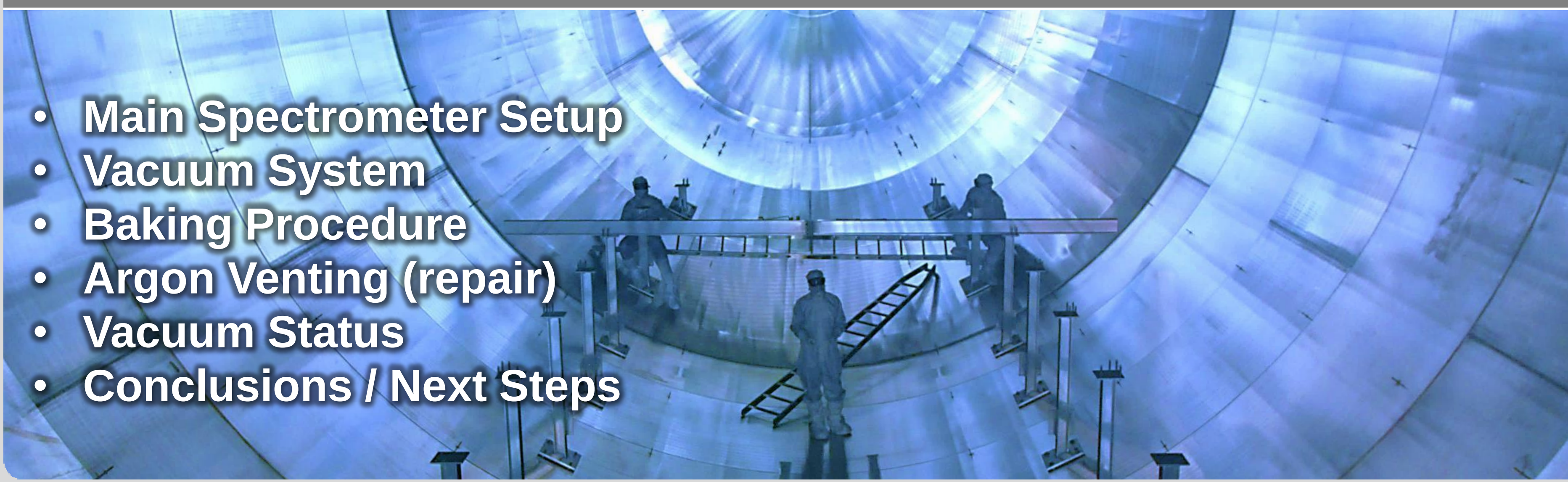
Commissioning of the KATRIN Main Spectrometer

Joachim Wolf for the KATRIN collaboration

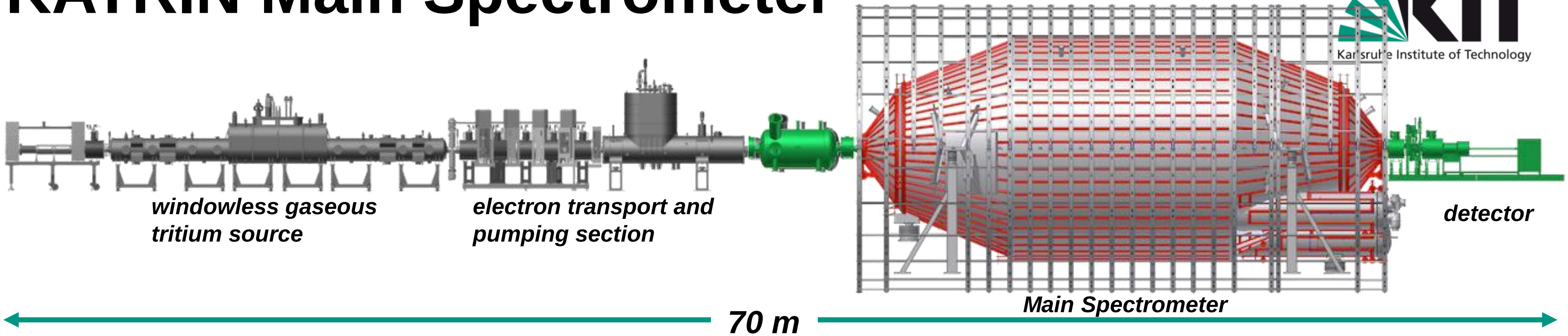
Institute of Experimental Nuclear Physics

AVS 61, Baltimore, 11/12/2014



- Main Spectrometer Setup
- Vacuum System
- Baking Procedure
- Argon Venting (repair)
- Vacuum Status
- Conclusions / Next Steps

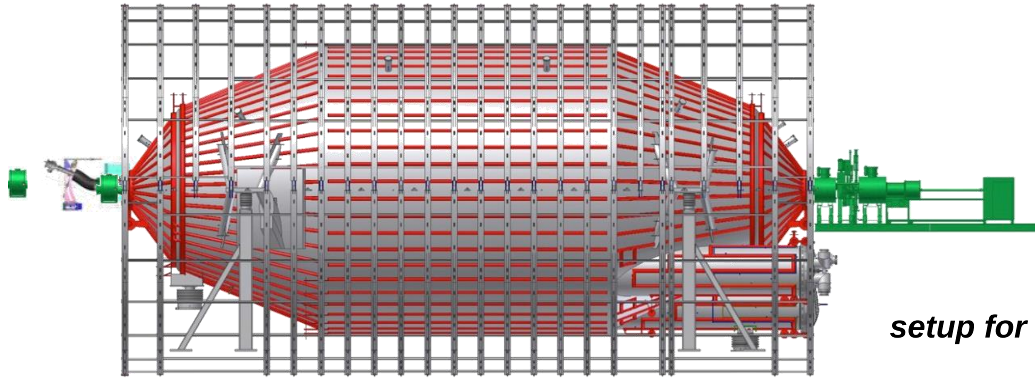
KATRIN Main Spectrometer



- **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**

arrival at KIT: 26.11.2006

KATRIN Main Spectrometer

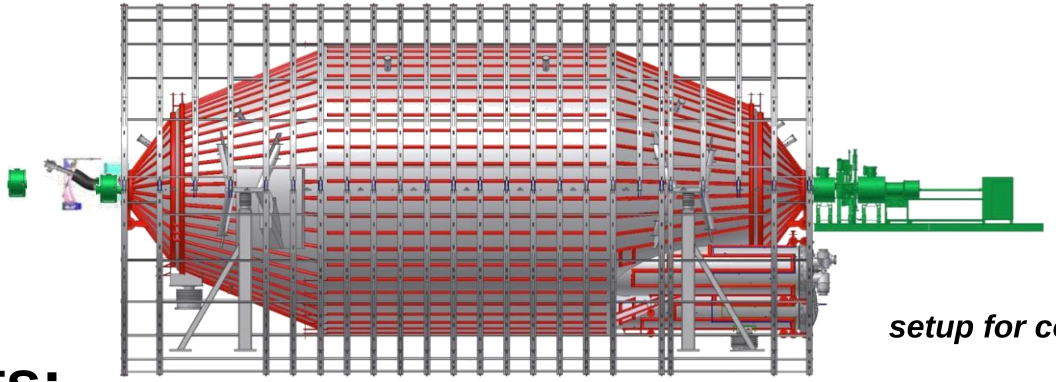


setup for comissioning 2013

- **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 m^3
  - inner surface: 1240 m^2 (including wire electrodes)

arrival at KIT: 26.11.2006

KATRIN Main Spectrometer Vacuum



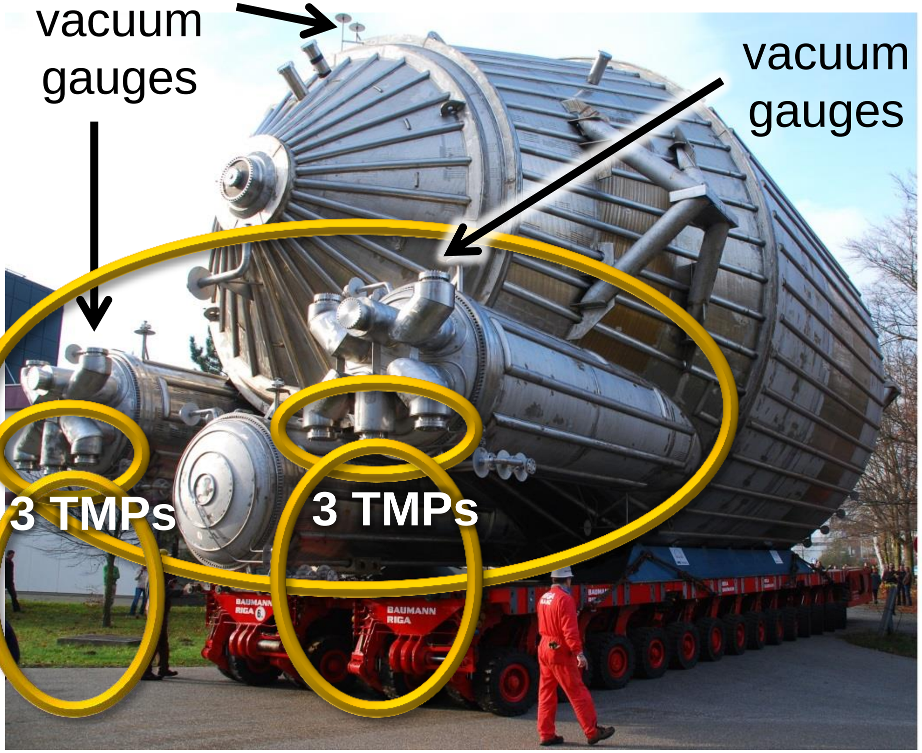
setup for comissioning 2013

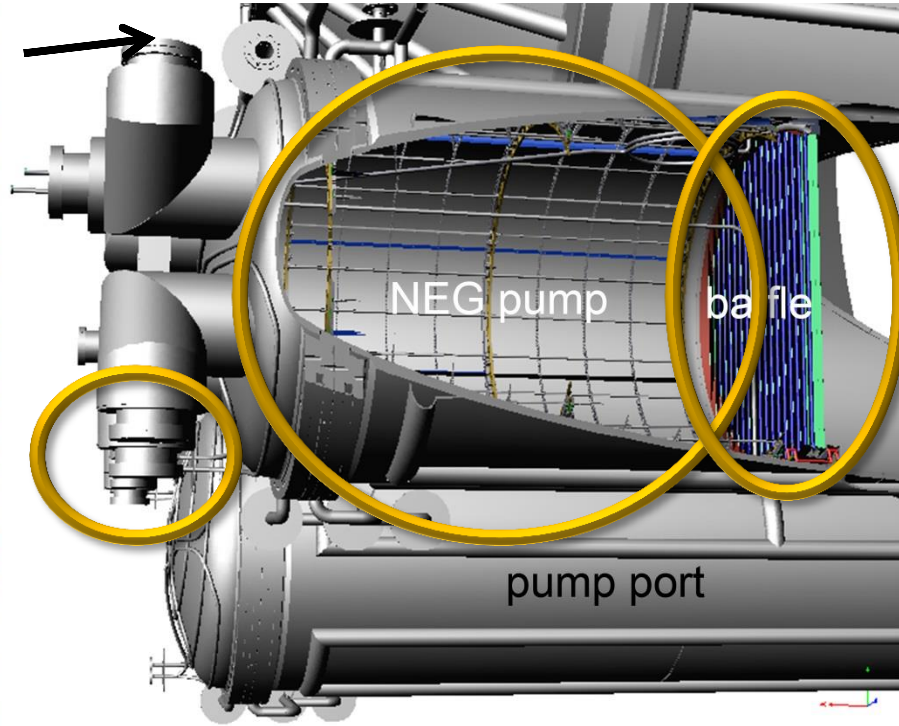
Requirements:

- **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

arrival at KIT: 26.11.2006

KATRIN Main Spectrometer Vacuum





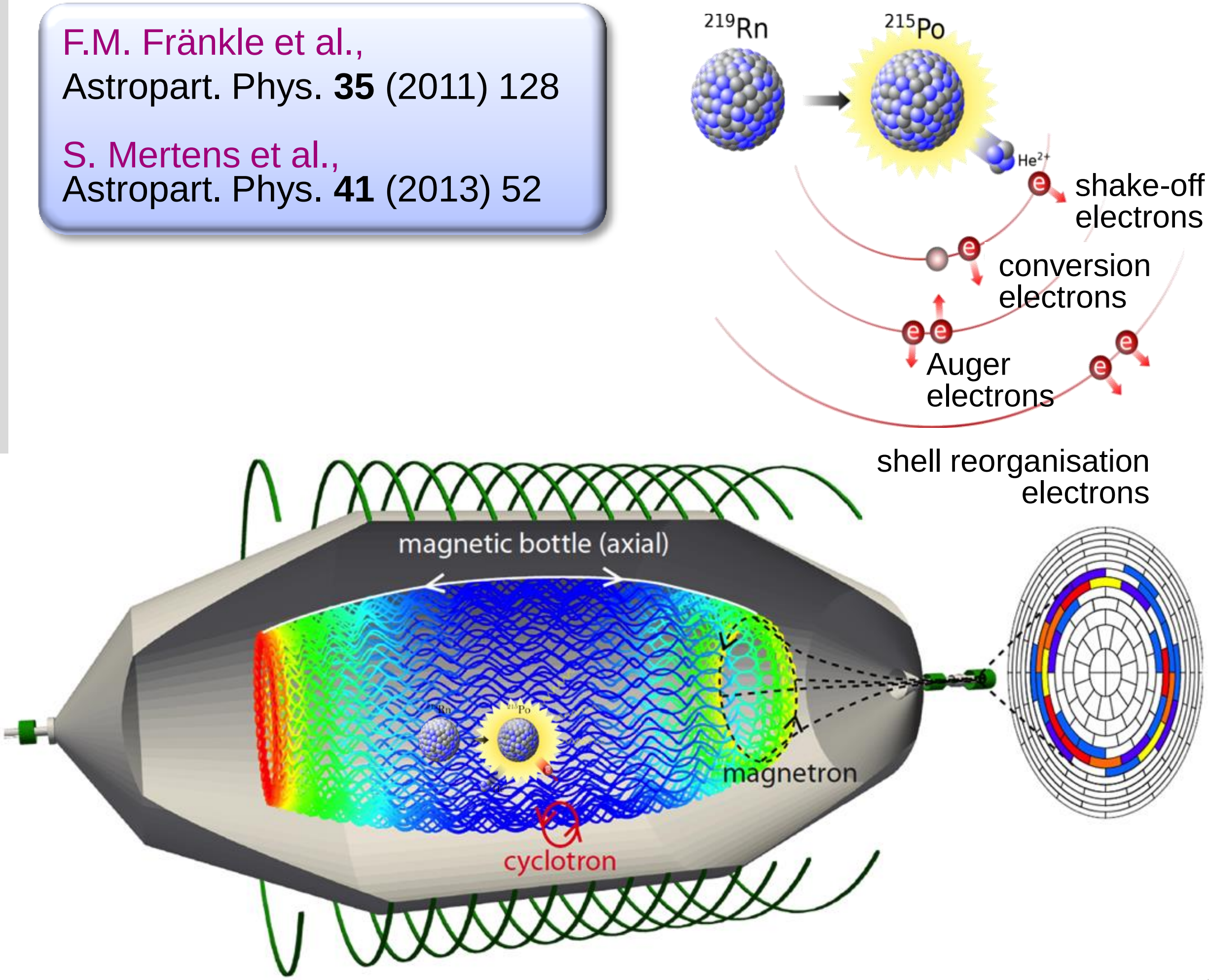
- **Roughing pump: 640 m³/h screw-pump**
- **6 turbo-molecular pumps (Leybold MAG-W 2800): 10 000 ℓ/s (H_2)**
- **Fore-vacuum: 300 ℓ/s TMP and scroll pump (30 m³/h)**
- **3 NEG-pumps (3000 m SAES St707 getter strips): ~~~10^6 ℓ/s (H_2)~~ 400 000 ℓ/s**
- **3 cryogenic LN_2 baffles (radon): ~170 000 ℓ/s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

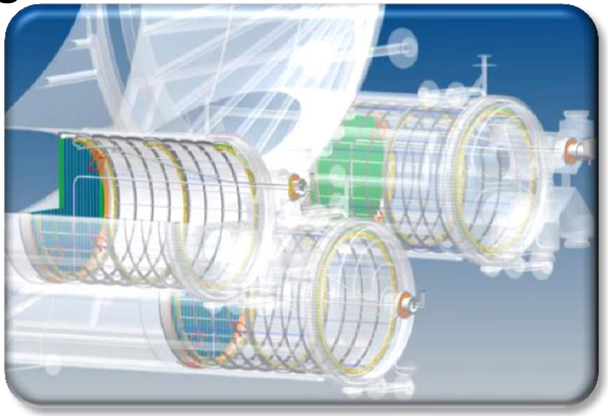
Radon as background source (problem)

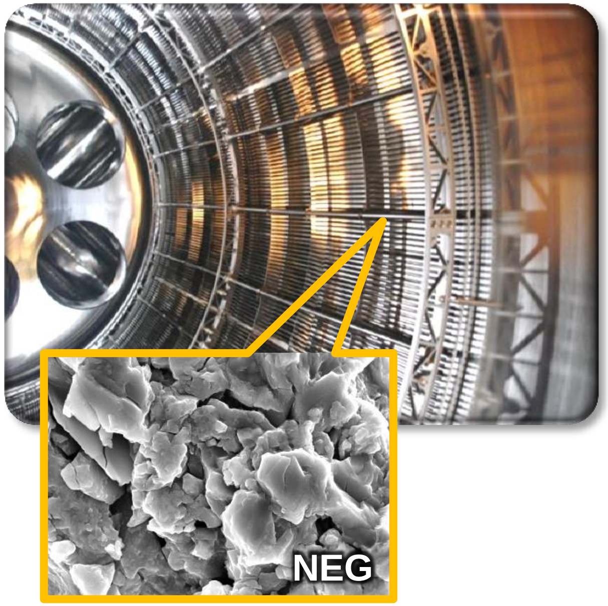
- ^{219}Rn emanation from St707 NEG getter strips (3000 m) in pump ports
- ^{220}Rn emanation from stainless steel walls/weldings

