Karlsruhe Institute of Technology

Simulation of rarefied gasflow in the KATRIN tritium source

Laura Kuckert
COMSOL Conference Rotterdam
24.10.2013

Karlsruhe Institute of Technology (KIT), Institute for Nuklear Physics (IK)

COMSOL CONFERENCE ROTTERDAM2013

KATRIN
Karlsruhe Tritium Neutrino Experiment

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1.THE KATRIN EXPERIMENT - A (SHORT) INTRODUCTION

- „Who“ is KATRIN? – Karlsruhe Tritium Neutrino Experiment

- Measurement of absolute neutrino mass through beta deca of T_2

$$T_2 \rightarrow {}^3He + T + e + \overline{\upsilon}_e$$

- Measurement of electron spectrum with MAC-E Filter (*Magnetic adiabatic Collimation with Electrostatic Filter*)

- Limit Today: m_v < 3eV → possible KATRIN limit: m_v<200meV

- Higher sensitivity through :
  larger experiment, higher luminosity, lower background,
  → **reduction of systematic errors** (Gasdynamics…)
  precision of simulated integrated density <0.2%!!!!!

1.1 Tritium Source WGTS
(Windowless Gaseous Tritium Source)

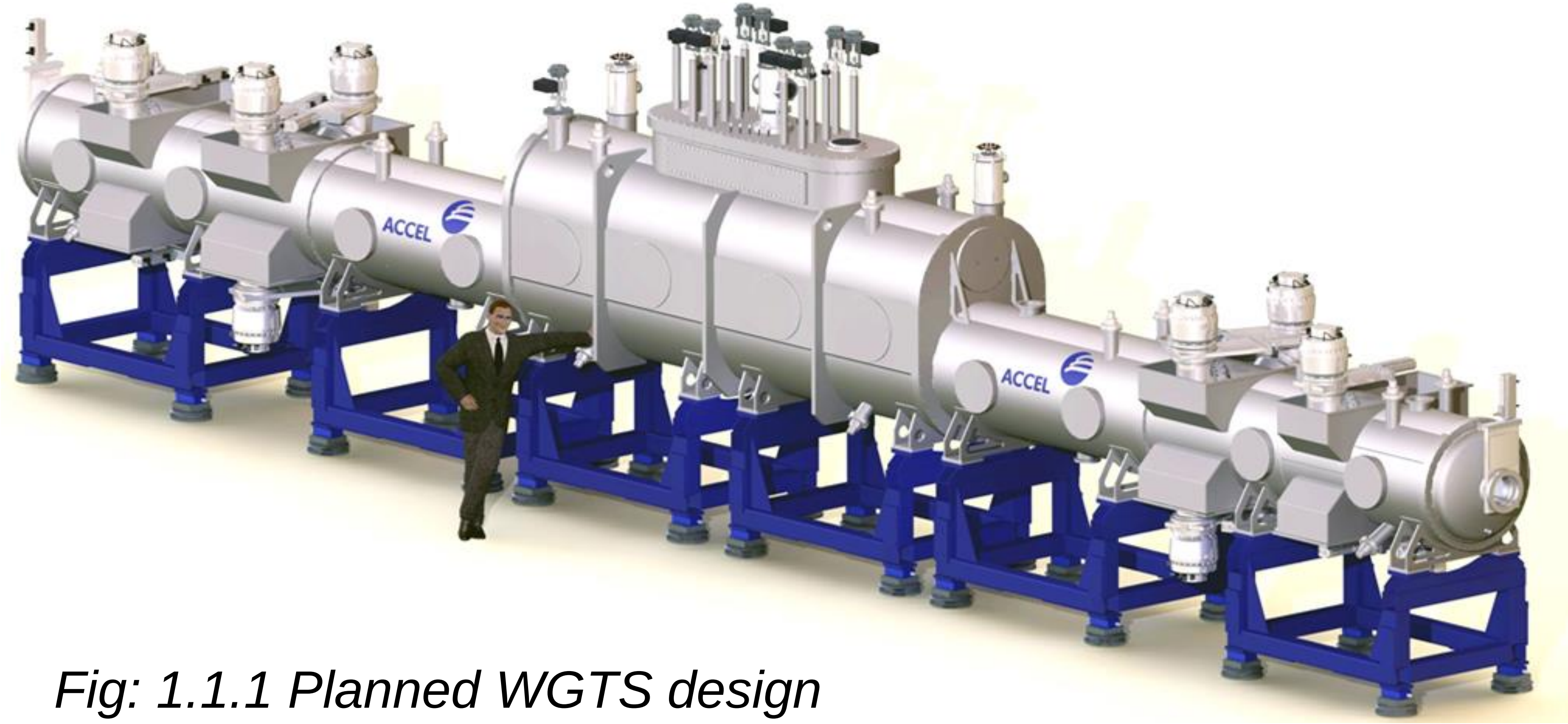


Fig: 1.1.1 Planned WGTS design

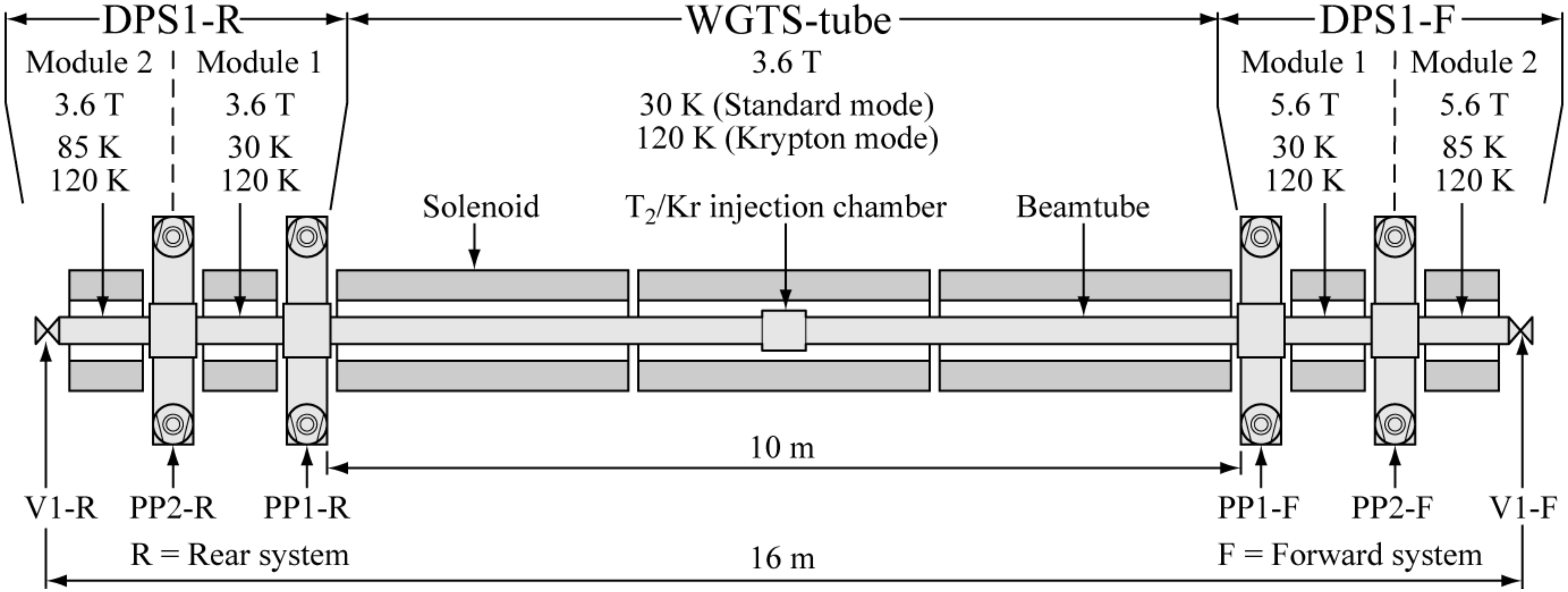


Fig. 1.1.2 WGTS scheme

- 10 m stainless steel tube, diameter 90mm
- High Temperature stability at 27-30K
- T_2 injection with pressure of 0.336 Pa through small orifices
- Avoid Tritium in spectrometer $\rightarrow$ 10^{14} pressure reduction factor
- Reduction factor WGTS end: 10^3

2. KATRIN GASDYNAMIC SIMULATION – A STATUS REPORT

