Karlsruhe Institute of Technology

Characterization and Optimization of the KATRIN Tritium Source

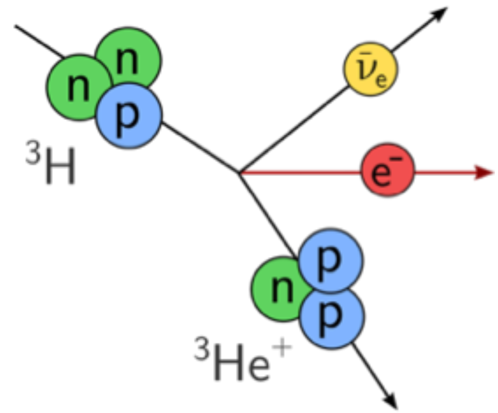
Tritium Laboratory Karlsruhe (IKP), KIT department of Physics

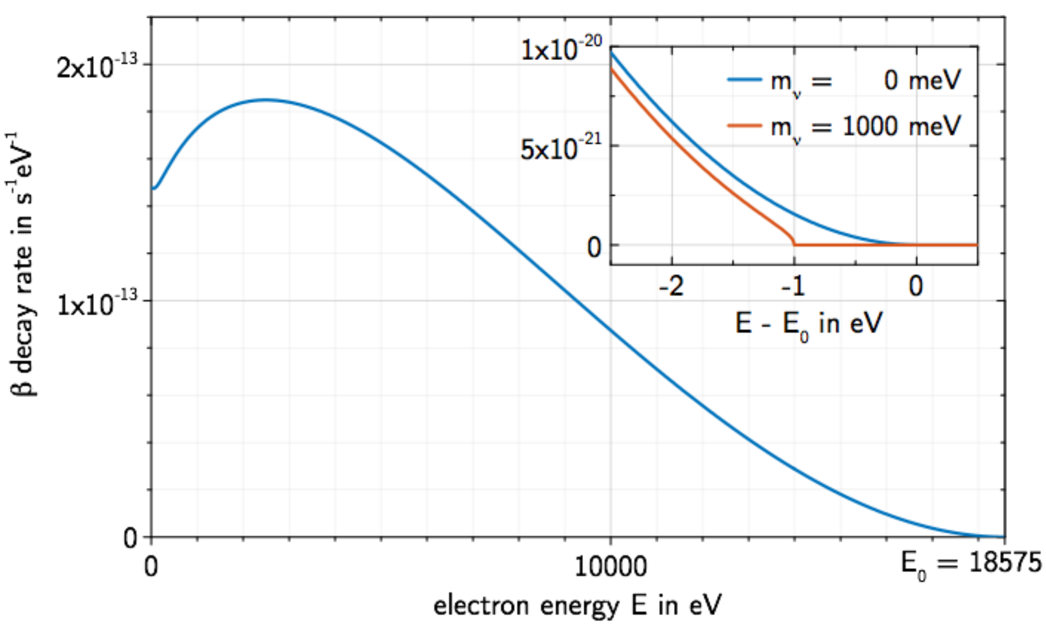
Alexander Marsteller for the KATRIN collaboration

Neutrino mass measurement with KATRIN

KArlsruher **TRI**tium **N**eutrino Experiment

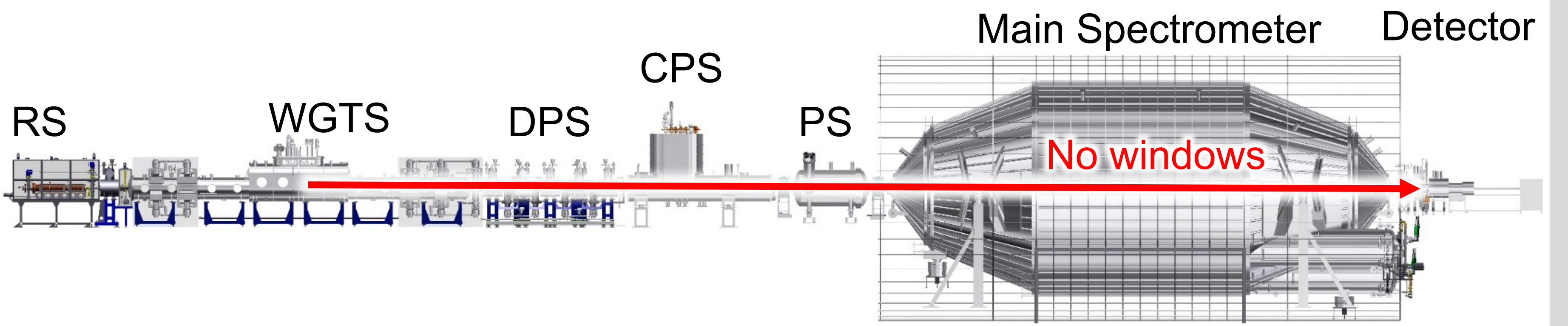
- Mass measurement via energy spectroscopy of electrons created in beta-decay of tritium
- Initial and final energies in tritium decay can be calculated with a high degree of precision
- Low endpoint energy of 18.6 keV
- Model-independent



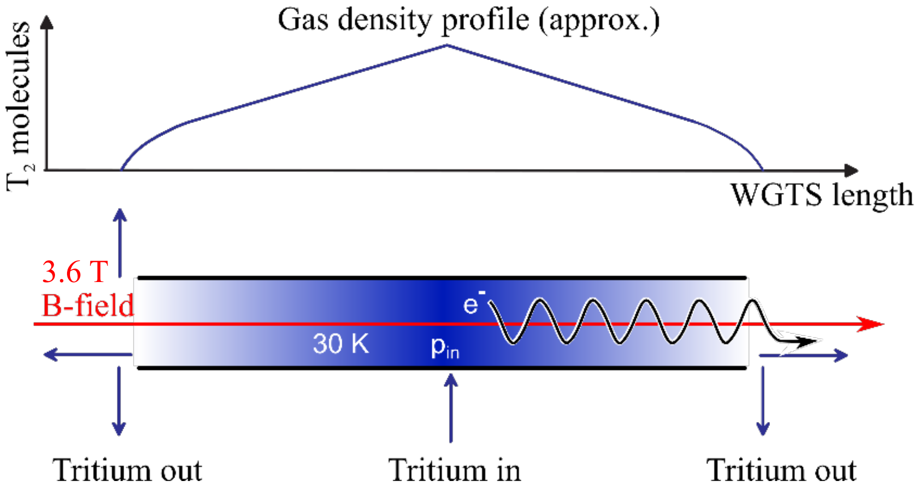


KATRIN target sensitivity (90% C.L.): 0.2 eV/c² neutrino mass

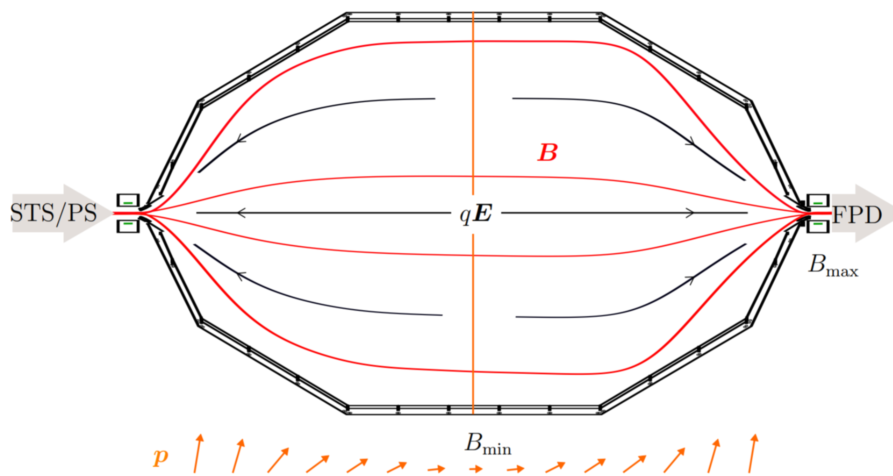
The setup of KATRIN



Windowless gaseous tritium source



MAC-E filter



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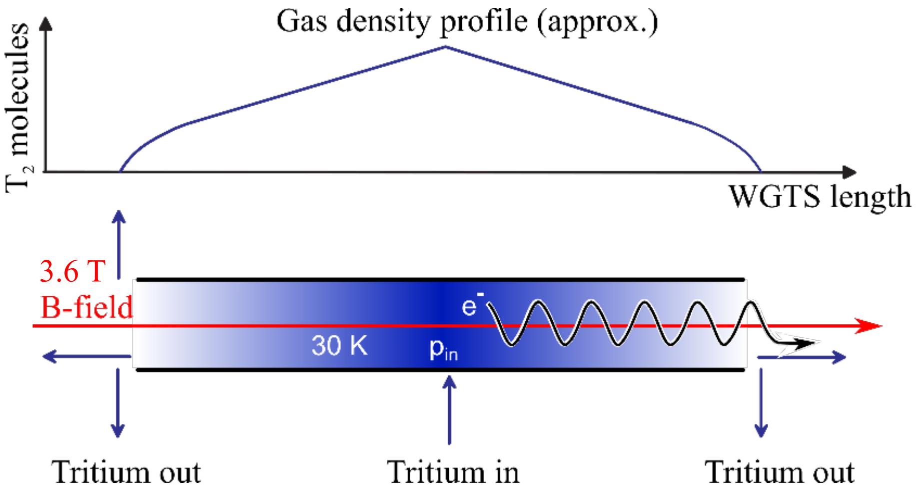
Requirements on the tritium source

- Luminosity of 10^{11} e^-/s
- Tritium throughput of 40 g/day
- Tritium purity >95%
- Continuous 24/7 operation over periods of 60 days

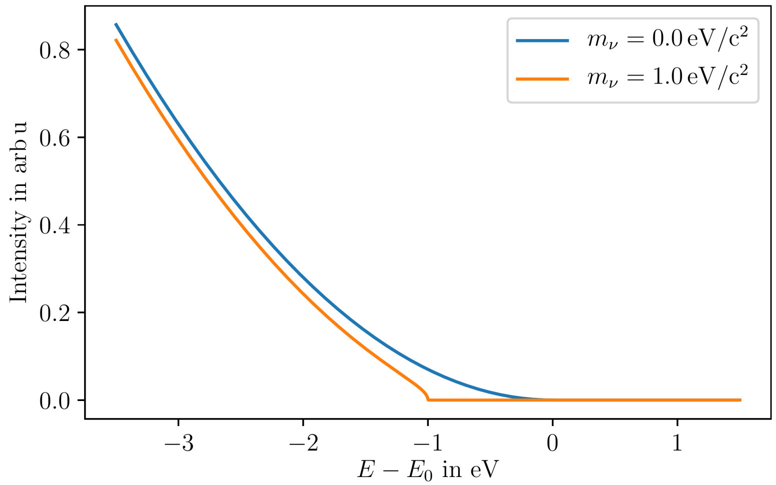
Windowless gaseous tritium source



KATRIN needs a tritium source with a stability of 0.1% to reach its target sensitivity

Importance of source stability

- KATRIN measures the shape of the spectrum
- MAC-E type spectrometers can only measure the spectrum by scanning point for point
- Fluctuations of the source during a scan distort the shape of the spectrum
  →Fake neutrino mass signal



