Karlsruhe Institute of Technology

Simulation and analysis of source related effects for KATRIN

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Graduiertenkollegs-Workshop, Bad Liebenzell 2012

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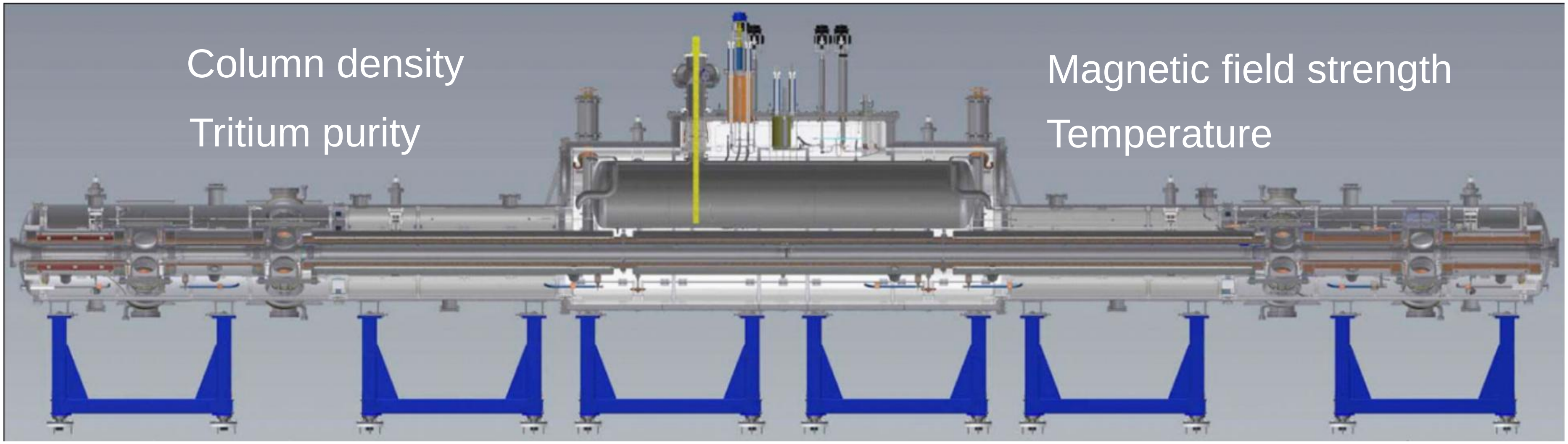
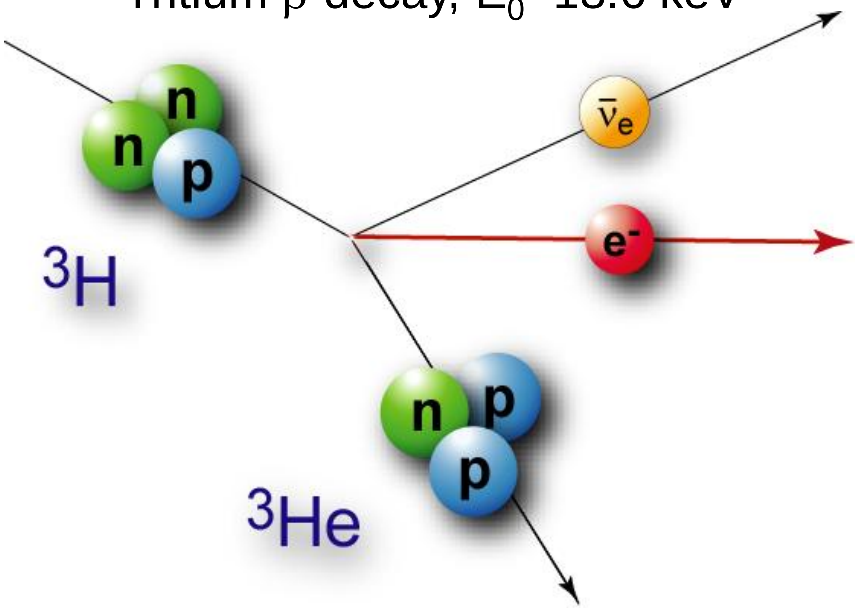
Institute of Experimental Nuclear Physics (IEKP)

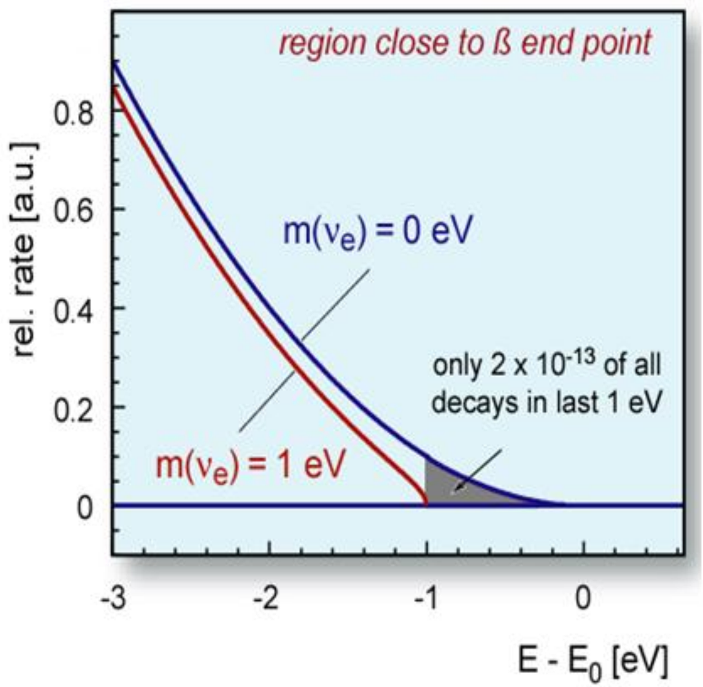


Contents

Direct determination of neutrino mass: β-decay

Tritium β-decay, E_0=18.6 keV



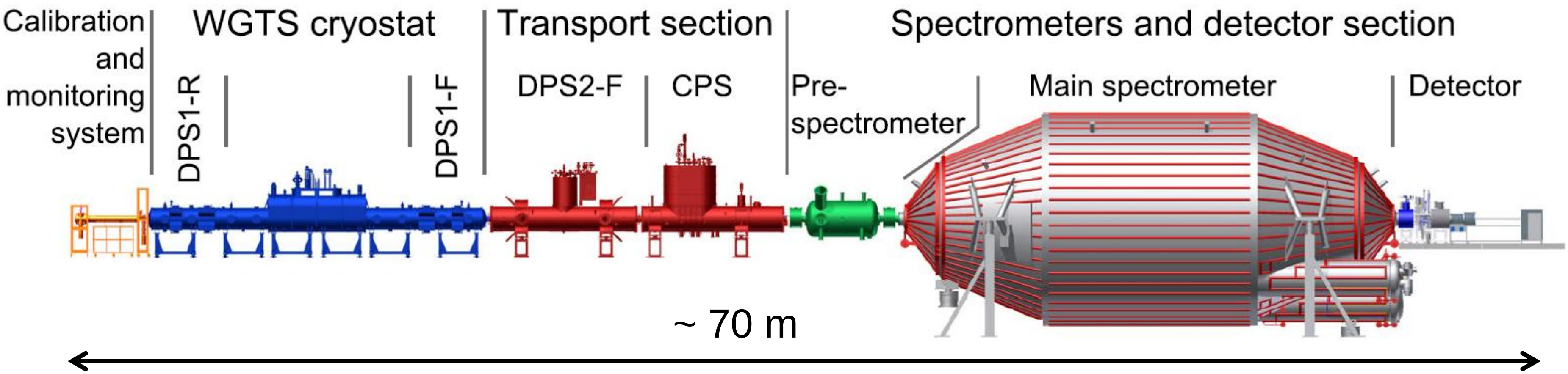


$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$

$$\frac{dN_i}{dE} \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_i^2 c^4}$$

