Vacuum Simulations of the KATRIN Experiment

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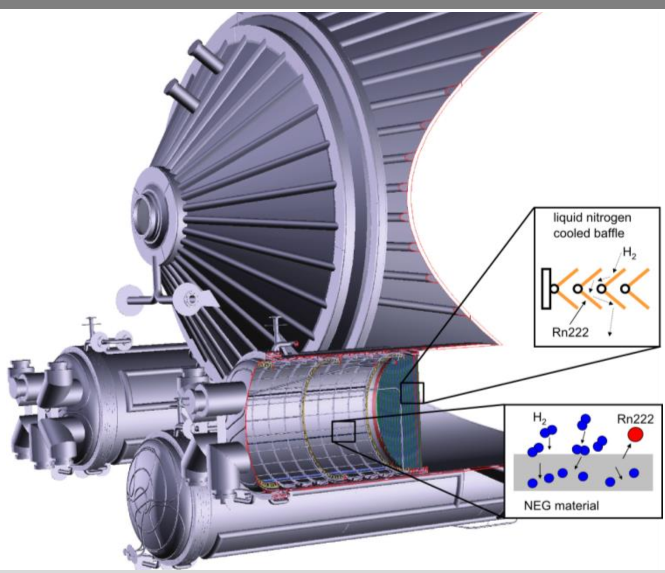
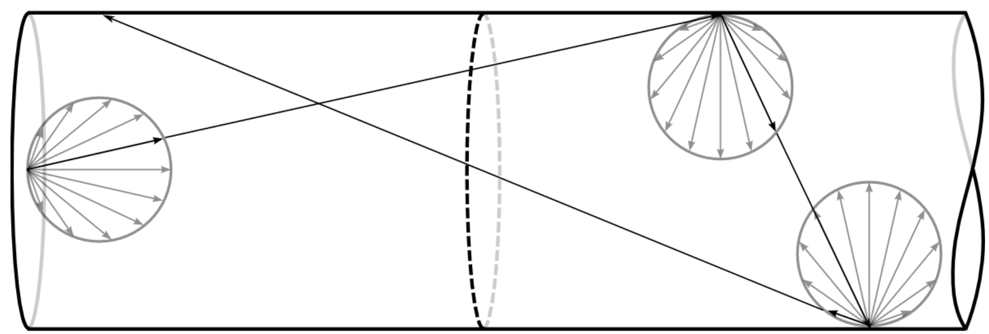
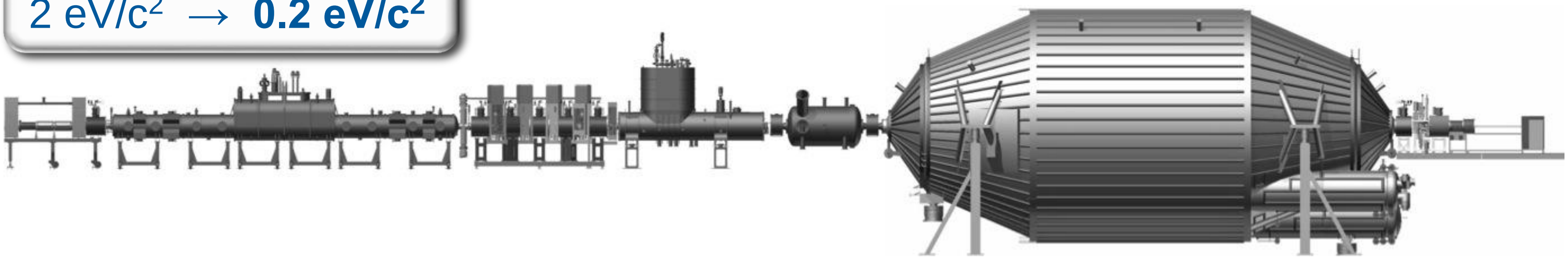




The **Karlsruhe Tritium Neutrino** Experiment

Karlsruhe Institute of Technology

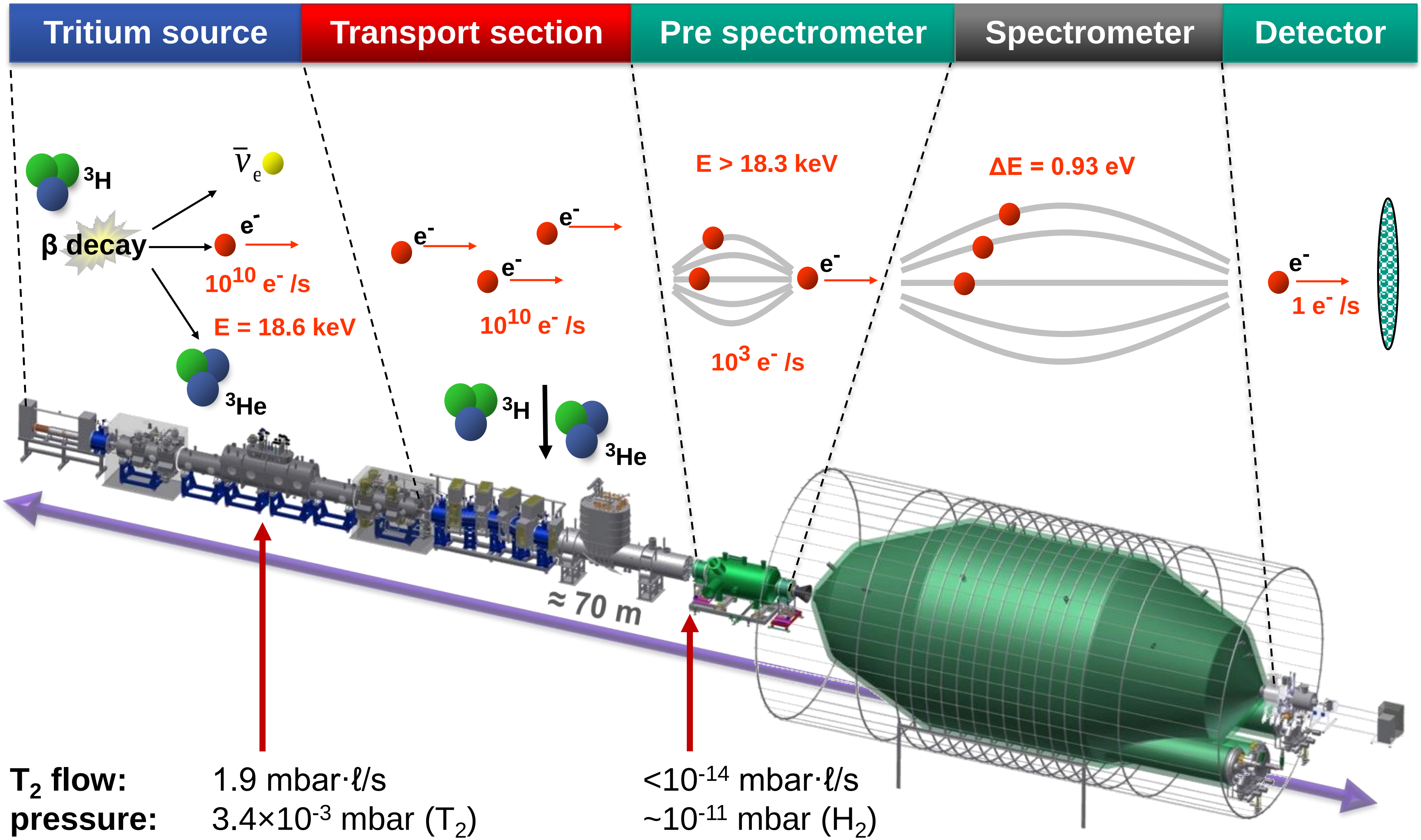
Sensitivity on $m(\nu_e)$:
$2\ eV/c^2 \rightarrow$ **$0.2\ eV/c^2$**



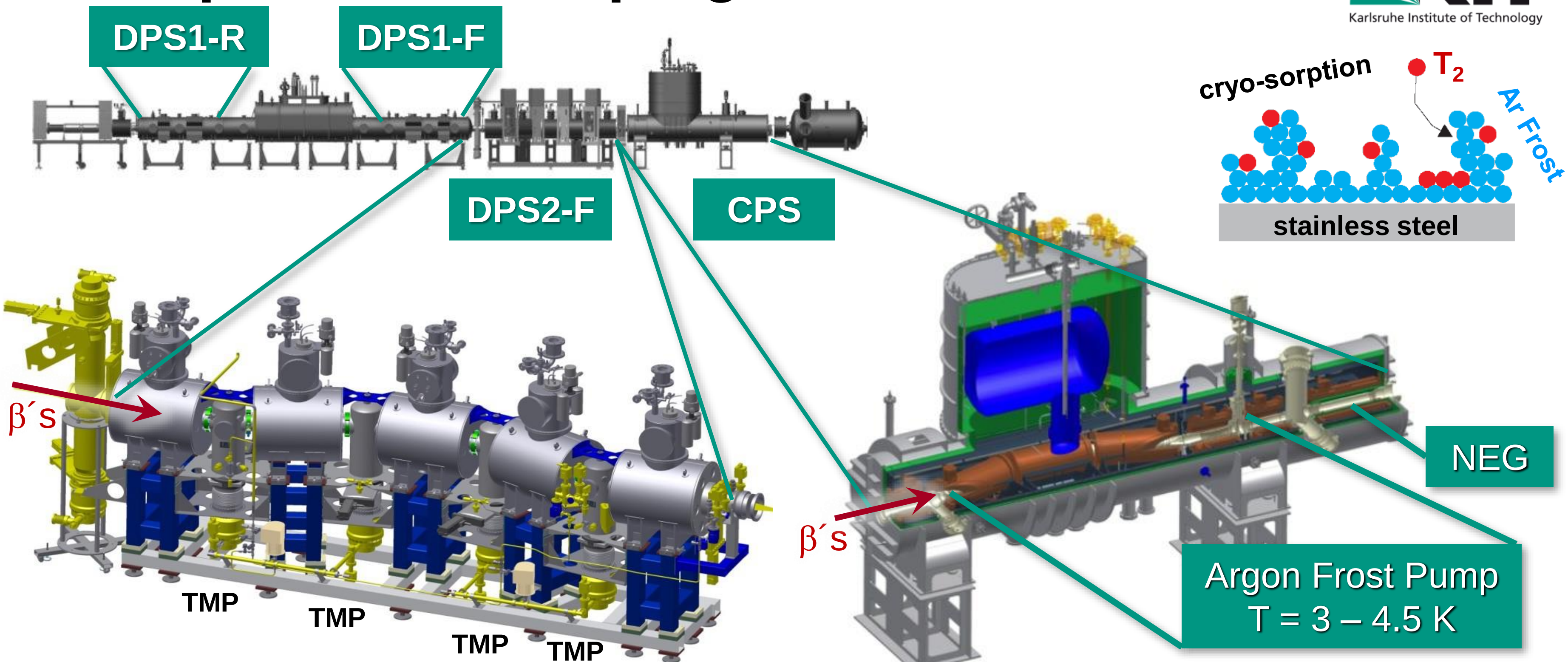
The KATRIN collaboration

- objective: measure eff. neutrino mass with electrons from tritium β-decay
- international collaboration from 5 countries (D, US, CZ, RUS, UK)
- ~ 130 scientists

The KATRIN Setup - Overview



Transport and Pumping Sections



Differential Pumping Section (DPS)

- active pumping: 4 TMPs
- tritium retention: 10^5
- magnetic field: 5.6 T

Cryogenic Pumping Section (CPS)

