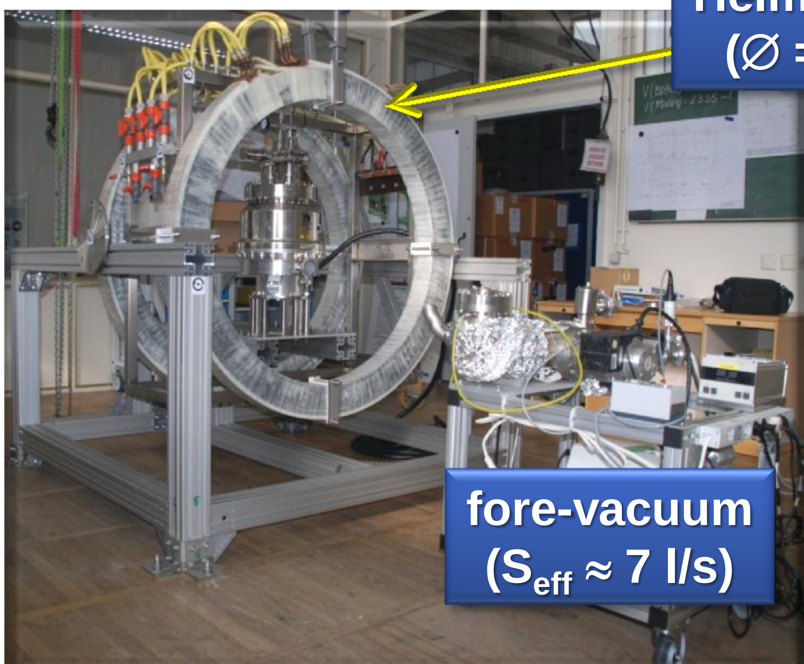
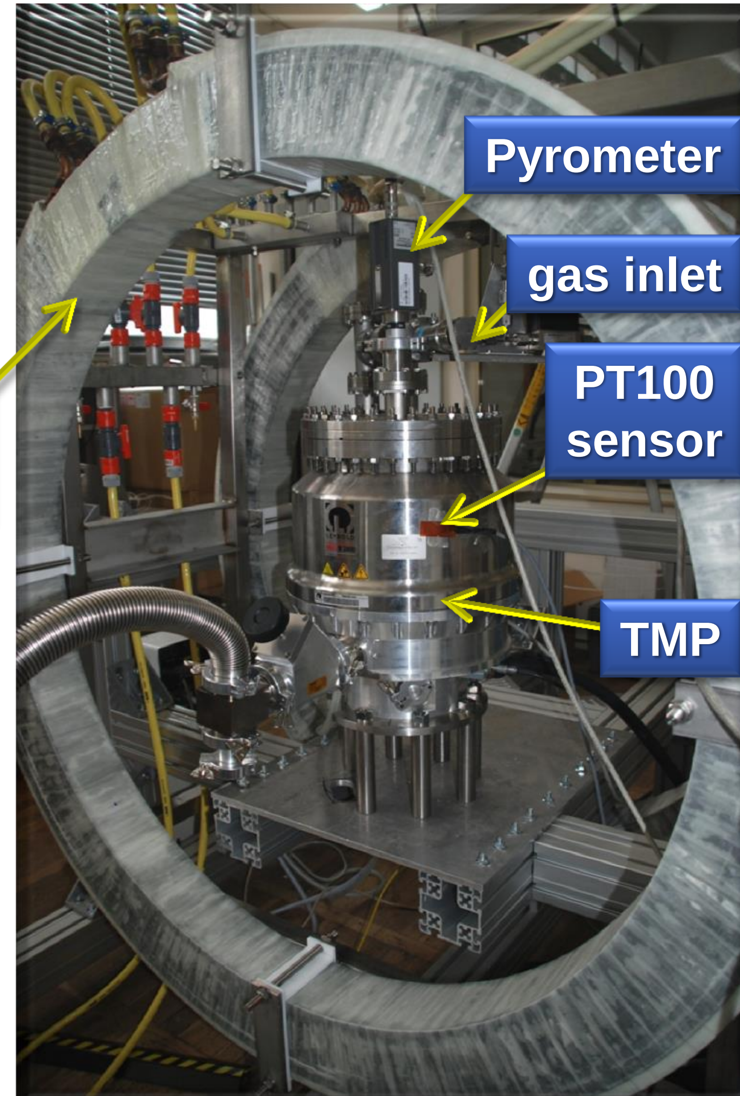
no indications of damages or imminent failure

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

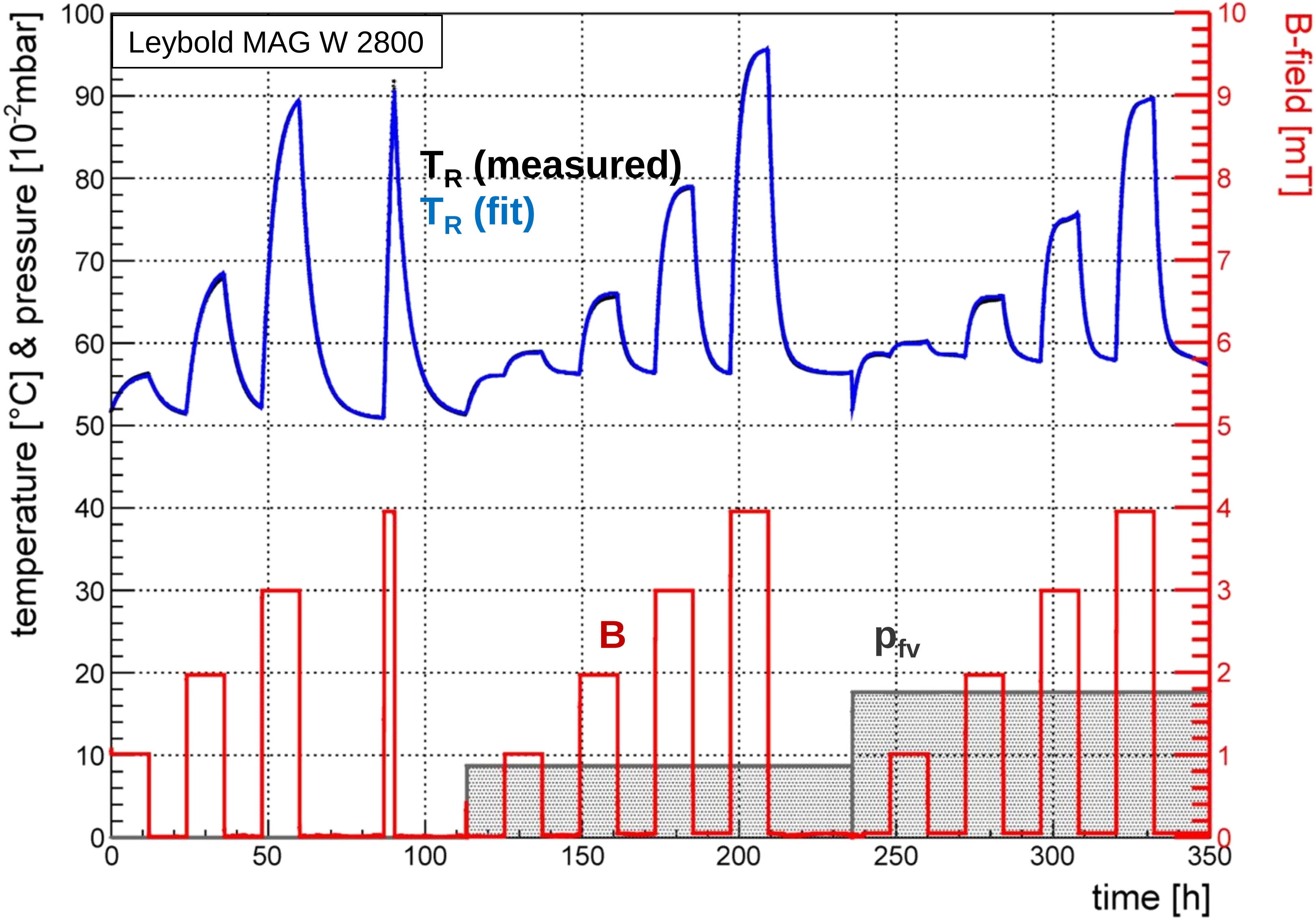
TMP in a magnetic field

- Helmholtz coils: radius = 60 cm
- B-field: 0 – 50 mT
- coils can be turned by 90°
- pyrometer used for rotor temperature
- gas flow possible

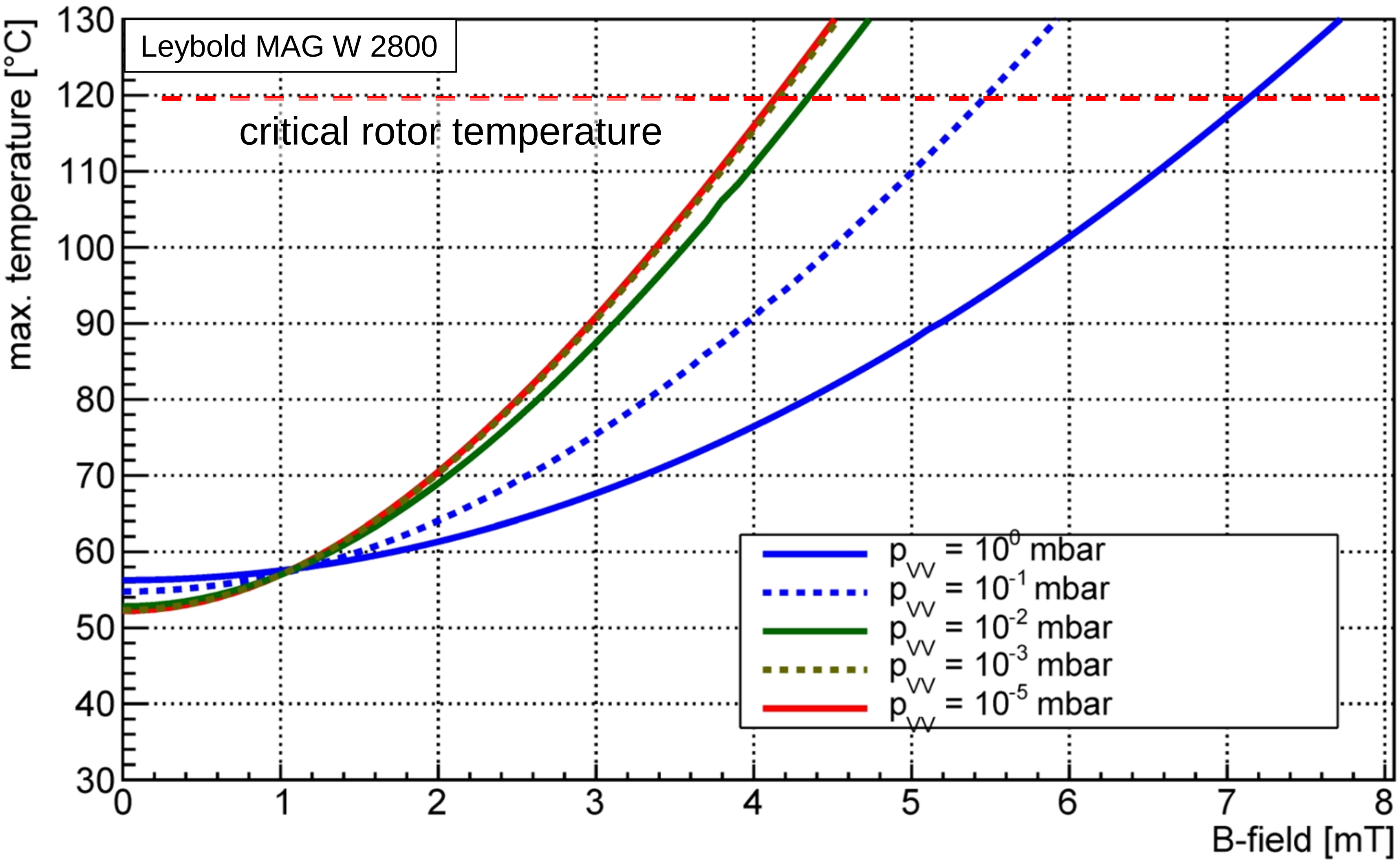




Model 1: fit of parameters $k_1 \dots k_6$

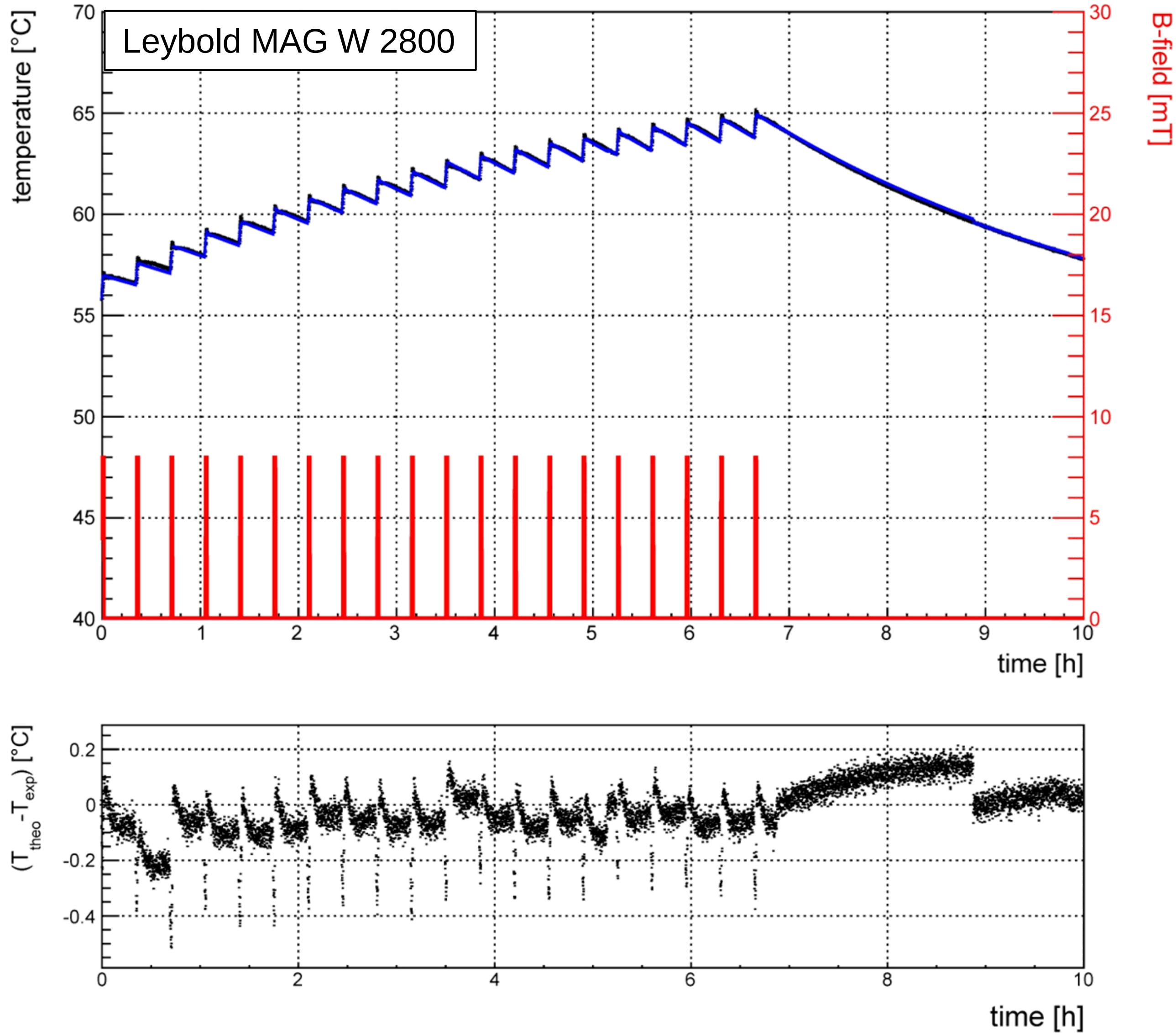


Model 1: maximum temperature



Rotor temperature also depends on cooling temperature !

Model 1 test:
Rotor temperature in a pulsed mag. field



Influence of magnetic field on TMP

parallel field:

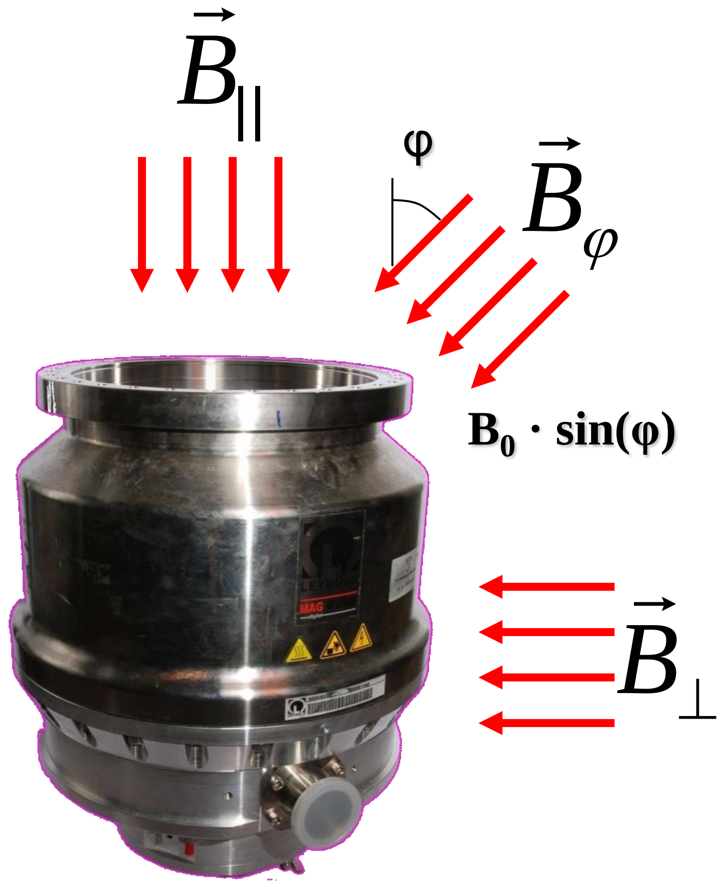
- failure of magn. bearing (PZ12)
  - for B ↑ at 12.6 mT
  - for B ↓ at 21.5 mT
- no heating of the rotor

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:

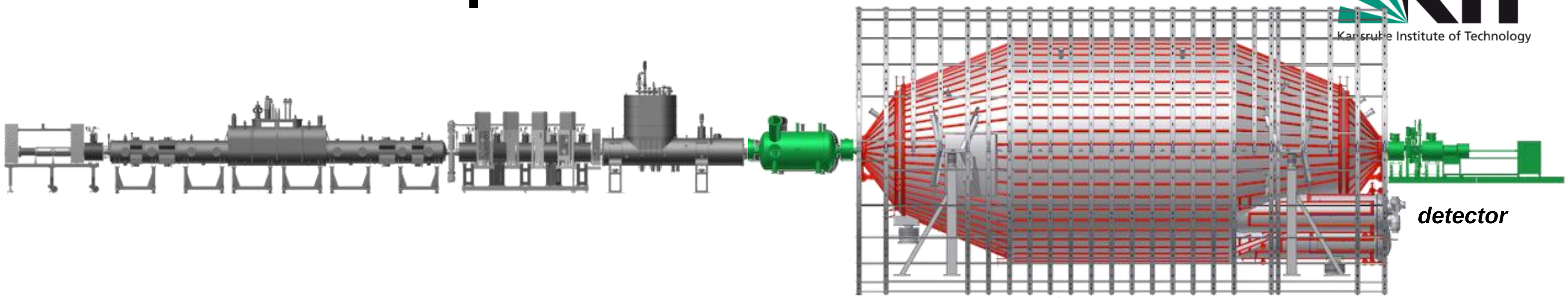
- fan fails at 6.5 mT
- pump shut down at 11 mT



➯ TMPs need magnetic shielding at WGTS and DPS

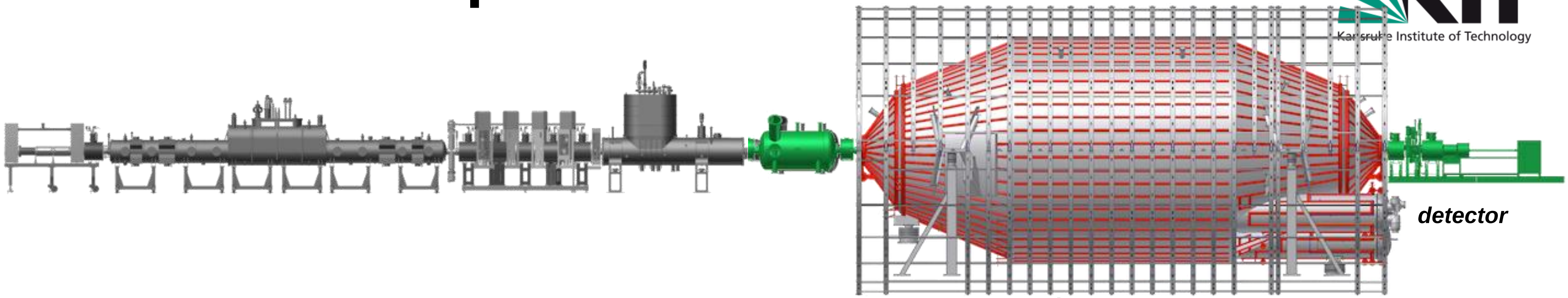
(magnetic field values valid for MAG W 2200 and 2800)

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: **ΔE = 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)

KATRIN Main Spectrometer Vacuum



Requirements:

- **Low pressure (< 10^{-11} mbar)**
  - tritium partial pressure <10^{-21} mbar
  - few radon decays per day
  - outgassing rate <10^{-12} mbar·ℓ/s·cm^2
  - 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

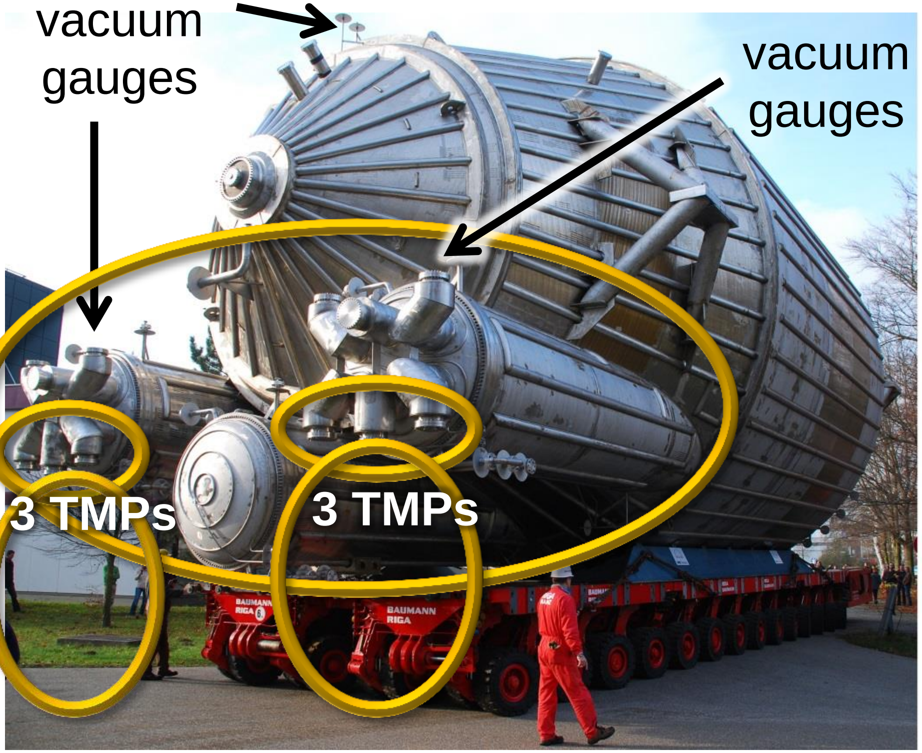
KATRIN Main Spectrometer (Deggendorf)