Model independent approach: kinematics & energy conservation

The KATRIN experiment

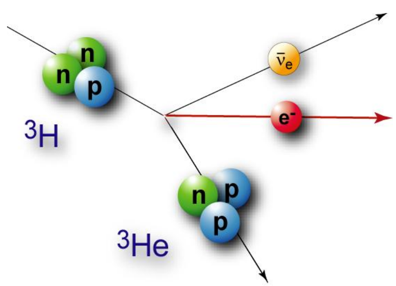


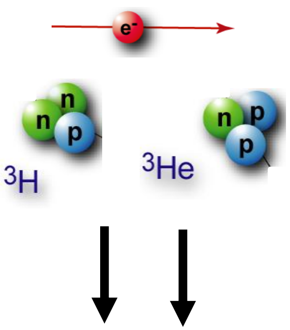
Strong β-source $>10^{11}$ e$^-$/s

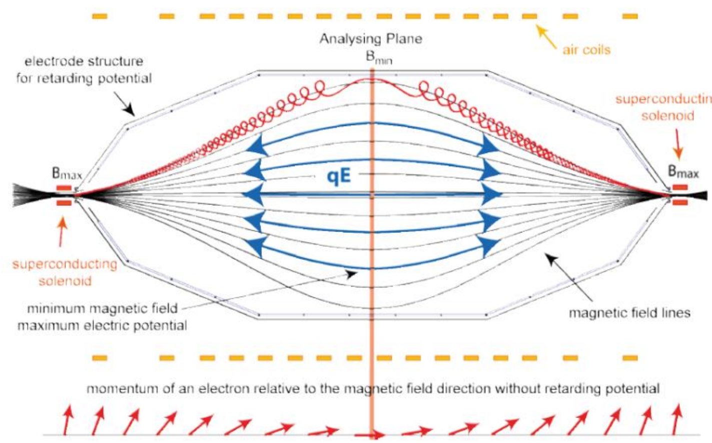
Remove mole-cules and ions

Transmit e$^-$ with E>qU
ΔE=0.93 eV

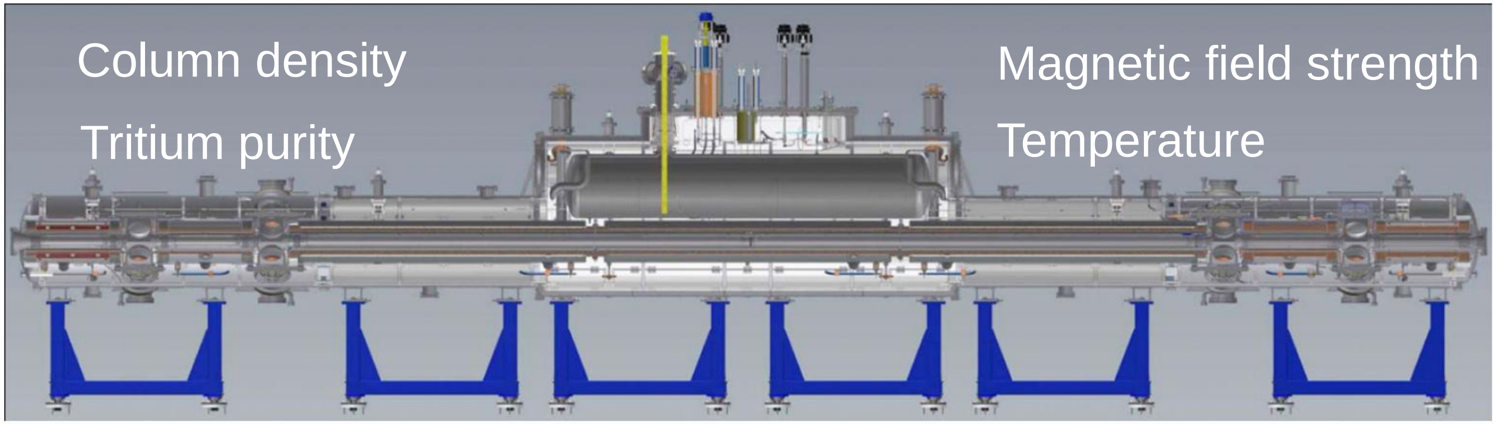
Count e$^-$
~ 1 e$^-$/s

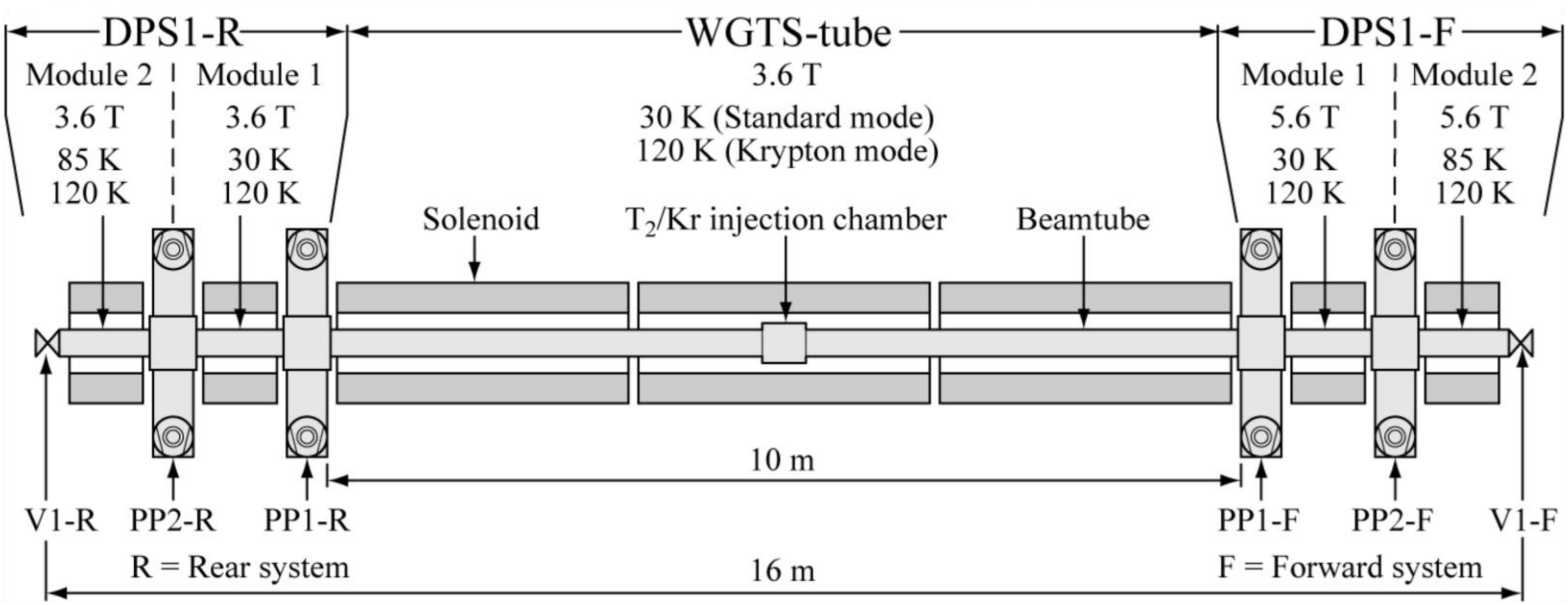






Windowless Gaseous Tritium Source WGTS





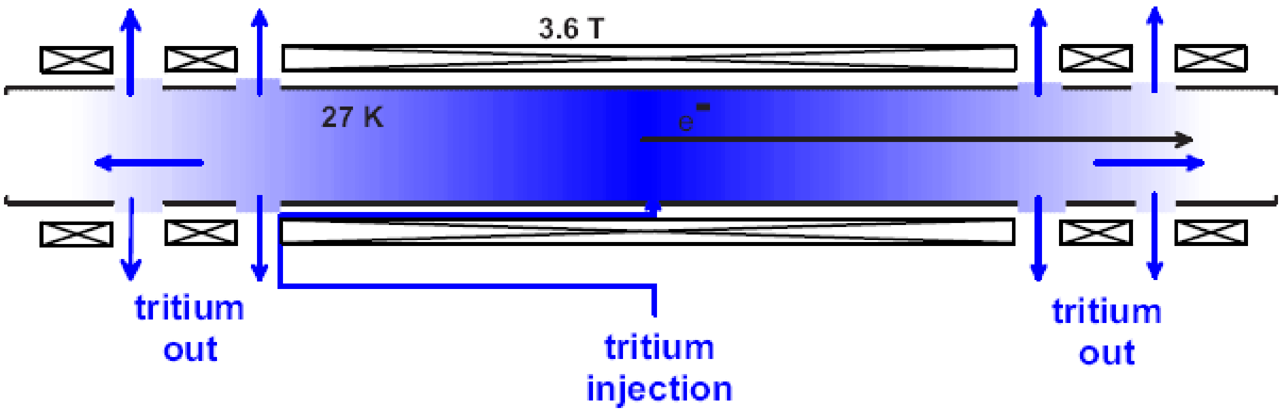
Motivation: Systematic effects of the source

