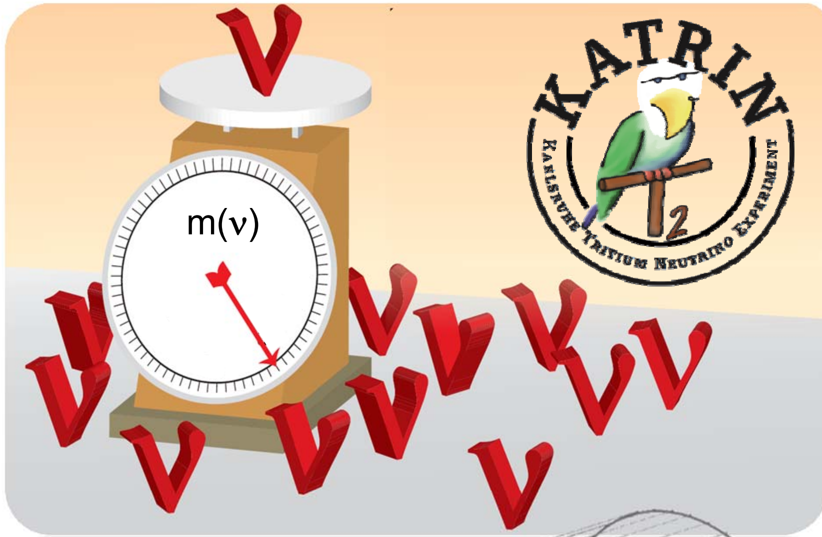
Karlsruher Institut für Technologie

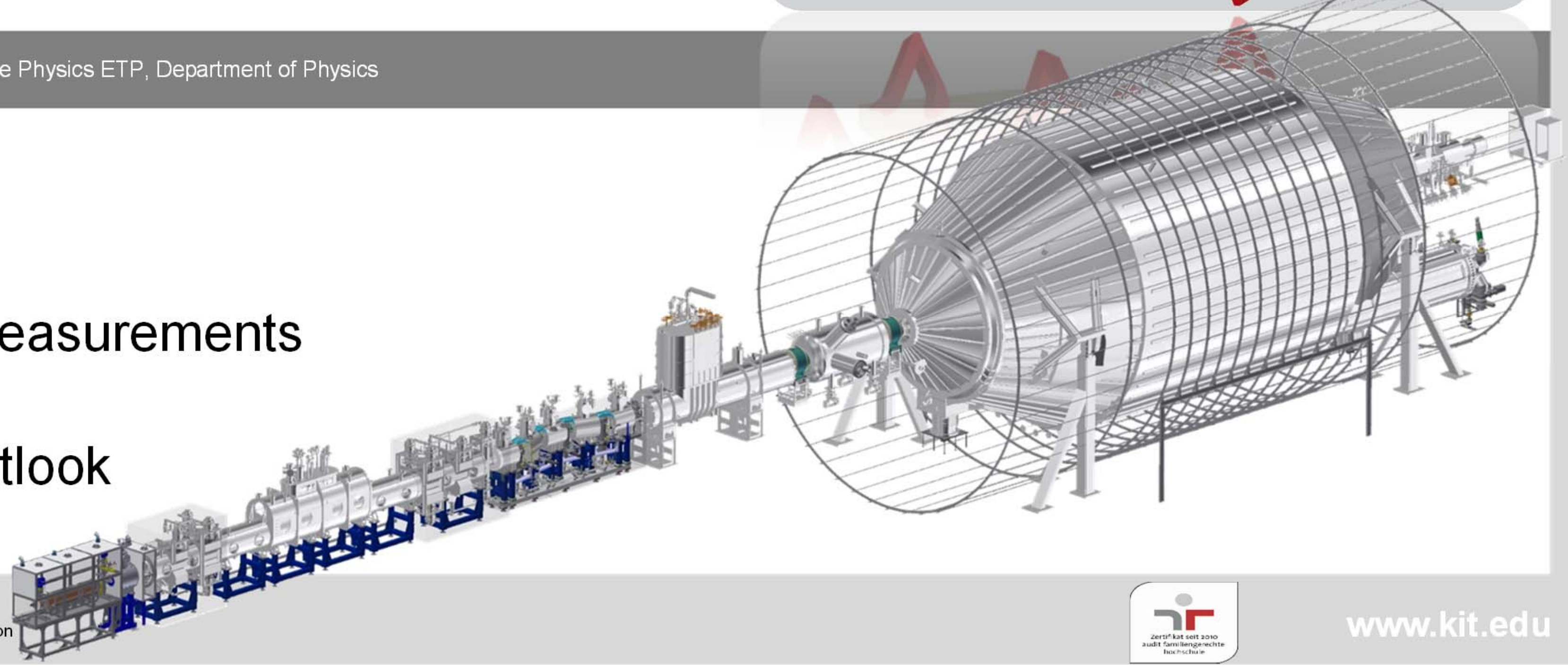
Neutrino physics at KATRIN



2017 STJU-KIT Collaborative Research Workshop
September 6-8, 2017

Guido Drexlin, Institute for Experimental Particle Physics ETP, Department of Physics

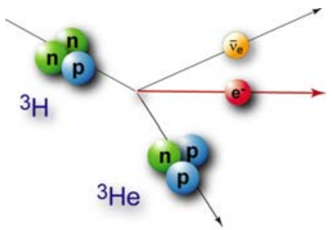
- Introduction
- Overview
- Commissioning measurements
- Selected results
- Conclusions & Outlook

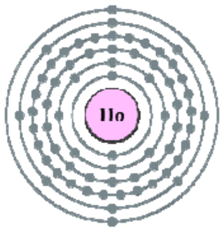


neutrino mass: status and perspecives

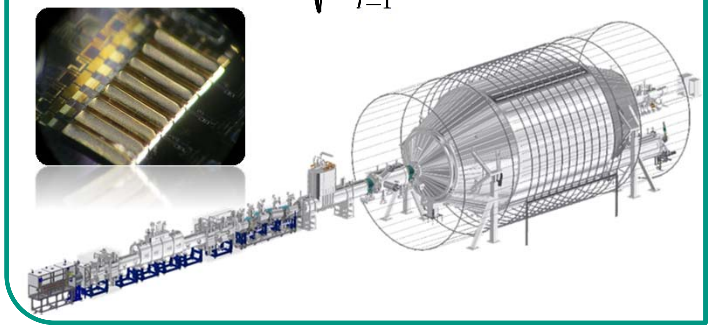
kinematics of weak decays

- **ß-decay**: ^{3}H, EC: ^{163}Ho
- **model-independent**



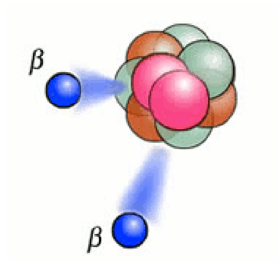


$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}\right|^2 \cdot m_i^2}$$

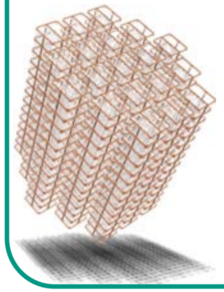


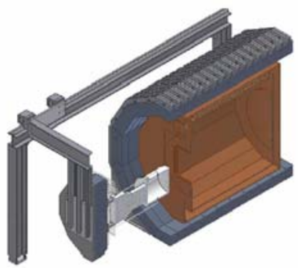
search for 0νßß-decay

- **ßß-decay**: ^{76}Ge,^{130}Te,^{136}Xe, …
- model-dependent (phases α_i)



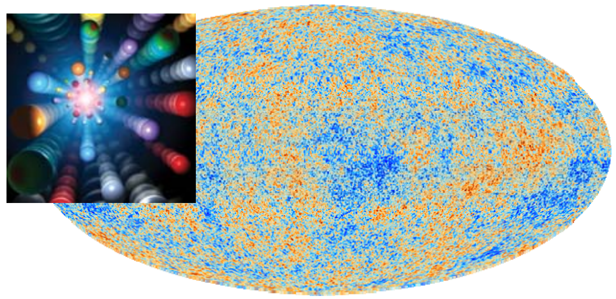
$$\left\langle m_{ßß} \right\rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$





cosmology

- **LSS**: CMB, GRS, WL,…
- model-dependent (w⇔H_0)

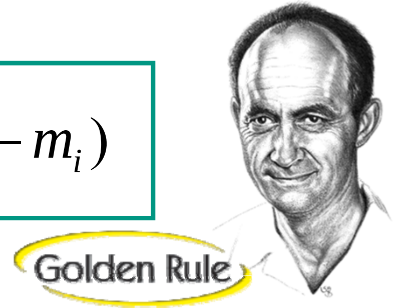


$$m_{tot} = \sum_{i=1}^{3} m_i$$

ß-decay: kinematics

- model independent measurement of m(ν_e), based solely on **kinematic parameters & energy conservation**

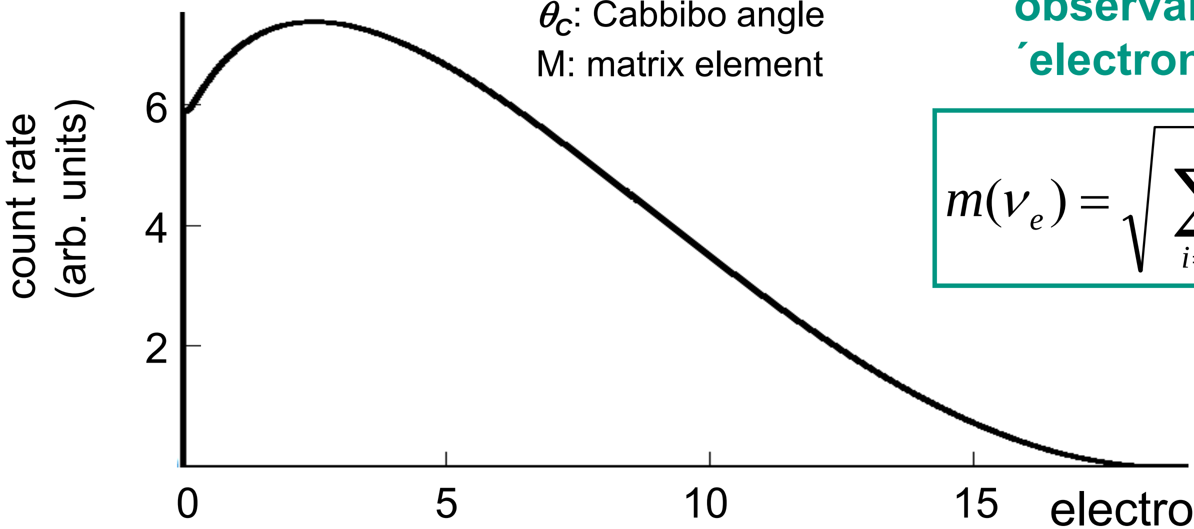
$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$



Enrico Fermi

$$G_F^2 \cdot \frac{m_e^5}{2\pi^3} \cdot \cos^2\theta_C \cdot |M|^2$$

θ_C: Cabbibo angle
M: matrix element



observable m²(ν_e): ´electron-ν-mass´

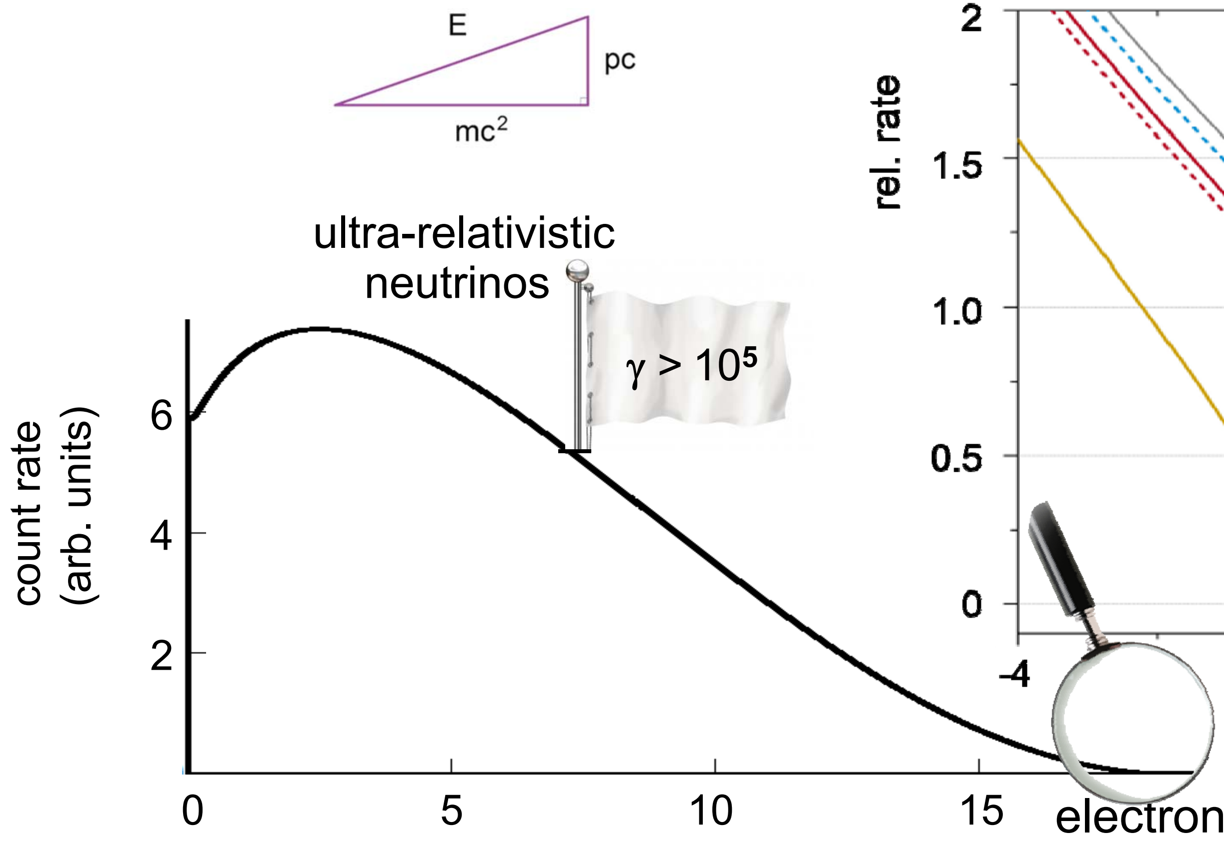
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$

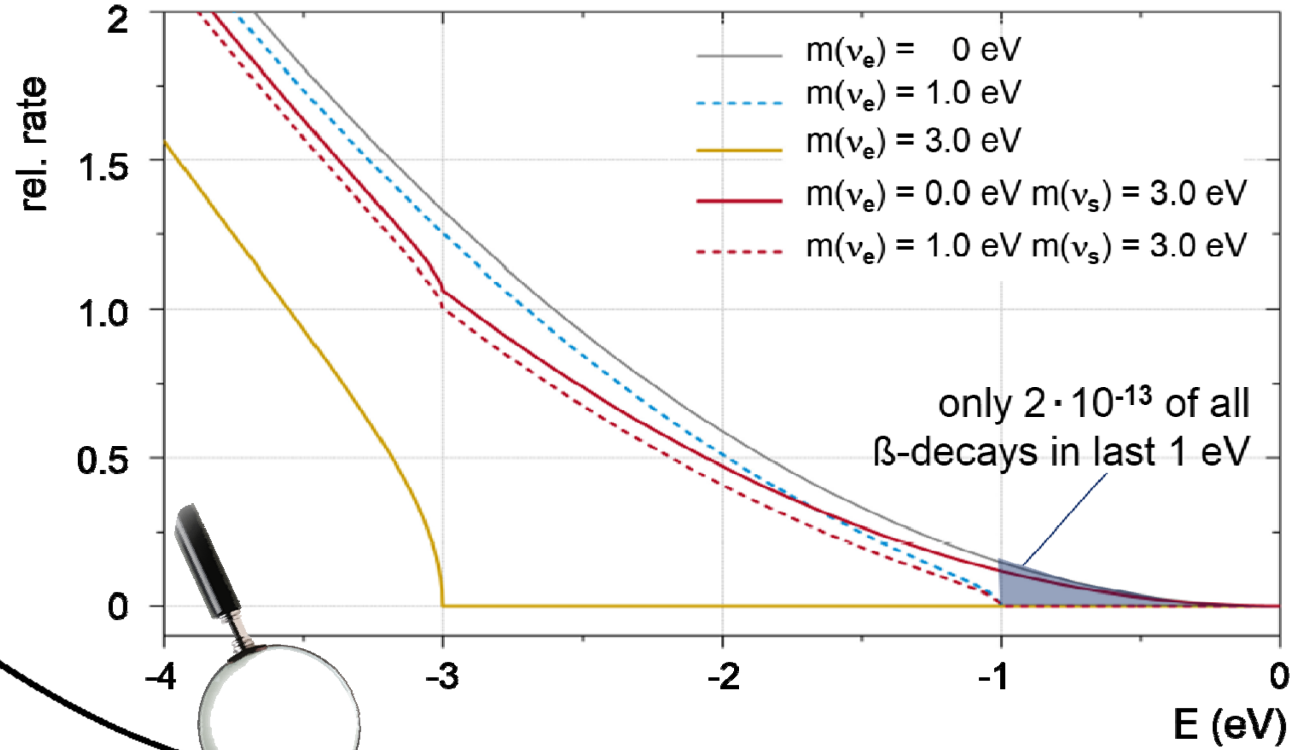
´incoherent´ sum of the mass eigenstates m_i

mass splittings Δm^2_{ij} cannot be observed as $\Delta E >> \sqrt{\Delta m^2_{ij}}$

ß-decay: kinematics

- neutrino mass manifests itself only close to endpoint at E_0, as neutrinos there are only „mildly relativistic“ [$E^2 = p^2c^2 + (mc^2)^2$]



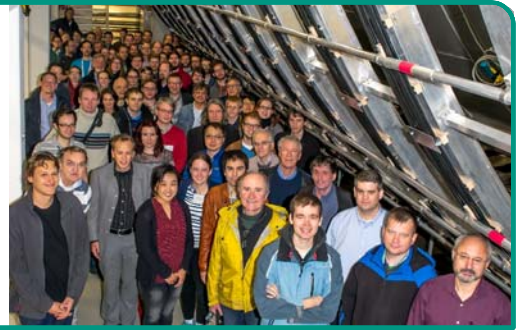


KATRIN experiment

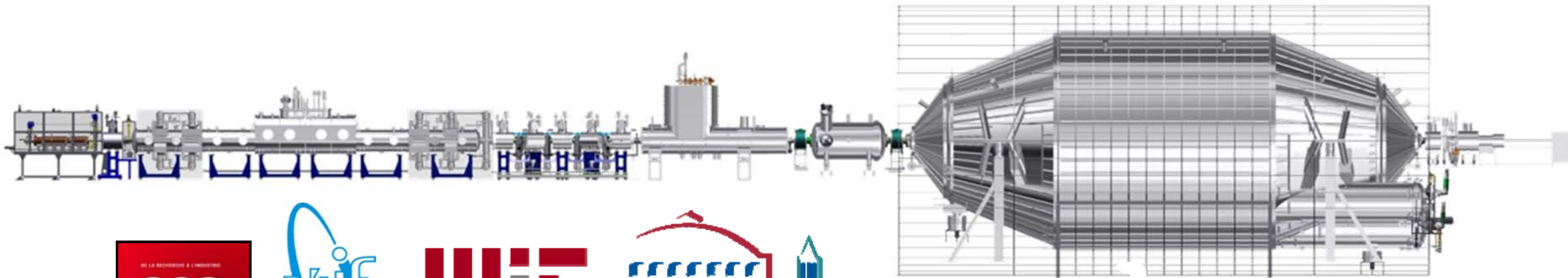
Karlsruhe Institute of Technology

■ Karlsruhe Tritium Neutrino Experiment

- **direct ν–mass experiment**: located at Tritium Laboratory (TLK), KIT
- international collaboration ~130 members
  from 6 countries: D, US, CZ, RUS, F, ES



KATRIN – Karlsruhe Tritium Neutrino Experiment



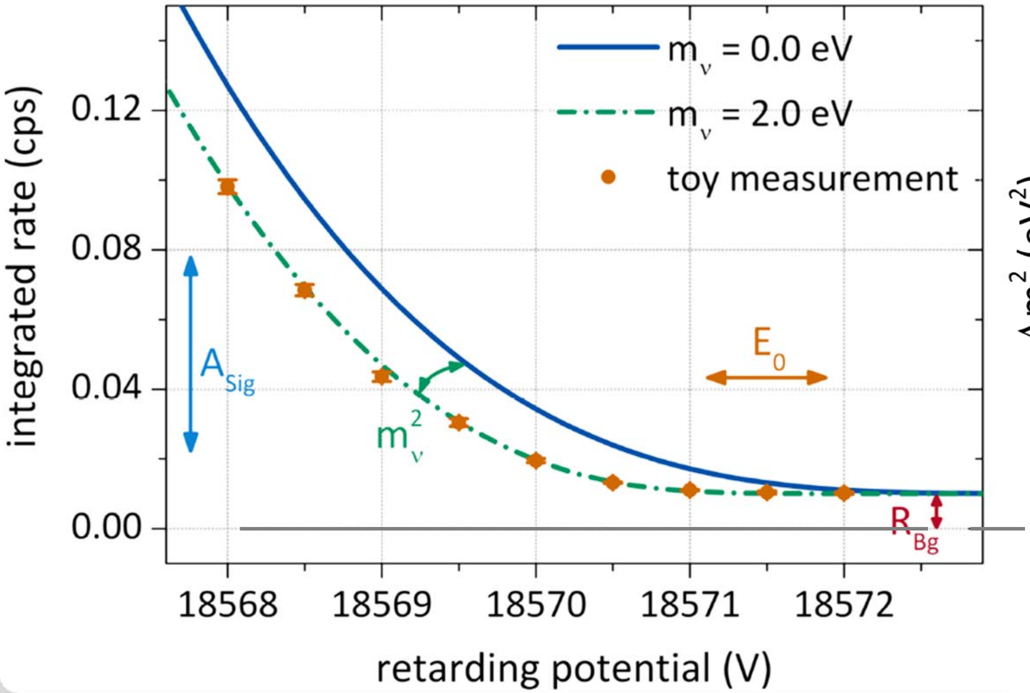
■ 19 institutions:

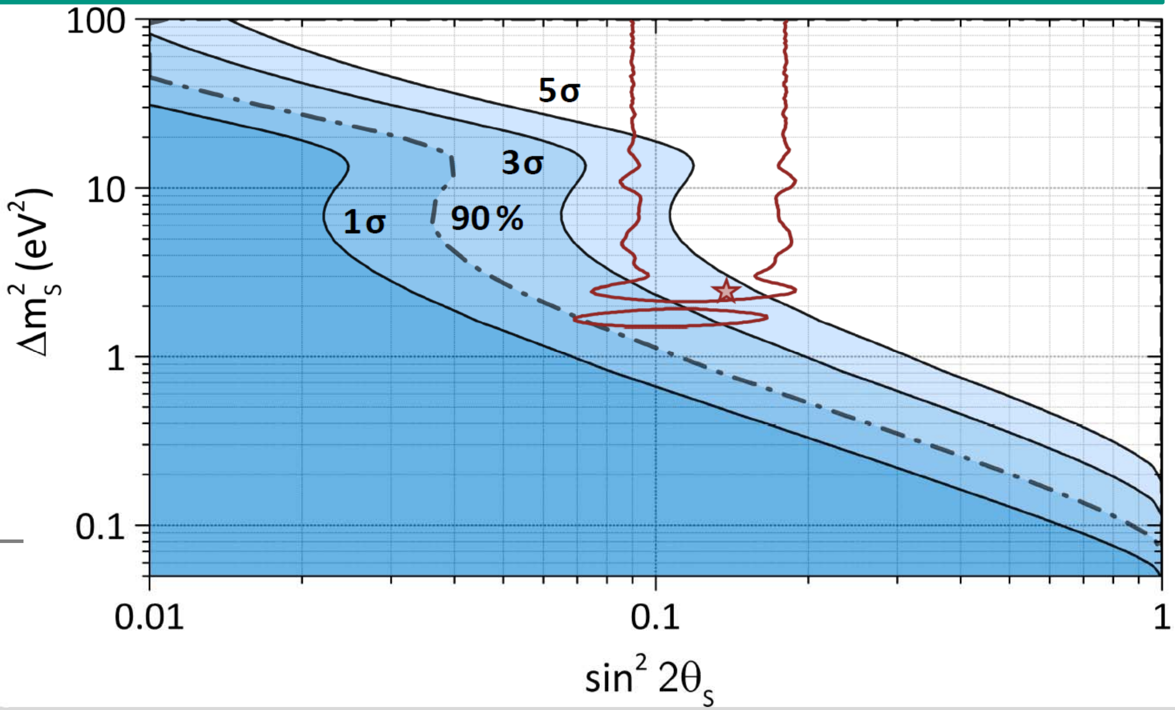
Karlsruher Institut für Technologie
TUM
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
universität bonn
cea
ujf
MIT
Berkeley Lab
Hochschule Fulda University of Applied Sciences
The University of North Carolina at Chapel Hill
INR
University of Washington
Carnegie Mellon University, Pittsburgh Pennsylvania 1900
Westfälische Wilhelms-Universität Münster
Bergische Universität Wuppertal
JGU Johannes Gutenberg Universität Mainz
Max-Planck-Institut für Kernphysik
Universidad Complutense Madrid
Case Western Reserve University est. 1826

KATRIN experiment – science case

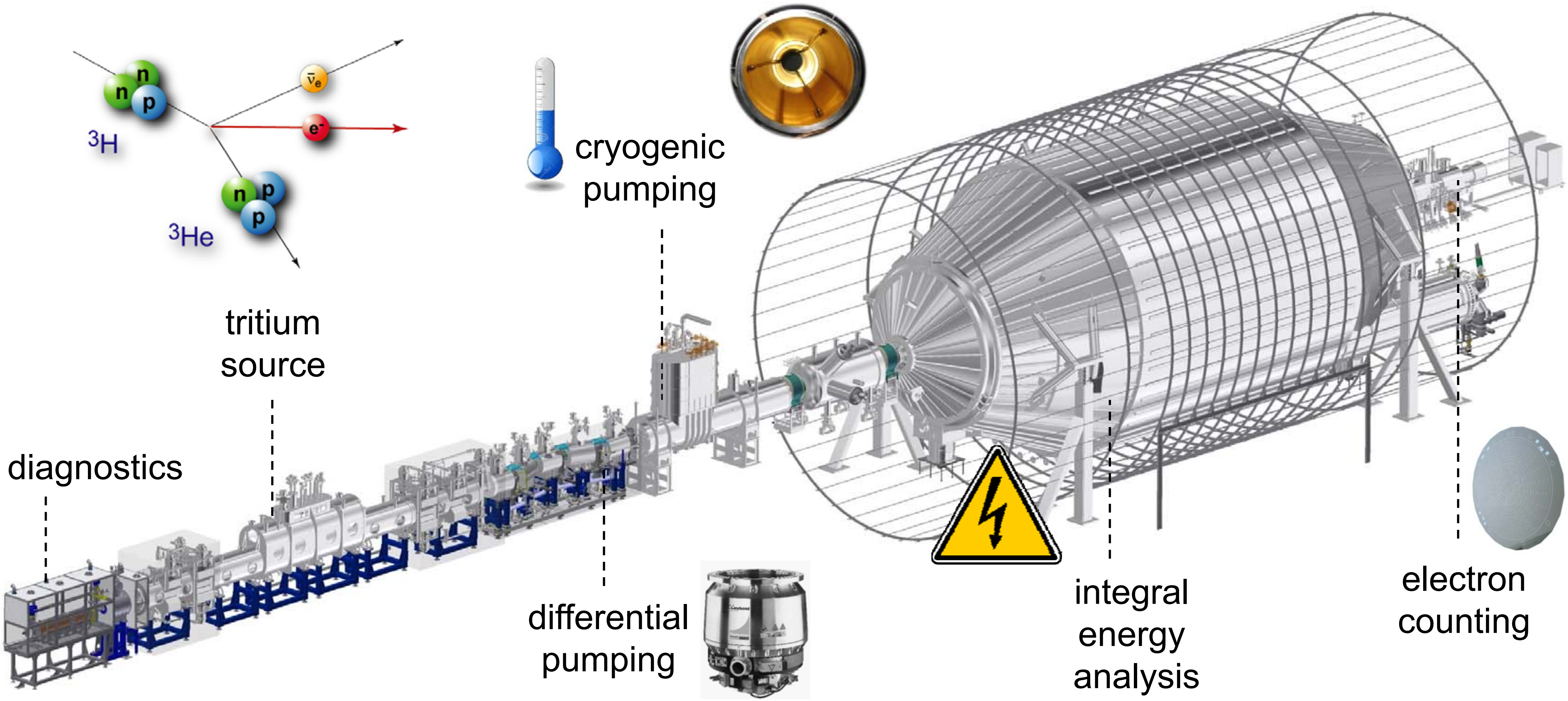
physics programme

- ***model-independent*** effective electron (anti-)neutrino mass: **$m(\nu_e)$ = 0.2 eV** (90% CL)
- search for sterile neutrinos (or other non-SM particles) from sub-eV … keV mass scale
- search for exotic currents, BSM physics & Lorentz violations, constrain local relic-ν density

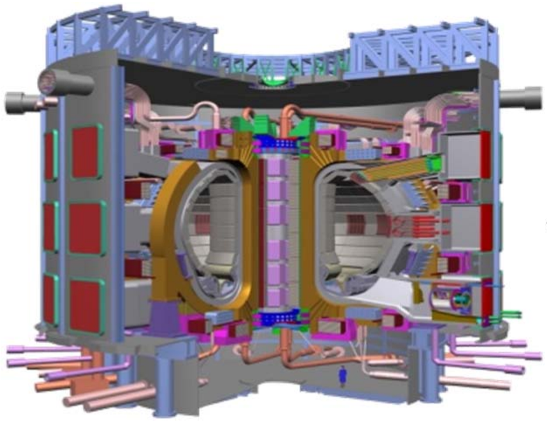




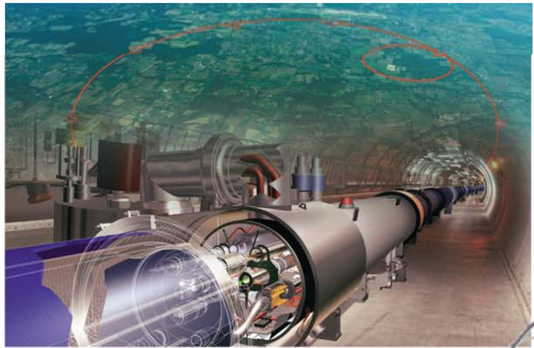
KATRIN overview: 70 m long beamline



KATRIN overview: challenges-I

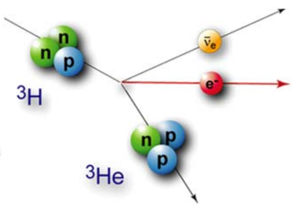


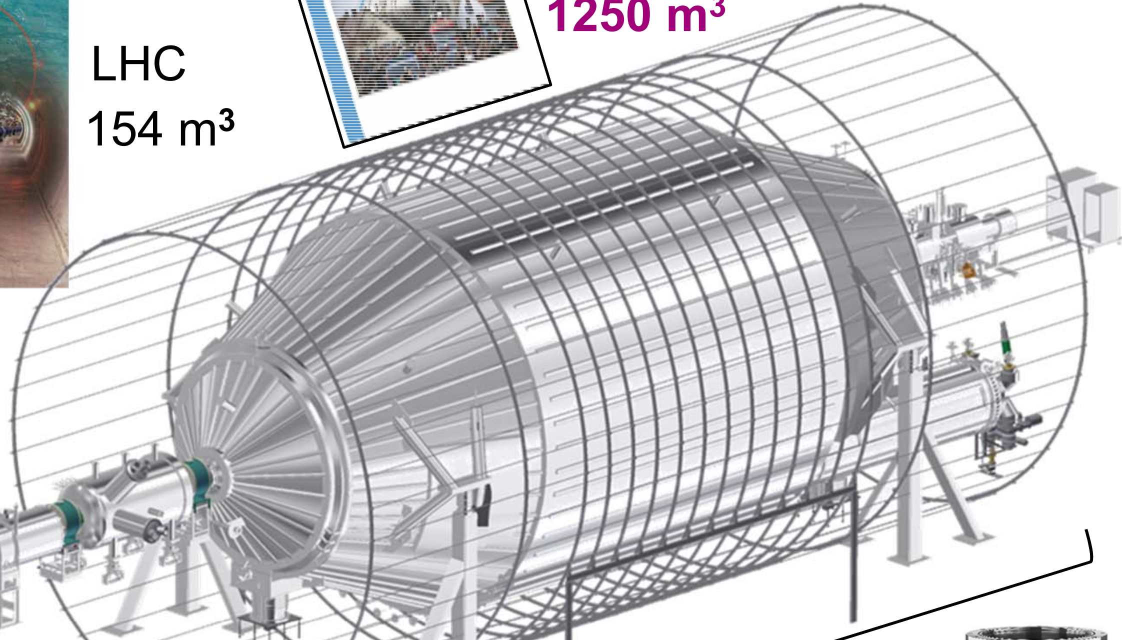
ITER
(2035)

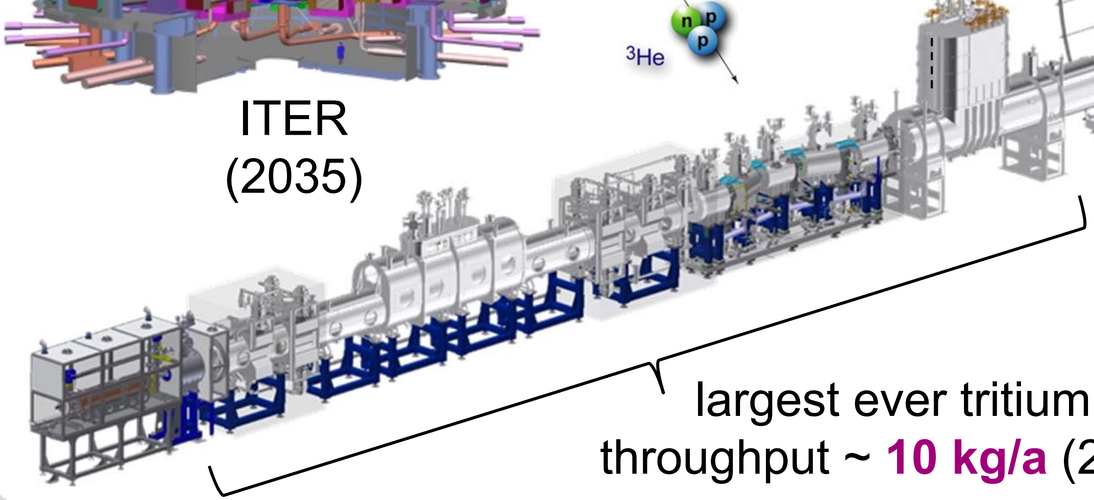


LHC
154 m^3

1250 m^3



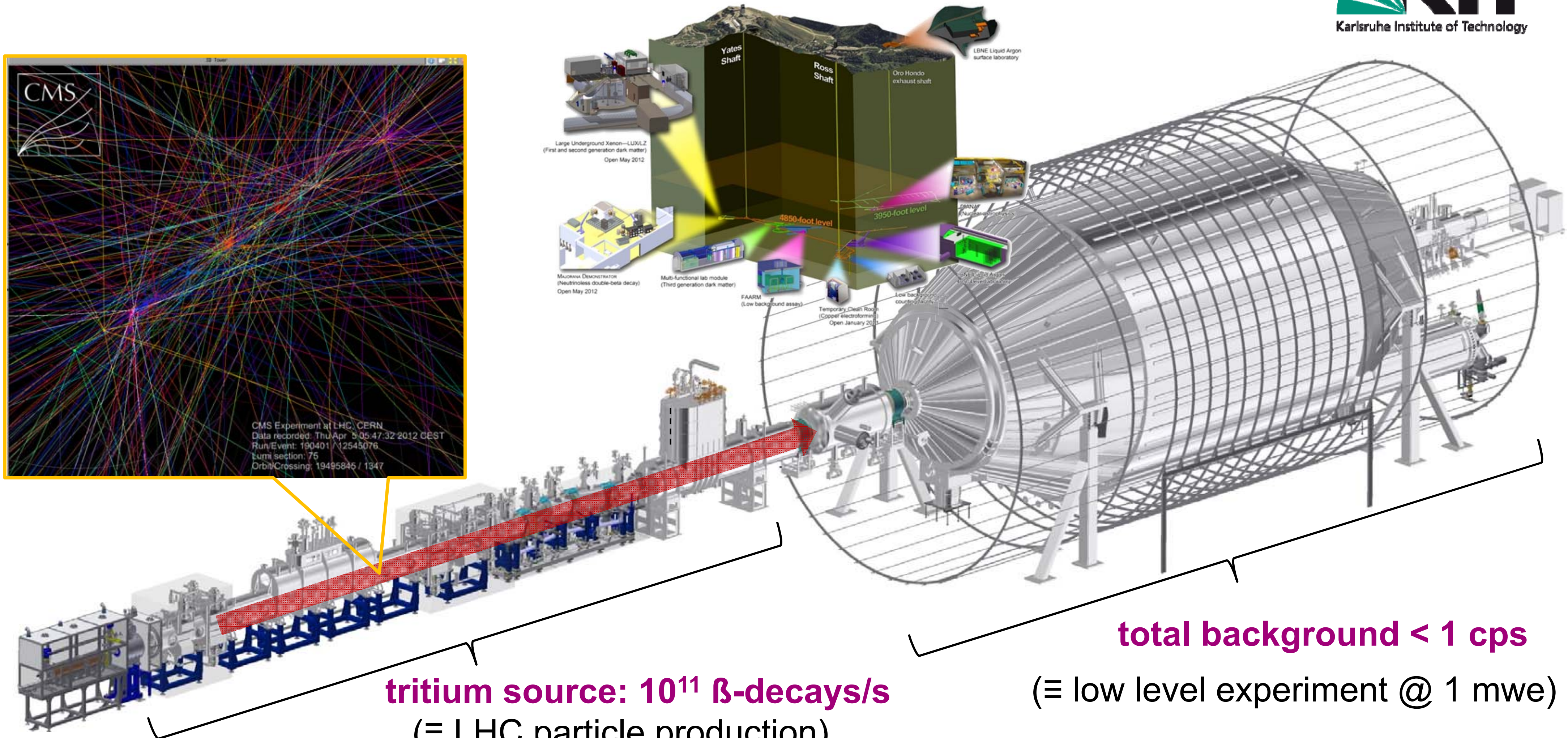




largest ever tritium
throughput ~ **10 kg/a** (2018)

largest ever UHV
recipient: p ~ 10^{-11} mbar
(2013)

KATRIN overview: challenges-II



tritium source: 10^{11} ß-decays/s

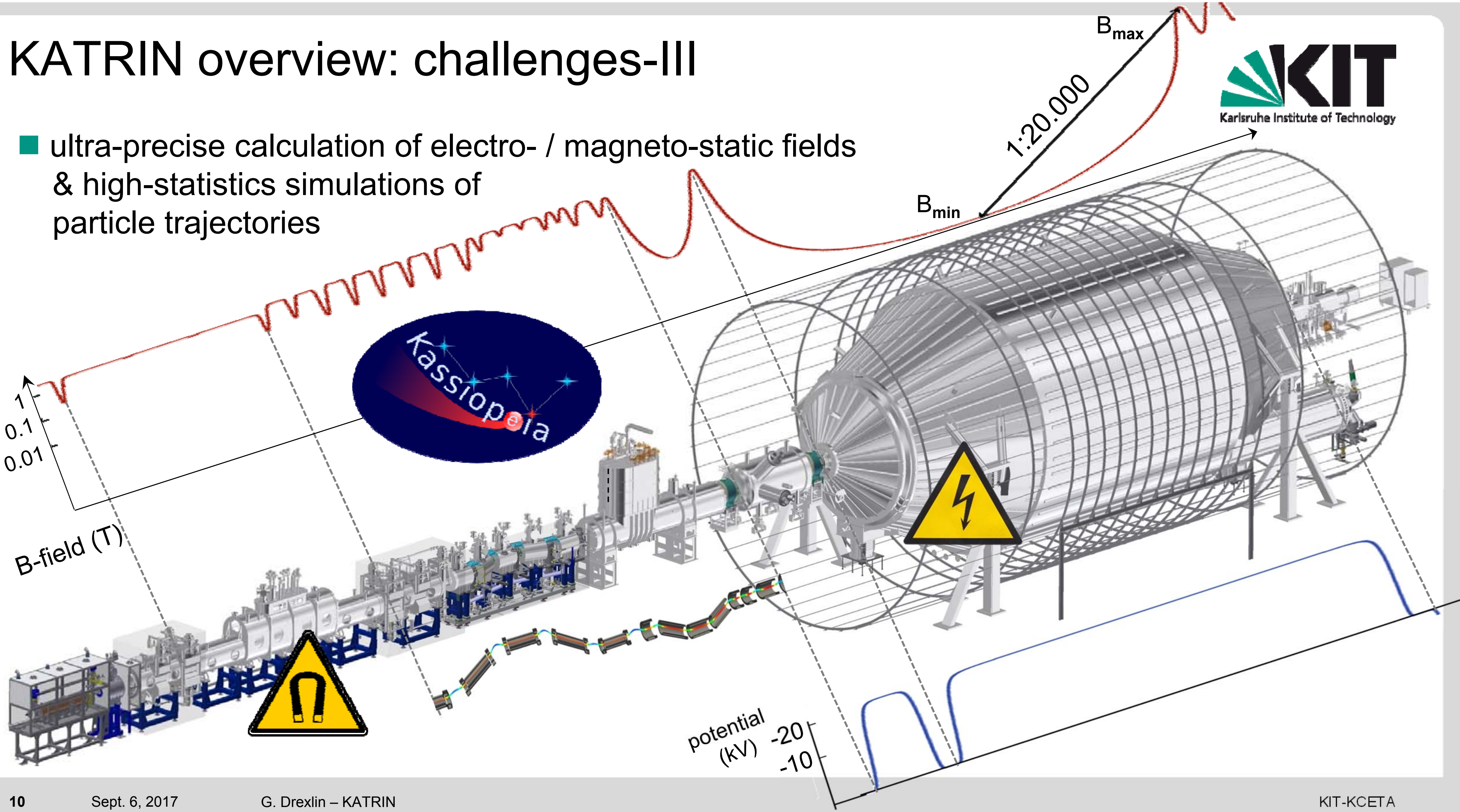
(≡ LHC particle production)

total background < 1 cps

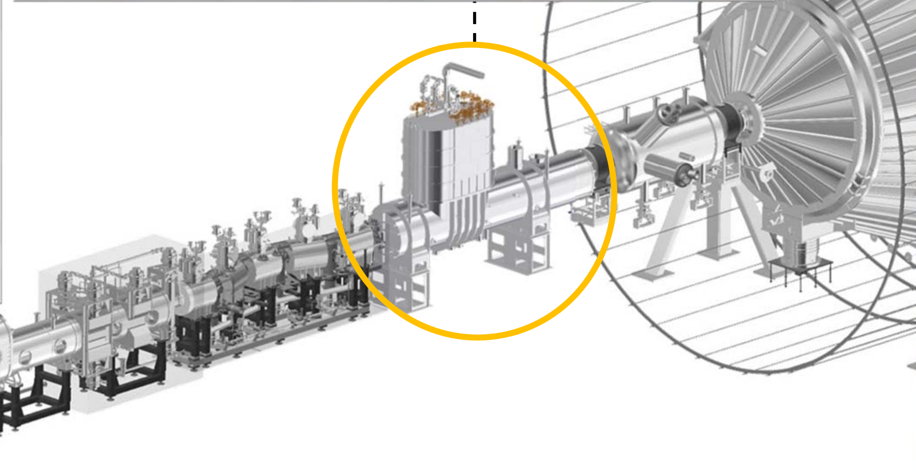
(≡ low level experiment @ 1 mwe)

KATRIN overview: challenges-III

- ultra-precise calculation of electro- / magneto-static fields & high-statistics simulations of particle trajectories