- based on by cryo-sorption
- tritium retention: $>10^7$
- magnetic field: 5.6 T

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

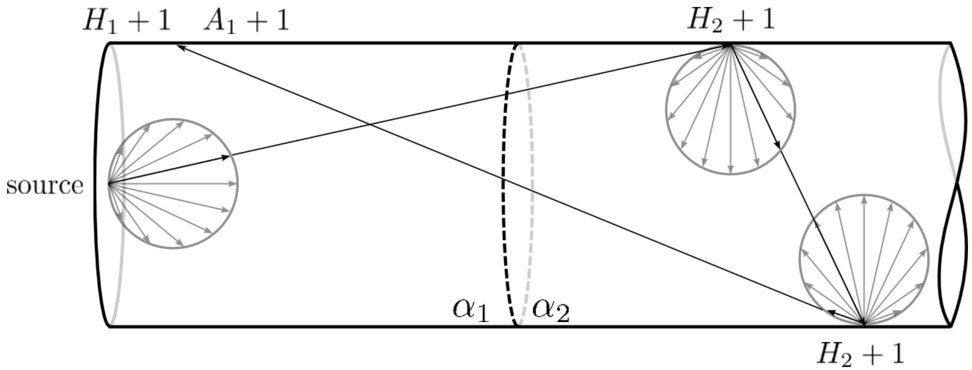
F. Eichelhardt et al, Fusion Science and Technology 54 (2008) 615

Vacuum simulations of KATRIN setup

- **Demanding vacuum requirements need accurate simulations**
  - **Optimization** of vacuum setup
  - Monitoring of vacuum performance (**interpretation** of measured pressure)
- **Accuracy vs. optimization of simulation time**
  - Detailed simulations very **time consuming**
  - Saving time for **membrane bellows**
  - Accuracy: **emission characteristics** of arbitrary gas sources and coupled devices
- **KATRIN specific simulations**
  - Tritium suppression factor in **DPS** & CPS
  - Simulation of the **Main Spectrometer** **(see next talk by J. Wolf)**

Vacuum simulations: method

- **Test particle Monte Carlo simulation for free molecular flow**
  - **Molflow+** and ProVac3D
- **Surfaces approximated by mesh**
  - Individual properties of each surface element:
    - Sticking coefficient α_i
    - Desorption probability and angular distribution $\cos^n(\Theta)$
    - Diffuse (Lambertian) reflection
- **Particle tracking produces for each surface**
  - Number of desorptions D_i
  - Number of hits H_i
  - Number of adsorptions A_i



Vacuum simulations: results

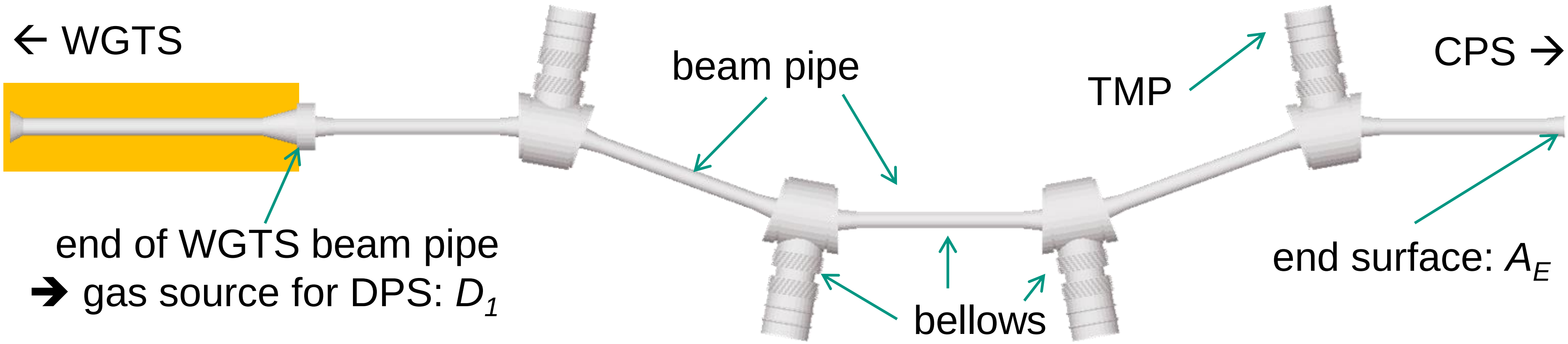
- **Conductance**
  - Desorbing and adsorbing surface (α_1 = 100%) at entrance D_1, A_1
  - Adsorbing surface (α_E = 100%) at exit A_E
  - Conductance: flow times **transmission probability** $w = A_E/D_1$
- **Effective pumping speed**
  - Desorbing and adsorbing surface F_1 (α_1 = 100%) at entrance D_1, A_1
  - Adsorbing surfaces of pumps (α_P < 100%) at exit ΣA_P
  - Pumping speed: flow times **pumping probability** $w = \Sigma A_E/D_1$

$$\boxed{S(M) = \frac{1}{4} \cdot \bar{c}_\mathrm{M} \cdot F_1 \cdot w}$$

- **Ratio of pressures**
  - Number of hits H_i *normalized to surface area* F_i
  - **Pressure ratio** of two surfaces: $p_1/p_2 = H_1 \cdot F_2 / H_2 \cdot F_1$

KATRIN example: DPS suppression factor for T_2

- **Objective: determine the tritium suppression factor of the DPS**

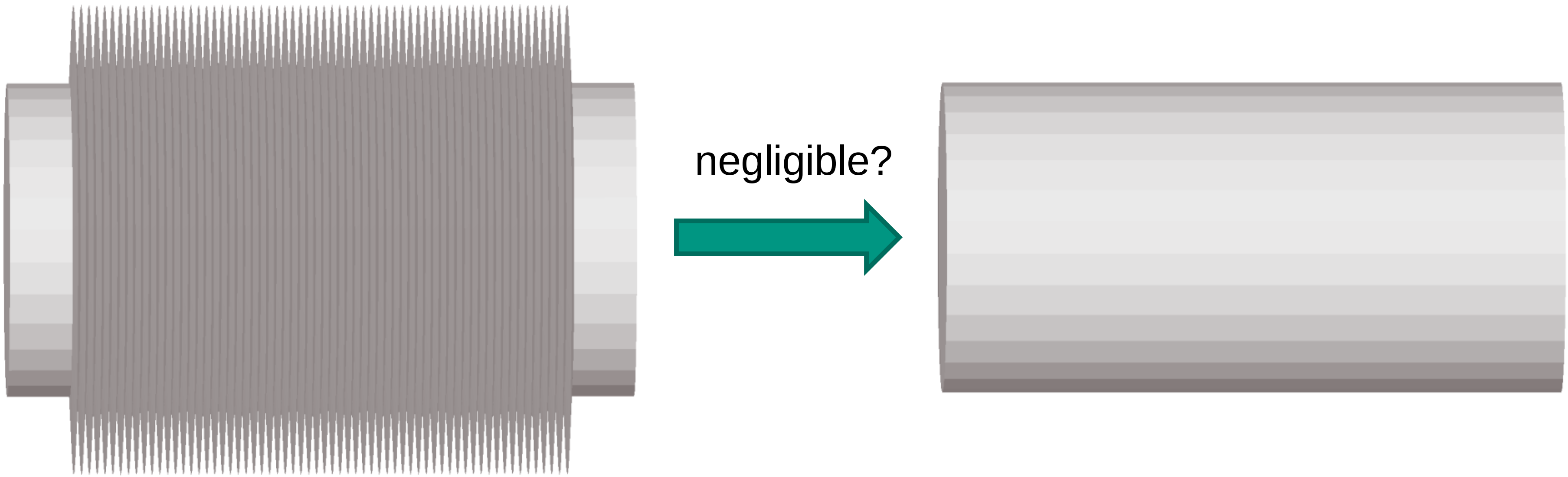


- **Suppression factor**: $w = A_E/D_1$
- **Problems:**
  - **membrane bellows** ➔ long simulation time
  - WGTS beaming characteristics: gas source not a cos(Θ) **desorption**
  - DPS ➔ CPS beaming characteristics
  - Define proper **interface** between subsequent components

Membrane bellow analysis

- **Objective:** determine the **difference of transmission probabilities** for tubes with and without membrane bellows ➔ **save computation time**

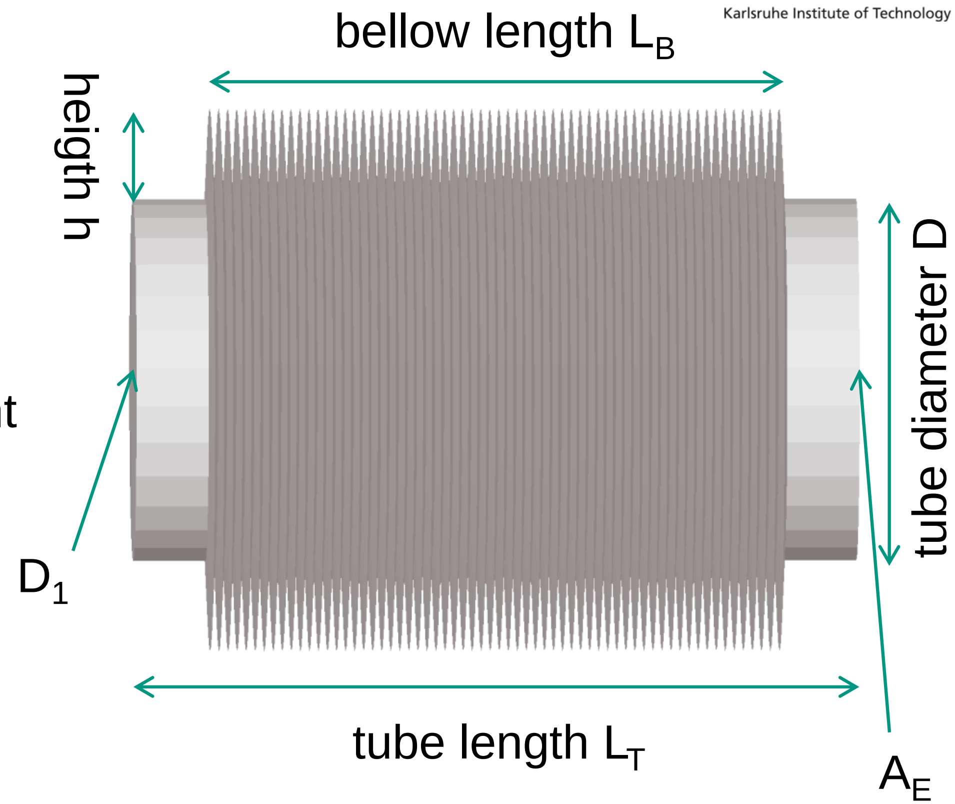
- Important for KATRIN: are the bellows of the DPS **negligible**?



- If not negligible, can the bellow be **approximated with a smaller tube**?

