Karlsruhe Institute of Technology

Introduction to direct neutrino mass measurements and KATRIN

Thomas Thümmler for the KATRIN collaboration

XXIV International Conference on Neutrino Physics and Astrophysics, Athens, 2010

KIT Center Elementary Particle and Astroparticle Physics (KCETA)
Institute for Nuclear Physics (IK)

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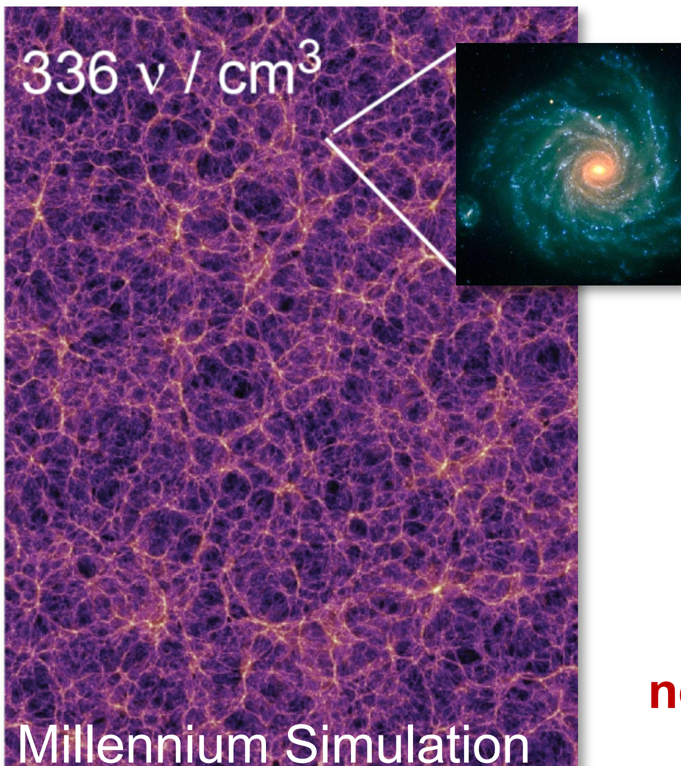
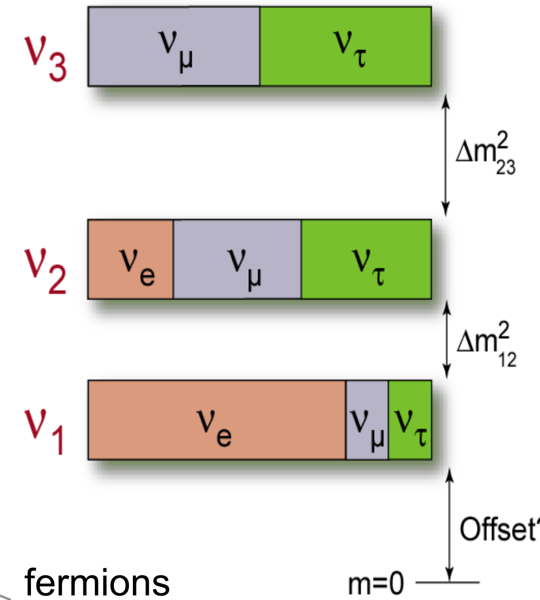
Motivation: ν´s in Astroparticle Physics

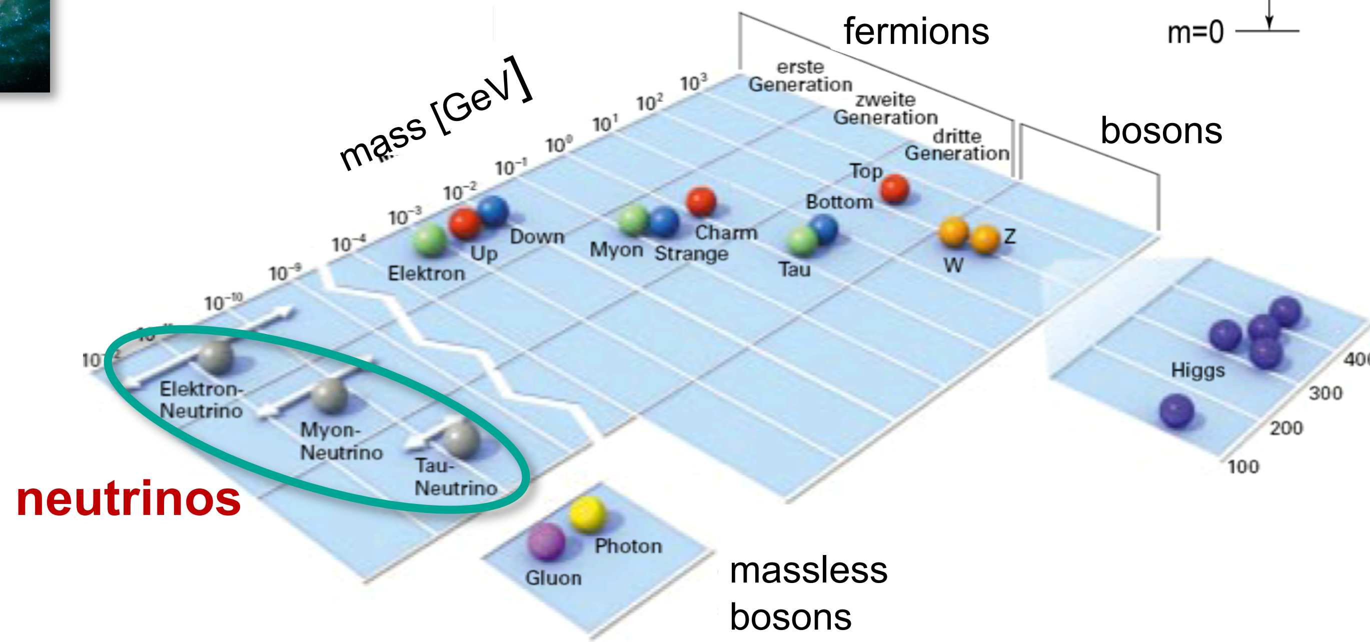
cosmology: role of ν´s as hot dark matter?

particle physics: origin and hierarchy of the ν-mass?