F.M. Fränkle et al.,
Astropart. Phys. **35** (2011) 128

S. Mertens et al.,
Astropart. Phys. **41** (2013) 52

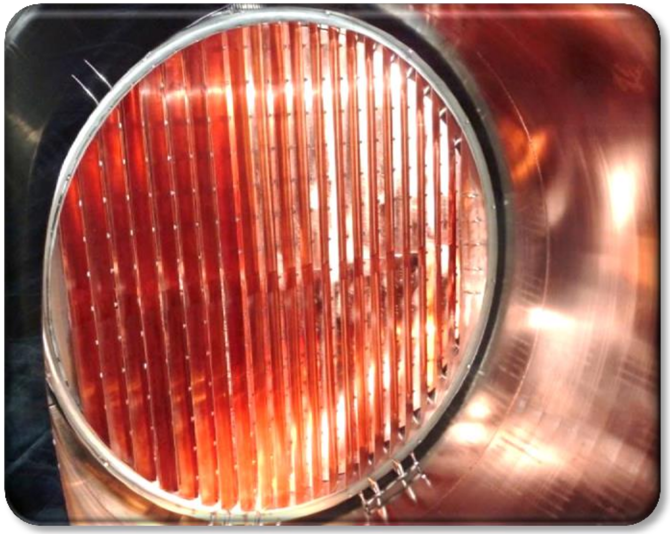


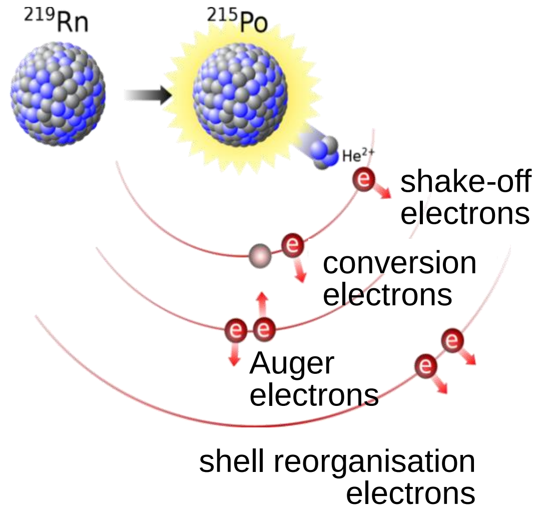


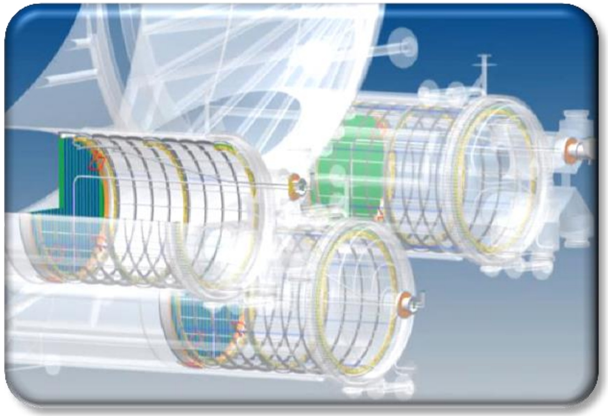


Radon as background source (solution)

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



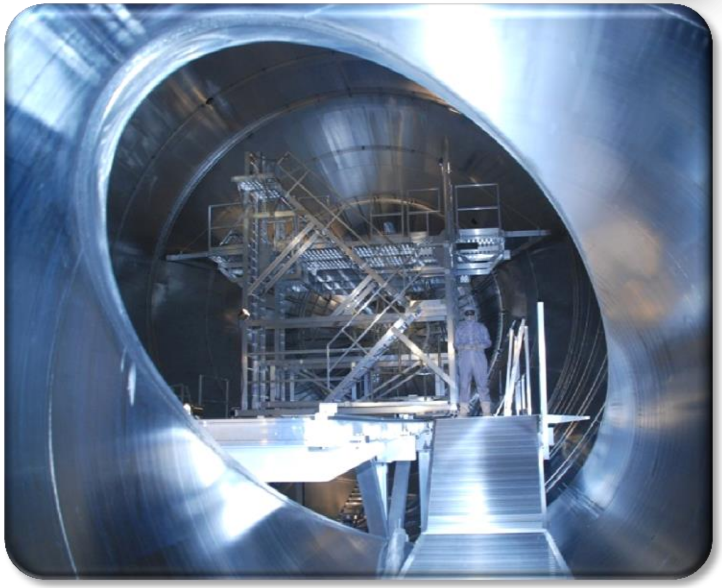




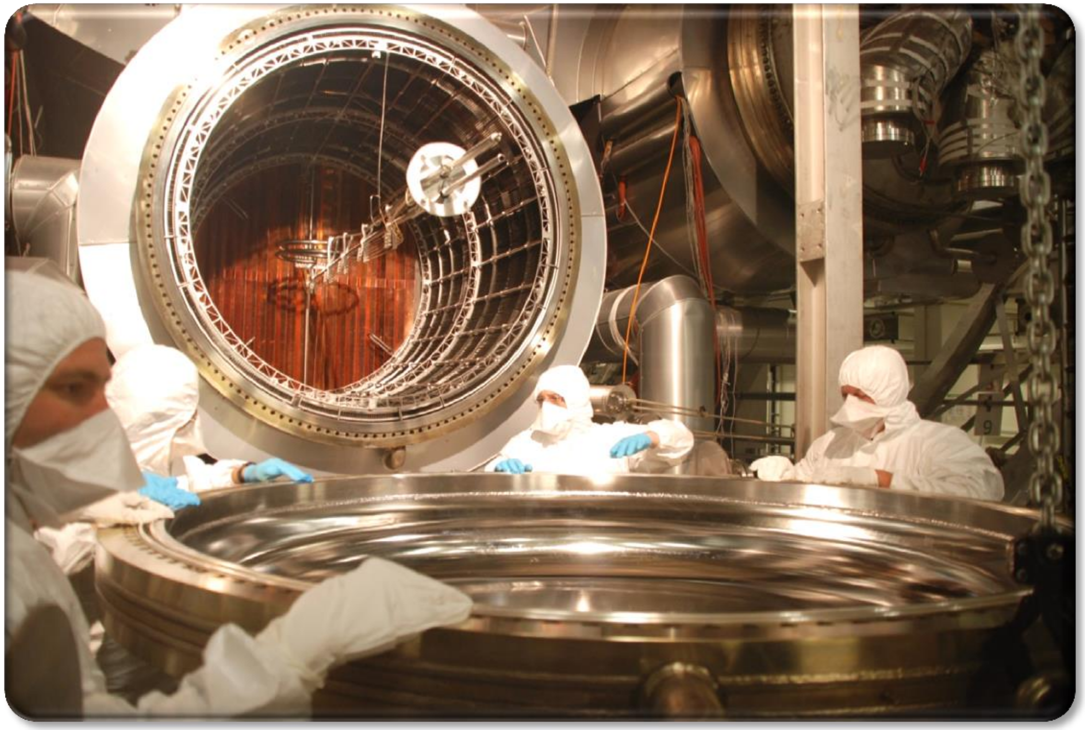
- Reduction of effective NEG pumping speed: 40%
- Reduction of Rn flow into main volume : ~ 0.4%
- Pumping speed for Rn from walls: 170 000 ℓ/s

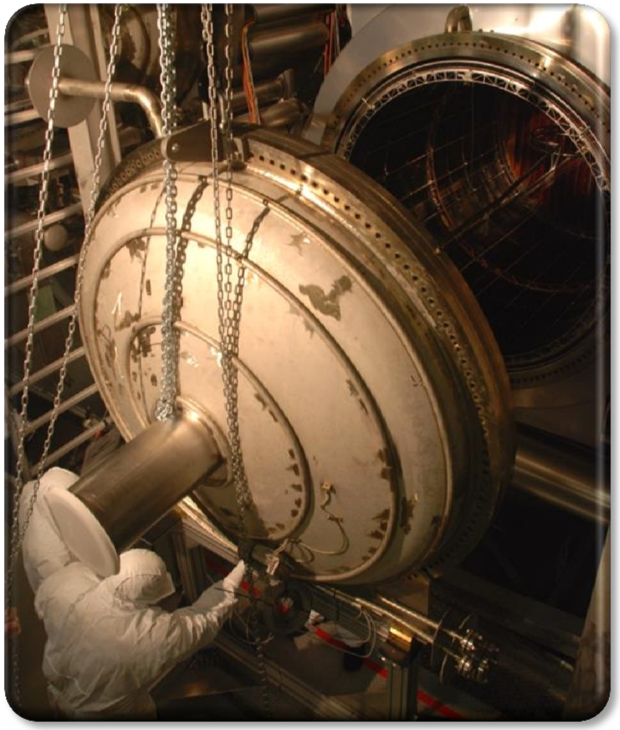
2008 – 2012: Wire Electrode Installation

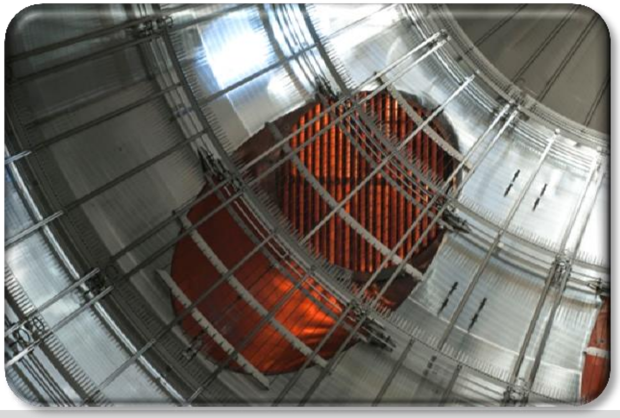
- **248 wire electrodes on the inner surface**
  - 23 440 insulated wires
  - 120 000 individual parts
- **Installed under cleanroom conditions**



2012: All Components Installed



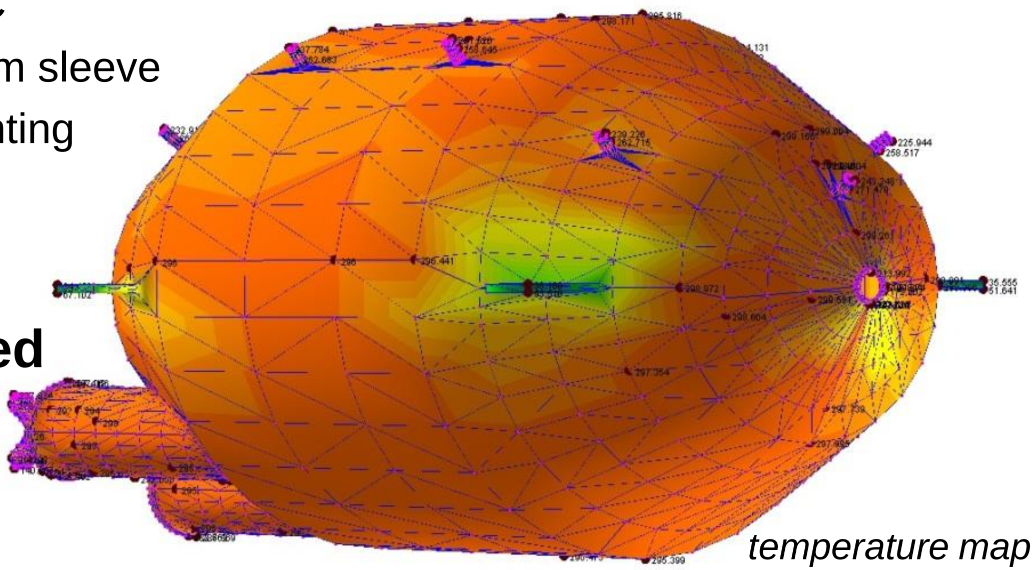




- **Electrode installation completed**
- **Vacuum system installed**
- **Successful leak test**
- **Commissioning of heating and vacuum control system (PCS7)**