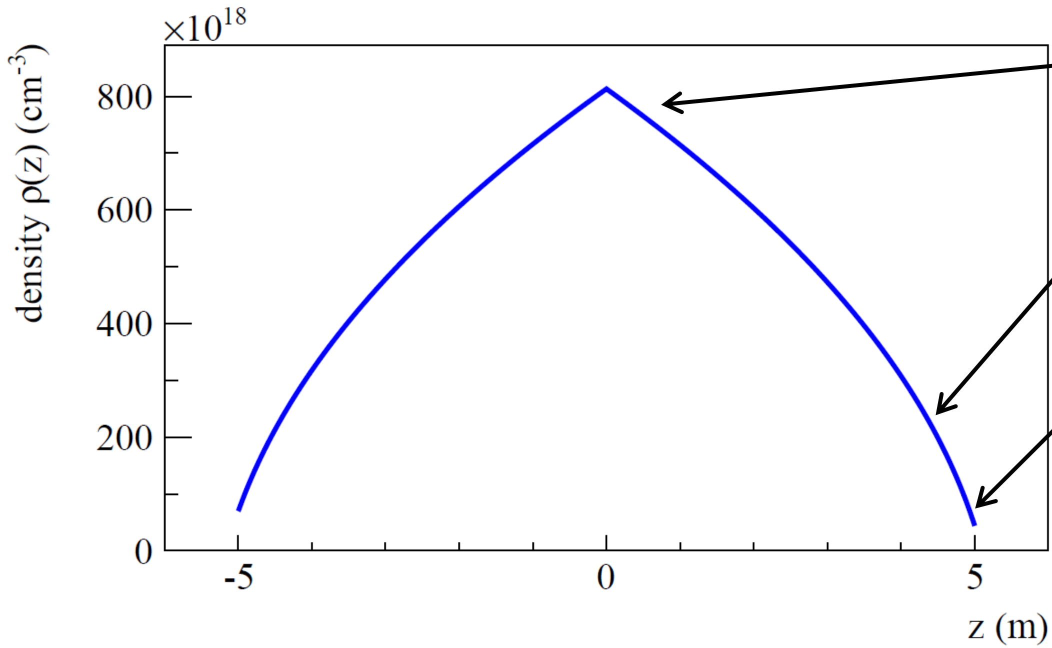
- KATRIN sensitivity: $m_\nu < 200\,\text{meV/c}^2$ (90% C.L.)
- 3 years measurement time: $\sigma_{\text{stat}} = 0.018\,\text{eV}^2/\text{c}^4$
- Systematic effects: $\sigma_{\text{syst}} \leq 0.017\,\text{eV}^2/\text{c}^4$

- "4 out of 5 systematic effects are related with the WGTS"
  - Monitoring of the column density
  - Energy losses due to elastic/inelastic scattering
  - Magnetic field variations in the WGTS
  - Description of the final state distribution