Project milestones 2015 – CPS delivery

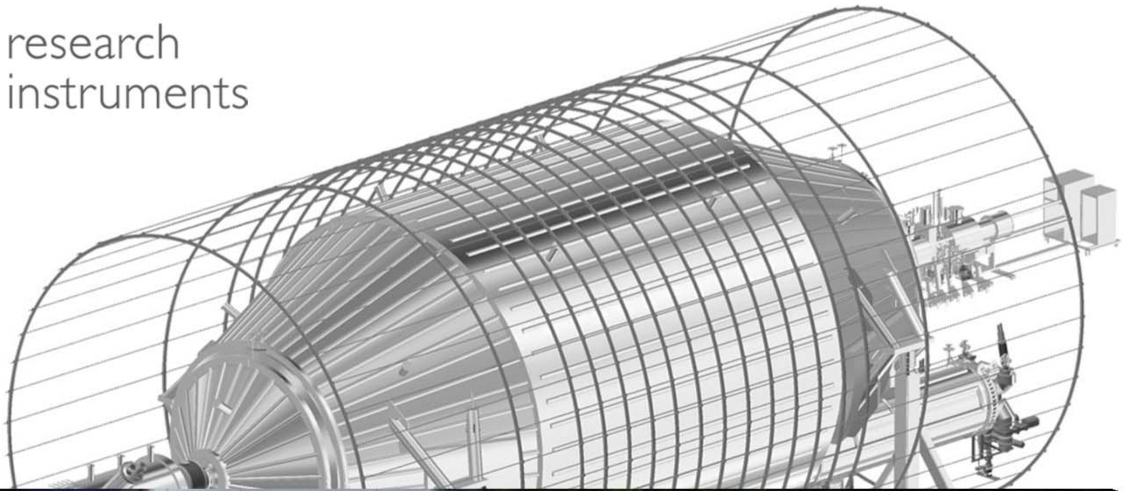


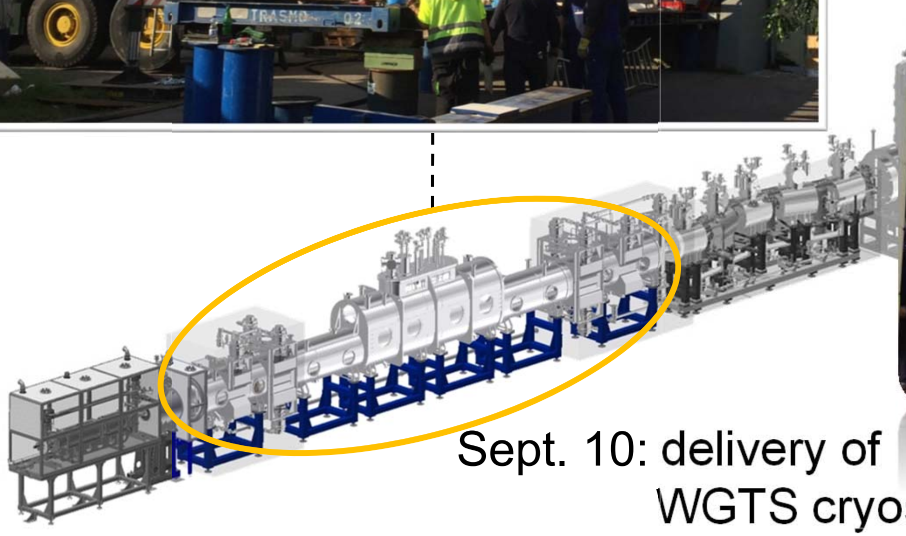
July 30: delivery of
CPS cryostat

ASG Superconductors

Project milestones 2015 – WGTS delivery

research
instruments





Sept. 10: delivery of
WGTS cryostat

Project milestones 2016 – first light

Karlsruhe Institute of Technology

Neutrinos auf der Waage

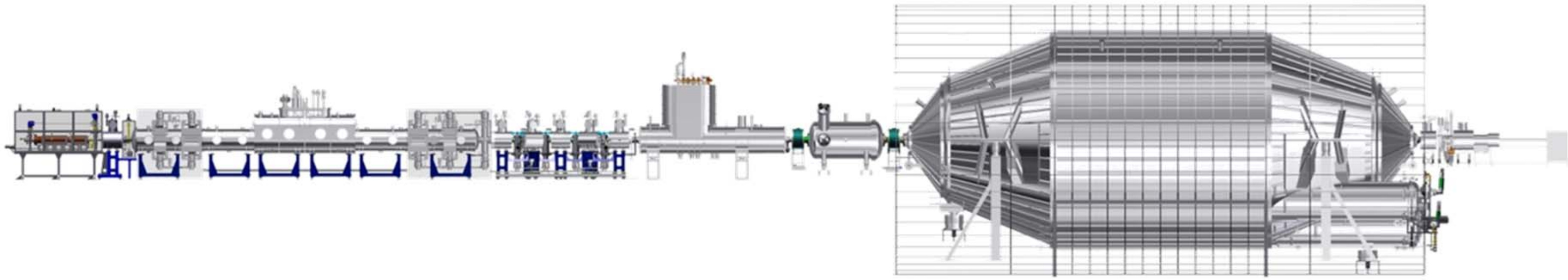
DPG

Am 14. Oktober durchflogen erstmals Elektronen das Experiment KATRIN am Karlsruher Institut für Technologie

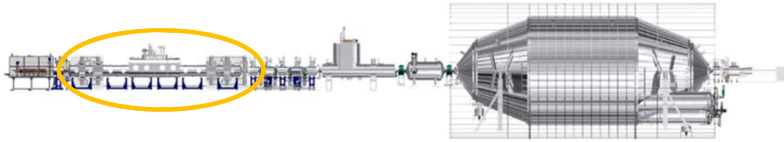
Neutrinos durchdringen uns jede
Sekunde milliardenfach, ohne dass
wir das Geringste davon bemer-
ken würden. Lange Zeit galten die
mysteriösen Teilchen daher als
masselos. Seit dem Nachweis
Neutrino-Oszillationen, de
vergangenen Jahr mit de
Nobelpreis ausgezeich
aber klar, dass Neutri
ge Masse besit
groß sie

technical inauguration of KATRIN
October 14, 2016

KATRIN:
main components



WGTS – source cryostat

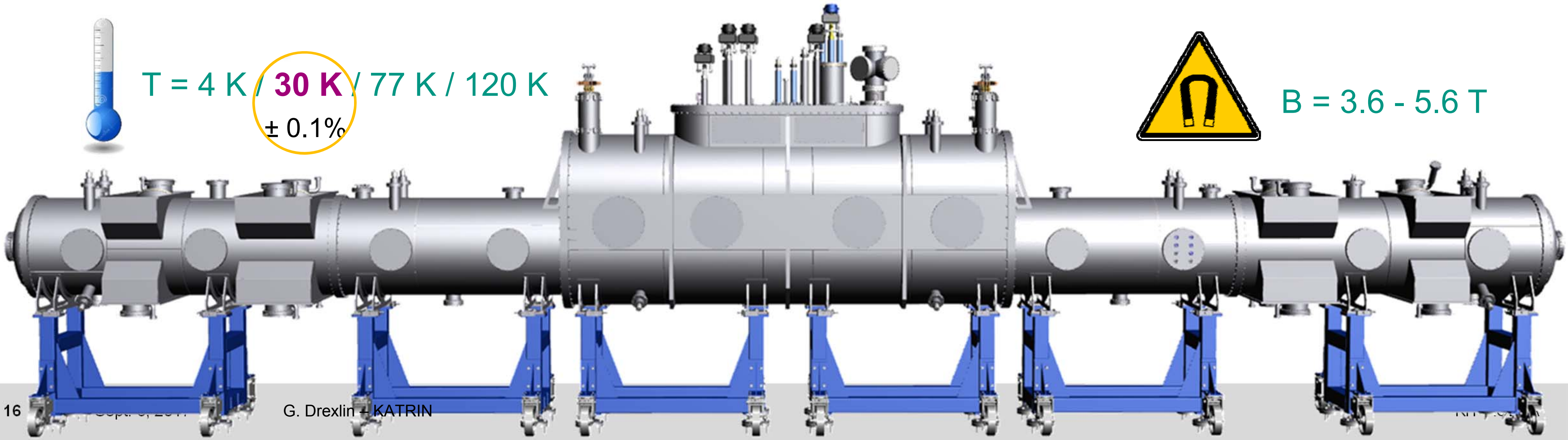


Windowless Gaseous Tritium Source cryostat

WGTS – source cryostat

Karlsruhe Institute of Technology

- **complex tritium source cryostat**:
  - 16 m length, 27 t total weight, ~ 40.000 pieces
  - 7 s.c. solenoids for adiabatic guiding of ß-decay electrons (3.6 – 5.6 T)
  - 7 cryogenic fluids for tritium operation (BT: 30-120K) & liquid He bath for magnets (4 K)
  - tritium beam tube @30K with stability and homogeneity of 0.1%
  - extensive instrumentations: >800 sensors (B, T, p, level, flow, …)



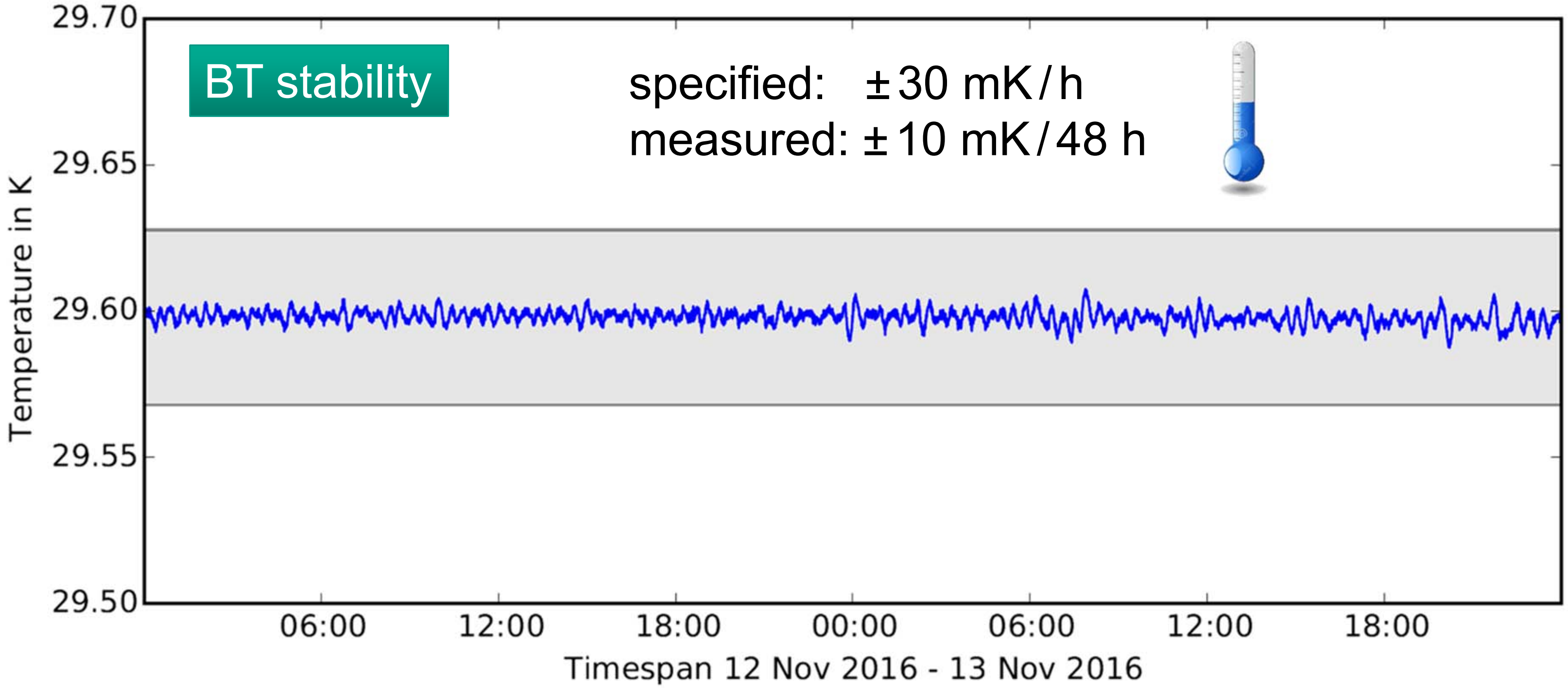
WGTS – commissioning of beam tube cooling system

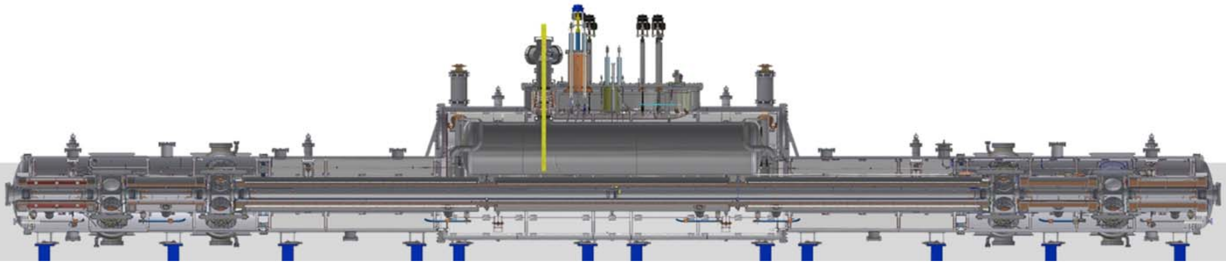
- **beam tube cooling system** exceeds specifications, excellent temperature stability ⇨ stable ρd

2-phase neon BT cooling system

beam tube

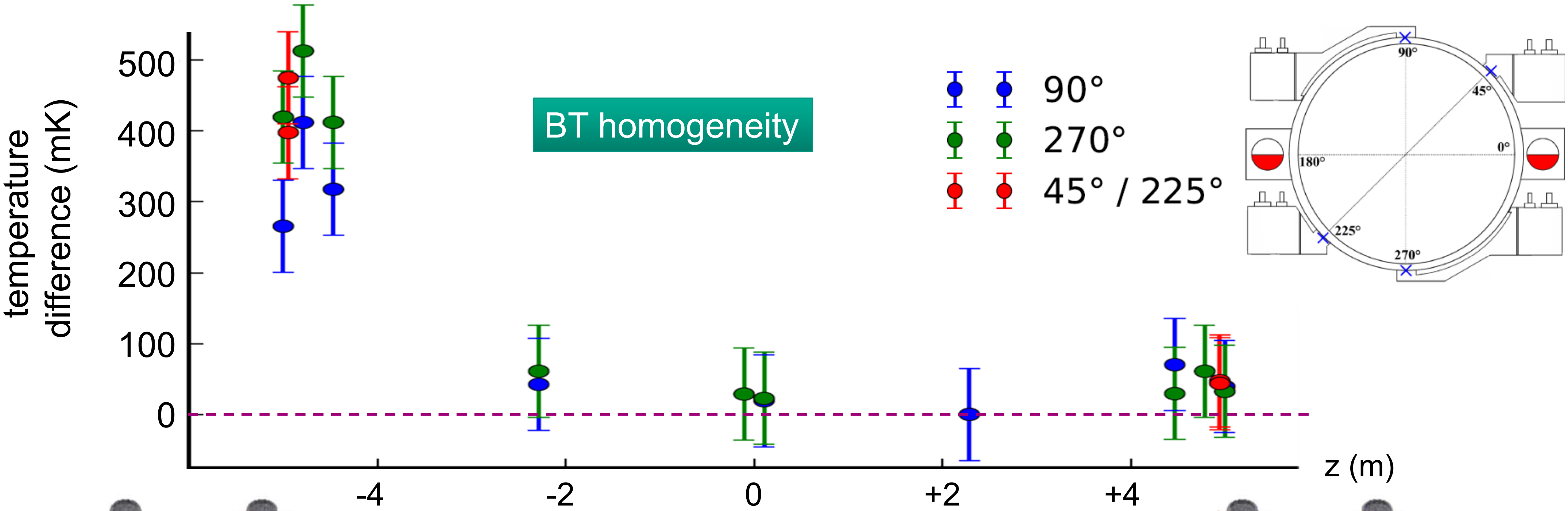
- long-term stable cryogenic operation
- thermosyphon principle

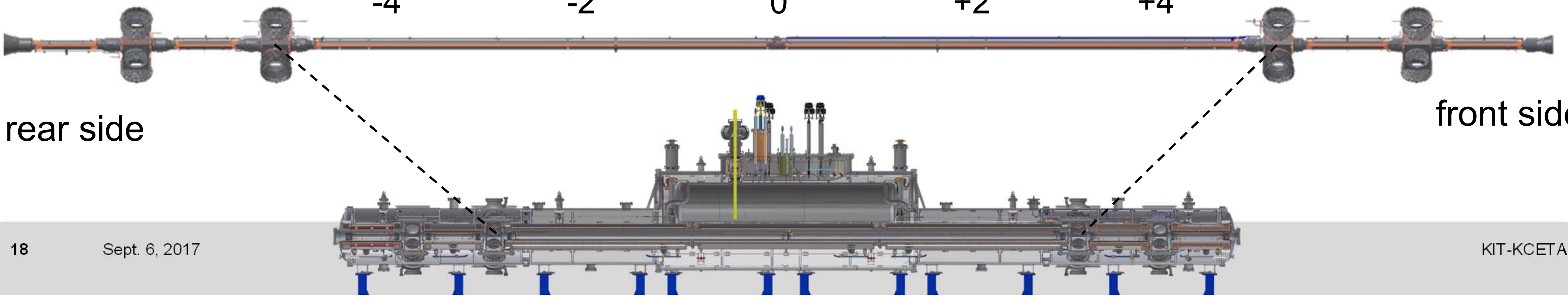




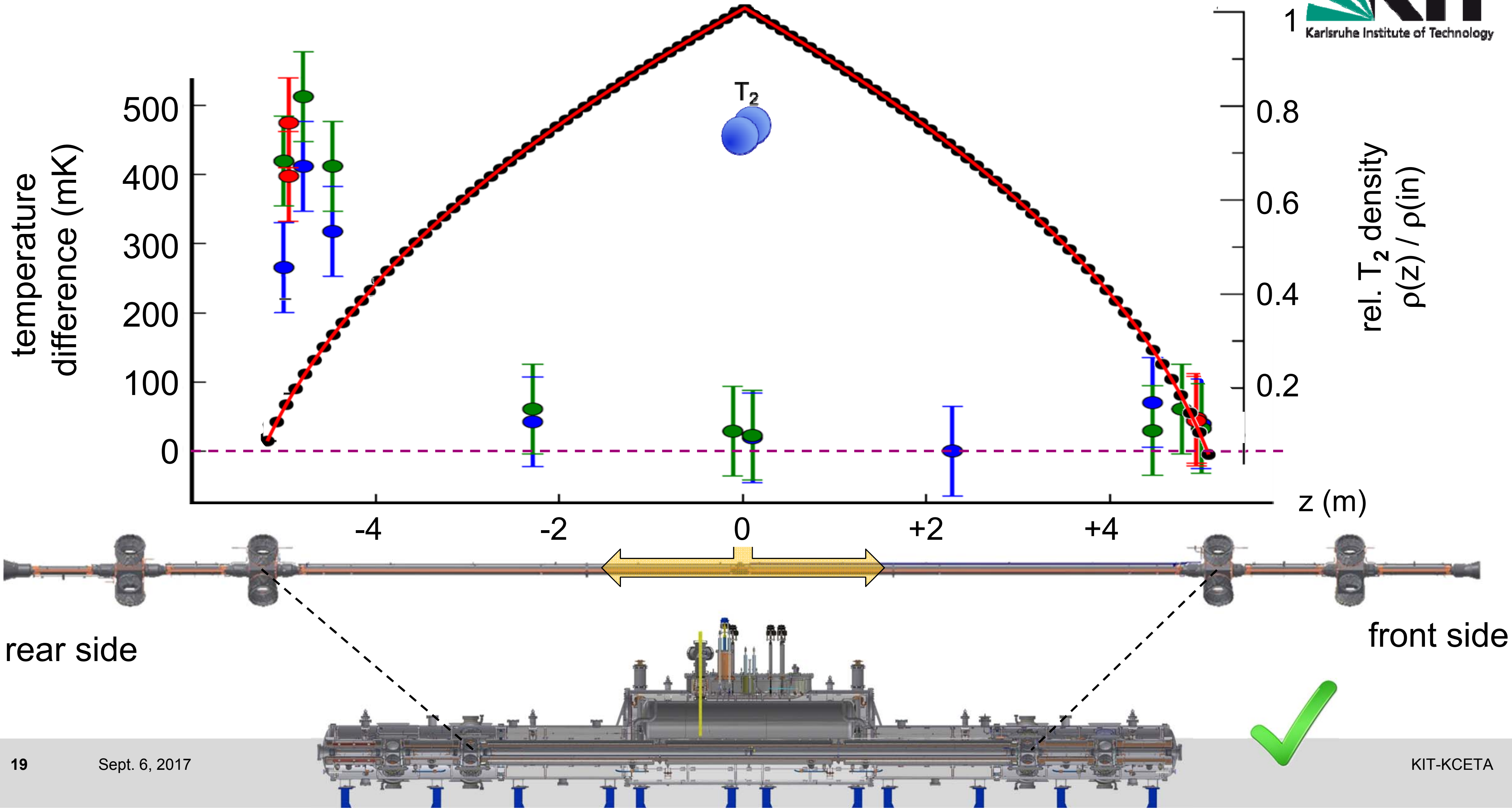
WGTS – commissioning of beam tube cooling system

Karlsruhe Institute of Technology

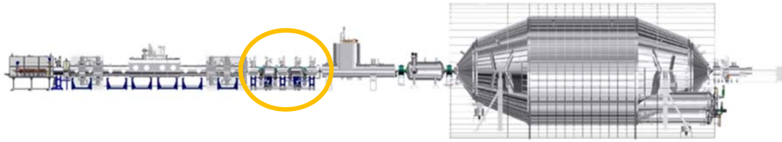




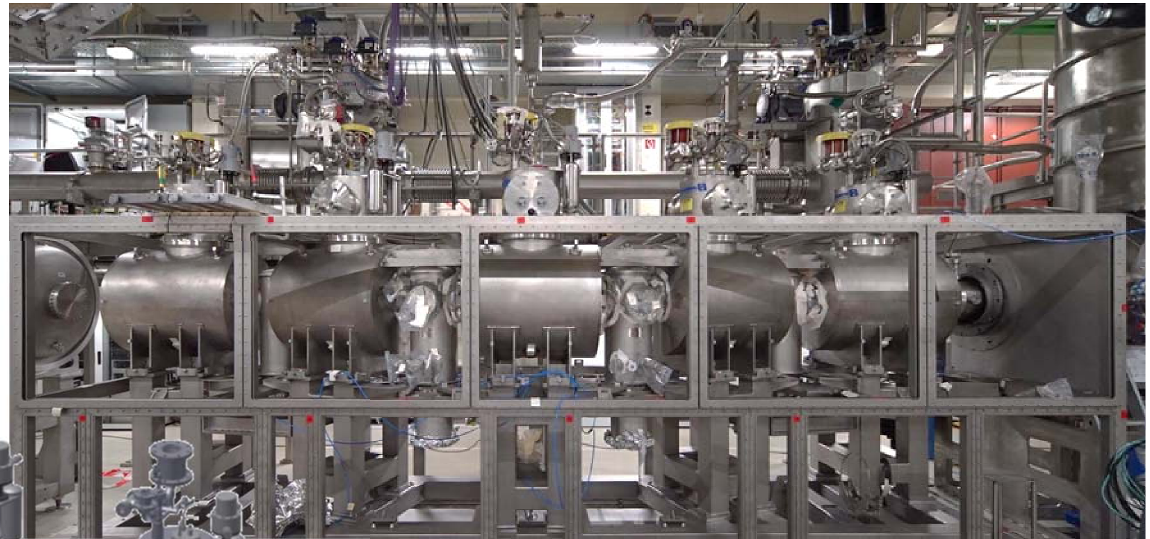
WGTS – commissioning of beam tube cooling system