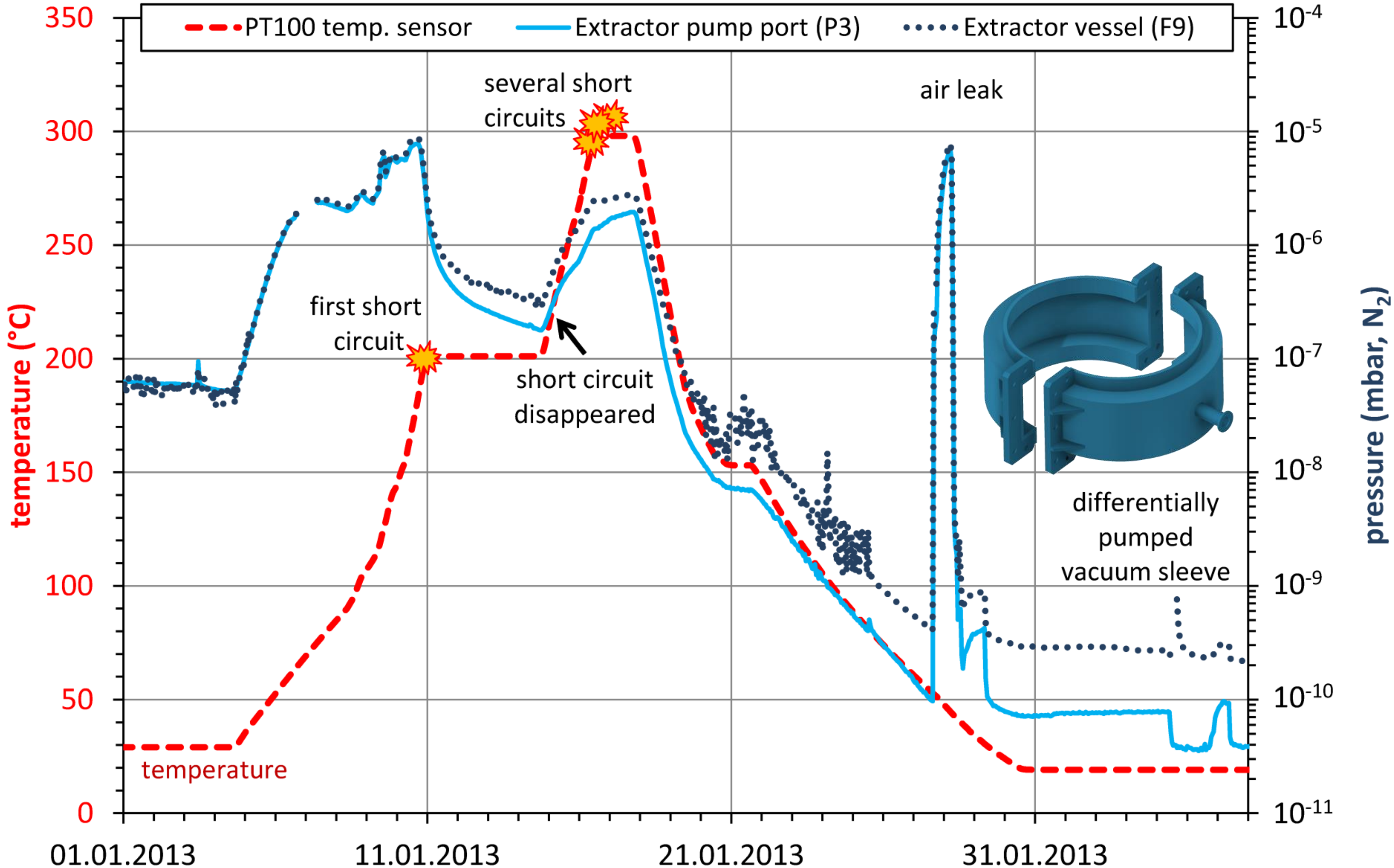
2013: Spectrometer Commissioning

- **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**



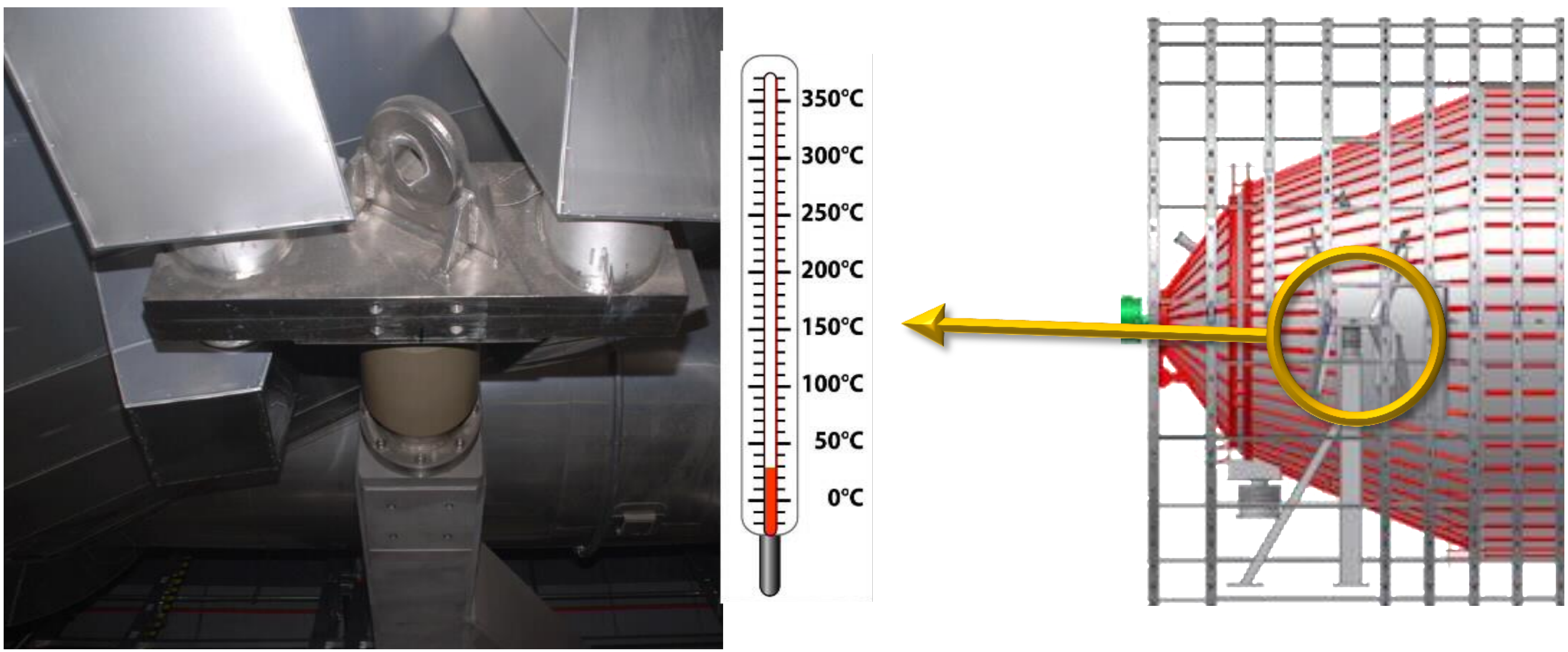
temperature map

Spectrometer Commissioning: Bake-out

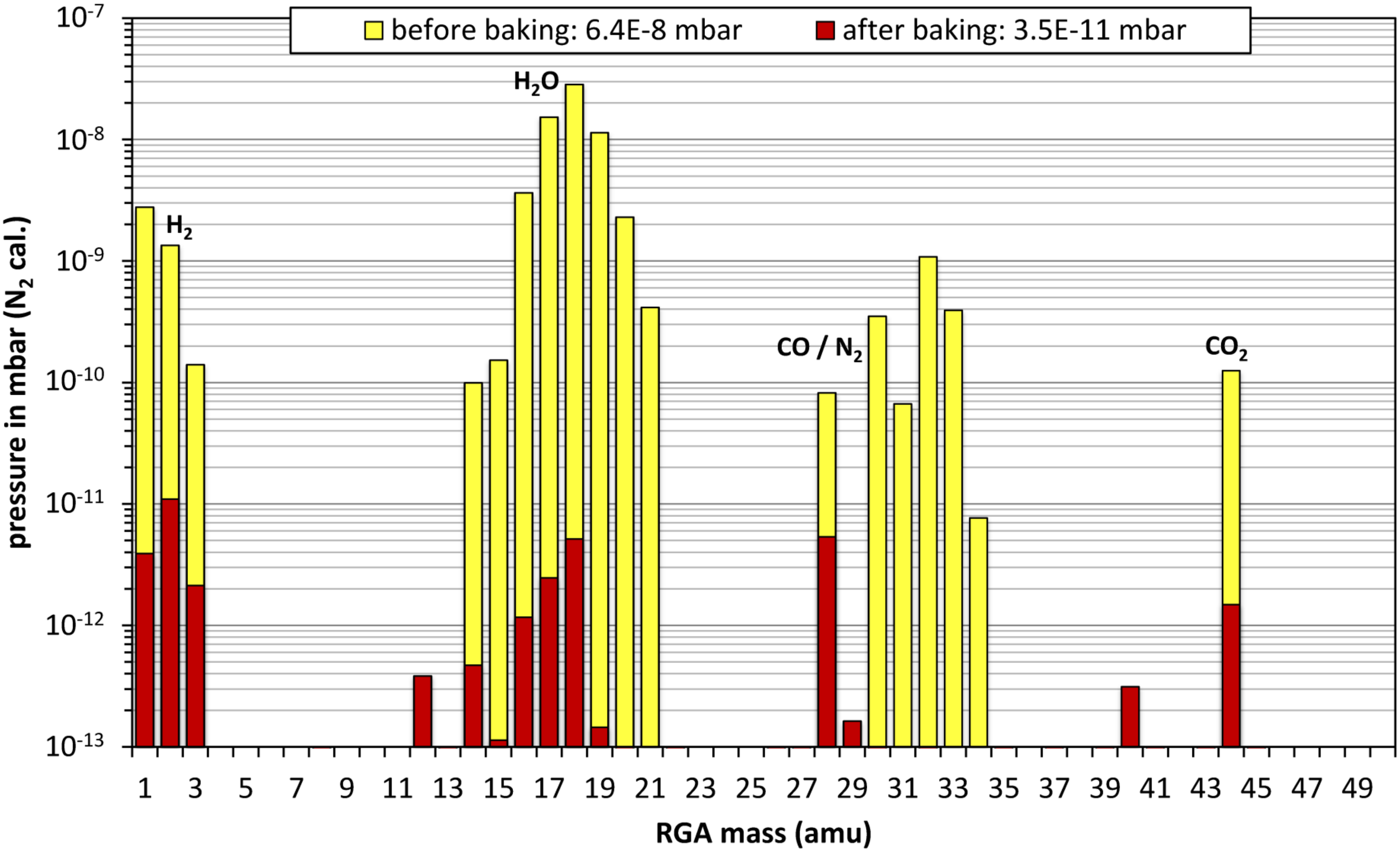


Baking of the Main Spectrometer

- **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**

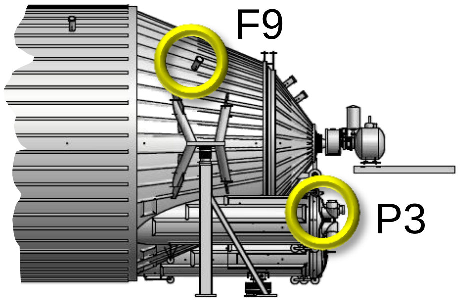


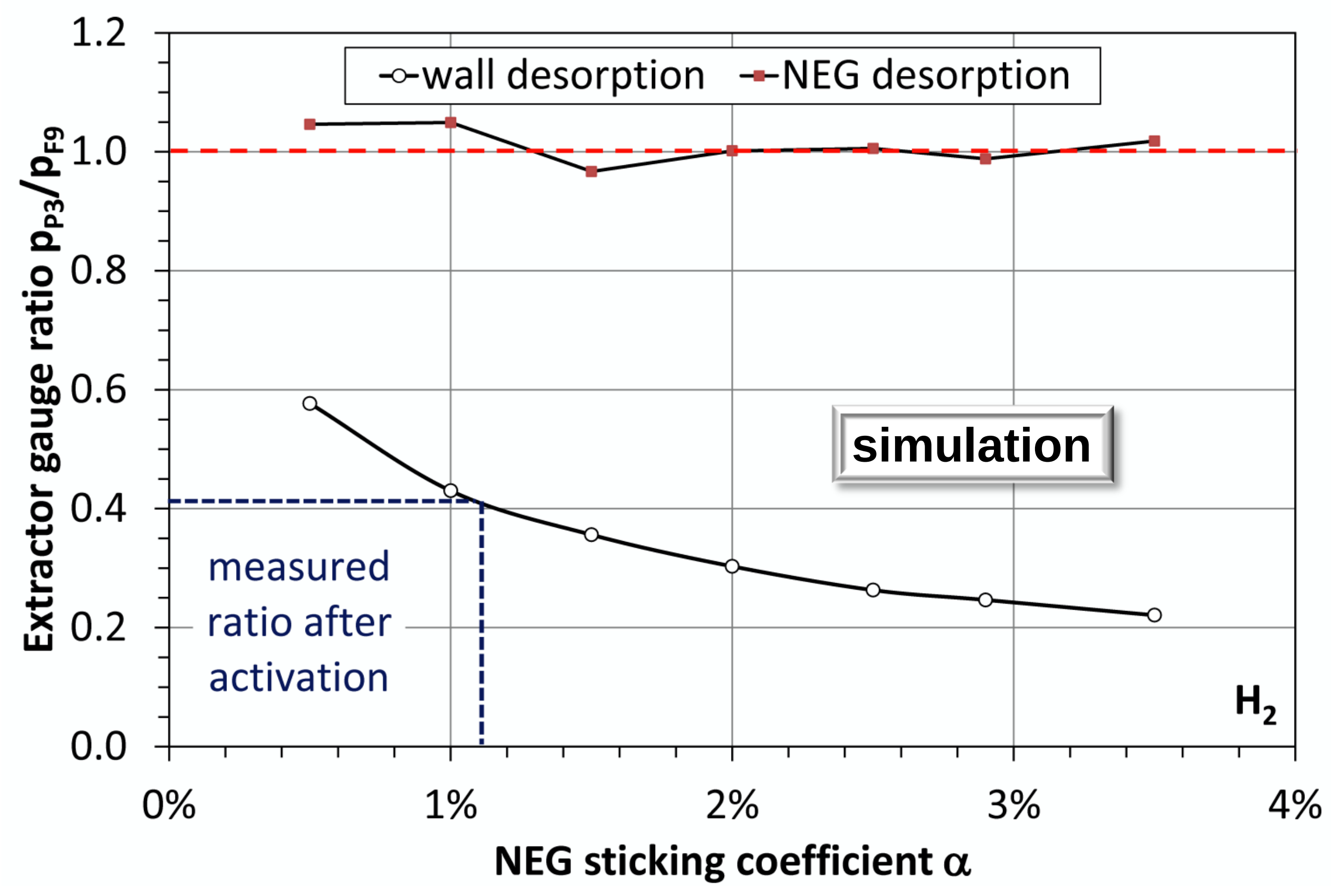
Vacuum status after bake-out



NEG activation

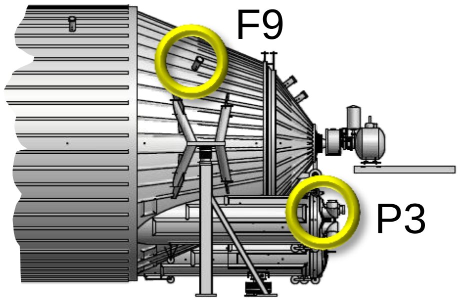
- **Indicator for NEG activation:**
  - pressure ratio between vessel and pump port

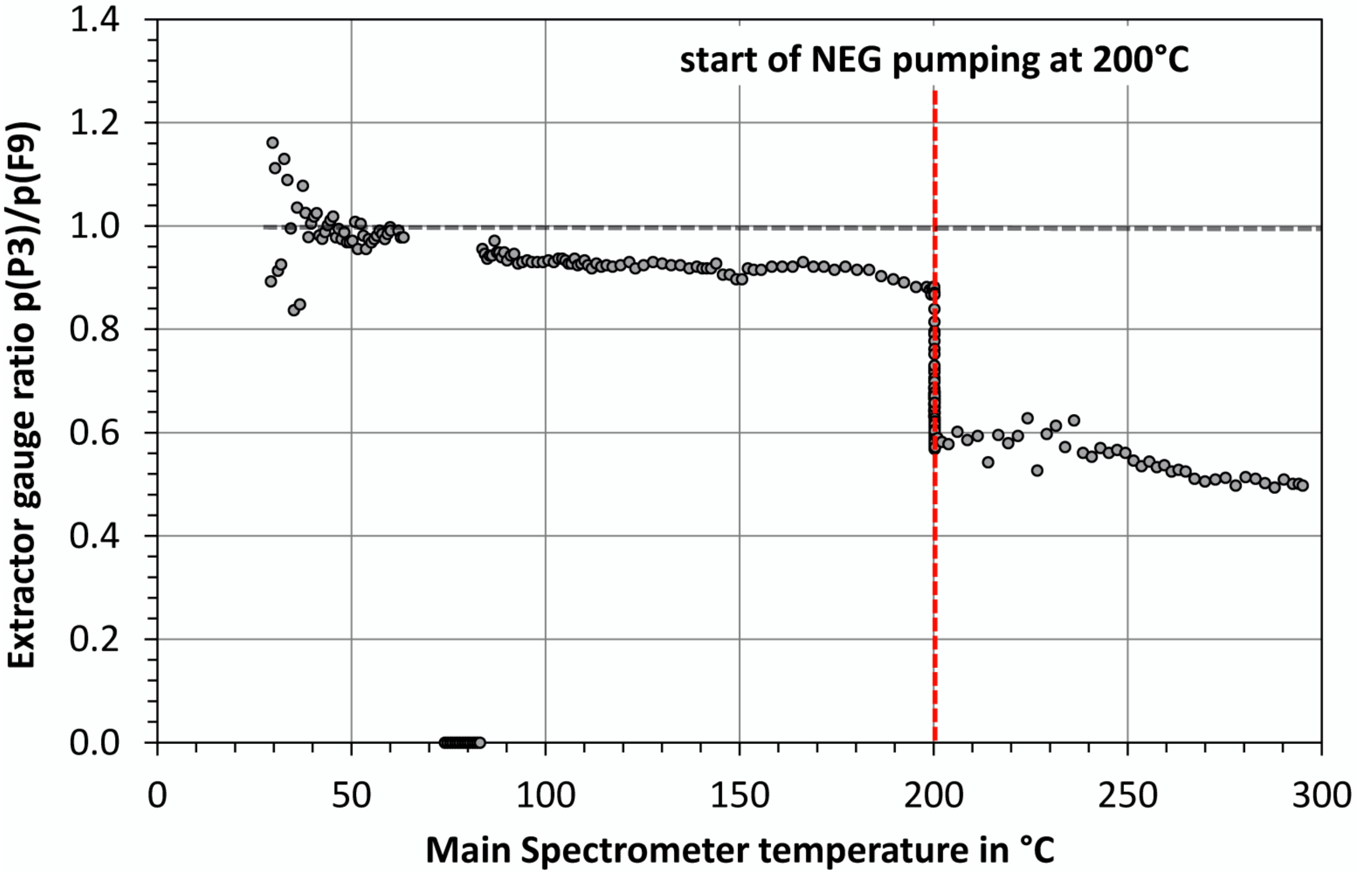




NEG activation

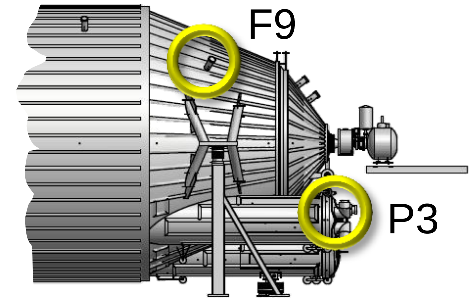
- **Indicator for NEG activation:**
  - pressure ratio between vessel and pump port
  - first indication for NEG pumping at 200°C