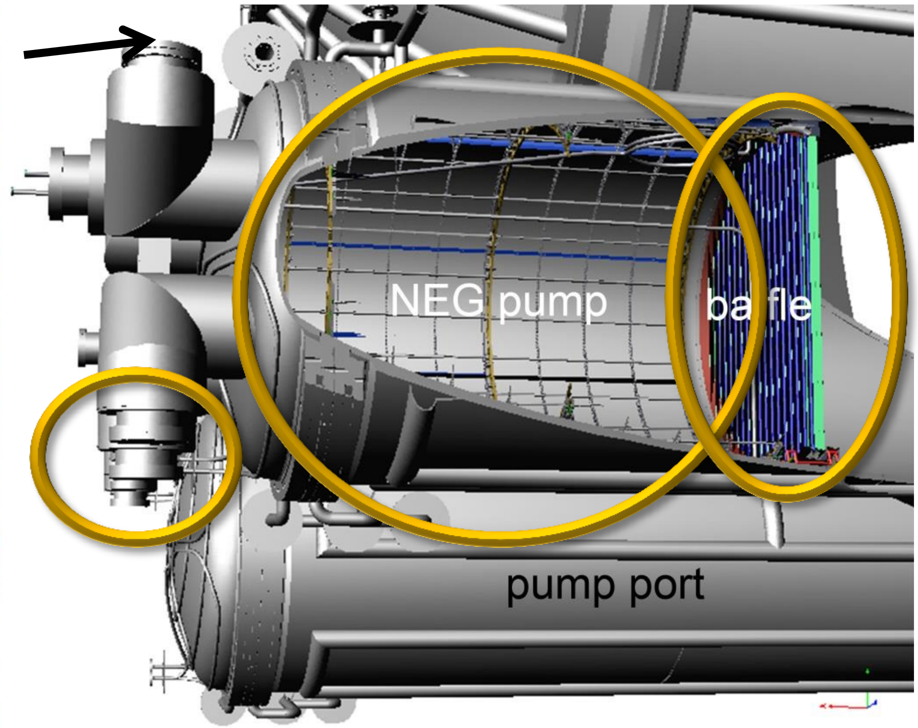
KATRIN Main Spectrometer Journey to KIT

26.11.2006

KATRIN Main Spectrometer Vacuum

KIT
Karlsruhe Institute of Technology





- **Roughing pump: 640 m³/h screw-pump**
- **6 turbo-molecular pumps (Leybold MAG-W 2800): 10 000 ℓ/s (H_2)**
- **Fore-vacuum: 300 ℓ/s TMP and scroll pump (30 m³/h)**
- **3 NEG-pumps (3000 m SAES St707 getter strips): ~~~10^6 ℓ/s (H_2)~~ 400 000 ℓ/s**
- **3 cryogenic LN_2 baffles (radon): ~170 000 ℓ/s (Rn)**

KATRIN Main Spectrometer Vacuum

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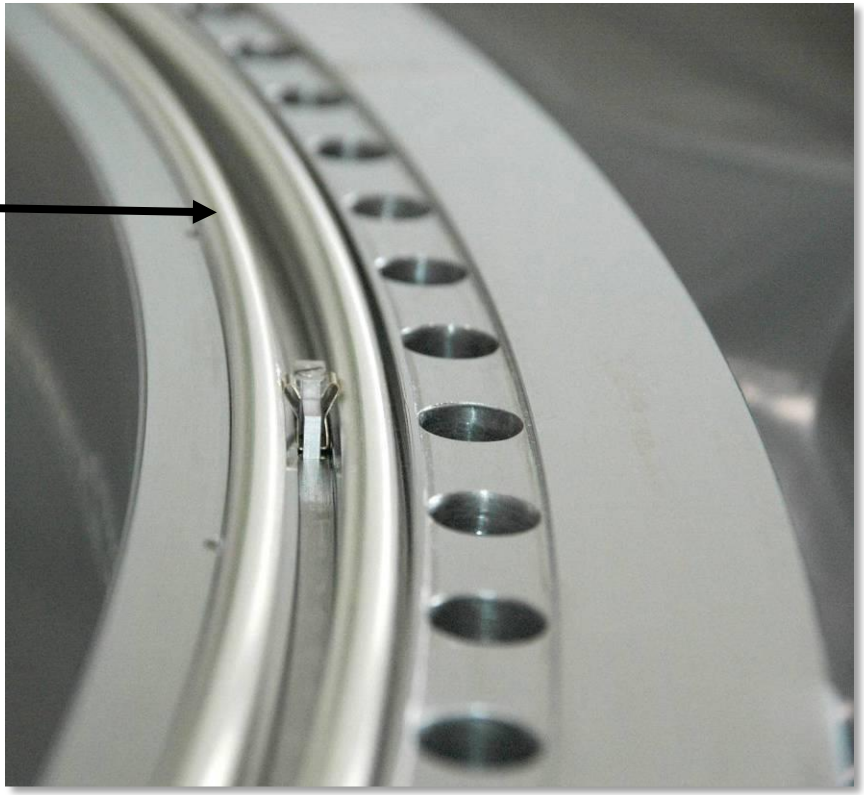
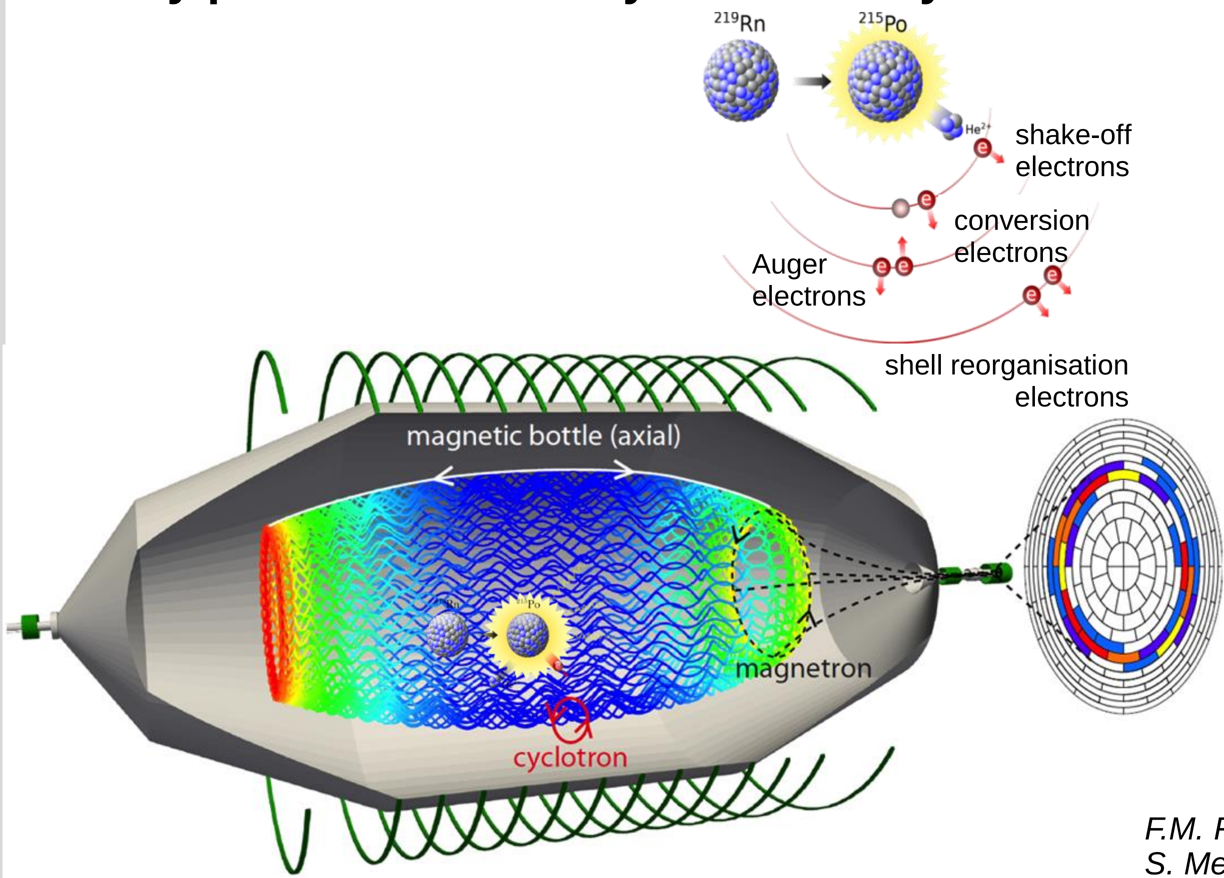
Flanges and Gaskets:

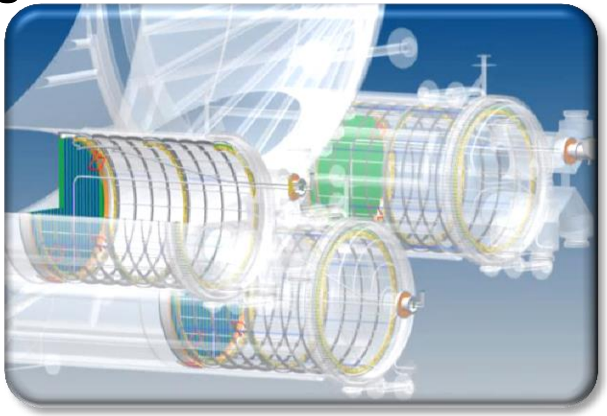
- **UHV:**
  - CF flanges up to 250 mm
  - HTMS double gaskets:
    - 500 mm flanges at ground-electrodes
    - 1700 mm flanges at pump ports
  - all gaskets bakable at 350°C
- **intermediate vacuum:**
  - CF flanges
- **fore-vacuum:**
  - KF flanges (Viton O-rings)
  - ISO K for pump-down and venting

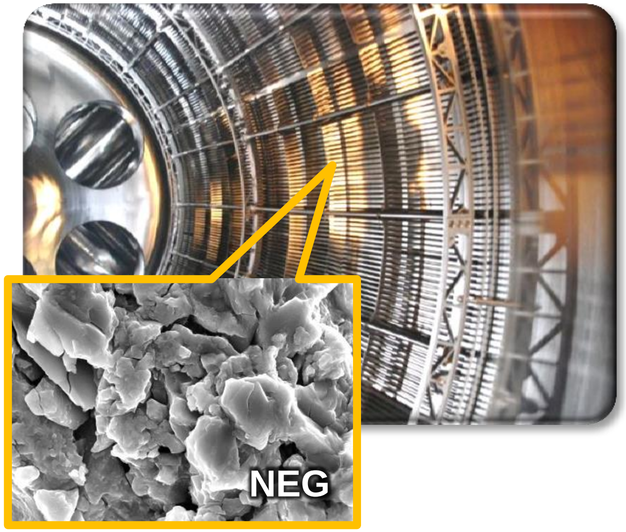


Radon as background source (problem)

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



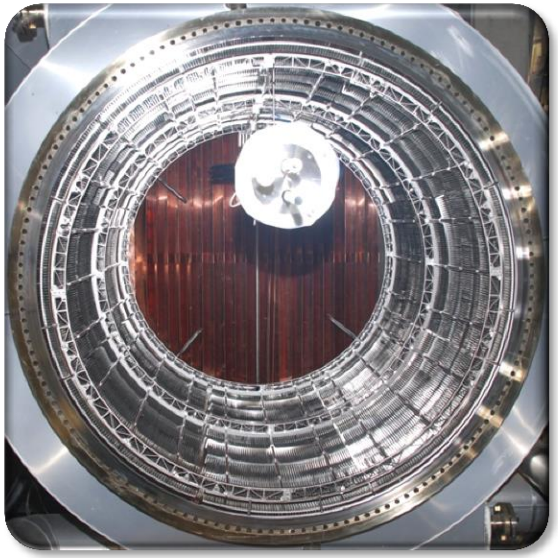




F.M. Fränkle et al., Astropart. Phys. 35 (2011) 128
S. Mertens et al., Astropart. Phys. 41 (2013) 52

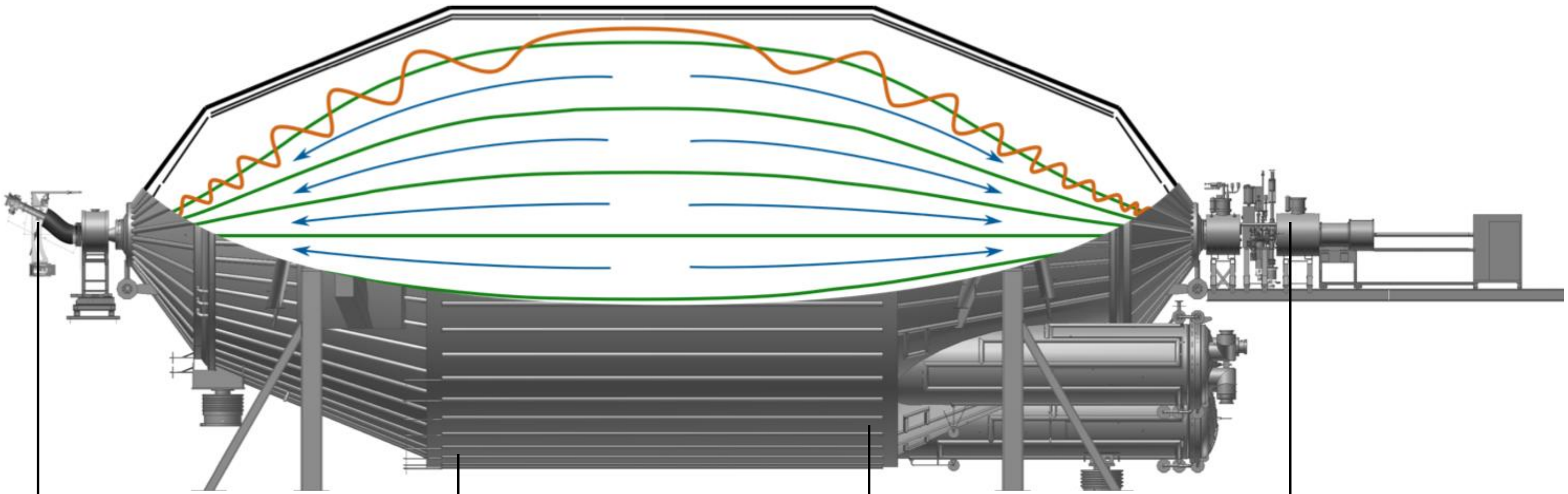
Radon as background source (solution)

- 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 : ~ 0.4%
- pumping speed for Rn from walls: 170 000 ℓ/s

KATRIN Main Spectrometer and Detector Commissioning 2013



angular selective electron gun
transmission function properties

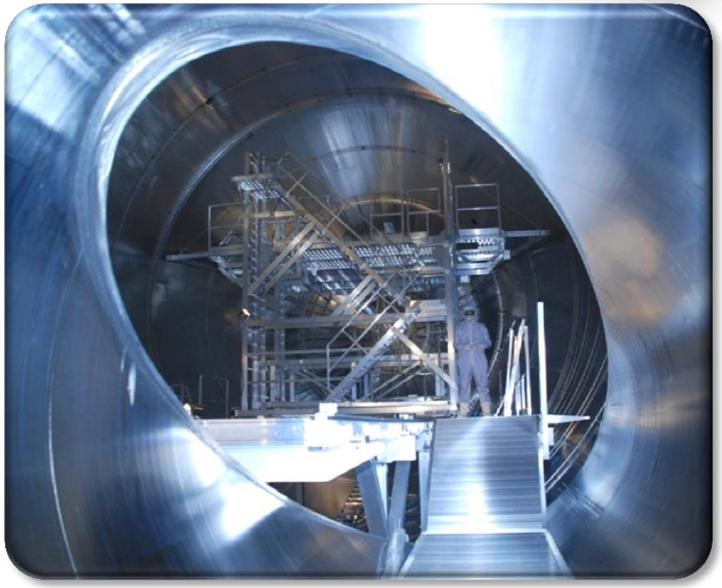
MAC-E filter, energy analysis
vessel on HV, wire electrode

UHV conditions 10^{-11} mbar
6 weeks baking, T_{max} = 300 °C

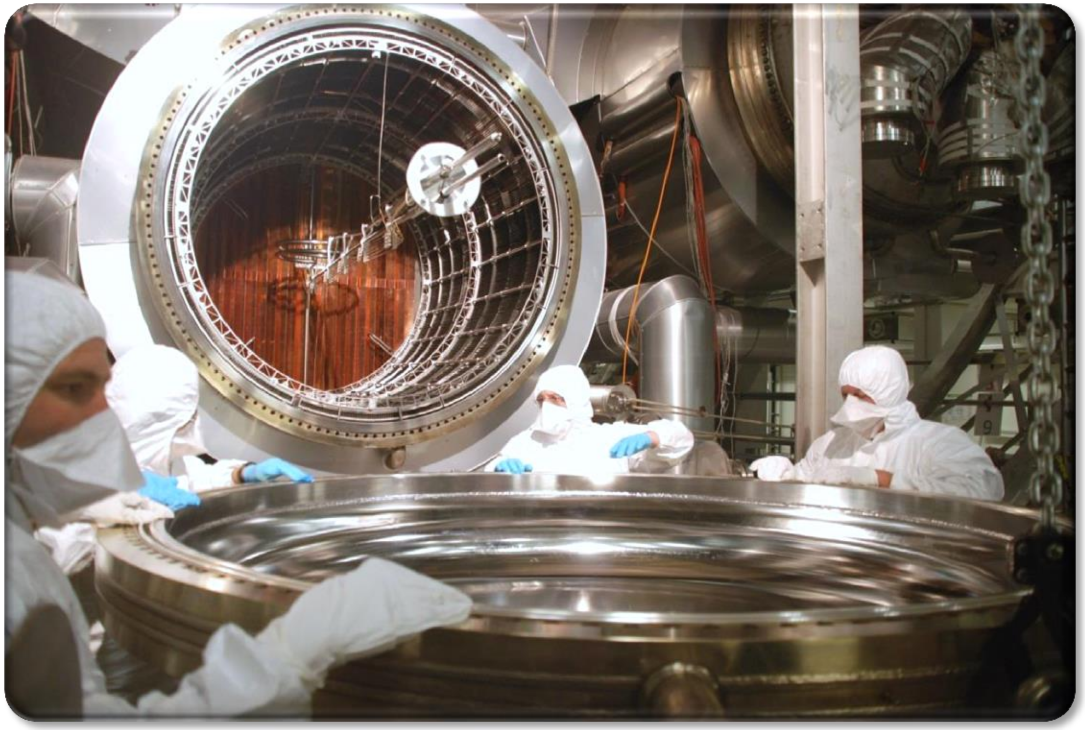
Si-PIN detector
low background, 148 pixel

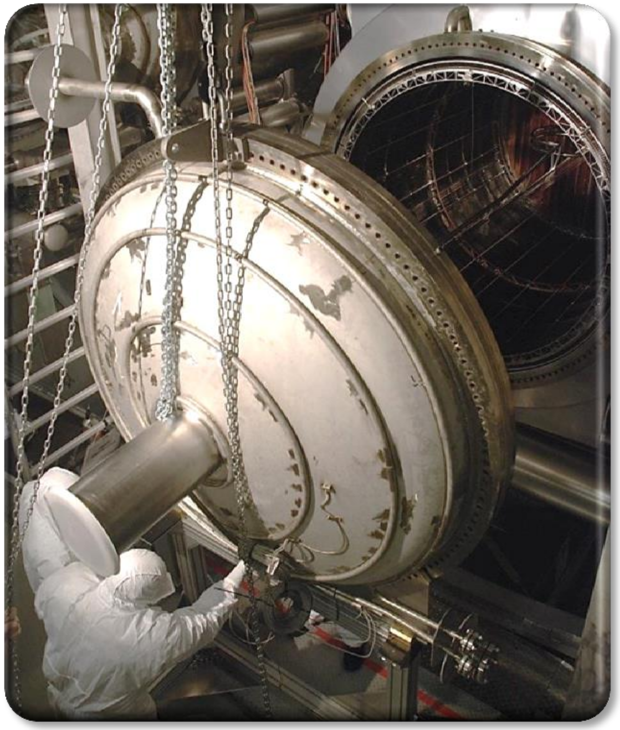
2008 – 2012: Wire Electrode Installation

- **248 wire electrodes on the inner surface**
  - 23 440 insulated wires
  - 120 000 individual parts
- **Installed under cleanroom conditions**

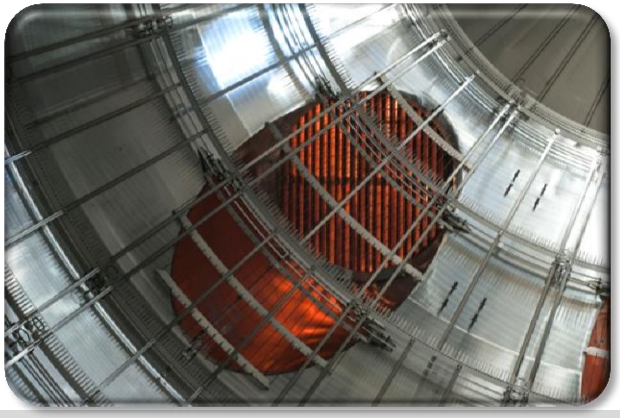


2012: All Components Installed

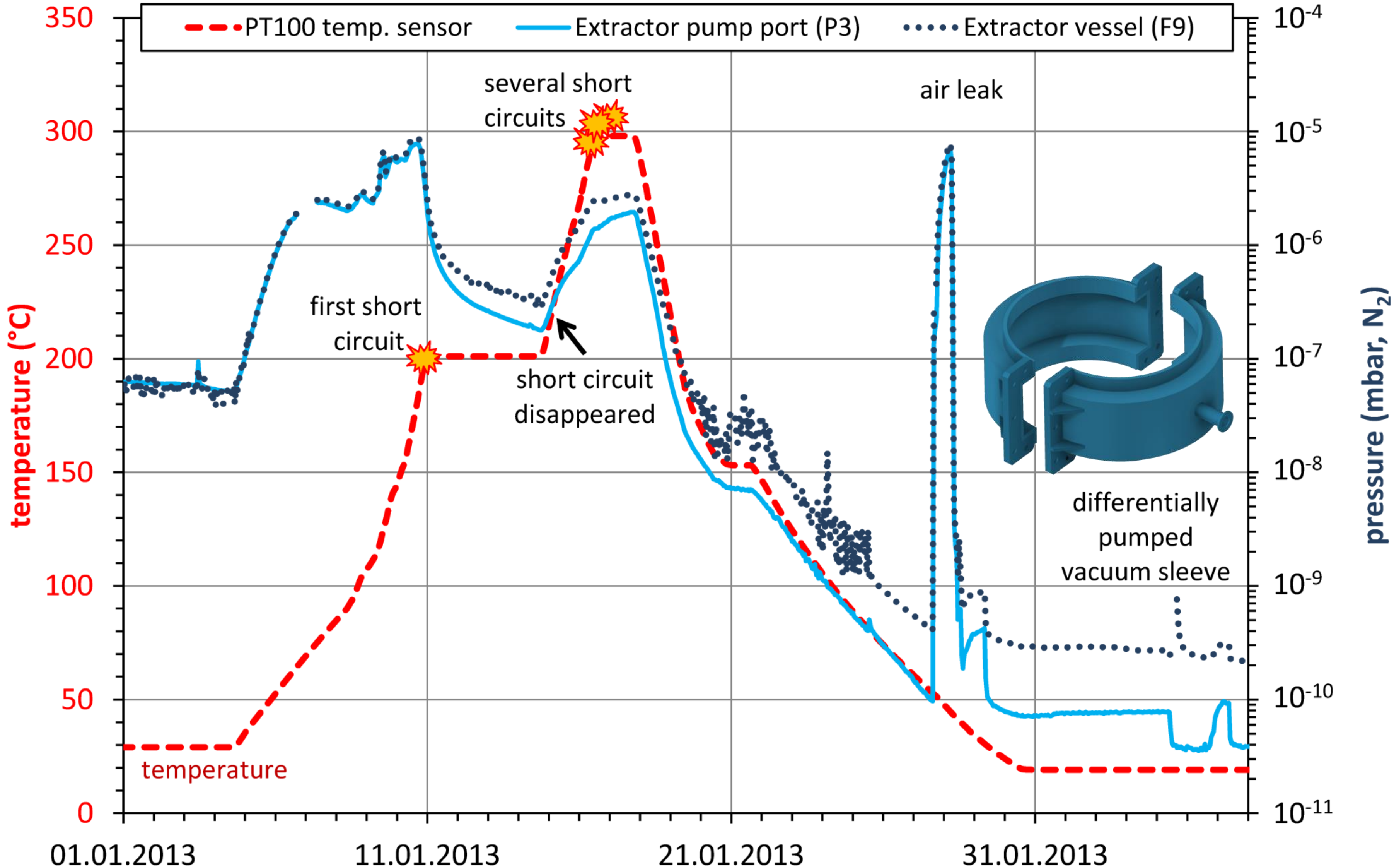




- Electrode installation completed
- Vacuum system installed
- Successful leak test
- Commissioning of heating and vacuum control system (PCS7)