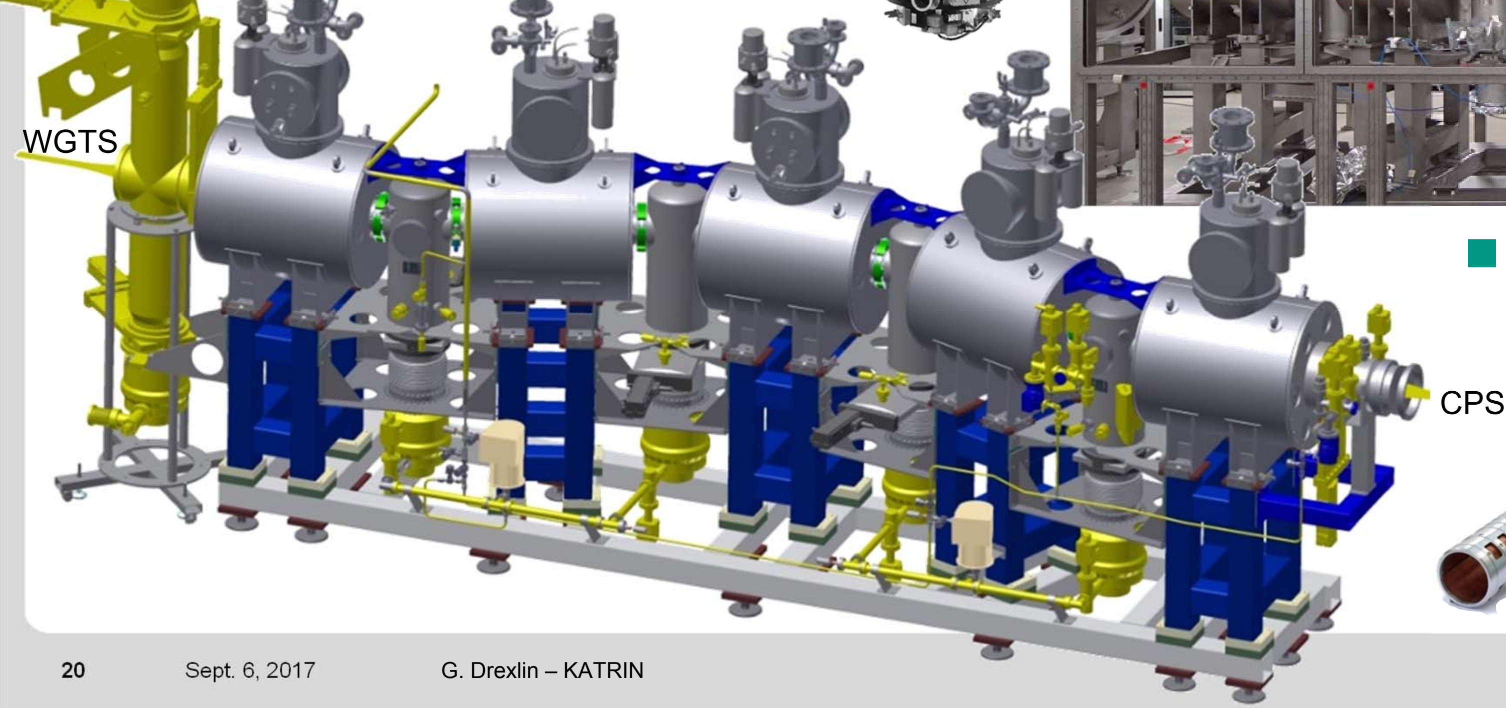


differential pumping - DPS

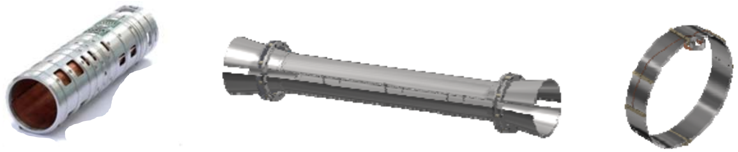


- **differential pumping section DPS2-F:**
  - serial pumping with TMPs → 10^5 reduction
  - ion elimination with E × B → 10^7 reduction

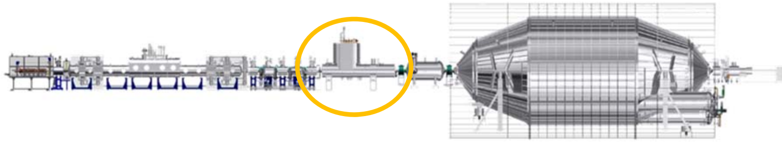




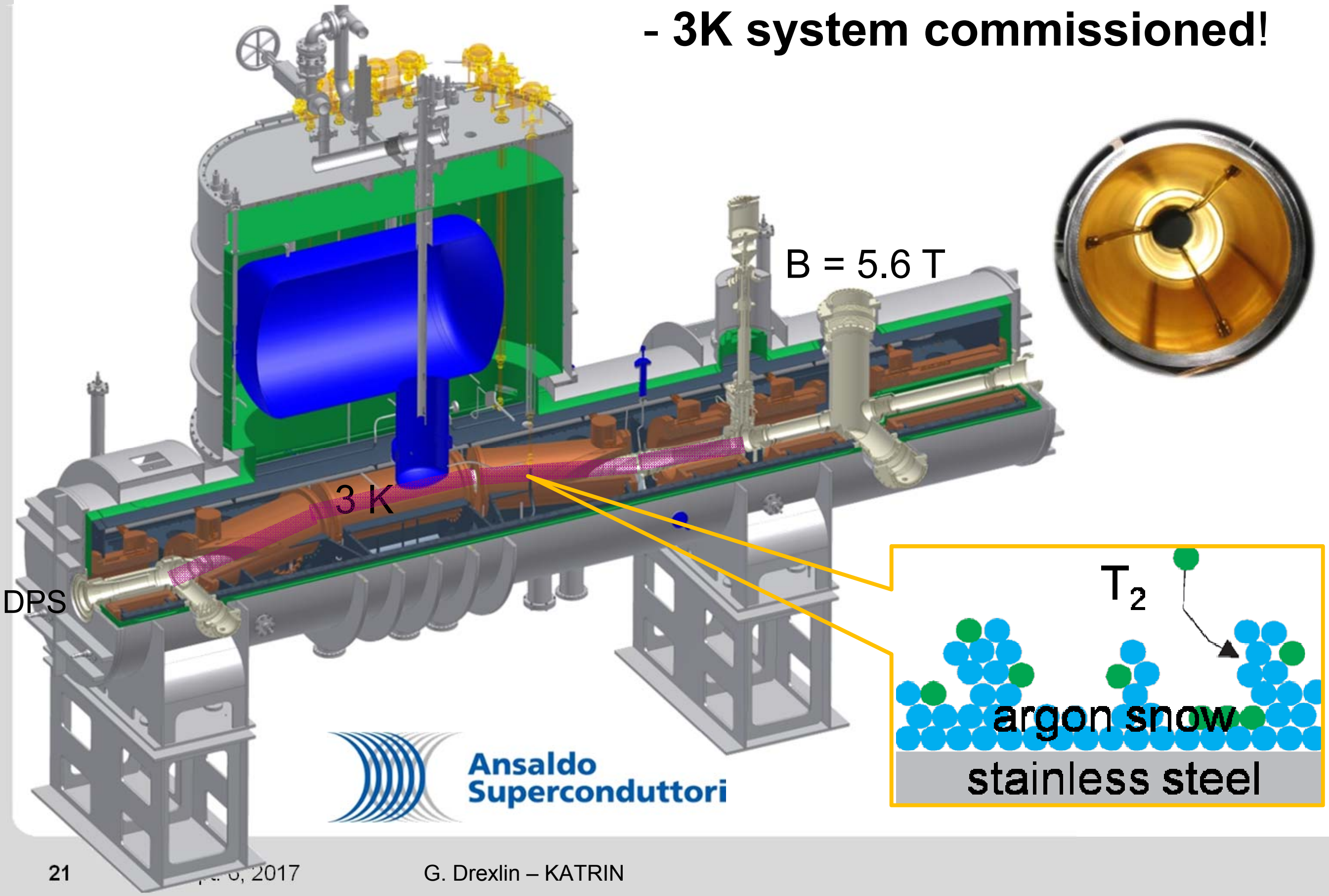
- **DPS instrumentation for ions:**
  - FT-ICR (ion diagnostics)
  - dipoles (ion elimination)
  - ring electrode (ion blocking)



cryogenic pumping - CPS



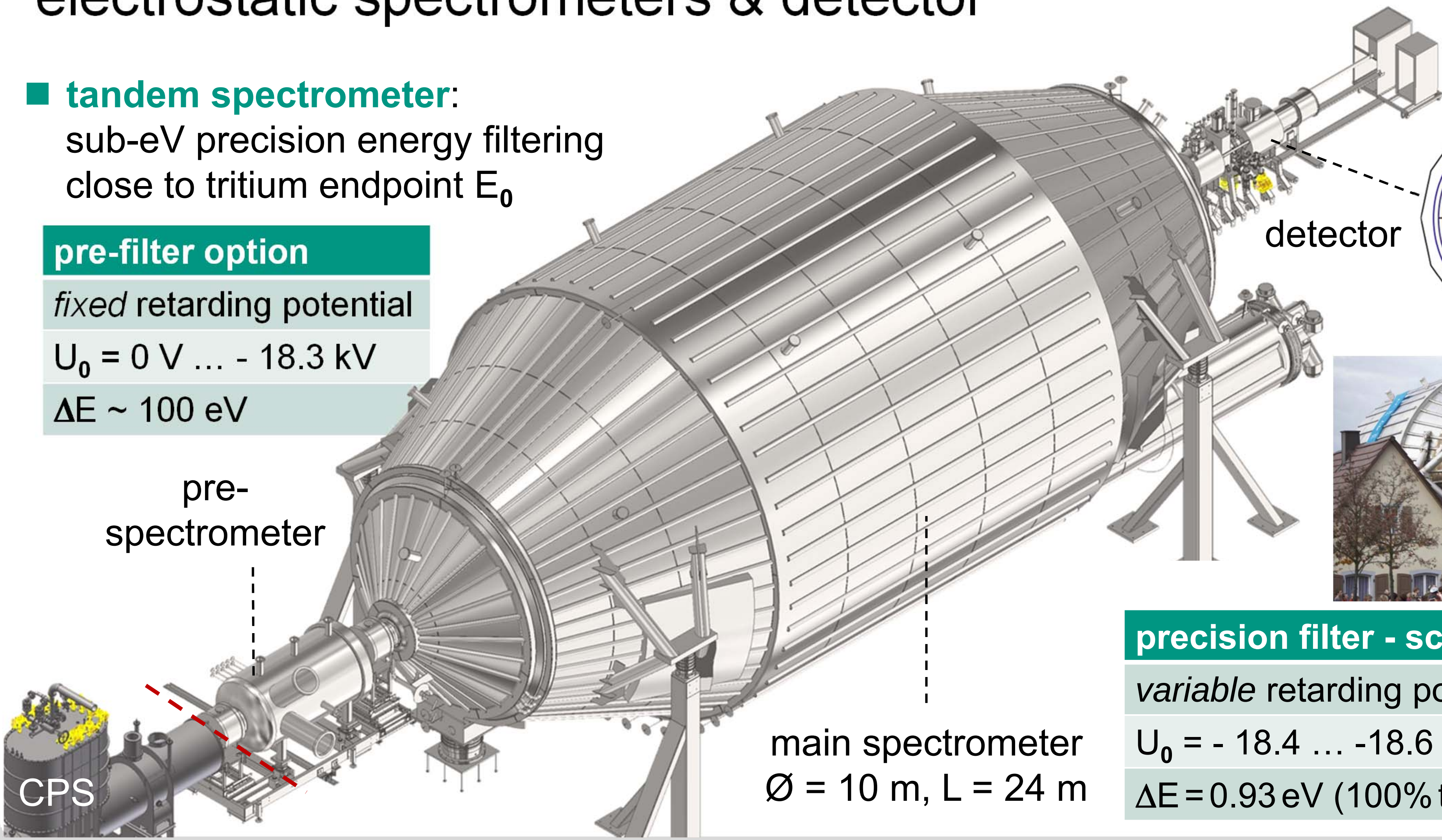
- **cryogenic pumping section CPS:**
  - 3K section with Ar-frost layer → $>10^7$ reduction of T_2
  - **3K system commissioned!**

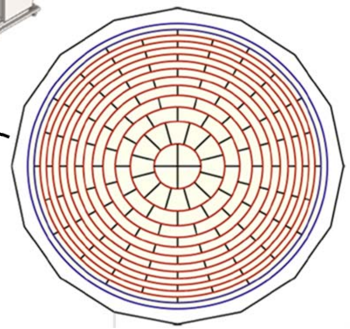


electrostatic spectrometers & detector

- **tandem spectrometer**:
  sub-eV precision energy filtering
  close to tritium endpoint E_0

pre-filter option
fixed retarding potential
U_0 = 0 V … - 18.3 kV
ΔE ~ 100 eV

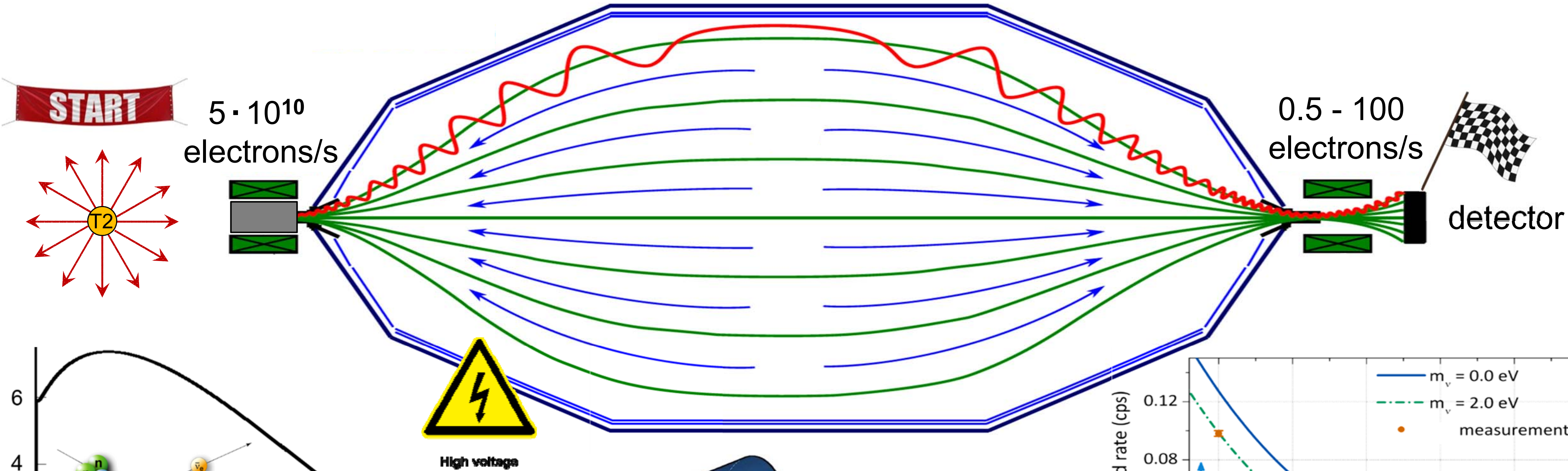


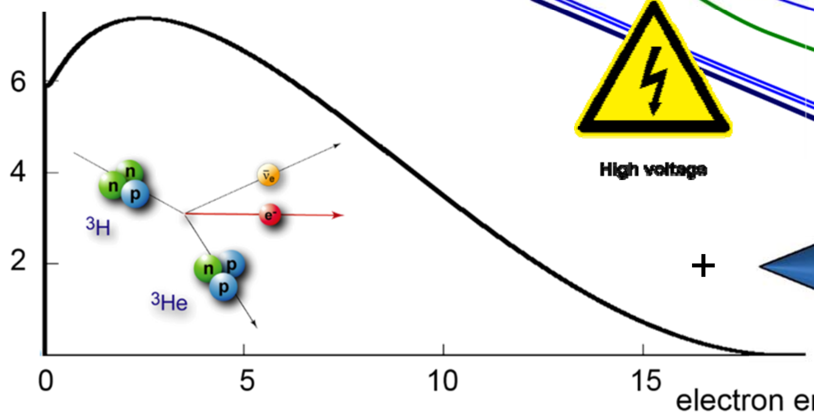


precision filter - scanning
variable retarding potential
U_0 = - 18.4 … -18.6 kV (ppm-scale)
ΔE = 0.93 eV (100% transmission)

MAC-E principle: high-intensity tritium ß-spectroscopy

- **Magnetic Adiabatic Collimation & Electrostatic Filter:** scan high-intensity T2 source





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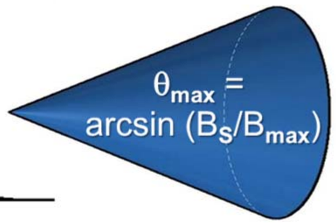
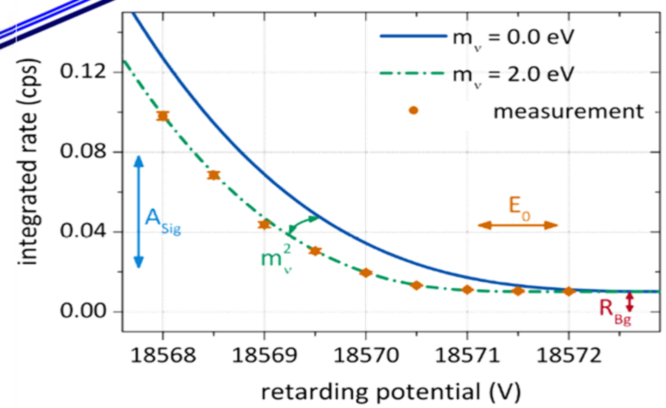