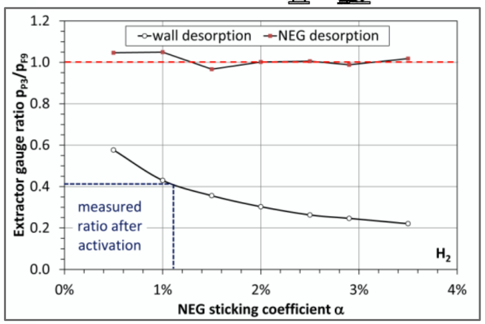


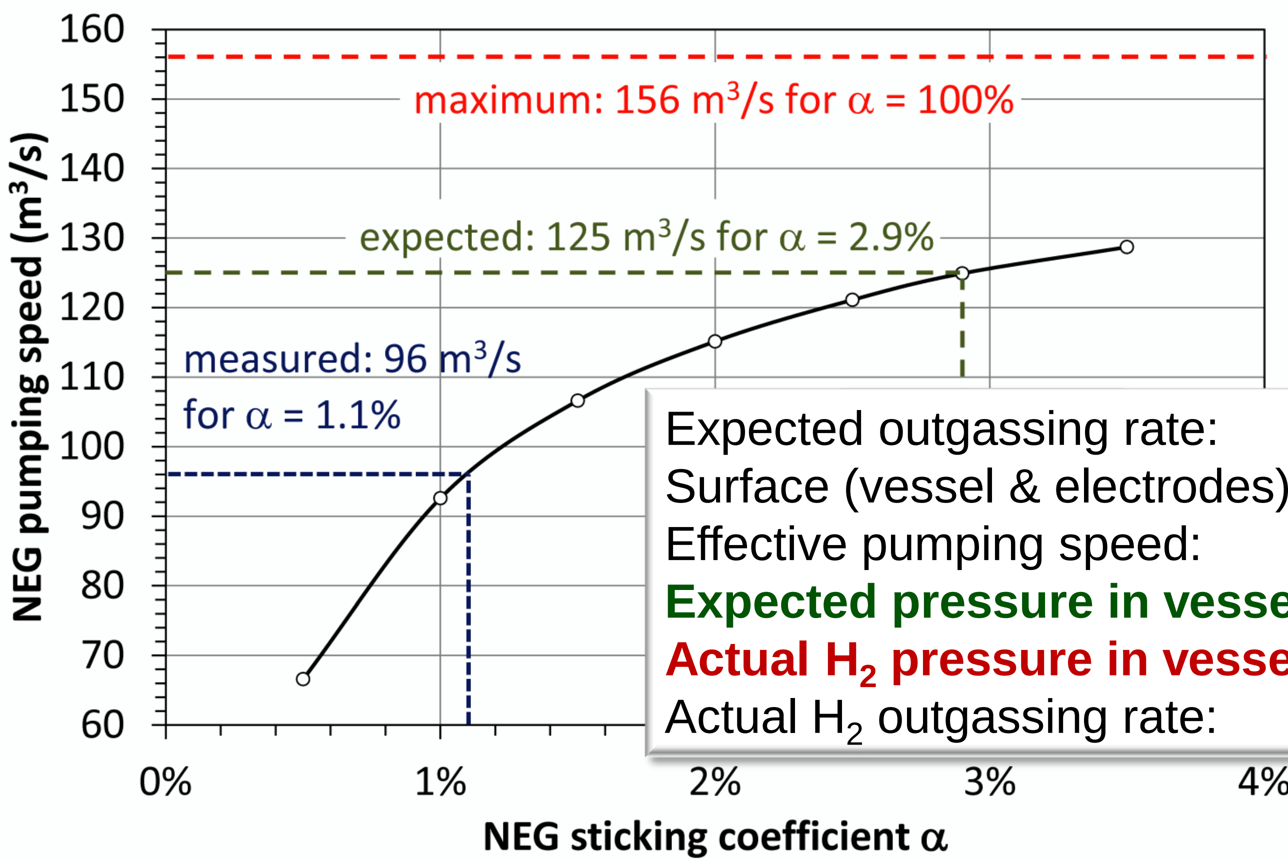


NEG activation

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



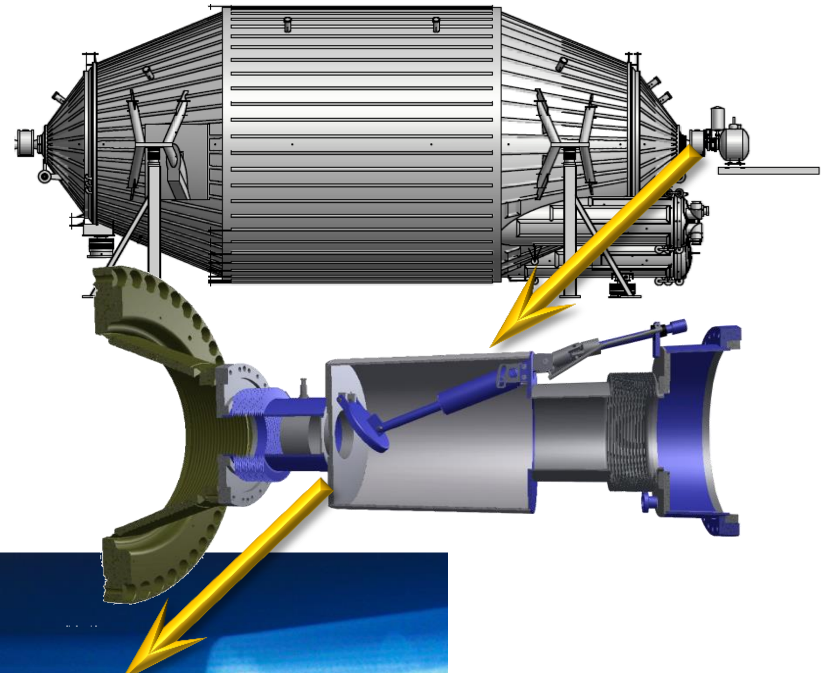


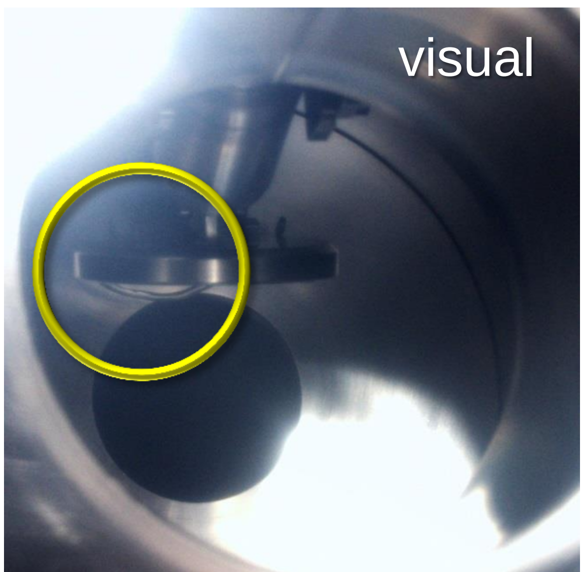


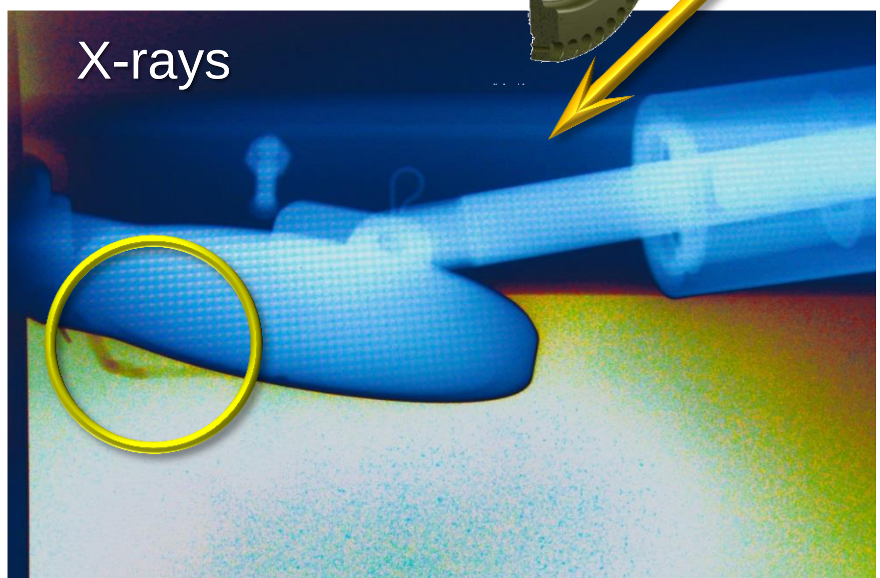
Expected outgassing rate:	10^{-12} mbar·ℓ/s·cm^2
Surface (vessel & electrodes):	1240 m^2
Effective pumping speed:	375 m^3/s
Expected pressure in vessel:	**$3.3 \cdot 10^{-11}$ mbar**
Actual H_2 pressure in vessel:	**$5.7 \cdot 10^{-11}$ mbar**
Actual H_2 outgassing rate:	$1.4 \cdot 10^{-12}$ mbar·ℓ/s·cm^2

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



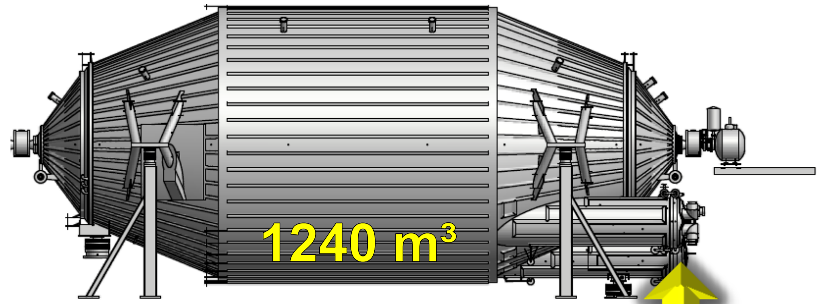




Coupling of Spectrometer and Detector

Karlsruhe Institute of Technology

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



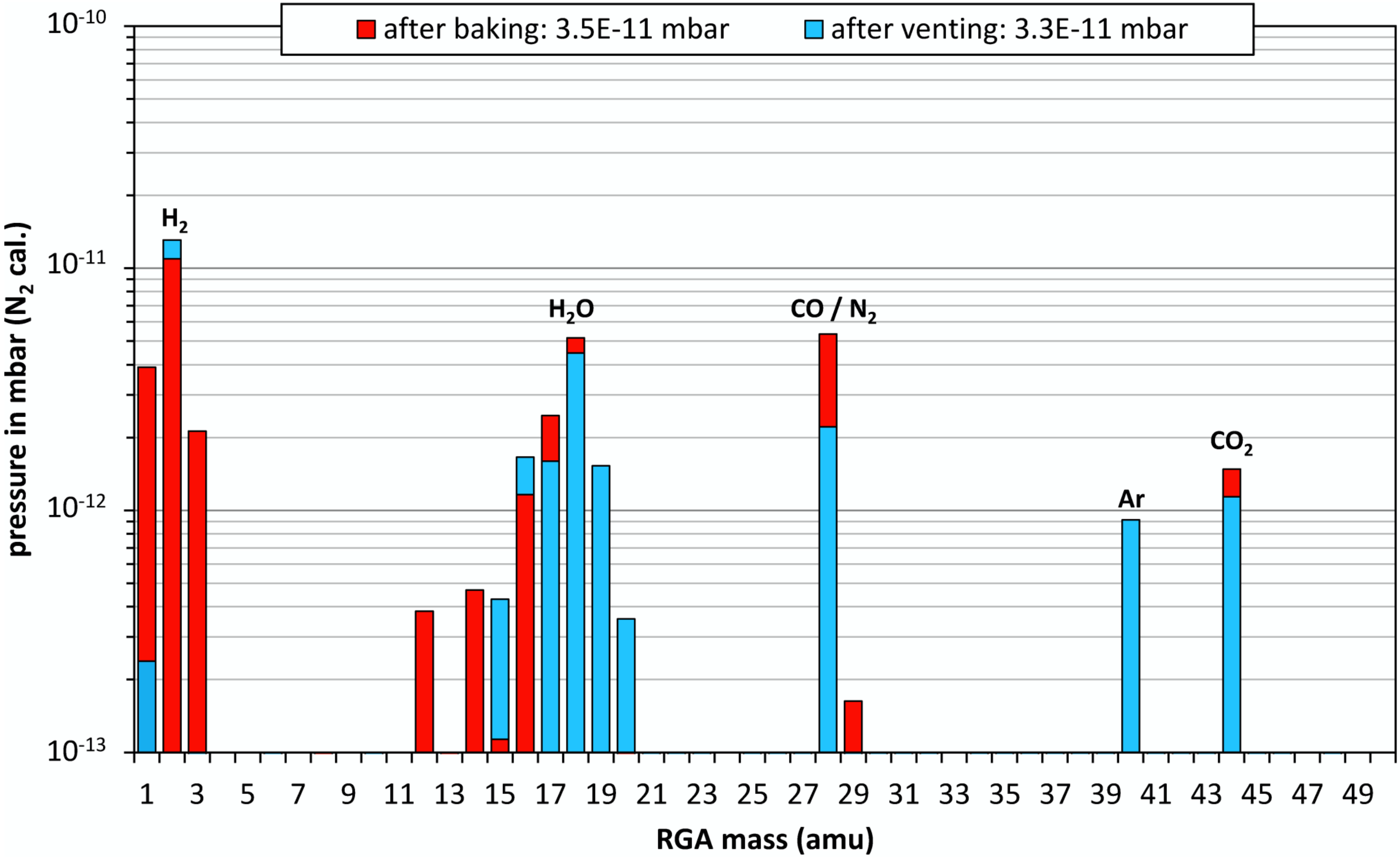
Ar 9.0

144 bottles Argon N6.0

XENON 1t
gas purification system (SAES)

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

Vacuum status after venting with argon



Conclusions / next steps

- **KATRIN Main Spectrometer has been commissioned in 2013**
  - Vacuum system works as expected, despite some problems
  - Leaks in 2 CF flanges reduced with vacuum sleeves
- **NEG activation at 300°C / 28h successful**
  - Effective pumping speed at 77% of expected value
- **Vessel vented with ultra-clean argon**
  - Valve repaired under Ar atmosphere
  - NEG still active after venting and pump-down
  - Similar pressure as before venting
- **LN2 baffles for radon capture work**
  - Clear background reduction observed
- **Improvements / repairs:**
  - Repair short circuits (partly done)
  - Re-modelling of NEG pumps for electrical heating (one finished and tested)
  - Improved vacuum diagnostics (remote controlled gas inlet, flow measurement)
- **Next round of test measurements started in Oct. 2014**
- **Start of neutrino measurements: end of 2016**

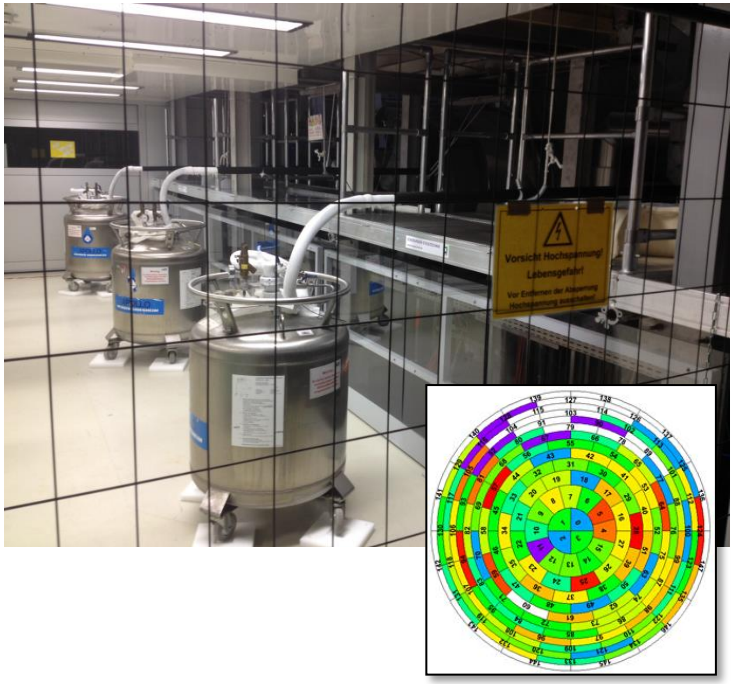
Thank you for your attention

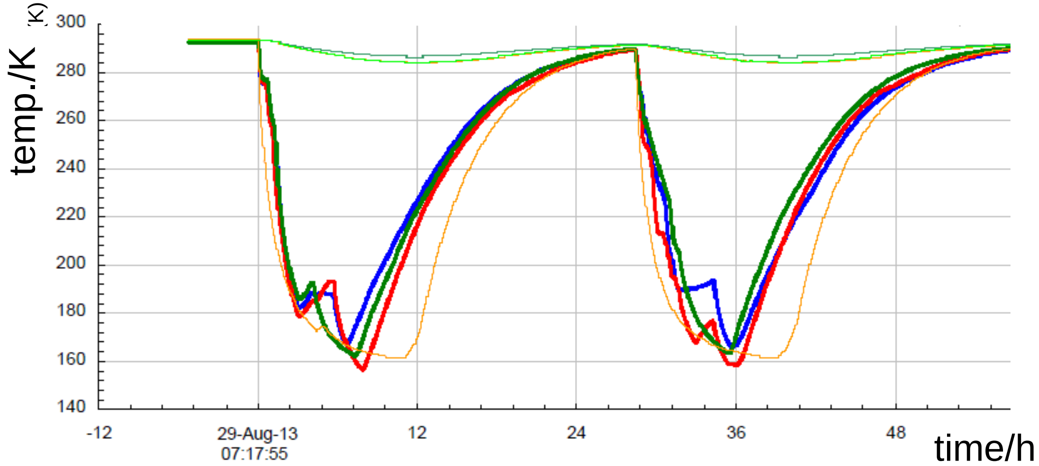
Supported by: *DoE and* Federal Ministry of Education and Research