Simulation

1-D density calculations





Hydrodynamical regime

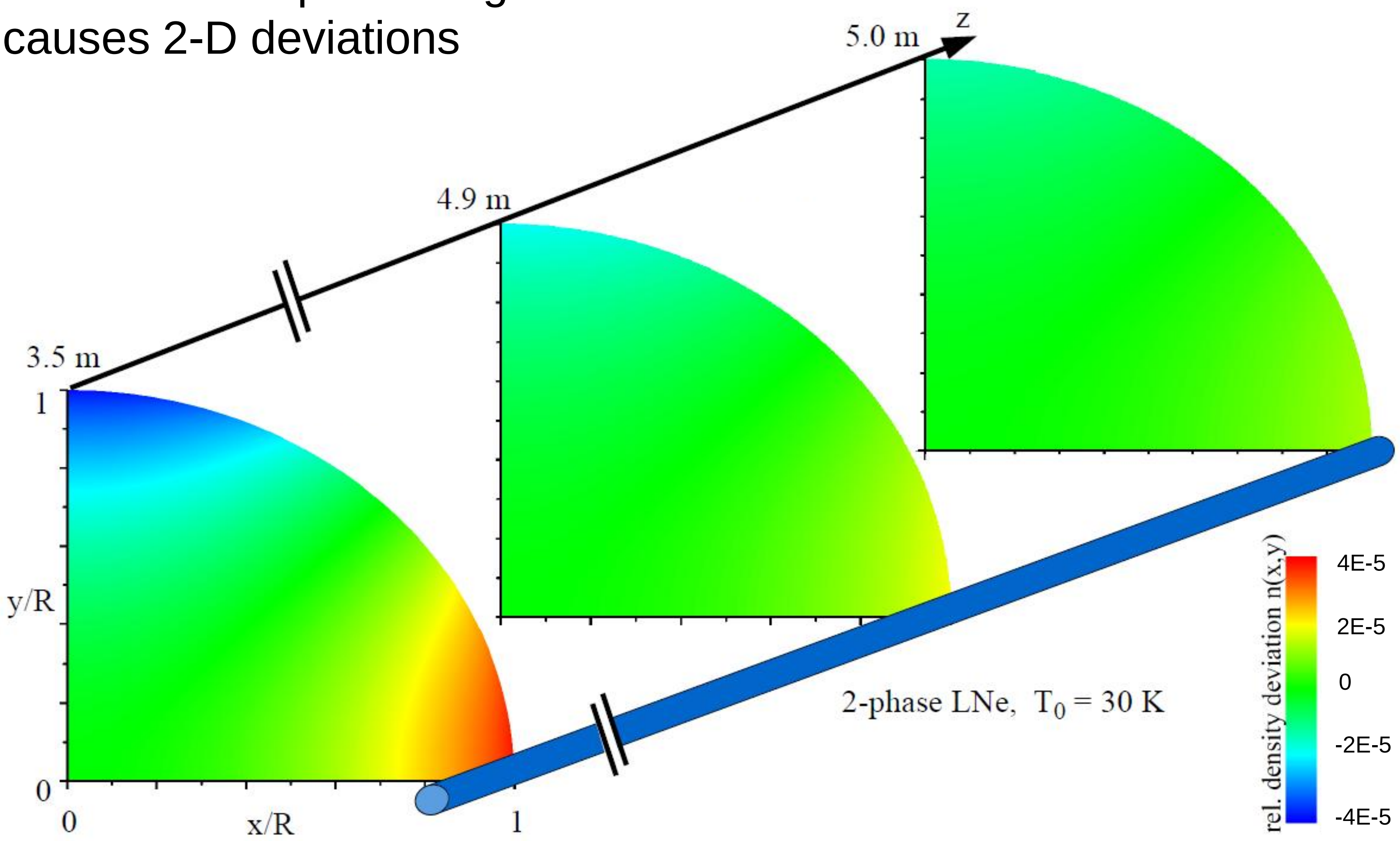
Transitional regime

Free molecular flow

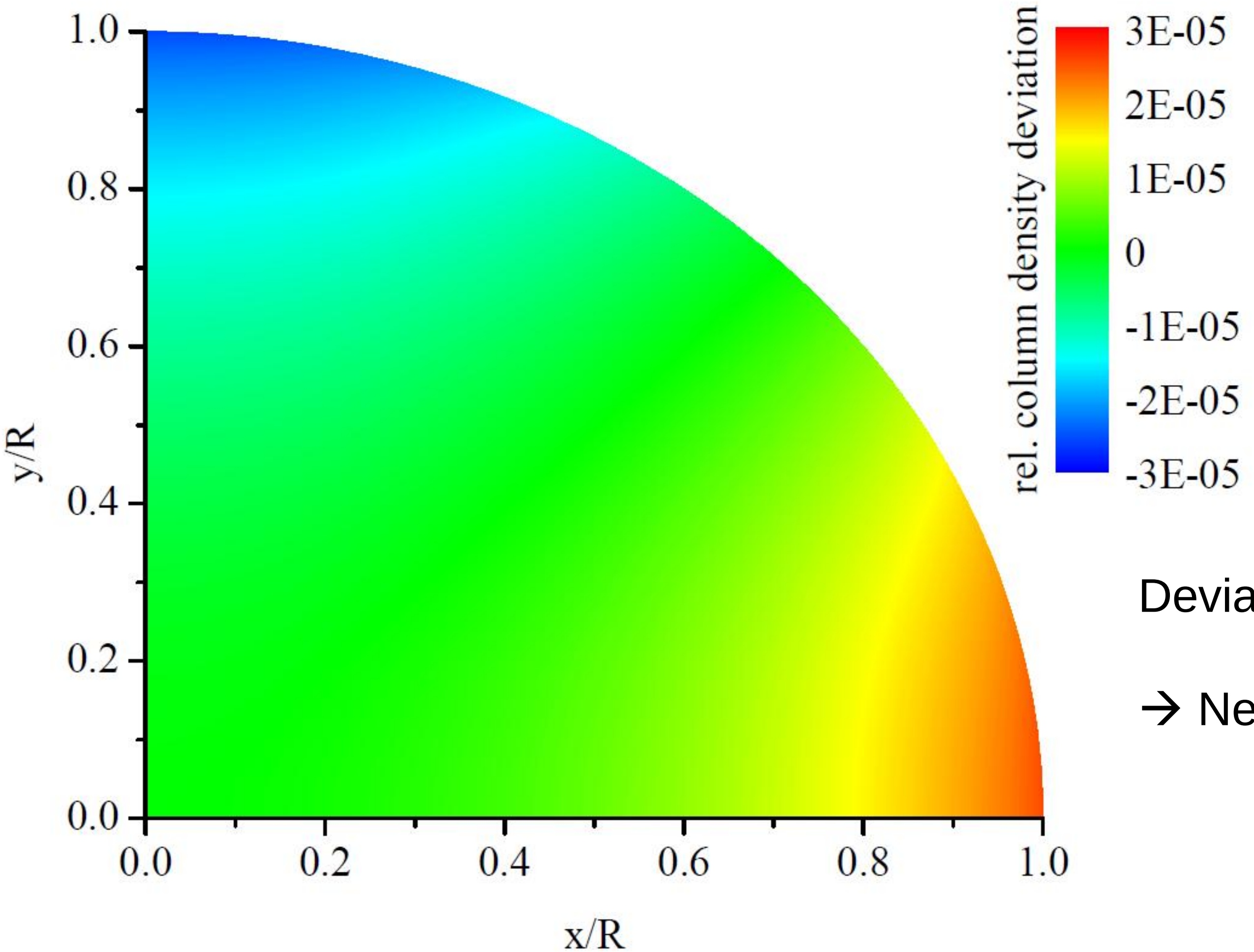
→Unified calculation based on Boltzmann equation

2-D / Pseudo-3-D density profile

- Azimuthal temperature gradient causes 2-D deviations



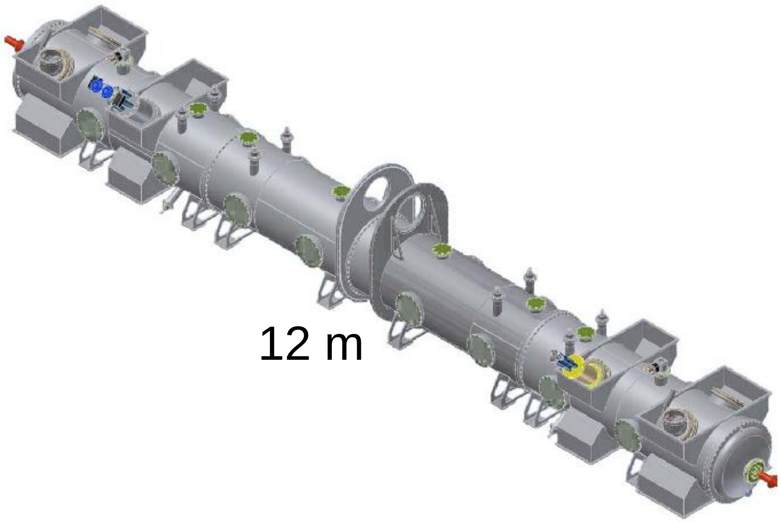
Column density of the WGTS



Deviations on the 10^{-5} level

→ Negligible for KATRIN

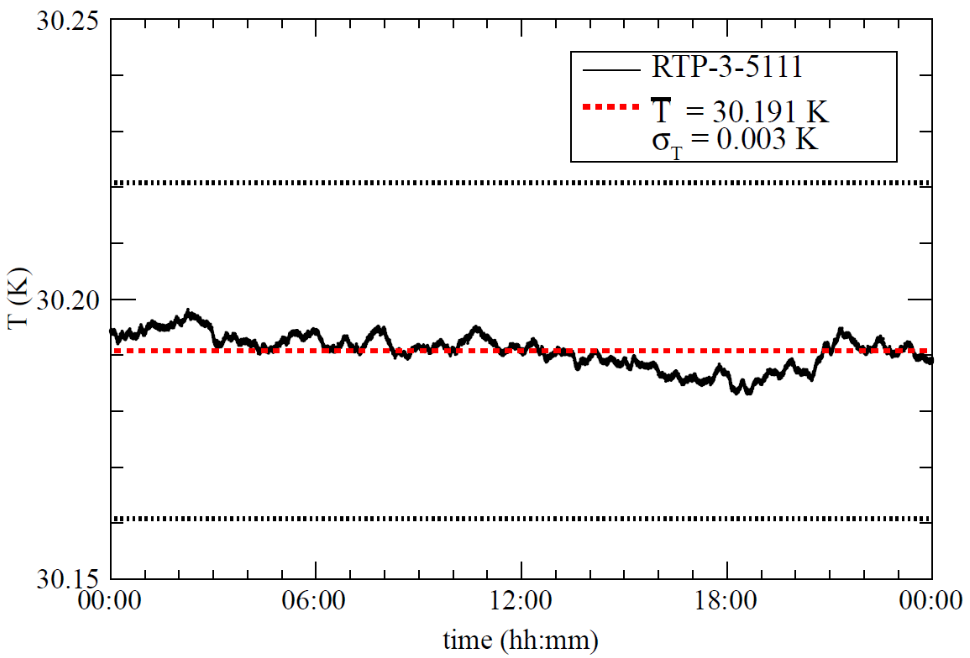
Temperature profile (Measurement)



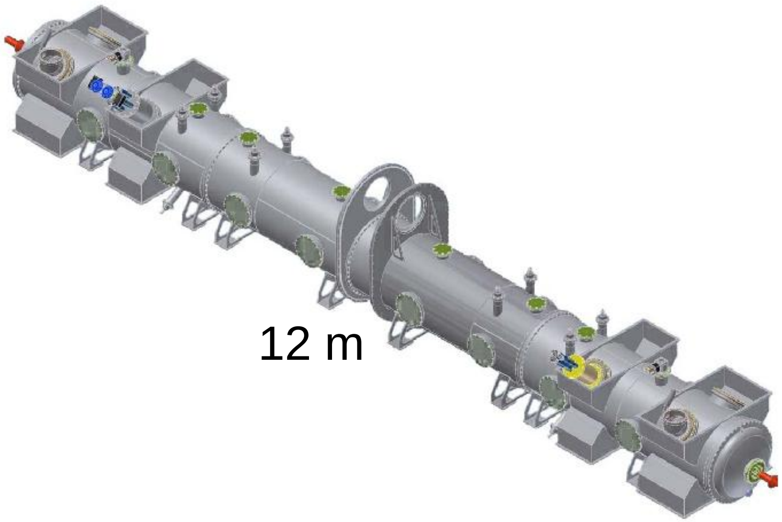
- „Demonstrator“ tests, 2011
- Original components, cryosystem
- Test of beam tube cooling
- No tritium circulation

- Temperature stability

$$\Delta T / T = 1 \cdot 10^{-4}$$



Temperature profile (Measurement)