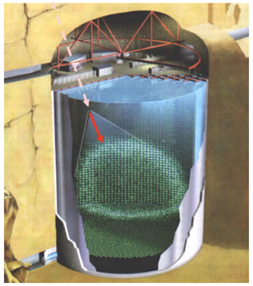
cosmology ⇔ **particle physics**

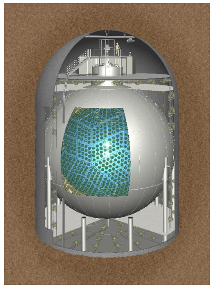


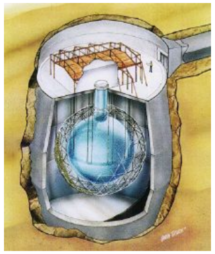




Neutrinos mass: status and perspectives







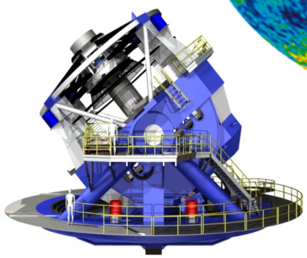
Experiments on Neutrino Oscillations:

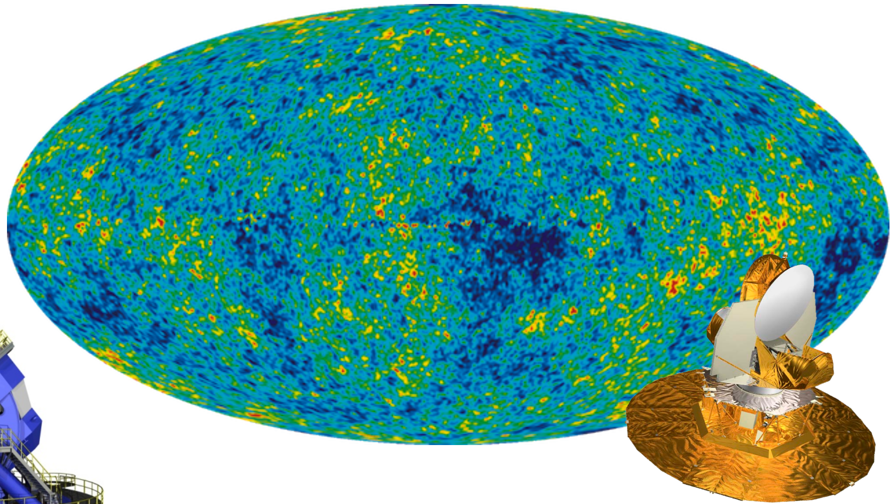
- Clear evidence for neutrino flavour oscillations:
  - Atmospheric neutrinos: $(\Delta m_{32})^2 \cong 2.4 \times 10^{-3}\ \mathrm{eV}^2/c^4$
  - Solar neutrinos: $(\Delta m_{21})^2 \cong 7.6 \times 10^{-5}\ \mathrm{eV}^2/c^4$

➔ Well established fact: $m_\nu \neq 0$

Input from Cosmology:

- measures Σm_i and HDM Ω_ν
- very sensitive, but model dependent!
- WMAP 7yr: $\Sigma m_i < 1.2$ eV
  (Hannestad et al., arXiv:1004.0695)
- potential: $\Sigma m_i = 20\text{-}50$ meV
  (Planck, LSST, weak lensing)





Talk: Y. Wong (Session III / Friday)

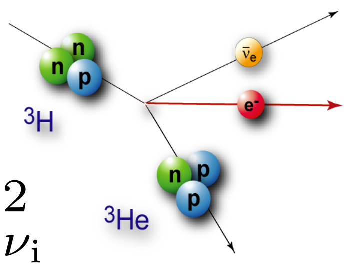
Neutrinos mass: status and perspectives

status and potential of neutrino masses in lab experiments

kinematics of ß-decay absolute ν_e-mass: m_ν

model-independent

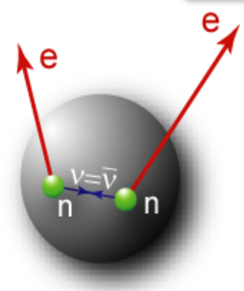
squared neutrino mass:



$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

- direct, from kinematics
- status: $m_\nu < 2.3$ eV
- potential: $m_\nu = 200$ meV
- MARE, Project 8, KATRIN

search for 0νßß eff. Majorana mass $m_{ßß}$



model-dependent (CP-phases)

effective Majorana mass:

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$$

- probe ν as Majorana particle: $\nu = \bar{\nu}$?
- status: $m_{ßß} < 0.35$ eV, evidence?
- potential: $m_{ßß} = 20\text{-}50$ meV
- GERDA, SNO+, EXO, CUORE

Talks by: Rodejohann/Pavan/Dolinski/Nakamura
F. Simkovic (Session II / Friday)