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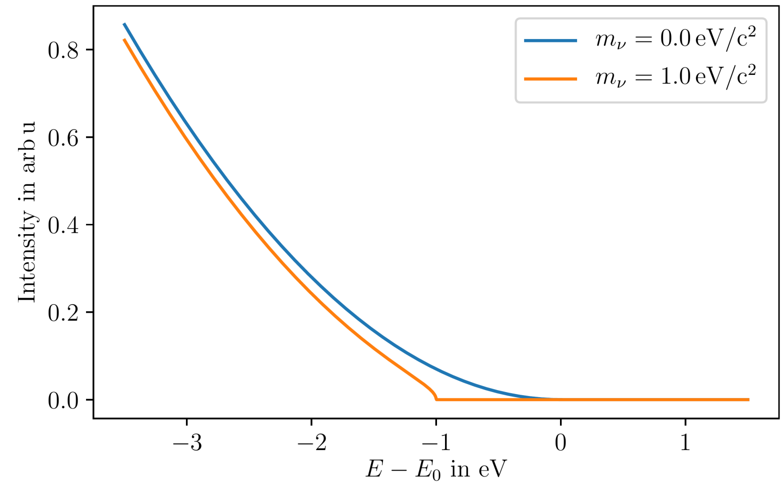
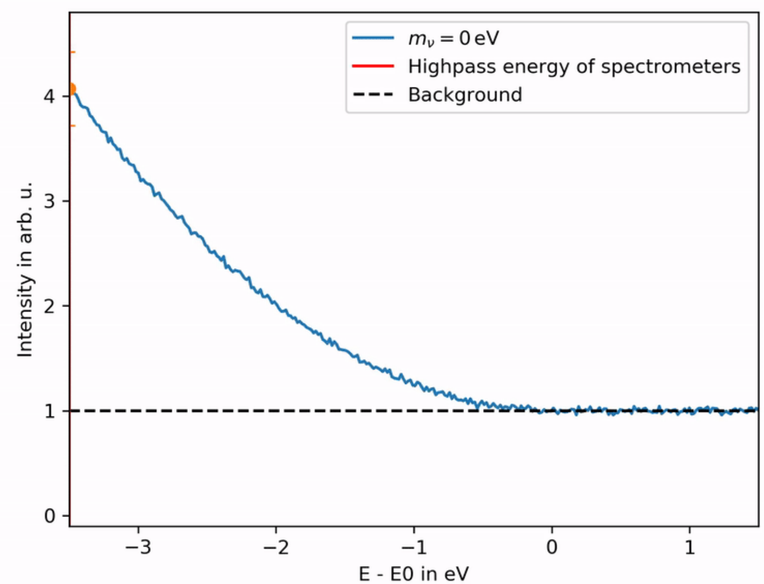


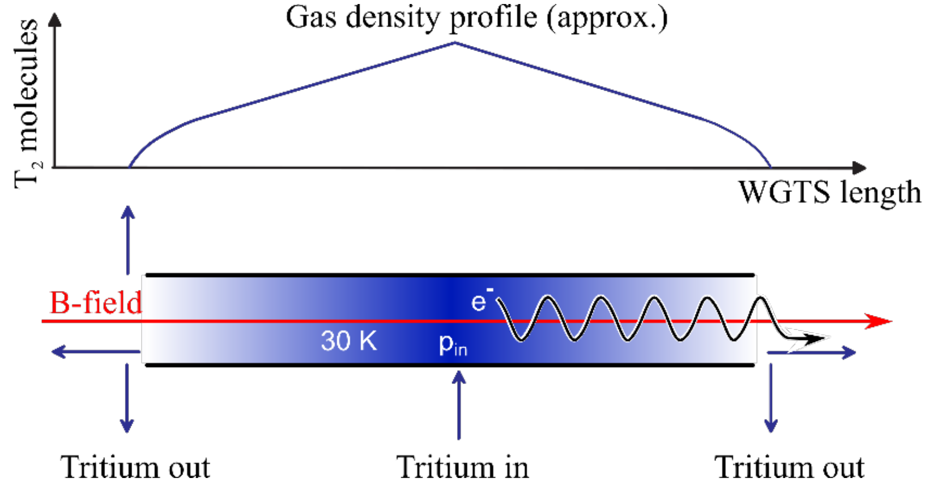


KATRIN needs a tritium source with a stability of 0.1% to reach its target sensitivity

Parameters influencing the source stability

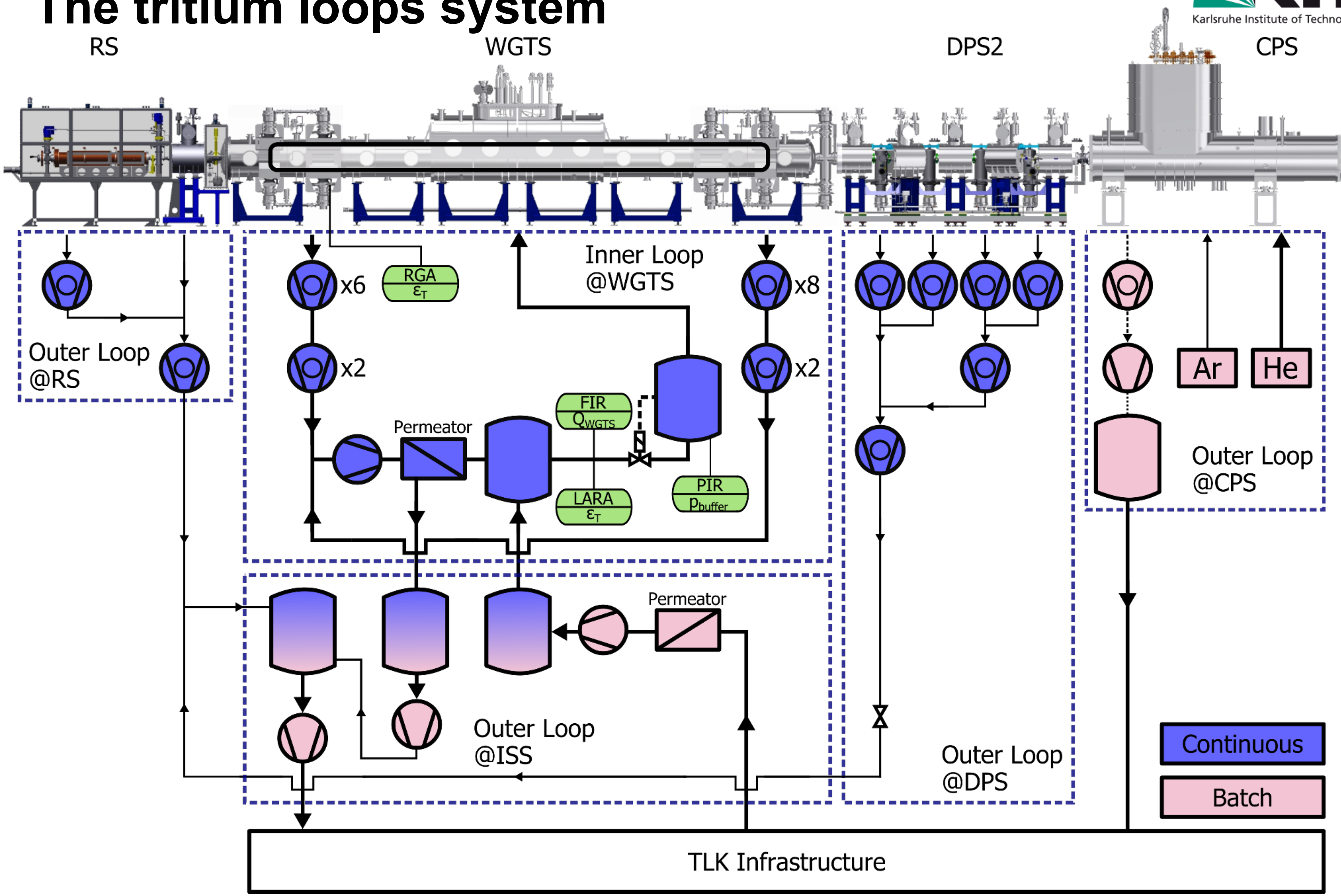
- Temperature of the beam tube ✓
- Pumping speed at the ends of the source ✓
- Injection pressure
- Gas composition
- Conductance of the injection system

Windowless gaseous tritium source



All parameters need to be stable for the source activity to be stable!

The tritium loops system



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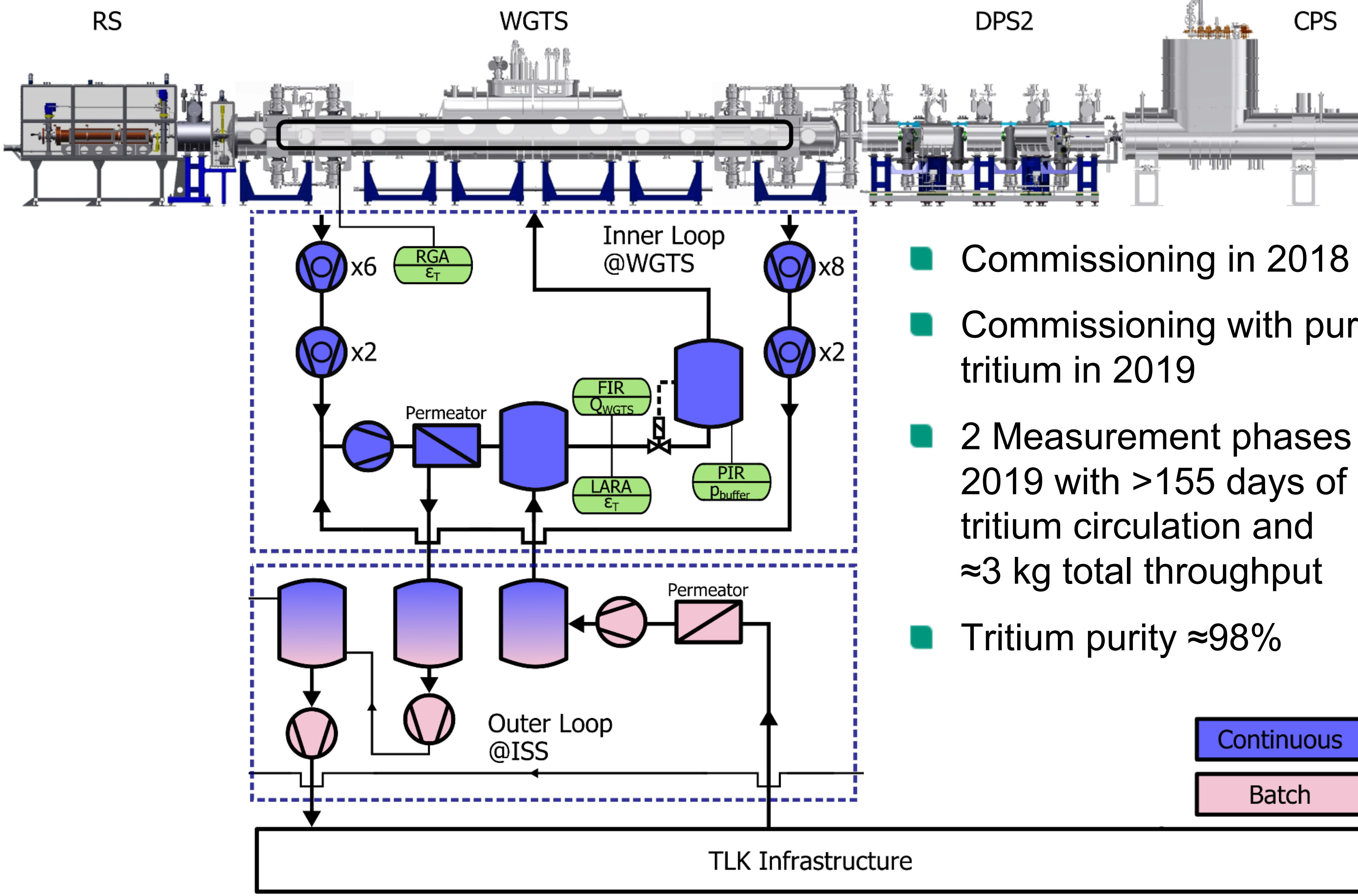
Relevant systems for gas stabilization



- Commissioning in 2018
- Commissioning with pure tritium in 2019
- 2 Measurement phases in 2019 with >155 days of tritium circulation and ≈3 kg total throughput
- Tritium purity ≈98%

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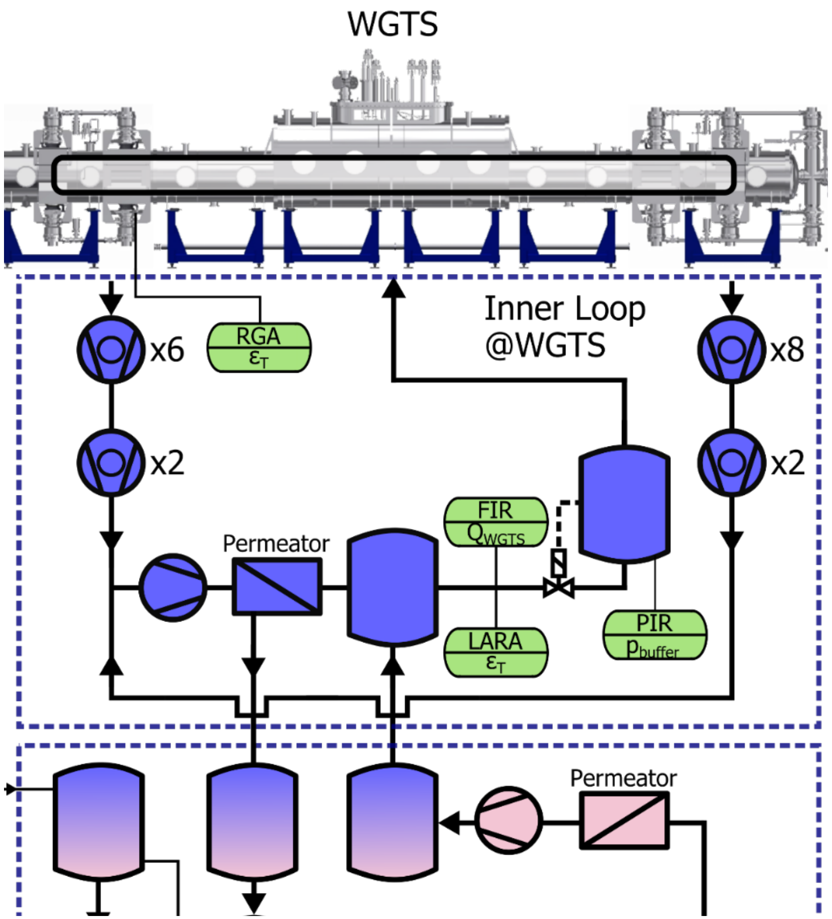
Topics of this presentation