Membrane bellow analysis

- **Simulation parameters:**
  - tube length / tube diameter
  - bellow length / tube length
  - bellow height / tube diameter
  - length of single bellow element



- **Monte Carlo data:**
  number of desorptions D_1
  and adsorptions A_E

- **Analysis of simulation data:**
  - transmission probability: $w(L_\mathrm{B},\ L_\mathrm{T}) = \frac{A_\mathrm{E}}{D_1}$
  - difference of transmission probabilities with and without bellow:

$$\Delta = \frac{w(L_\mathrm{B},\ L_\mathrm{T}) - w(0,\ L_\mathrm{T})}{w(0,\ L_\mathrm{T})}$$

Membrane bellow analysis

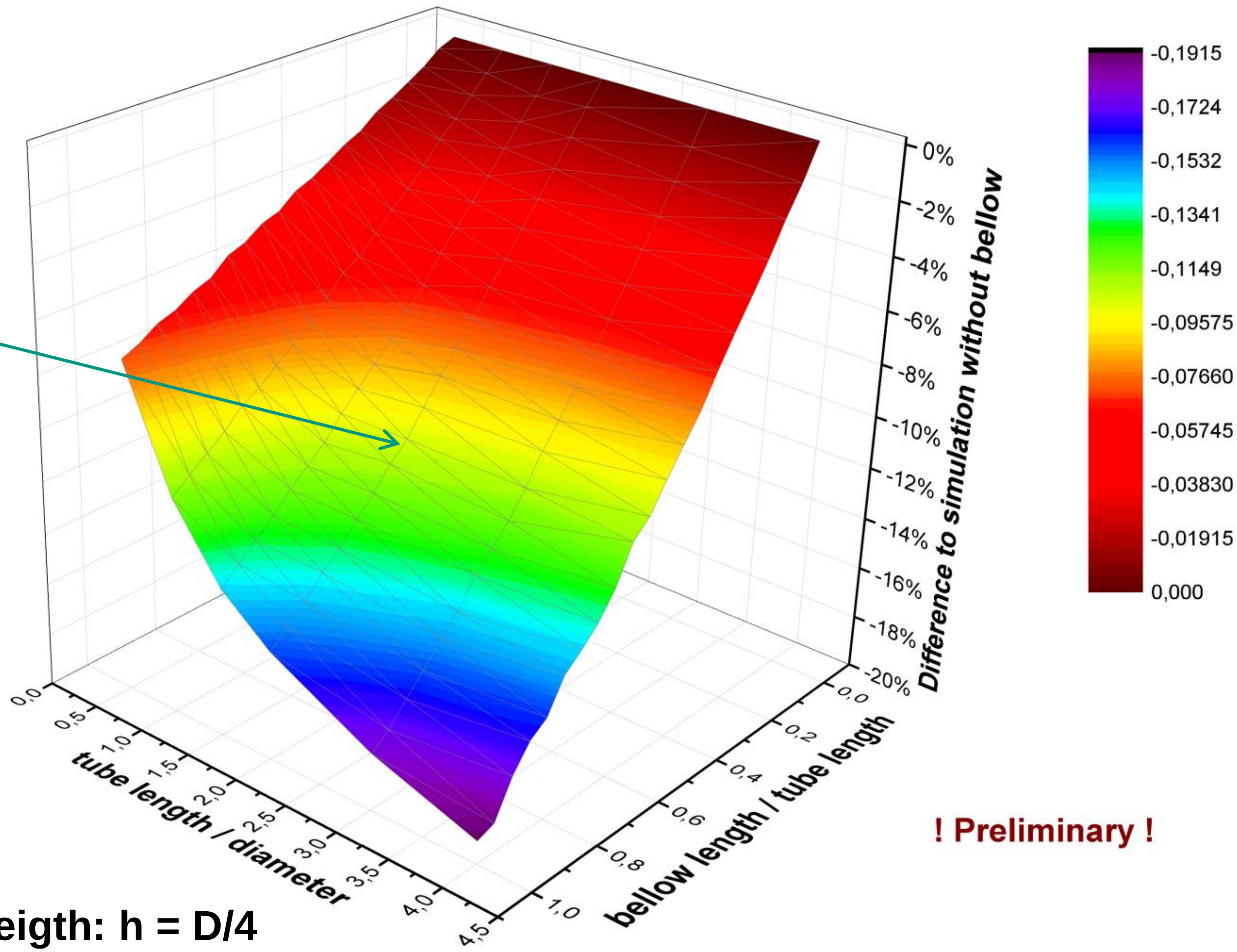
- **Simulation results** for wide variation of the simulation parameters

Example:
given design values

$L_T / D = 2.0$
$L_B / L_T = 0.6$

→ Δ = 10.4%

bellow is **negligible**
if allowed uncertainty is
over 10.4%

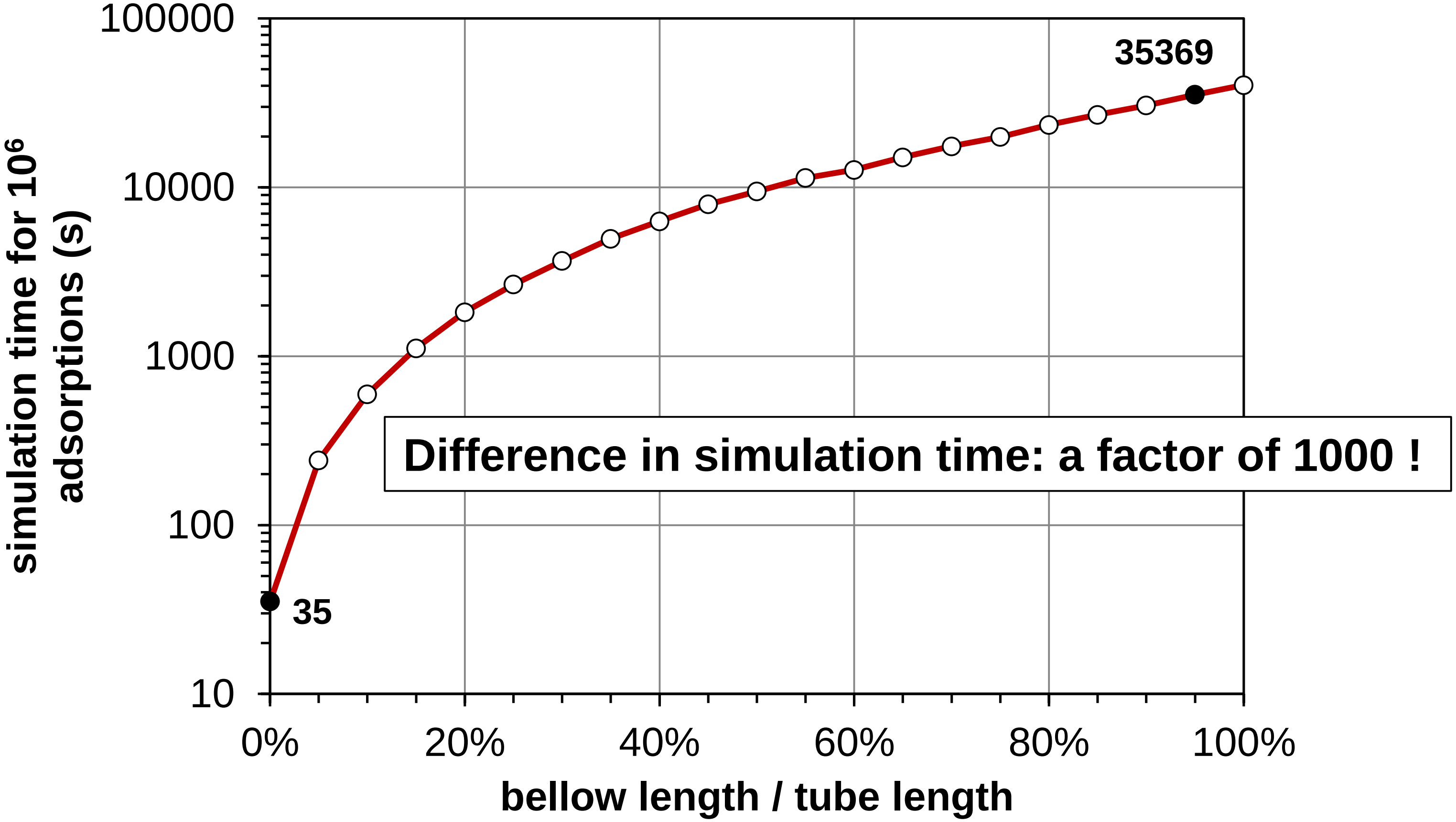


! Preliminary !

fixed bellow heigth: h = D/4

Membrane bellow analysis

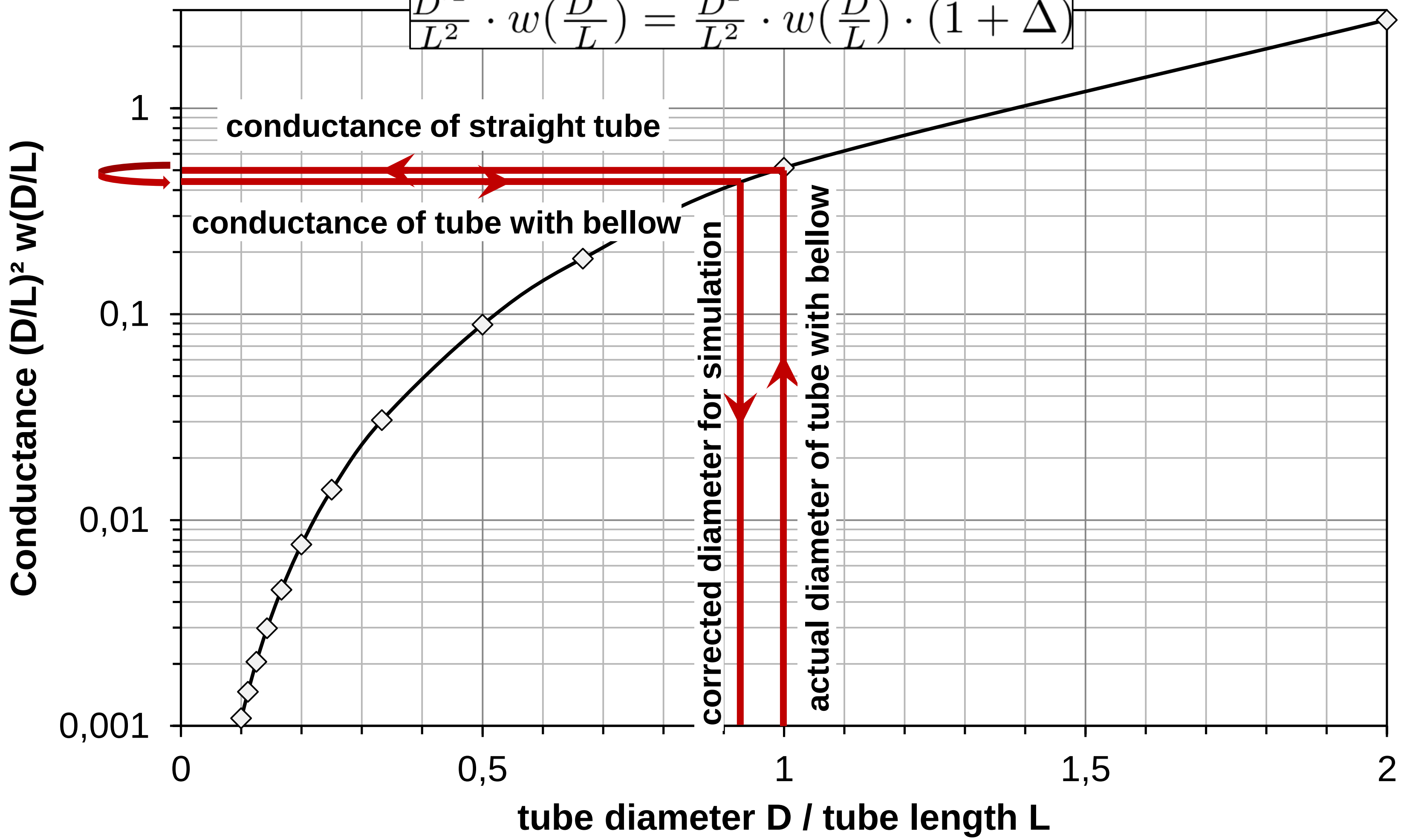
- **Benchmark analysis** for fixed tube length / diameter value L_T / D = 4.0
- Measure **simulation time** for 10^6 adsorptions at end surface of tube