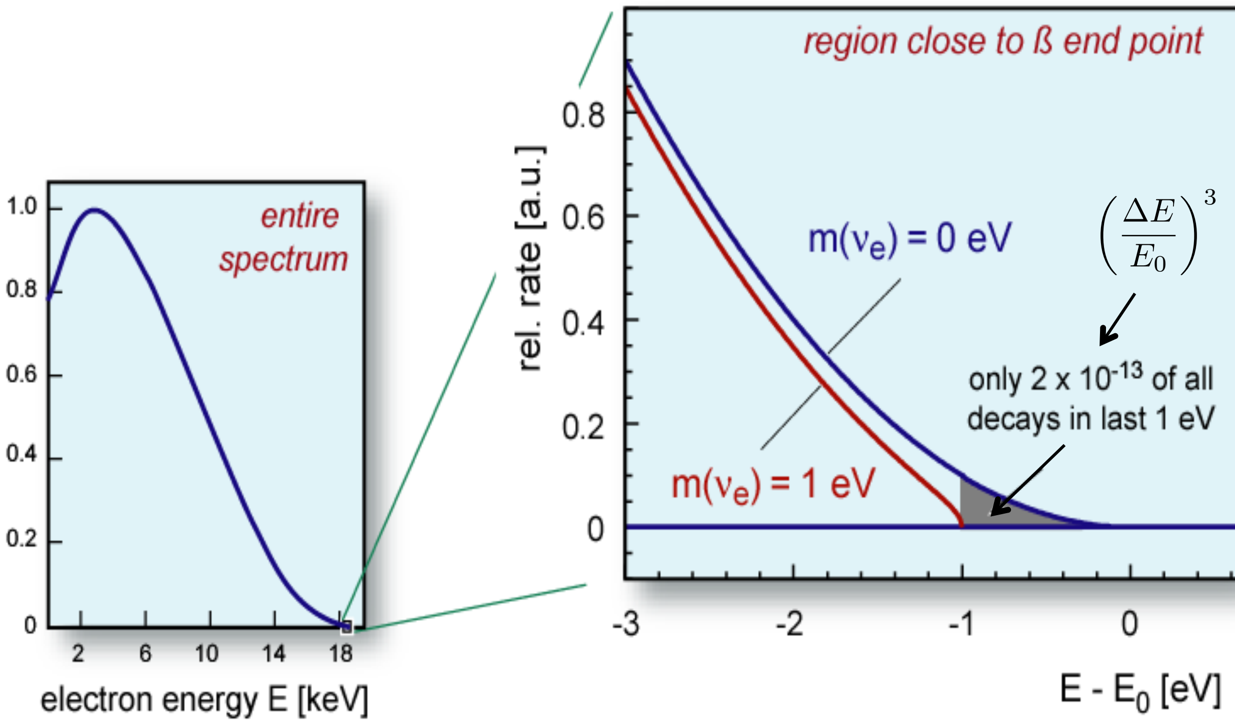
Measuring the Neutrino Mass

m(ν$_e$) from β decay: model-independent, based on kinematics and energy conservation

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

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

(ν– mass)²



$m_\nu \neq 0$ influence:

- shift of E_0
- changed shape
- shape to be analysed!

key requirements:

- low endpoint β source
- high count rate
- high energy resolution
- extremely low background

Measuring the Neutrino Mass

Two complementary approaches with different systematics:

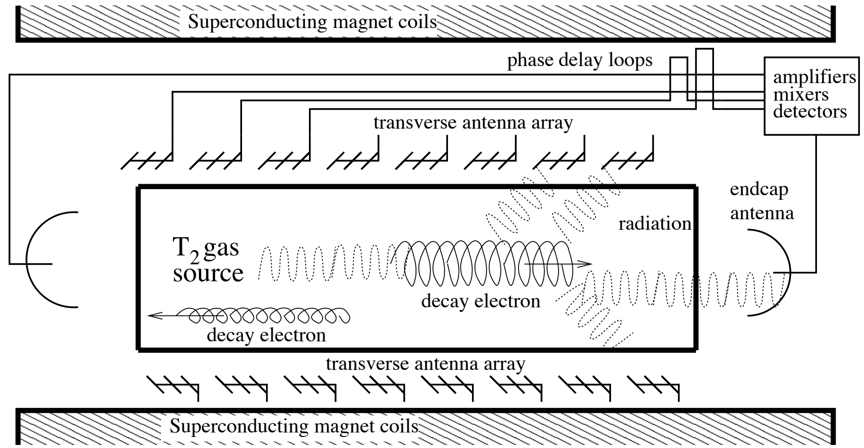
	calorimeter	spectrometer
source	^{187}Re (metallic or dielectric) • source = detector	T_2 (gaseous or condensed) • external β source
endpoint	2.47 keV	18.6 keV
$t_{1/2}$	4.3×10^{10} y	12.3 y
activity	low: < 10^5 β/s, ≈ 1 Bq / mg Re	high: ≈10^{11} β/s, 4.7 Ci/s injection
technique	single crystal bolometer	electrostatic spectrometer
response	entire β decay energy	kinetic energy of β decay electrons
interval	entire spectrum	narrow interval close to endpoint
method	differential energy spectrum	integrated energy spectrum
set-up	modular size, scalable	integral design, size limits
resolution	$\Delta E_{expected} \approx 5 - 10$ eV (FWHM)	$\Delta E_{expected} \approx 0.93$ eV (100 %)

→ MARE

→ KATRIN

Measuring the Neutrino Mass

3rd approach, proposed recently: Project 8



- source: gaseous T_2
- technique: radio-frequency spectroscopy of coherent cyclotron radiation of β decay electrons
- more details: arXiv:0904.2860v1 [nucl-ex]
- design values: projected energy resolution: 1 eV
  estimated sensitivity on $m(\nu_e)$: 0.1 eV
- status: preparations for a proof-of-principle experiment

Talk: J. Formaggio, Session II, Saturday

Measuring the Neutrino Mass

MARE: Microcalorimeter Arrays for a Rhenium Experiment

- ^{187}Re as β-emitter: isotropic abundance of 62.6 %
- $5/2^{+}$ to $1/2^{-}$ first order unique forbidden transition

$$^{187}_{85}\mathrm{Re} \longrightarrow ^{187}_{86}\mathrm{Os} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

MARE Phase-I:

ΔE = 15 eV
Δt = 50 μs
3 years

- based on MANU and MIBETA (result: $m_\nu < 15$ eV / 6×10^{6} β's)
- improve sensitivity for m_ν by factor 10
- increase statistics to 10^{10} β decays
- scrutinize tritium-based MAINZ and TROITZK result

$$m_\nu \approx 2 \text{ eV}$$

- Genova: metallic Re, superconducting at T = 1.6 K, 1 mg absorber
- Milano: new $AgReO_4$ crystals, 500 μg absorber at T ≈ 85 mK, 6x6 pixel arrays, energy resolution ΔE = 34 eV at 2.5 keV