Spectrometer Commissioning: Bake-out



Baking of the Main Spectrometer

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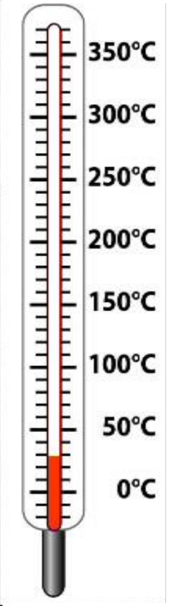
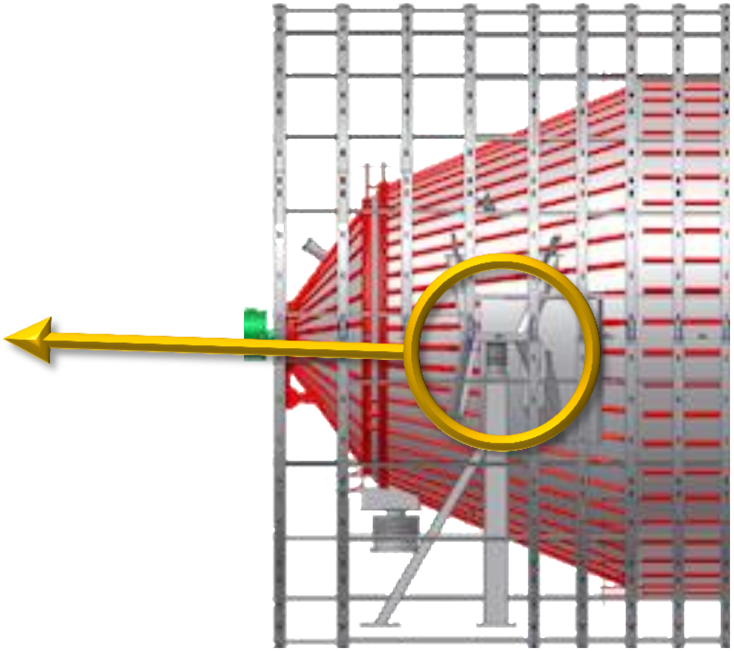
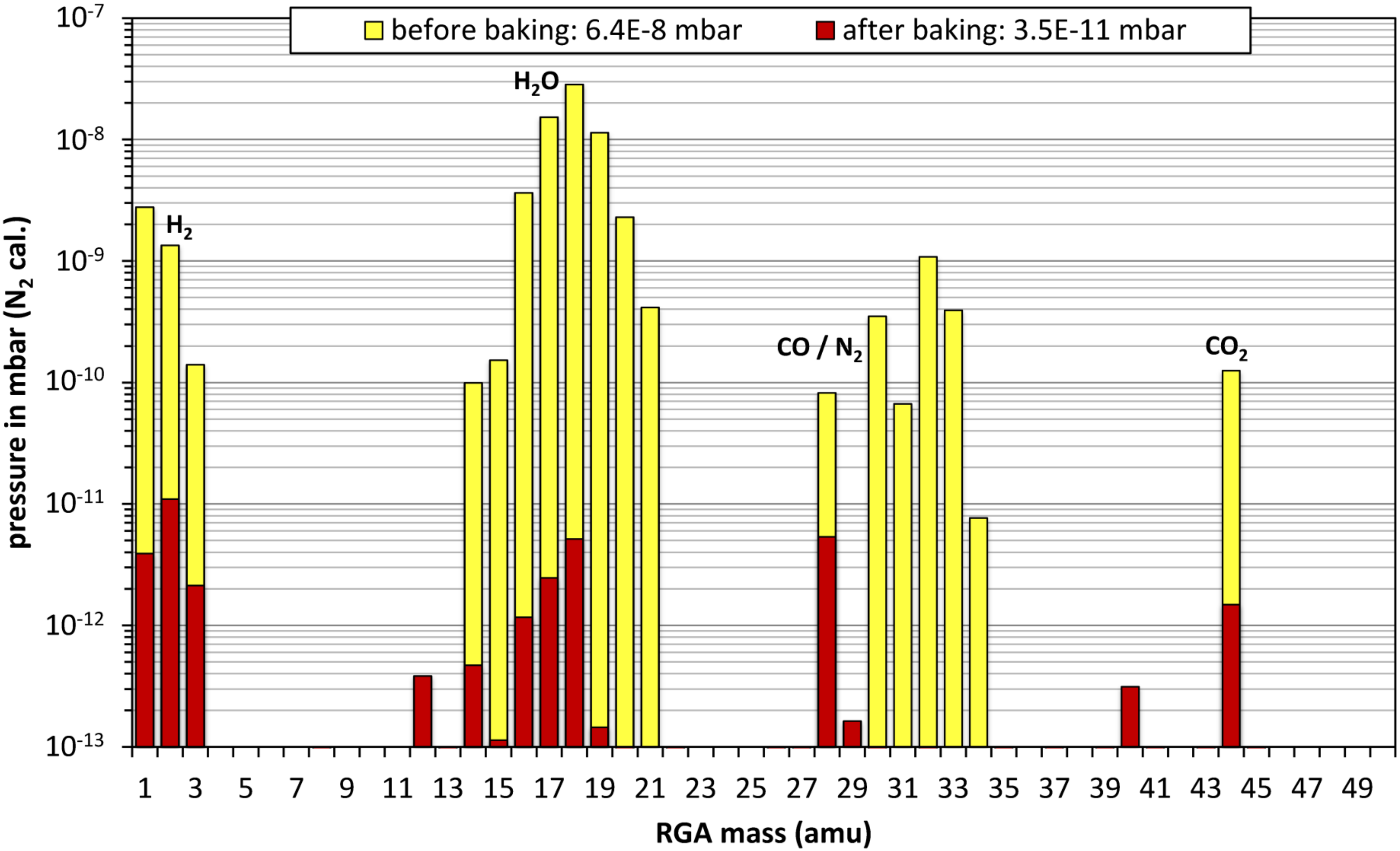
- Duration of baking: 4 weeks
- 24/7 shifts
- Max. temperature: 300°C
- Heating rate: 1°C – 5°C/h
- Thermal expansion during bake-out: ~ 10 cm



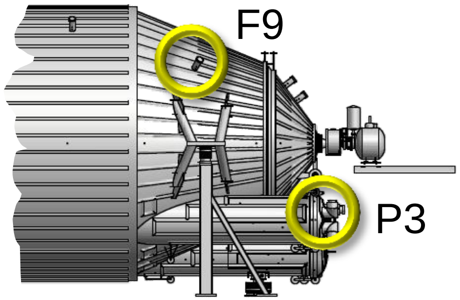


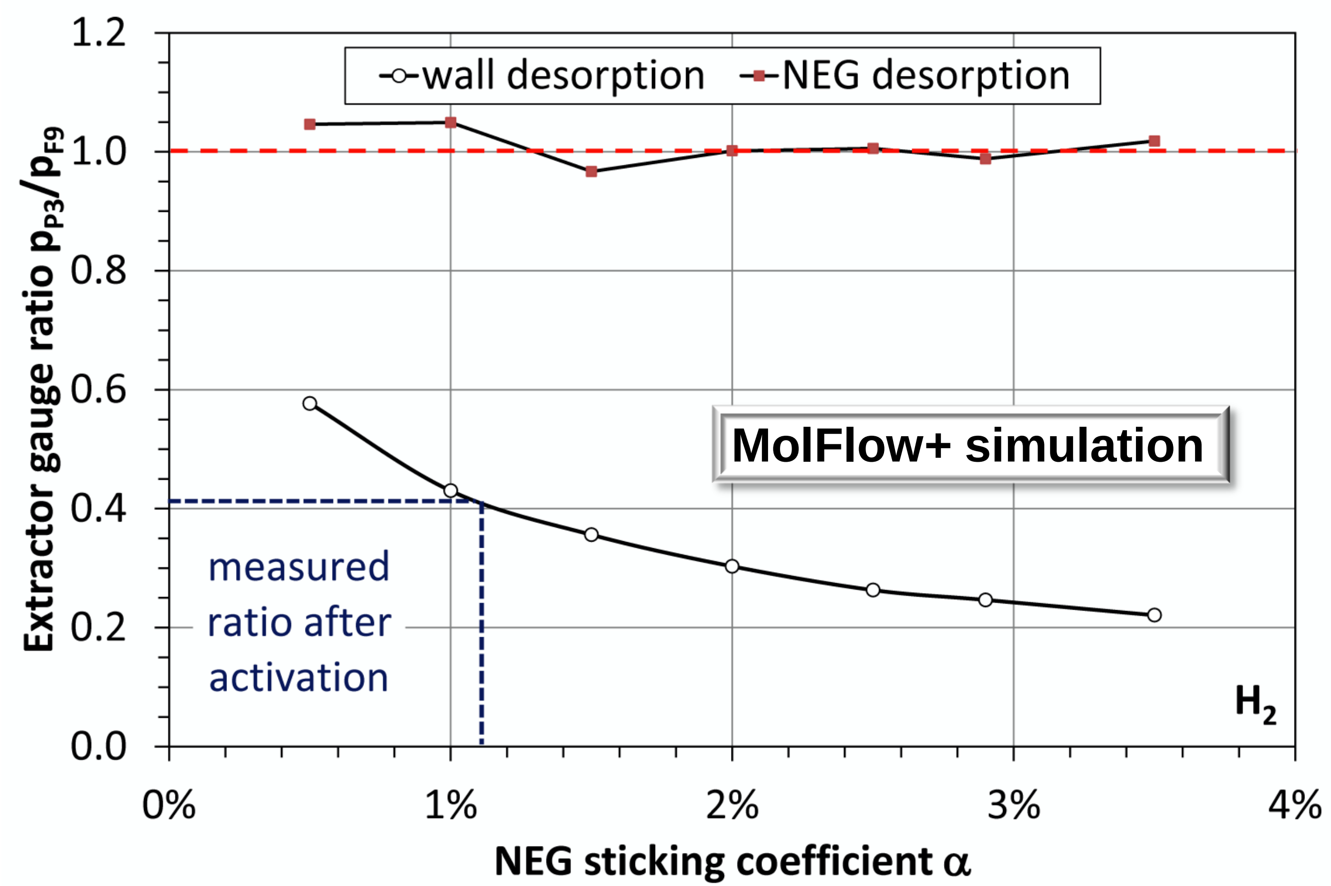
Vacuum status after bake-out



NEG activation

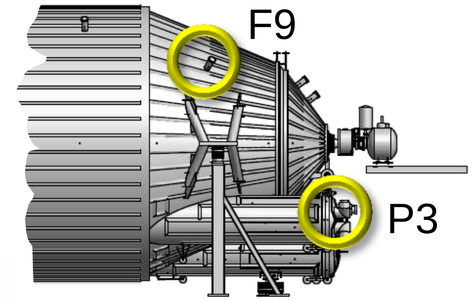
- **Indicator for NEG activation:**
  - pressure ratio between vessel and pump port

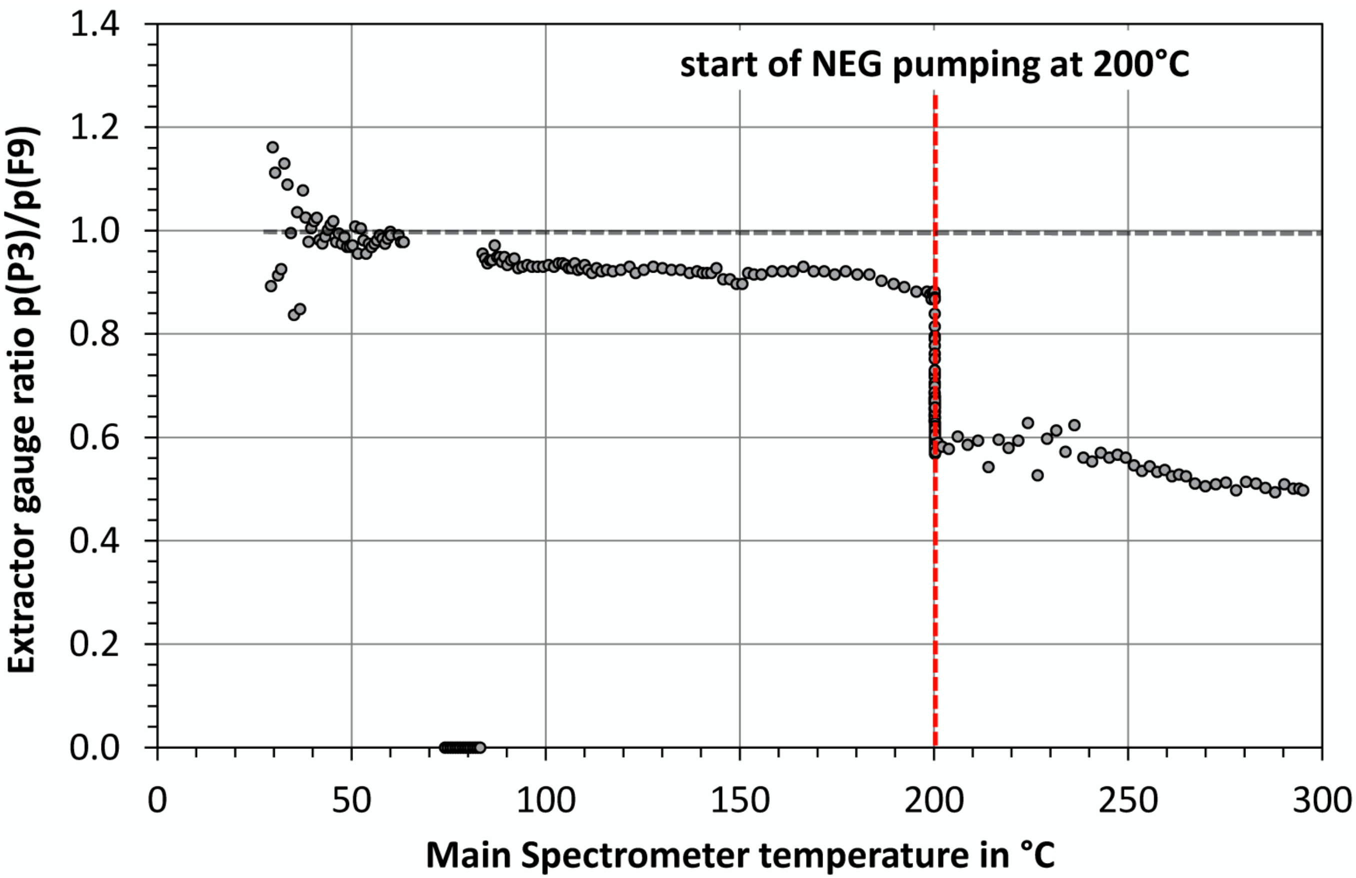




NEG activation

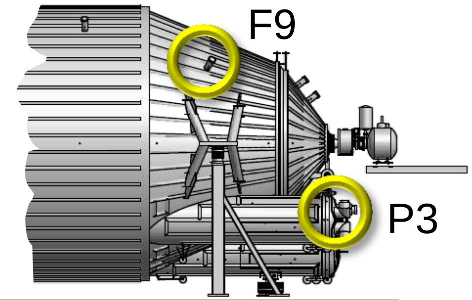
- **Indicator for NEG activation:**
  - pressure ratio between vessel and pump port
  - first indication for NEG pumping at 200°C

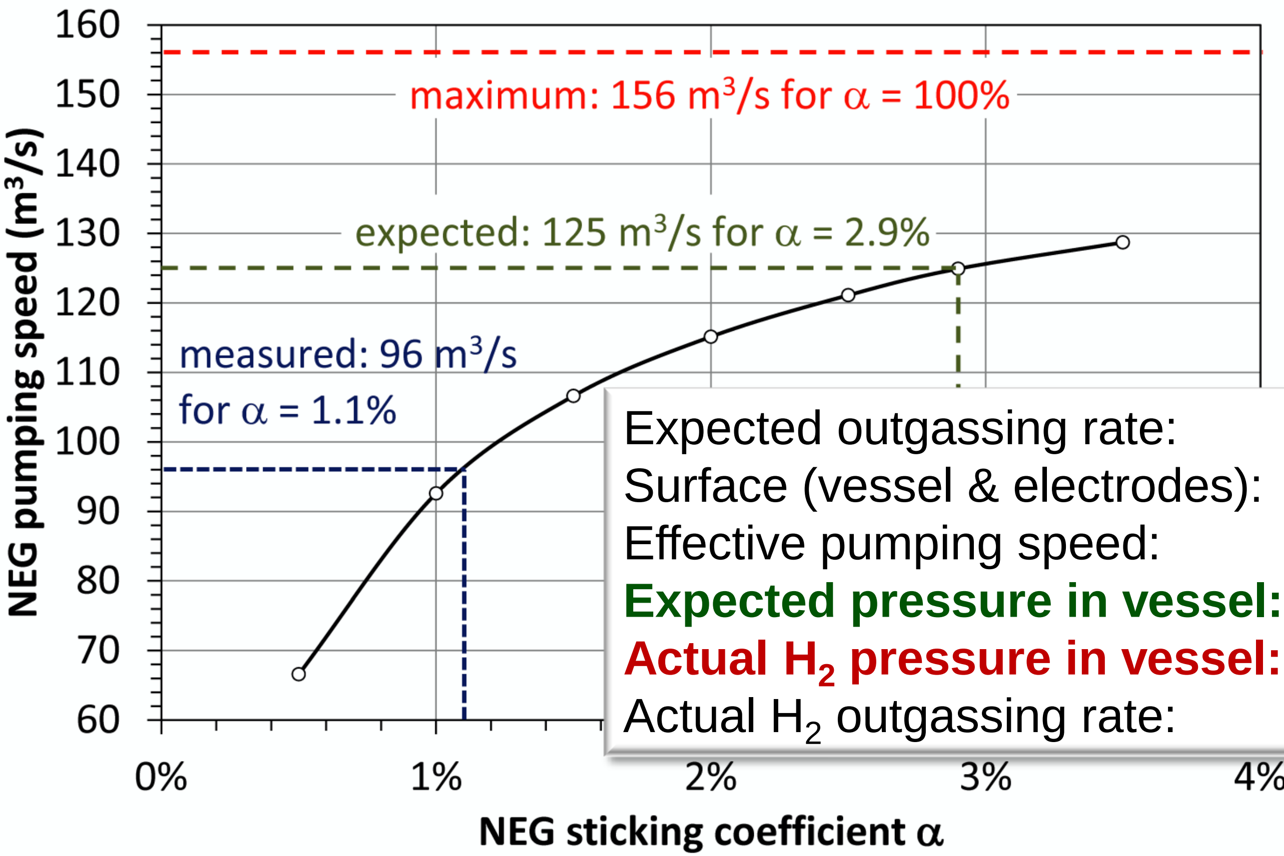


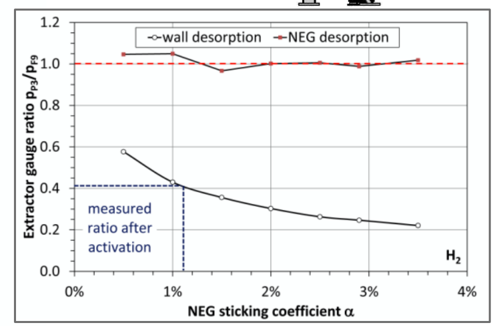


NEG activation

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



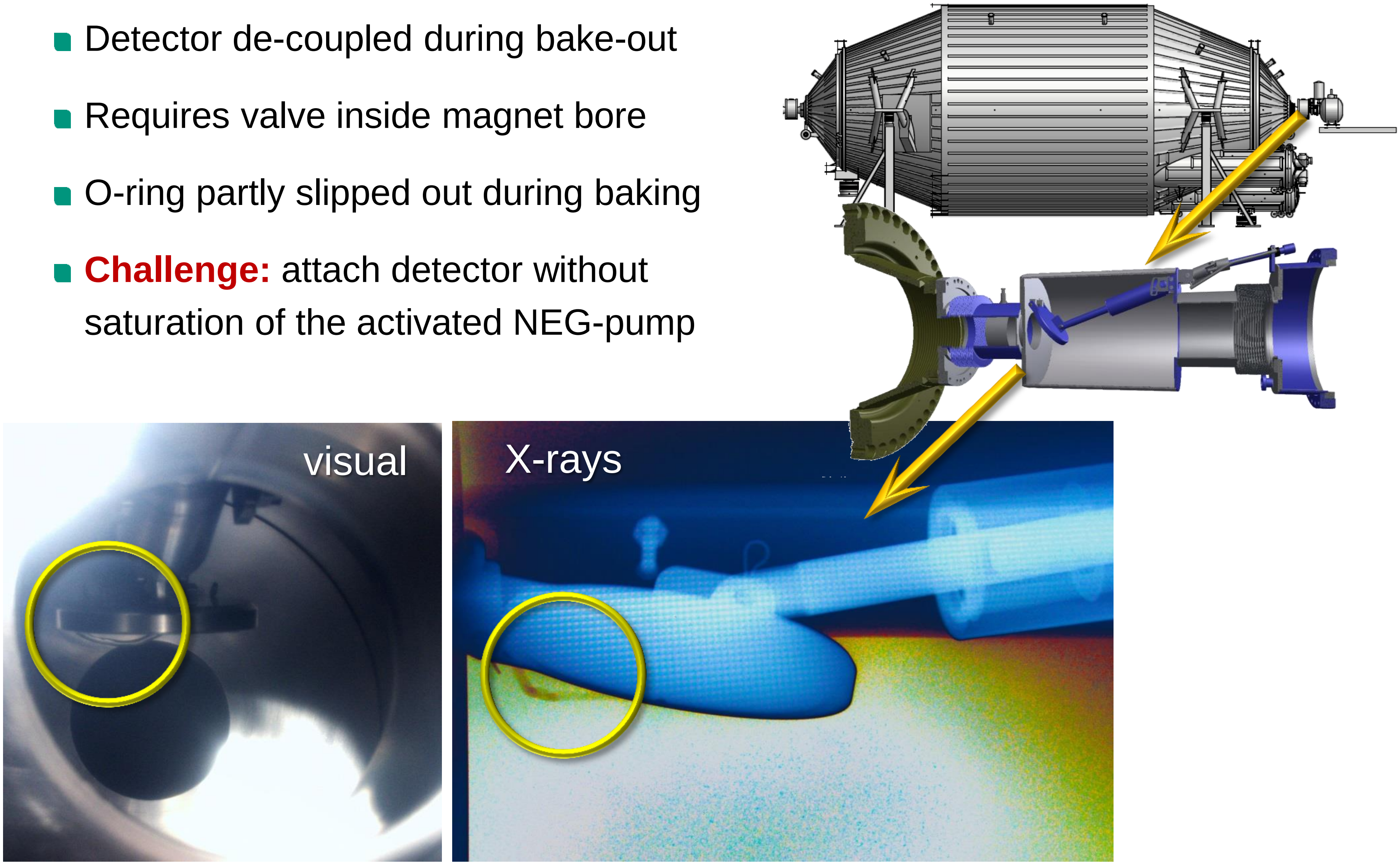




Expected outgassing rate:	10^{-12} mbar·ℓ/s·cm²
Surface (vessel & electrodes):	1240 m²
Effective pumping speed:	375 m³/s
Expected pressure in vessel:	**$3.3\cdot10^{-11}$ mbar**
Actual H_2 pressure in vessel:	**$5.7\cdot10^{-11}$ mbar**
Actual H_2 outgassing rate:	$1.4\cdot10^{-12}$ mbar·ℓ/s·cm²