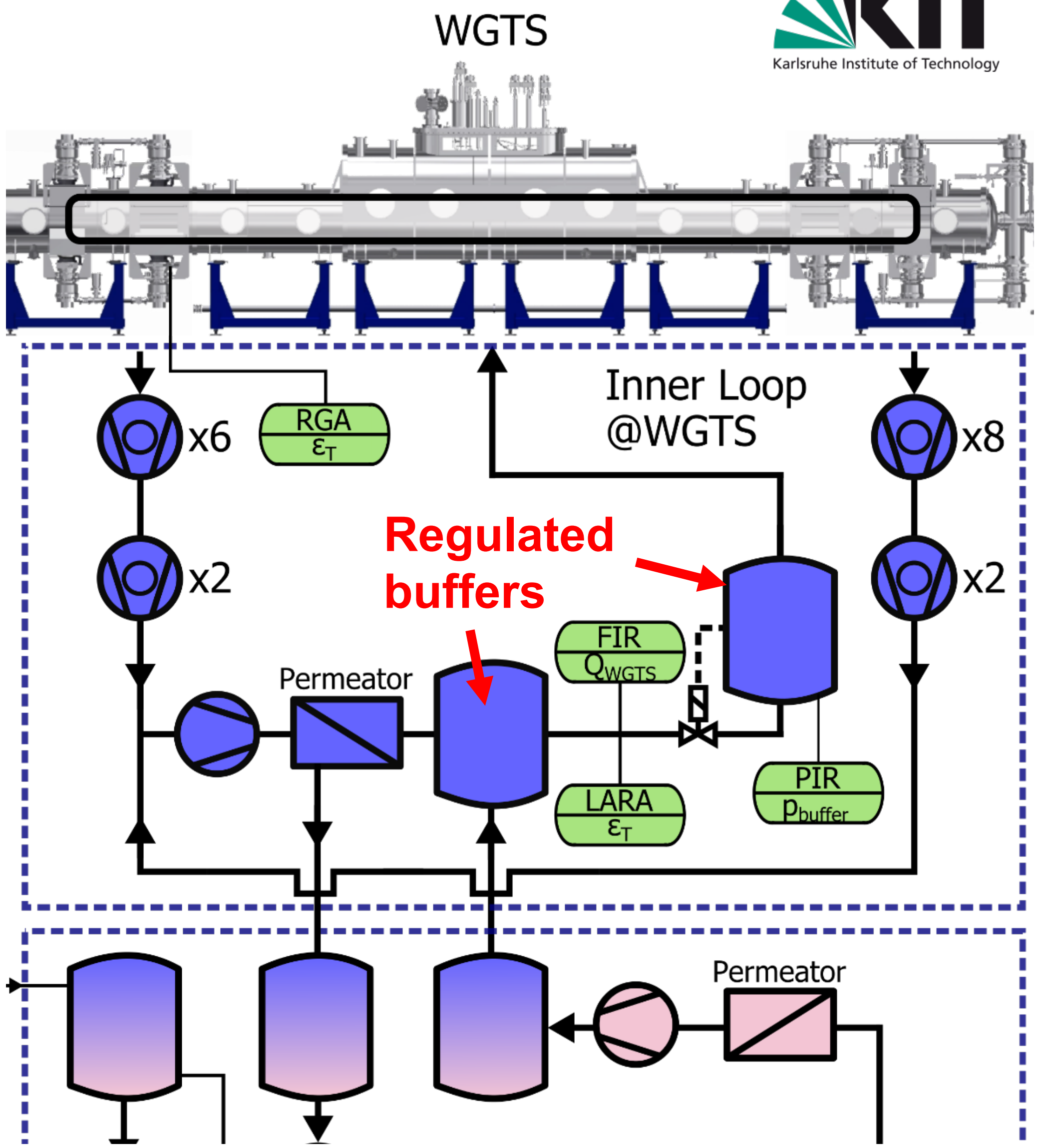
Investigation of source stability parameters:

- Injection pressure
- Gas composition
- Conductance of the injection system



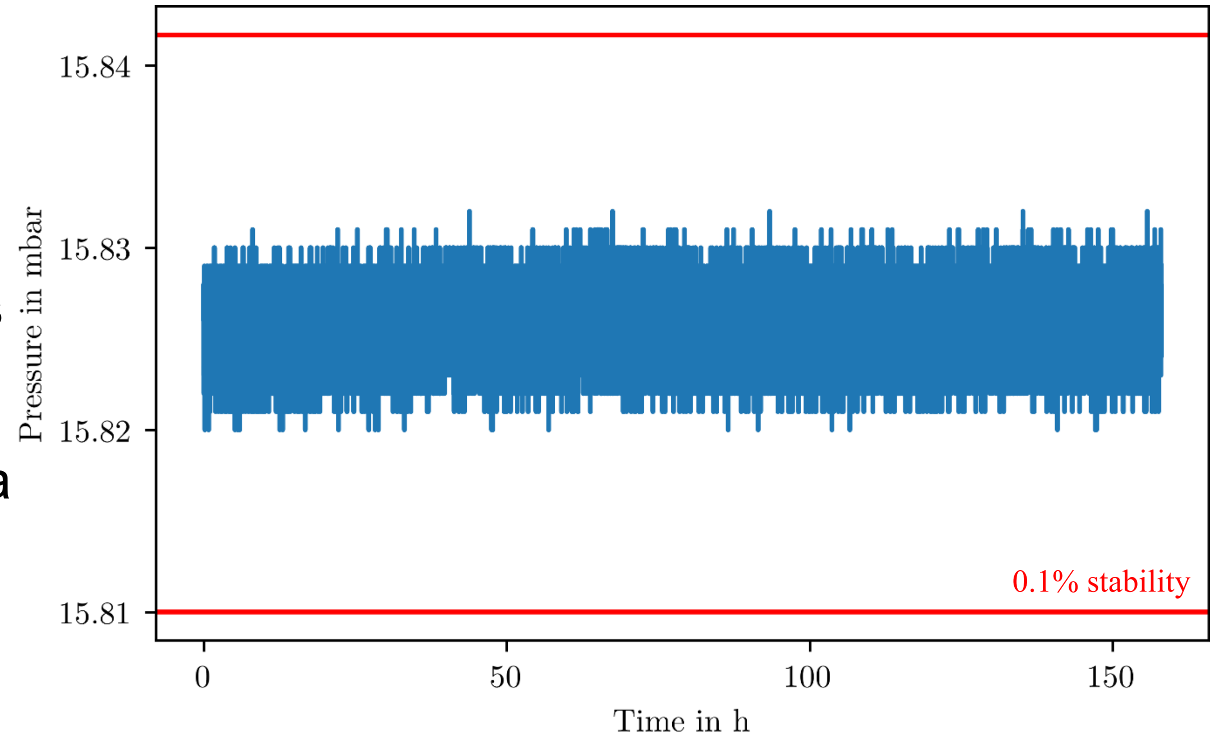
Stabilized gas injection

- Goal:
  Stabilization of injection pressure of 10-20 mbar to less than 0.1%
- Two stage stabilization
- Injection buffer temperature stabilized to within 1 K
- Pressure in injection buffer measured using calibration transfer standard quality capacitance diaphragm pressure gauges



Status after initial commissioning

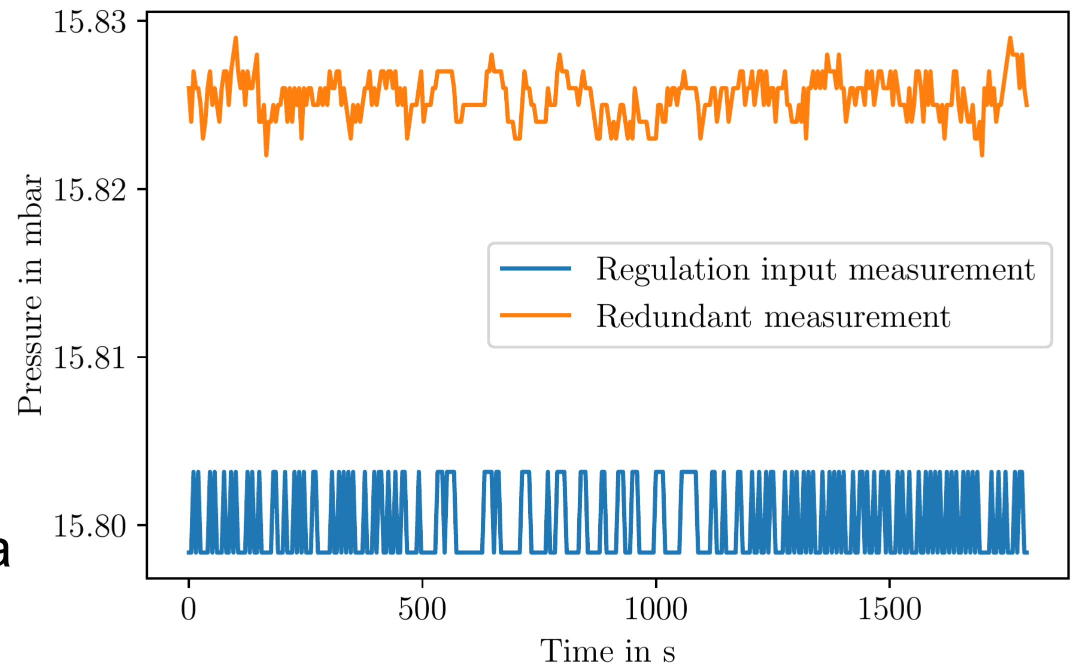
- Stabilization system works as intended
- Long term operation within specifications is possible
- Steps in pressure data show limitation by digitization of the sensor signal
- Remaining structure visible in signal



There is room for improvement in the stabilization system!

Investigating the pressure signal in detail

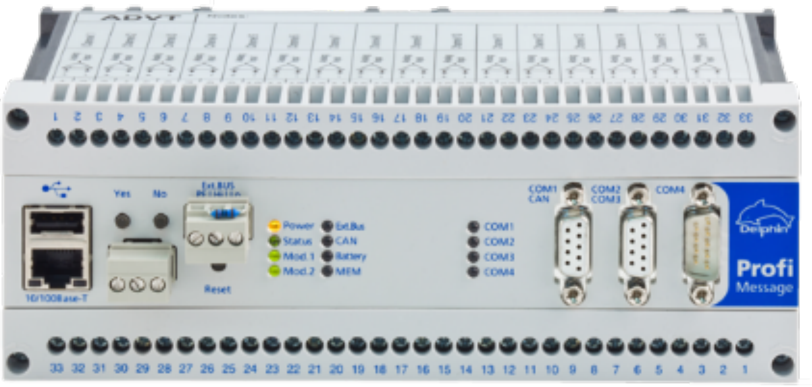
- Two redundant pressure sensors connected to the final buffer
- Sensor controller output is digitized RS-232 and analog 0-10 V
- Regulation system used analog signal digitized by a 16-bit ADC card of the Siemens PCS7 process control system
- The regulation system has to work with only 2 ADC steps as input values