MARE Phase-II:

ΔE = 5 eV
Δt = 1 μs
> 5 years

- improve sensitivity for m_ν by another factor 10
- increase statistics to 10^{14} β decays
- scrutinize KATRIN in future

$$m_\nu \approx 0.2 \text{ eV}$$

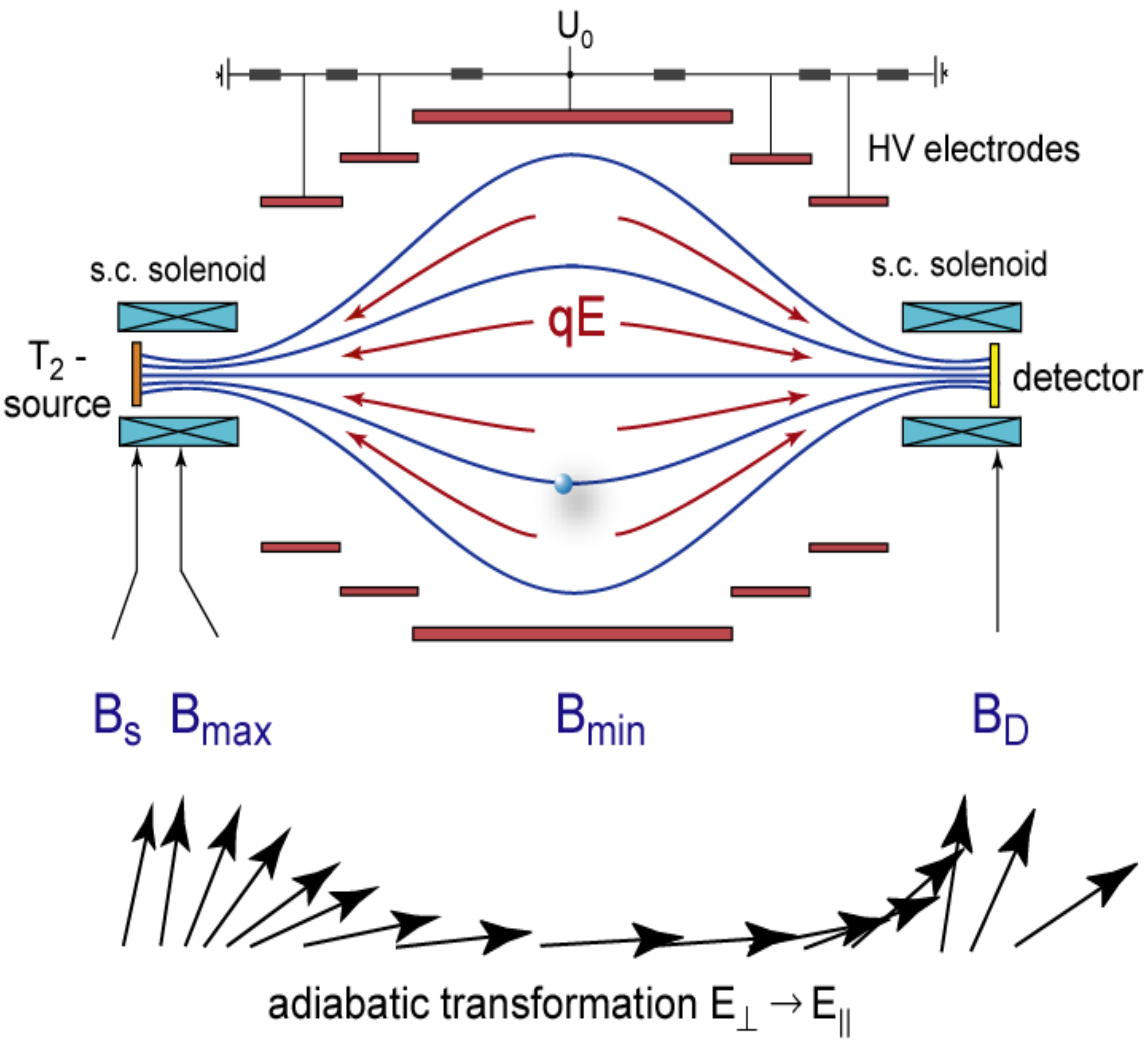
- R&D program for new detectors
- magnetic micro-calorimeters (MMC) + paramagnetic sensor + SQUID
- projected sensitivity requires ≈50000 bolometers and t > 5 years

for details see talk: A. Nucciotti (Session II, Friday)