2.1 General description of flow regimes in the WGTS

$$\delta = \frac{R \cdot p(z)}{\mu v_m}$$

δ = Rarefraction parameter

- **At Injection:**
  p ≈ 0.335 Pa → δ ≈ 23.4   Continuum, Navier Stokes equations
- **After 1st pump:**
  p ≈ 0.003 Pa → δ ≈ 0.2   Free molecular, collisions neglectable
- **In tube and 1st pump port:**
  0.02 < δ < 23   Collision term not neglectable (transition region), Boltzmann equation

2.2 Gasflow simulations of Felix Sharipov

- Numerical calculations based on Boltzmann equation (BE)

- Assumes BGK equation with S-model modification

- Gas – surface interaction included by Cercignani–Lampis scattering kernel

- Geometry and assumptions systematicly improved:
  - Exit pressure ≠ 0
  - Inlet and end effects
  - Longitudinal and radial temperature variation
  - 2D calculations (with temperature gradient)
  - To be continued with calculation of gas flow in first pump port…

- R/l = 0.0045 → first 1D calculation with p_{ex} = 0,T=const.

- Reduced flow rate *G* and local reduced flow rate G_p *connected*:

$$G = \frac{v_m (L/2)}{\pi R^3 p_{in}} \dot{M}$$

$$G_p = -\frac{v_m}{\pi R^3} \cdot \frac{dz}{dp} \cdot \dot{M}$$

→

$$G_p \frac{(L/2)}{\delta_{in}} \cdot \frac{d\delta}{dz} = -G$$

- $G_p(\delta)$*'s* from kinetic BE, calculate δ-values numericaly

- Interpolation formula for $\delta(z)$ for KATRIN source simulation

- Next steps: - T-profile and $p_{ex} \neq 0$ considered
  - Inlet and end effects considered