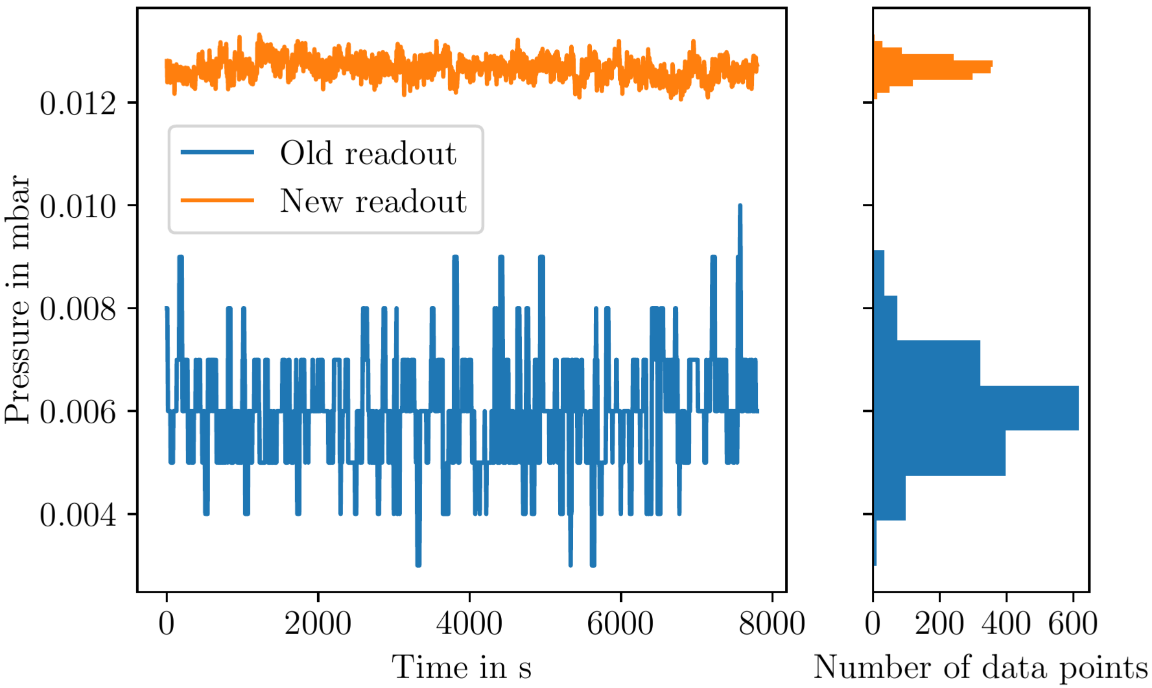
Try to measure the pressure with better precision!

Readout hardware upgrade

- Replaced the 16-bit PCS7 readout with a 24-bit ADC
- Additional improvement: 16-bit output for regulation compared to 12-bit PCS7 output



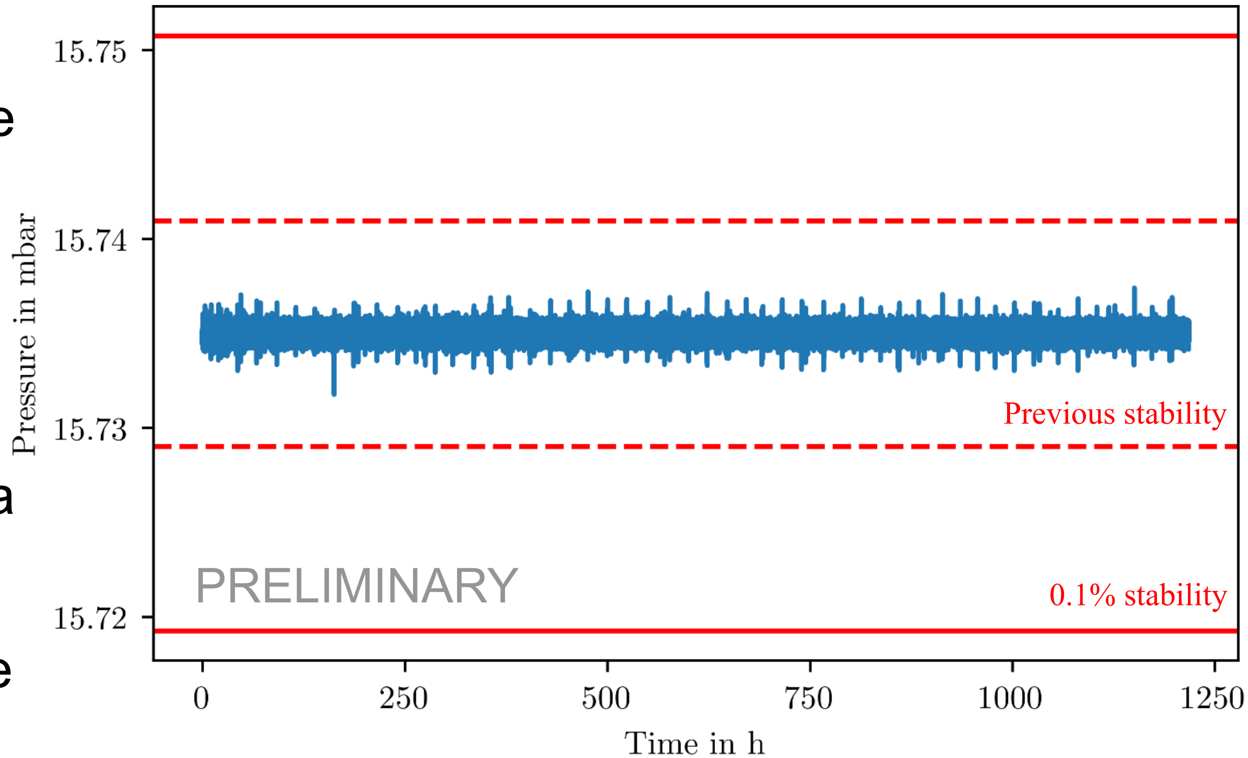
The pressure signal can now be measured with a much higher precision!



Improved stability after hardware changes

- Steps are no longer visible in the pressure signal

  →Digitization no longer bottleneck
- Improvement of pressure stability by a factor of ≈5
- Remaining spikes are effect of daily refill

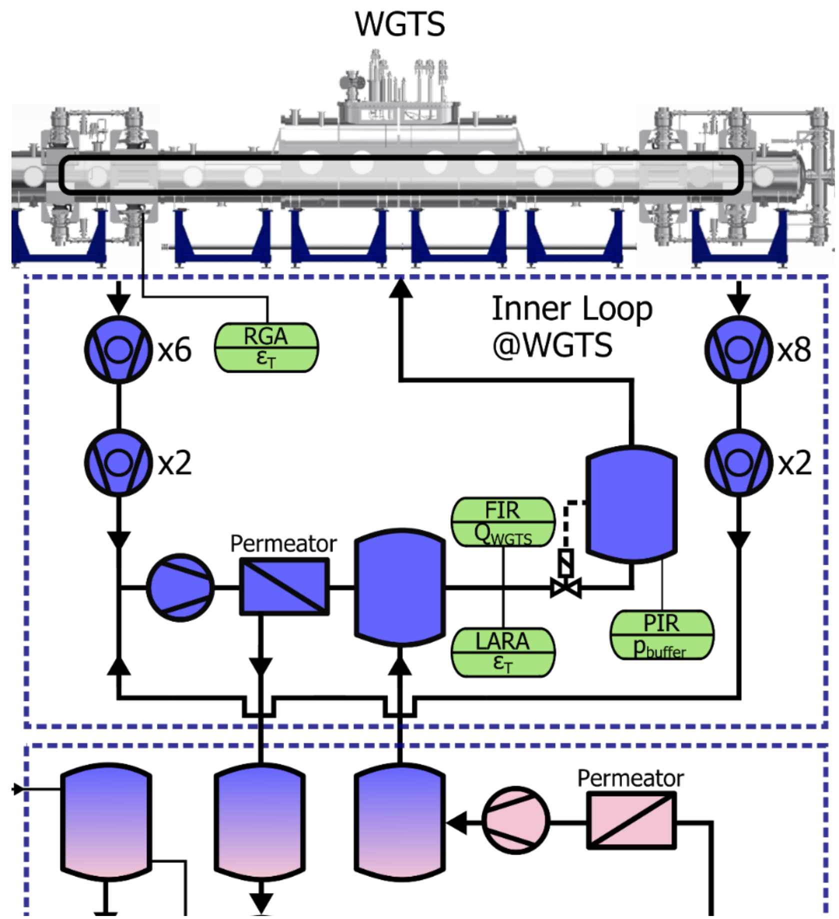


Improvement of the pressure stability was a complete success!

Topics of this presentation

Investigation of source stability parameters:

- Injection pressure ✓
- Gas composition
- Conductance of the injection system



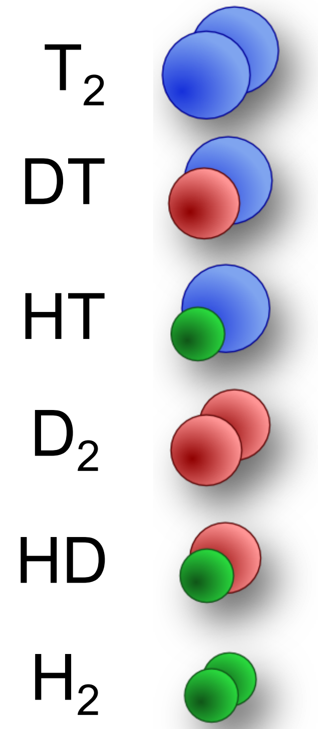
Gas composition in the inner loop

Gas composition has impact on:

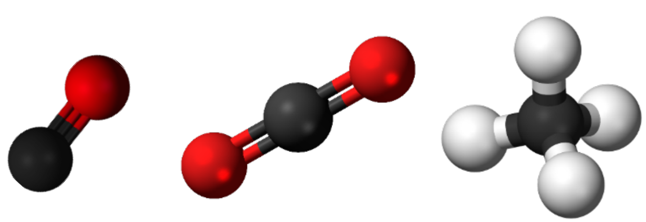
- Gas dynamical properties (viscosity, heat capacity…)
- Initial and final states of the β-decay
- Electron scattering in the source

Two kinds of gas composition changes:

- Isotopic exchange
  - Vacuum vessel steel walls contain much H which can form HT with the gaseous T_2
- Accumulation of non-Q_2 impurities
  - TMPs are not completely leak tight and contain bearings and electronics which gas out
  - Tritium induces the radiochemical formation of CT_4, CO, and CO_2

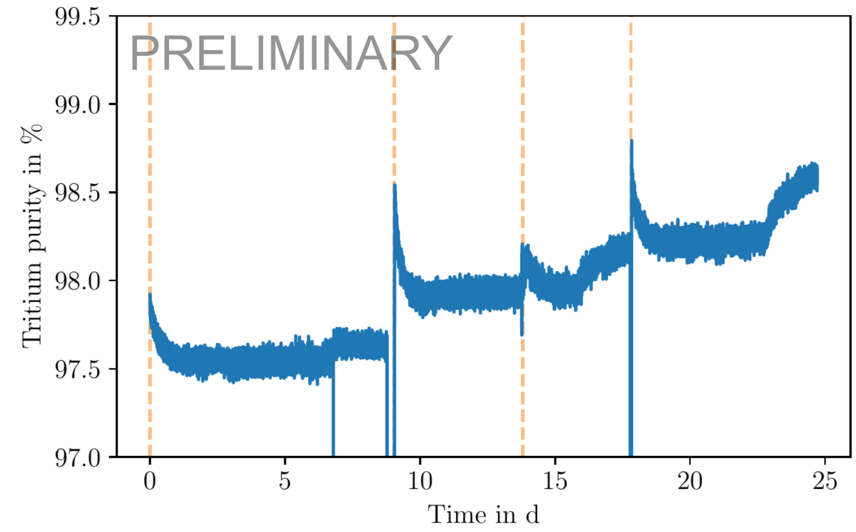


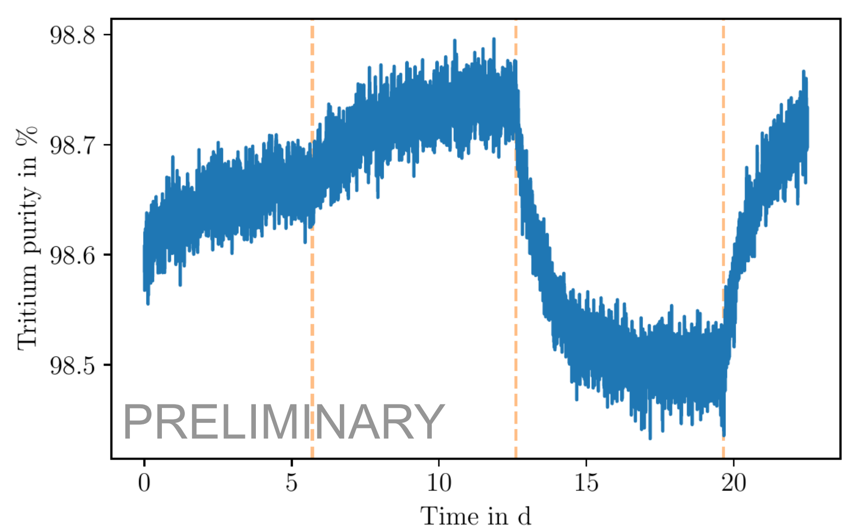
Filtration and monitoring of the gas composition are essential!