The MAC-E Filter

Magnetic Adiabatic Collimation with Electrostatic Filter

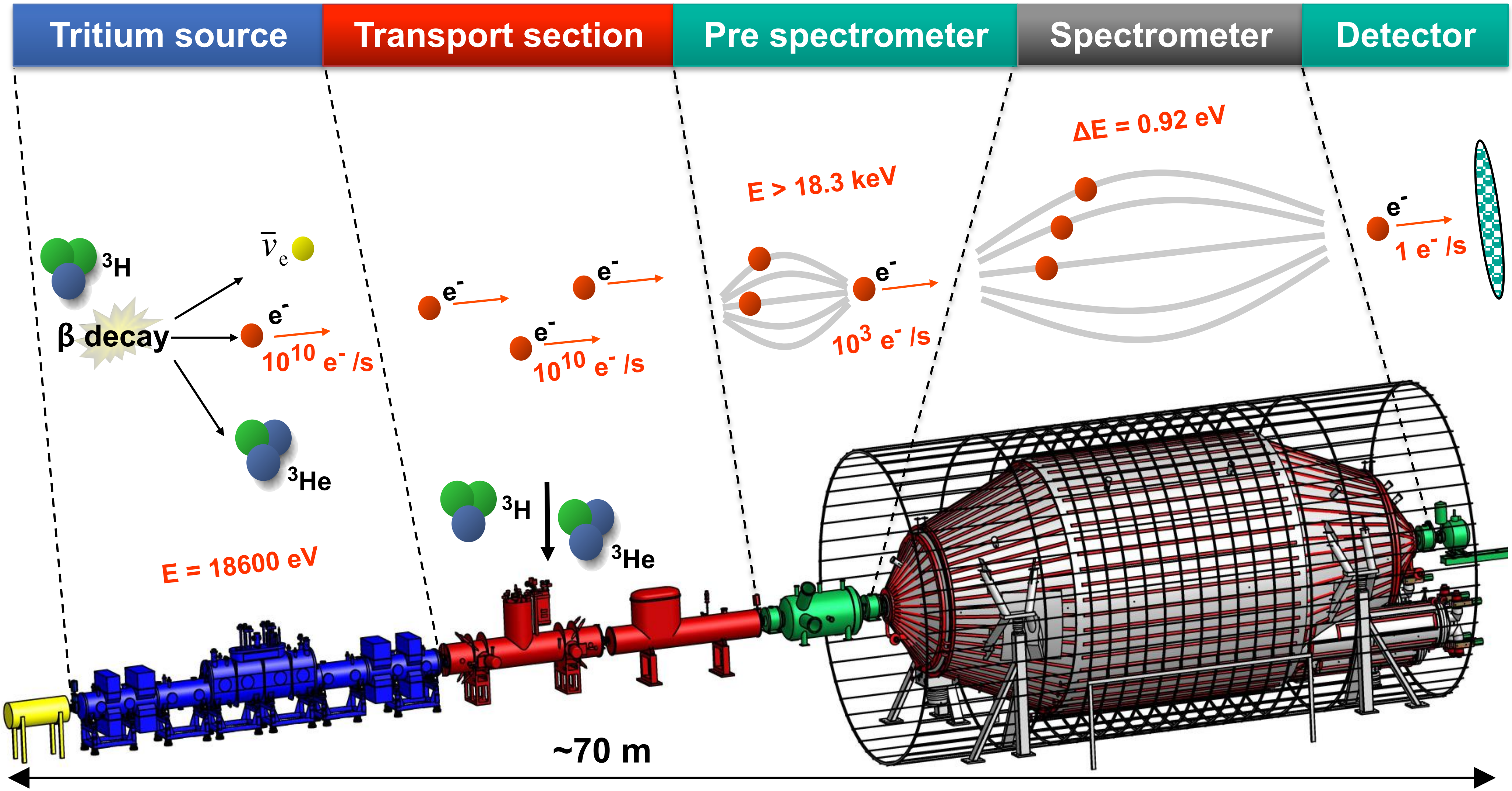
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)



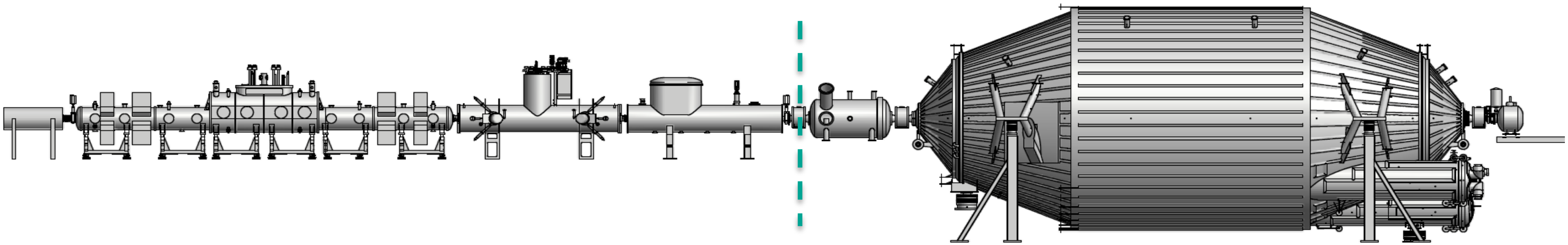
- inhom. magn. guiding field:
  → gradient force:
  adiab. transformation $E_\perp \rightarrow E_{||}$
  due to $\mu = E_\perp / B = \textit{const.}$
- momentum of e⁻ || magnetic field
  → el. retarding potential
  → energy analysis

  → **high-pass filter** with a sharp transmission function, no tails!
- high resolution:
  $\Delta E = E \cdot B_{min} / B_{max}$
- magn. adiab. collimation
  → large solid angle (2π)