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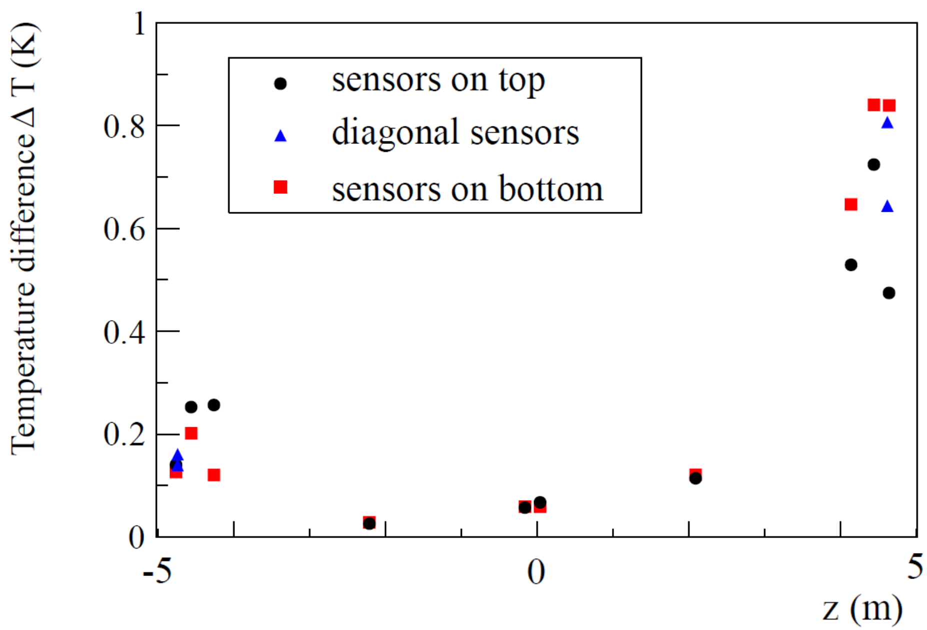
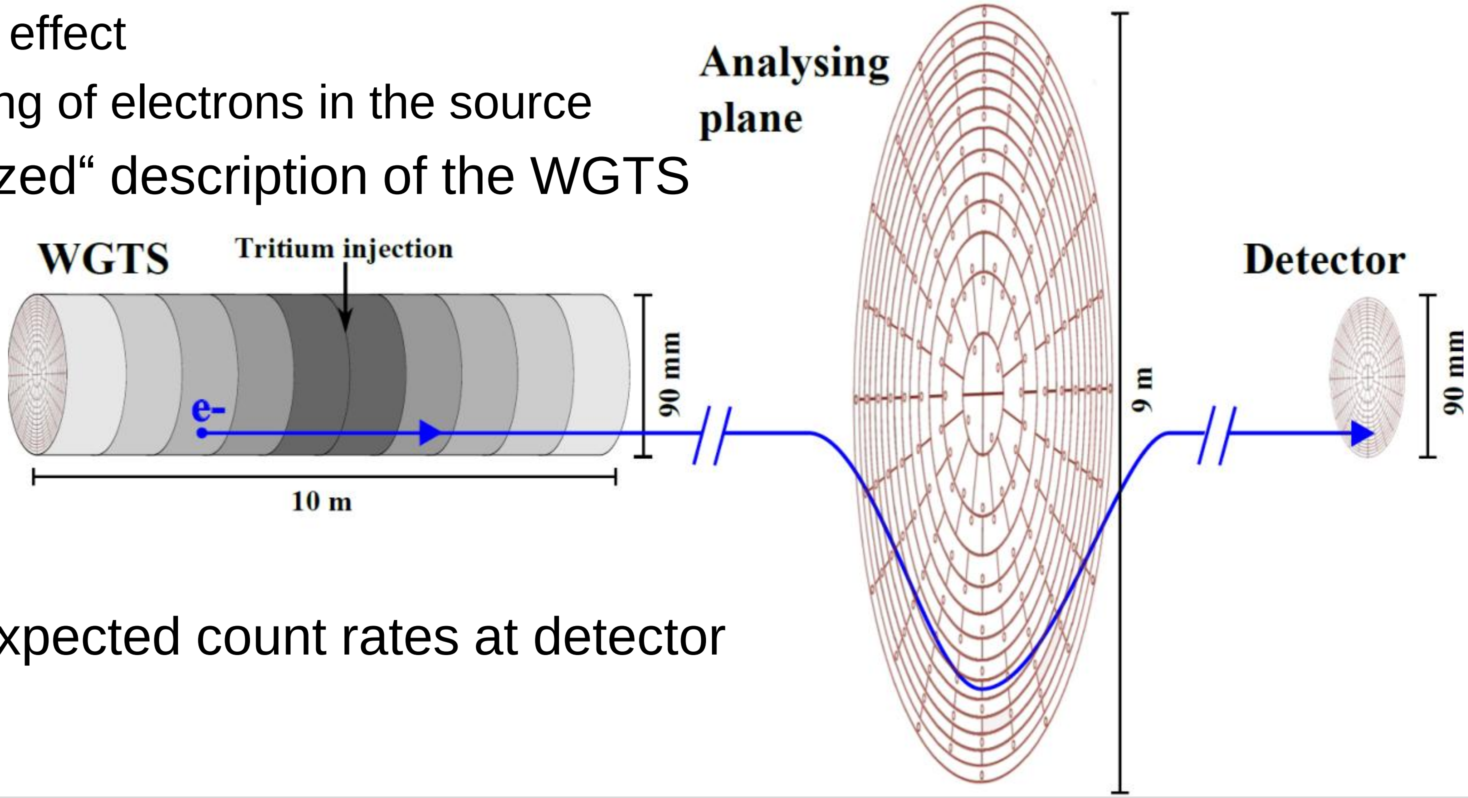


- Temperature gradient ~ 1 K
- Increased thermal radiation
- Thermal conduction identified

→Solved at assembly of the WGTS

Source Spectrum Calculation

- Combine various models of source parameters
  - Gas dynamics
  - Magnetic field
  - Energy spectrum of T_2
  - Doppler effect
  - Scattering of electrons in the source
- Use „voxelized“ description of the WGTS