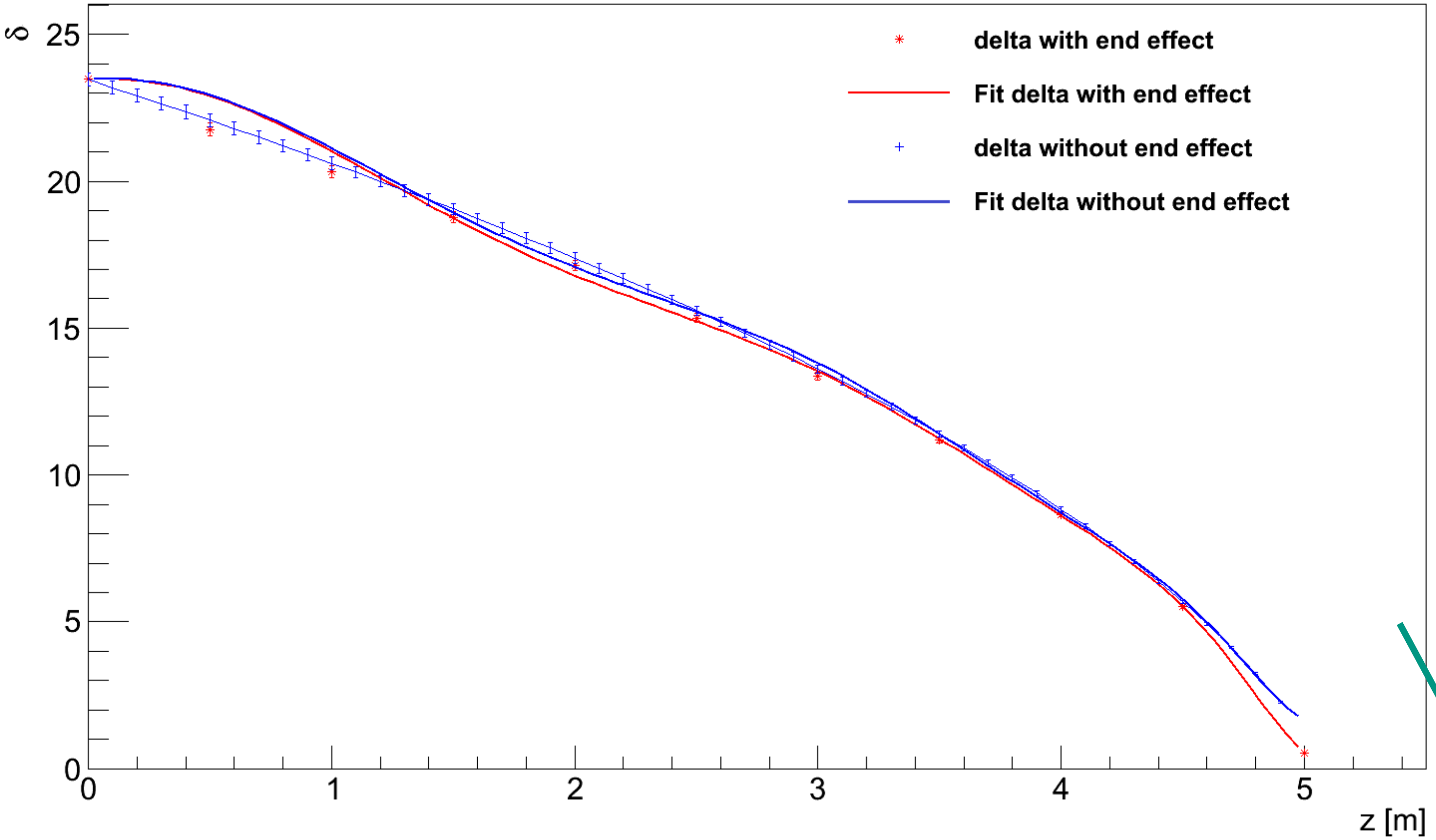


Fig.2.2.1 Rarefraction parameter δ with and without end effect (p_{ex}=5%p_{in})

Error from not considering end effects: z < 4m, **Δ < 2.5 %**
z = 4.5m, **Δ ≈ 4.5 %**

3D calculation :

- Same approach for solving BE as in 1D calculations
- Large computational effort → pseudo 3D-profil:

  2D calculations (include ΔT but no end effects) for 25 *δ*-values
- Combine with δ(z) from 1D calculation → 3D profile