The KATRIN Setup



The KATRIN Setup



tritium-bearing components

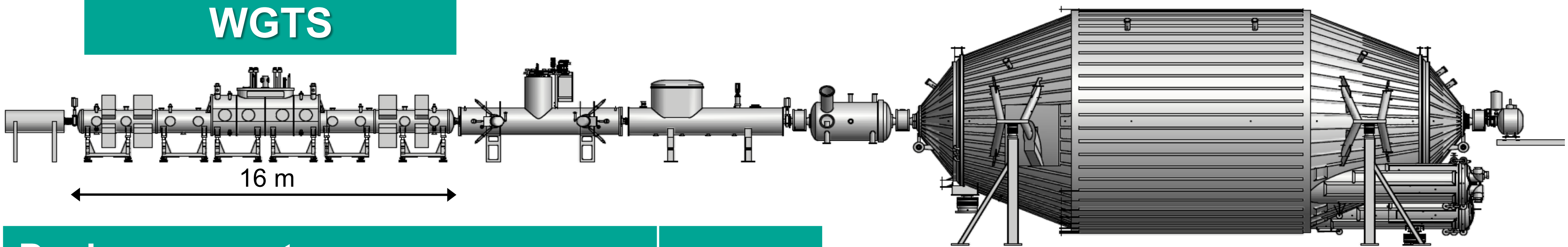
electrostatic spectrometers & detector

10^{11} electrons/s tritium source

<10^{-2} cps total background

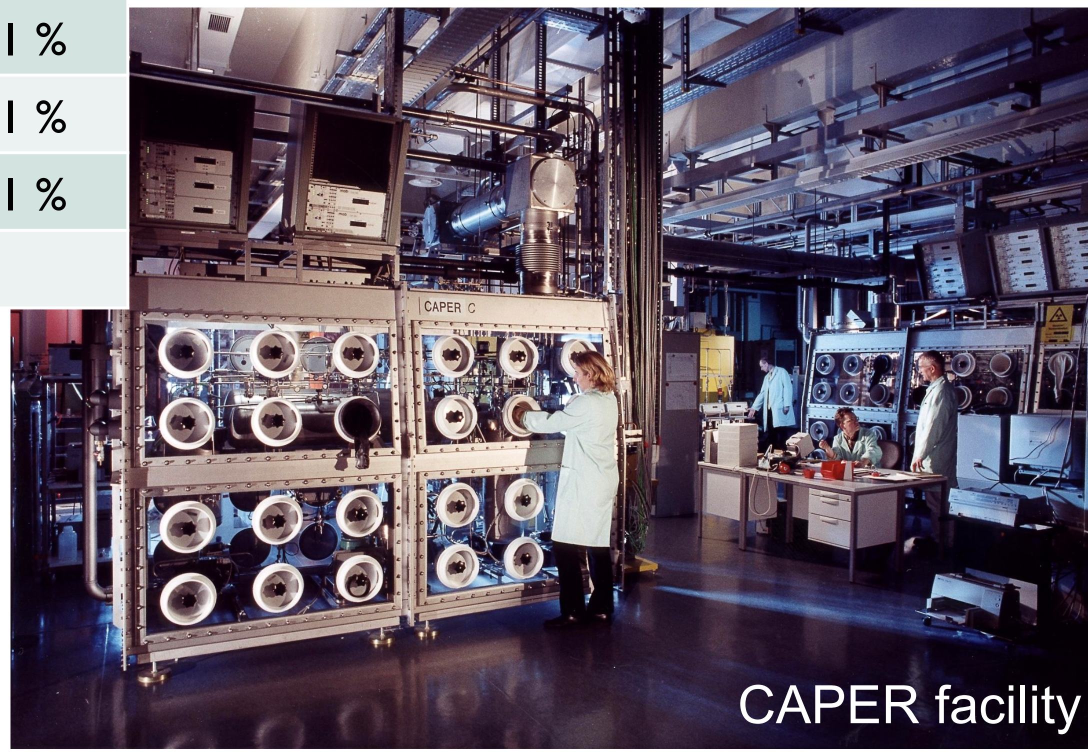
- 10^{-3} stability of tritium source column density ρd
- retention factor for molecular tritium R = 10^{14}
- effective removal of ions
- fully adiabatic (meV scale) transport of electrons over > 50 m
- avoid particle storage in Penning-like traps

Windowless Gaseous Tritium Source WGTS



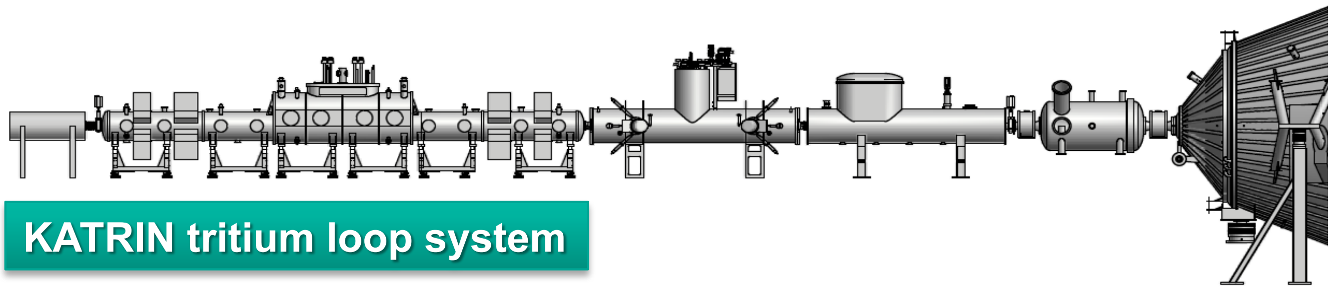
Design parameter		
luminosity	1.7×10^{11} Bq	
injection rate	5×10^{19} T_2/s ≈ 40 g/day	
Tritium purity	> 95%	±0.1 %
temperature	T = 27 K ± 30 mK	±0.1 %
pressure	$p_{inj} \approx 10^{-3}$ mbar	±0.1 %
magnetic guiding	B = 3.6 T	