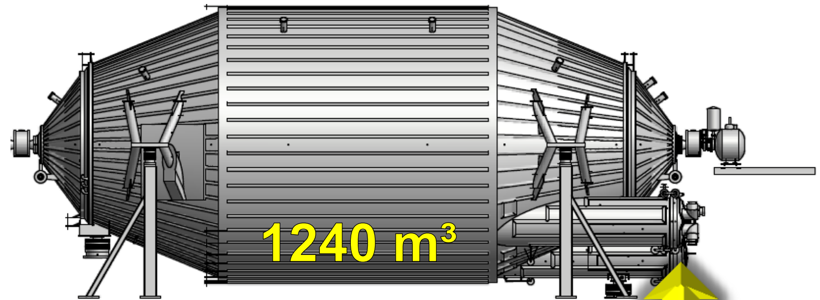
Coupling of Spectrometer and Detector

- 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

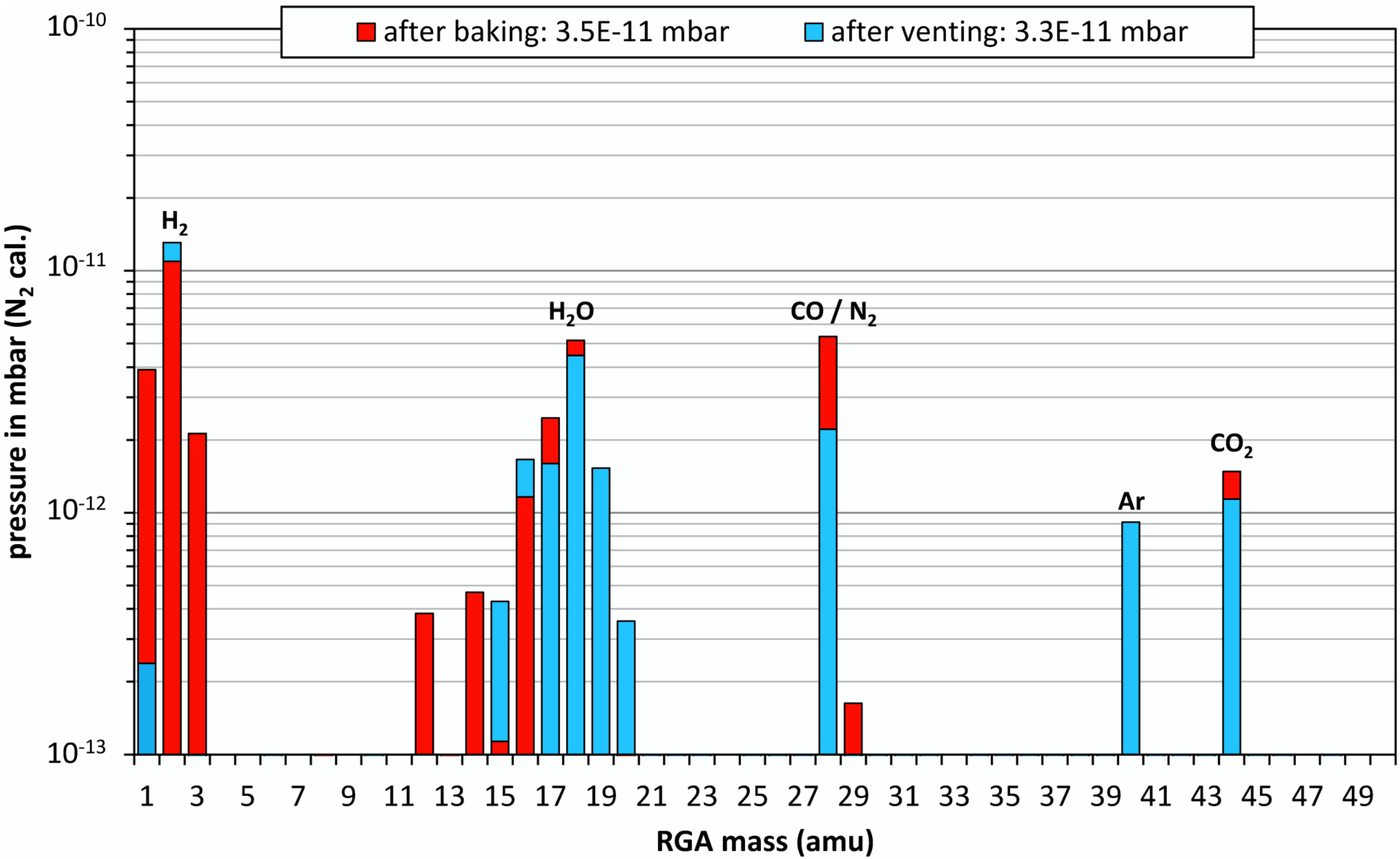


144 bottles Argon N6.0

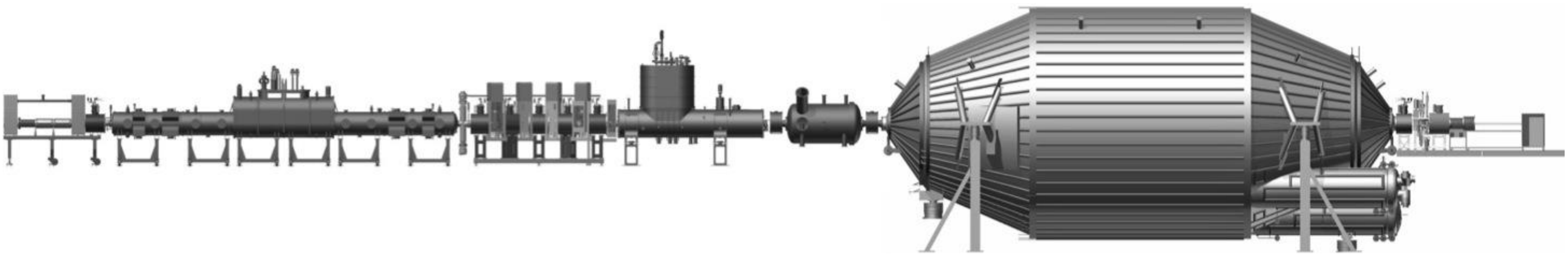
XENON 1t
gas purification system (SAES NEG)

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

Vacuum status after venting with argon

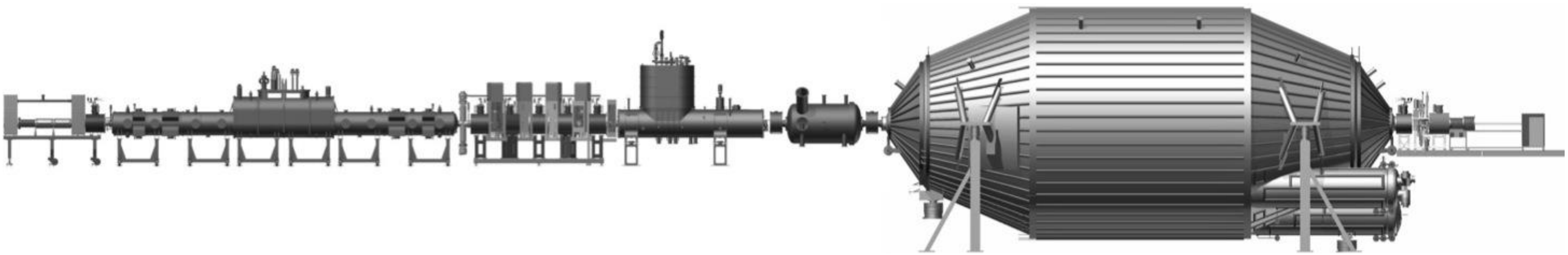


KATRIN Schedule



- 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 ρd Q1-Q2/2016
- first tritium data with entire beam line mid-2016

Conclusions

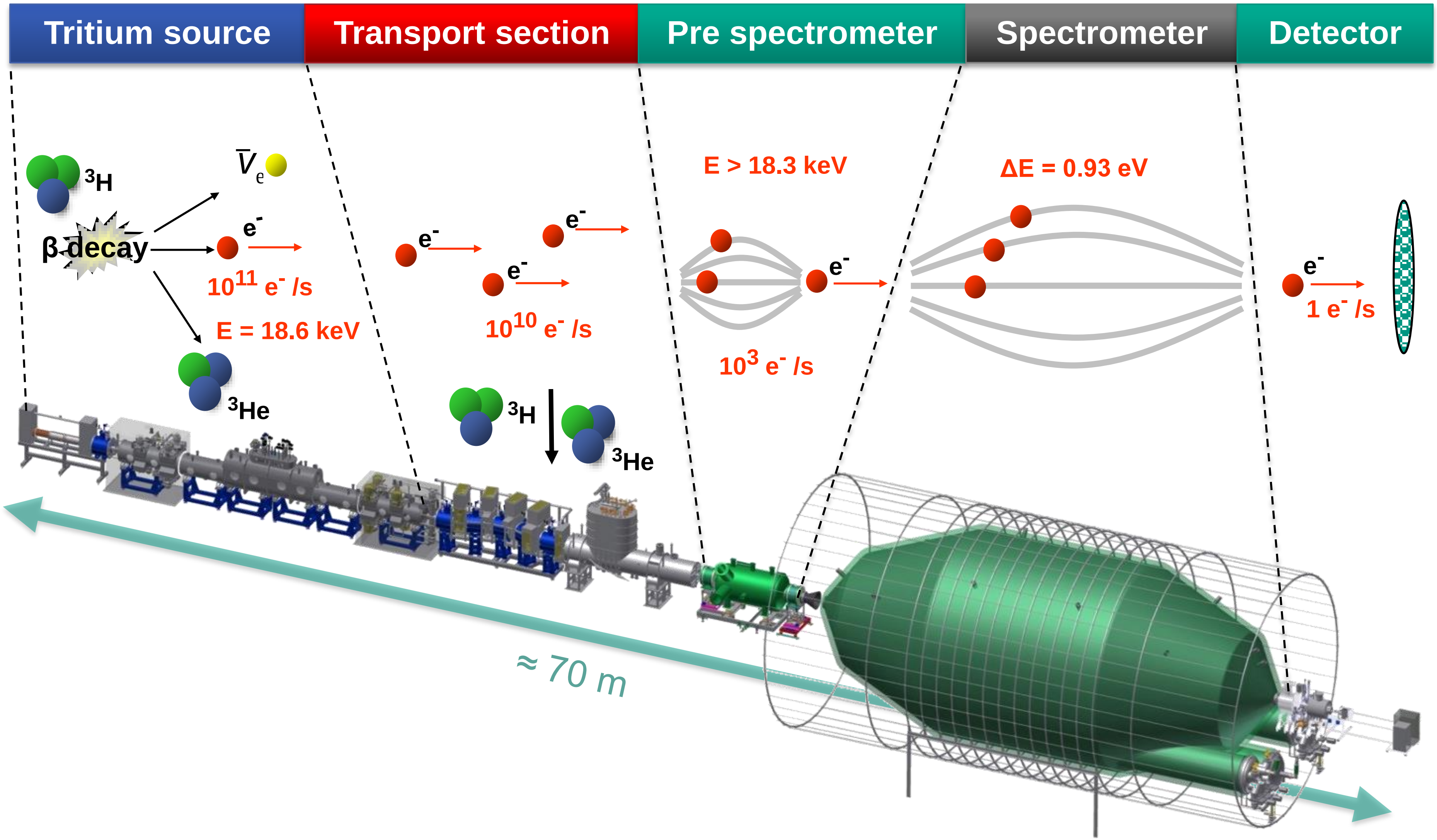


- Source and Transport Section still under construction
- Spectrometer and Detector Section commissioned
- Various smaller experiments investigate specific questions
  - TMPs in magnetic fields
  - Tritium compatibility of TMPs
  - Outgassing rates
  - …


Thank you for your attention
Supported by:
Federal Ministry
of Education
and Research

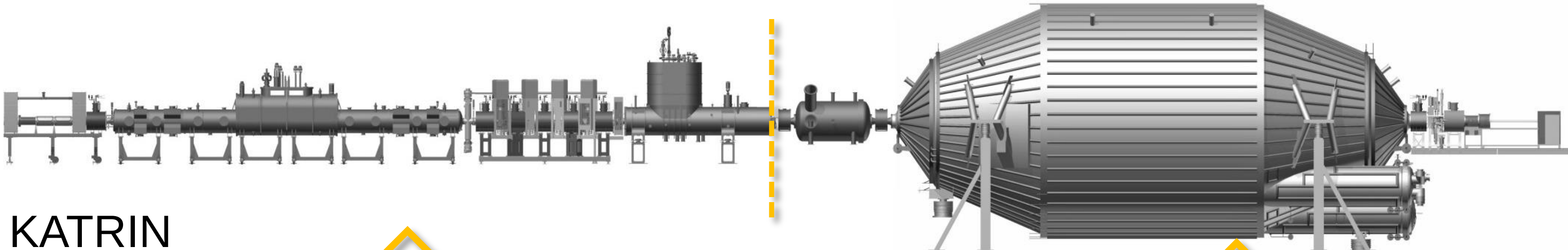
Backup slides

The KATRIN Setup - Overview



KATRIN experiment – overview

Karlsruhe Institute of Technology

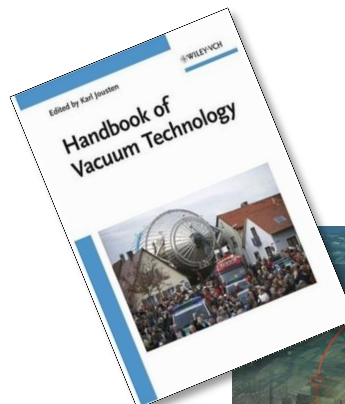


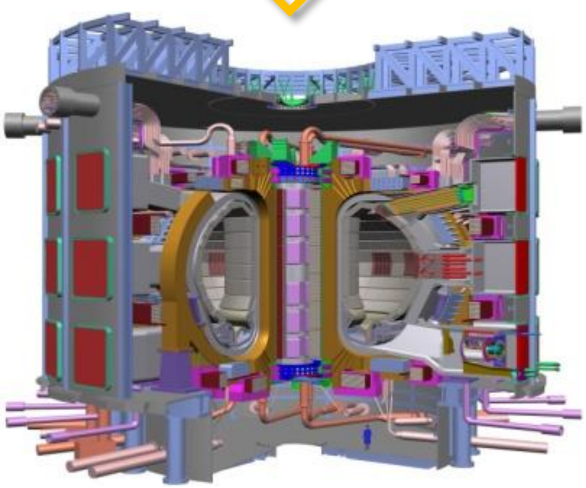
KATRIN
(2015)

$1240\ m^3$

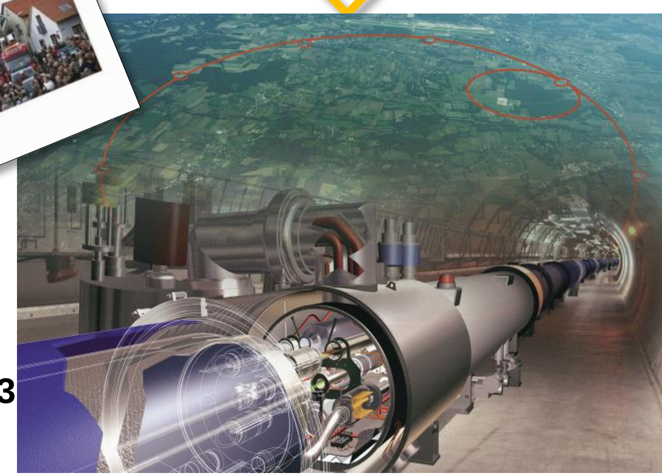
large tritium throughput
~ **10 kg/a**

one of largest UHV-recipient ($<10^{-11}$ mbar)



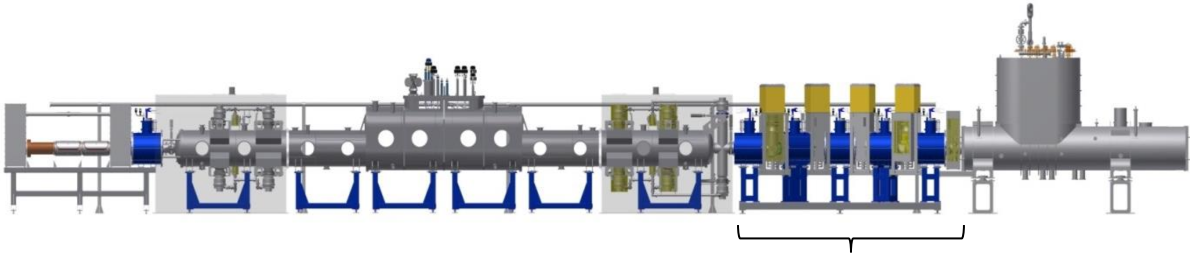


ITER
(2027)

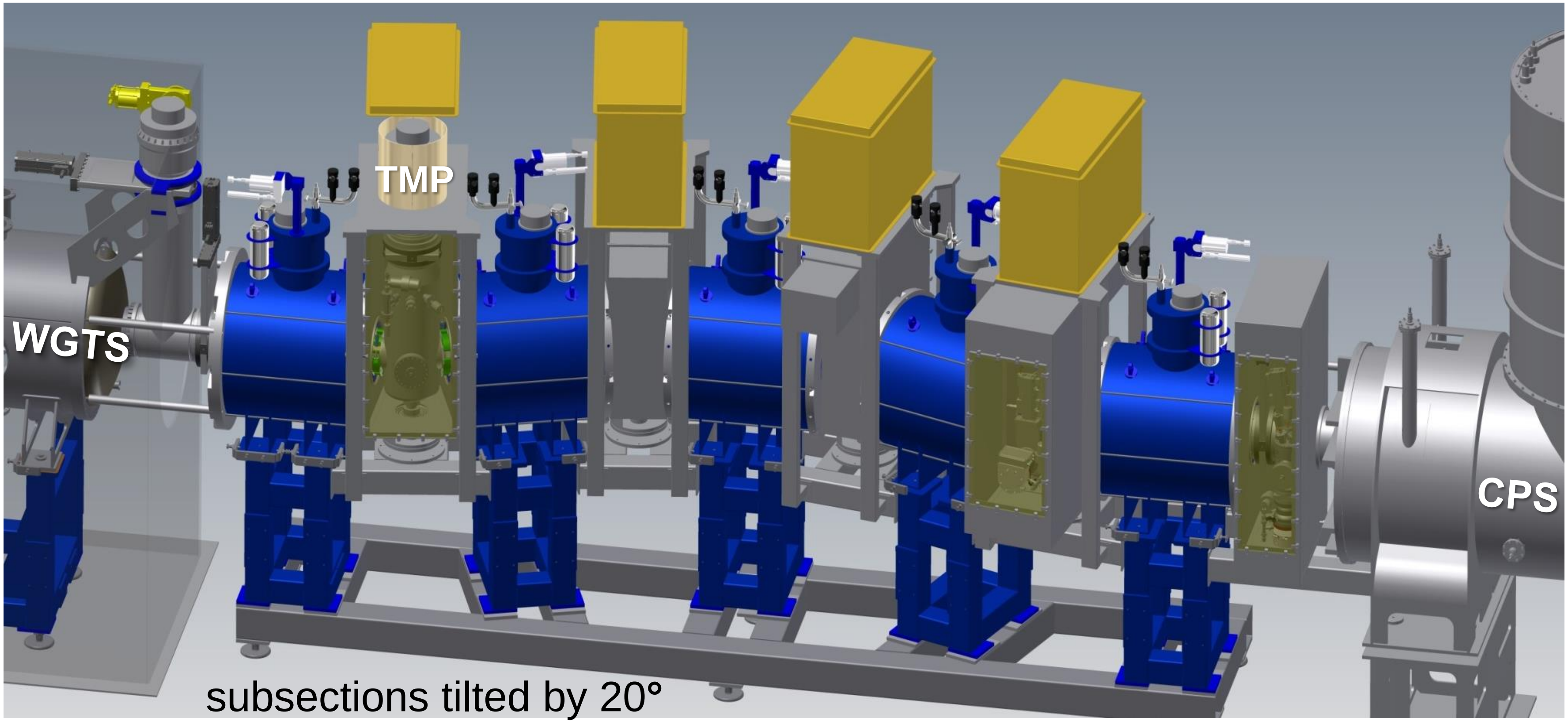


LHC
$154\ m^3$

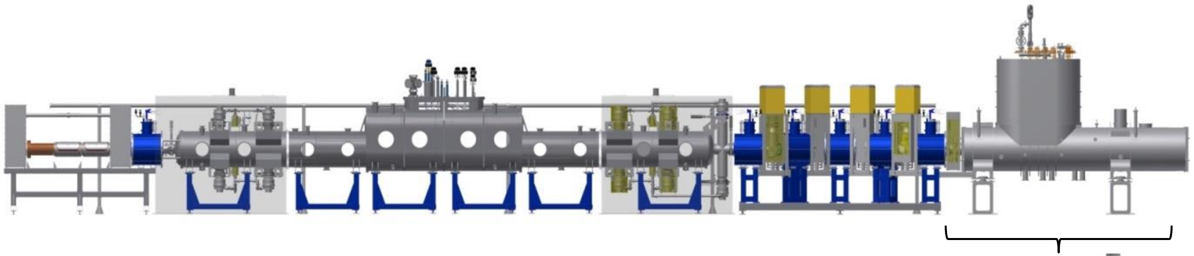
DPS 2-F – differential pumping section

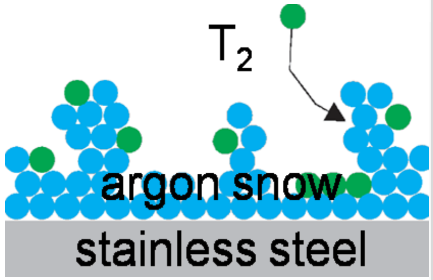


- **DPS:** active differential pumping by 4 main TMPs - retention factor 10^5



CPS – cryogenic pumping section





- **CPS:** passive cryotrap

cryogenic pumping

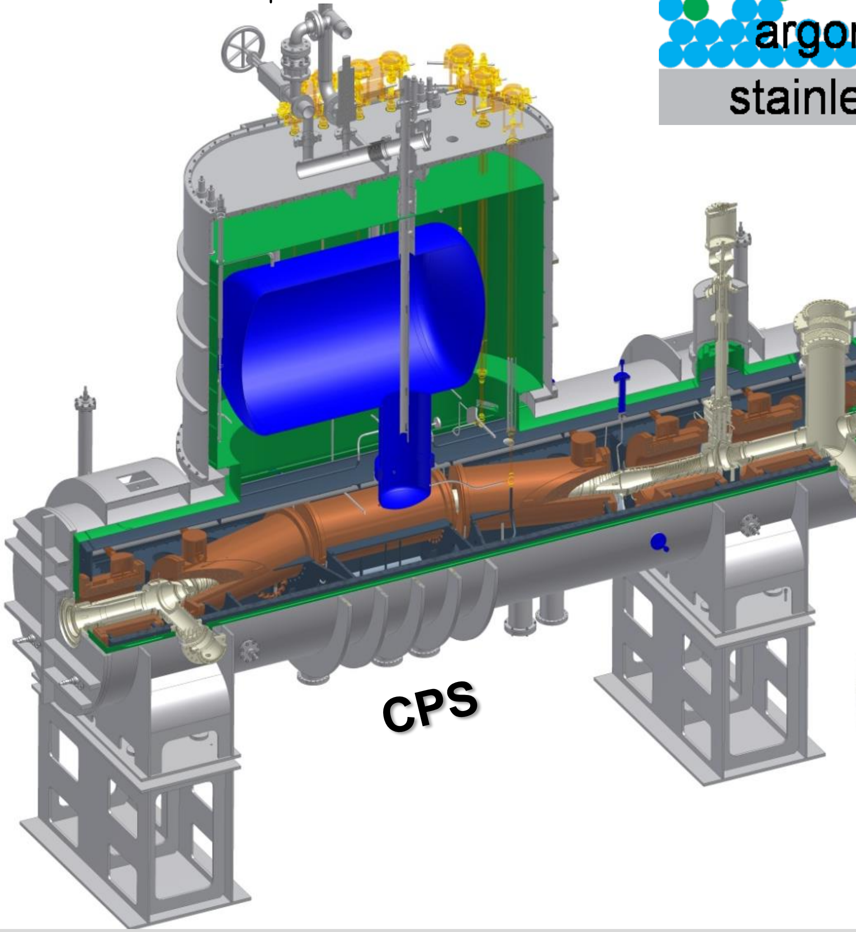
- 3 K beam tubes with Ar frost
- tritium retention factor > 10^7

adiabatic guiding of electrons

- 7 s.c. solenoids (B = 5.6 T)