Gas composition behavior during long term measurements

- Restarting the circulation always disrupts the equilibrium
- Impurities lead to a lower equilibrium purity than that of the „fresh“ tritium gas
- TLK infrastructure delivers tritium gas with slightly changing composition for each batch
- Different gas batches cause small changes in the equilibrium purity



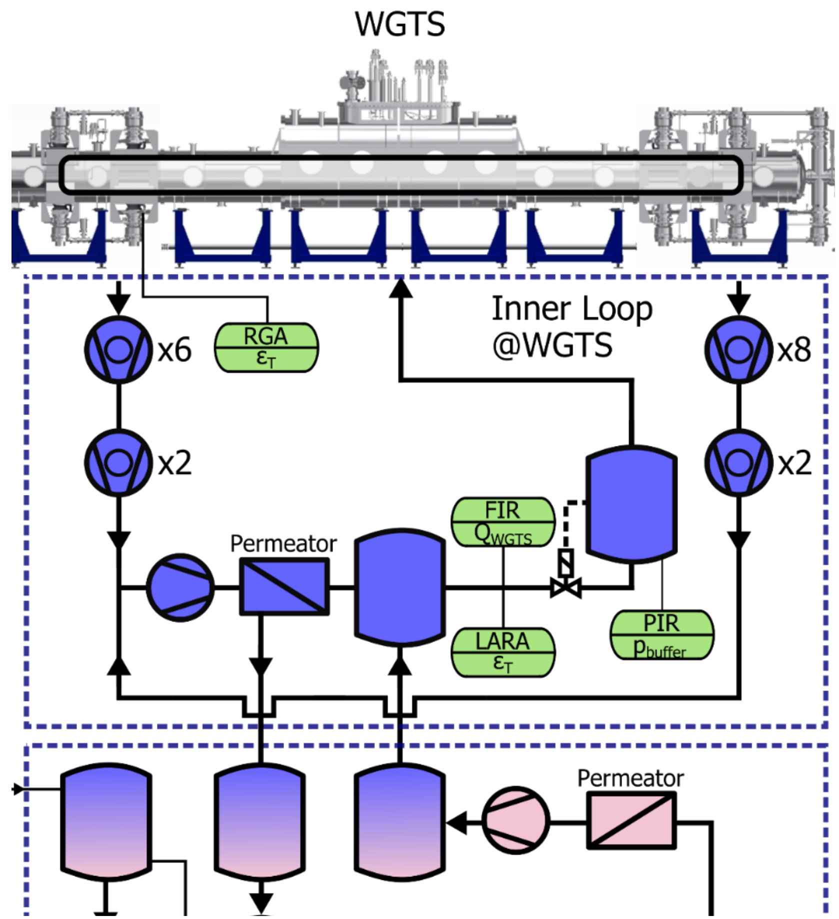


Long term operation well above 95% tritium purity

Topics of this presentation

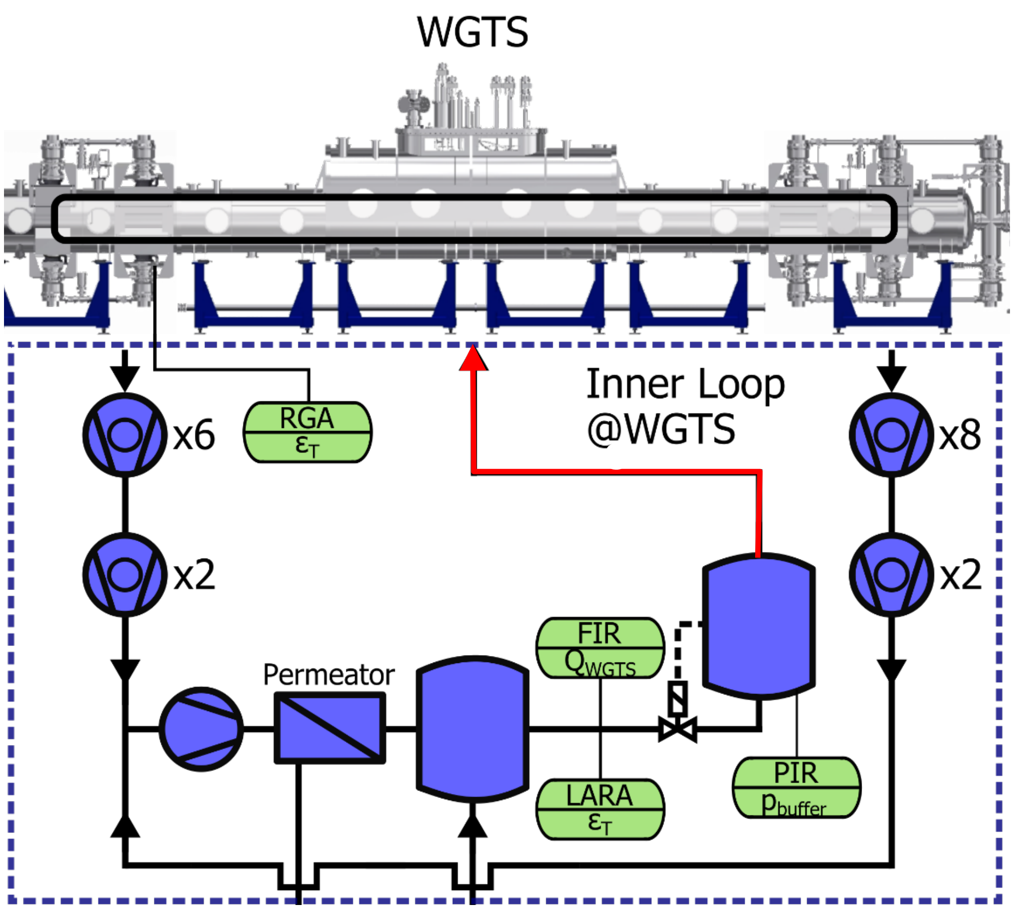
Investigation of source stability parameters:

- Injection pressure ✔
- Gas composition ✔
- Conductance of the injection system



Changes in the conductance of the injection system

- Conductance can only be derived from multiple parameters
- Absolute value of conductance less important than stability
- Causes for conductance changes:
  - ~~Changes in gas composition~~
  - Geometry changes in the injection piping
  - Temperature changes in the injection piping



Experiences during first operation with pure tritium

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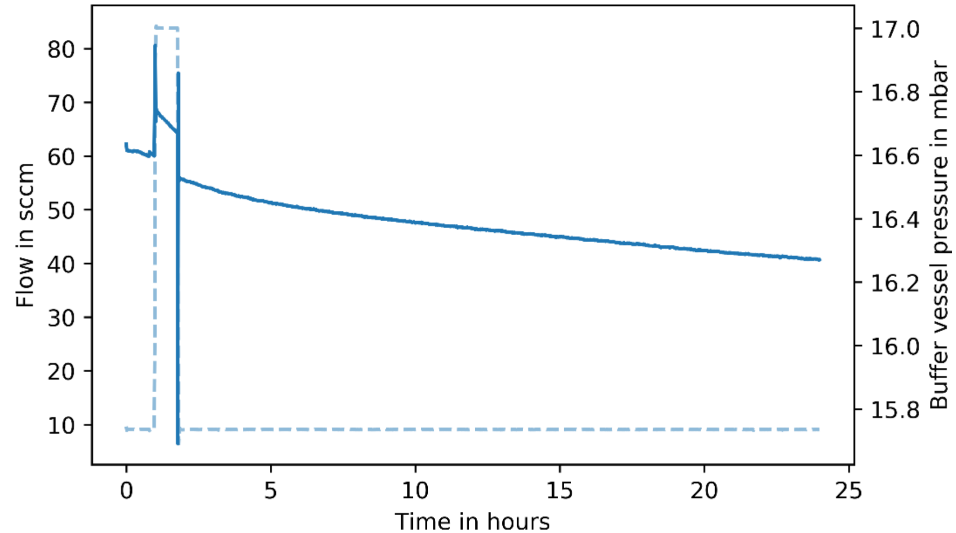
- Flow decrease over time observed upon initial operation with tritium
- No visible change in gas composition

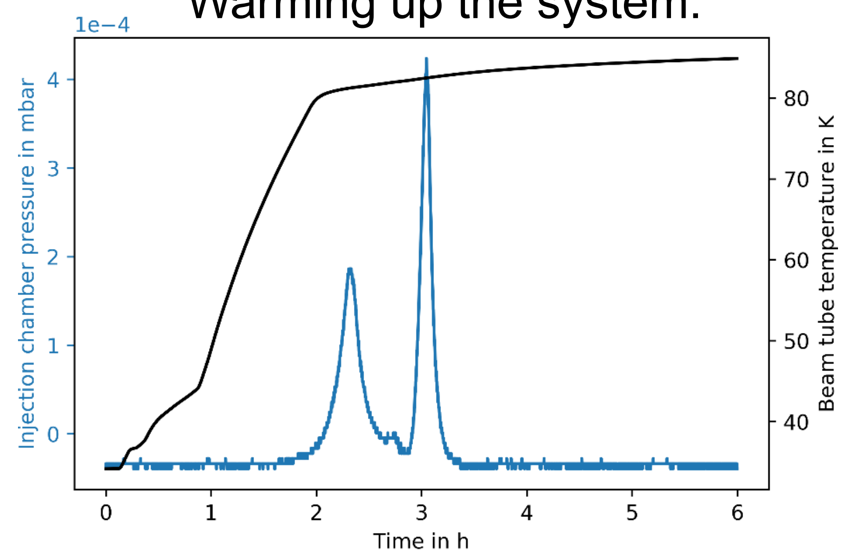
→ Blockage that grows with time

→ Growth of ice inside the injection piping

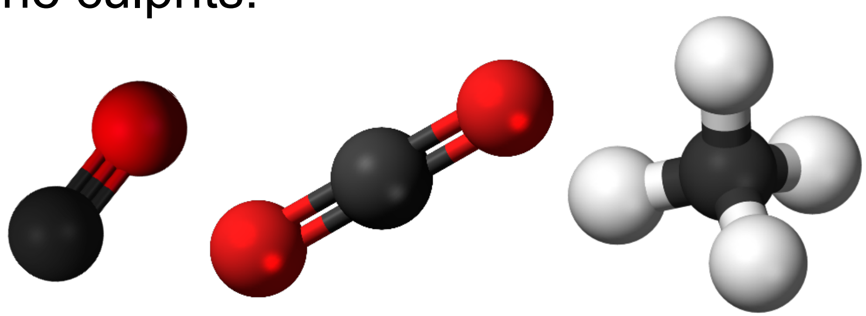
→ Warm up the system



Warming up the system:



The culprits:



CO CO_2 CT_4

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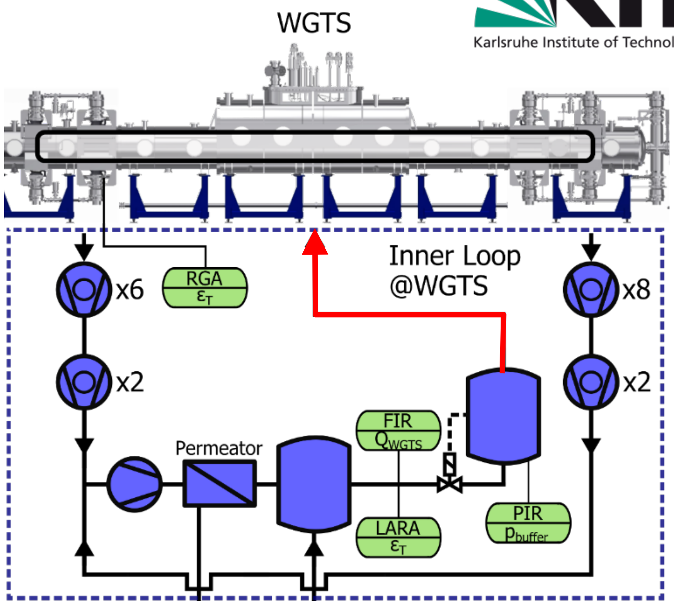
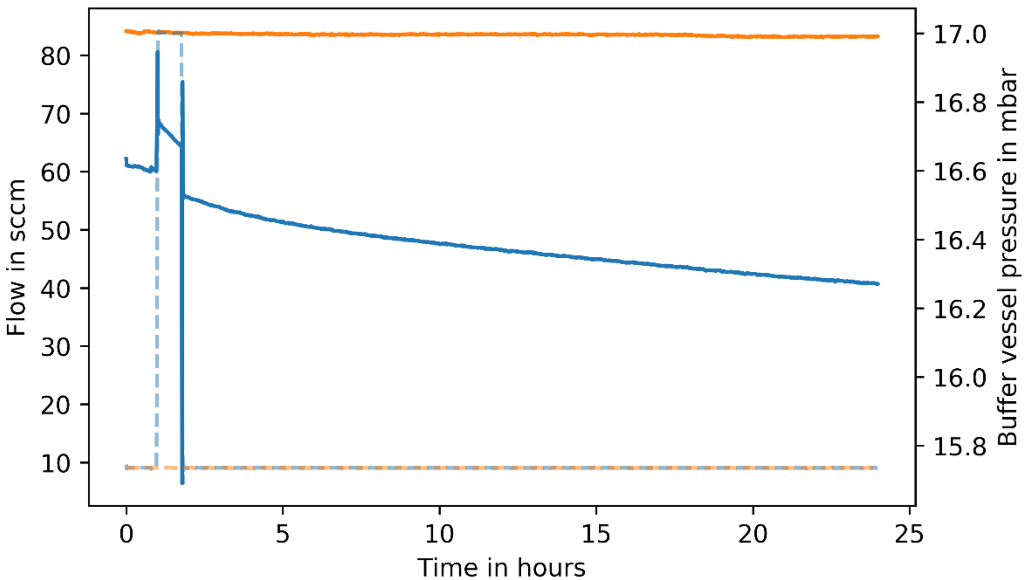
Countermeasures

- CT_4, CO, and CO_2 are created internally via radiochemistry
  →Filtration difficult
- <u>But:</u> only limited amount of carbon present in system
  →Exhaust production mechanism

  →Increase tritium pressure by more than 1 order of magnitude above normal level





Effect vanishes as expected after prolonged exposition to higher tritium pressure.

Changes in the conductance of the injection system

- Conductance can only be derived from multiple parameters
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- Causes for conductance changes:
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  - Geometry changes in the injection piping
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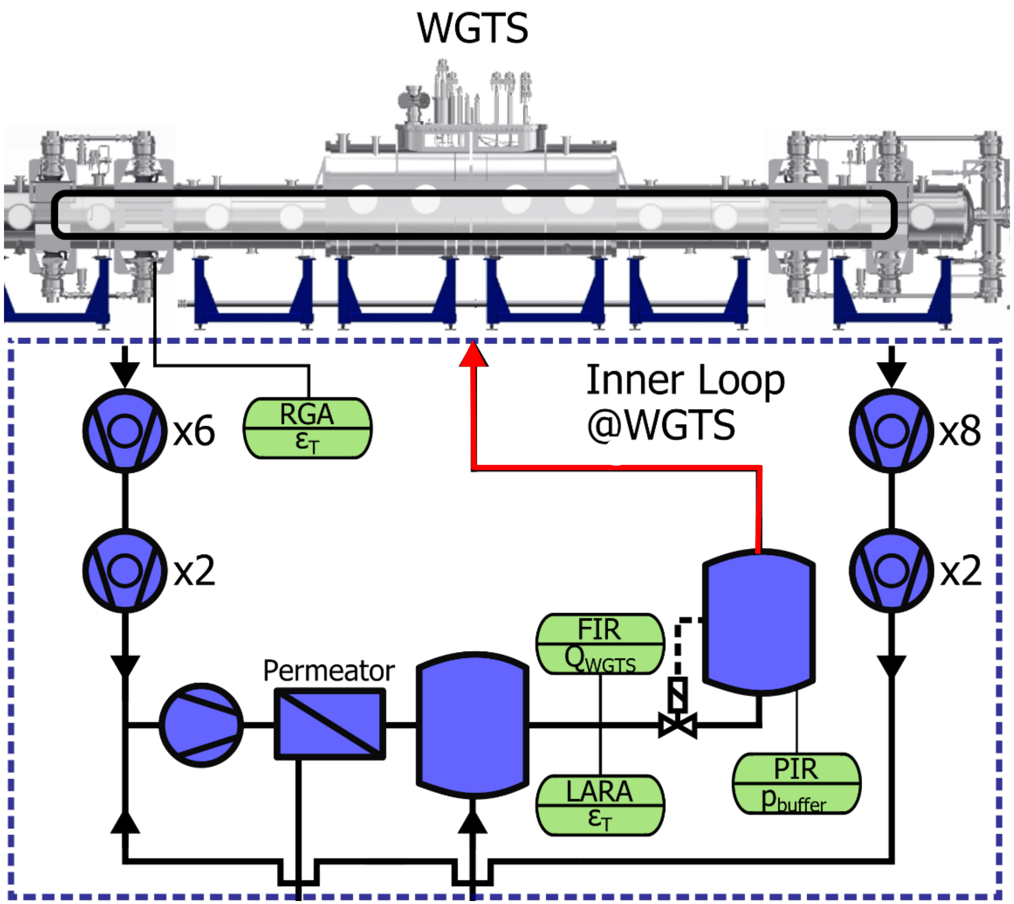
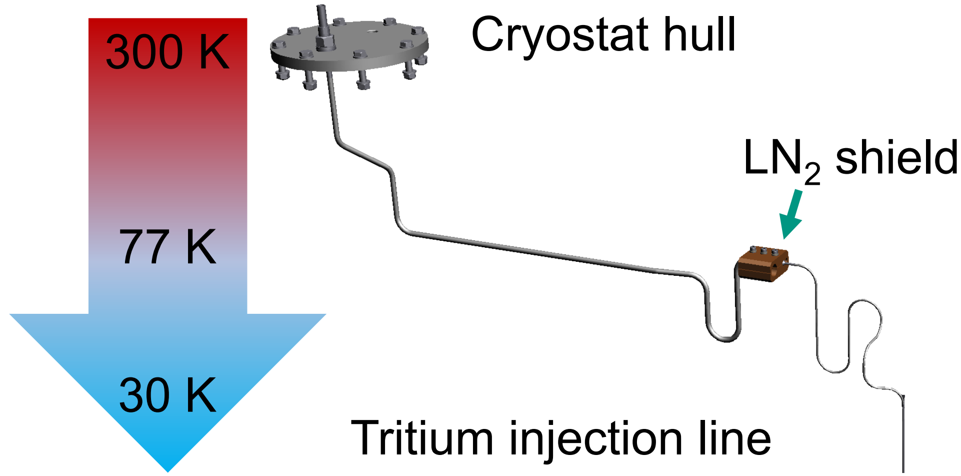
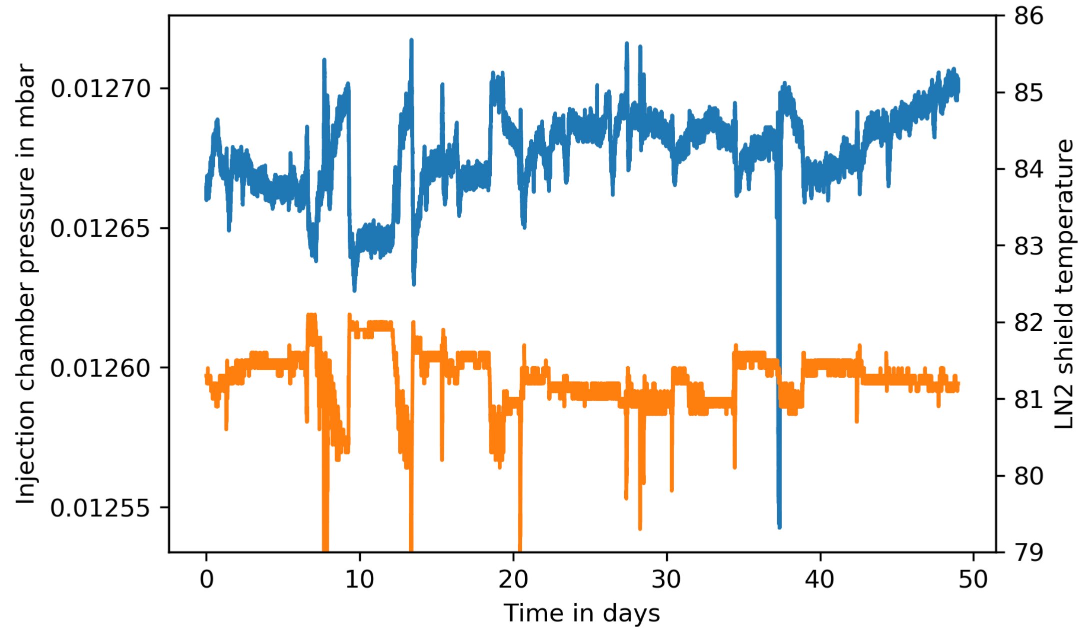


Temperature induced conductance changes

- To limit heat load on beam tube, injection system is connected to LN_2 shield
- LN_2 shield fluctuations change conductance of small connected section
- Reason: Pressure changes in LN_2 storage tank cause temperature changes of LN_2 cooling



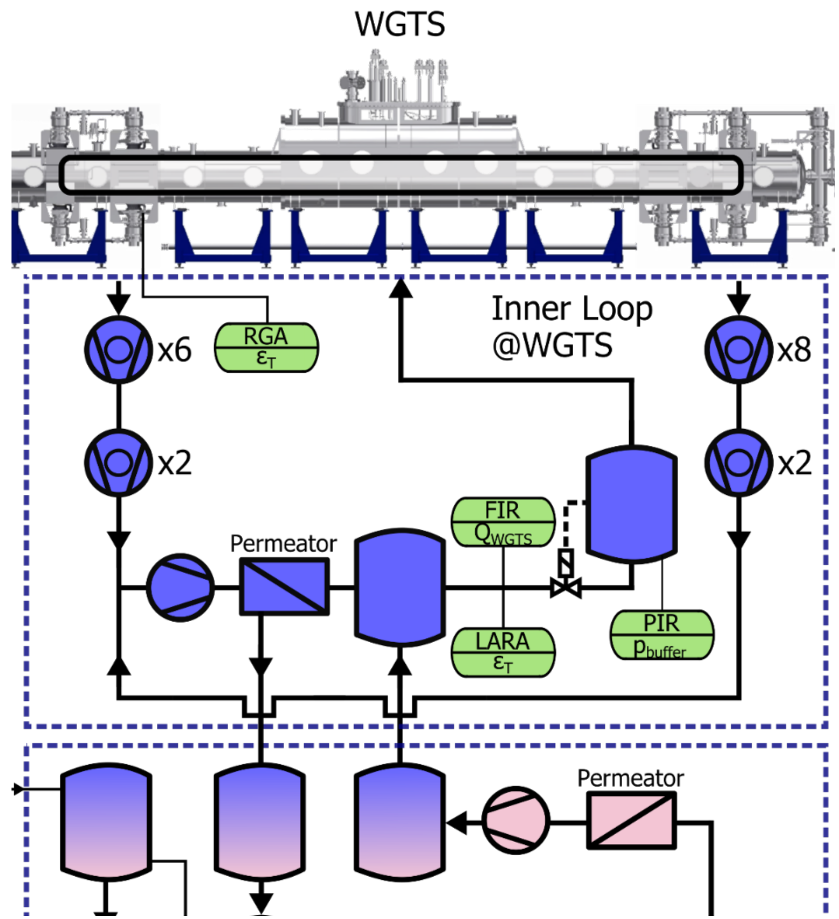


The source is highly sensitive to outside influences!