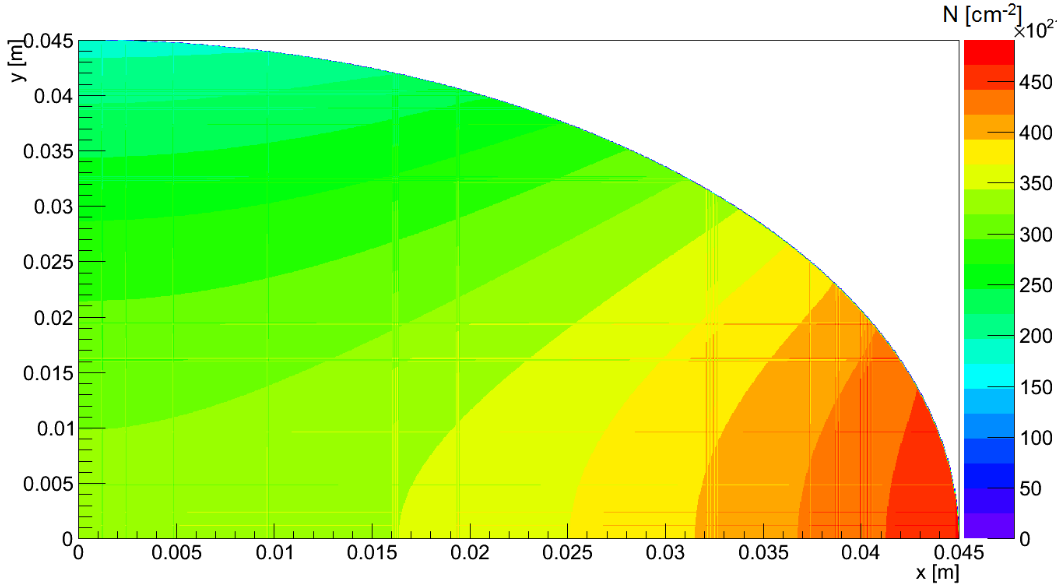


Fig 2.2.2 2D density profile at z=0

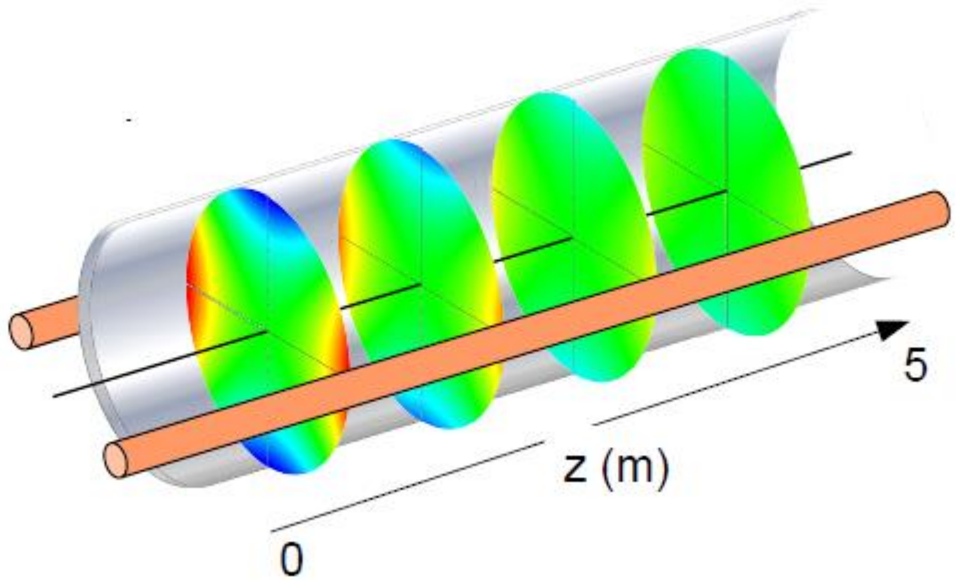
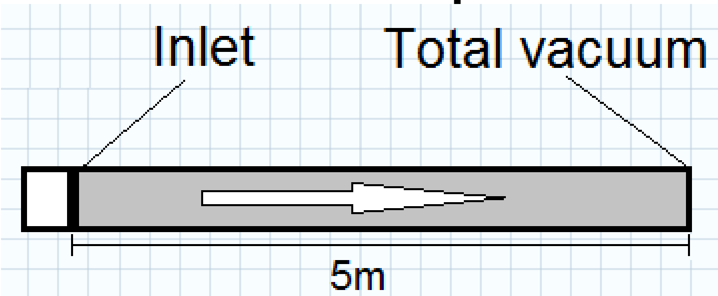


Fig 2.2.3 Pseudo 3D profile

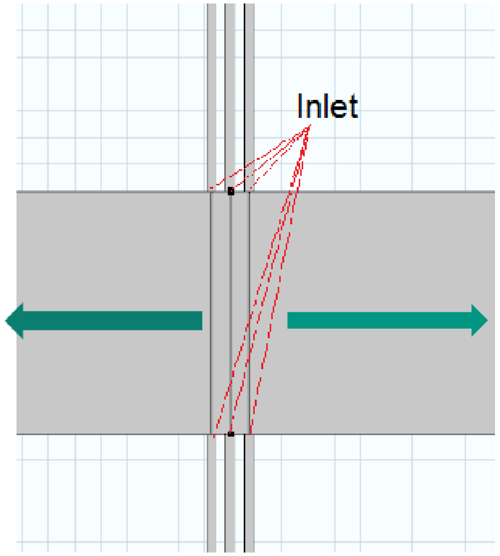
3. THE WGTS IN COMSOL

3.1 2D Geometry

1. Simplified tube for comparison with 1st Sharipov data:

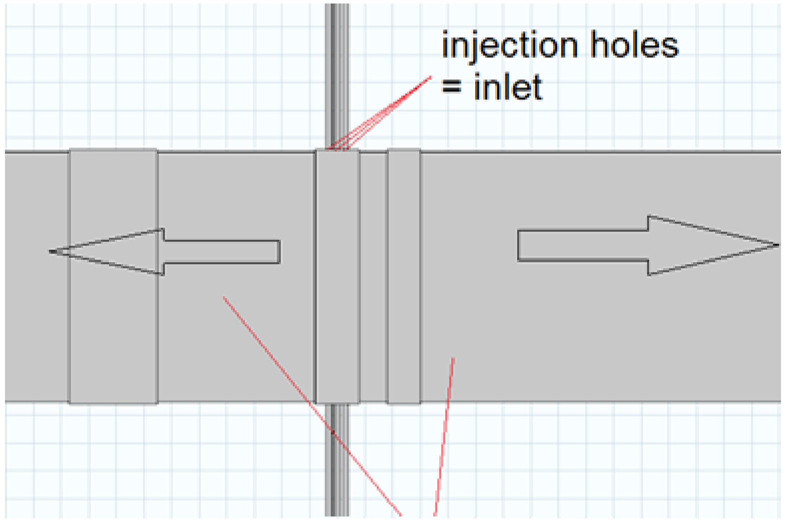


2. As 1. with exact inlet configuation:

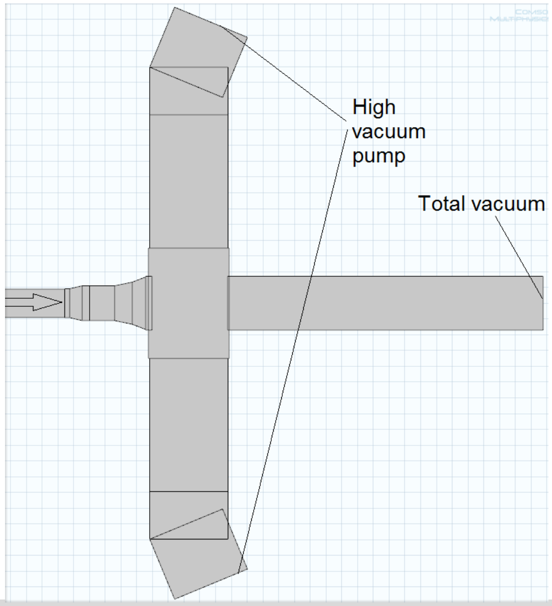


3. Exact WGTS geometry:

Inlet region:



Outlet region:



Transitional Flow Parameter:
P_{in} = 0.3368 Pa, M = 6.003 kg/mol
T = 30K = const !!! ,μ = 2.245*10^{-6} Pa*s

Case 1:

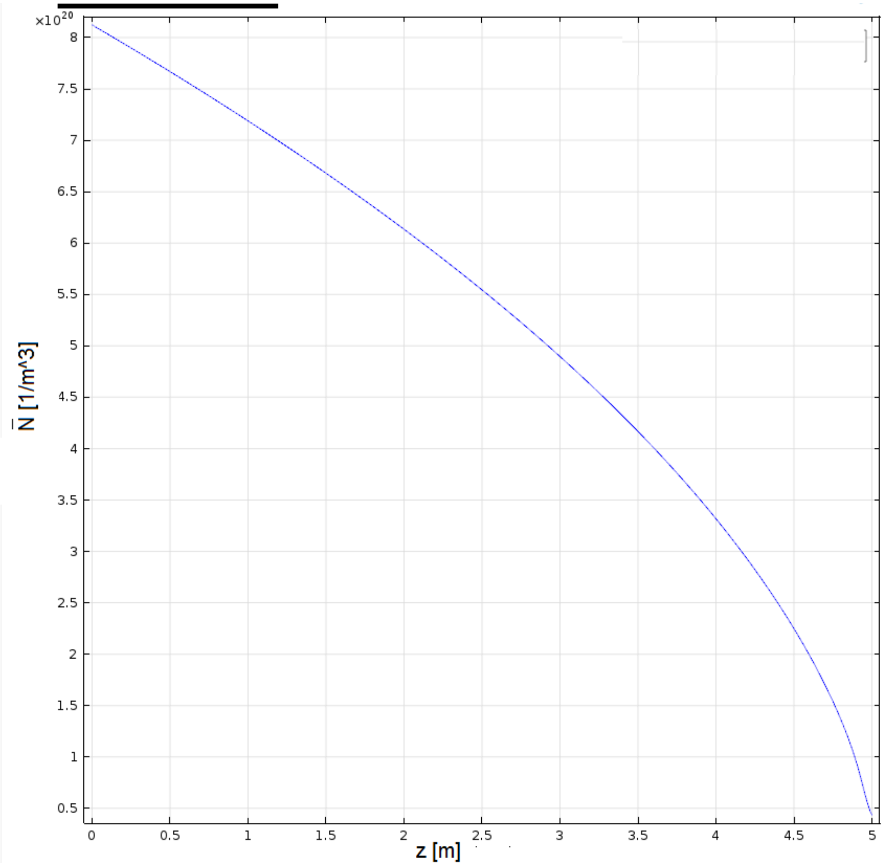


Fig. 3.1. Average N (z),

$N_{average}$ tube end=5.3% $N_{in,}$

N_{col}= 5.12*$10^{21}$$m^{-2}$

Case 2:

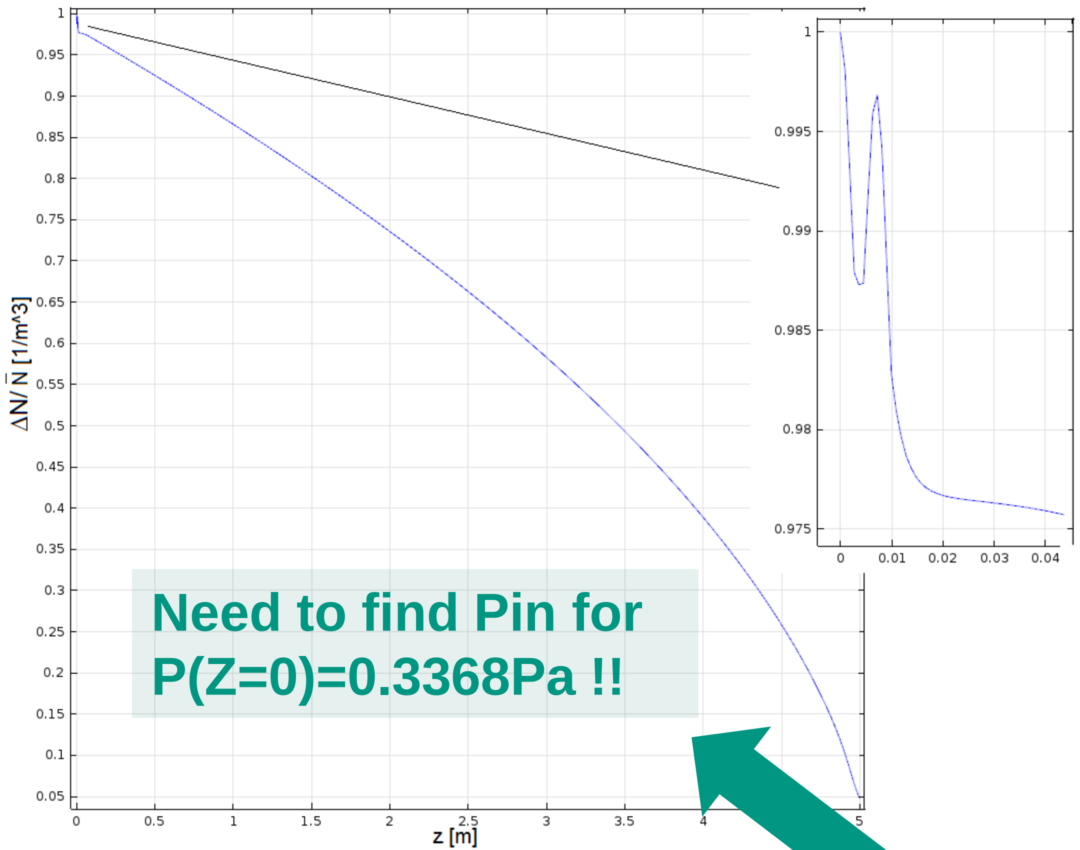


Fig. 3.2. Average N(z)