Port instrumentation

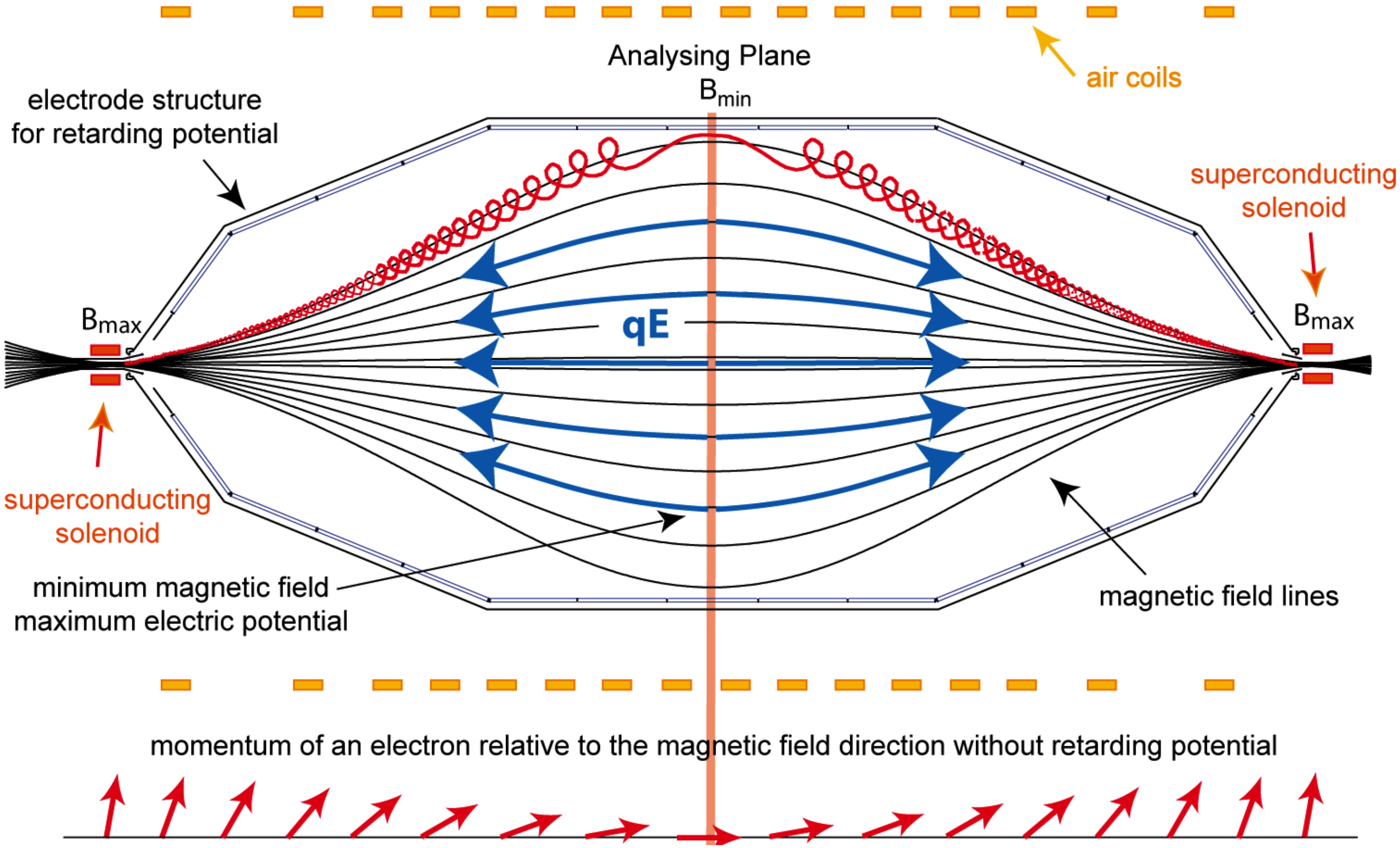
- vertical access port for condensed ^{83m}Kr source
- horizontal port for monitoring



The MAC-E Filter

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

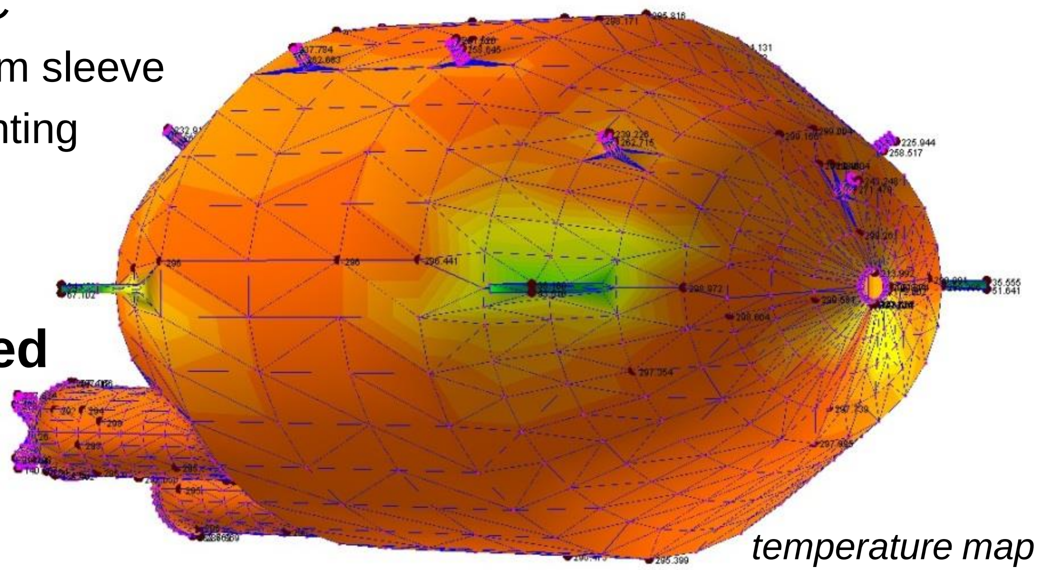
***M**agnetic **A**diabatic **C**ollimation with **E**lectrostatic Filter*



- **collimation:** $\mu = E_\perp / B = const$, ➔ $E_\perp \rightarrow E_{||}$ for $B = 6\ T \rightarrow 3mT$
- **energy analysis:** transmission condition: $E_{||} > eU_0$ (retarding potential)
- **energy resolution:** $\Delta E = E \cdot B_{min} / B_{max}$ = 18.6 keV · 0.3 mT / 6 T **= 0.93 eV**

2013: Spectrometer Commissioning

- **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 ≈ 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**



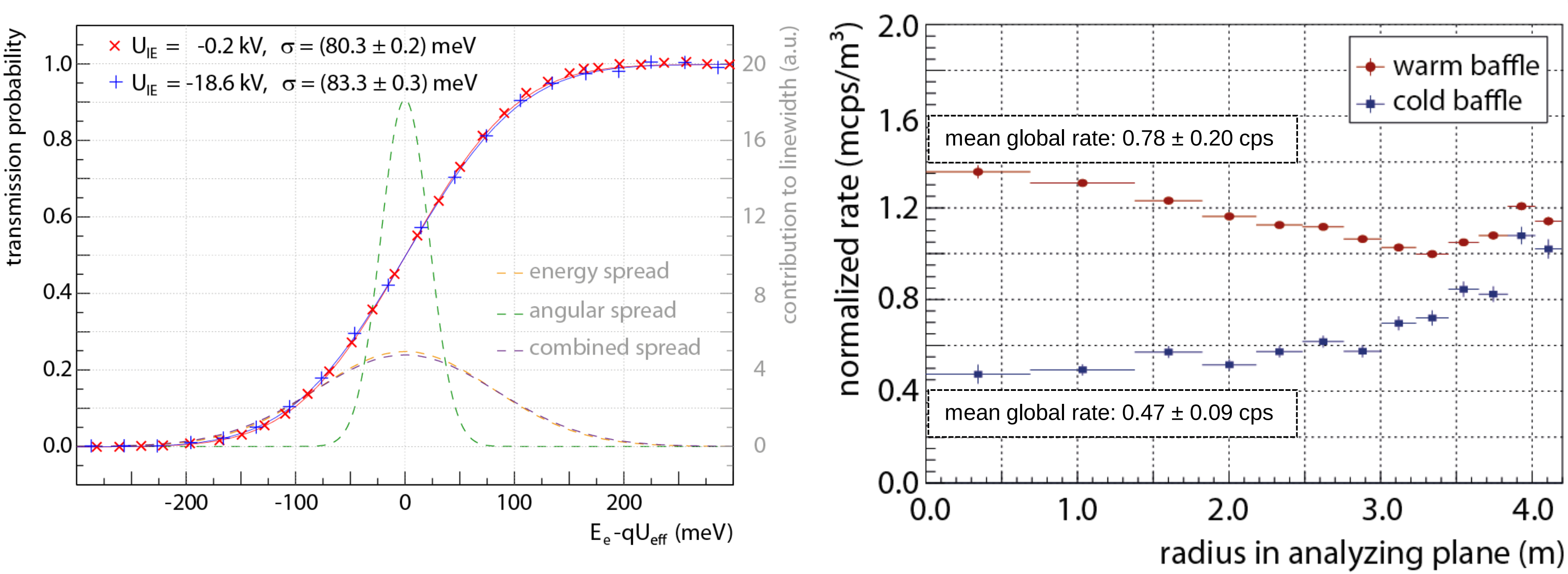
temperature map

KATRIN Main Spectrometer Measurements

Karlsruhe Institute of Technology

detailed transmission and background studies

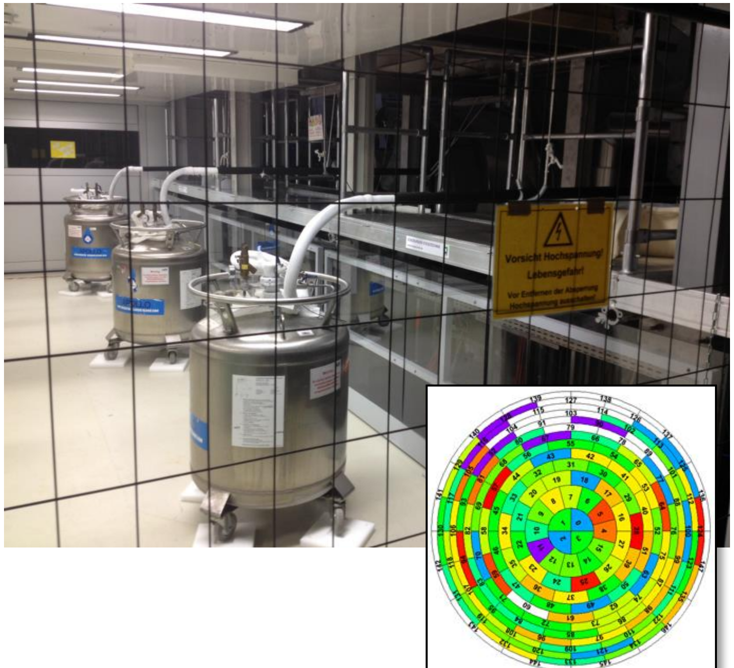
- sharpest transmission function ever measured with MAC-E filter
- background from $^{219}Rn/^{220}Rn$ emanation eliminated

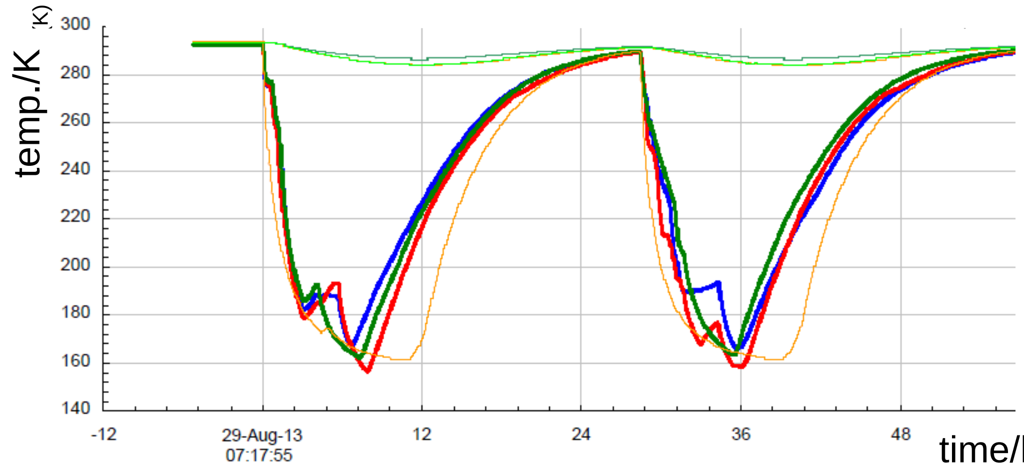


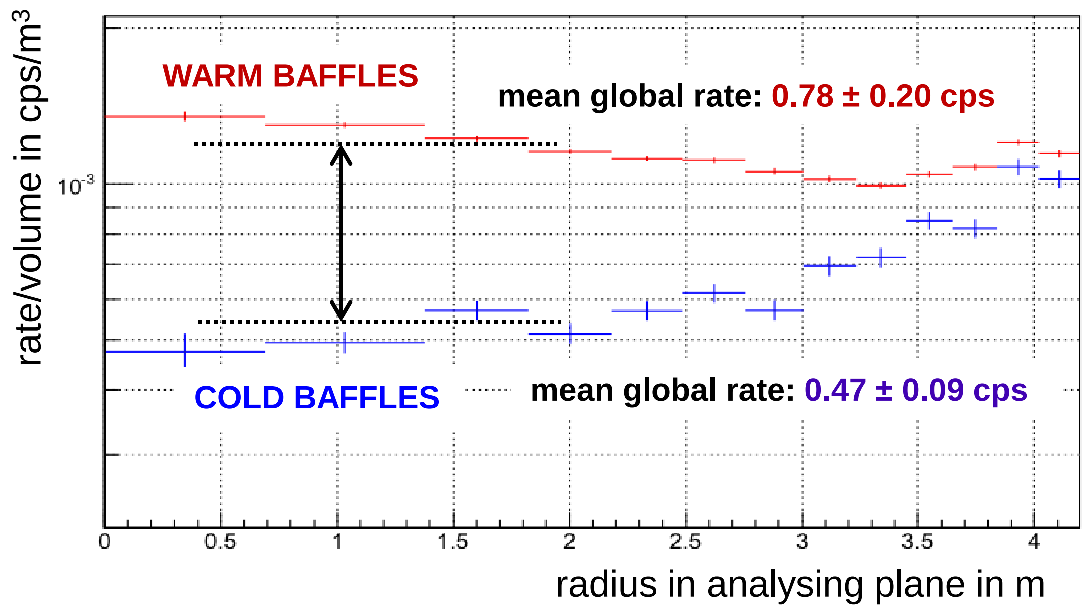
- will be improved during 2014 commissioning runs

Results on the Radon Induced Background

Measurements with cold baffles and high voltage

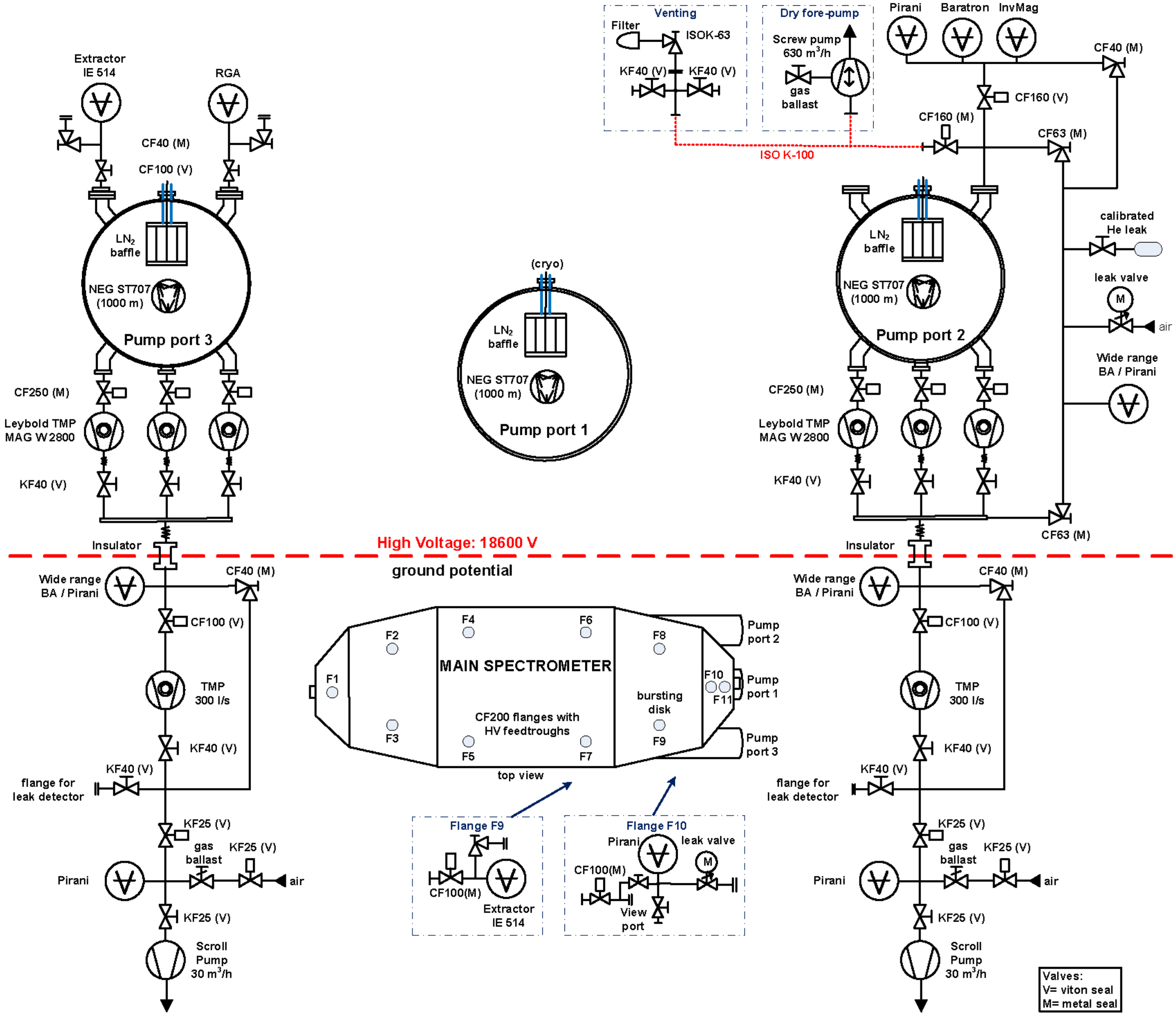






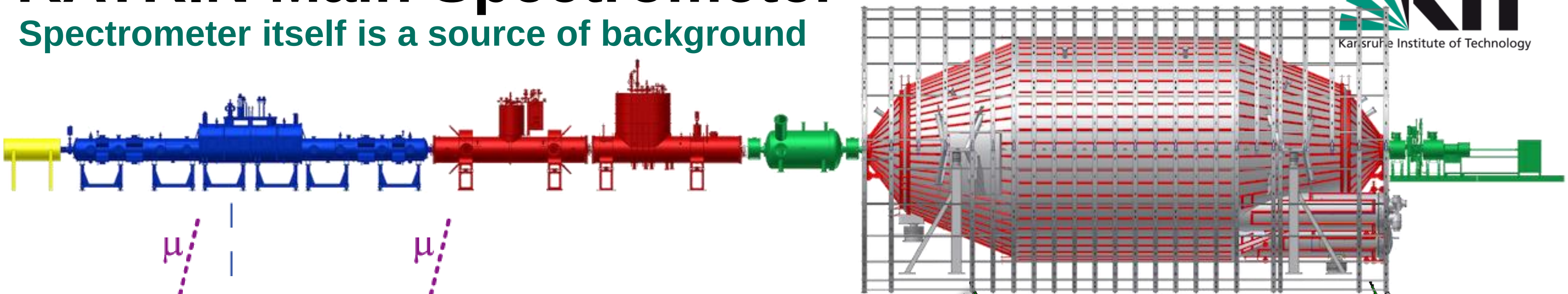
- Two short measurements
- Background strongly reduced
- Proof of principle: baffles work as expected
- Long-term performance will be tested in 2014/2015