Topics of this presentation

Investigation of source stability parameters:

- Injection pressure ✓
- Gas composition ✓
- Conductance of the injection system ✓



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Summary

- Tritium loops successfully commissioned with pure tritium in 2019 and operated for >155 d for a total throughput of ≈3 kg
- The stabilization of the injection pressure of KATRIN's tritium source has been improved by a factor of 5
- The measurement methods for the gas composition have been characterized w.r.t. the composition inside the source
- The time evolution of the gas composition has been understood and can be modelled
- Effects influencing the conductance of the injectio
have been studied
- Effects of radiochemical impurity
observed and successfully mitiga

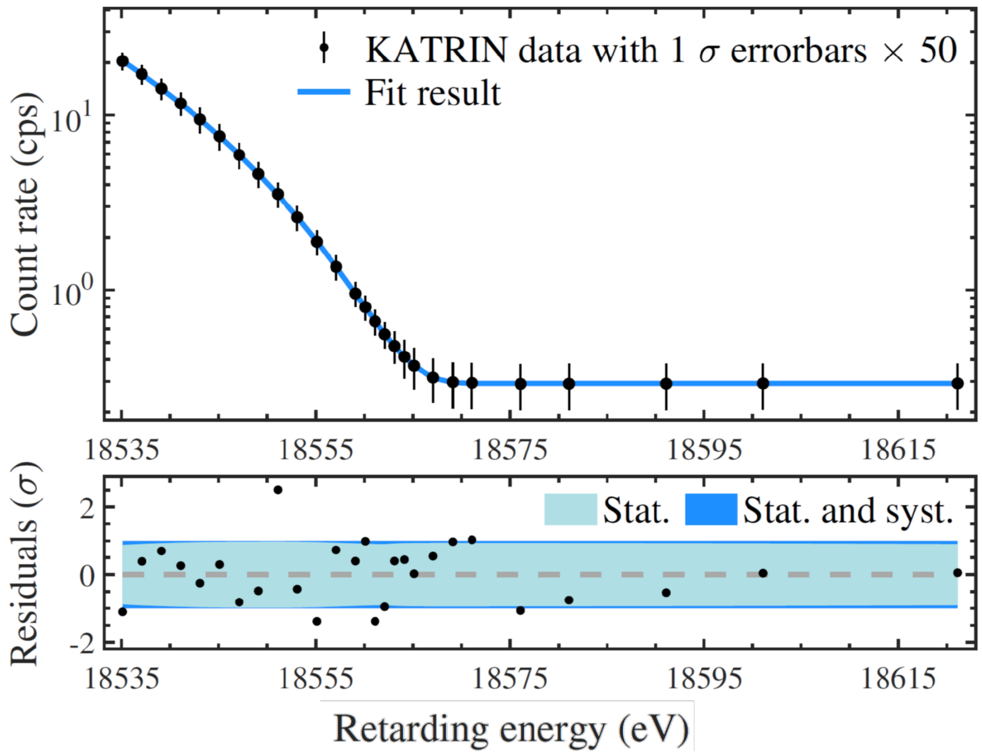
From the standpoint of gas dynamics, the source of KATRIN is well understood!

Thank you for your attention

New upper limit on the nautrino mass by KATRIN

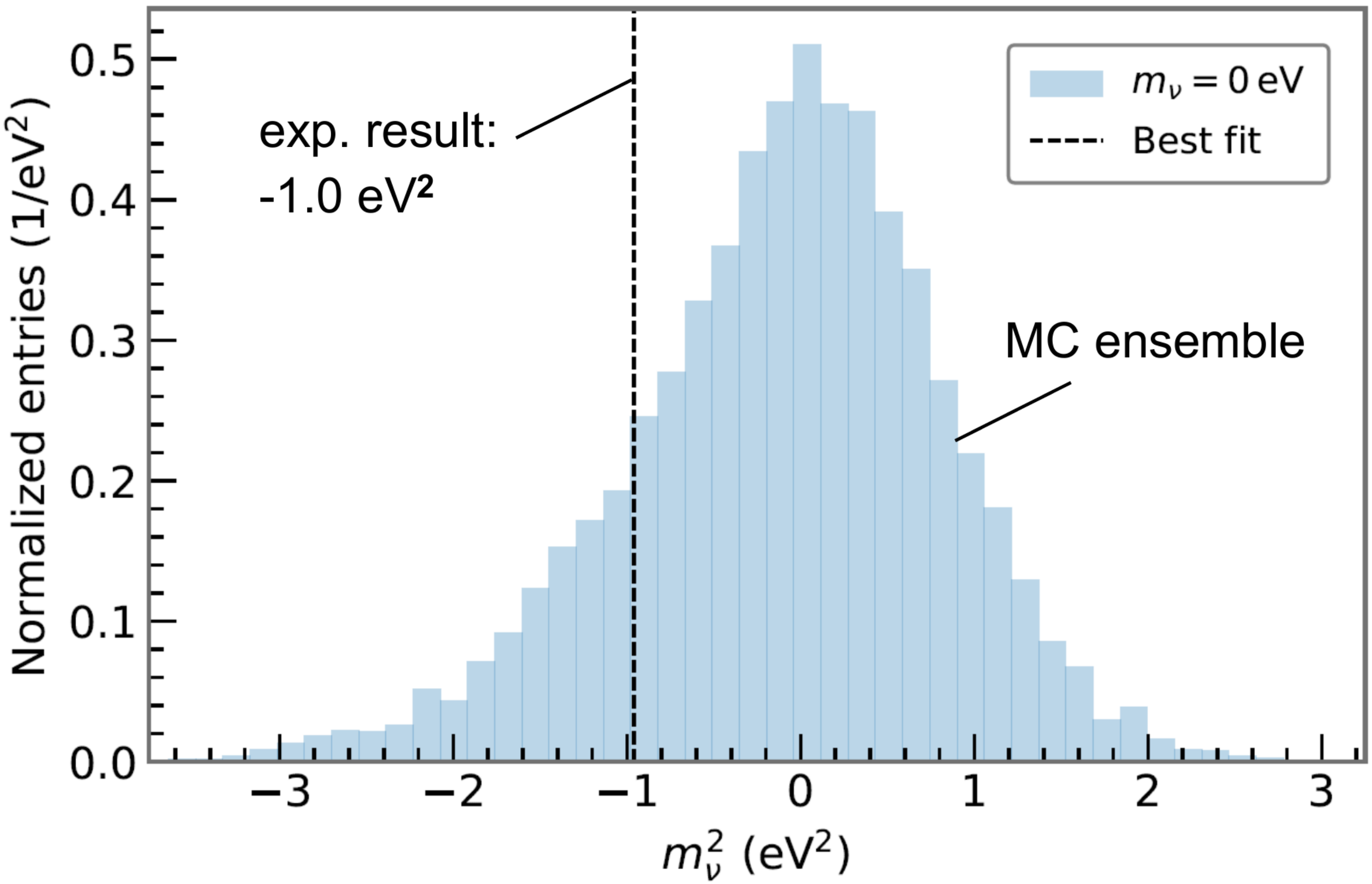
- A total of 522 h of scanning
- 2 million events in a 90 eV wide interval
- An excellent goodness of fit:
  - χ^2 = 21.4 for 23 d.o.f
- Best fit value:

$$m^2(\nu_e) = \left(-1.0 \begin{matrix} +\,0.9 \\ -\,1.1 \end{matrix}\right) \mathrm{eV}^2 \text{ (90\% CL)}$$



New upper limit:
Lokhov Tkachov: **$m(\nu_e)$ < 1.1 eV (90% C.L.)**
Feldmann Cousins: **$m(\nu_e)$ < 0.8 eV (90% C.L.)**

Statistical probability to measure negative neutrino mass squared



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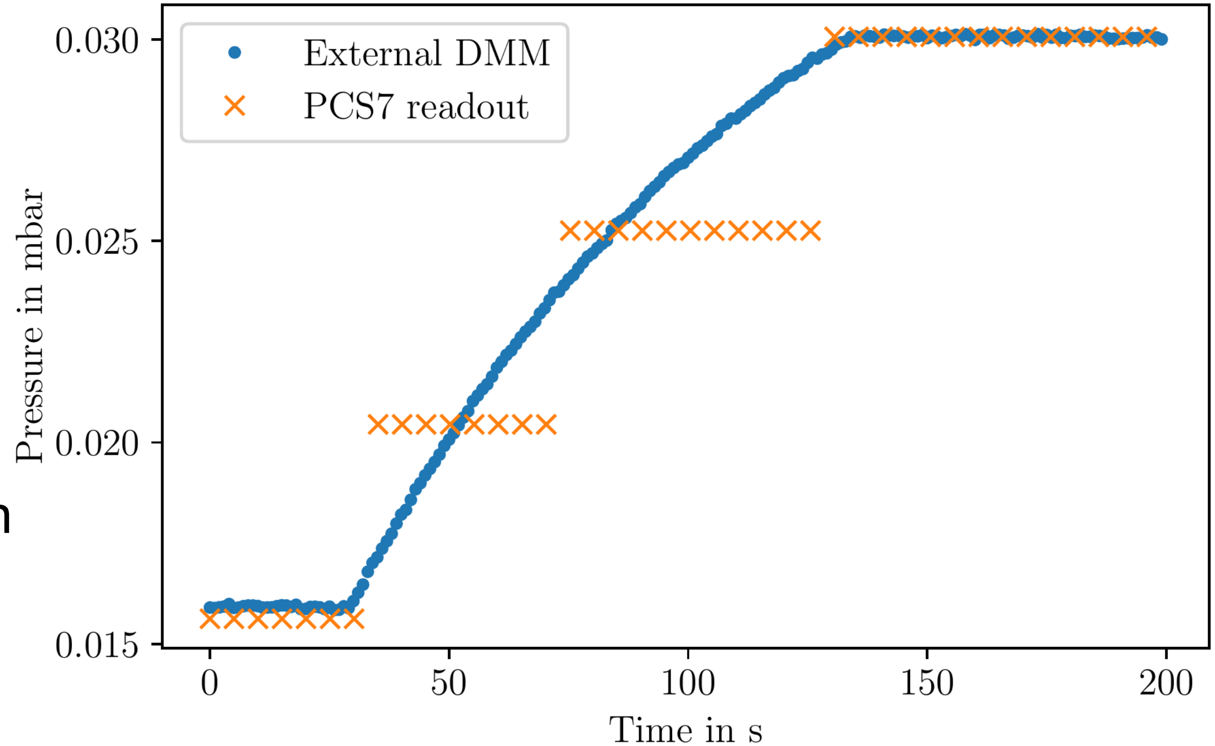
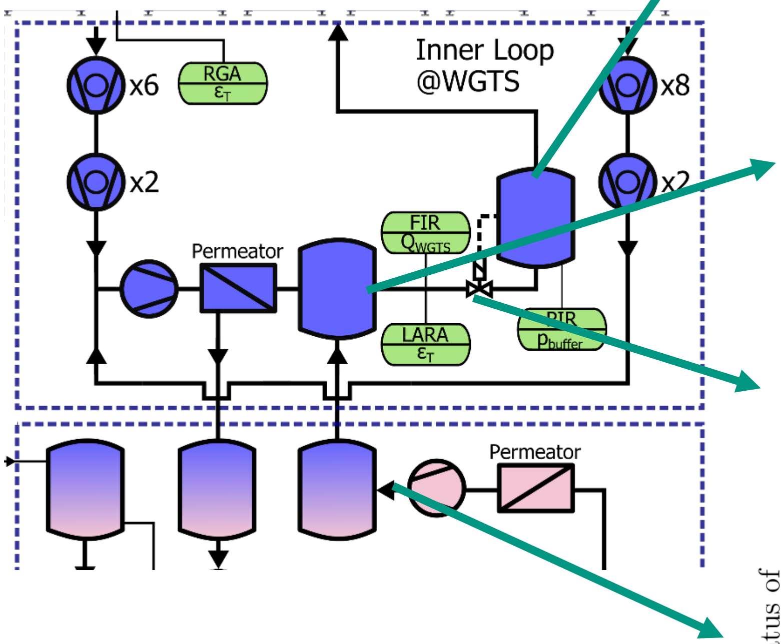
A smooth world between the steps