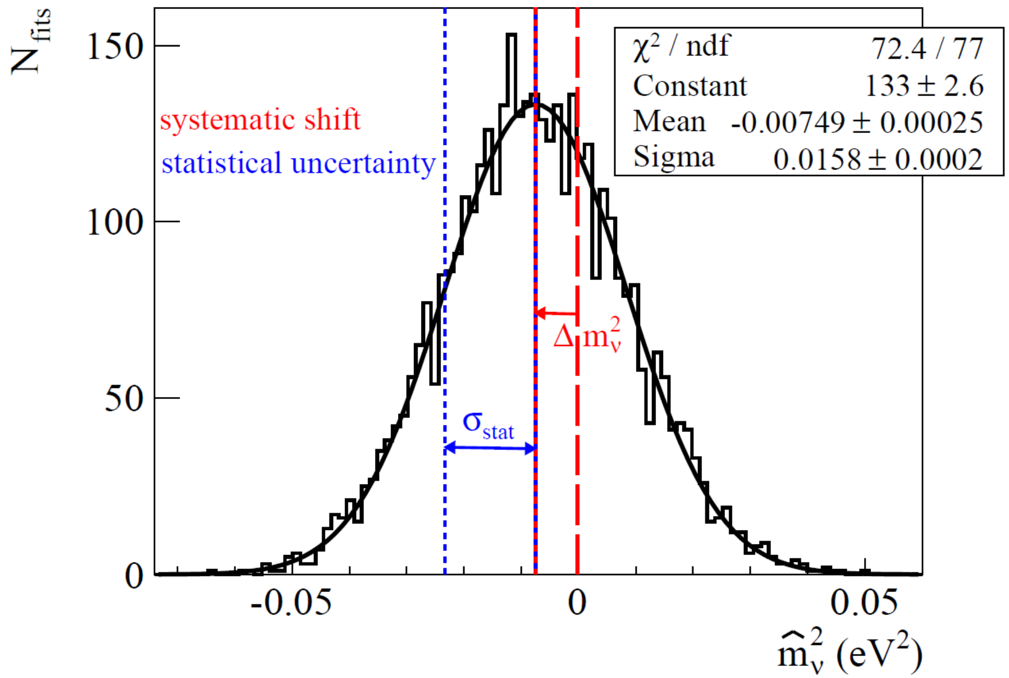


- Calculate expected count rates at detector

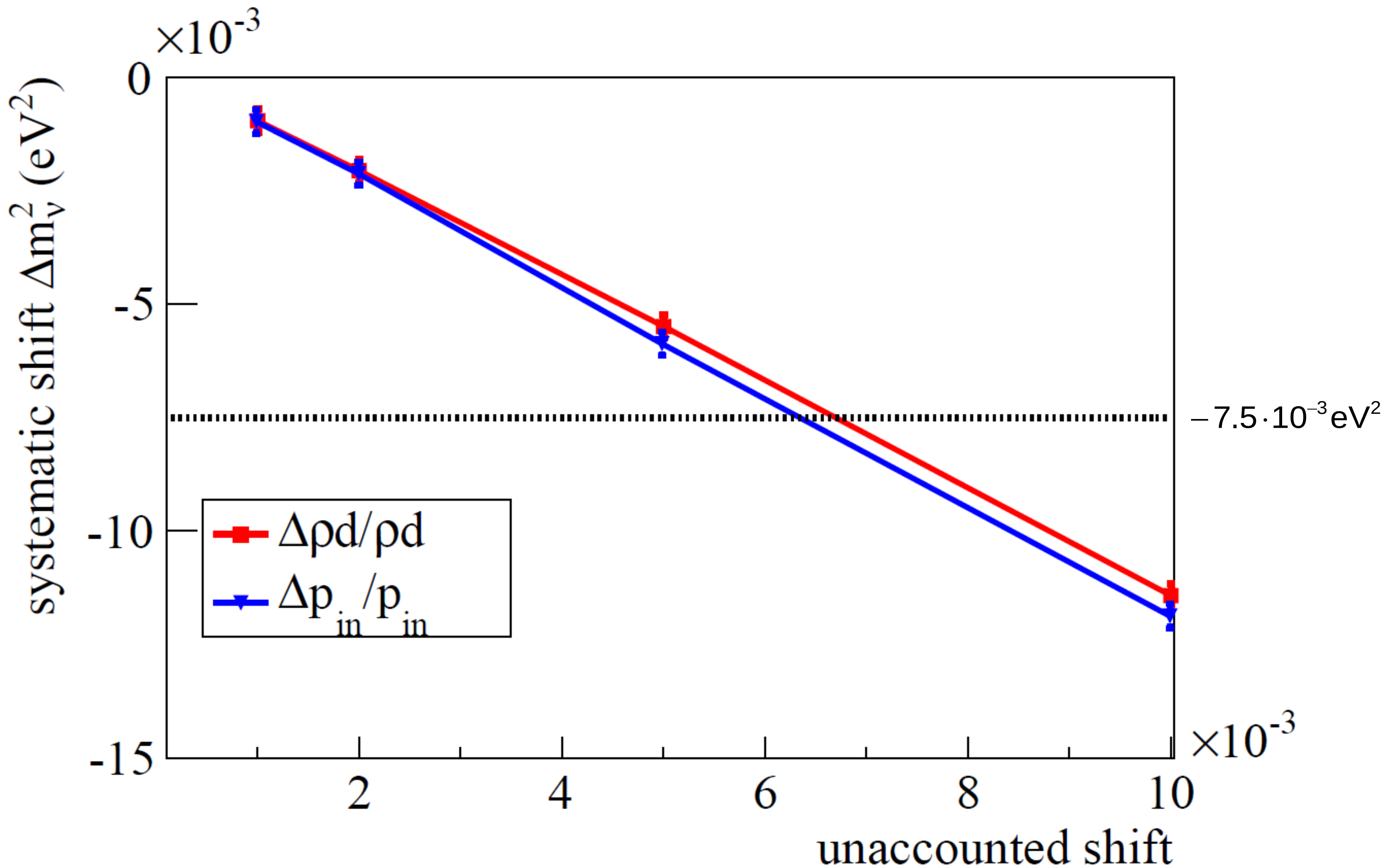
Analysis

Variance of ML estimator: MC method

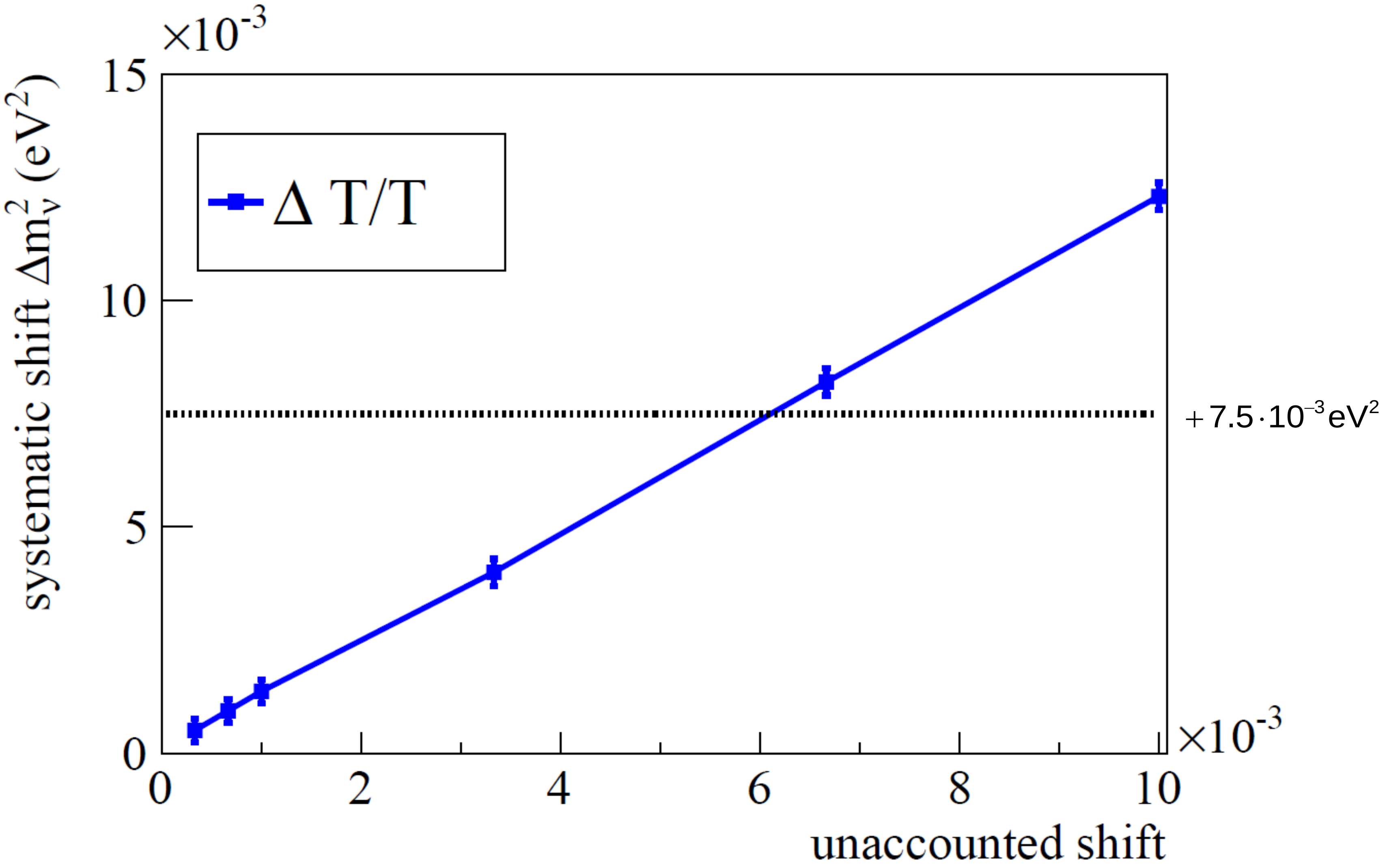
- Simulate a „measured spectrum“ of KATRIN
- Use slightly different source parameters as “theoretical spectrum”
- Fit and store best fit value $\hat{m}_\nu^2$
- Repeat e.g. 4000 times
- Read off systematic shift Δm_ν^2 and statistical uncertainty σ_{stat}



Systematic influence of the column density

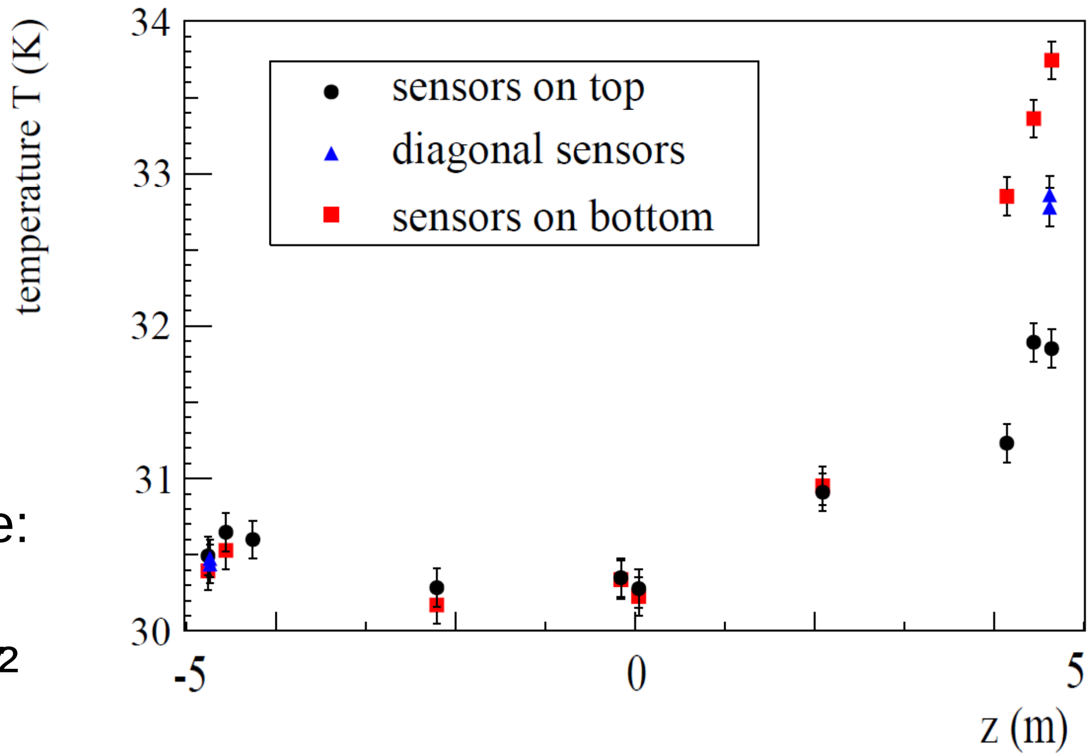


Systematic influence of the source temperature



Influence of the temperature profile

- Increased temperature gradient >3K due to additional thermal radiation



- Neglect temperature profile:

$$\Delta m_\nu^2 = (1.0 \pm 2.3) \cdot 10^{-4}\,\mathrm{eV}^2$$

Requirements & Achievements

source of syst. uncertainty	requirements	syst. shift $\Delta m_\nu^2\,(10^{-3}\,\mathrm{eV}^2)$	achievements
variations of			
column density	$\Delta\rho d/\rho d < 2\cdot 10^{-3}$	< 1.5	
injection pressure	$\Delta p_{\mathrm{in}}/p_{\mathrm{in}} < 2\cdot 10^{-3}$		$1.3\cdot 10^{-4}$
exit pressure	$\Delta p_{\mathrm{ex}}/p_{\mathrm{ex}} < 0.06$		$1\cdot 10^{-4}$
temperature	$\Delta T/T < 2\cdot 10^{-3}$		$5\cdot 10^{-5}$
tritium purity	$\Delta\epsilon_{\mathrm{T}}/\epsilon_{\mathrm{T}} < 2\cdot 10^{-3}$		$1\cdot 10^{-3}$
WGTS magnetic field	$\Delta B_{\mathrm{S}}/B_{\mathrm{S}} < 2\cdot 10^{-3}$	< 2	
WGTS potential	$\Delta U < 10\,\mathrm{mV}$	< 1.2	

Experimental achievements reported in arXiv:1205.5421

Profile likelihood & Systematics

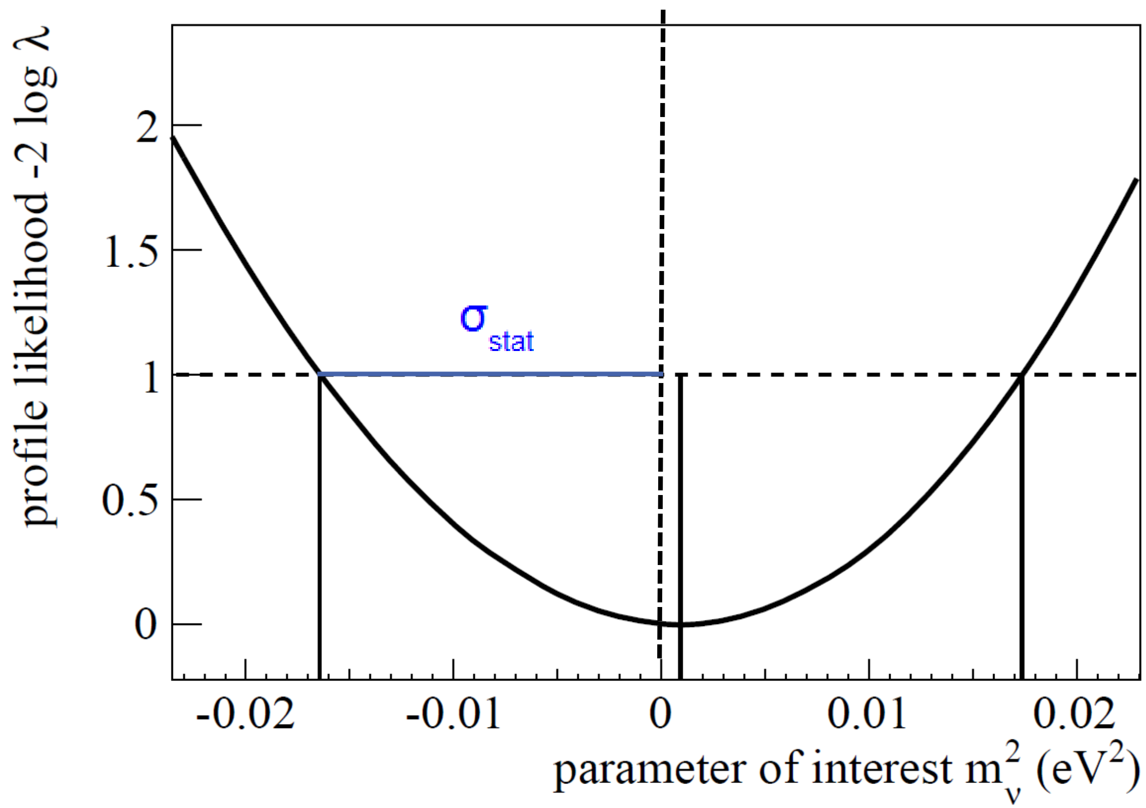
- Include systematics into analysis

- W. Rolke et al., “Limits and confidence intervals in the presence of nuisance parameters”, Nucl. Instr. Meth. A 551 (2005)

- At KATRIN
  - Parameter of interest : m_ν^2
  - Nuisance parameters: $\vec{\theta} = \{\rho d, \varepsilon_T, ...\}$
  - Profile likelihood: $\lambda(m_{\nu,0}^2 \mid \vec{X}) = \dfrac{\sup\{L(m_{\nu,0}^2, \vec{\theta} \mid \vec{X}); \vec{\theta}\}}{\sup\{L(m_\nu^2, \vec{\theta} \mid \vec{X}); m_\nu^2, \vec{\theta}\}}$

Profile likelihood

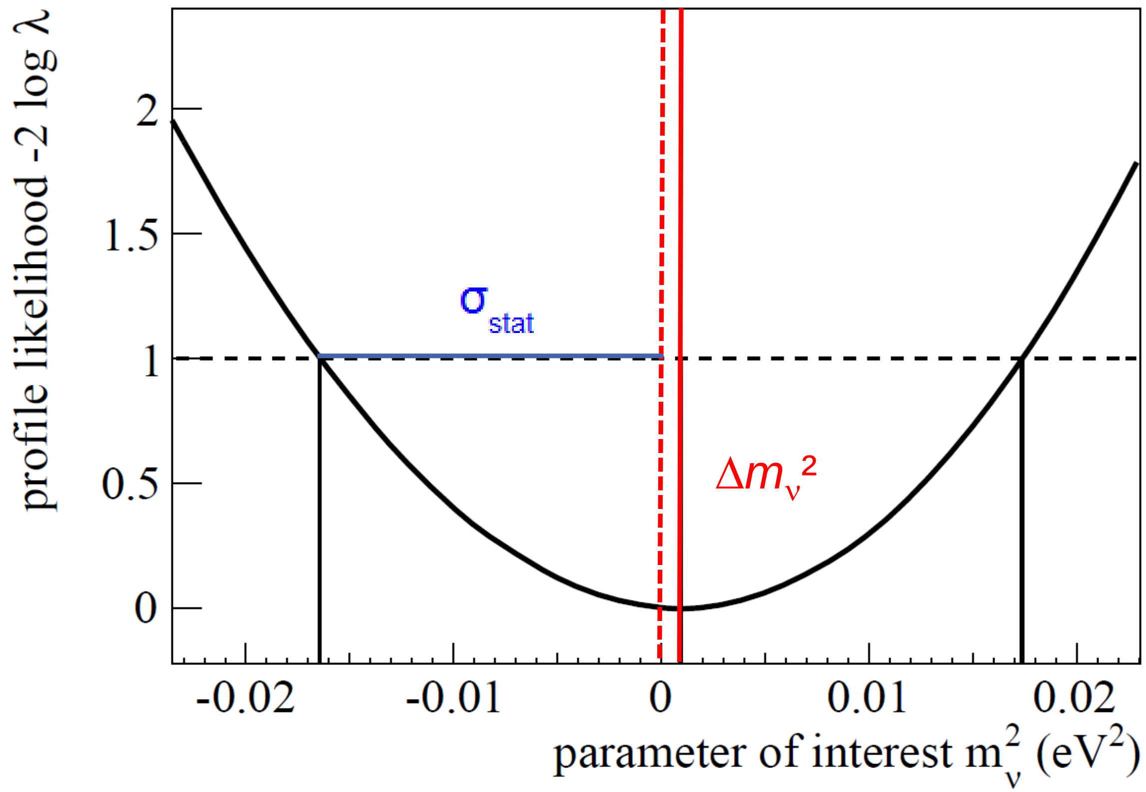
$$-\log L(\vec{X} \mid m_\nu^2, \vec{\theta}) = -\sum_i p(X_i \mid m_\nu^2, \vec{\theta})$$