Membrane bellow analysis

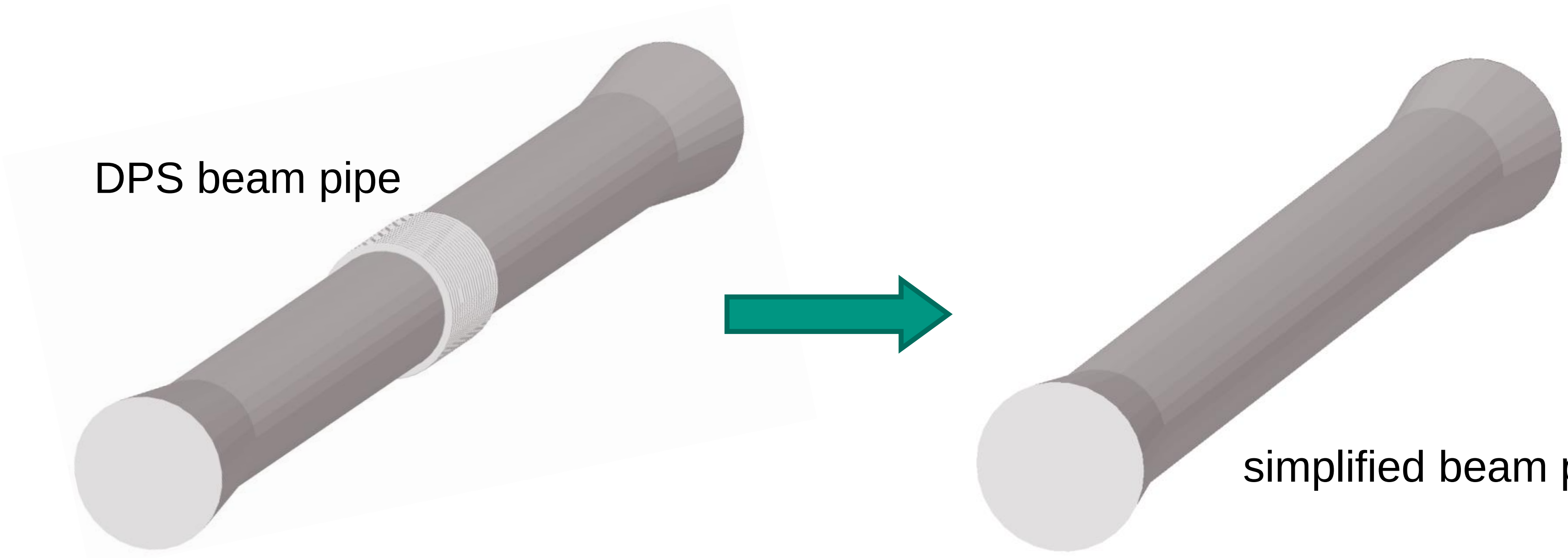
- If bellow is **not negligible**, replace it with **smaller tube**

$$\frac{D'^2}{L^2} \cdot w\left(\frac{D'}{L}\right) = \frac{D^2}{L^2} \cdot w\left(\frac{D}{L}\right) \cdot (1 + \Delta)$$



Membrane bellow analysis

- **Important for KATRIN**: analysis has shown that bellows in DPS beam pipes are negligible → **7 to 8 weeks saved** computation time!

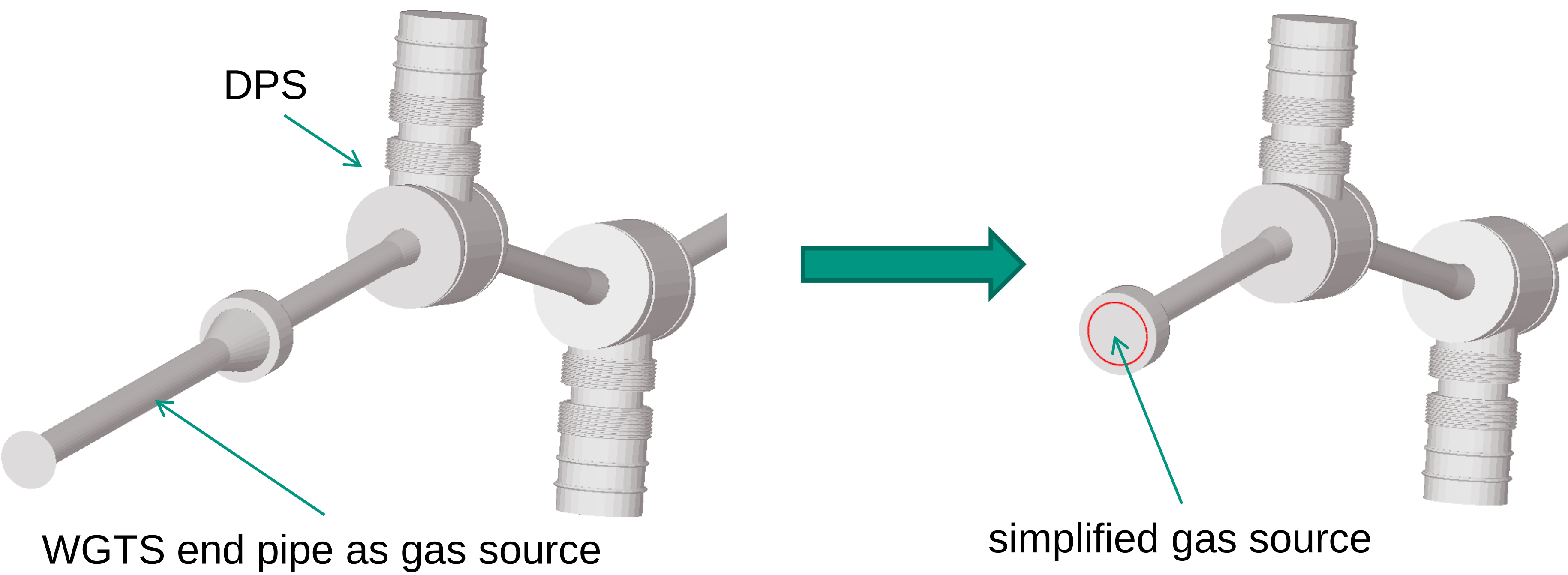


- **Future work**:
  - double the range of simulation parameters
  - quantify the **dependences** of transmission probability differences
  - determine the influence of **bellow height / diameter ratio**
  - determine the influence of the number of bellow segments

Radiation characteristics of arbitrary gas sources

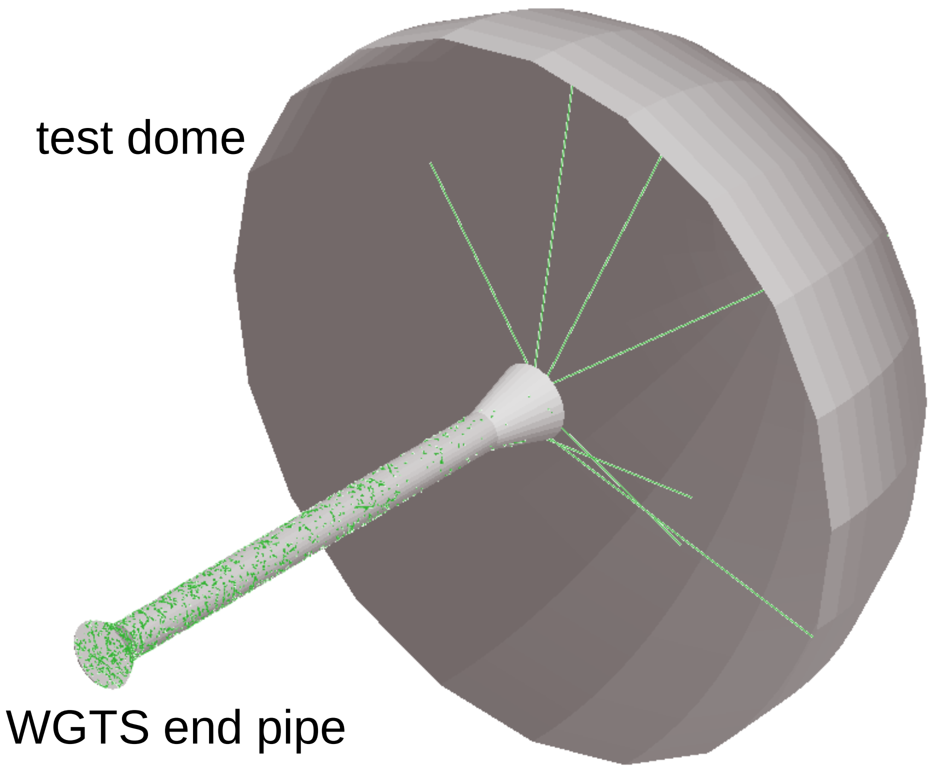
- **Objective**: determine **emission characteristics** of arbitrary gas sources → save computation time, increase accuracy of simulated gas sources

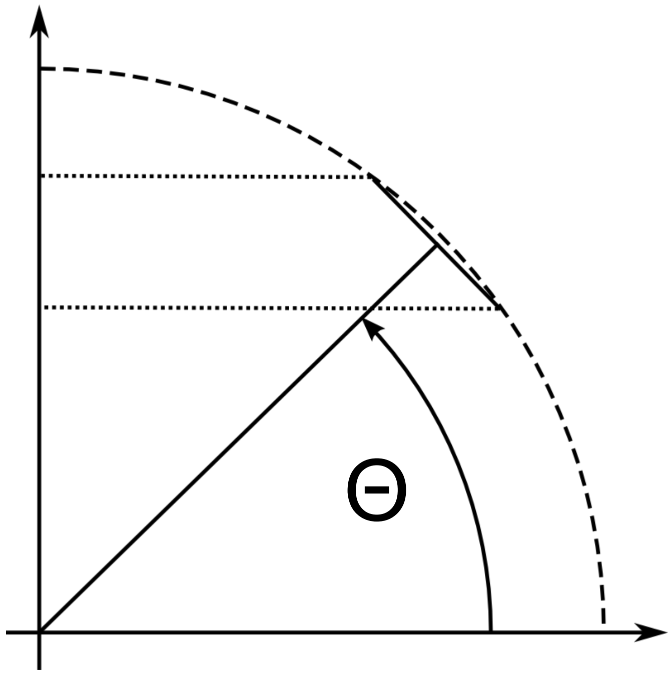
- **Example for KATRIN**: recreate the gas flow from the WGTS into the DPS with simple surfaces to **save computation time**



Radiation characteristics of arbitrary gas sources

- **Method:**
  - gas source emits particles into test dome with α = 100%
  - measure **number of adsorptions** in dependence of **angle Θ**