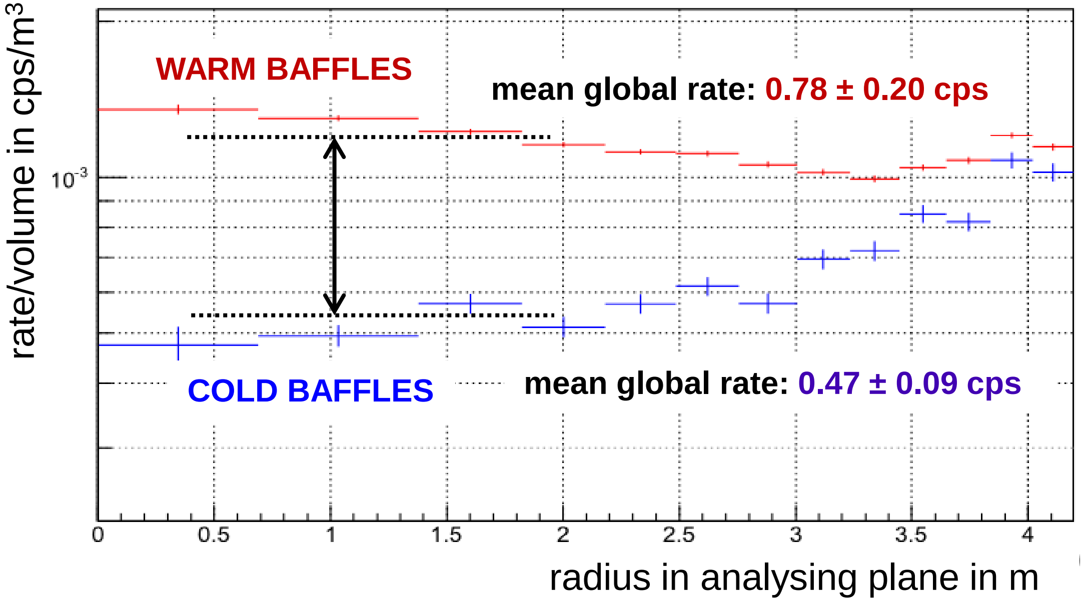
Backup slides

Results on the Radon Induced Background

Measurements with cold baffles and high voltage

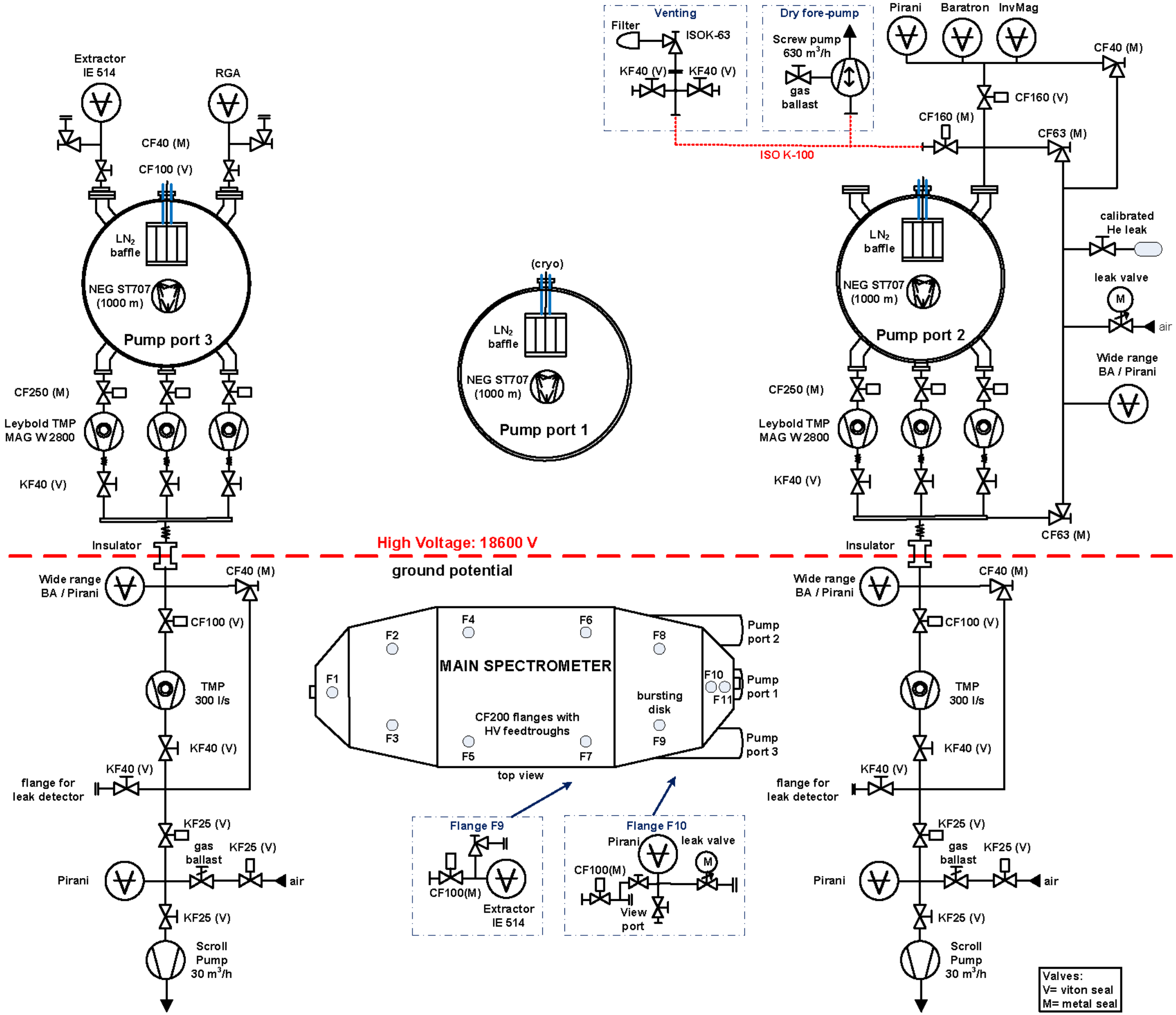






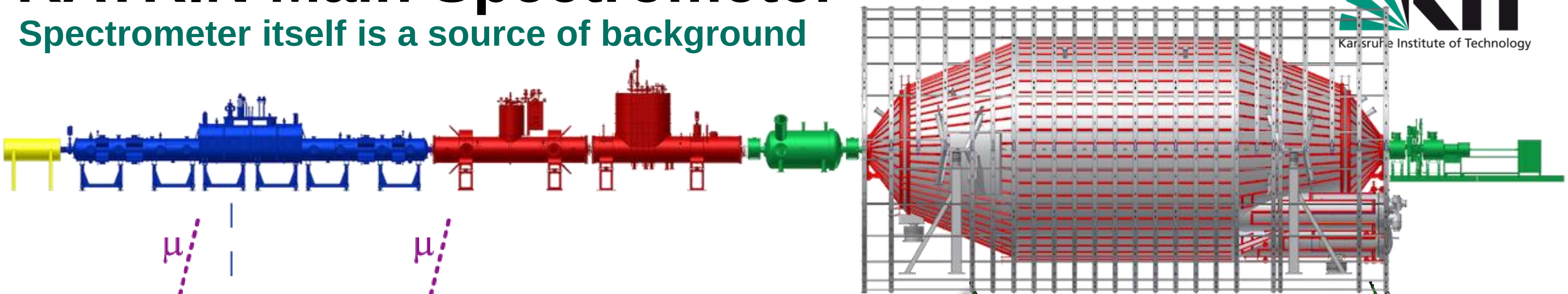
- Two short measurements
- Background strongly reduced
- Proof of principle: baffles work as expected
- Long-term performance will be tested in 2014/2015

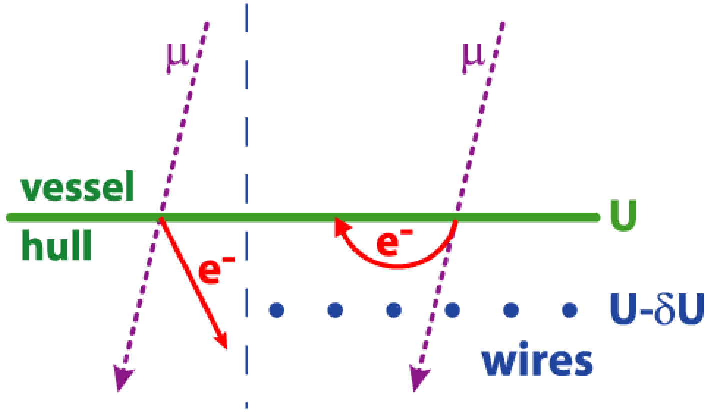
Vacuum scheme of the Main Spectrometer

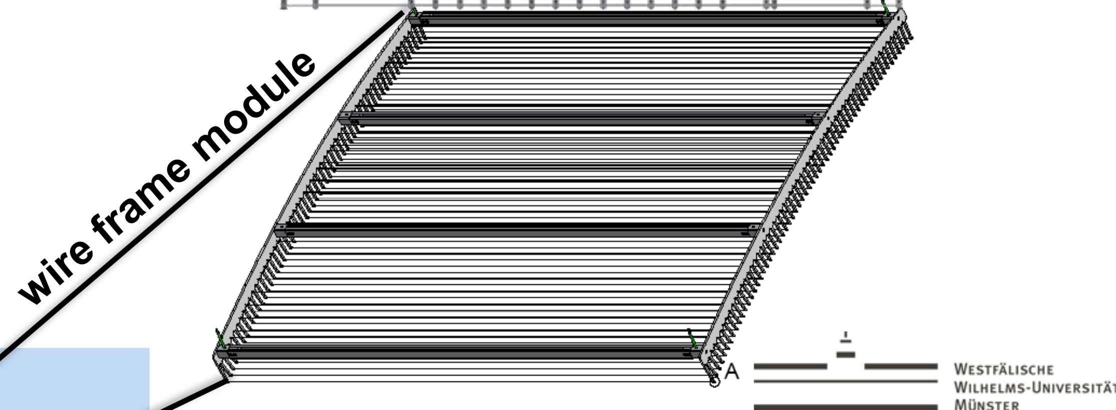


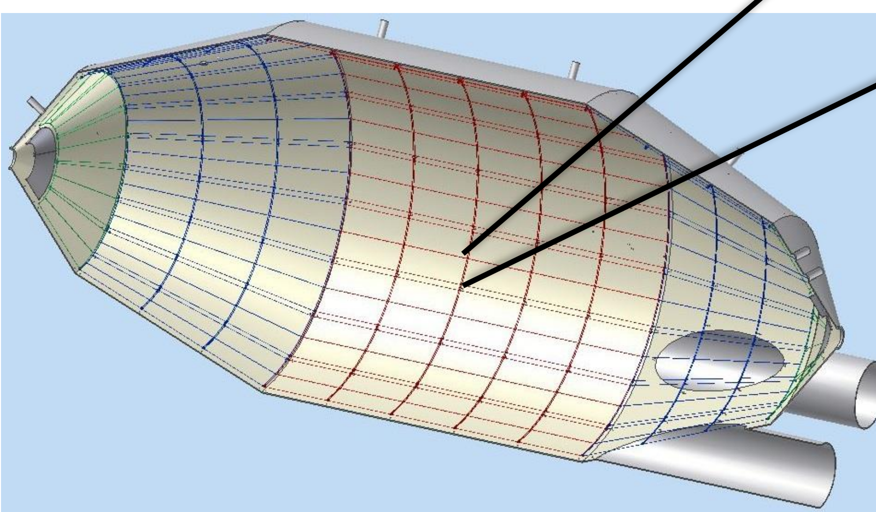
KATRIN Main Spectrometer

Spectrometer itself is a source of background









Wire defines electrostatic filter:

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

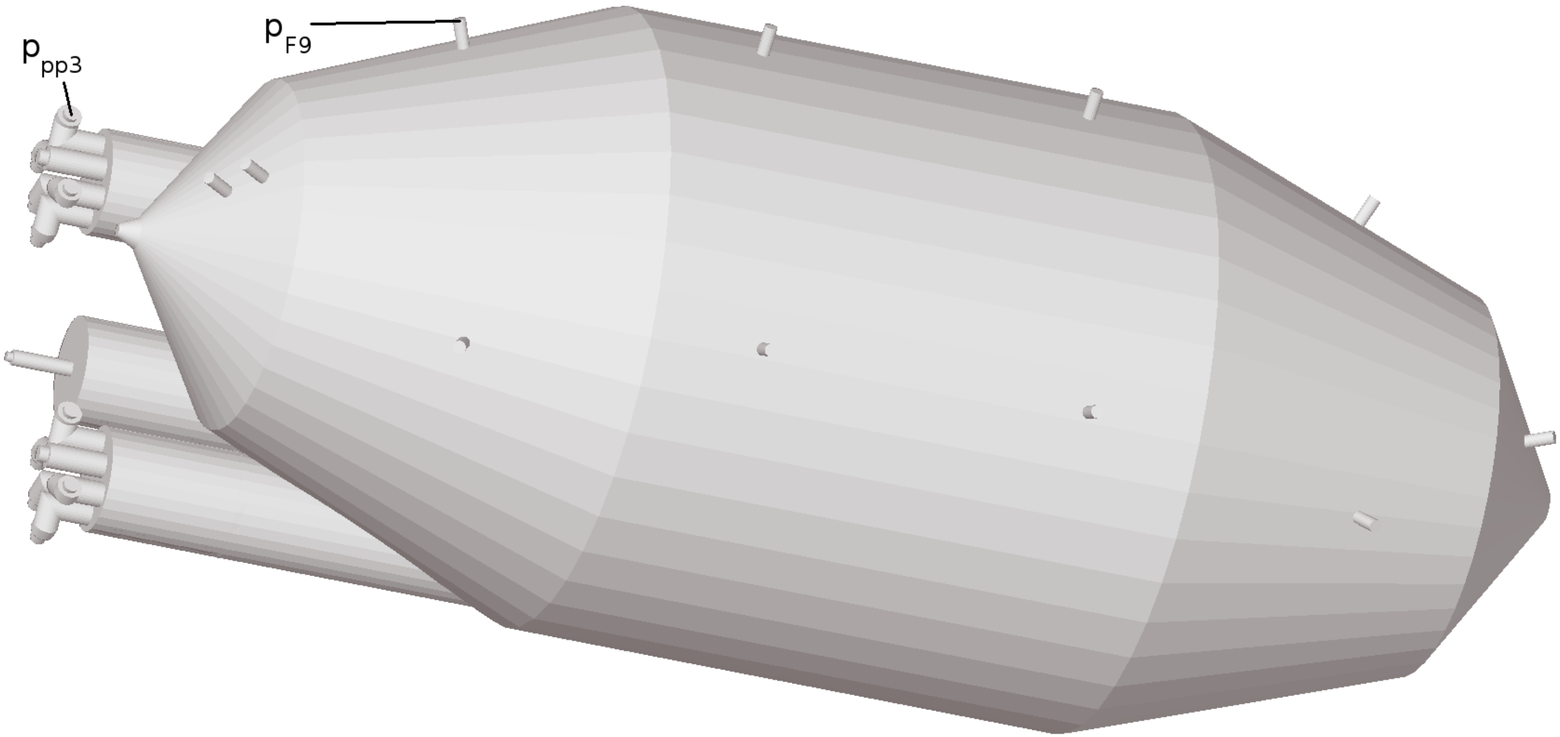
K. Valerius et al., Particle and Nuclear Physics, Volume 64, Issue 2, April 2010

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

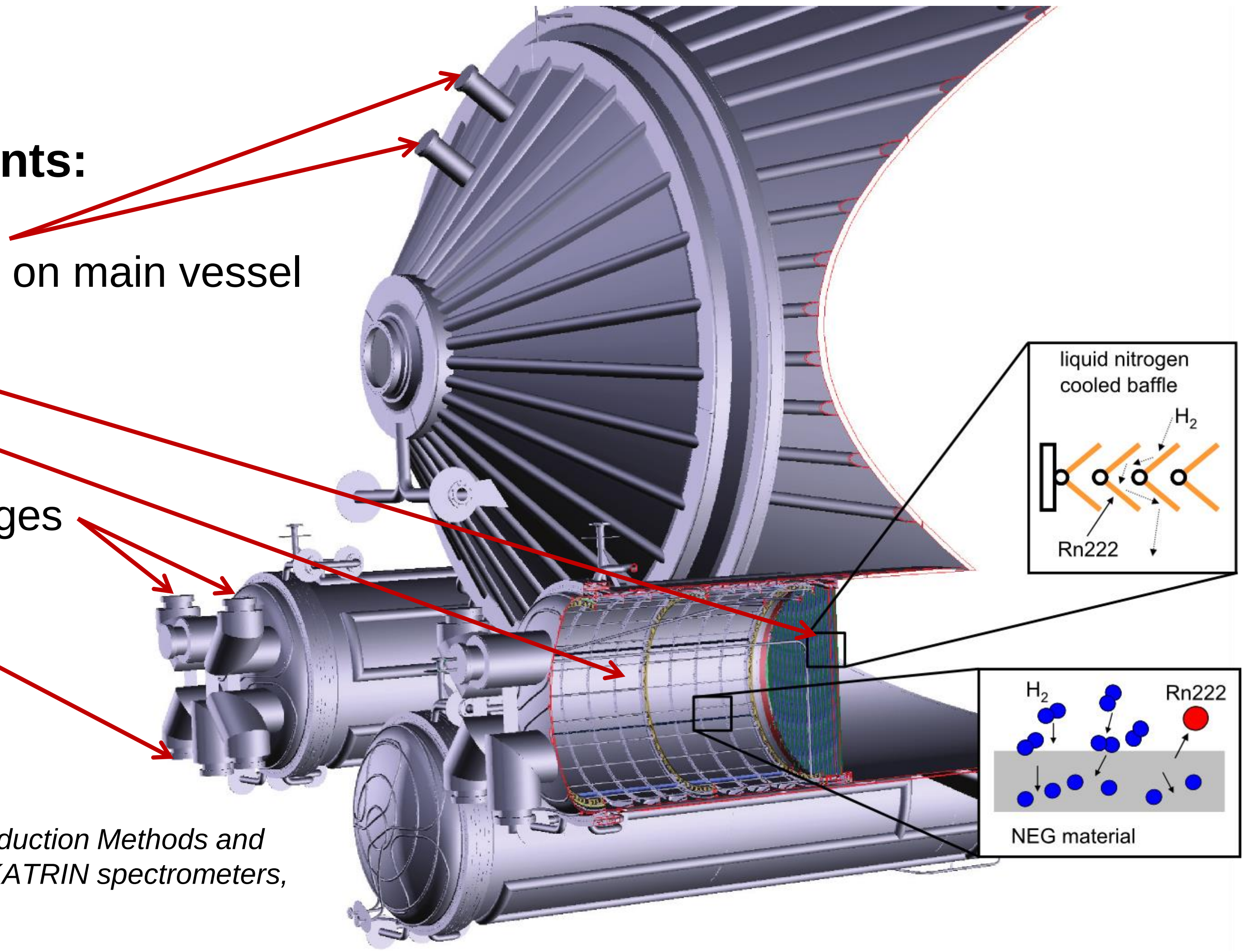
- **three possible gas sources for hydrogen and radon:**
  - complete stainless steel tank
  - NEG strips in pump ports
  - diagonal virtual area in one pump port (cross section between port and vessel) for determination of pumping speeds

- **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**: $\boldsymbol{S}(\mathrm{M}) = {}^{1}/_{4}\, \bar{c}_M \cdot A_{port} \cdot \boldsymbol{w}$

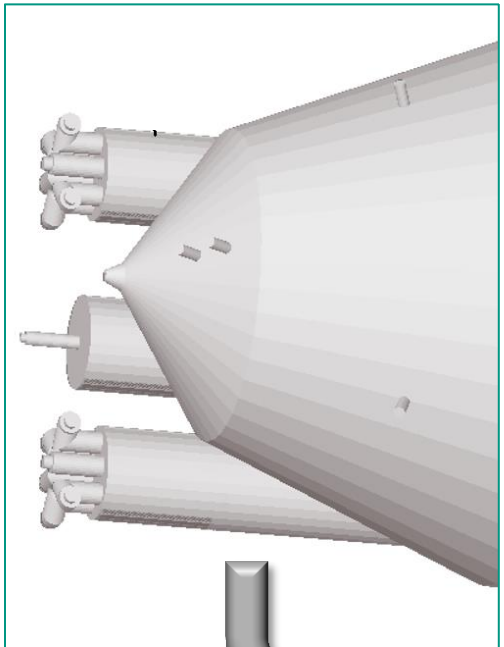
$\bar{c}$: mean molecular speed for mass M