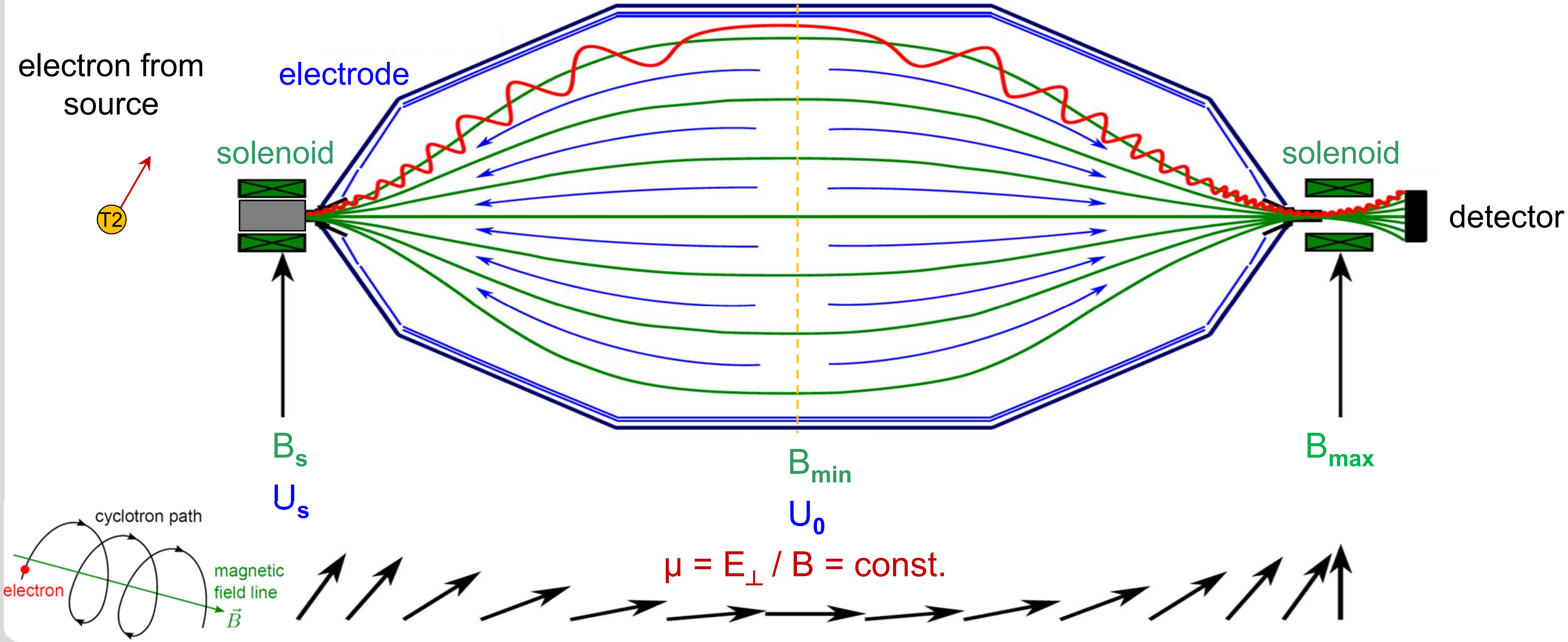
large acceptance angle ⇨

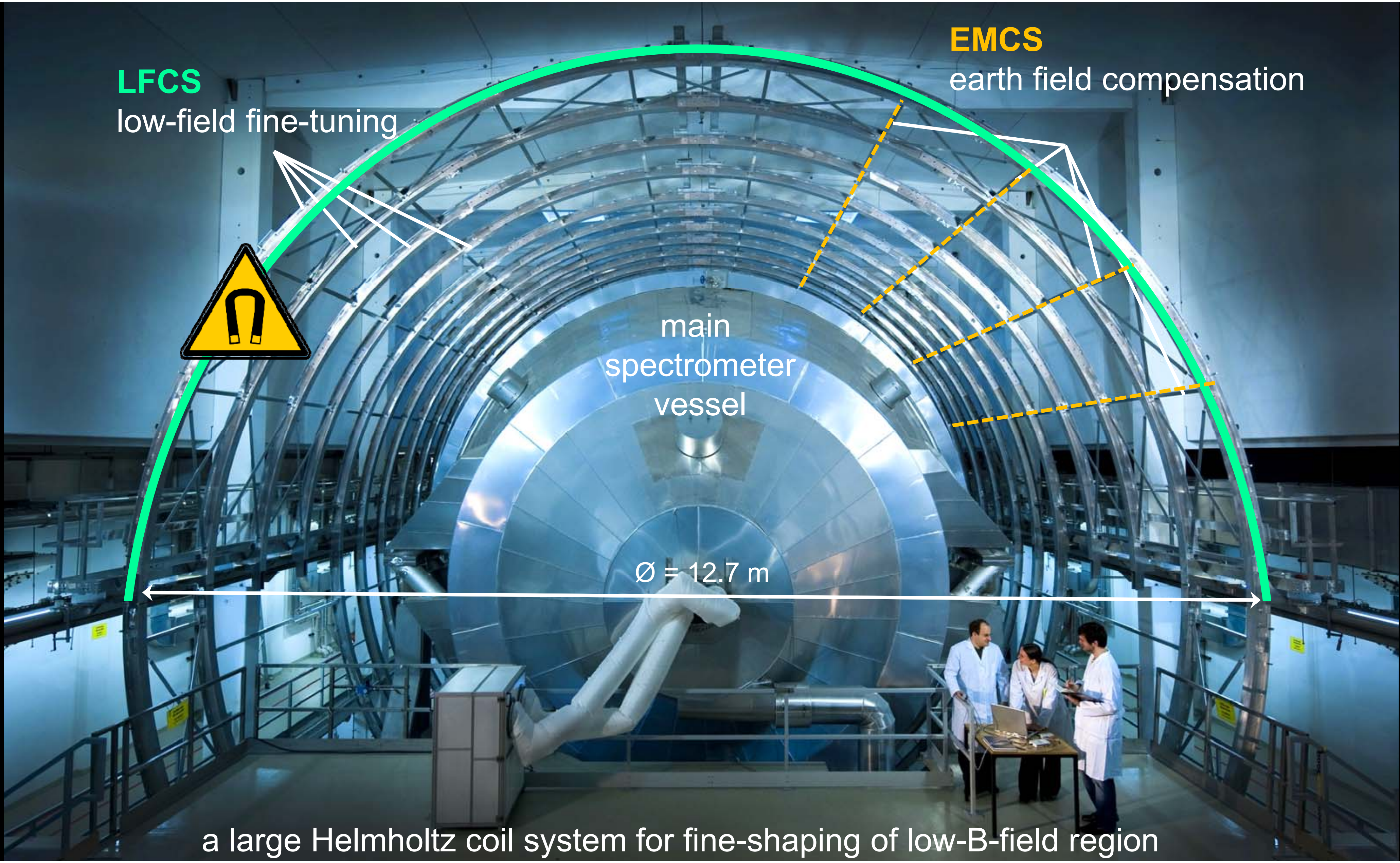


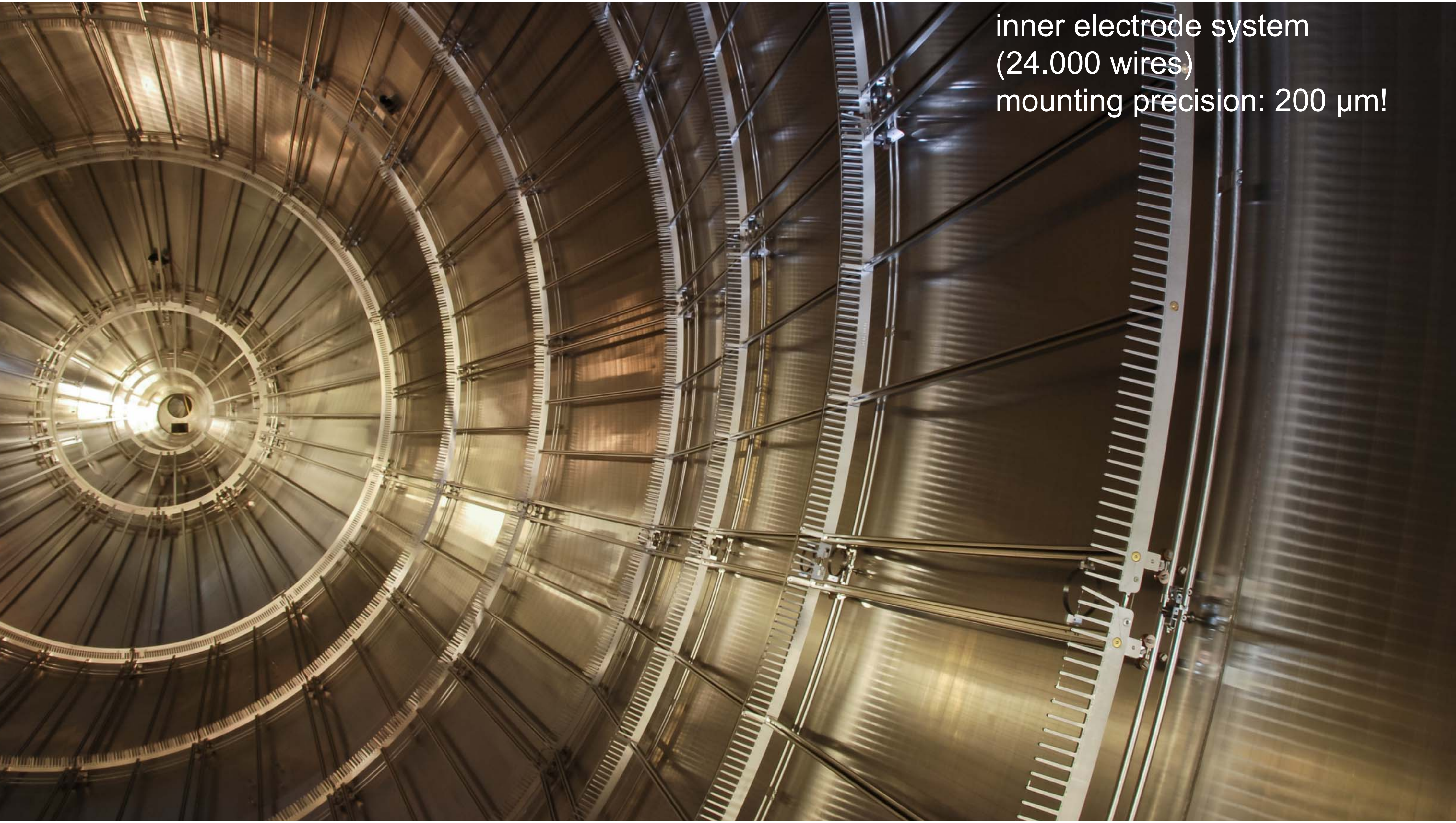
MAC-E principle: high-resolution tritium ß-spectroscopy

Karlsruhe Institute of Technology

- **M**agnetic **A**diabatic **C**ollimation **& E**lectrostatic **Filter:** adiabatic conversion $E_\perp \rightarrow E_\parallel$



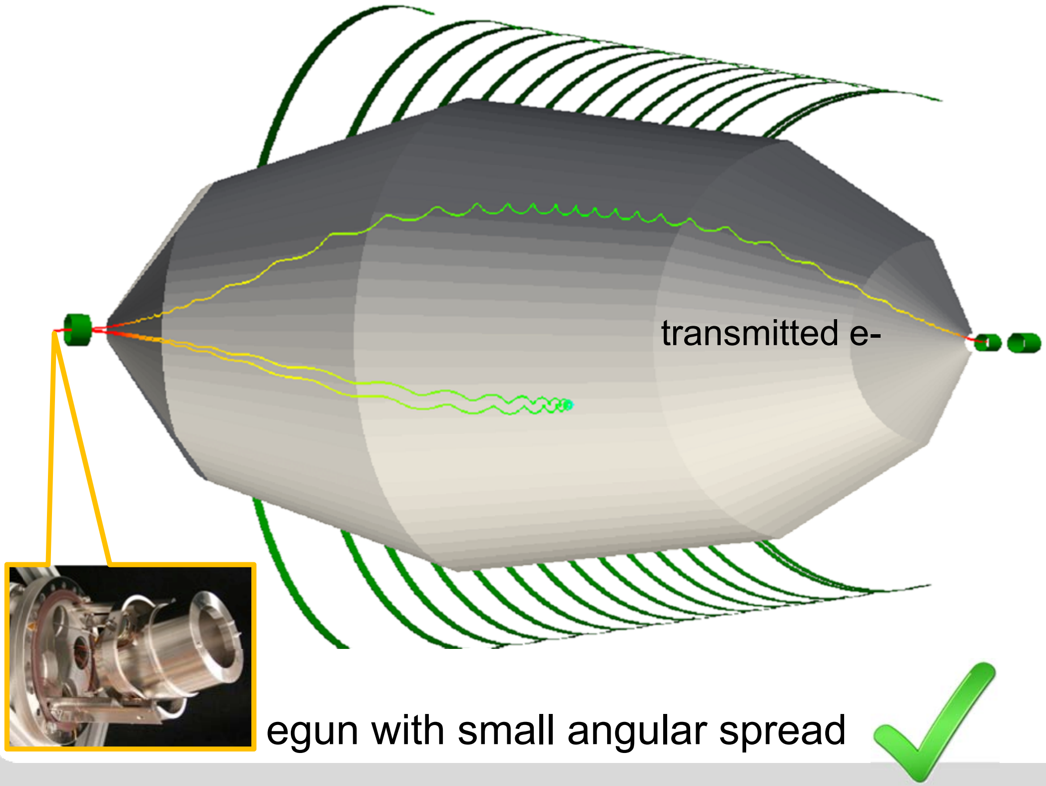

LFCS
low-field fine-tuning
EMCS
earth field compensation
main
spectrometer
vessel
Ø = 12.7 m
a large Helmholtz coil system for fine-shaping of low-B-field region

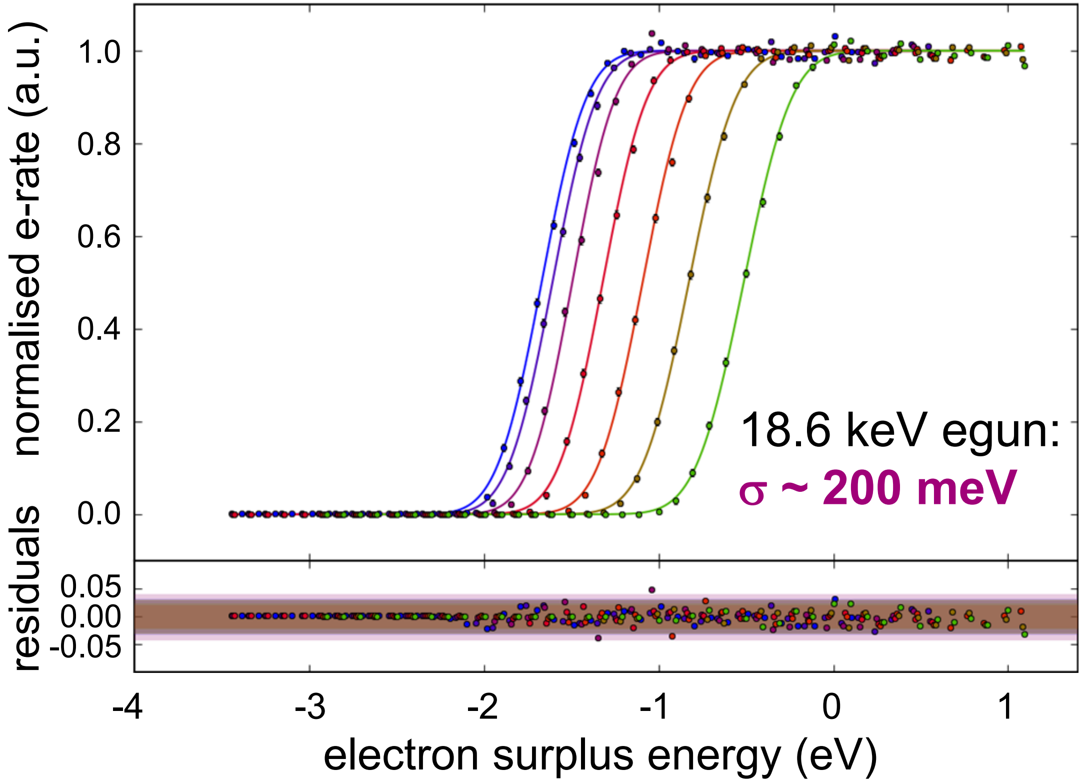

inner electrode system
(24.000 wires)
mounting precision: 200 µm!

KATRIN: selected results of commissioning

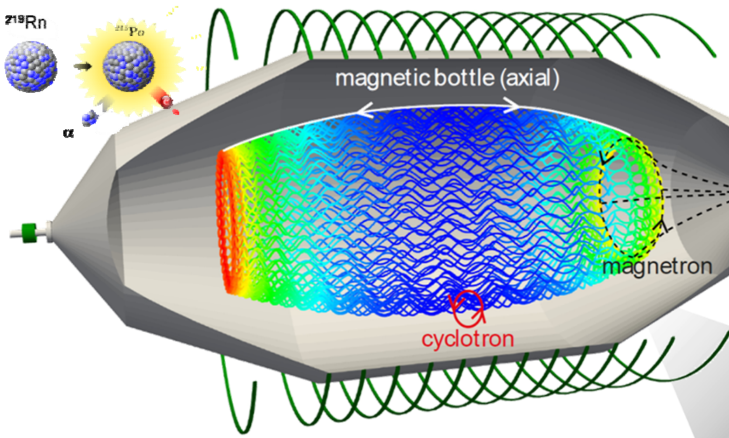
main spectrometer: MAC-E characteristics

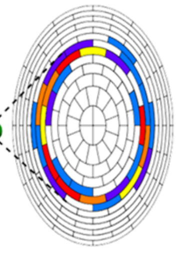
- **main spectrometer** works as high-resolution MAC-filter:
  - sharp transmission function for 18.6 keV e- from egun, width limited by egun emission spectrum
  - HV stability on ppm-scale via post-regulation, long-term sub-ppm monitoring via ^{83}Kr

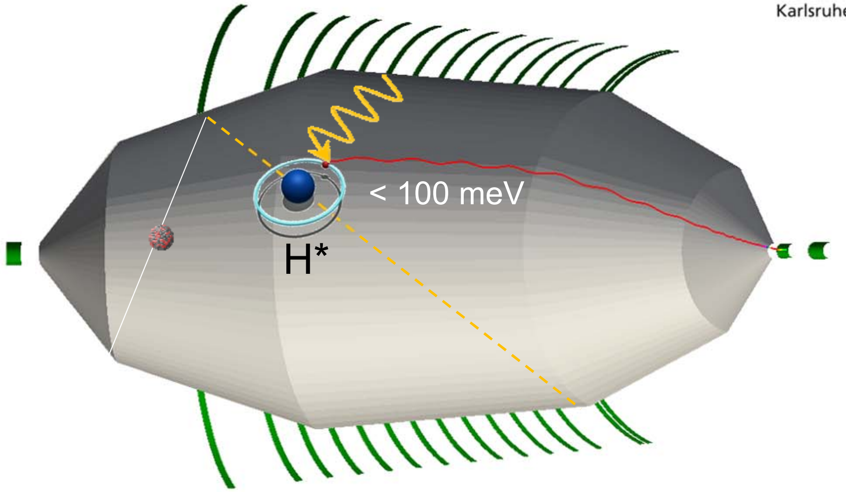


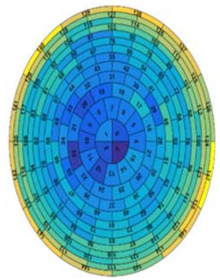


Background from decays of neutral unstable atoms

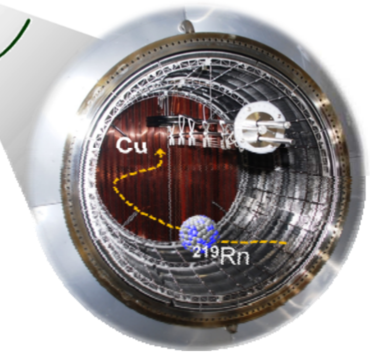






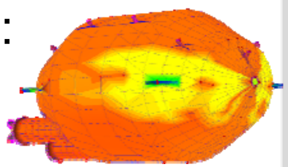


isotropic bg for
longer exposure



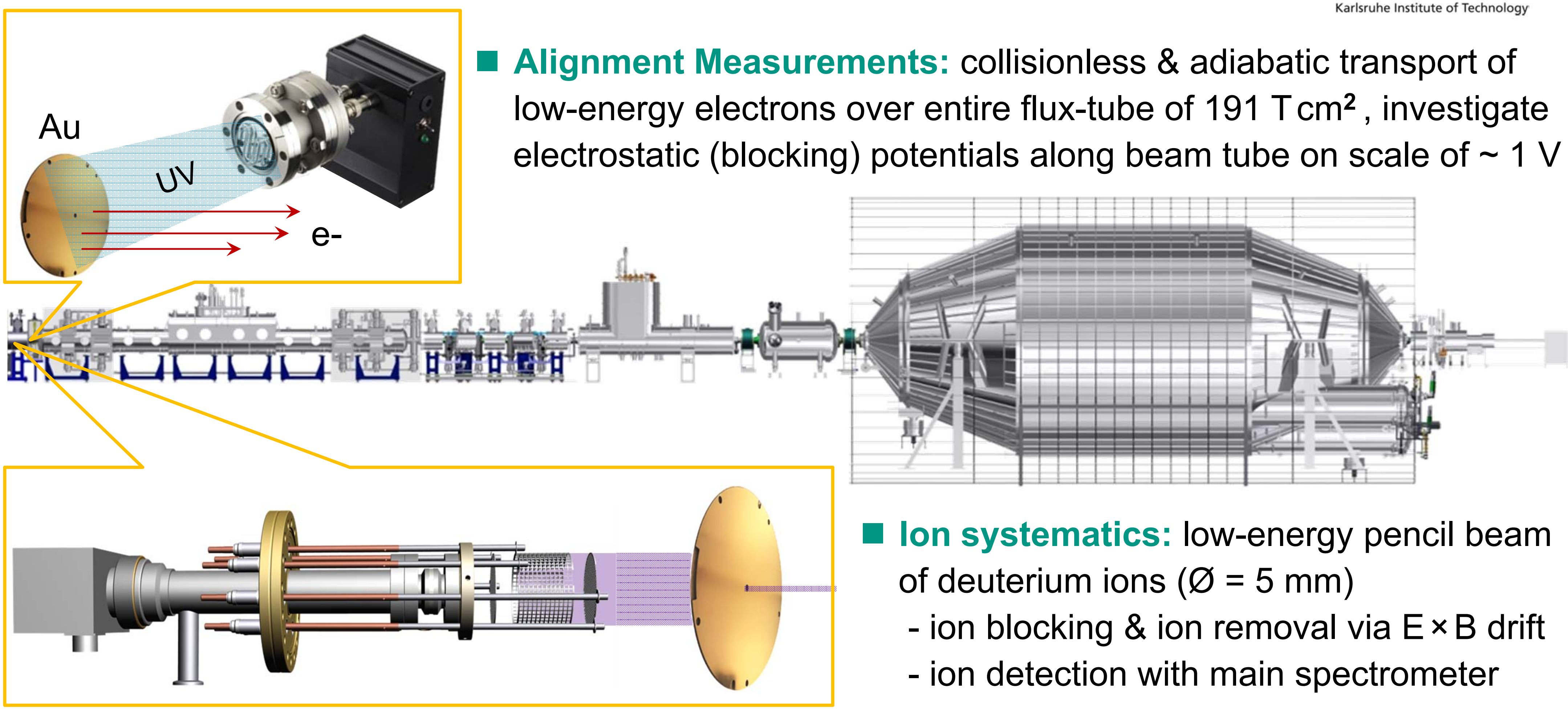
- **^{219}Rn atoms:**
  - ^{219}Rn emanates from NEG
  - stored electrons eV…keV
  - bg-rate: ~0.5 cps
  - **countermeasure (passive)**:
    - cryotraps in front of NEG
    - 3 LN2-cooled Cu-baffles eliminate ~97% of emanated ^{219}Rn atoms

- **H* Rydberg atoms:**
  - desorbed from walls due to ^{206}Pb recoil ions
  - non-trapped electrons on meV-scale
  - bg-rate: ~0.5 cps
  - **countermeasures**:
    reduce H-atom surface coverage:
    - extended bake-out phase
    - strong UV illumination source



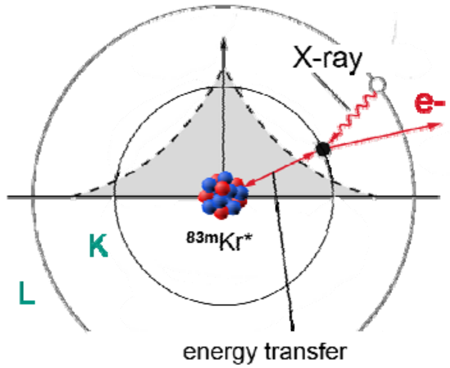
KATRIN First Light: Alignment & Ion Systematics

- **Alignment Measurements:** collisionless & adiabatic transport of low-energy electrons over entire flux-tube of 191 T cm², investigate electrostatic (blocking) potentials along beam tube on scale of ~ 1 V

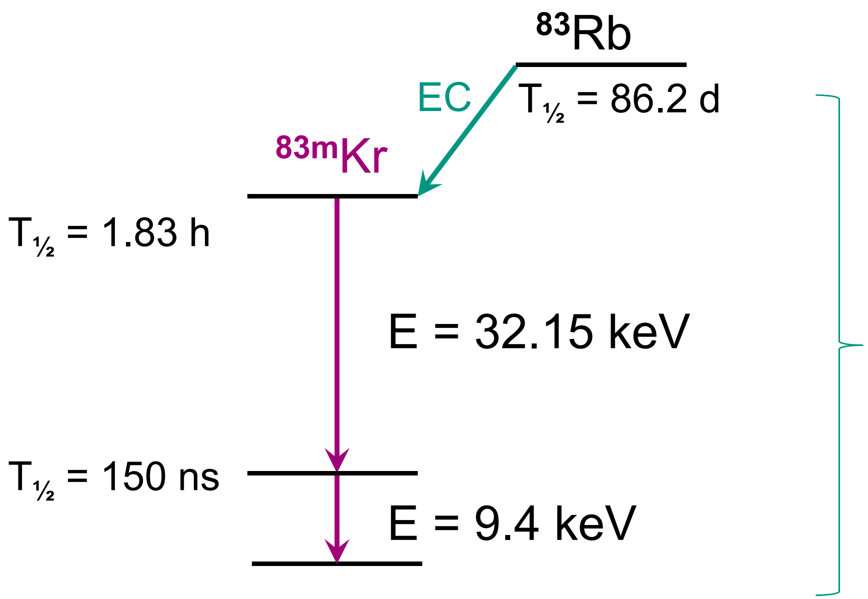


- **Ion systematics:** low-energy pencil beam of deuterium ions (Ø = 5 mm)
  - ion blocking & ion removal via E × B drift
  - ion detection with main spectrometer

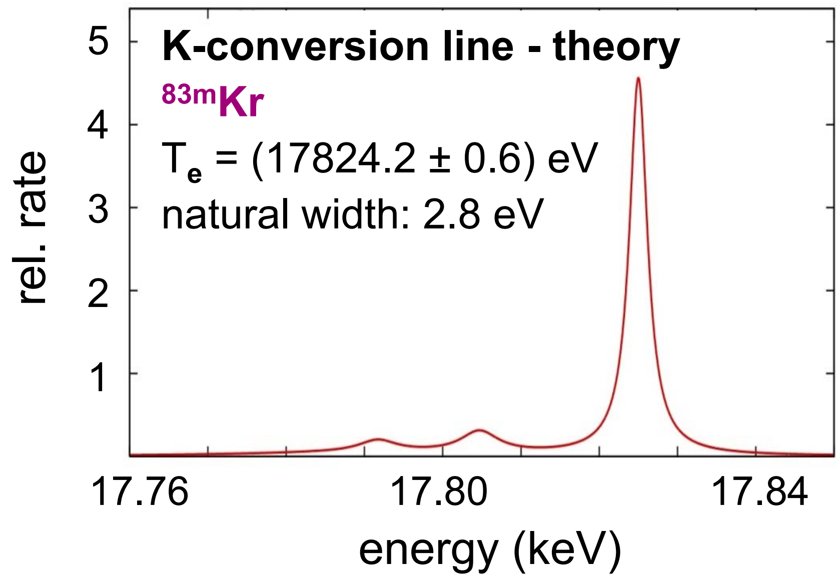
Krypton Commissioning measurements



- **mono-energetic conversion electrons** from Kr-83m:
  - series of sharp lines (1 K-line, 3 L-lines, 5 M-lines) & satellites
  - ^{83m}Kr now also in use in DM-searches