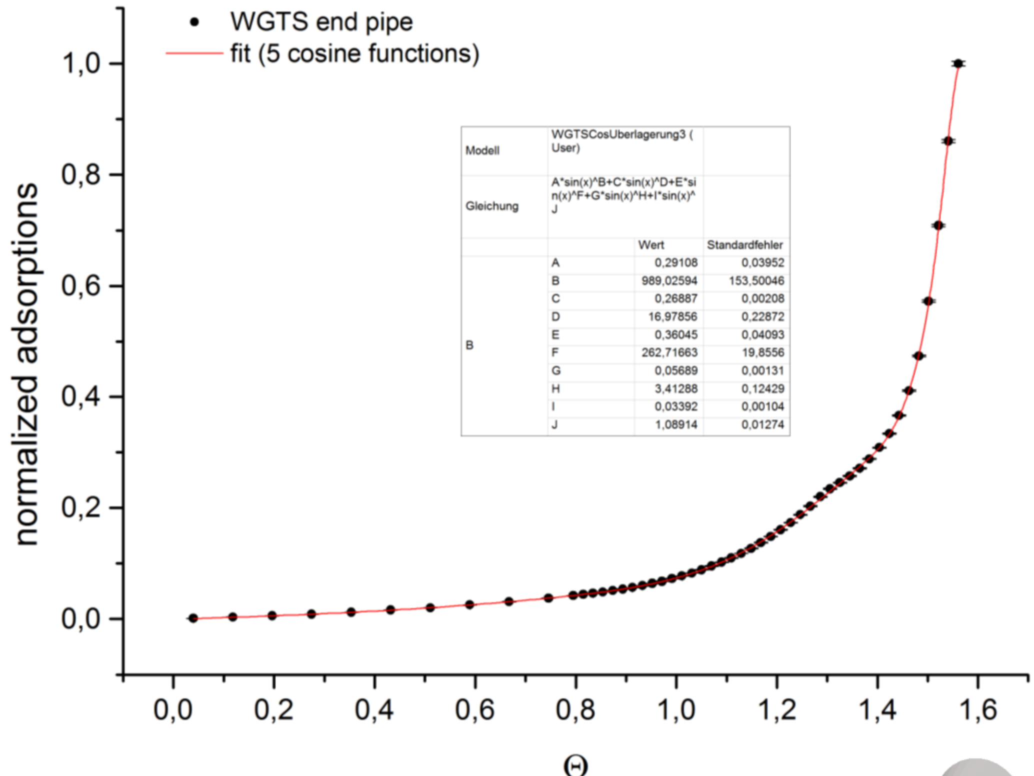
Radiation characteristics of arbitrary gas sources

- Molflow supports emission characteristics in **powers of cosine functions** → suitable fit function:

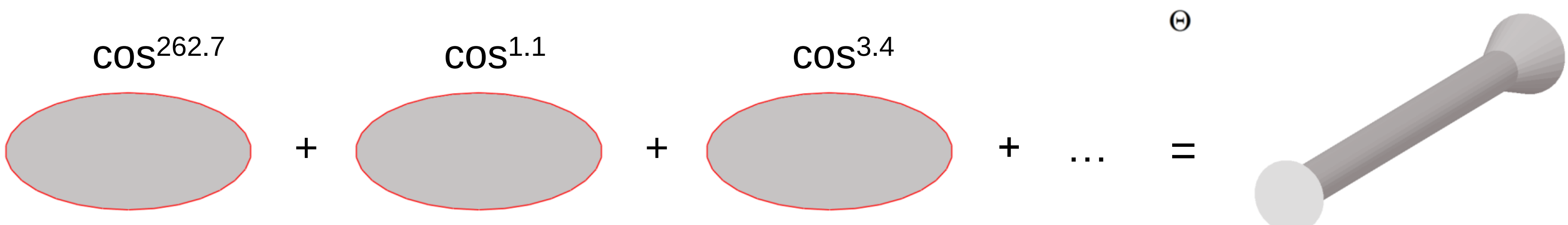
$$f(\Theta) = \sum_{i=1} c_i \cdot \cos^{n_i} \Theta$$

- Fit gives parameters c_i and n_i

- Recreation of gas source in Molflow by **superimposing** many transparent **circular gas sources** with n_i from fit

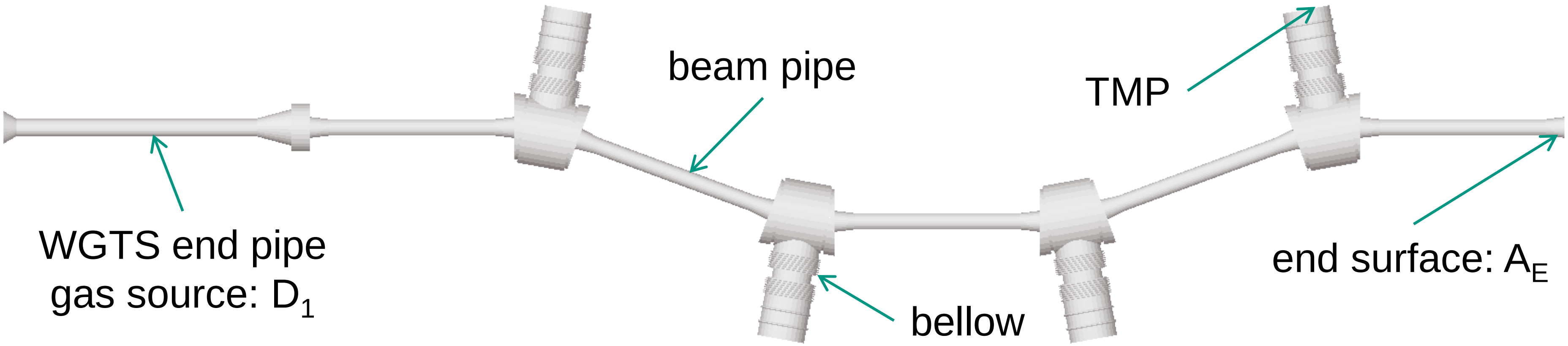


Modell	WGTSCosUberlagerung3 (User)		
Gleichung	A*sin(x)^B+C*sin(x)^D+E*sin(x)^F+G*sin(x)^H+I*sin(x)^J		
		Wert	Standardfehler
B	A	0,29108	0,03952
	B	989,02594	153,50046
	C	0,26887	0,00208
	D	16,97856	0,22872
	E	0,36045	0,04093
	F	262,71663	19,8556
	G	0,05689	0,00131
	H	3,41288	0,12429
	I	0,03392	0,00104
	J	1,08914	0,01274



Simulation of the DPS suppression factor for T_2

- **Objective:** determine the **tritium suppression factor** of the DPS
  → comparison with experimental data shows reliability of simulation



- Membrane bellow analysis → **bellows** in beam pipes **negligible**
- Radiation characteristics analysis → **simplified gas source** implemented

Simulation of the DPS suppression factor for T_2

- **Simulations with five different gas sources:**
  - WGTS end pipe
  - transparent circle with cosine-fit emission from radiation analysis
  - transparent circle with cosine emission
  - “black” circle with cosine emission
  - “gray” circle with cosine-fit emission from radiation analysis

- Preliminary result: difference between transmission probabilities for “black” and WGTS-like emission is **one order of magnitude**
  → **emission characteristic** is important for **accuracy**

- **Future work:**
  - Simulations for all gas sources with **~1000 adsorptions** on end surface
  - Comparison of transmission probabilities for **different gas sources**
  - **Check of reliability** of the radiation analysis
  - Comparison with **experimental data**

Conclusion

- Membrane bellow analysis: useful for vacuum simulations of all kinds
  → **saves a lot of computation time**

- Radiation characteristics analysis: recreation or simplification of complex gas sources
  → saves a lot of computation time
  → **increases the accuracy of the simulation**

- Both analyses were used to **simplify the DPS simulations**

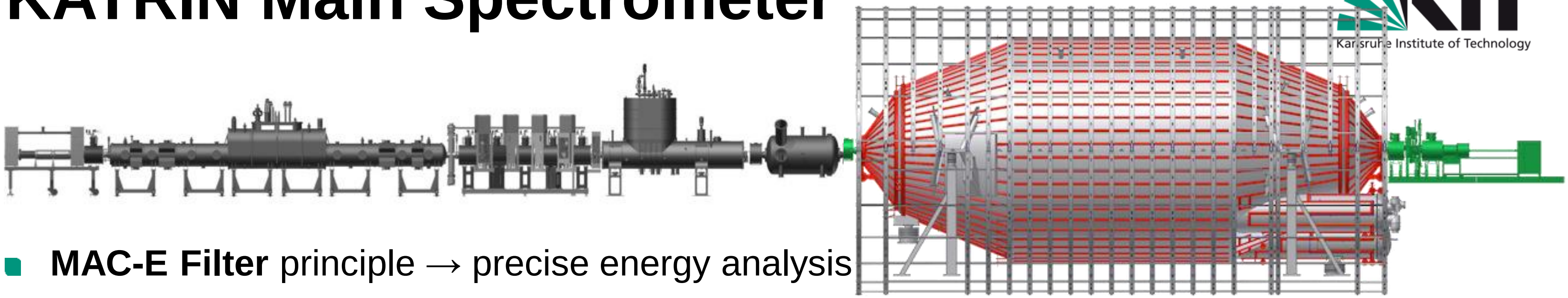
- **Tritium suppression factor** of KATRIN's DPS will be simulated for different gas sources

- The KATRIN **main spectrometer** has been simulated, **results** presented in **next talk** by J. Wolf

Thank you very much
for your attention!

Backup slides

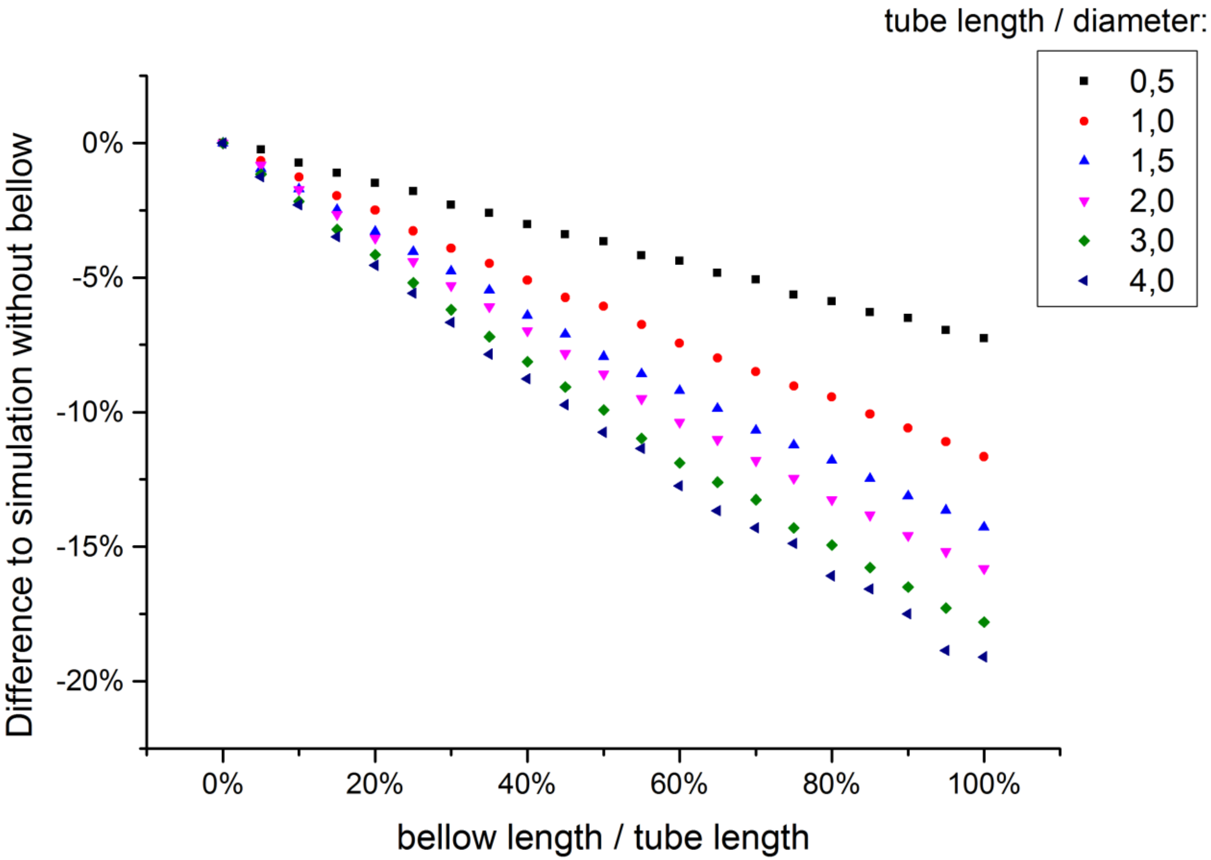
KATRIN Main Spectrometer



- **MAC-E Filter** principle → precise energy analysis
- vacuum vessel on **variable retarding potential** (18.6 kV)
- high energy resolution: **ΔE = 0.93 eV @ 18.6 keV**
- **size:**
  - diameter: 10 m
  - length: 23 m
  - volume: 1240 m^3
  - inner surface: 1150 m^2 (including wire electrodes)
- **stainless steel** 200 to (316LN)
- **vacuum** (design values)**:**
  - pressure: ~10^{-11} mbar
  - outgassing rate: <10^{-12} mbar·ℓ/s·cm^2
  - pumping speed: ~10^6 ℓ/s