Tritium Laboratory Karlsruhe
- a unique research facility in Europe

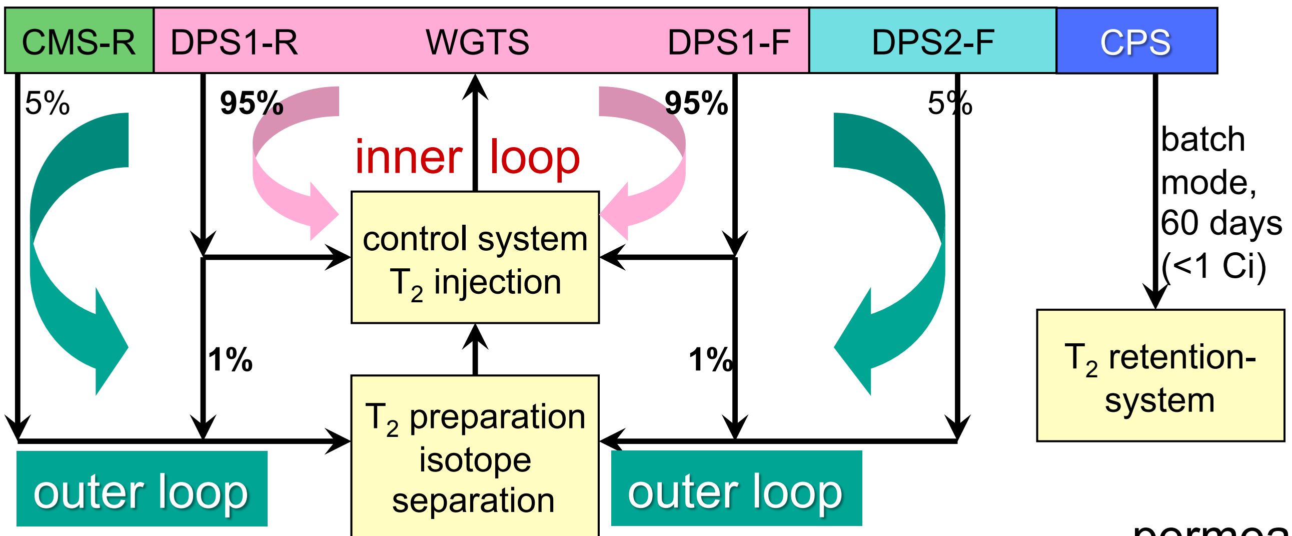


CAPER facility

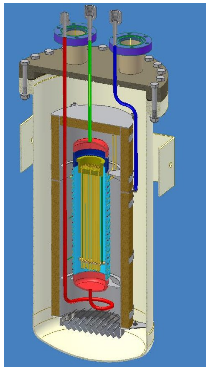
Windowless Gaseous Tritium Source WGTS

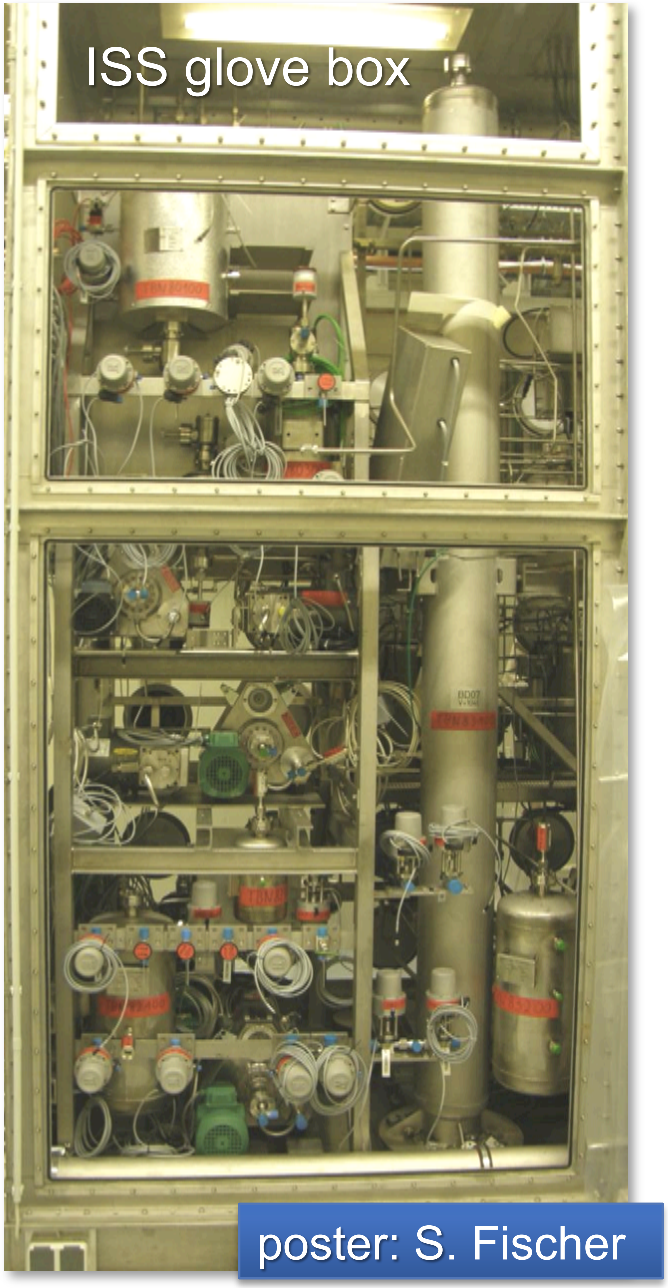


KATRIN tritium loop system



permeator

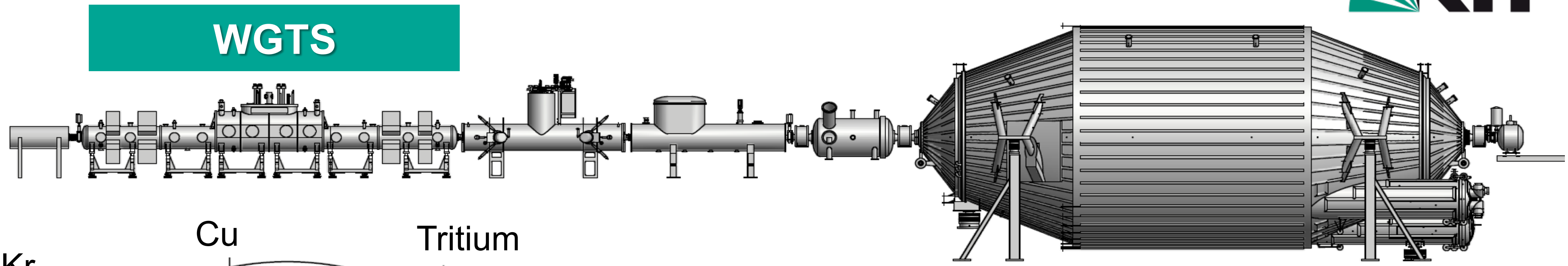


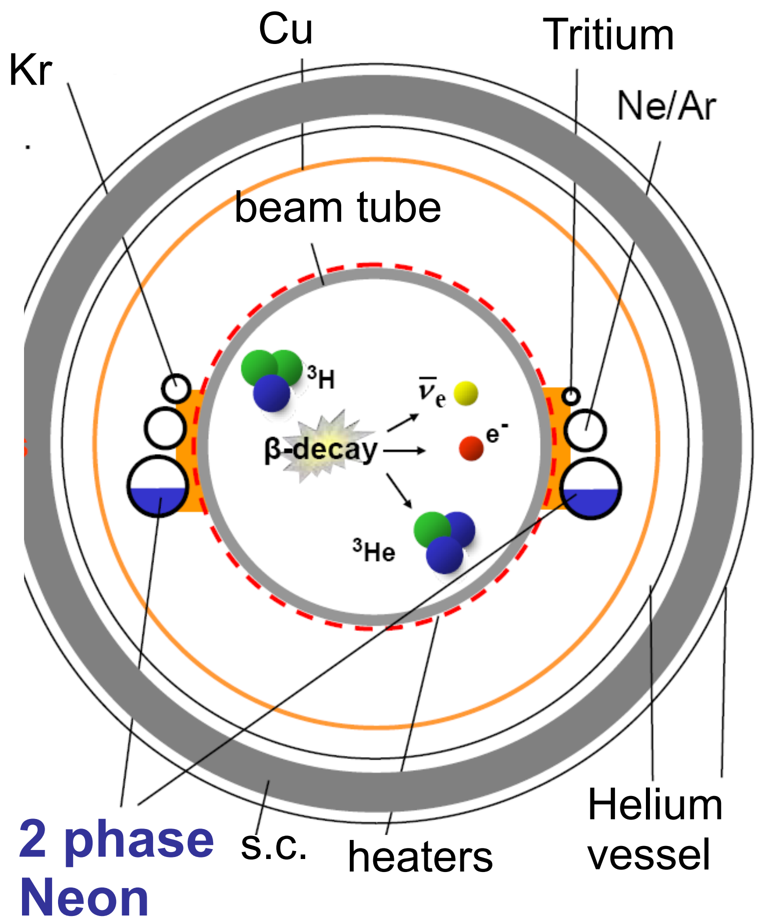