Profile likelihood with constraints (pull method)

Constraint, e.g. external measurement $\bar{\varepsilon}_T$ of tritium purity

$$-\log L(\vec{X} \mid m_\nu^2, \vec{\theta}) = -\sum_i p(X_i \mid m_\nu^2, \vec{\theta}) - \frac{(\varepsilon_T - \bar{\varepsilon}_T)^2}{2\sigma^2}$$



Summary

- „4 out of 5 systematic uncertainties are related with the WGTS“
- Simulation with detailed source model
  - Density profile
  - Temperature profile
  - Spectrum Calculation
- Analysis
  - MC methods
  - Profile likelihood to include systematics
- Results
  - Requirements on source parameters validated
  - Experimental achievements e.g. „Demonstrator“ measurements

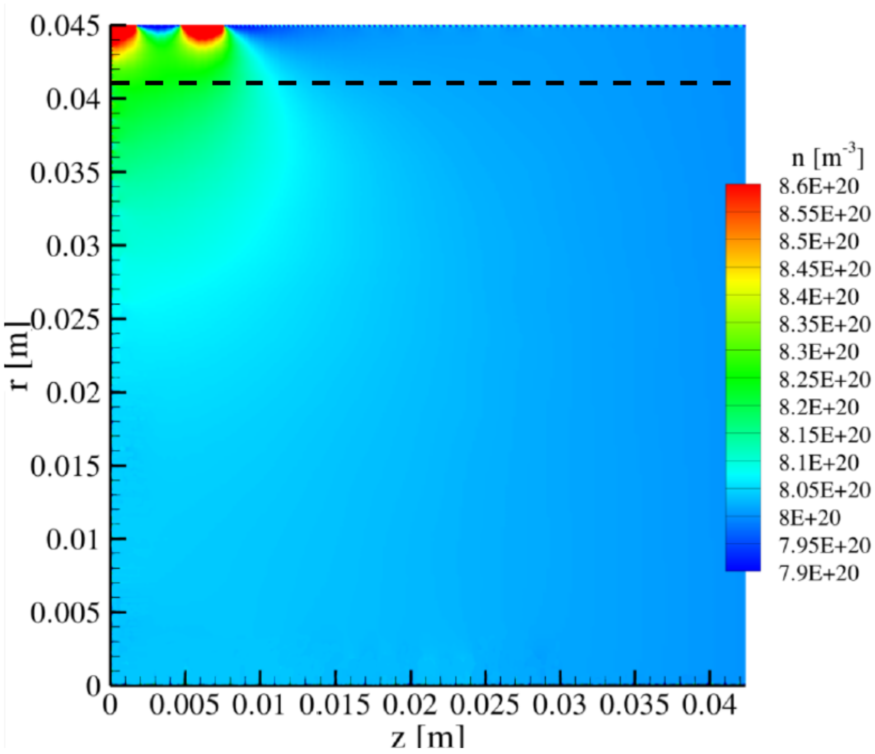
Outlook

- Full 3-D gasdynamics simulation of pumping chambers
- Use provided analysis routines to investigate further systematic effects

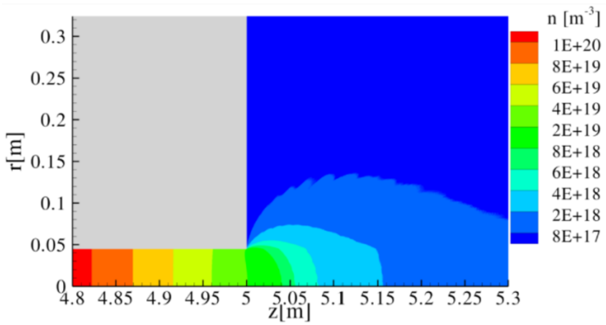
Backup

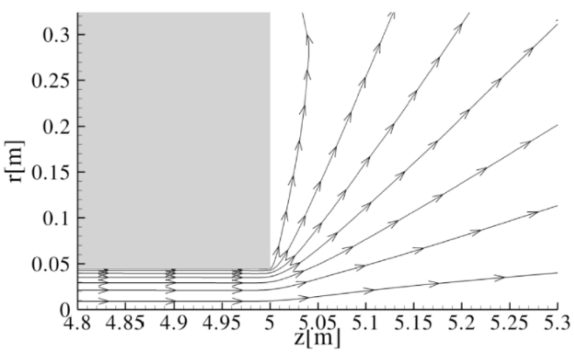
2-D density calculations

Injection region

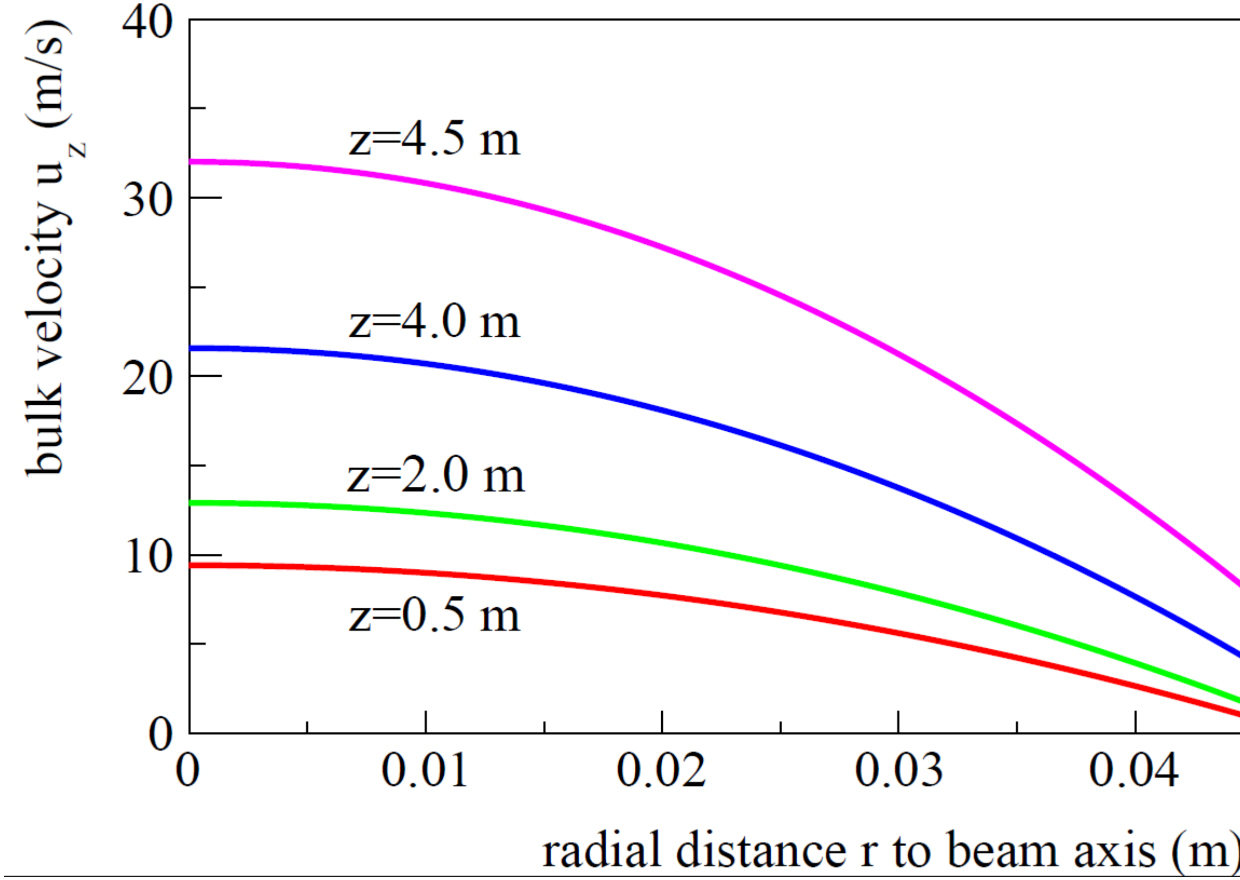


Pumping chamber





Bulk velocity in the WGTS



Systematic influence of the tritium purity