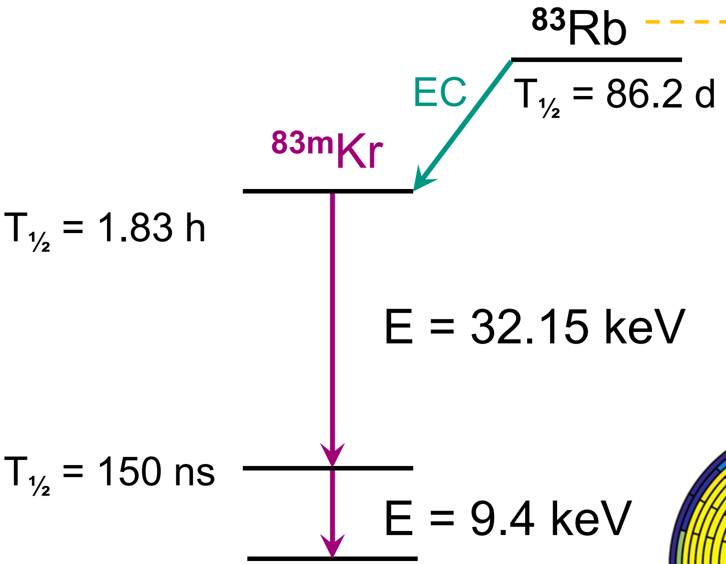


- Rb-mother: long-lived, high ^{83m}Kr activity
- K-32 line is close to ß-endpoint of T2

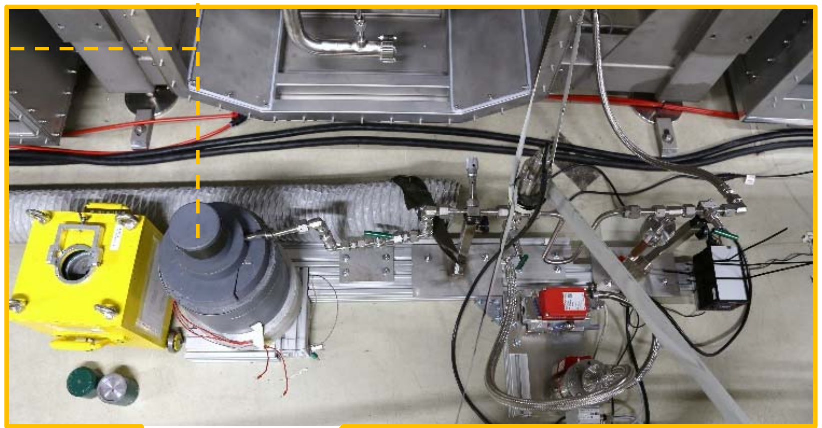


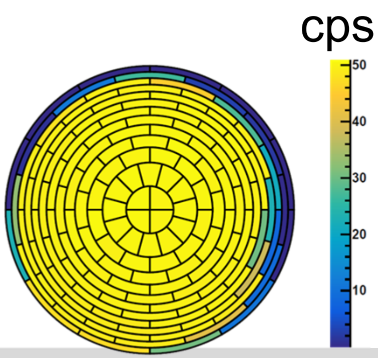
Krypton Commissioning measurements

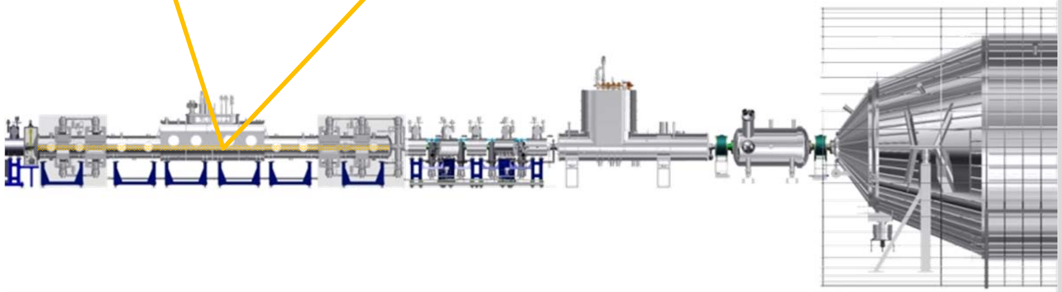
- **Gaseous Krypton Source (GKrS)**
  - Rb-generator (~ 1 GBq) releases ^{83m}Kr atoms into WGTS beam tube (T ~ 100 K): extended source, broad beam covering entire flux tube



Rb-generator in shielding

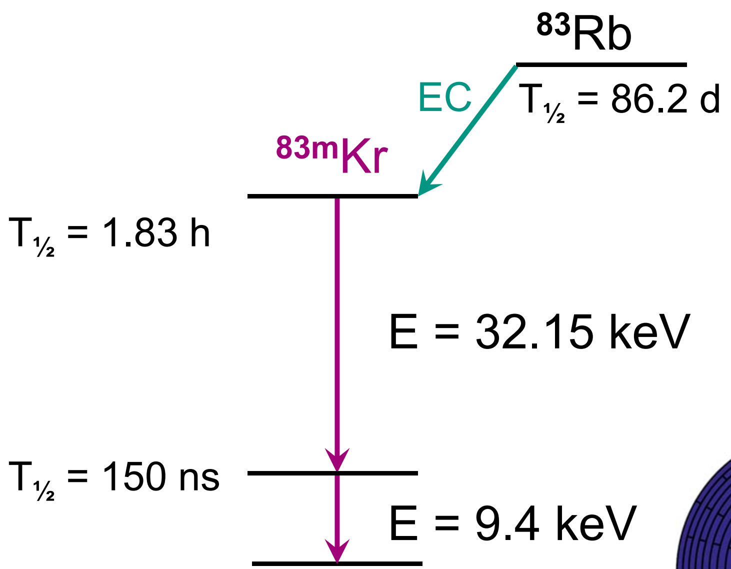


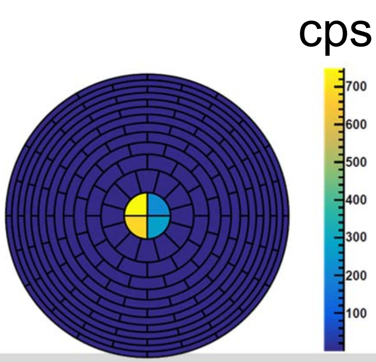


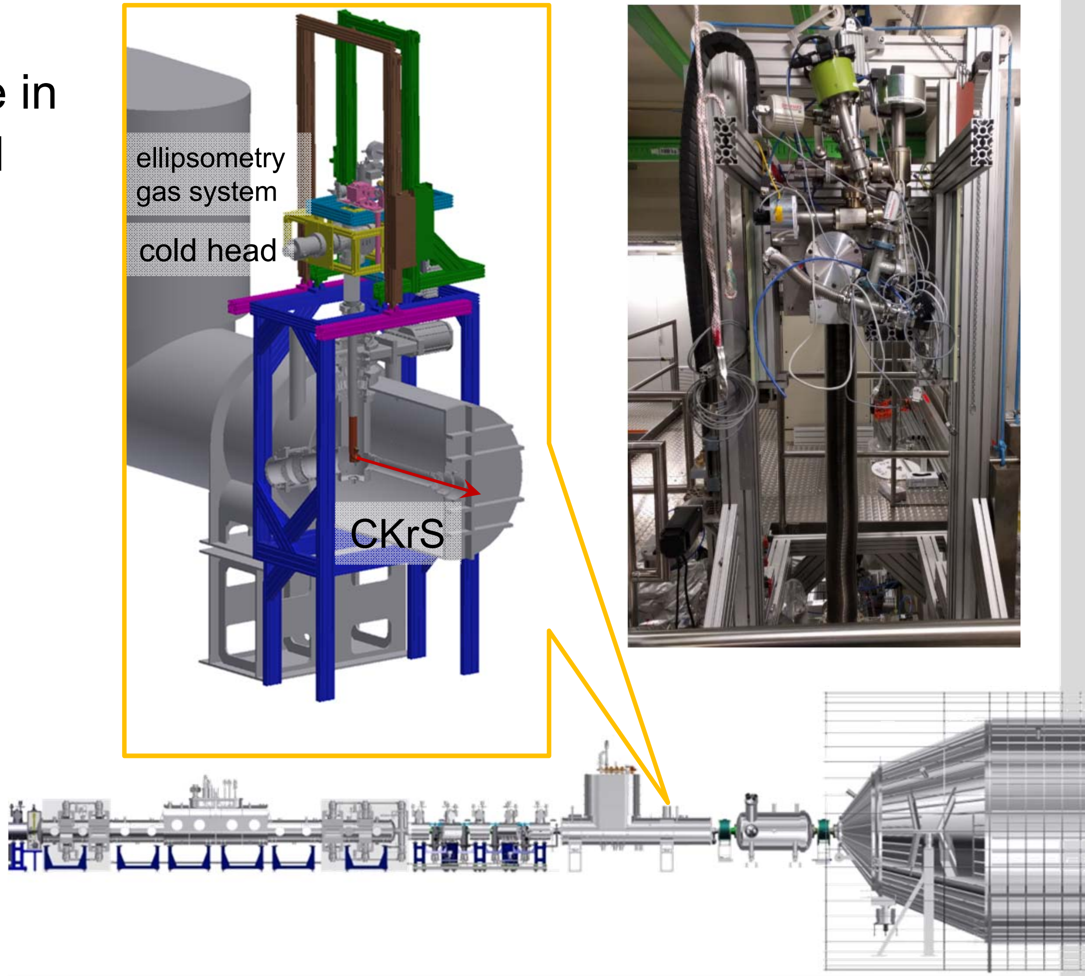


Krypton Commissioning measurements - CKrS

- **Condensed Krypton Source (CKrS)**
  - thin ^{83m}Kr film condensed onto HOPG substrate in CPS beam tube: narrow beam, can be scanned across flux tube



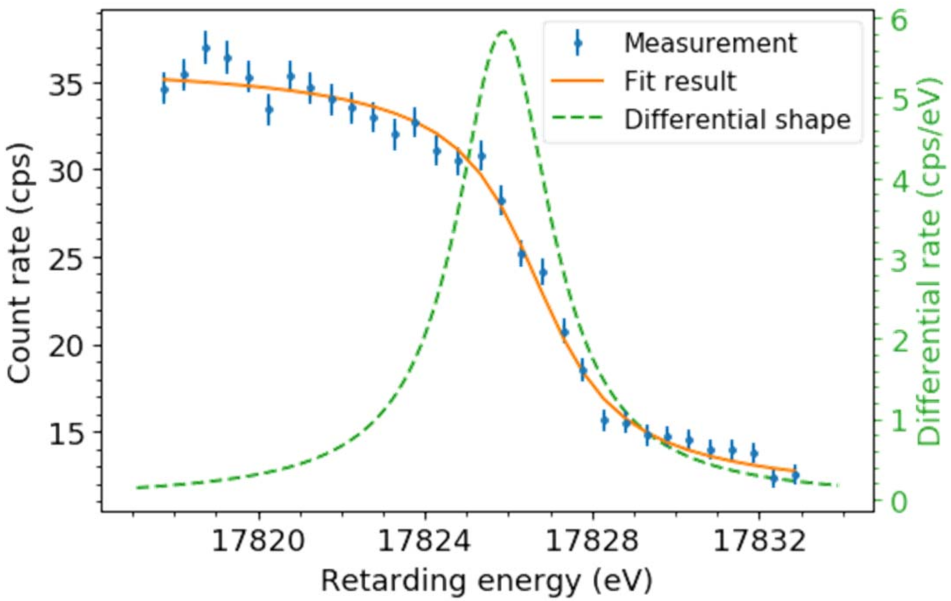




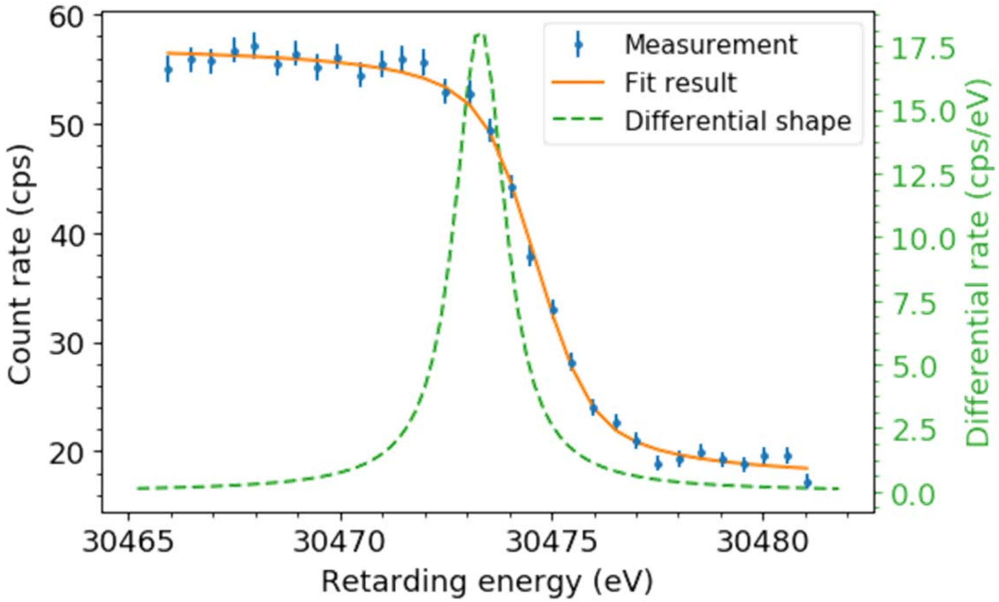
Krypton Commissioning measurements – July 2017

- **mono-energetic conversion electrons** from Kr-83m:
  - lines shapes for inner flux tube part of GKrS
  - excellent filter characteristics of main spectrometer

K-32 line: 17.82 keV

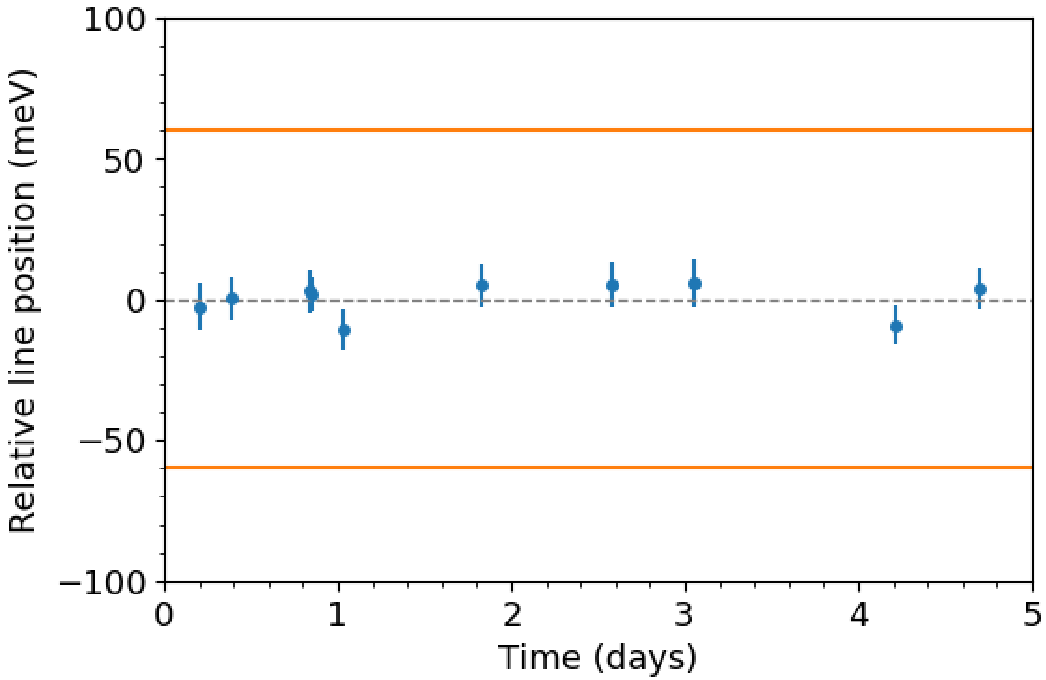


L3-32 line: 30.47 keV



Krypton Commissioning measurements – July 2017

- **mono-energetic conversion electrons** from Kr-83m:
  - repeated scans of L3-32 line over one week
  - excellent stability of KATRIN energy scale, need to demonstrate over 8 weeks

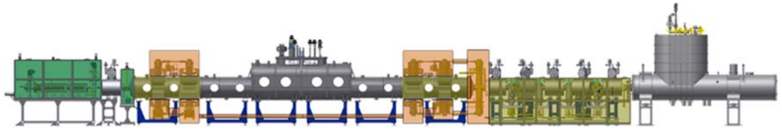


stability goal: ± 60 mV

GKrS, preliminary

the KATRIN road to „First Tritium“

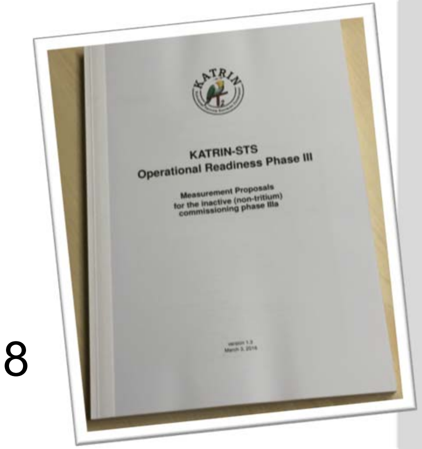
Karlsruhe Institute of Technology



❶ **connect KATRIN beam line to TLK infrastructure**:
- final installation of loop piping 1-9/2017
- commissioning of loop system 8-11/2017

❷ **measurements with inactive gas species - STSIIIa**
- deuterium: gas dynamics, ^{83m}Kr runs, retention systems
- electrons: energy losses in source, transmission function, HV

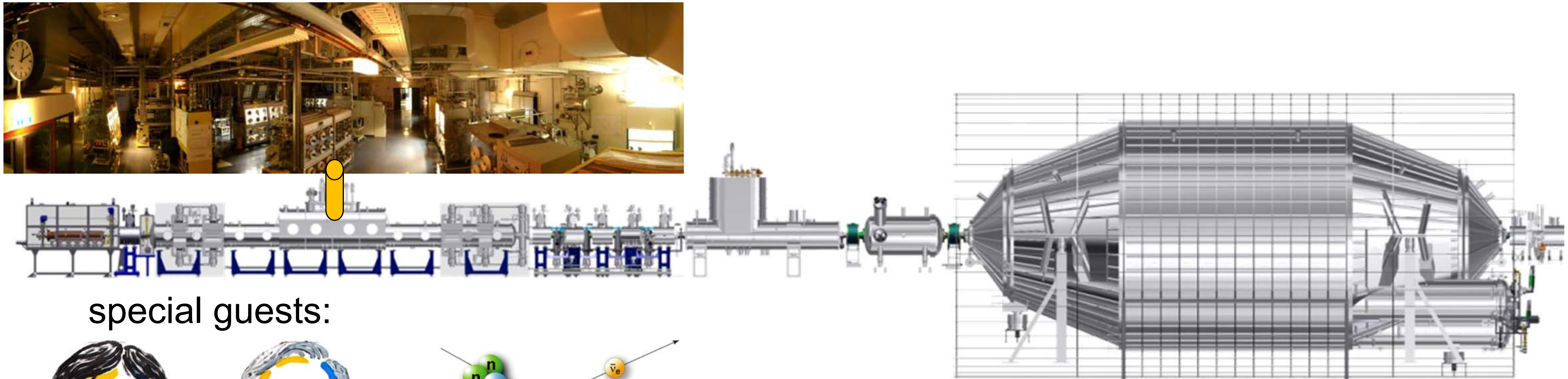
} 1-3/2018



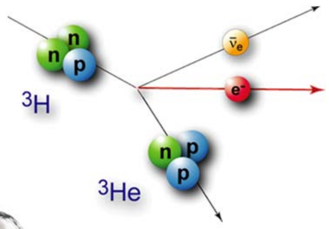
❸ **measurements with ß-active tritium**
- tritium-I: commissioning with T2 traces & safety checks 5-6/2018
- tritium-II: low ß-activity runs for keV-mass sterile ν-search 7-12/2018

Official KATRIN inauguration: June 11, 2018

- **First Tritium run & official KATRIN inauguration** : June 11, 2018



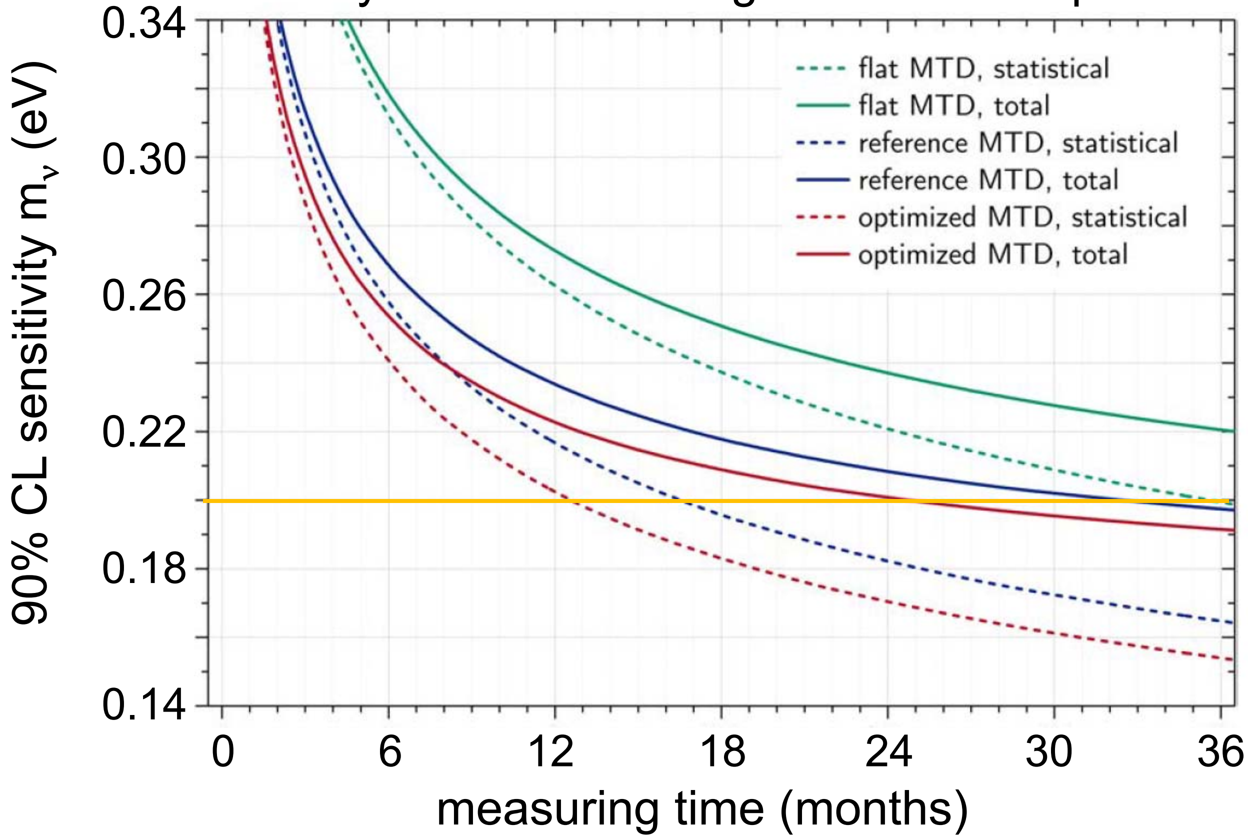
special guests:



KATRIN - reference neutrino mass sensitivity

- **KATRIN reference ν-mass sensitivity** for 3 ´full beam´ (5 calendar) years:

analysis for nominal bg-level of 10 mcps



sensitivity $m(\nu_e)$ = 0.2 eV (90% CL)

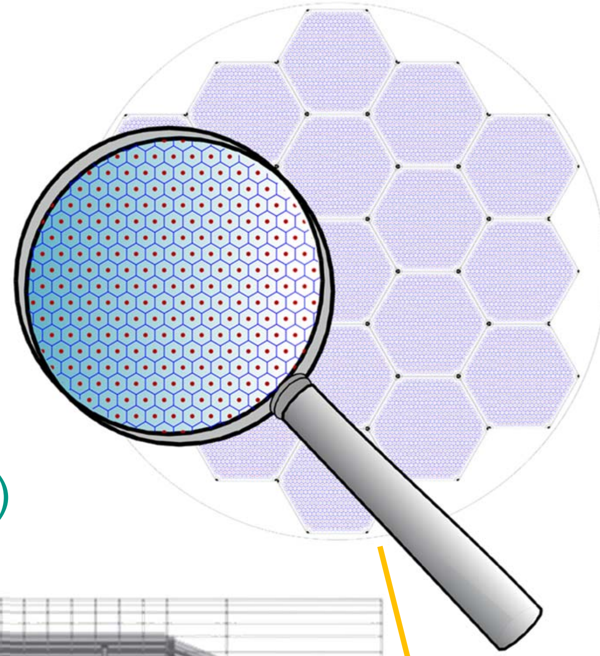
0.35 eV (5σ)

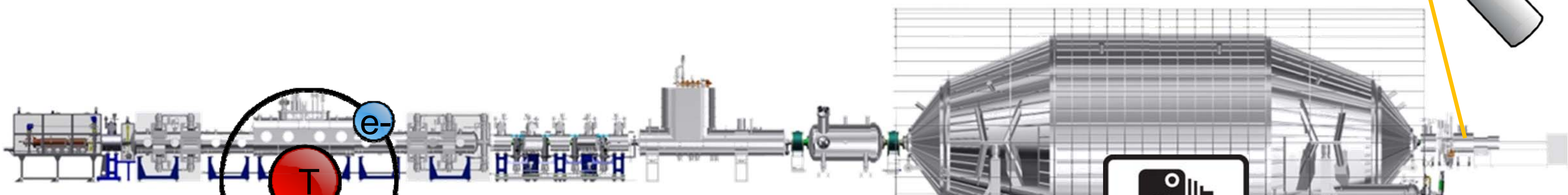
- very moderate impact of enhanced background level due to shape analysis & specific coutermeasures:
  - optimized scanning strategy
  - range of spectral analysis
  - reduced flux tube volume

  for bg-level of 2015 with 0.5 cps:
  $m(\nu_e)$ = 0.24 eV (90%) CL
  expect further bg-reduction!