$N_{average}$ at tube end = 4.7% N_{in},

N_{col}= 4.4*$10^{21}$$m^{-2}$, $P_{average}$(z=0)=0.292 Pa

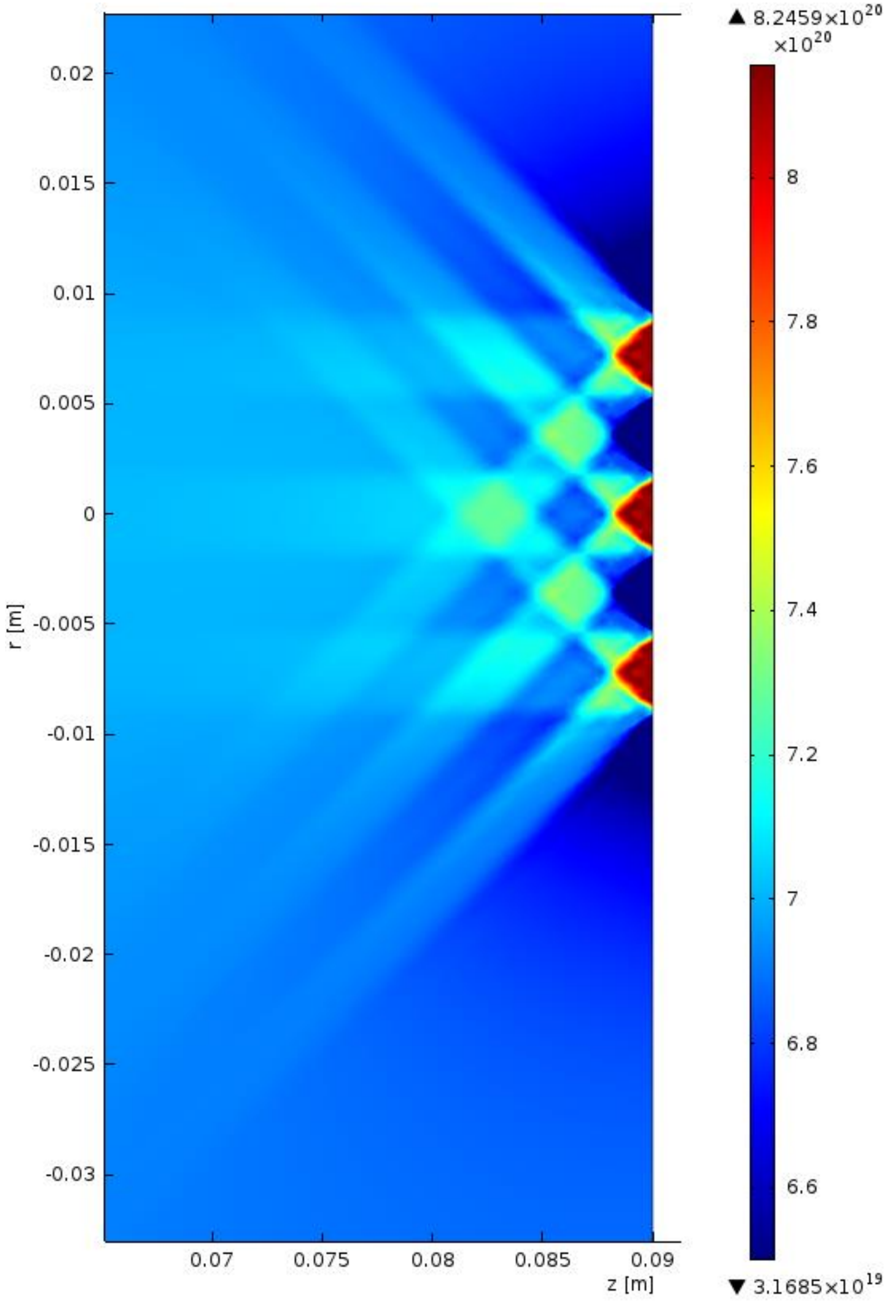


Fig. 3.1. Number density in injection region

4. Sharipov vs. COMSOL simulation

a) Comparison COMSOL vs Sharipov data without end effect

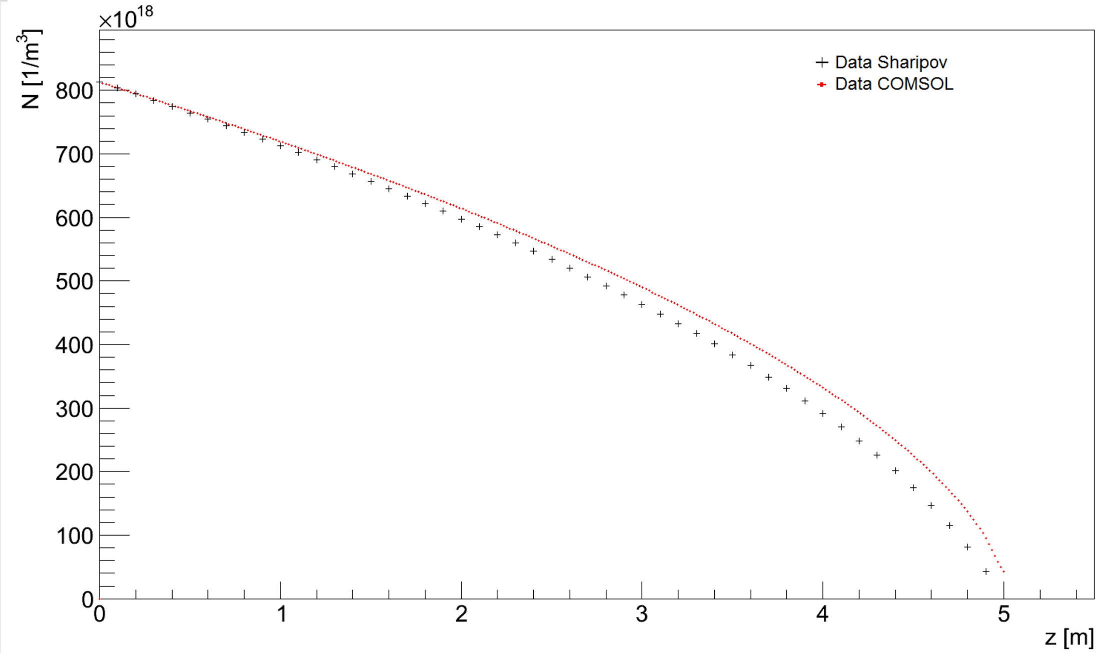


Fig. 4.1 N(z) simple inlet configuration and Sharipov simulation with $p_{ex}=0.53p_{in}$

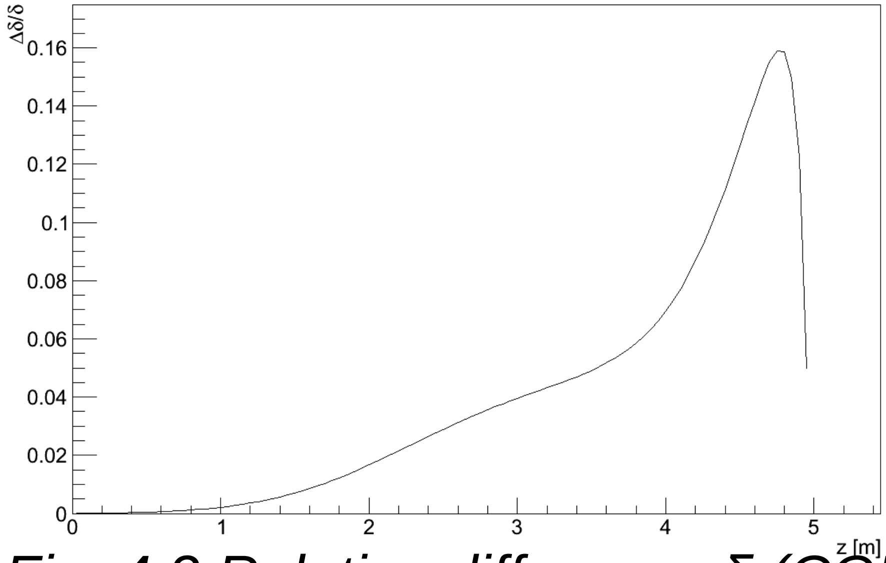


Fig. 4.2 Relative difference δ (COMSOL vs Sharipov)