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

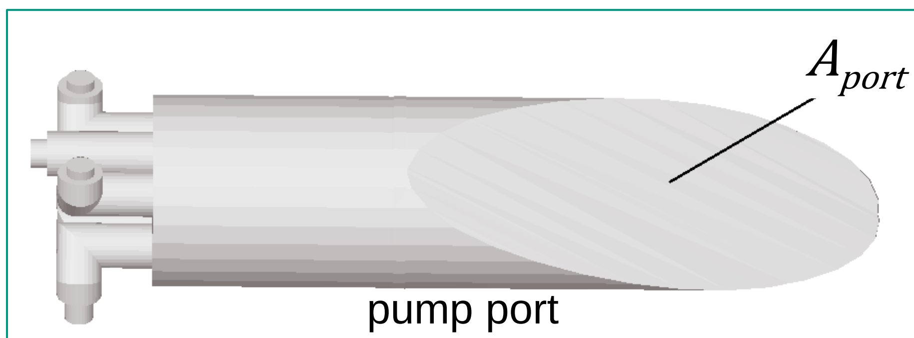
A_{port} : desorption area (virtual area)

N_{ads} : number of adsorptions in pump

N_{des} : total desorption number

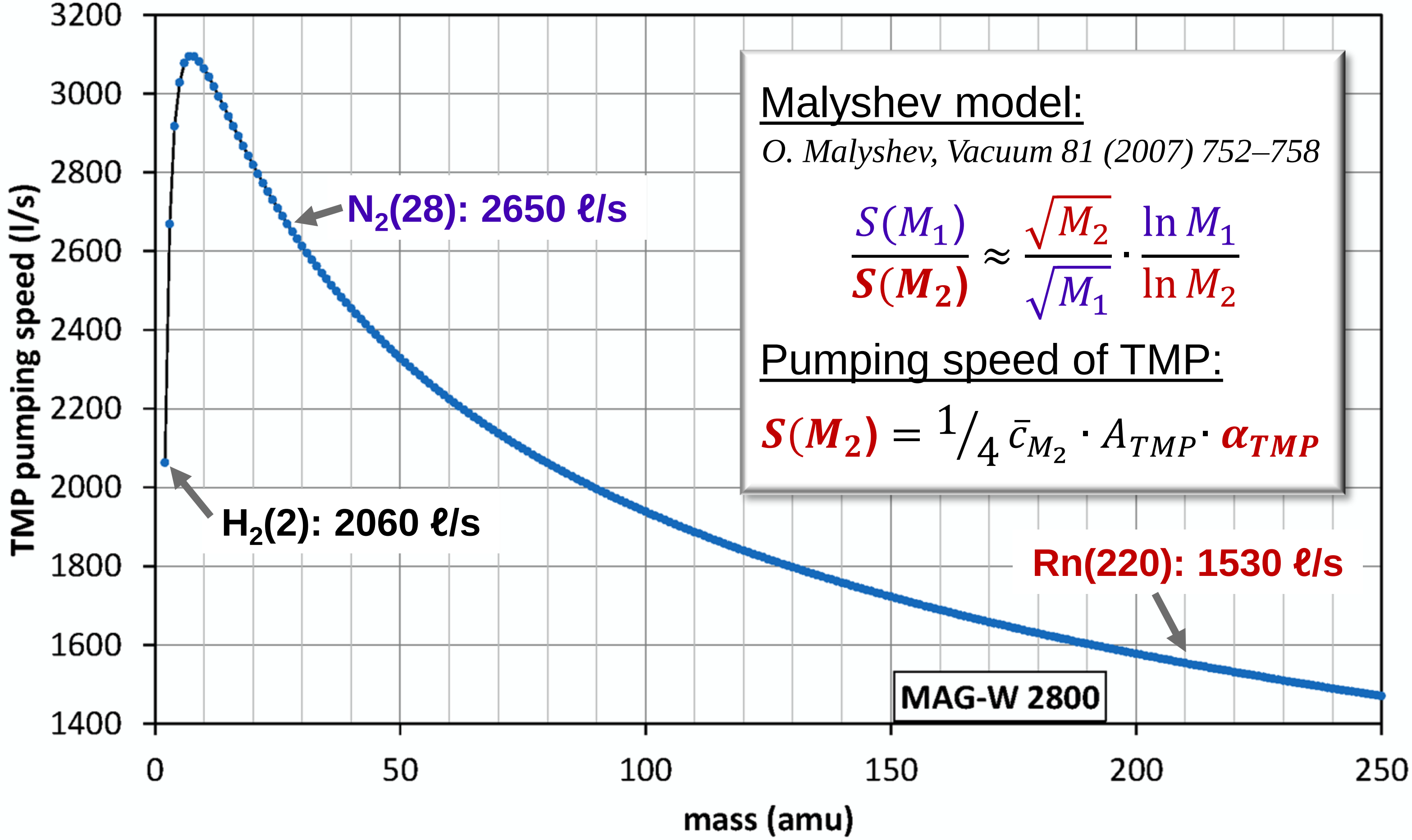


simplified model



TMP simulation

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



Malyshev model:

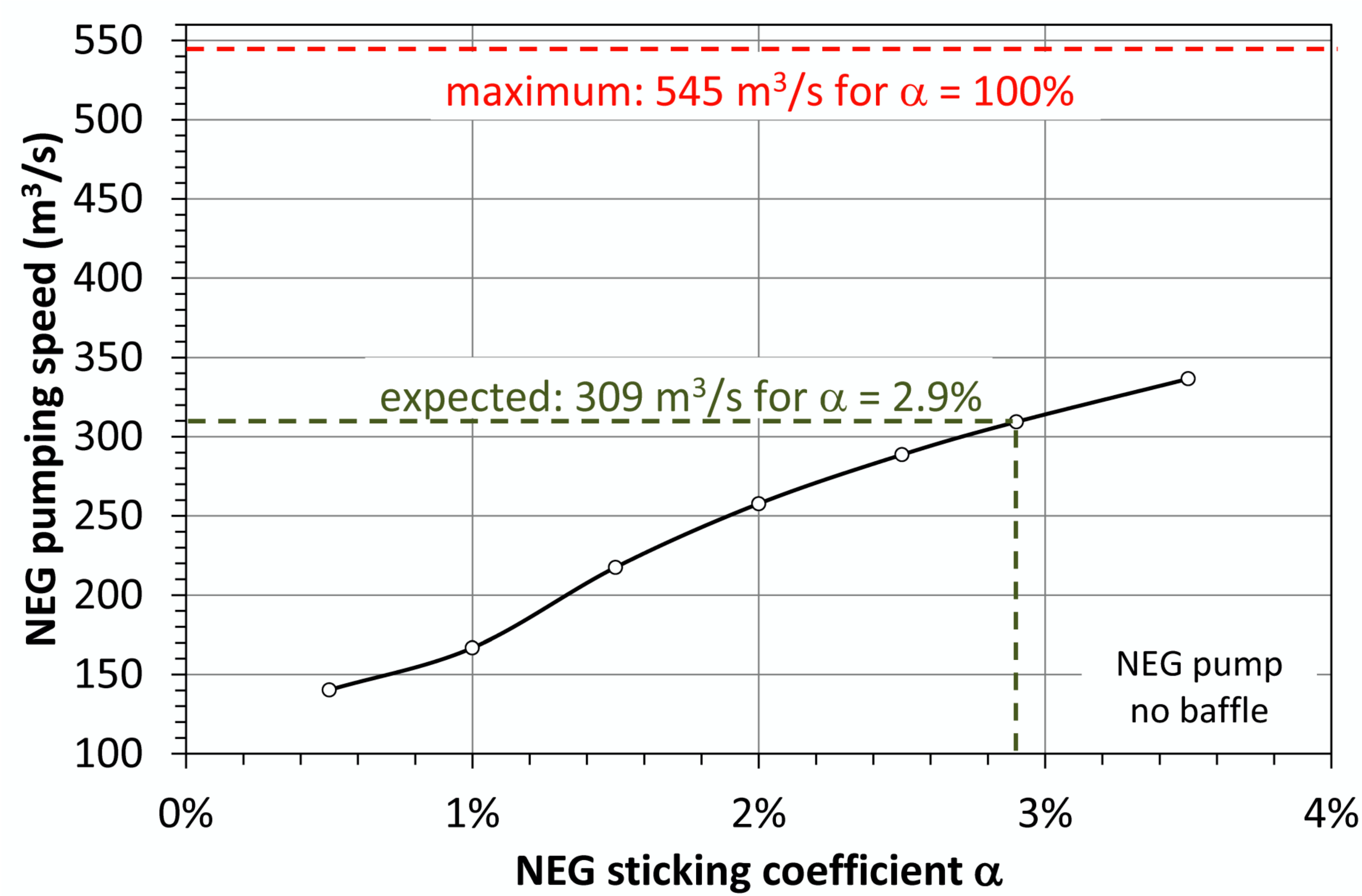
O. Malyshev, Vacuum 81 (2007) 752–758

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

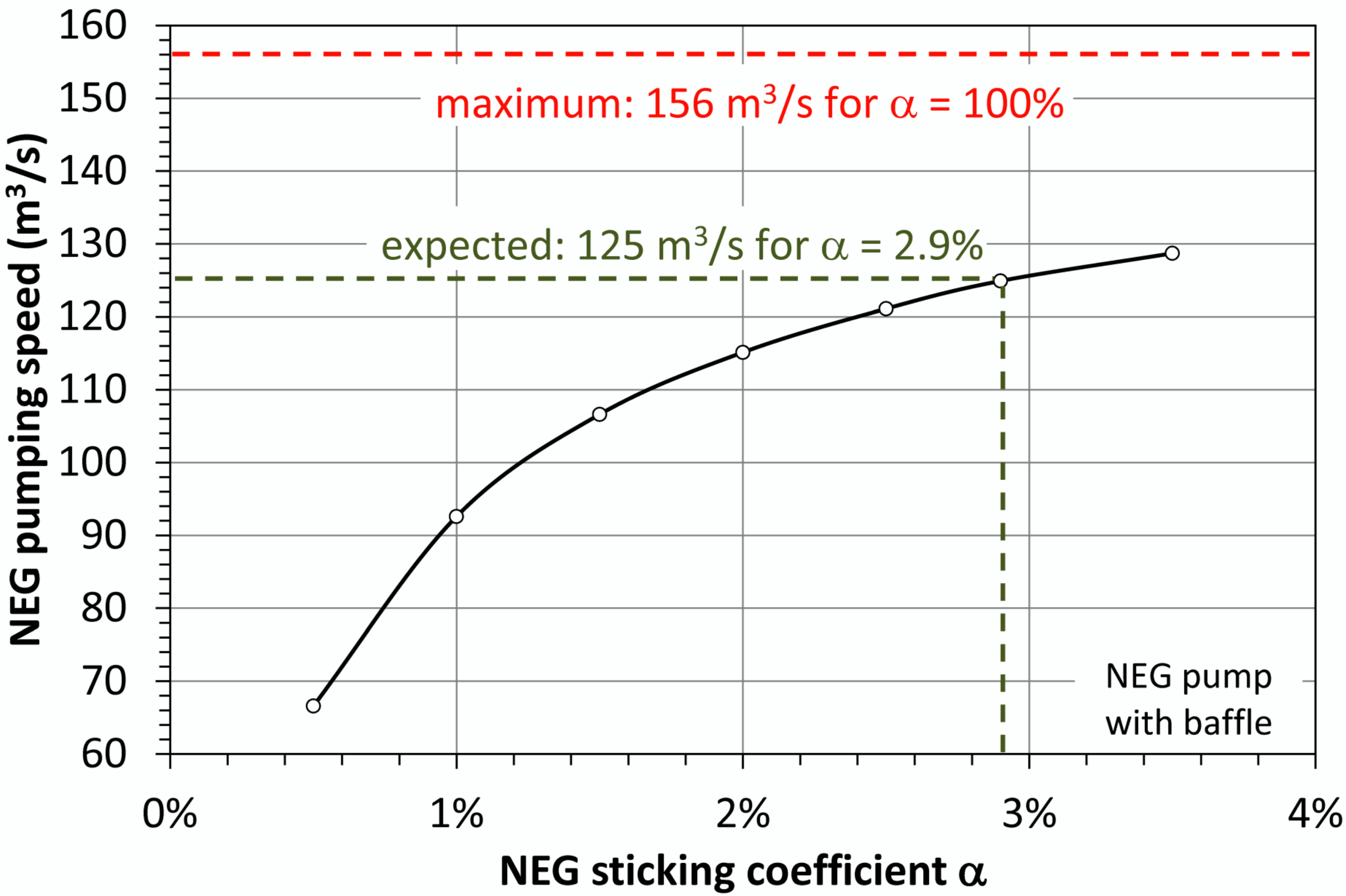
Pumping speed of TMP:

$$S(M_2) = {}^1/_4\, \bar{c}_{M_2} \cdot A_{TMP} \cdot \alpha_{TMP}$$

NEG-pump simulation (without baffle)

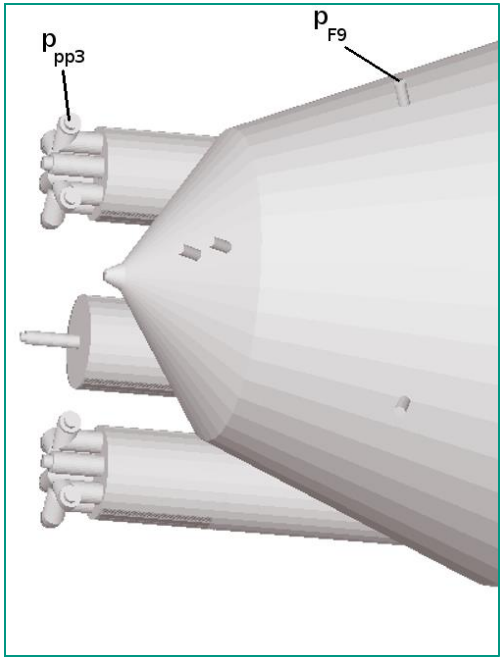


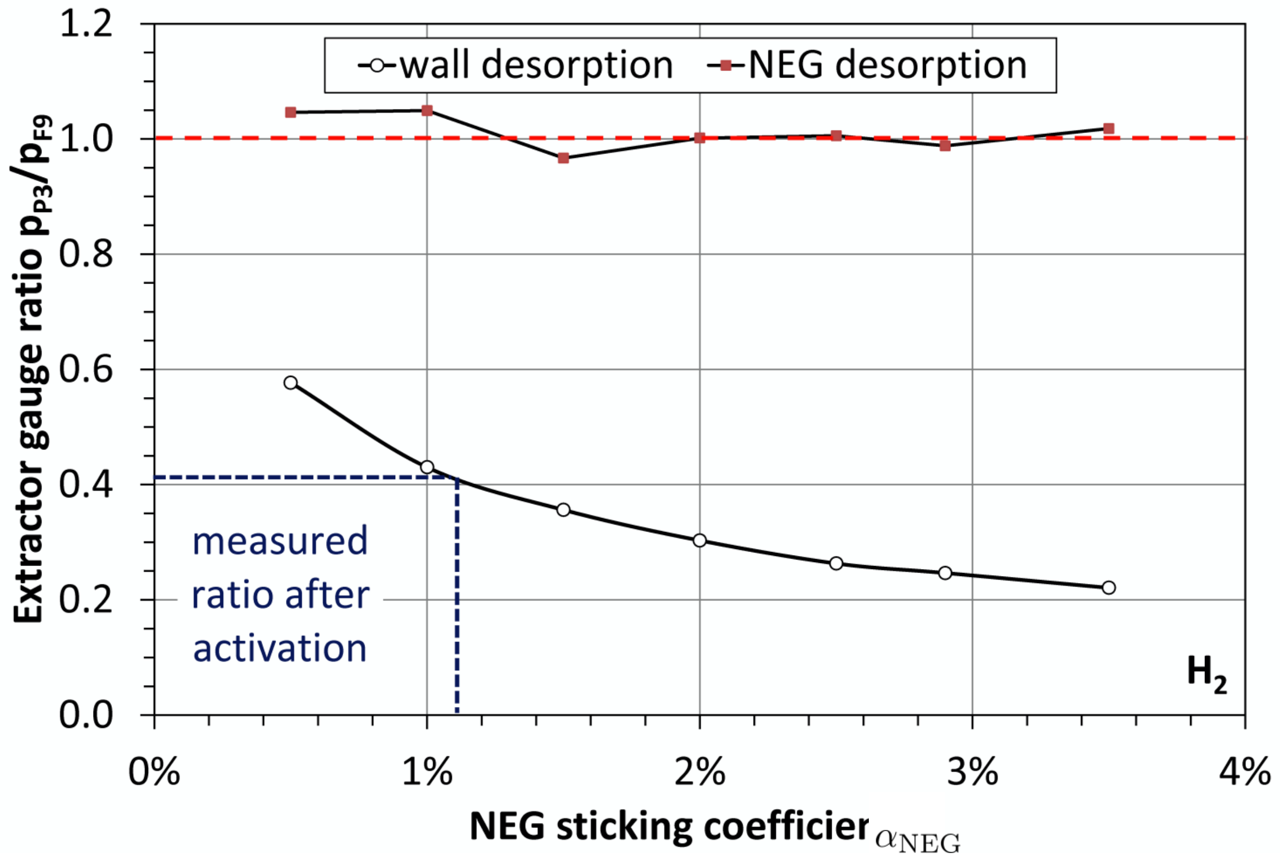
NEG-pump simulation (with baffle)



Simulation results for the NEGs as primary pumps

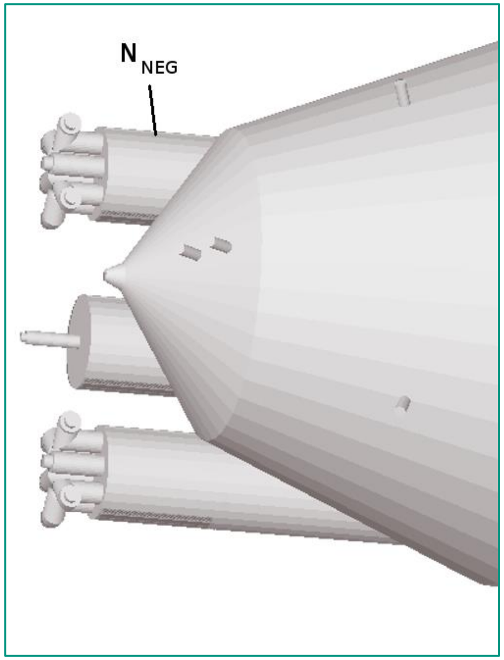
- ratio of hit numbers in vacuum gauges ≈ ratio of pressures: p_{PP3} / p_{F9}
- gas: hydrogen