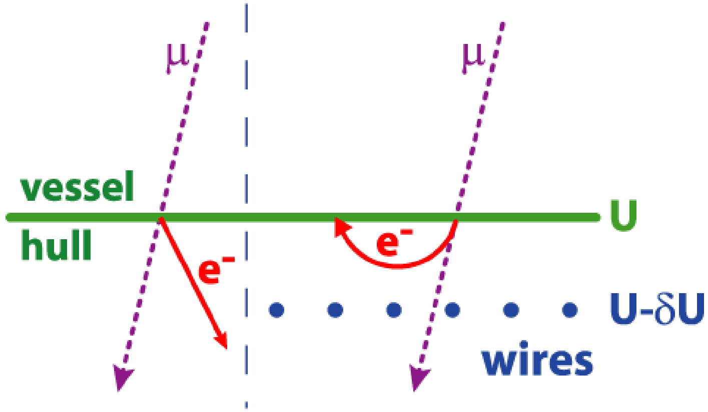
Vacuum scheme of the Main Spectrometer

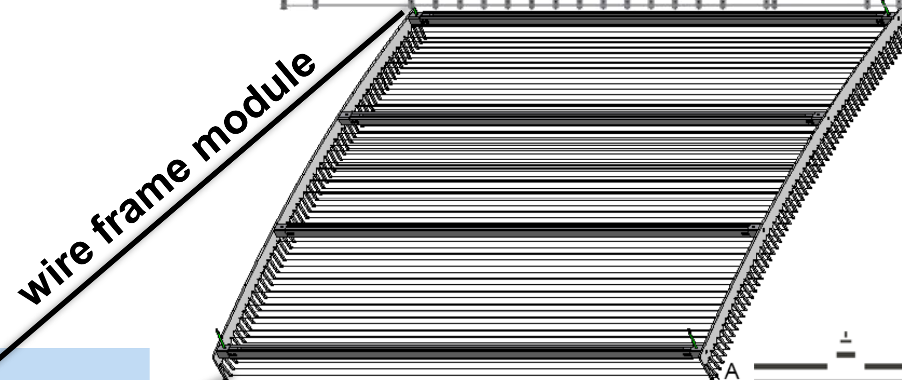


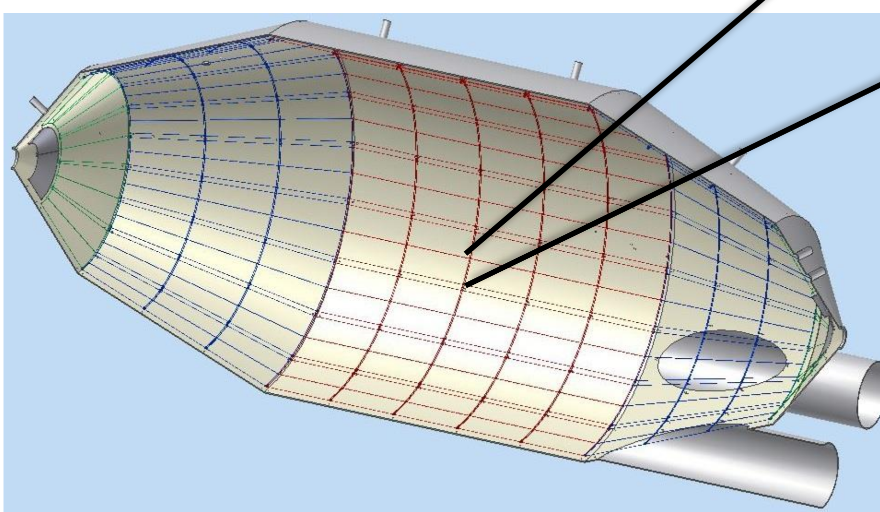
KATRIN Main Spectrometer

Spectrometer itself is a source of background









Wire defines electrostatic filter:

- 248 modules, 23440 wires
- precision requirement 0.2 mm
- compatible to UHV

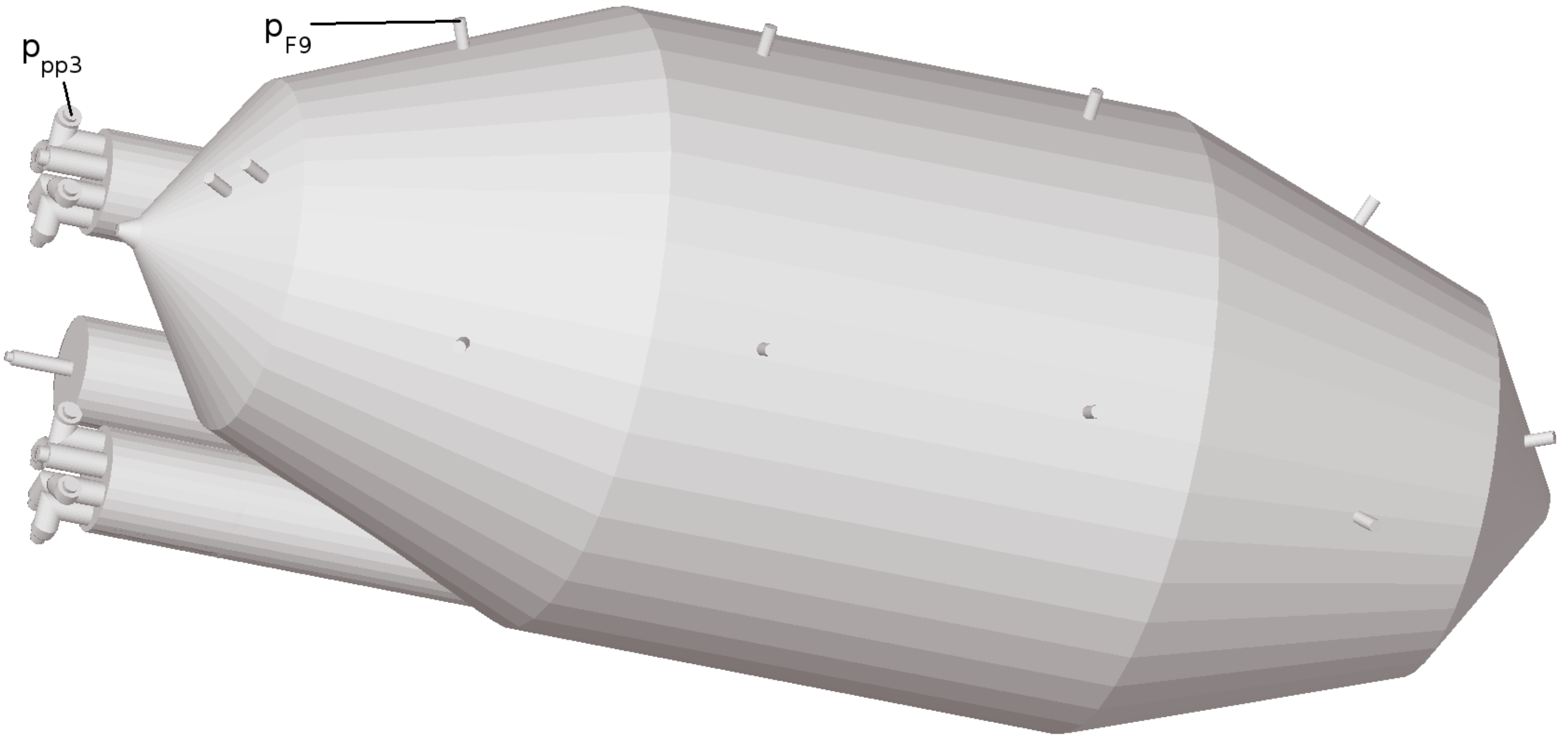
K. Valerius et al., Particle and Nuclear Physics, Volume 64, Issue 2, April 2010

KATRIN Main Spectrometer

Component	Material	Temp.	Surface
Main Spectrometer vacuum vessel	316LN	20°C	690.0 m^2
Wires (23440 wires with a total length of 42400 m)	316L	20°C	33.6 m^2
Electrode frames (248 modules)	316L	20°C	436.8 m^2
Electrode rail system	316LN	20°C	58.0 m^2
Feedtrough flanges	316LN	20°C	2.0 m^2
Small components (frame NEG-pumps, etc.)	316L	20°C	1.5 m^2
Σ stainless steel	**316L(N)**	**20°C**	**1221.9 m^2**
Σ ceramic insulators	**Al_2O_3**	**20°C**	**5.8 m^2**
Σ anti-penning electrodes	**Ti**	**20°C**	**11.0 m^2**
Σ ground electrodes	**Al**	**20°C**	**1.3 m^2**
Σ surfaces at room temperature		**20°C**	**1240 m^2**
Σ cryogenic baffles	**Cu**	**77 K**	**31 m^2**
Σ NEG-strips	**St707**	**20°C**	**180 m^2**
Volume Main Spectrometer			**1240 m^3**

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



Simulations of the Main Spectrometer

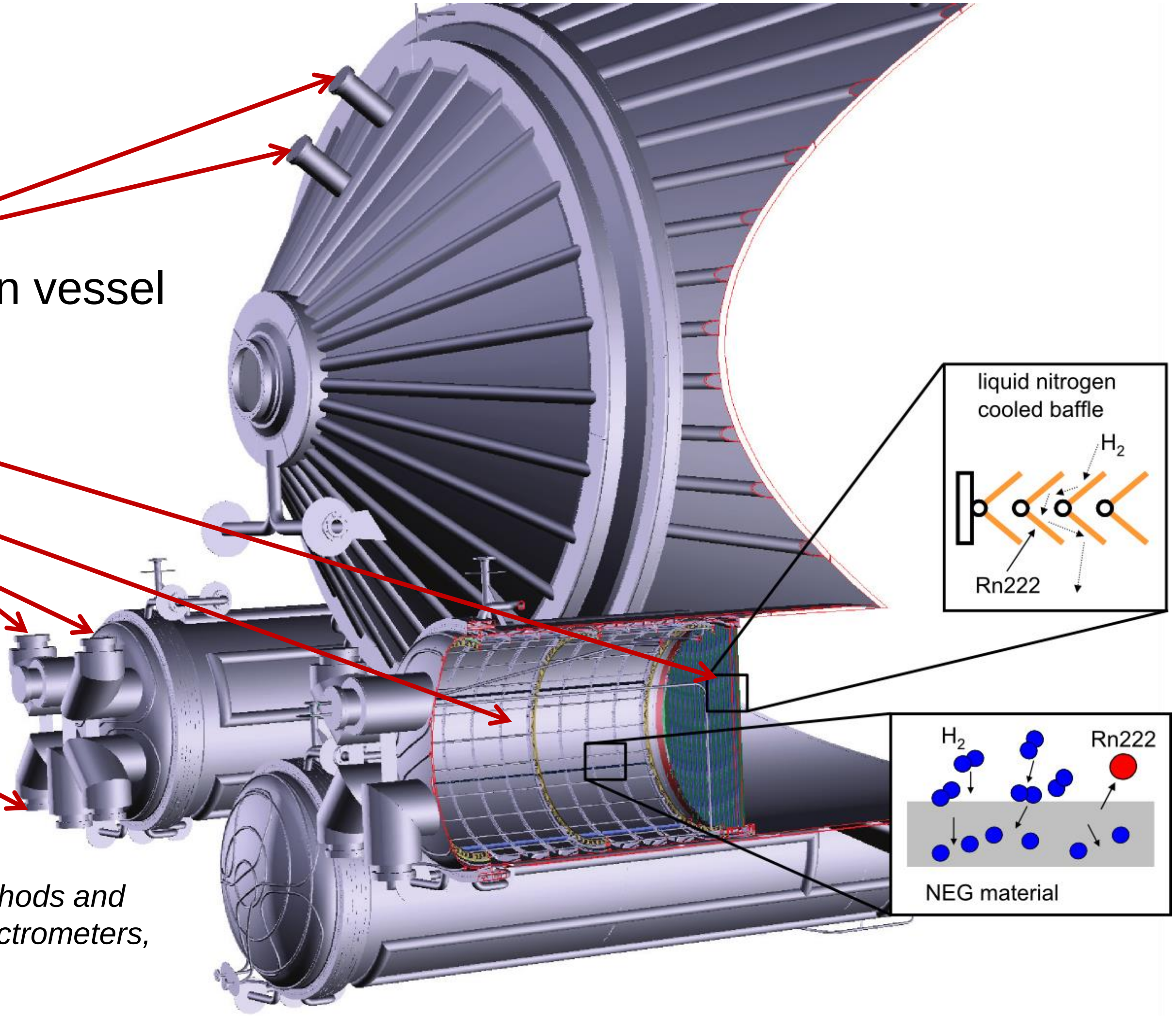
- **three possible gas sources for hydrogen and radon:**
  - complete stainless steel tank
  - NEG strips in pump ports
  - diagonal virtual area in one pump port (cross section between port and vessel) for determination of pumping speeds

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

- **aims:**
  - find correlations between α_{baffle} , α_{NEG} and pressure ratios
  - simulation of effective pumping speed of NEG, TMPs and baffles
  - comparison with experimental ratios ➔ effective pumping speed
  - simulate radon suppression factor

Simulation of the Main Spectrometer (MolFlow+)

- **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** α
- Determine **pumping probability**: $\boldsymbol{w} = N_{ads}/N_{des}$
- Calculate the **effective pumping speed**: $\boldsymbol{S}(\mathrm{M}) = {}^{1}/_{4}\, \bar{c}_M \cdot A_{port} \cdot \boldsymbol{w}$

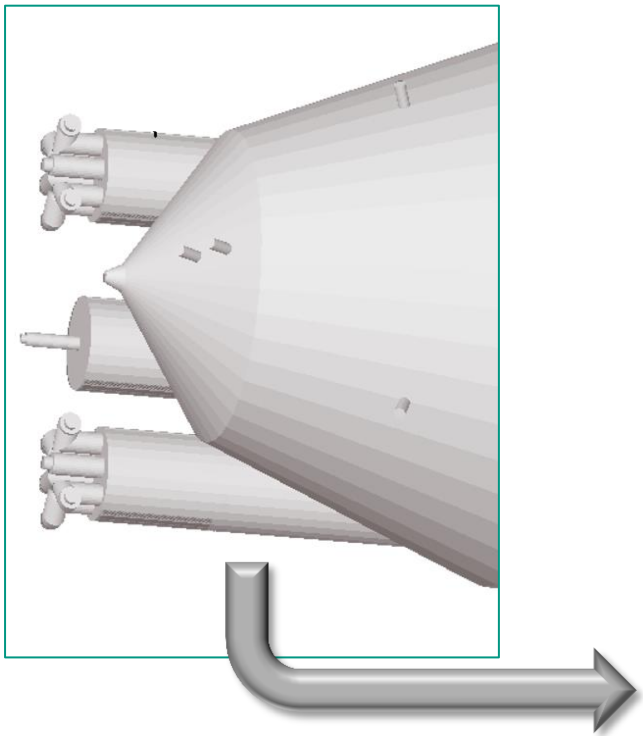
$\bar{c}$: mean molecular speed for mass M

$$\bar{c} = \sqrt{\frac{8 k_{\mathrm{B}} T}{\pi M}}$$

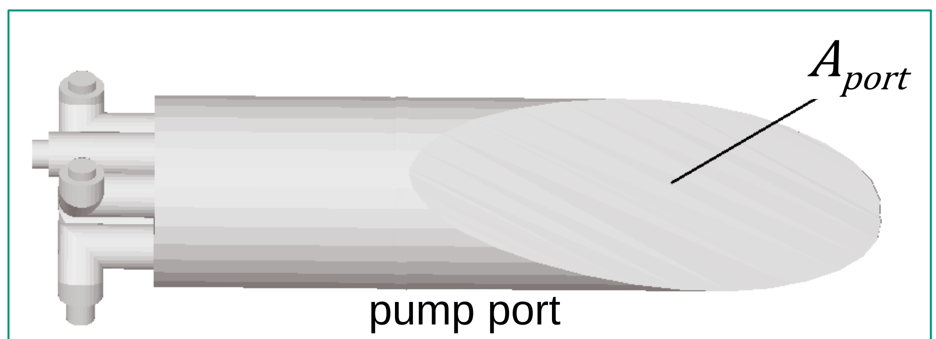
A_{port} : desorption area (virtual area)

N_{ads} : number of adsorptions in pump

N_{des} : total desorption number

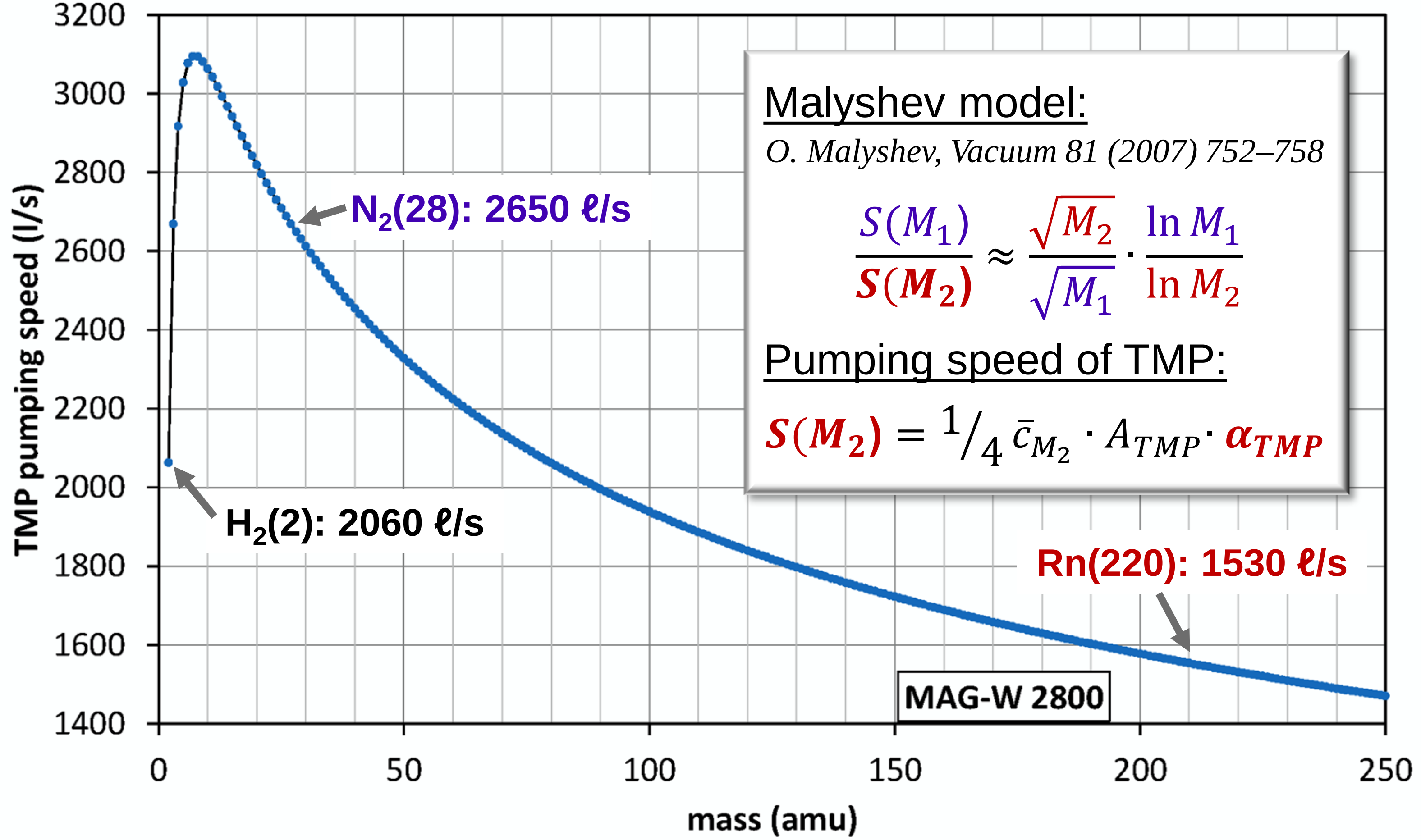


simplified model

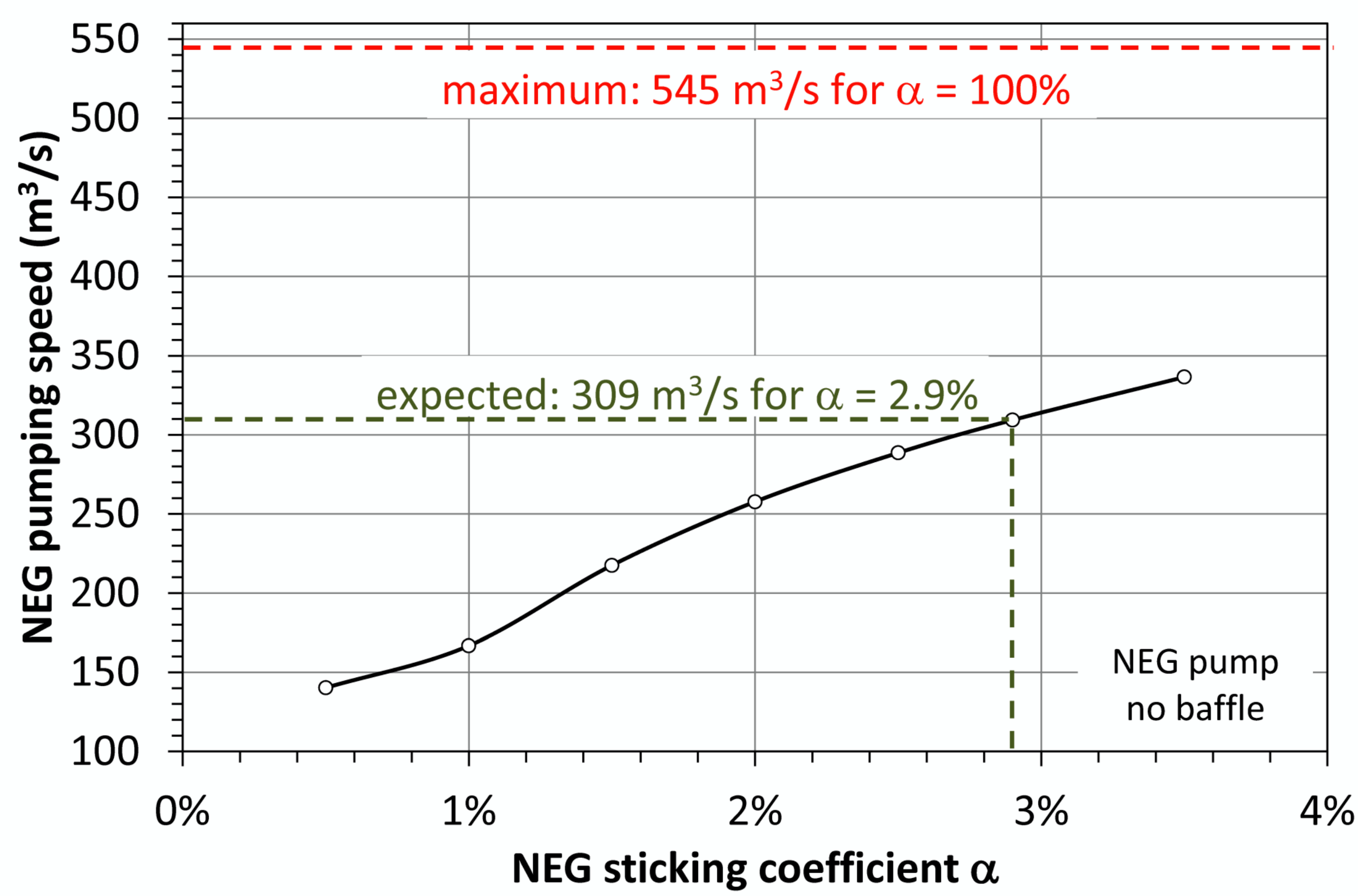


TMP simulation

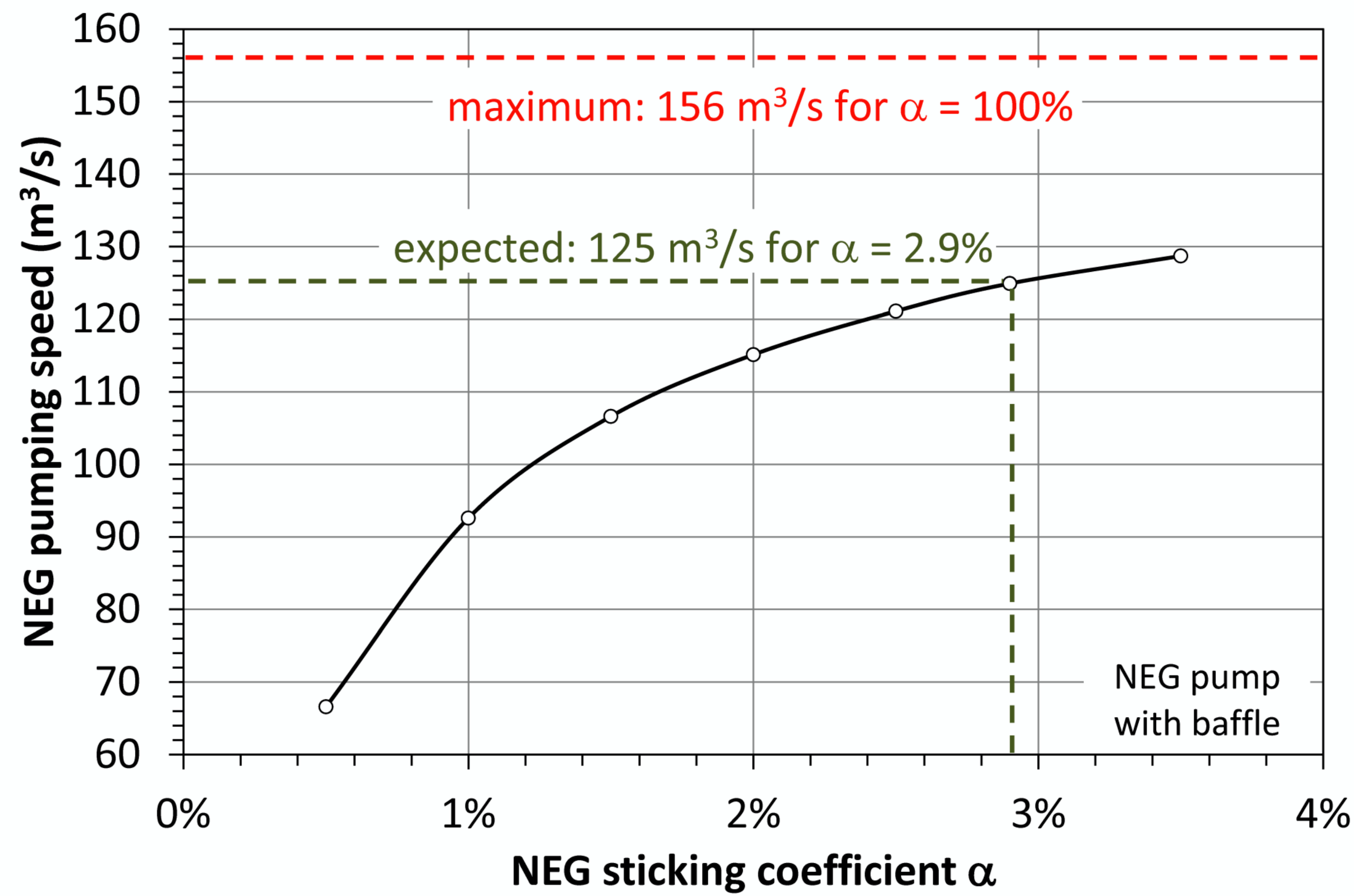
- Determine pumping speed of TMP for **mass of gas particle** (Malyshev model)
- Simulate **pumping probability** $\boldsymbol{w} = N_{ads}/N_{des}$
- **Effective pumping speed**: $\boldsymbol{S(M_2)} = {}^1/_4\, \bar{c}_{M_2} \cdot A_{port} \cdot \boldsymbol{w}$