Deviation in column density 2.5%

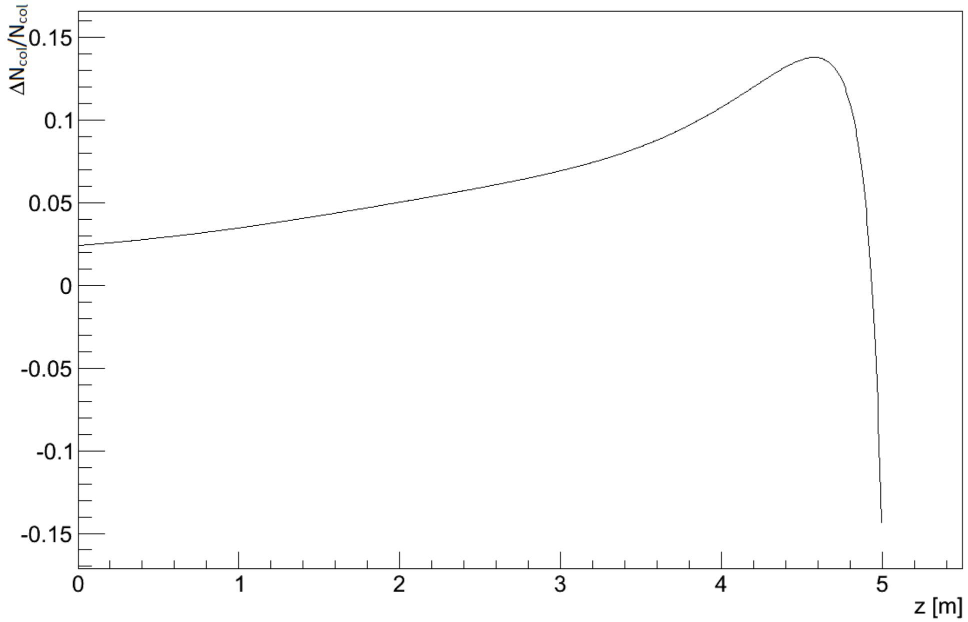


Fig. 4.3 Relative difference N_{col}

b) Comparison COMSOL vs Sharipov data with end effect

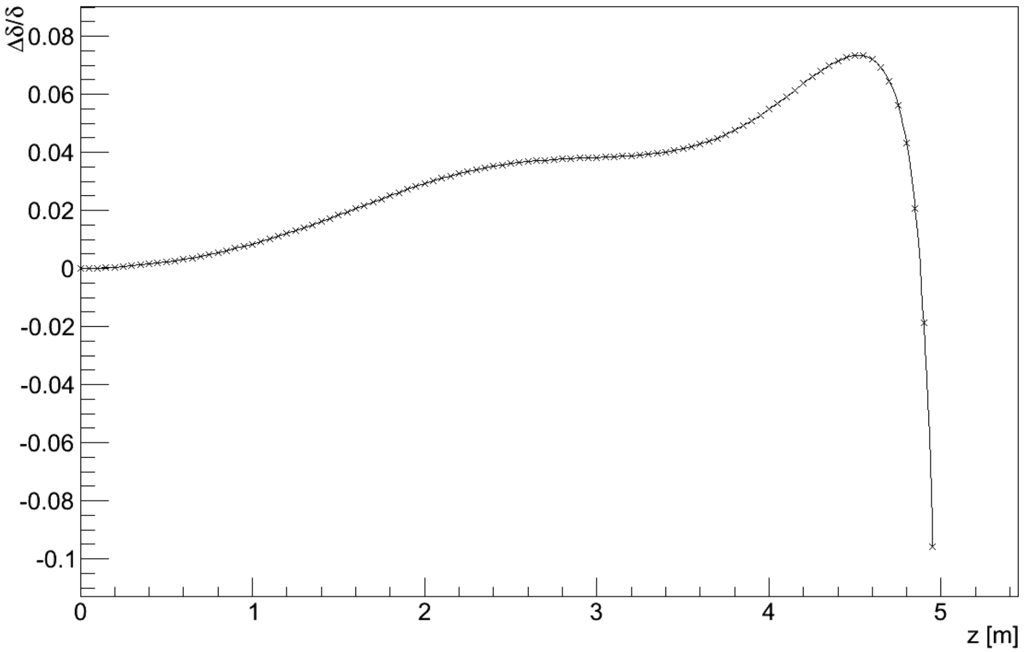


Fig. 4.4 Relative difference δ (3 fold inlet configuration)

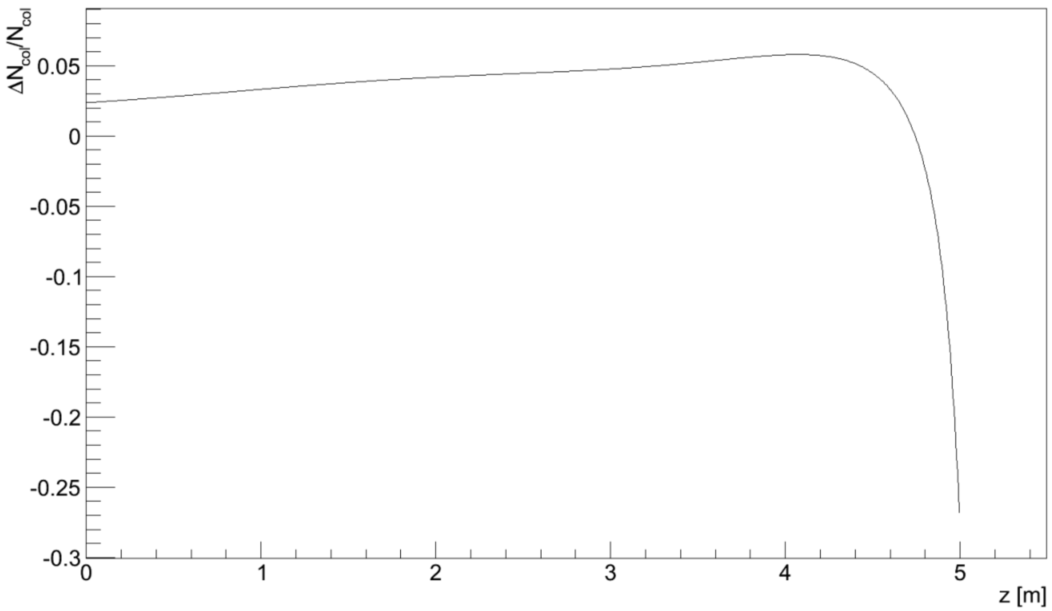


Fig. 4.5 Relative difference N_{col}

Still 2.5% deviation in column density

5. CONCLUSION

- Different 2D models of the WGTS using Transitional flow interface had been simulated with COMSOL

- Comparison of average 2D results with 1D Sharipov calculation:
  - Deviations in density of end region (up to 8%)
  - Disagreement in column density (for z=0) 2.5%, KATRIN needs N_{col} precision of 0.2%...
  - Disagreement in pressure distribution inlet region

- No ΔT and accomodation coefficient in COMSOL simulation

- **ToDo:** improve 2D simulation (all pump ports, mesh size), simulate 3D geometry, find correct inlet pressure, simulate test experiment

Thank you for your attention…