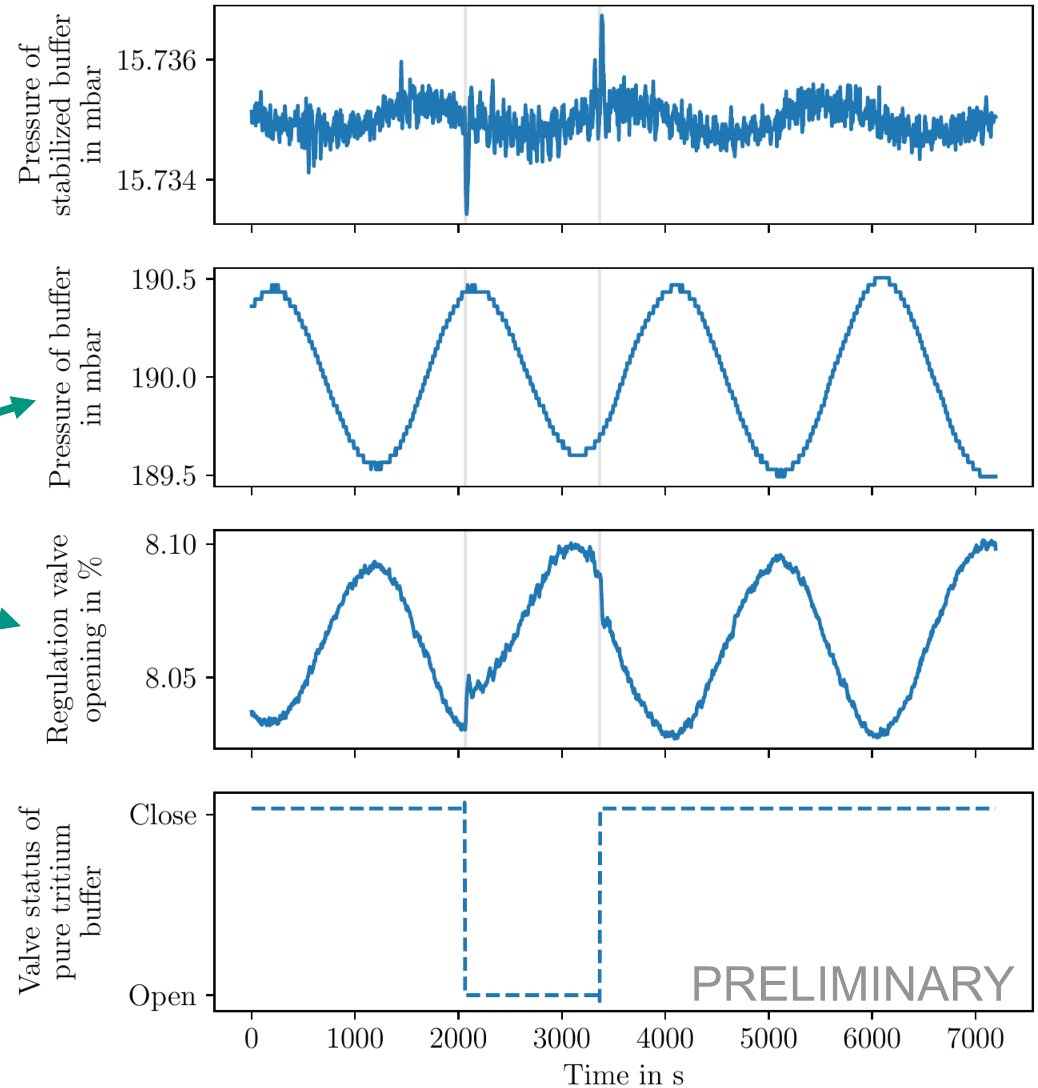
- Check the analog sensor output with an external DMM with high resolution
- <u>Unexpected Observation:</u>
  The signal at the analog output is much smoother than expected



There is much to gain by exchanging the readout!

Remaining spikes on the pressure signal





- Refilling of pure tritium buffer causes the spikes

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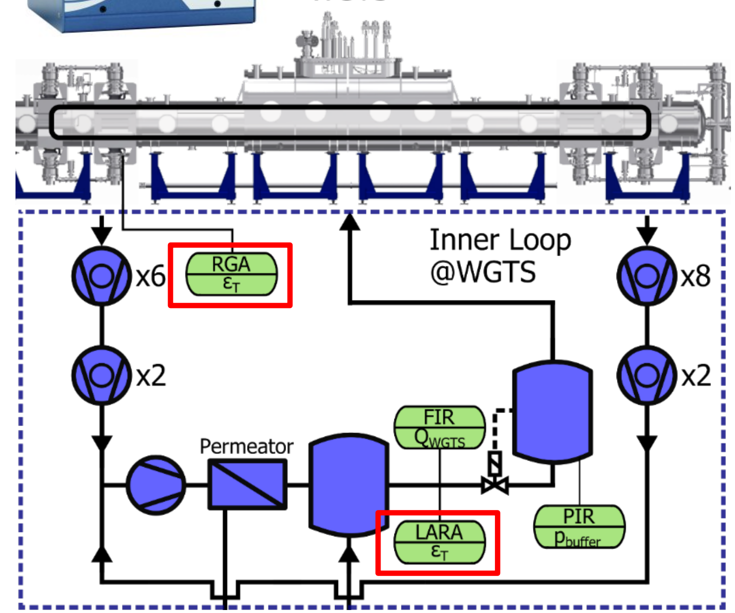
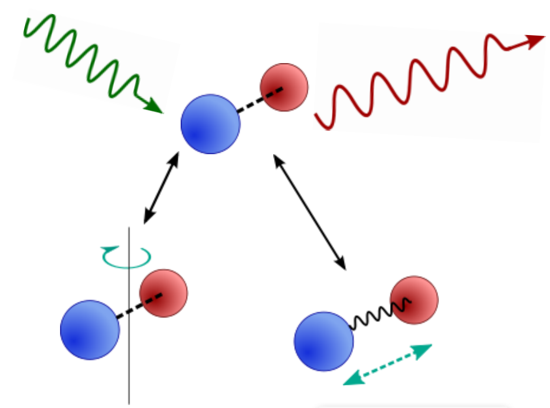
Monitoring the gas composition

- Residual Gas Analyzer (RGA)
  - Very high dynamic range
  - Sensitive to all gas components
  - Needs low operation pressure
    → Only usable in beam tube
  - Not usable in external magnetic field
    → No online measurements



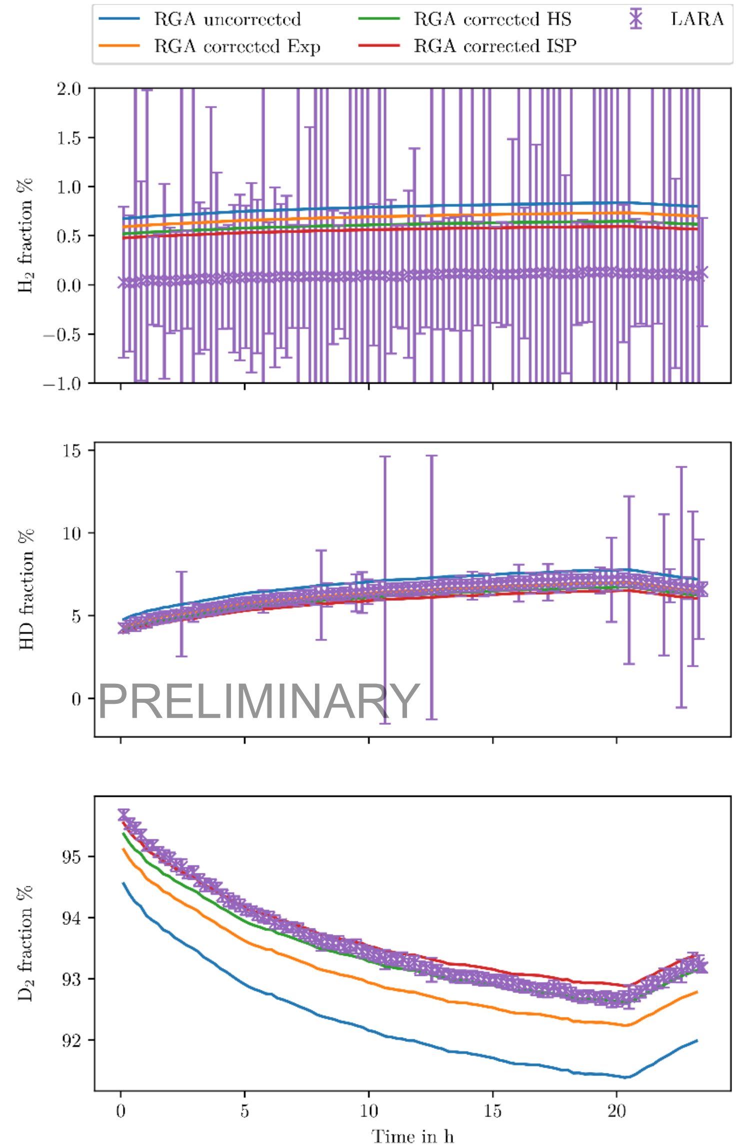
- Laser Raman Spectroscopy (LARA)
  - High precision measurement
  - Online measurements
  - Only sensitive to Raman active molecules (not to e.g. ^3He)
  - Needs high pressure (≈200 mbar)
    → Not usable in beam tube



Comparability of gas composition measurement methods

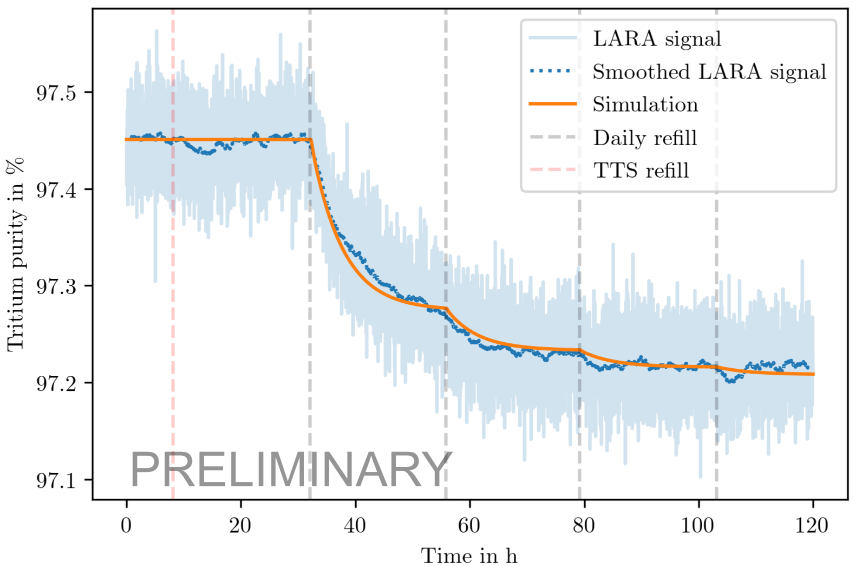
- Traces of gases are difficult to quantify accurately with LARA
- RGA data hard to quantify accurately
  - Different ionization energies make comparing peak heights difficult
- Slight delay between RGA and LARA
  - Gas needs time to travel from LARA through stabilized buffer and ≈20 m piping into beam tube

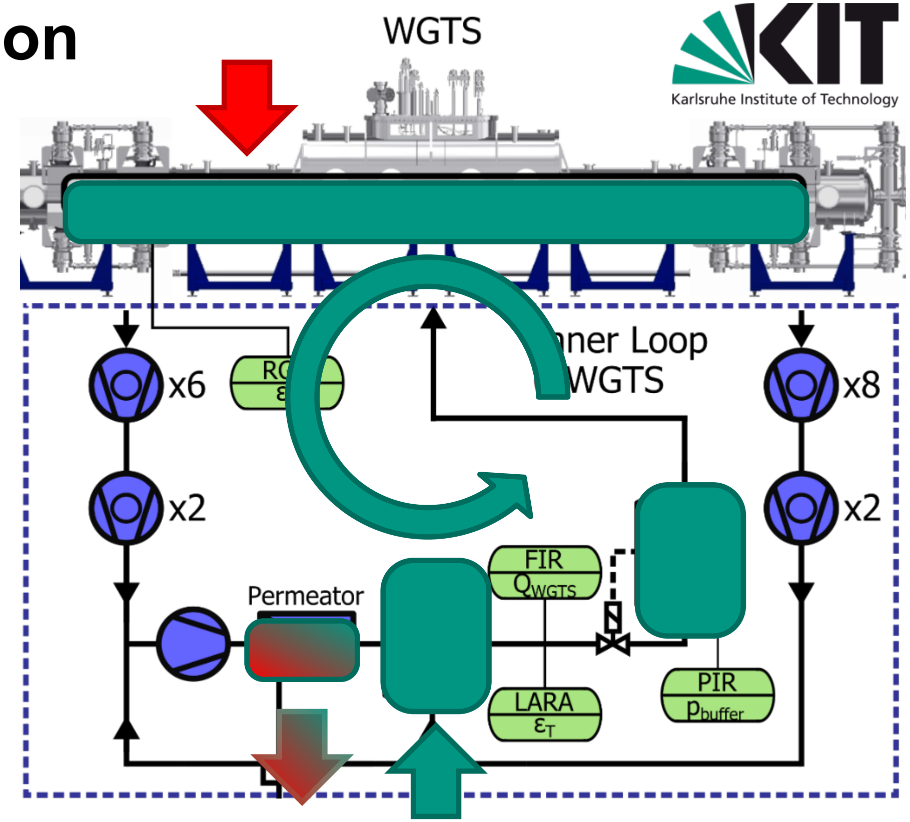
LARA is a good method to measure the gas composition of highly pure hydrogen isotopes in quasi equilibrium.



Modelling the gas composition

- Simple model of connected vessels
- Initial concentration parameters from LARA
- Flow rates and impurity generation rates from measured data





The gas composition can be modelled successfully using a simple model and some experimental values.