KATRIN: Upgrade plans

- **goal-I**: improve sensitivity to push for $m(\nu_e)$ ~ 100 meV (and below?),
  on-going R&D works for:
  - differential read-out: ToF-technique & others
    aim: bg-free measurements
  - novel source concepts: atomic tritium source, …
- **goal-II**: explore entire T2 ß-decay phase space
  on-going R&D: high-resolution Si-pixel arrays (TRISTAN) for
  - search for keV-mass scale sterile neutrinos (non-SM-particles) or exotic CCs in ß-decay





Conclusions

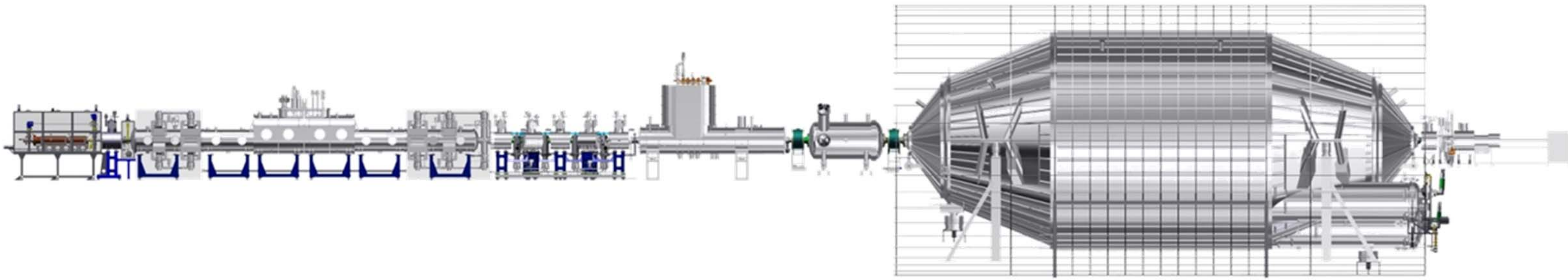
- highly dynamic & successful phase of commissioning of main components
  - excellent performance of all major components (WGTS temperature stability,…)
  - major goal in 2018: „first tritium“ with focus on keV-scale sterile ν´s, 2019ff: regular data taking

D2 | integral scan of endpoint m(ν) = 0.2 eV | differential read-out, entire phase space

2017	2018	2019	2020	2021	2022	2023	2024	2025	2026

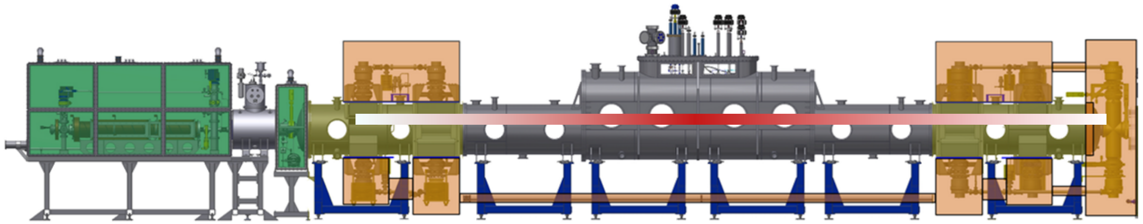
BMBF Verbund ….

PoF-3 PoF-4 ….

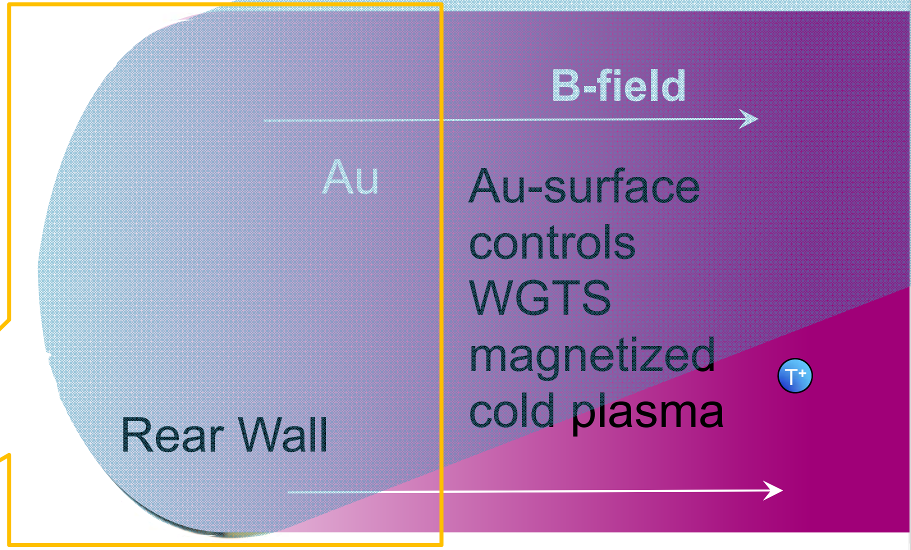


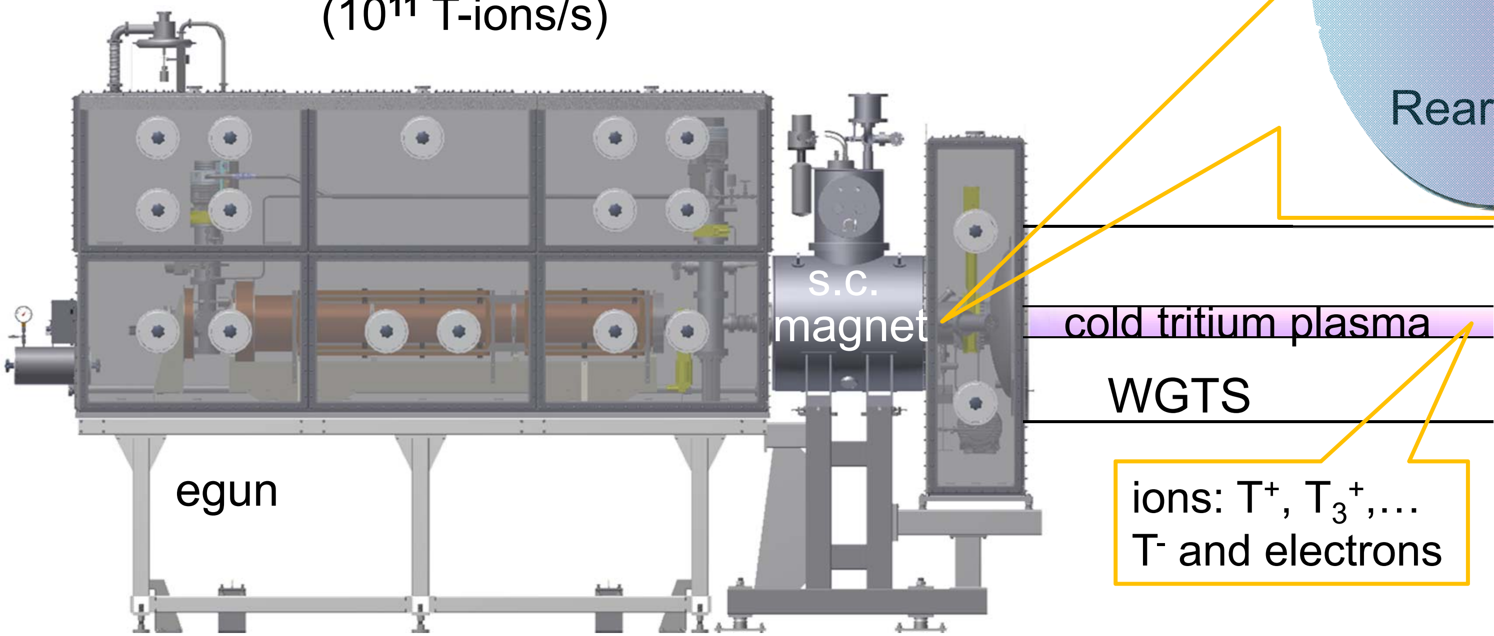
additional transparencies

source challenges: plasma controlled by Rear Wall



⑤ plasma properties: $T_2 \rightarrow (T\,^3He)^+ + e^- + \bar{\nu}_e$
(10^{11} T-ions/s)

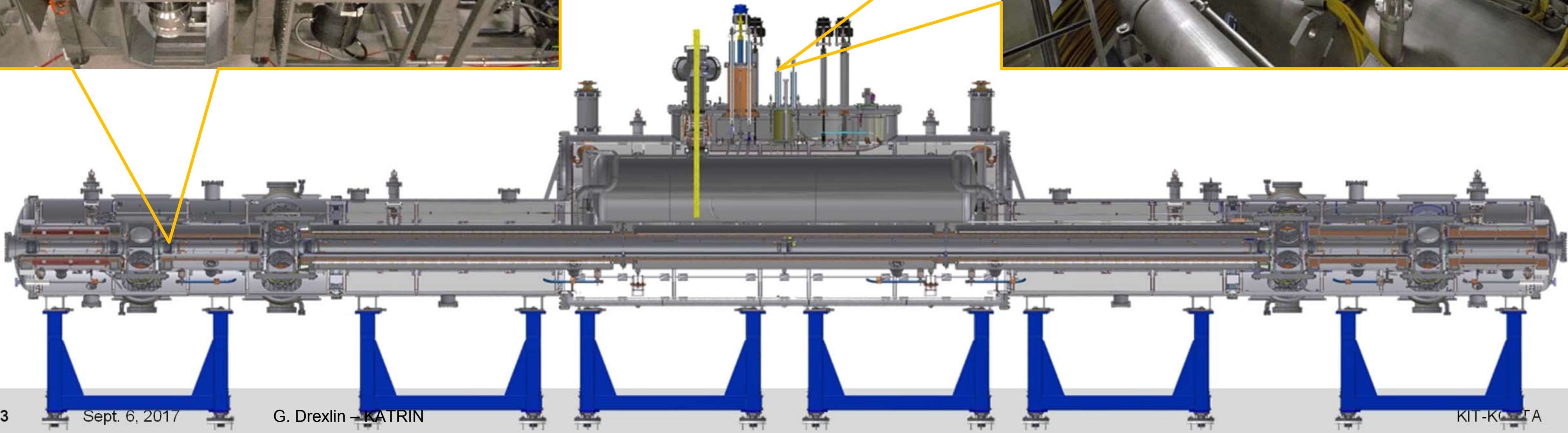




plasma parameters:
$n_e = 10^5 \ldots 10^6\ cm^{-3}$
E_e = 2 meV (T = 30 K)
λ_{Debye} = 0.2 … 3 mm
f_{Debye} ~ 10 MHz
B = 3.6 T (axial direction)
neutral T_2 gas: p = $10^{-3} \ldots 10^{-5}$ mbar
boundary conditions by walls

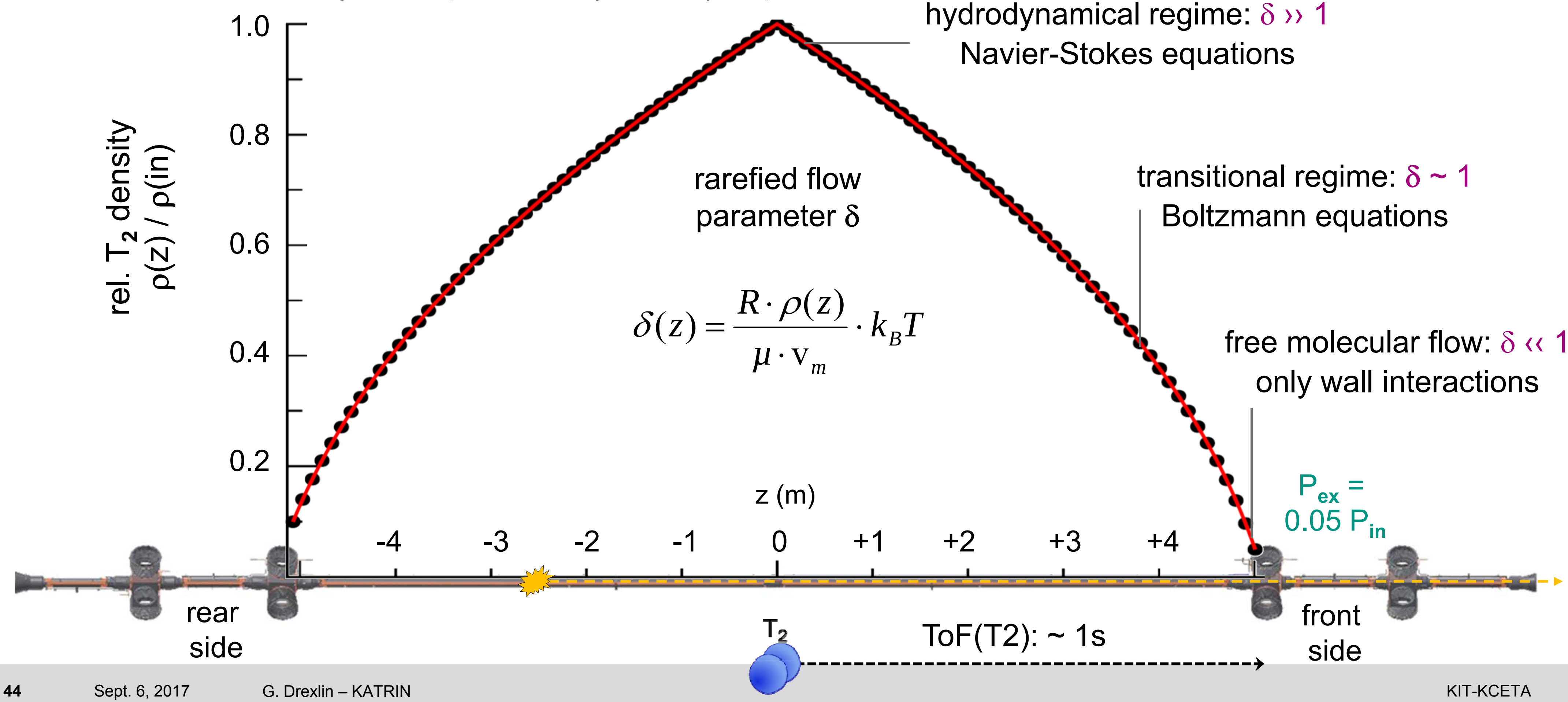
WGTS – source cryostat

- **commissioning**:
  - cryogenics
  - s.c. magnets
  - vacuum system
  - instrumentation
  - PCS7 control



source challenges: injection & gas flow calculation

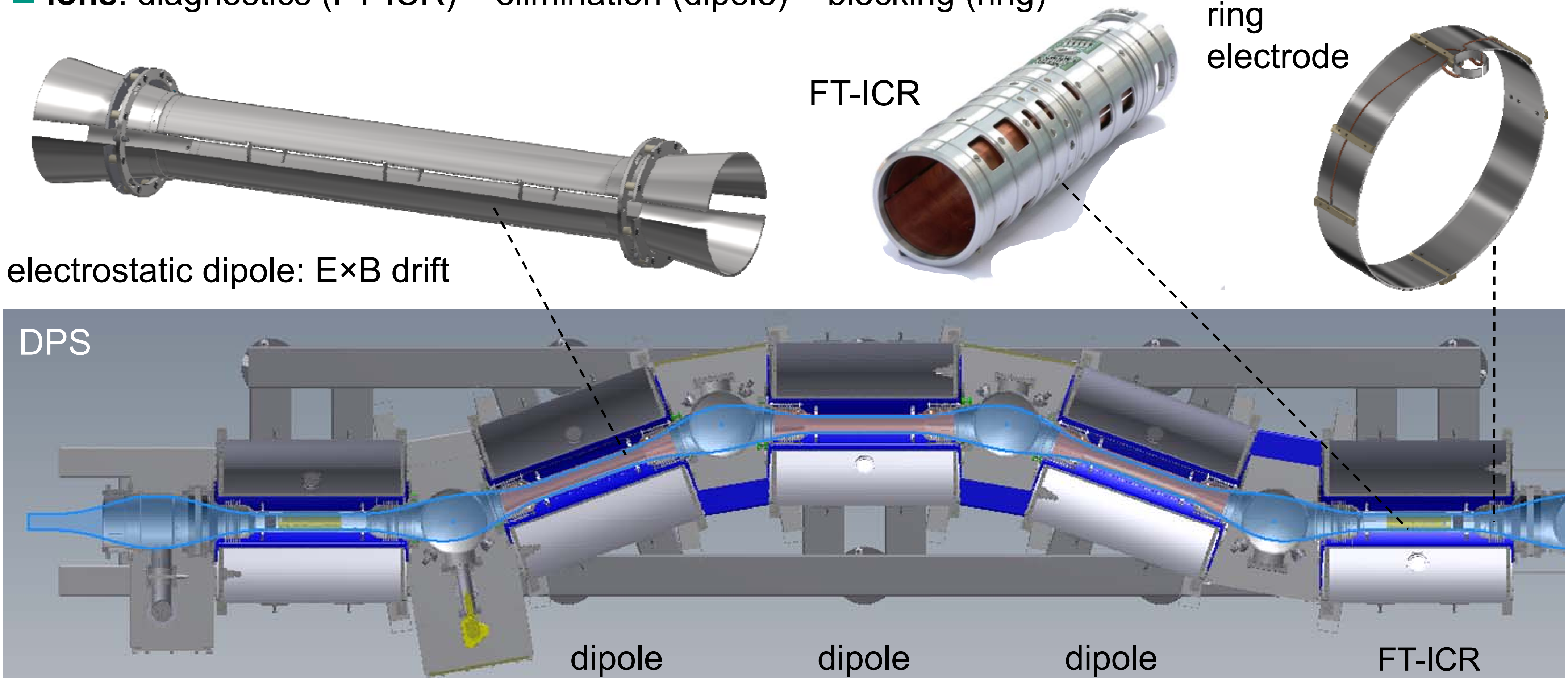
① injection pressure (± 0.1%): 3 μbar



$$\delta(z) = \frac{R \cdot \rho(z)}{\mu \cdot v_m} \cdot k_B T$$

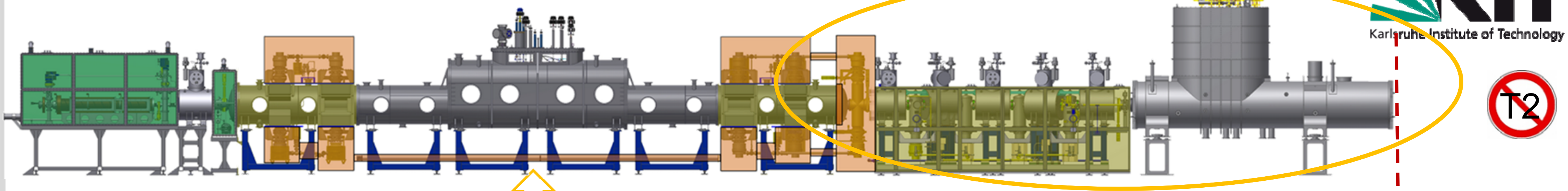
DPS – beam tube instrumentation for tritium ions