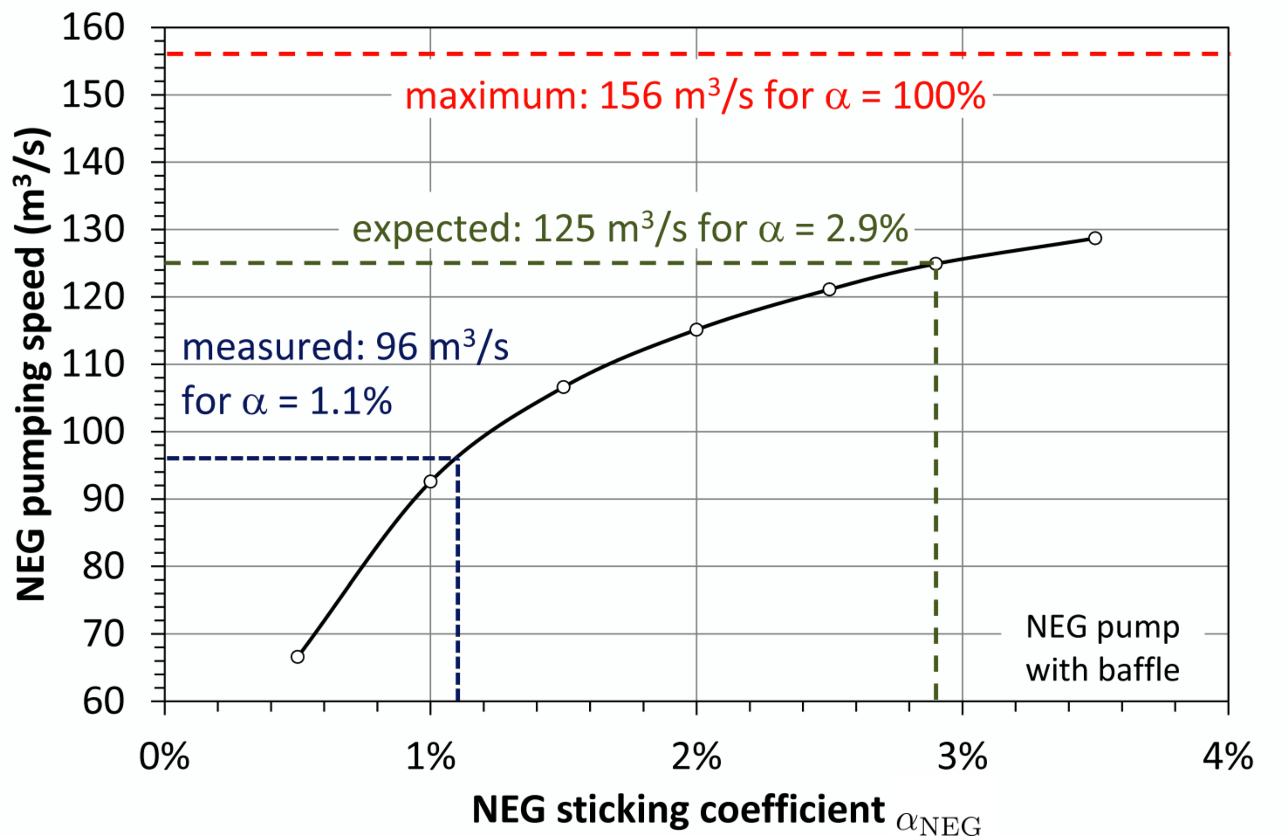




Simulation results for the NEGs as primary pumps

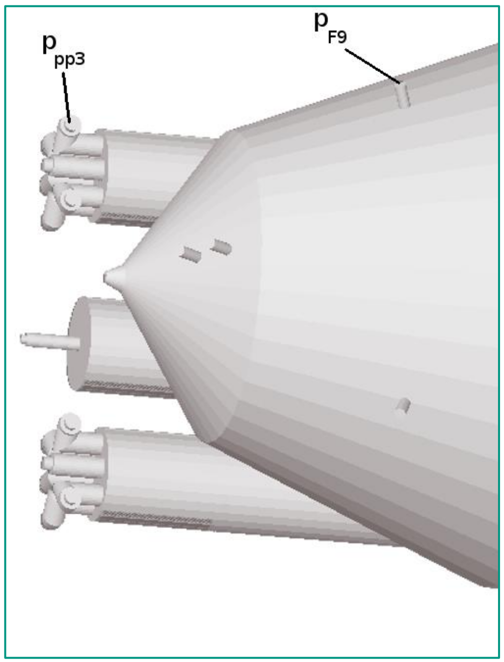
- calculation of the NEG pumping speed: $S = \frac{1}{4} \cdot \bar{c} \cdot A \cdot \frac{N_{\mathrm{NEG}}}{N_{\mathrm{des}}}$
- gas: hydrogen

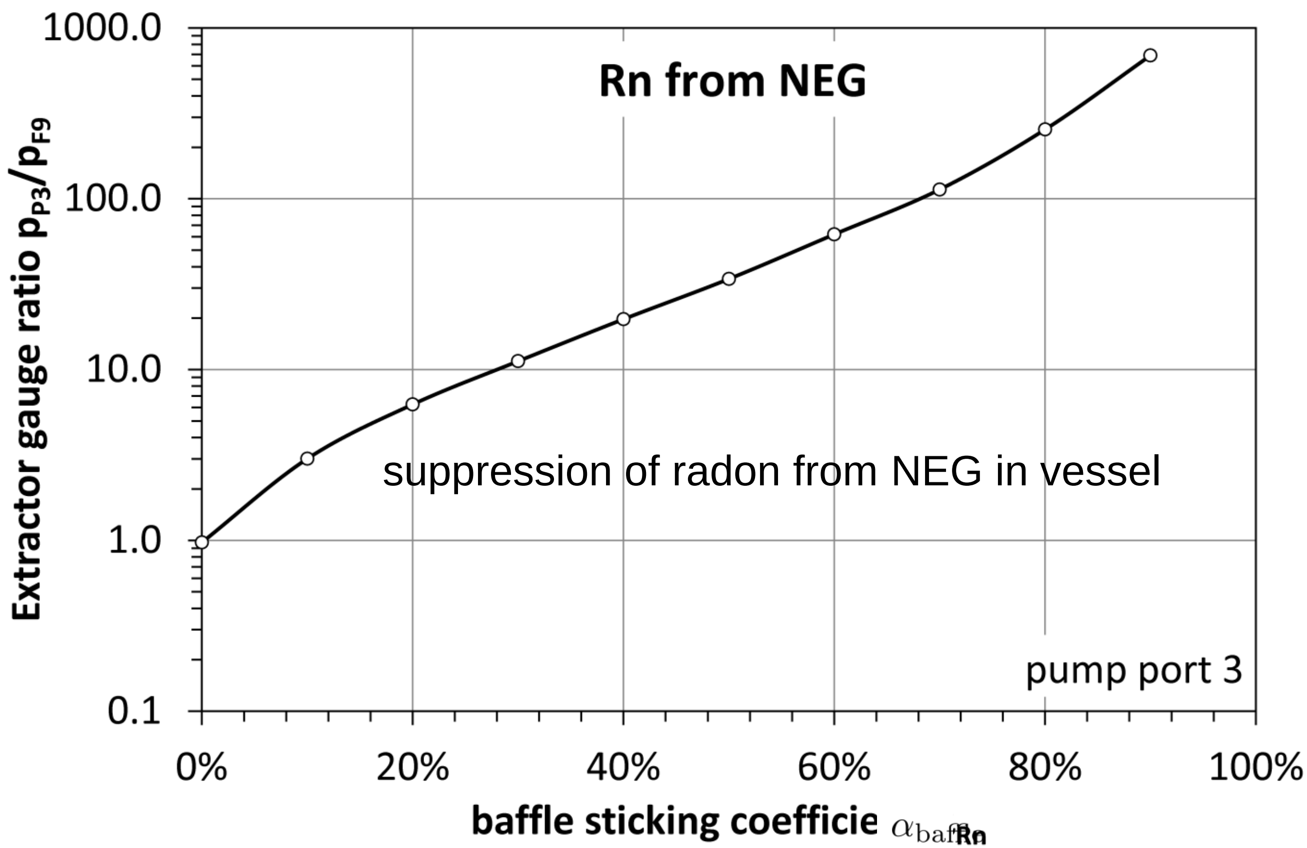




Simulation results for the TMPs as primary pumps

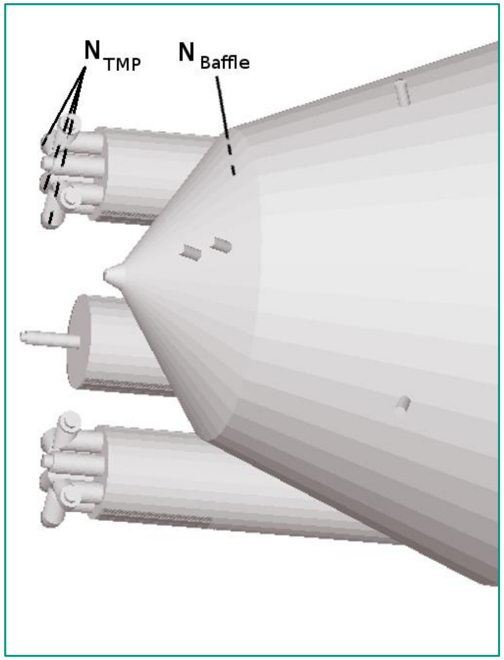
- ratio of hit numbers in vacuum gauges ≈ ratio of pressures: p_{P3} / p_{F9}
- gas: radon

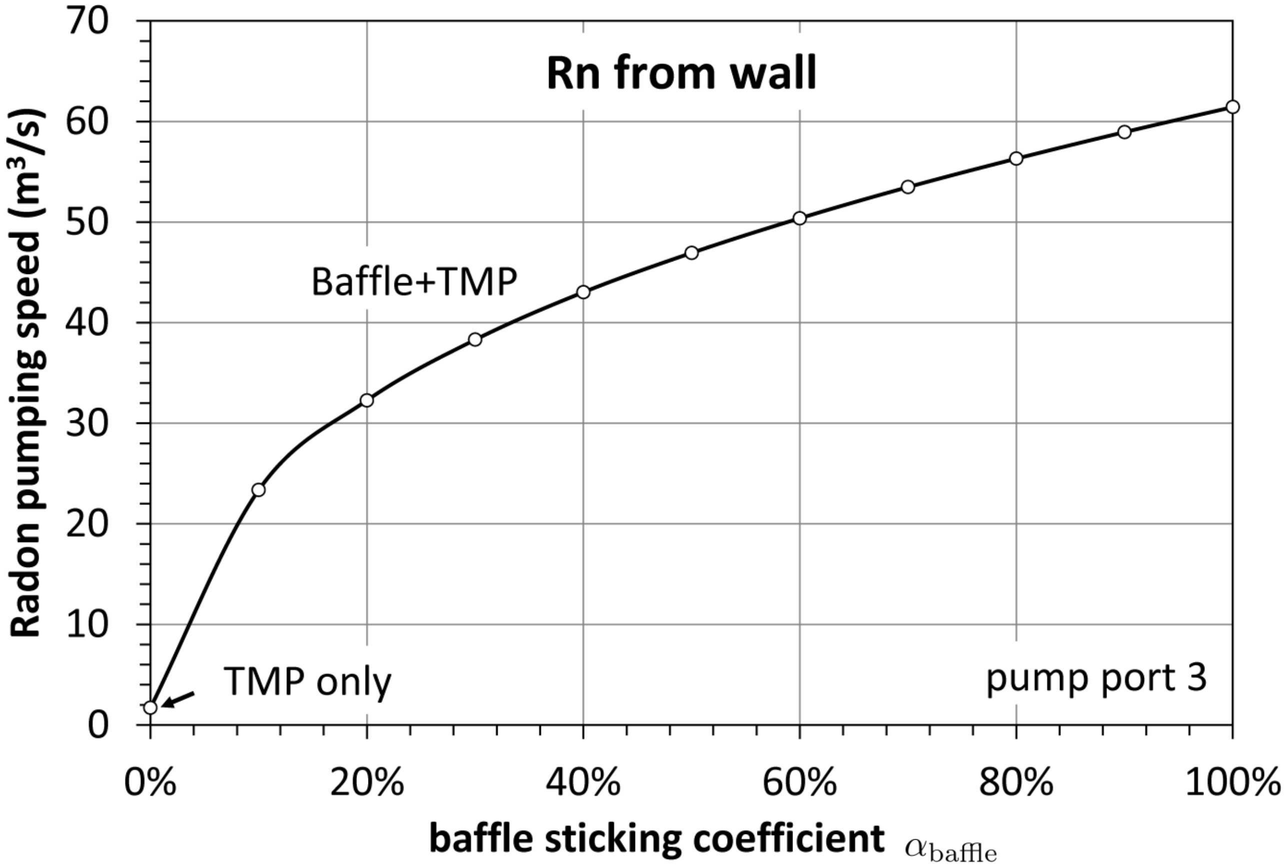




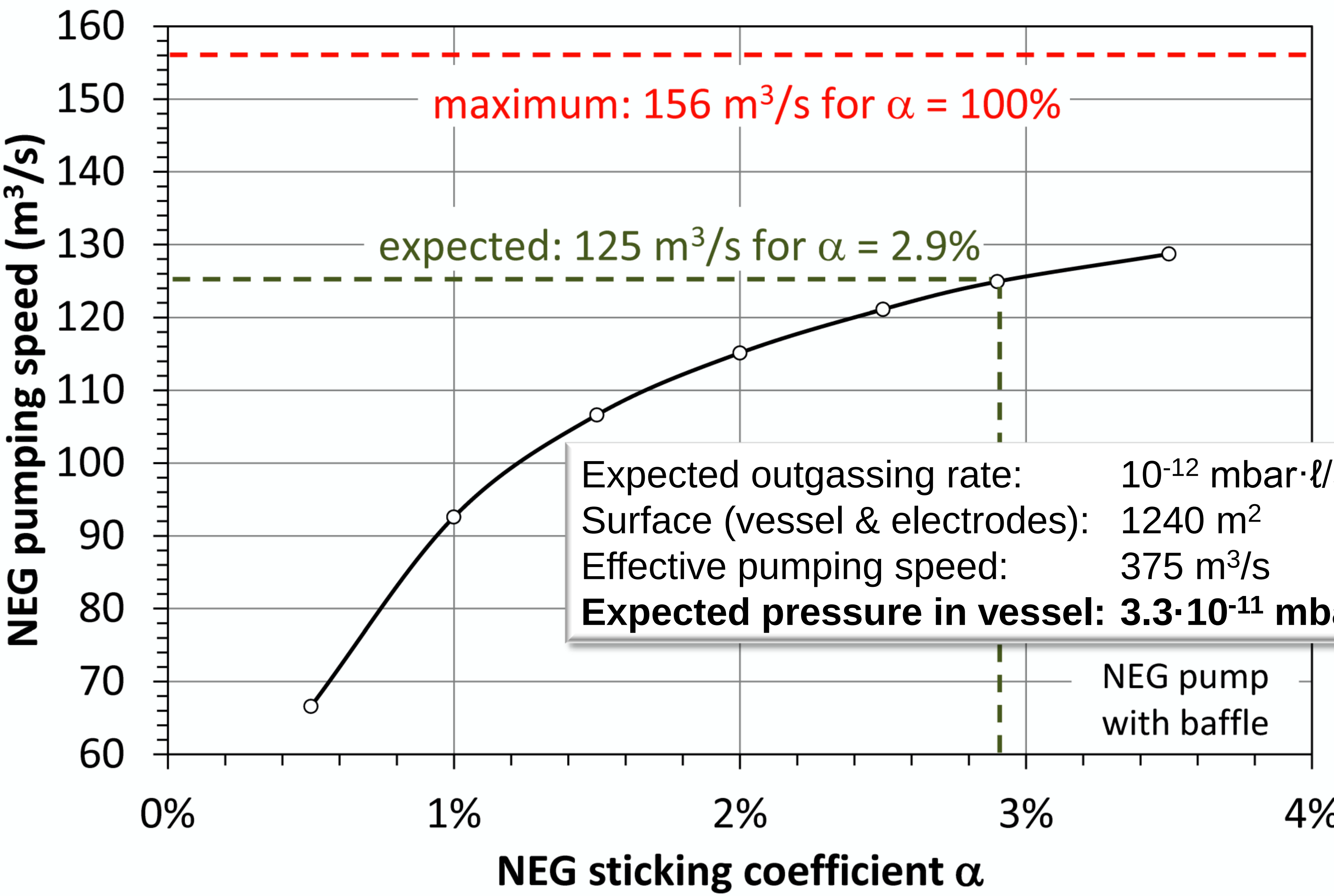
Simulation results for the TMPs as primary pumps