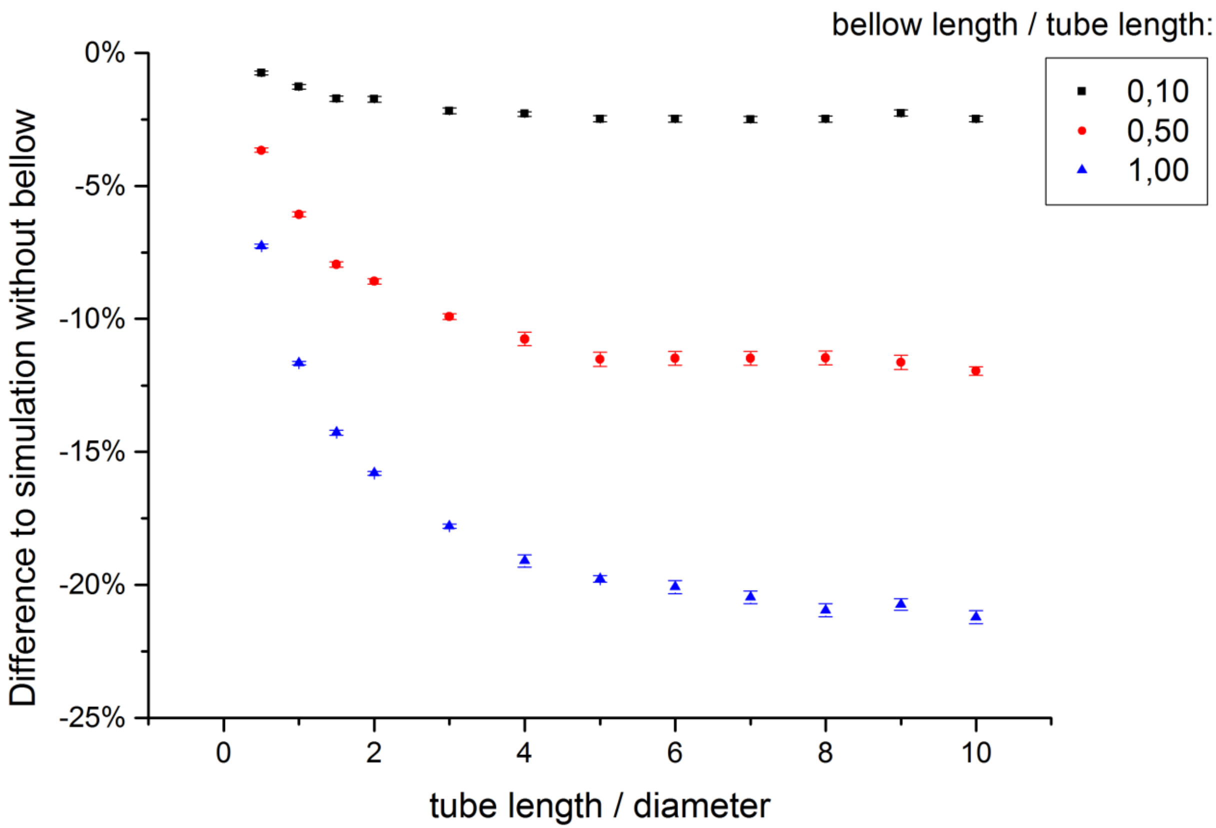
Membrane bellow analysis

- dependence of difference of transmission coefficients is approximately linear over the ratio bellow length / tube length



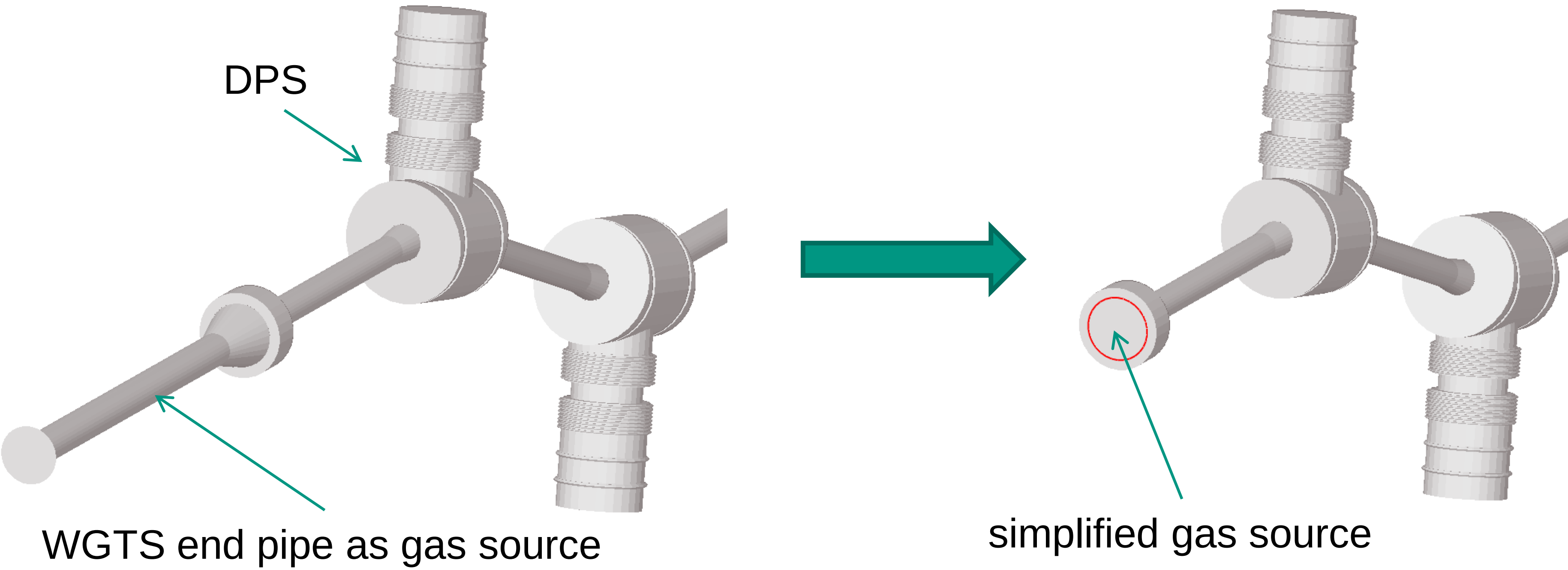
Membrane bellow analysis

- dependence of difference of transmission coefficients is highly nonlinear in tube length / diameter



Radiation characteristics of arbitrary gas sources

- **Example for KATRIN:** benchmark analysis has shown that simulations with simplified gas source are **twice as fast**

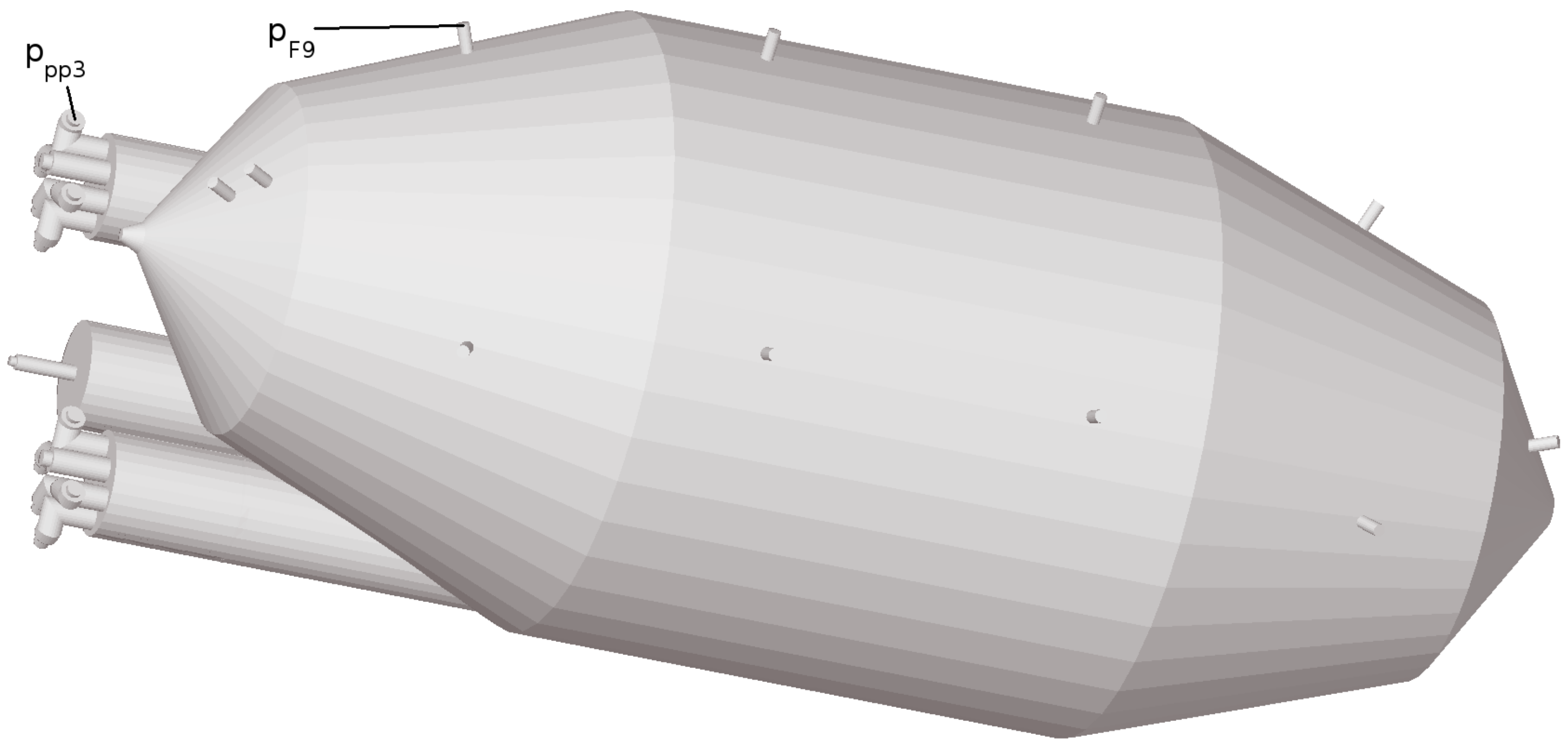


- **Future work:**
  - comparison of transmission probabilities between WGTS end pipe and simplified gas source → **check of reliability**