- **ions**: diagnostics (FT-ICR) – elimination (dipole) – blocking (ring)



tritium retention techniques

Karlsruhe Institute of Technology

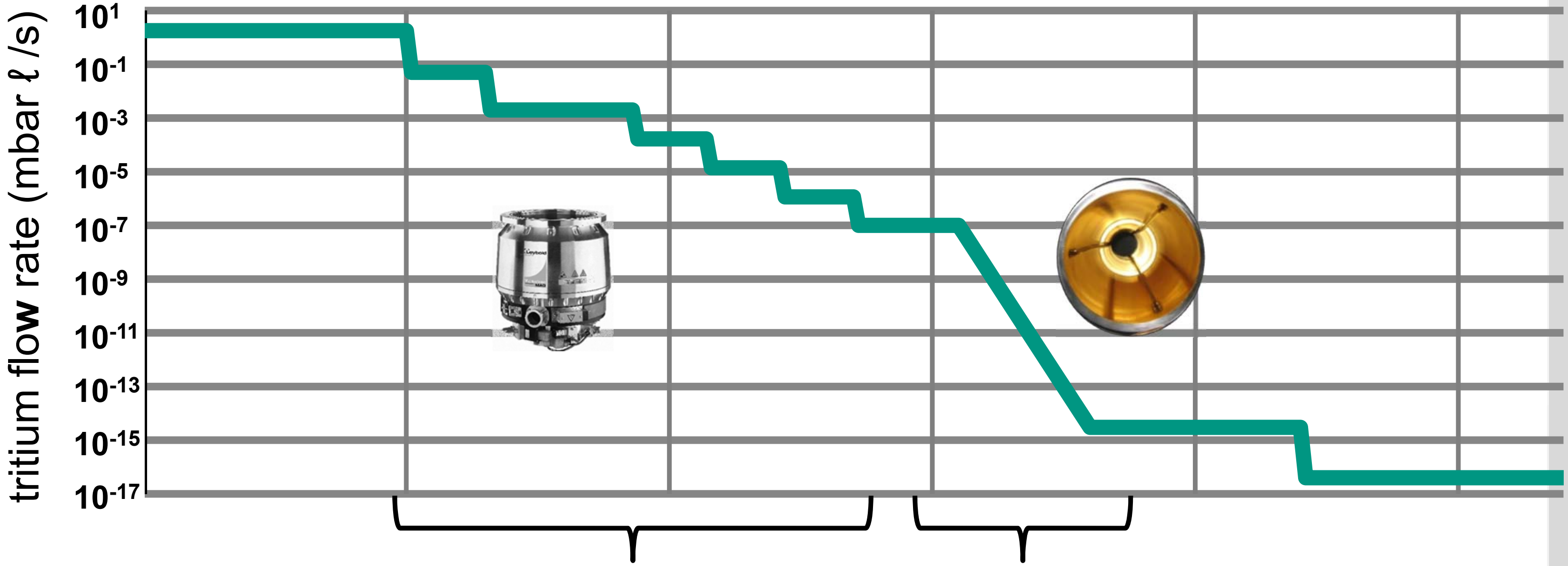


injection

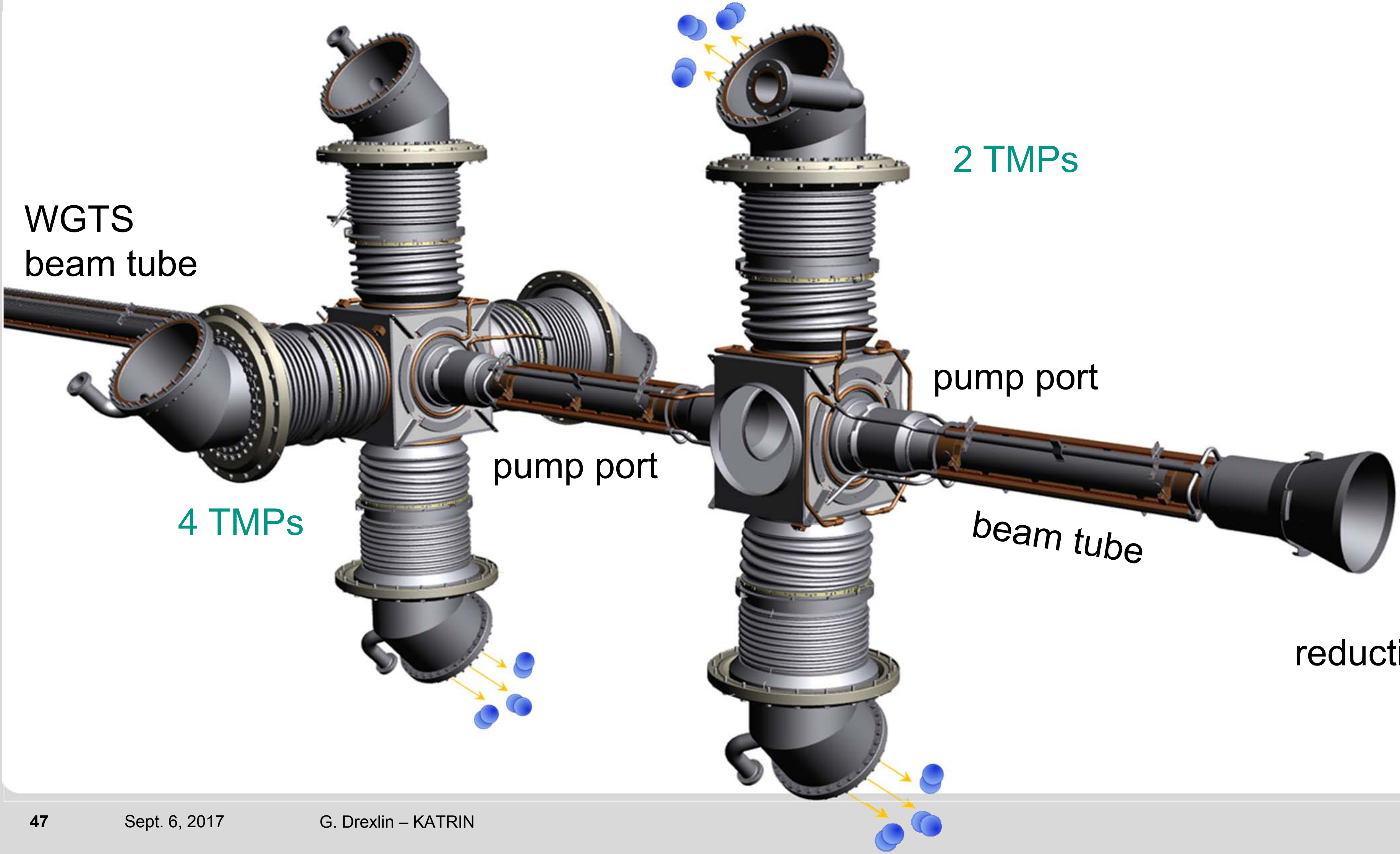
tritium retention steps

for overall **factor > 10^{14}**

- overall retention **factor > 10^{14}**



source challenges: tritium retention

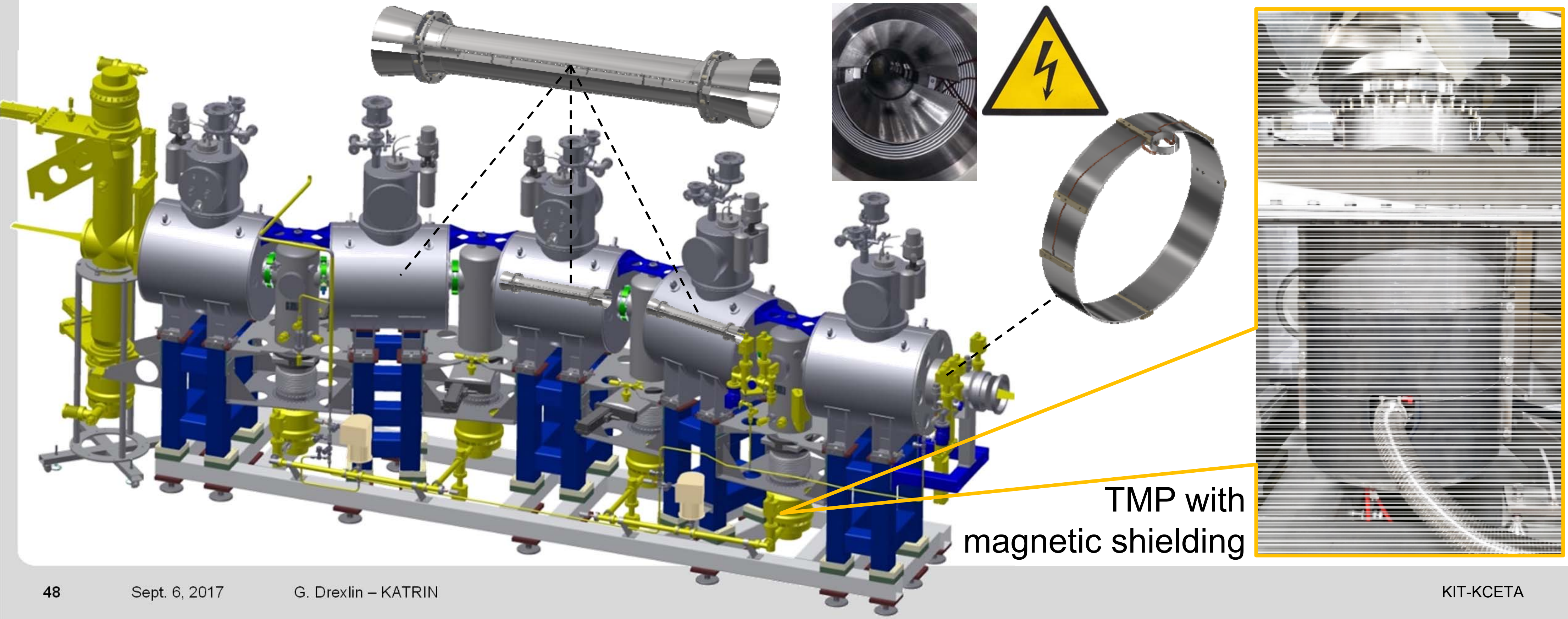


⑥ tritium retention (12 TMPs)

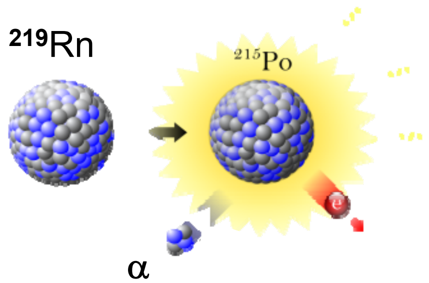
reduction factor ~100

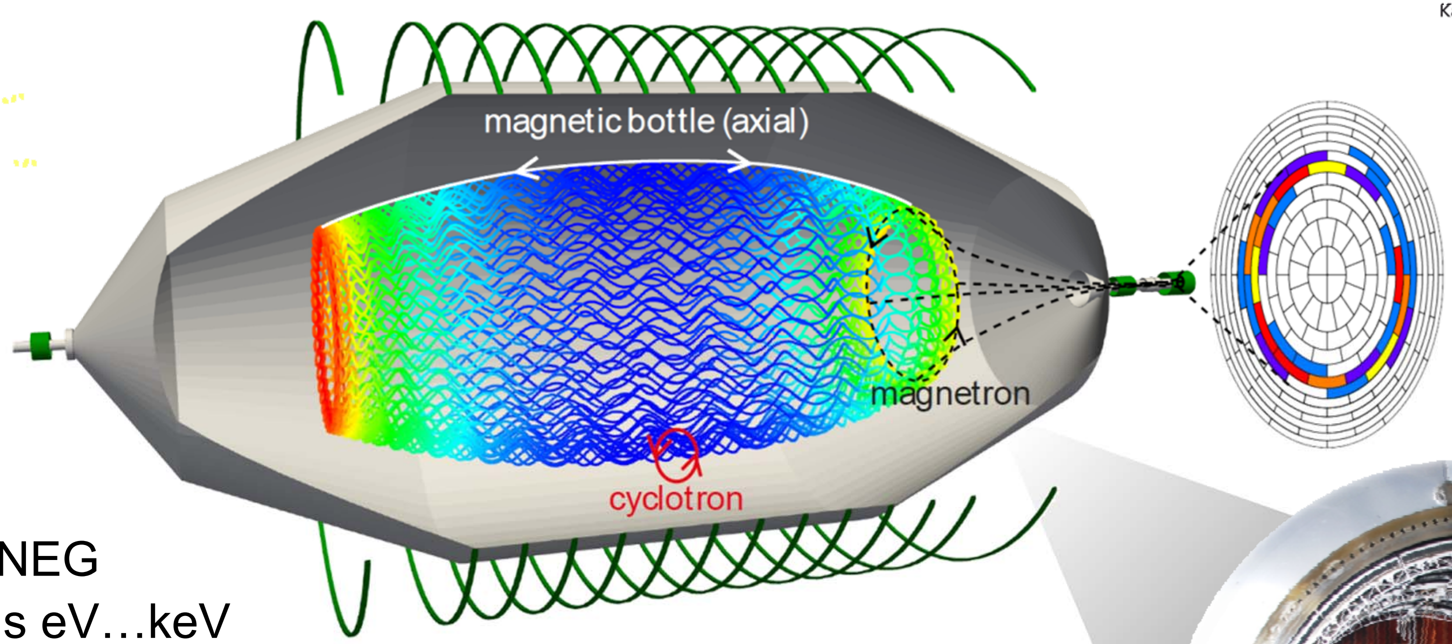
DPS – status: ion electrodes & TMPs

- **DPS status:**
  - all 4 TMPs mounted, 1 TMP in operation with full magnetic shielding
  - 3 electric dipoles for ion elimination & 1 ion blocking electrode in operation



background – ^{219}Rn from getter strips (NEG)

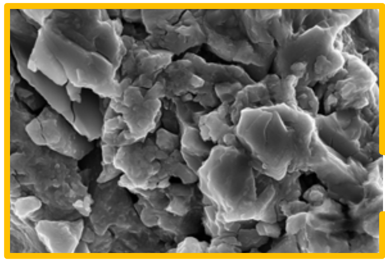


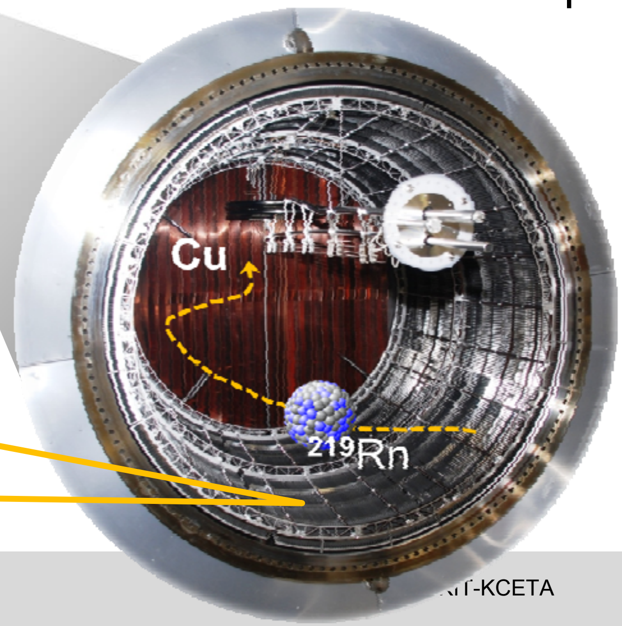


2 km of NEG strips

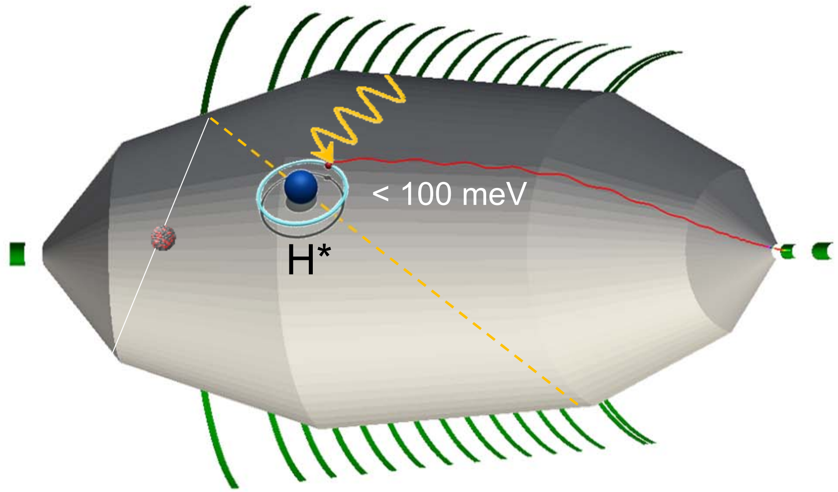
- **^{219}Rn atoms:**
  - emanate from NEG
  - stored electrons eV…keV
  - bg-rate: ~0.5 cps
  - **countermeasure (passive)**:
    - cryotraps in front of NEG
    - 3 LN2-cooled Cu-baffles eliminate ~97% of emanated ^{219}Rn atoms

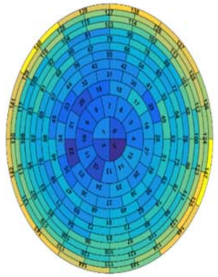
porous surface



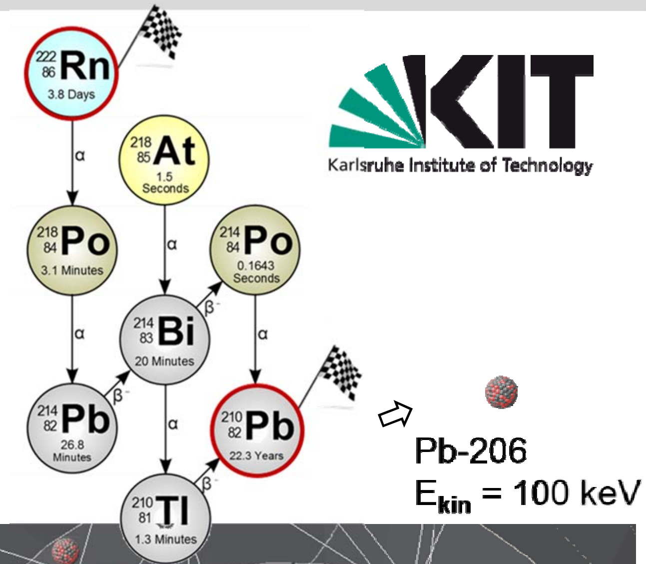


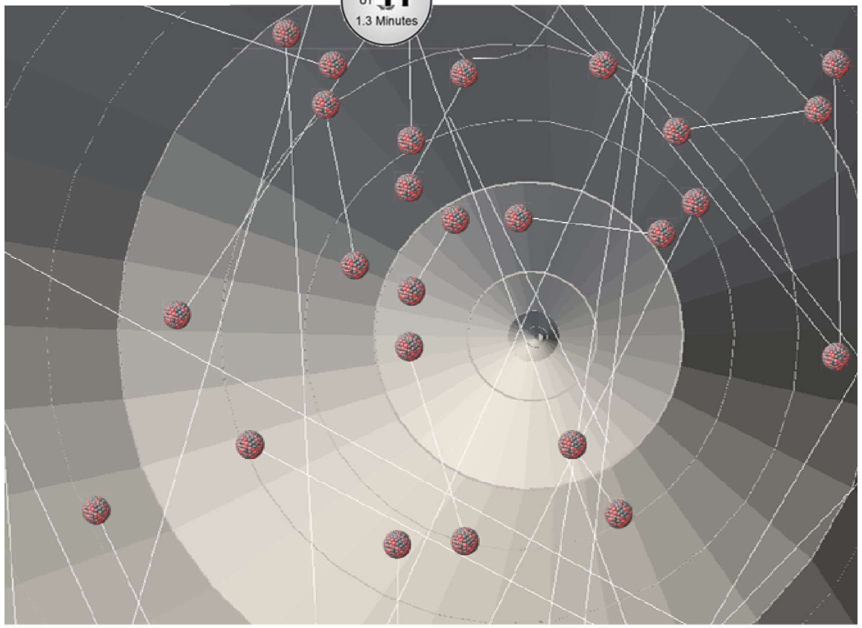
background – H*-Rydberg atoms from ^{206}Pb



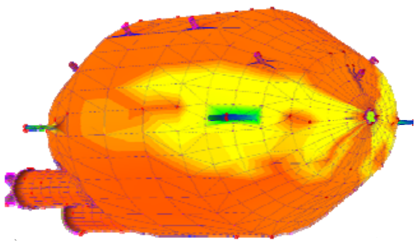


isotropic bg for longer exposure





- **H* Rydberg atoms:**
  - desorbed from walls due to ^{206}Pb recoil ions
  - non-trapped electrons on meV-scale
  - bg-rate: ~0.5 cps
  - **countermeasures**:
    reduce H-atom surface coverage:
    - extended bake-out phase
    - strong UV illumination source

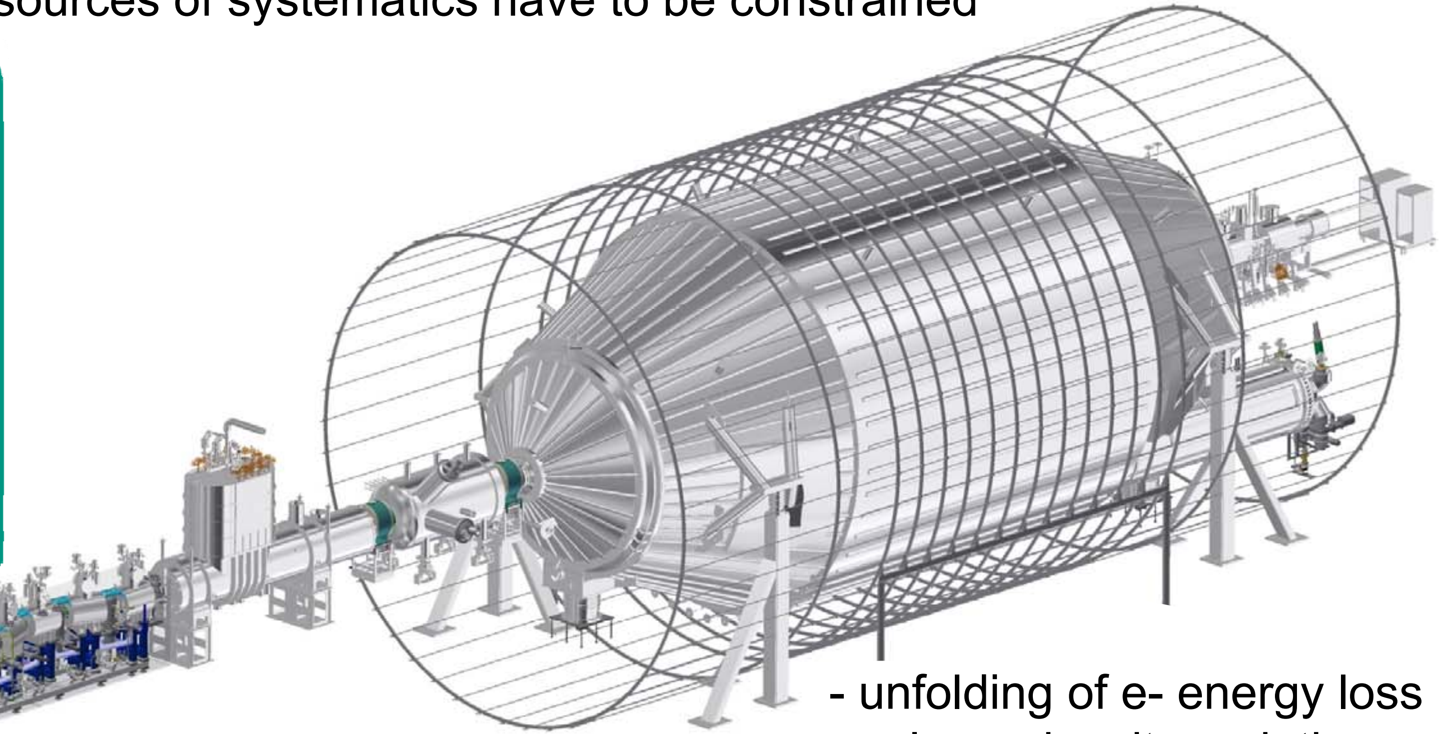


Statistical & systematic error budgets

- **systematics budget**: 5 major sources of systematics have to be constrained

statistics: σ_{stat} $(m_\nu^2) = 0.018$ eV^2

systematics: σ_{syst} $(m_\nu^2) < 0.017$ eV^2



- unfolding of e- energy loss
- column density variation
- HV/plasma fluctuations
- elastic e- scattering
- theory: final state spectrum

$$\Delta m_\nu^2 = -2 \cdot \sigma_{syst}^2$$