NEG-pump simulation (without baffle)

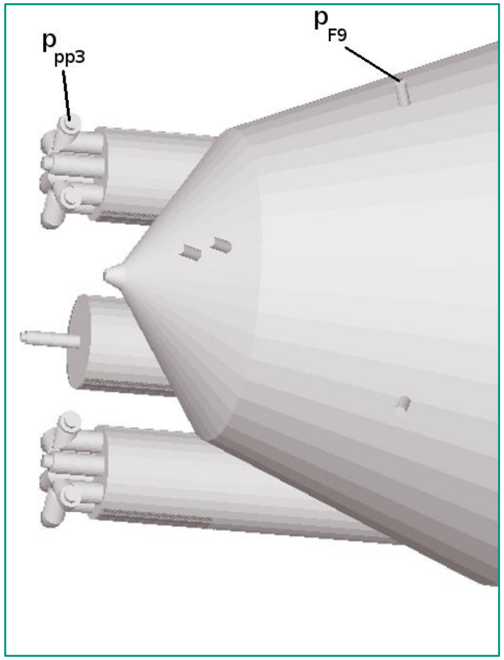


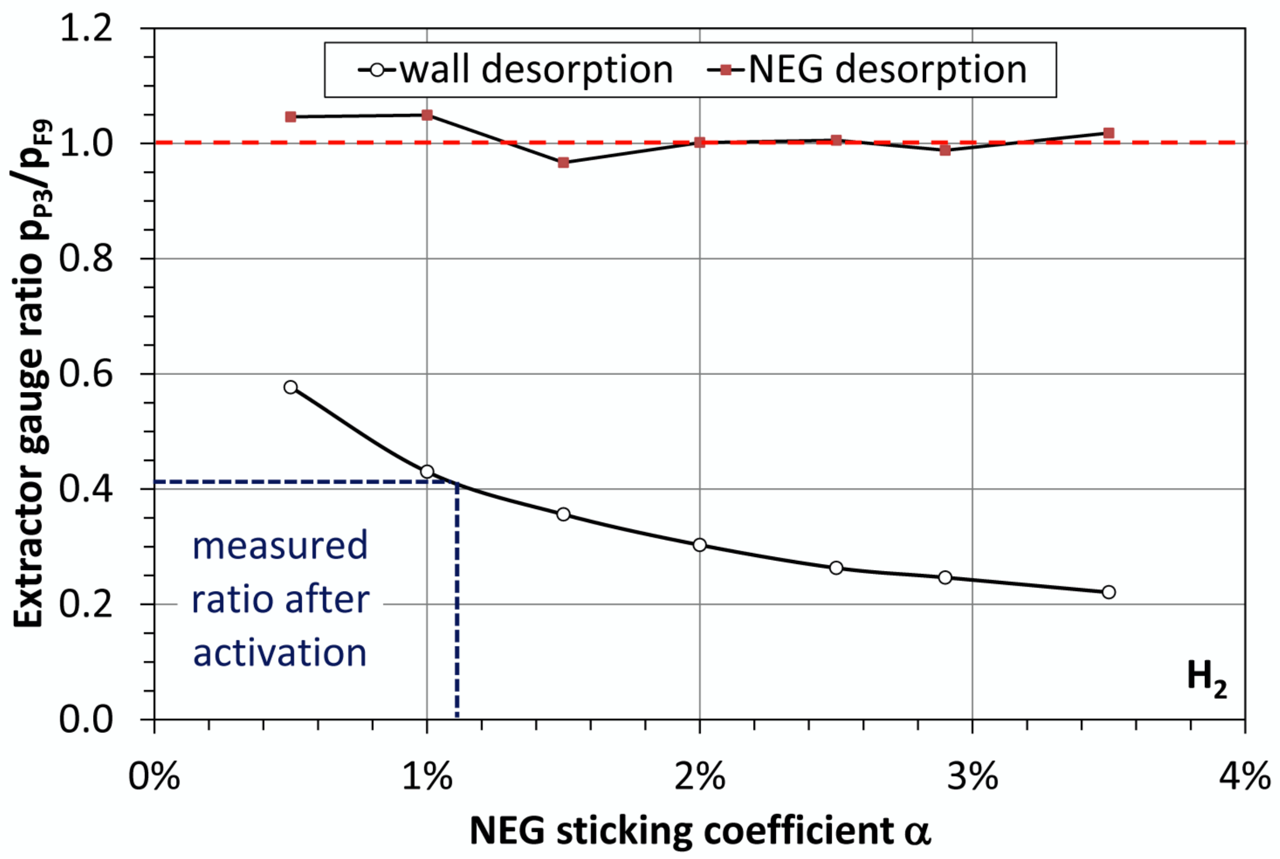
NEG-pump simulation (with baffle)



Simulation results for the NEGs as primary pumps

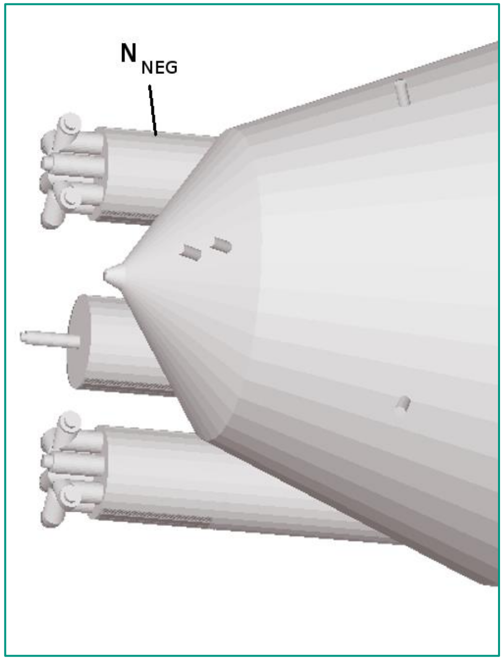
- ratio of hit numbers in vacuum gauges ≈ ratio of pressures: p_{PP3} / p_{F9}
- gas: hydrogen

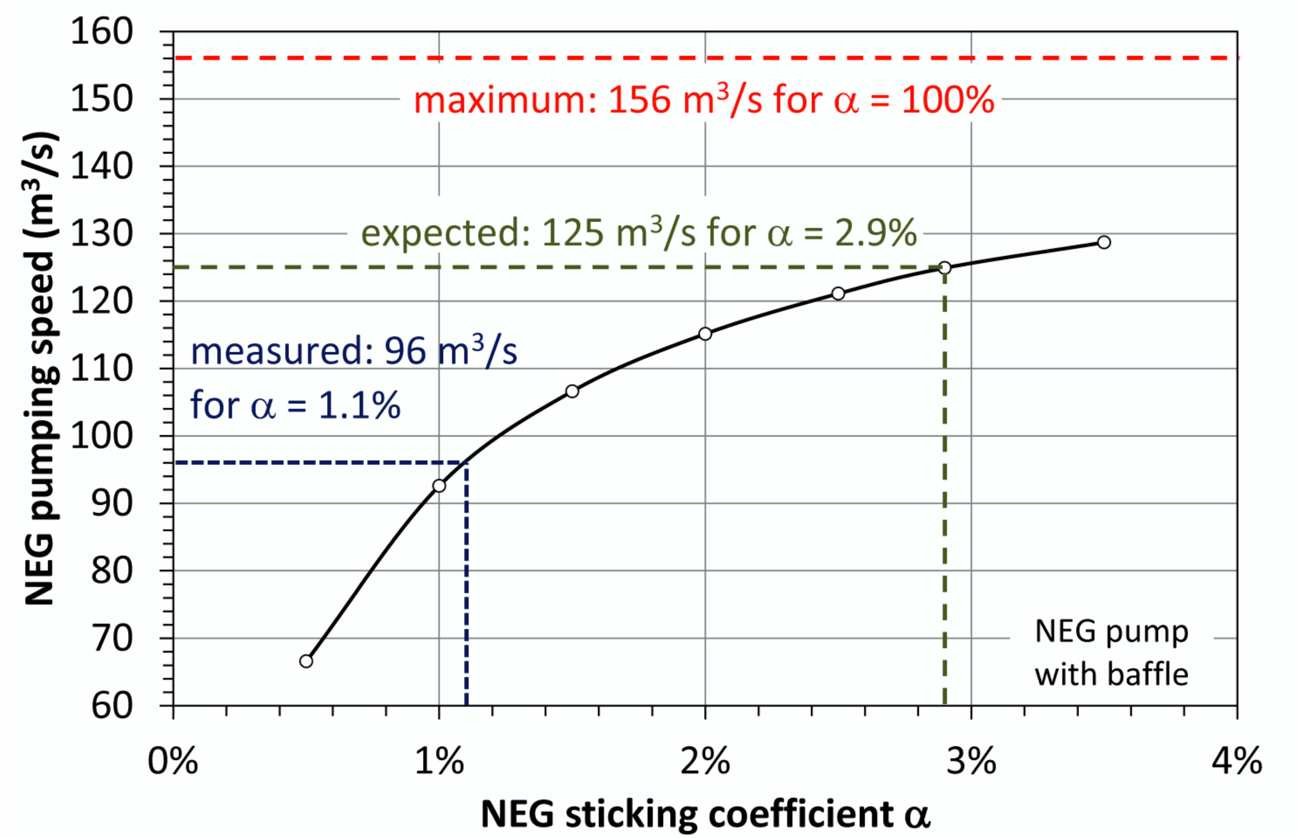




Simulation results for the NEGs as primary pumps

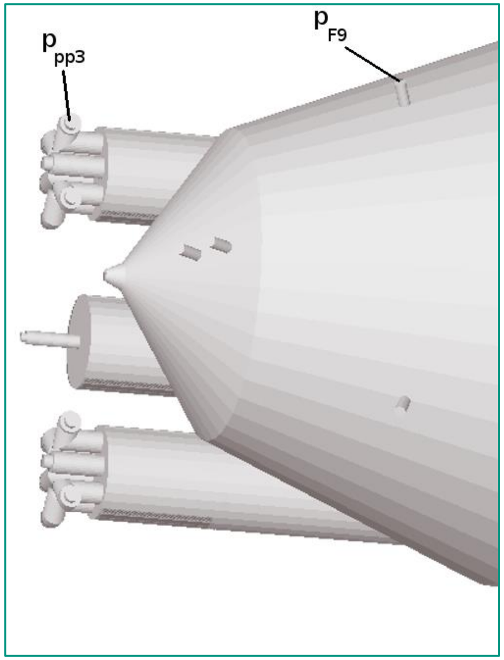
- calculation of the NEG pumping speed: $S = \frac{1}{4} \cdot \bar{c} \cdot A \cdot \frac{N_{\mathrm{NEG}}}{N_{\mathrm{des}}}$
- gas: hydrogen

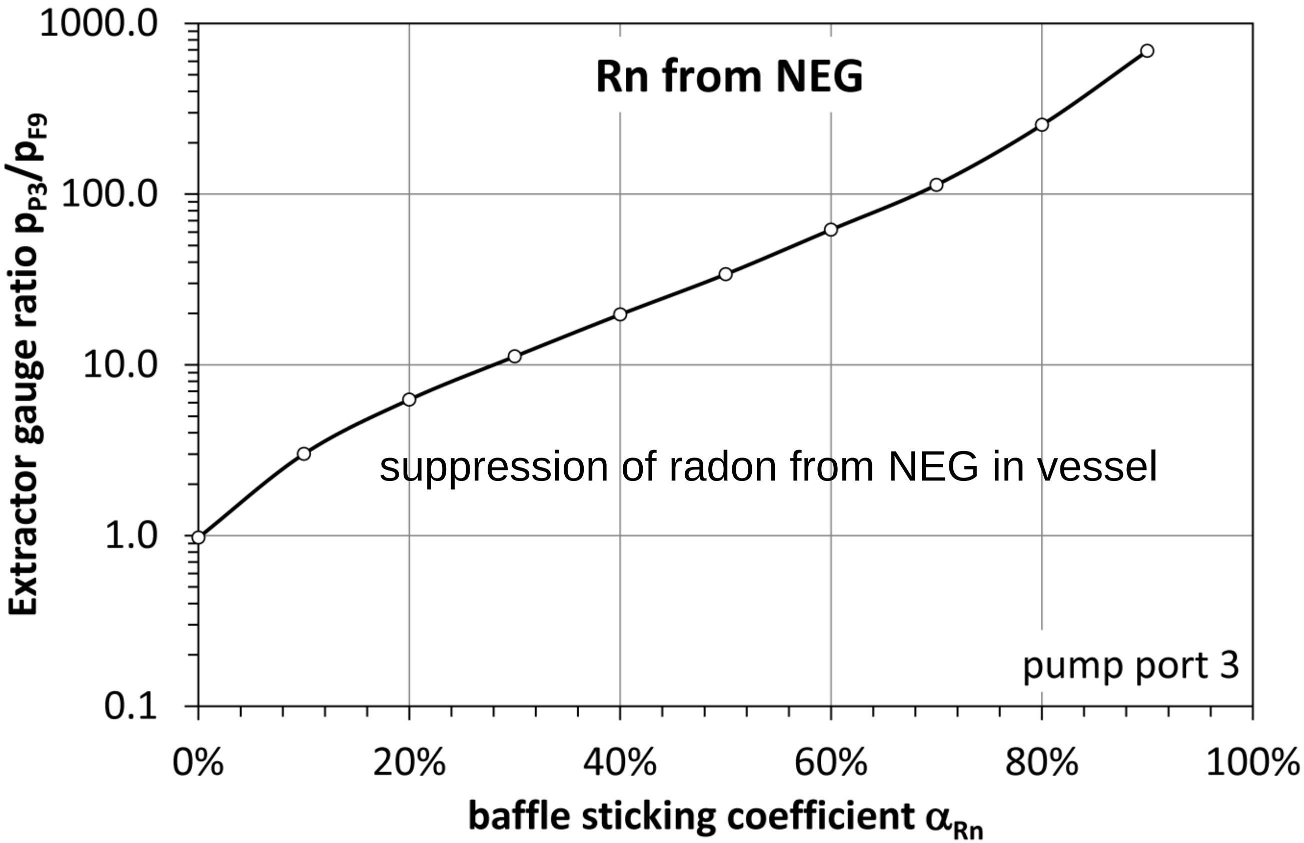




Simulation results for the TMPs as primary pumps

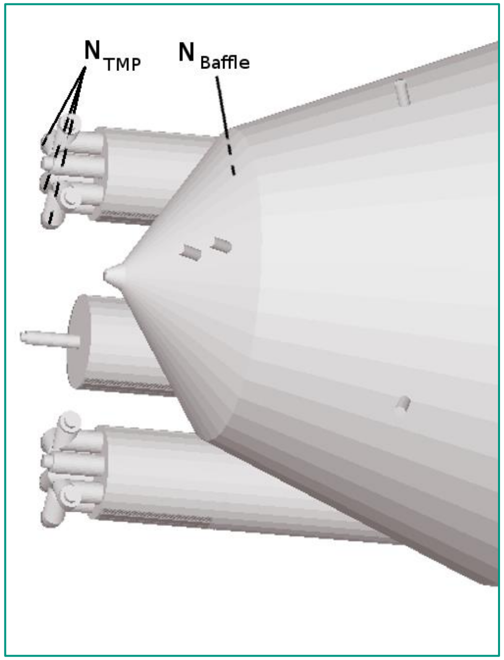
- ratio of hit numbers in vacuum gauges ≈ ratio of pressures: p_{P3} / p_{F9}
- gas: radon

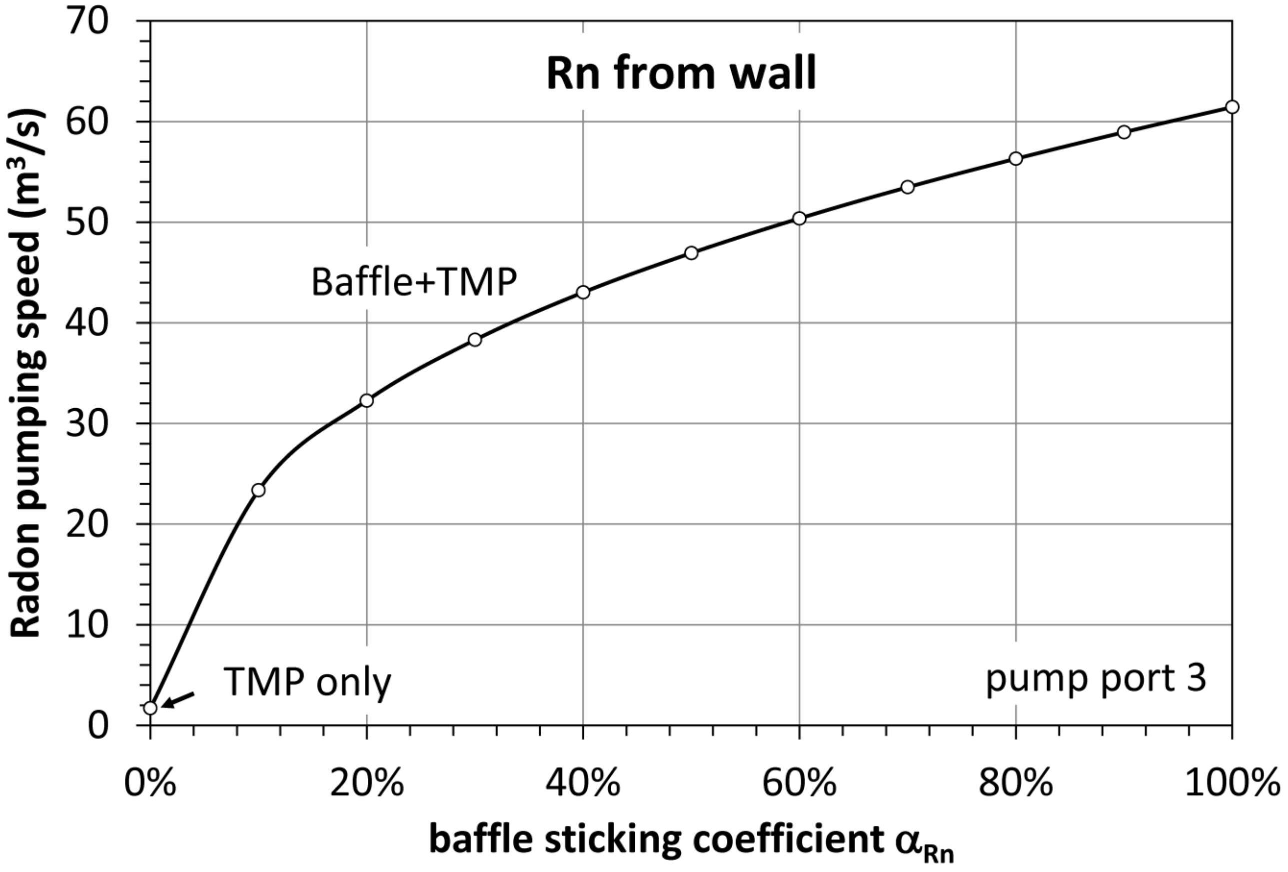




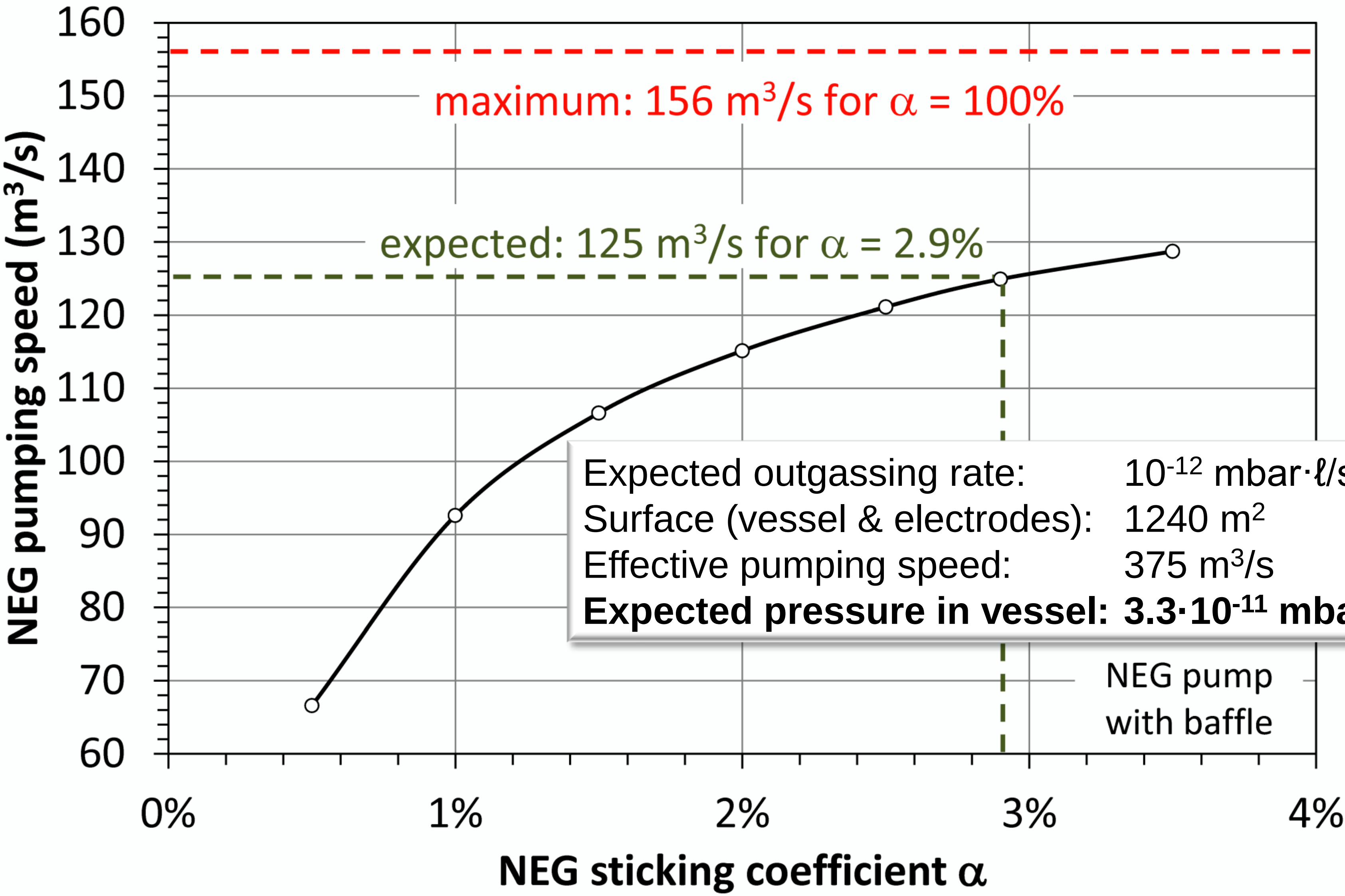
Simulation results for the TMPs as primary pumps