Simulations of the Main Spectrometer

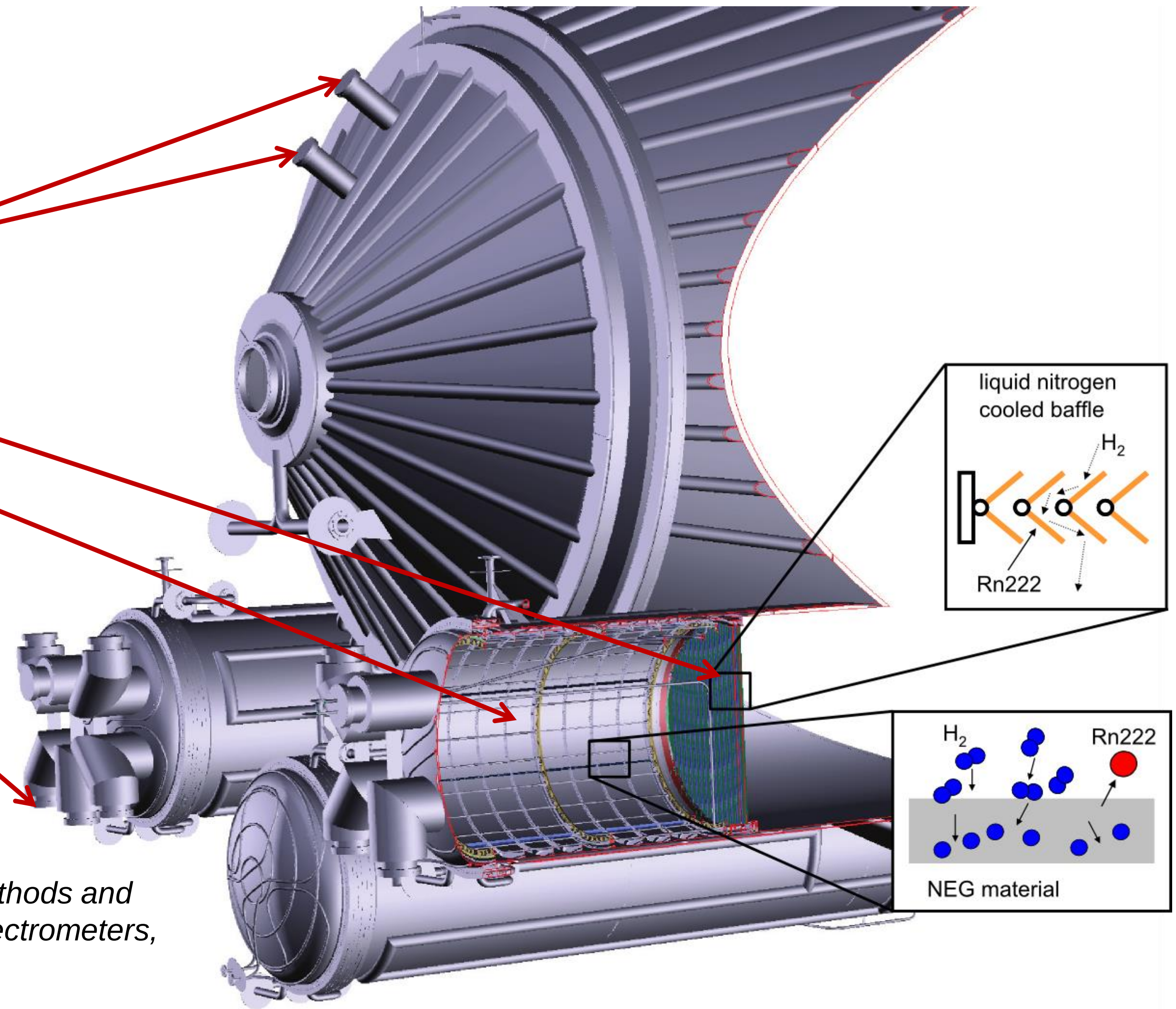
- simplified model of the main spectrometer created (optimized discretization for Molflow)

- simulate pressure ratio p_{PP3} / p_{F9} of pressure gauges



Simulations of the Main Spectrometer

- main components:
  - tank nozzles
  - baffles
  - NEG strips
  - TMPs



Source:
S. Görhardt: *Background Reduction Methods and Vacuum Technology at the KATRIN spectrometers,* PhD thesis, Karlsruhe 2014

Simulations of the Main Spectrometer

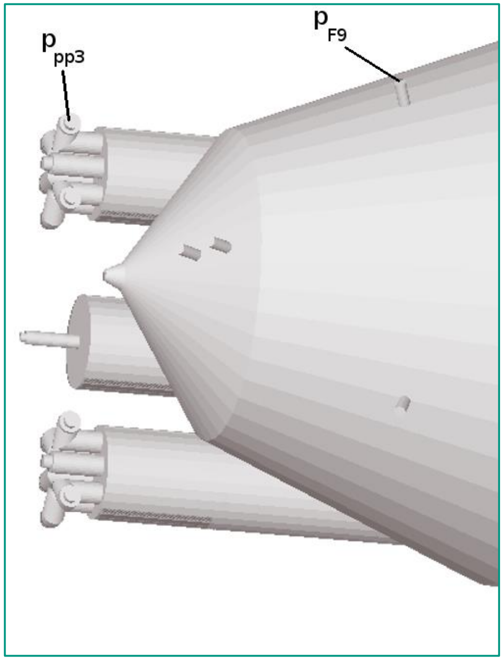
- three possible gas sources for hydrogen and radon:
  - complete stainless steel tank
  - NEG strips in pump ports
  - diagonal virtual area in one pump port (cross section between port and vessel) for determination of pumping speeds

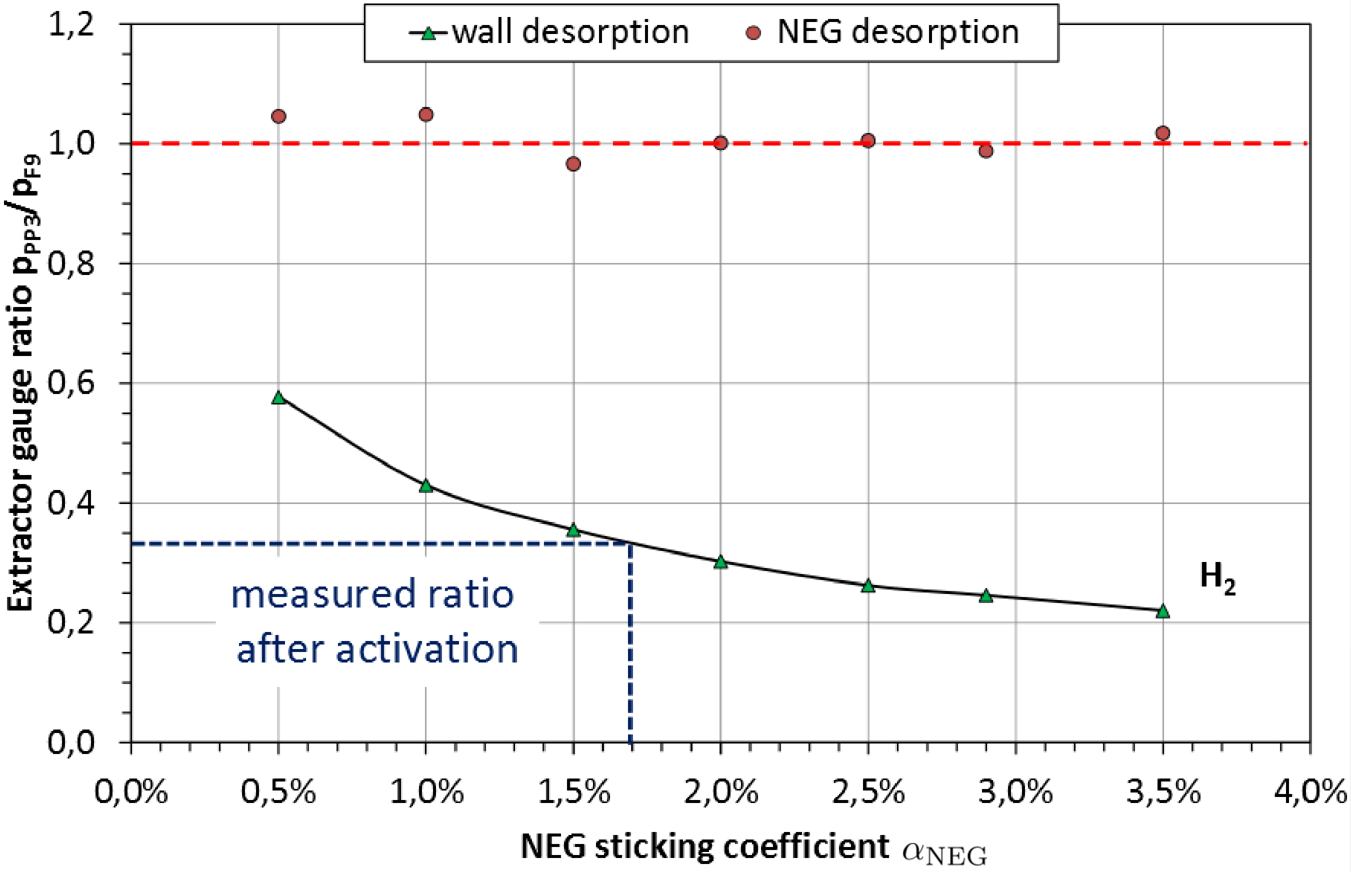
- three possible pump variations:
  - NEG pumps hydrogen with α_{NEG} between 0.5% and 3.5% (2.9% expected)
  - TMPs for hydrogen or radon with their respective α_{TMP}
  - baffles with α_{baffle} between 0% and 100% for radon

- 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 results for the NEGs as primary pumps

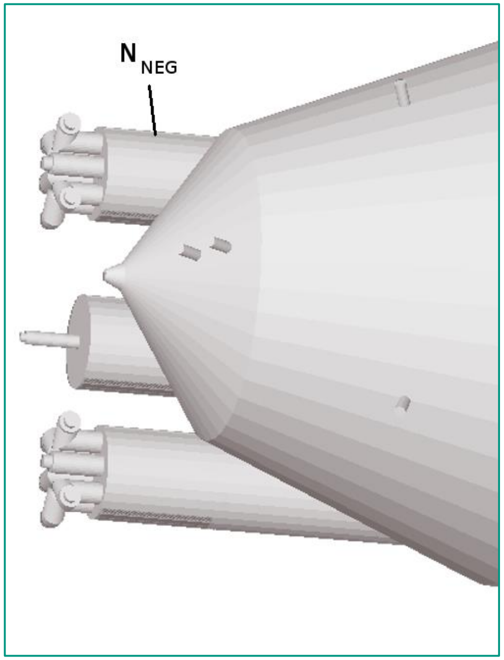
- ratio of hit numbers in vacuum gauges ≈ ratio of pressures: p_{PP3} / p_{F9}
- gas: hydrogen