- 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



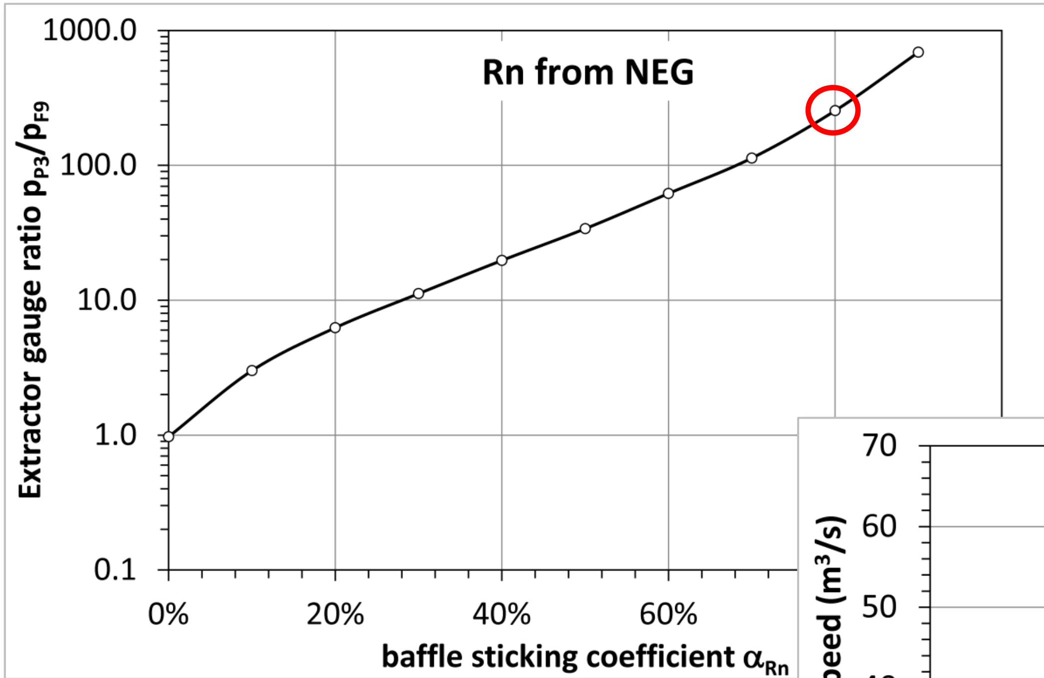


NEG simulation with baffle (MolFlow+)

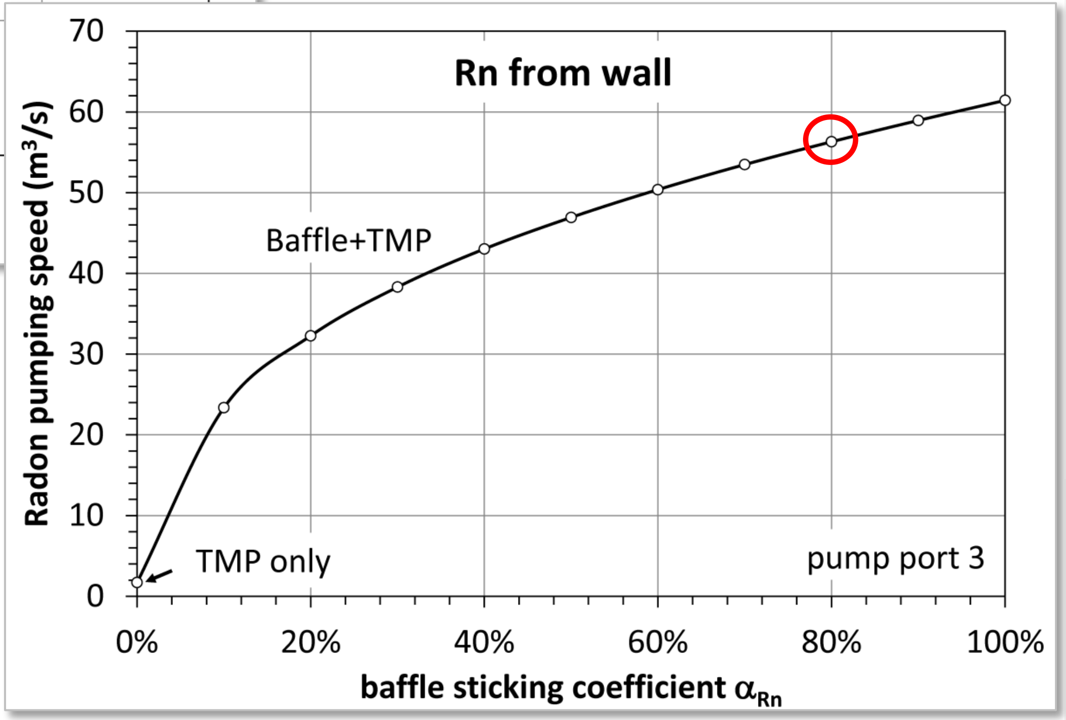


Expected outgassing rate:	10^{-12} mbar·ℓ/s·cm^2
Surface (vessel & electrodes):	1240 m^2
Effective pumping speed:	375 m^3/s
Expected pressure in vessel:	**$3.3 \cdot 10^{-11}$ mbar**

Baffle simulation for Radon (MolFlow+)



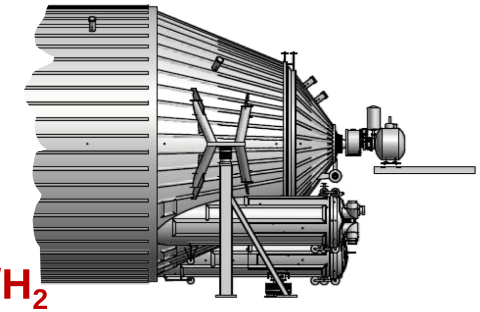
- α_{Rn}**~80%** estimated from Pre-Spectrometer results
- **Suppression factor** for radon emanating from NEG: **~250**

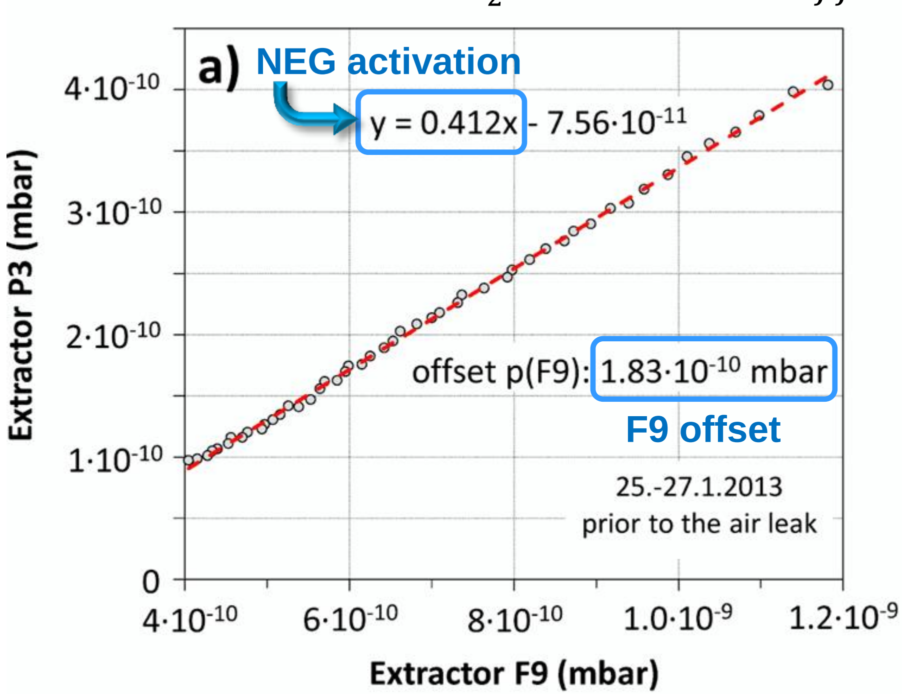


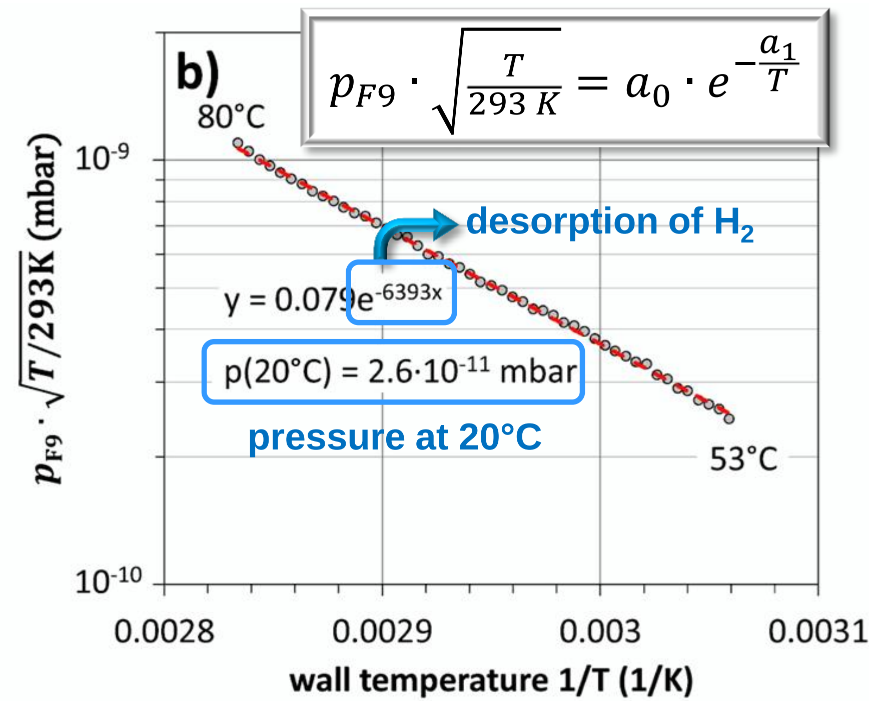
- Effective pumping speed for **6 TMPs: 3400 ℓ/s**
- Effective pumping speed for **3 baffles: ~170 000 ℓ/s**

Hydrogen outgassing and pressure at 20°C

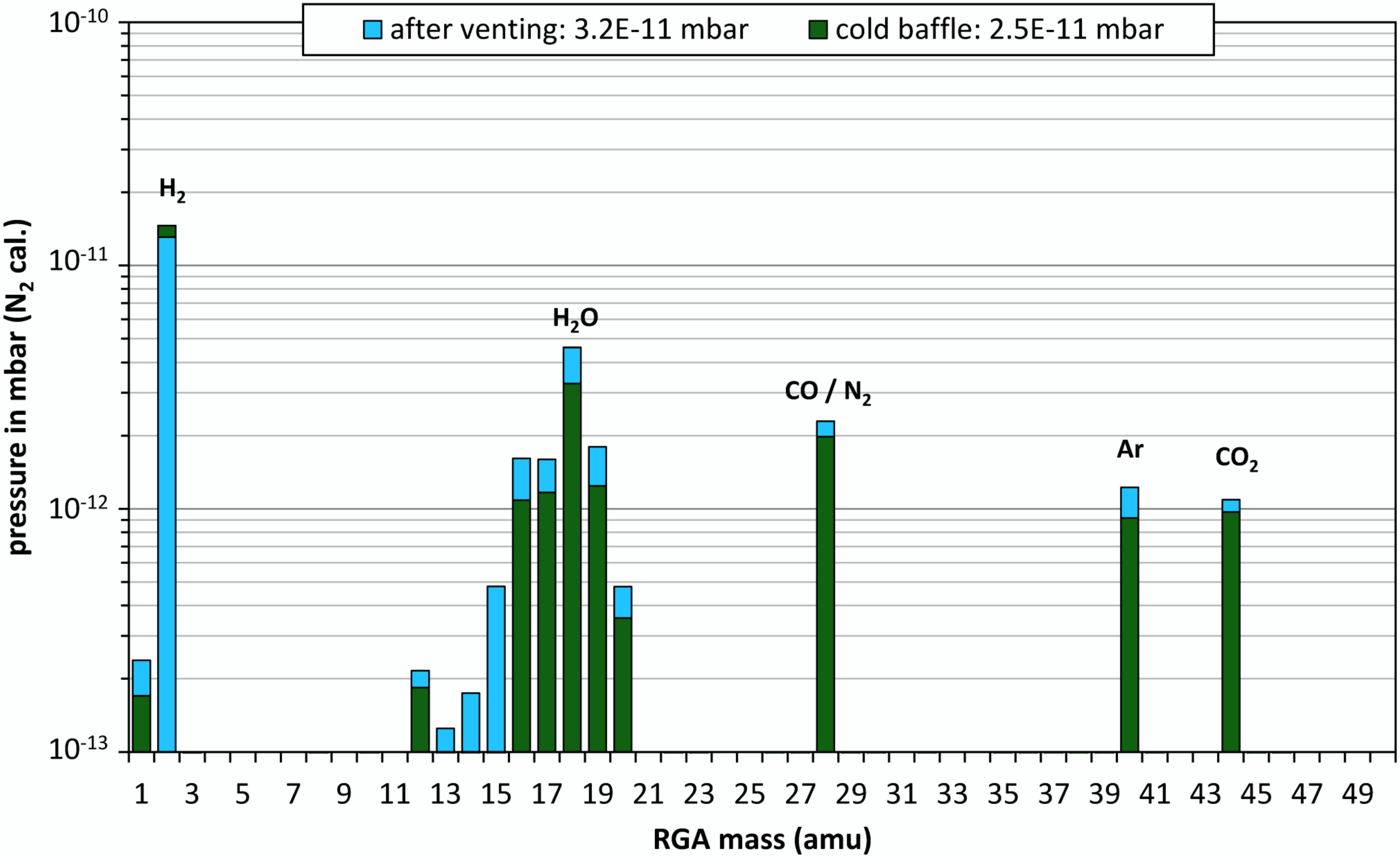
- Fit of p_{P3} versus p_{F9}
  - **NEG pumping speed** from p_{P3}/p_{F9}: **290 m³/s (α = 1.1%)**
  - **Offset** of Extractor gauge F9: **1.8·10^{-10} mbar**
- Fit of $p_{F9} \cdot \sqrt{T/293K}$ versus 1/T
  - **Desorption enthalpy** of H_2 on st. steel: **53 kJ/mol = 0.55 eV/H_2**
  - Extrapolated **pressure at 20°C**: 2.6·10^{-11} mbar **(gas corr. H_2: 5.7·10^{-11} mbar)**
- **Outgassing rate $j_{H_2} = p(20°C) \cdot S_{eff}/A$ = 1.4·10^{-12} mbar·ℓ/s·cm²**



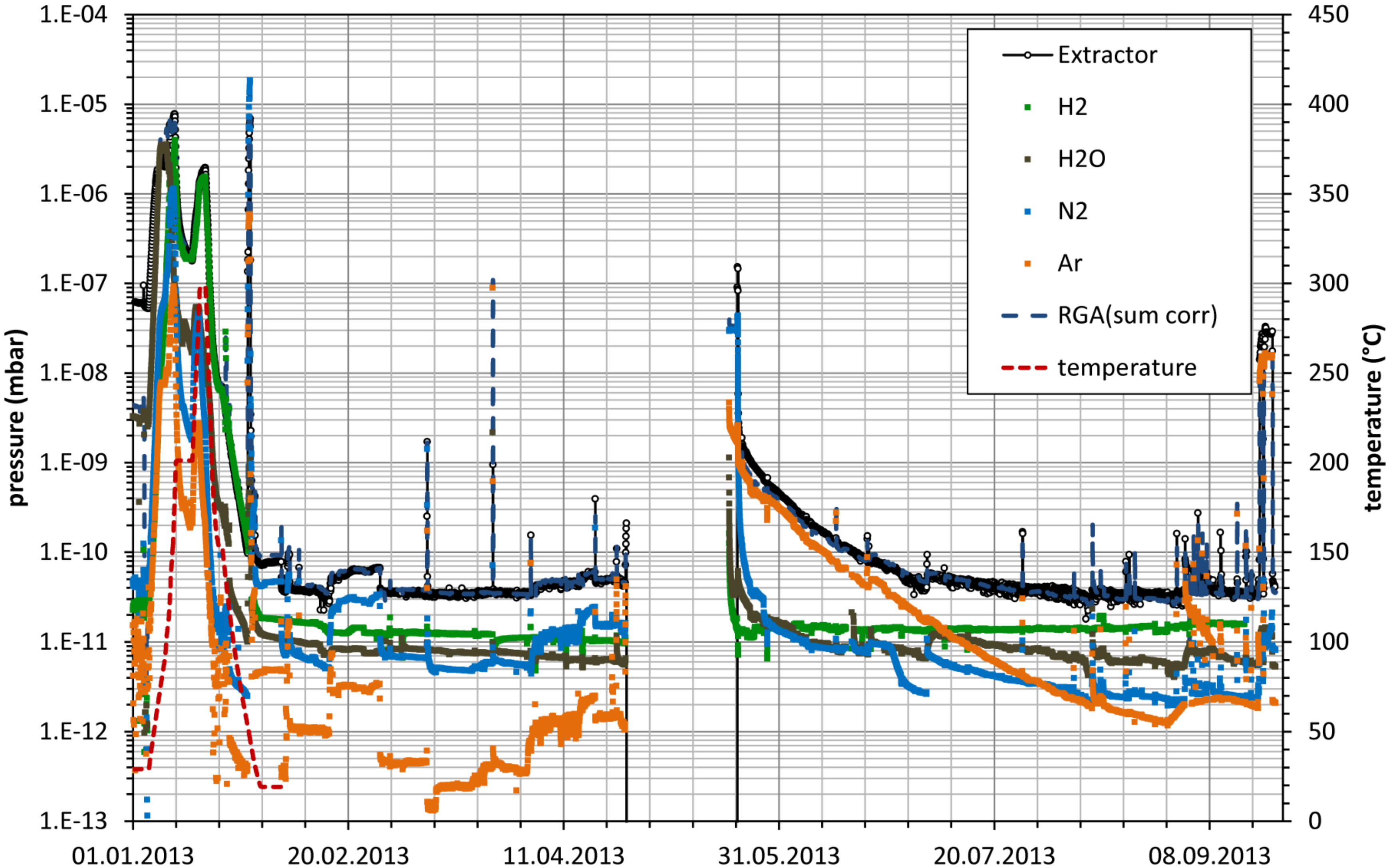




Vacuum status with cold baffles



RGA spectrum (all)



RGA spectrum after venting