- calculation of the pumping speed (TMP + Baffle): $S = \frac{1}{4} \cdot \bar{c} \cdot A \cdot \frac{N_{\mathrm{TMP}} + N_{\mathrm{Baffle}}}{N_{\mathrm{des}}}$
- gas: radon



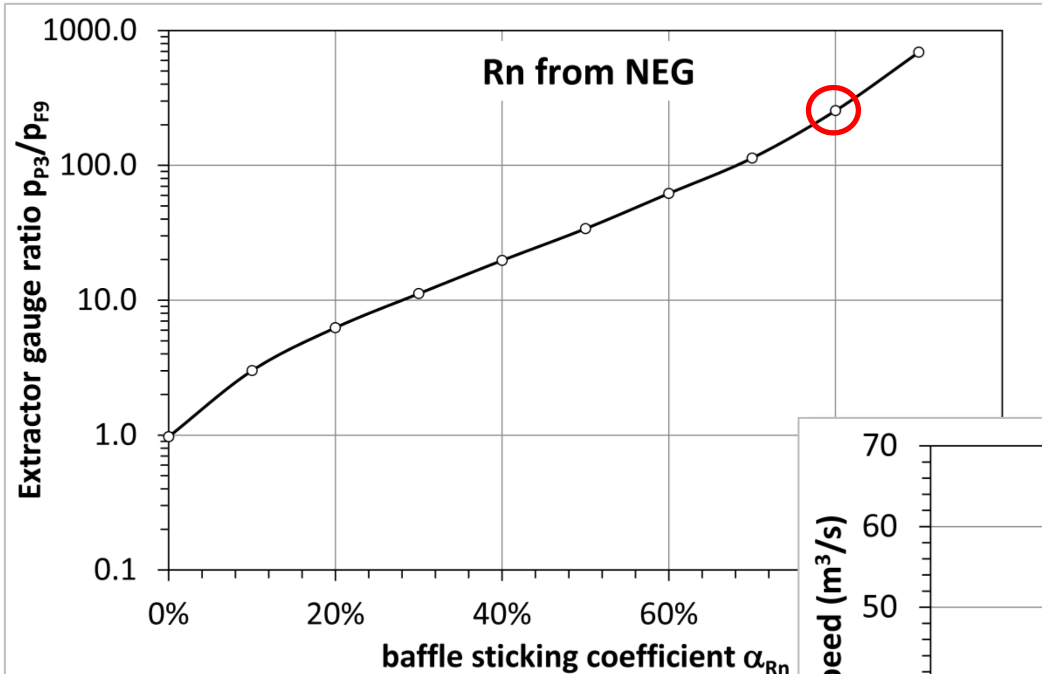


NEG simulation with baffle (MolFlow+)

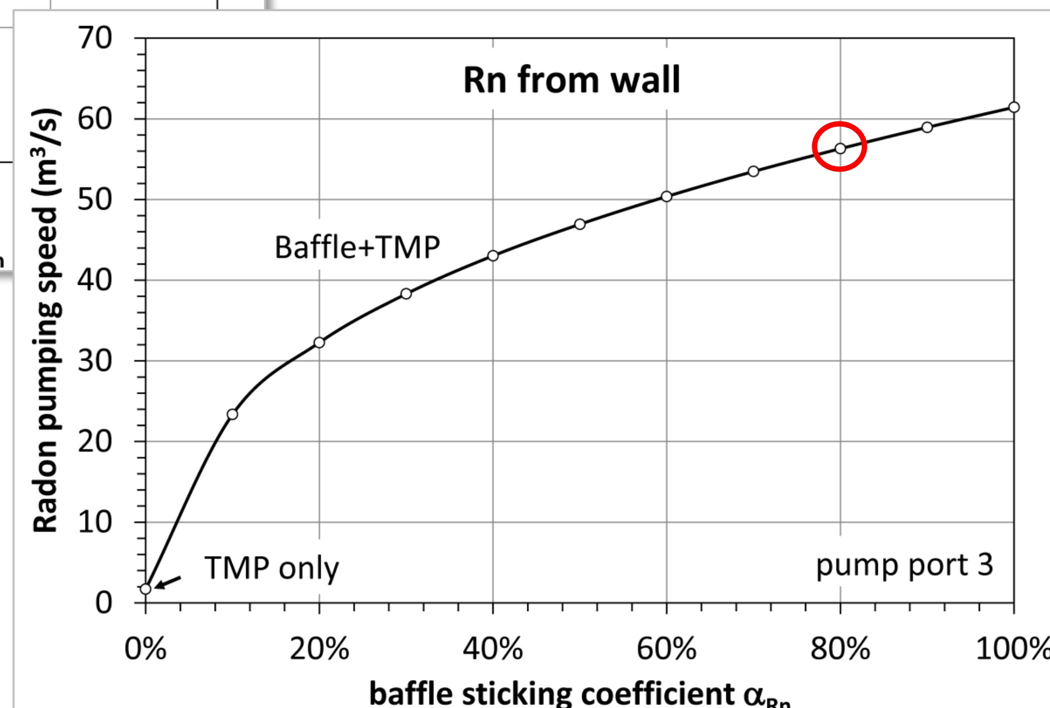


Expected outgassing rate:	10^{-12} mbar·ℓ/s·cm²
Surface (vessel & electrodes):	1240 m²
Effective pumping speed:	375 m³/s
Expected pressure in vessel:	**$3.3\cdot10^{-11}$ mbar**

Baffle simulation for Radon (MolFlow+)



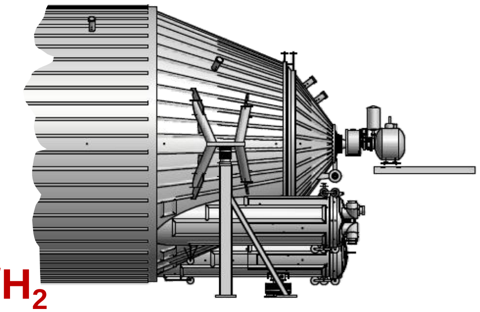
- **α_{Rn}~80%** estimated from Pre-Spectrometer results
- **Suppression factor** for radon emanating from NEG: **~250**

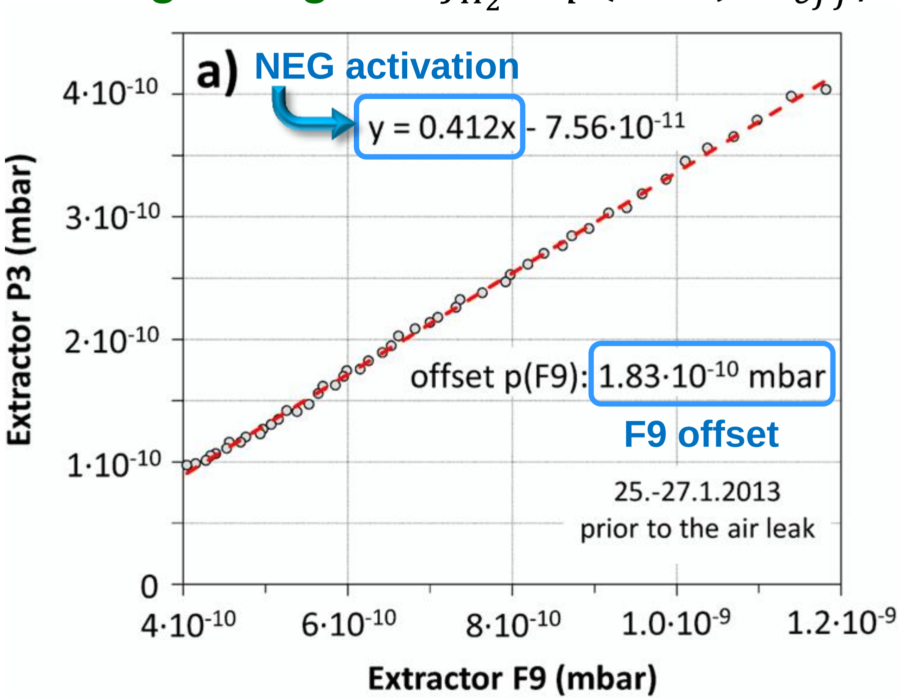


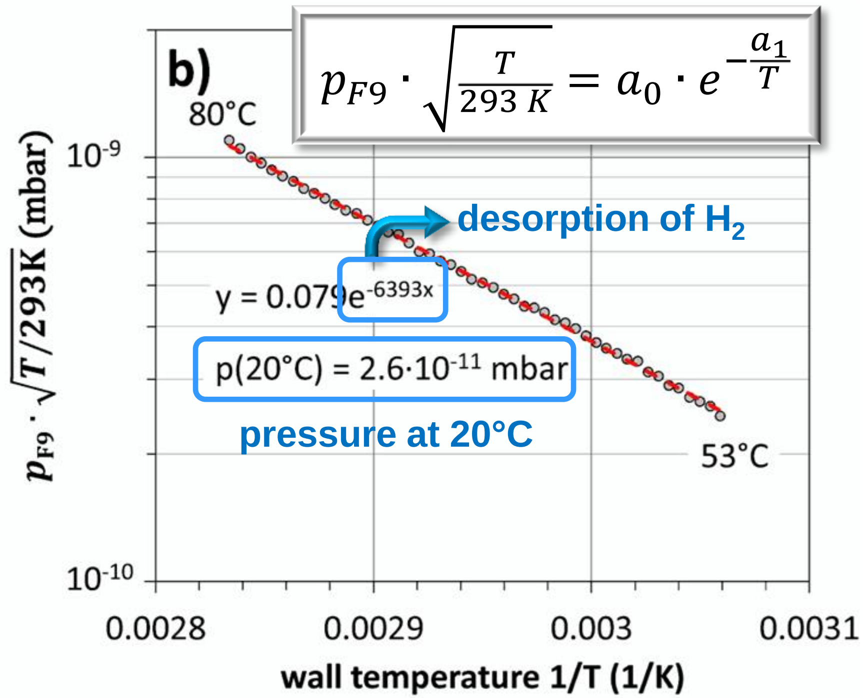
- Effective pumping speed for **6 TMPs: 3400 ℓ/s**
- Effective pumping speed for **3 baffles: ~170 000 ℓ/s**

Hydrogen outgassing and pressure at 20°C

- Fit of p_{P3} versus p_{F9}
  - **NEG pumping speed** from p_{P3}/p_{F9}: **290 m³/s (α = 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·cm²**







Vacuum status with cold baffles

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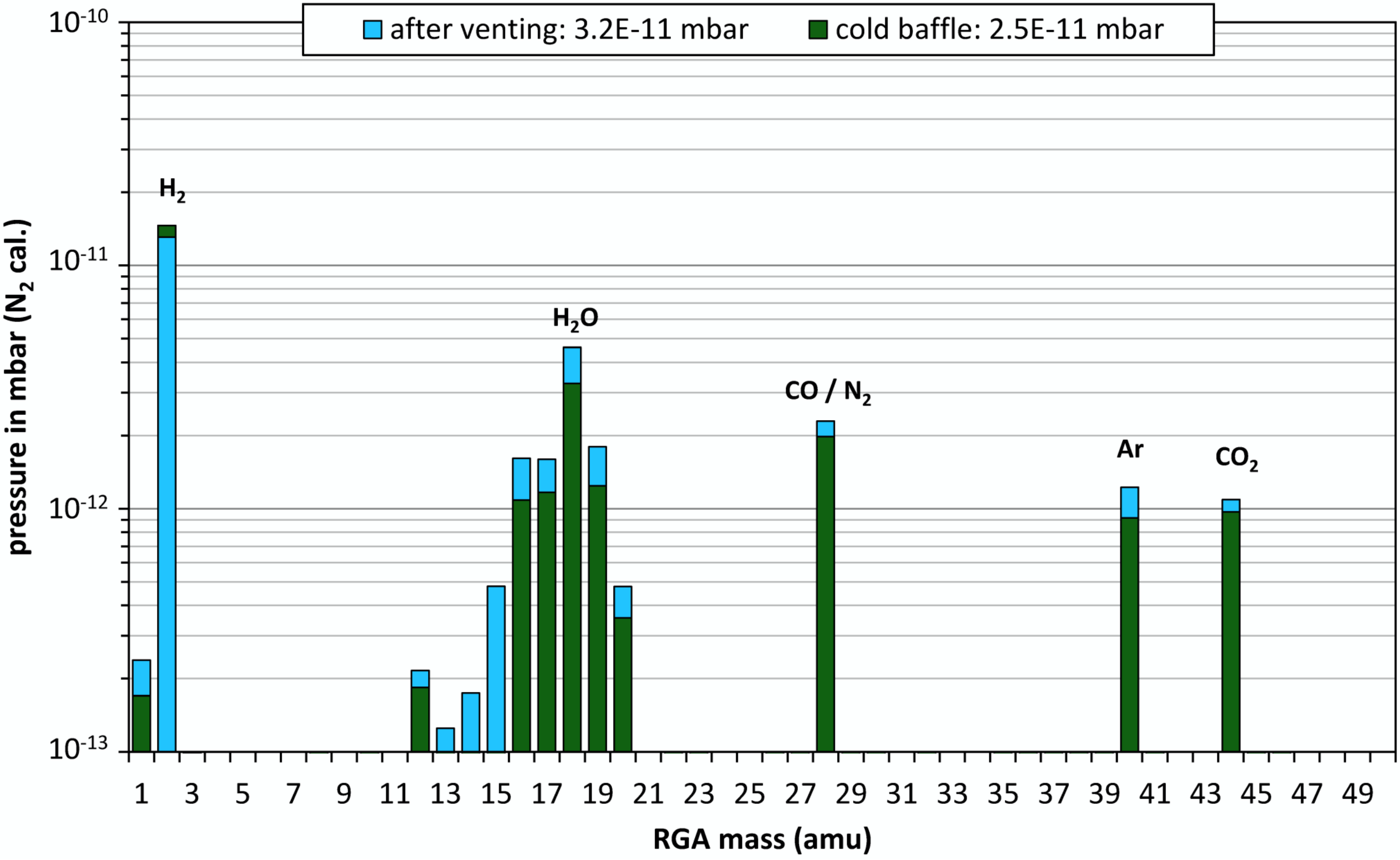
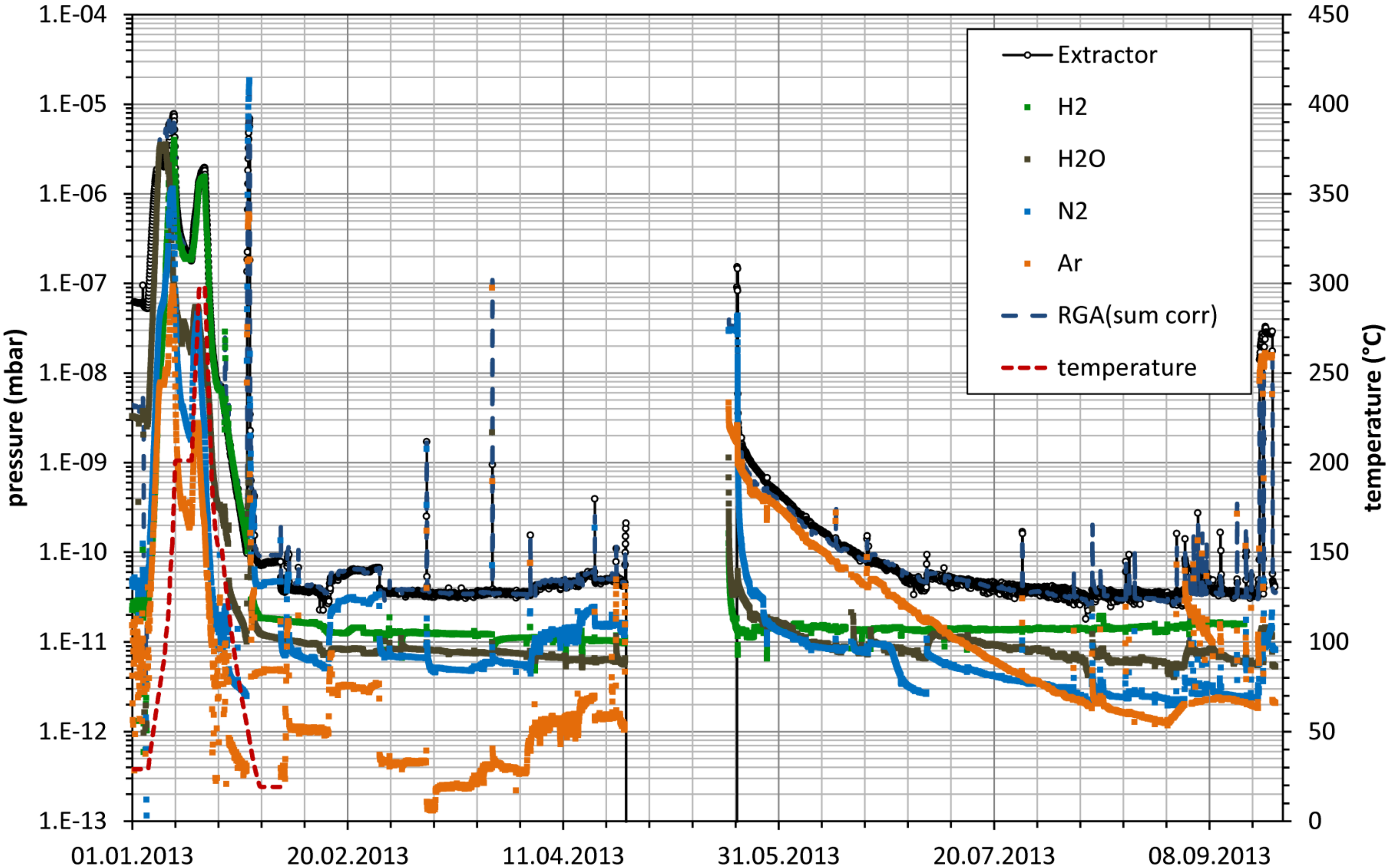
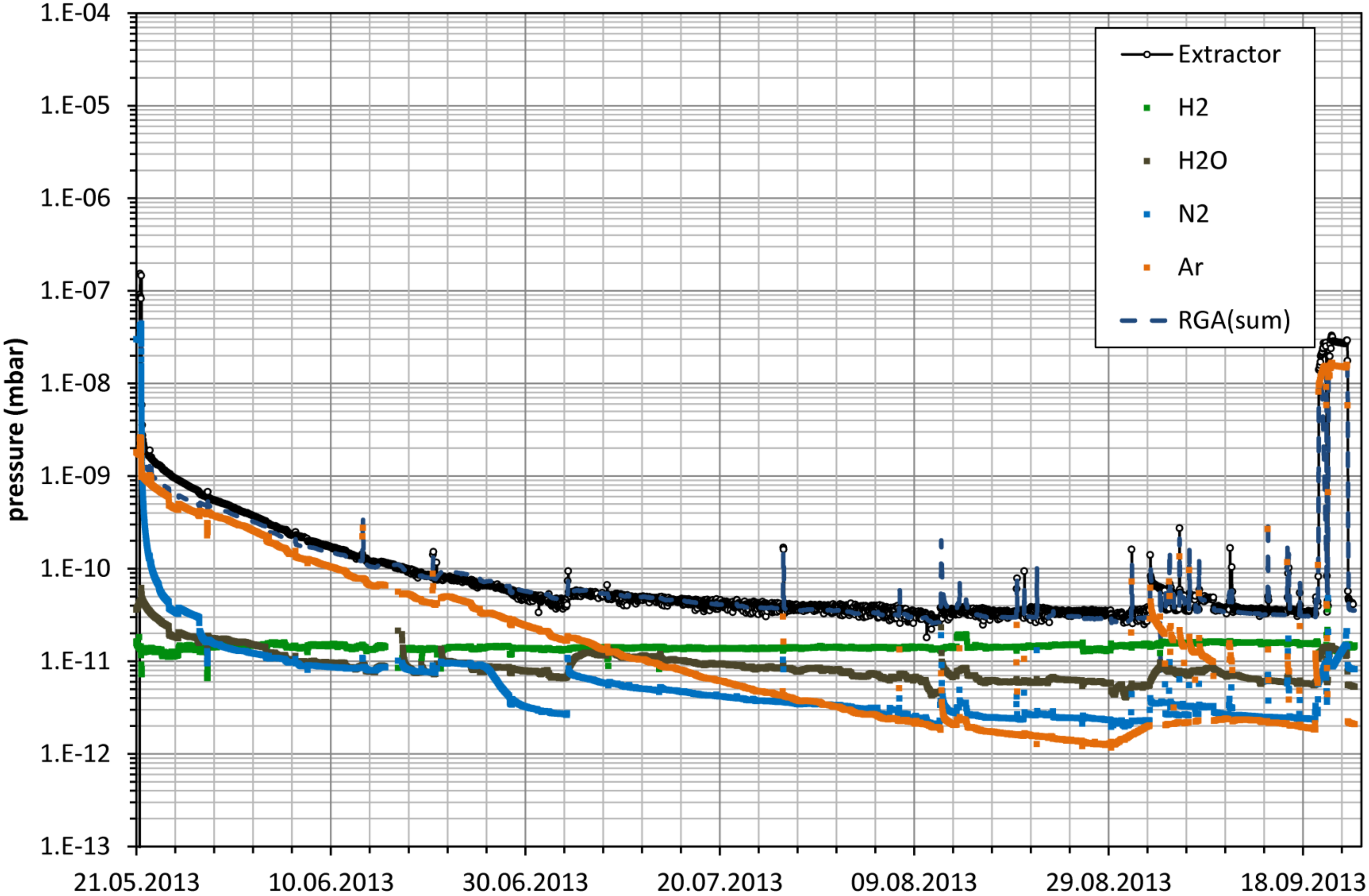
Karlsruhe Institute of Technology



RGA spectrum (all)



RGA spectrum after venting



KATRIN Main Detector

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