Simulation results for the NEGs as primary pumps

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



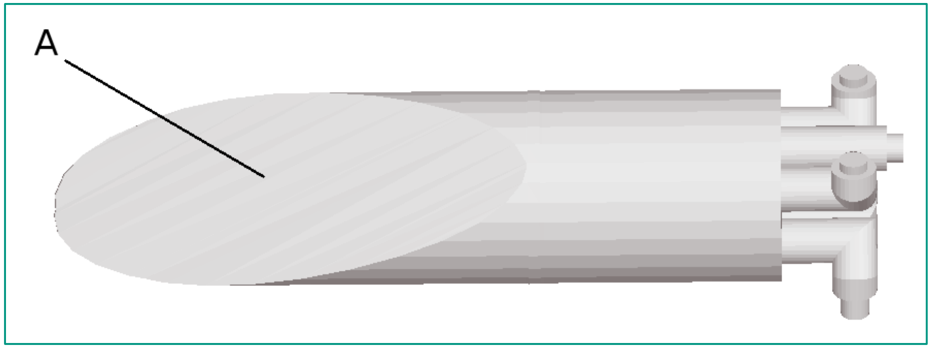
$\bar{c}$: mean molecular speed given by

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

A : desorption area (virtual area)

N_{NEG} : number of adsorptions in NEG strips

N_{des} : total desorption number



Simulation results for the NEGs as primary pumps

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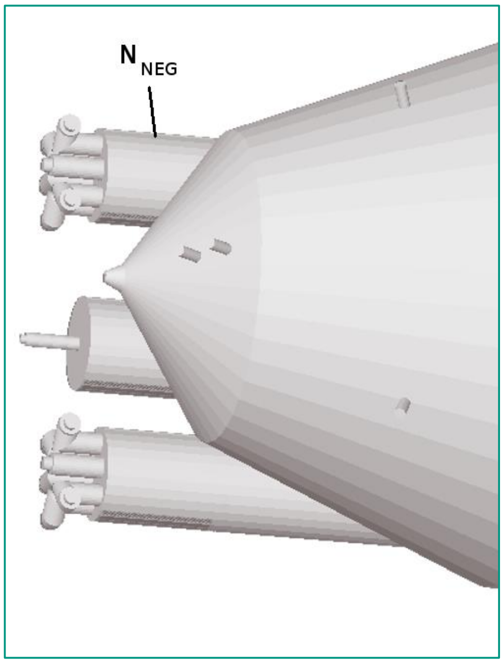
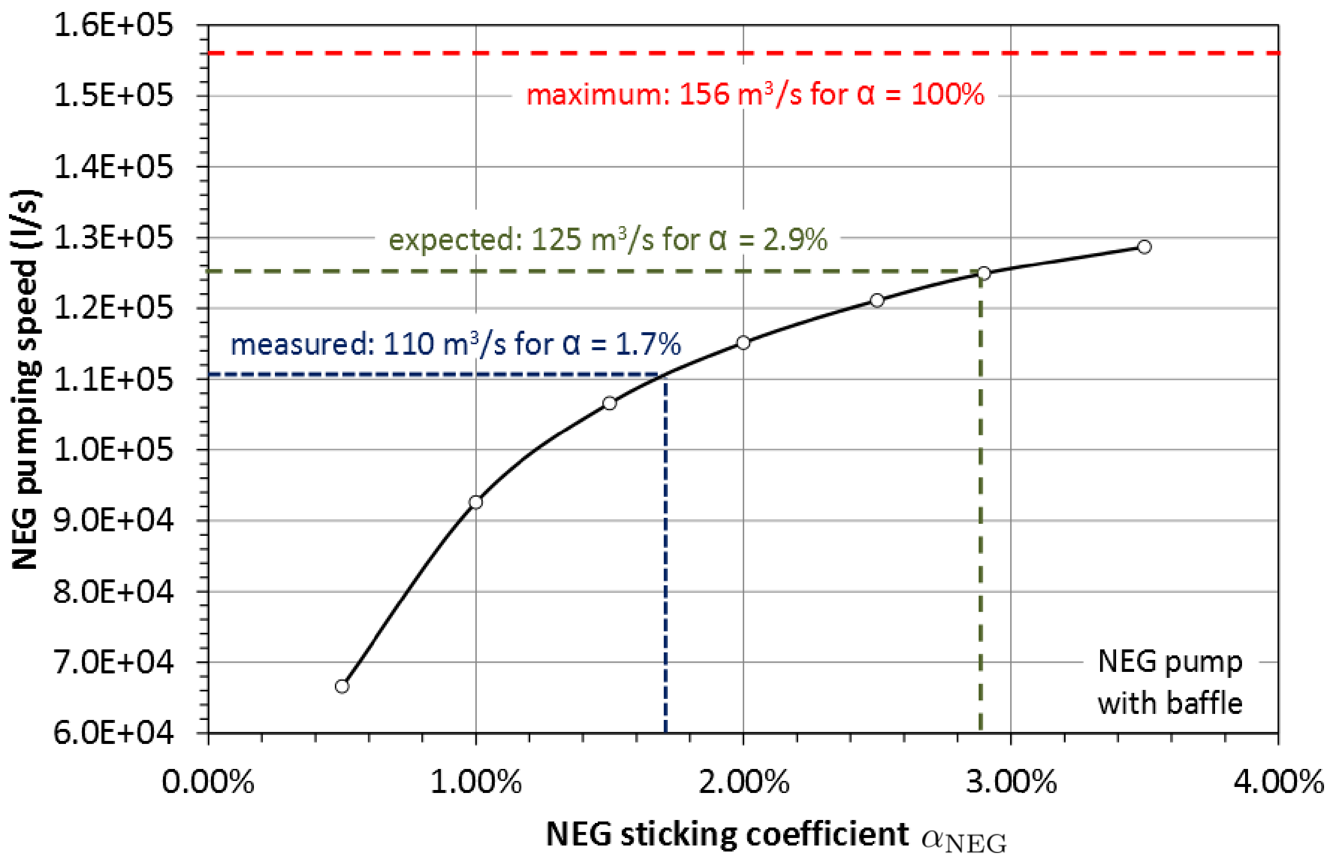




Simulation results for the NEGs as primary pumps

- main systematic uncertainty: estimation of outgassing rates

- many neglected surfaces: NEG cages in pump ports, electrodes in main vessel, …

  ➔ neglected outgassing sources

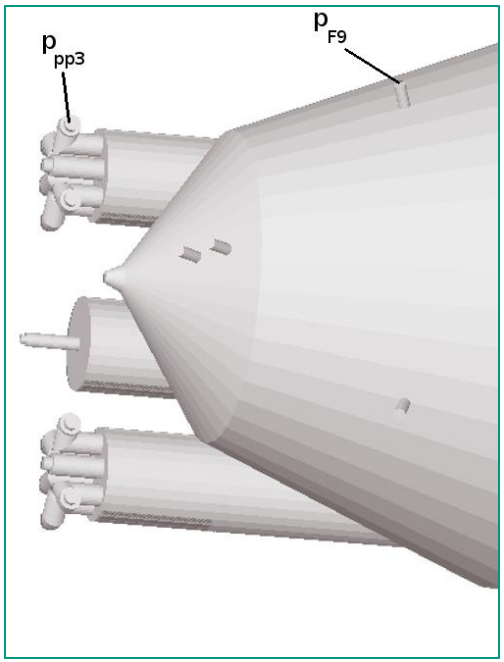
- three simulations with different outgassing properties for $\alpha_{\mathrm{NEG}} = 2.5\%$
  - homogenous outgassing of tank and pump ports
  - no outgassing in pump ports
  - 2:1 ratio of outgassing between tank and pump ports

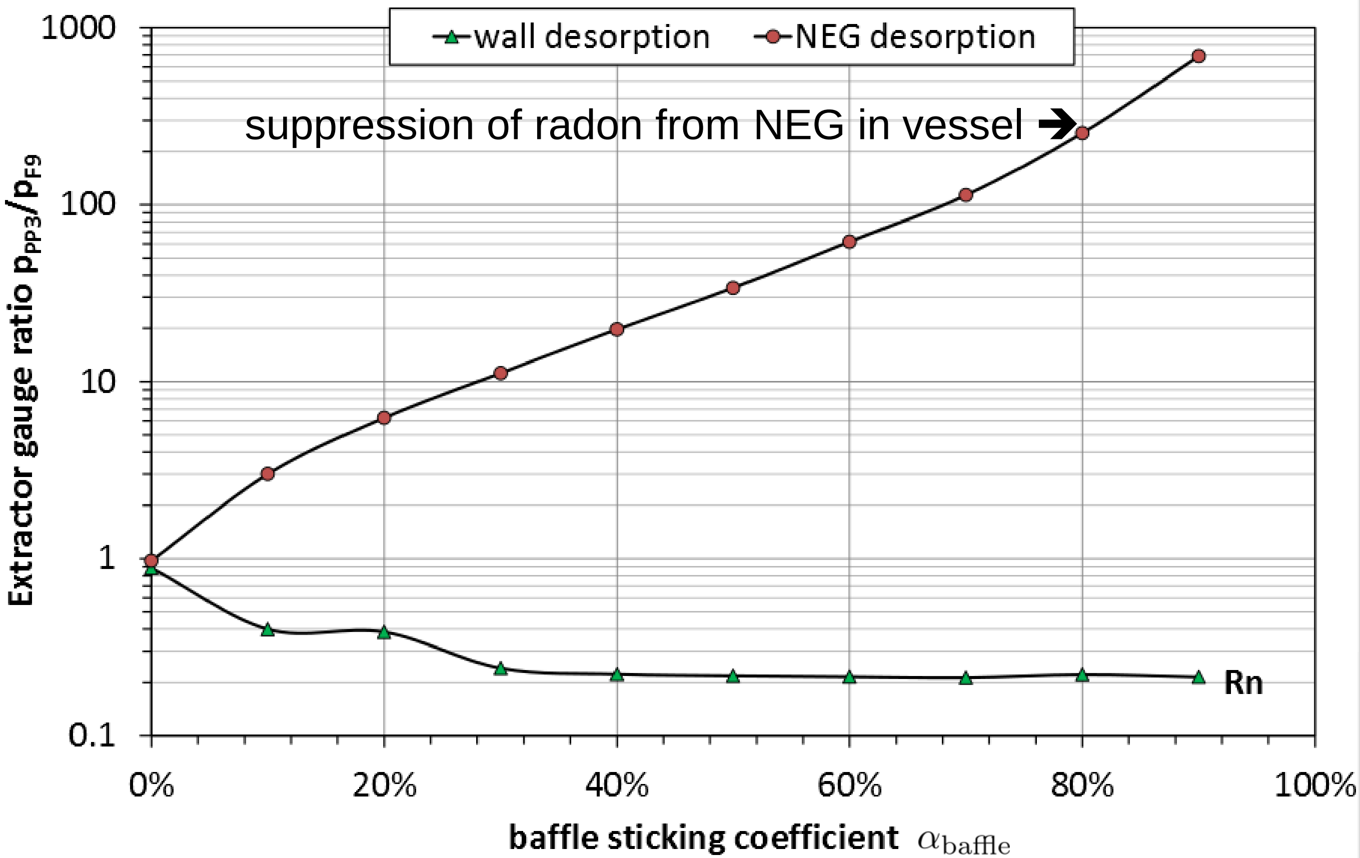
- simulated pressure ratios p_{PP3} / p_{F9} vary up to ~10%

  ➔ high systematic uncertainties

Simulation results for the TMPs as primary pumps

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