Up and running **extremely** stable!

- **designed for a stability at 10^{-3} level**
- **achieved: 2 × 10^{-4} over 4 months**

Windowless Gaseous Tritium Source WGTS





KATRIN requirement:

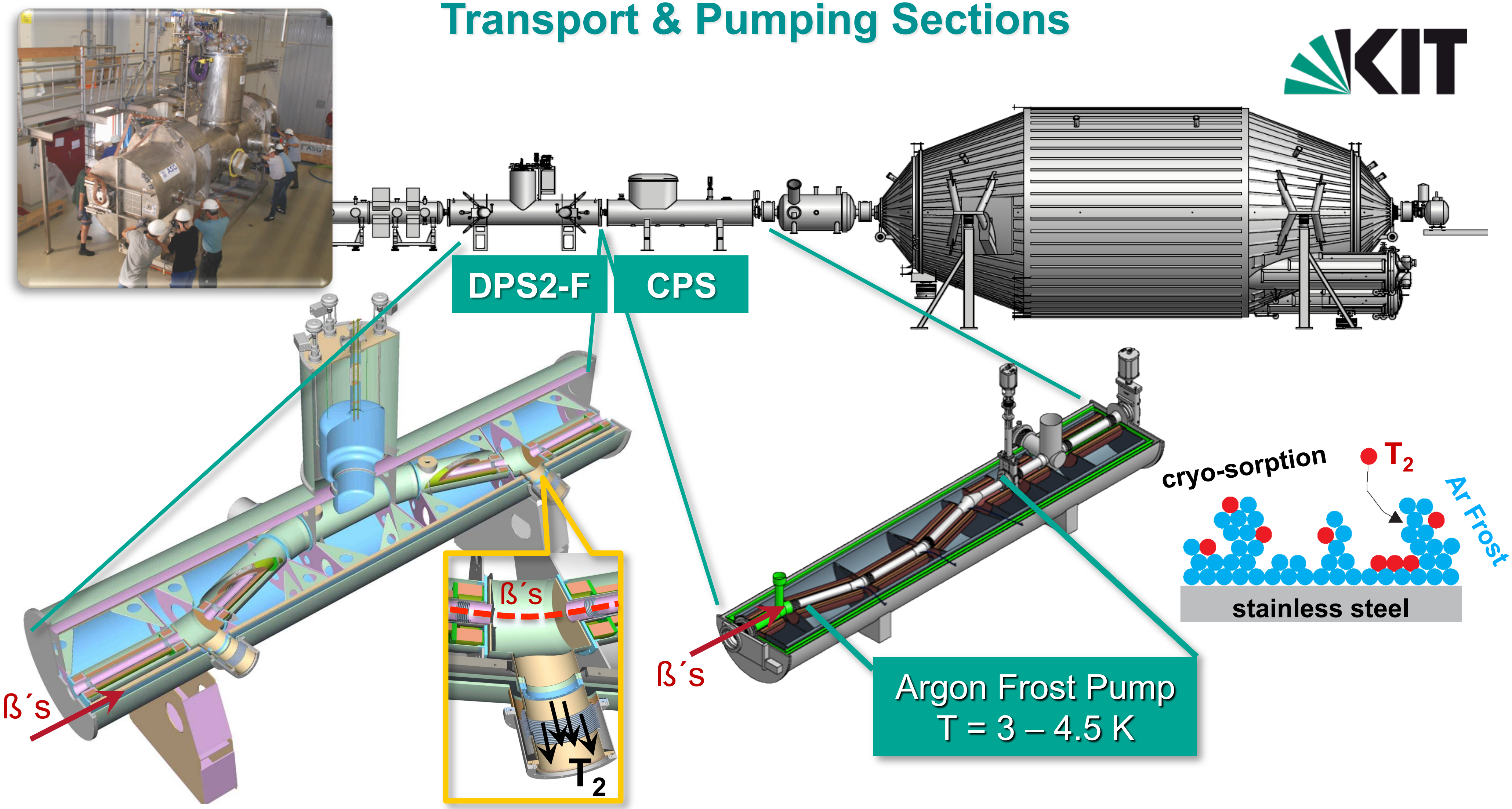
T = 27 K with ΔT < 30 mK

Control system designed for 10^{-4} level.

Demonstrator:

- **on-site since April 2010**
- tests until Fall 2010
- upgrade to WGTS

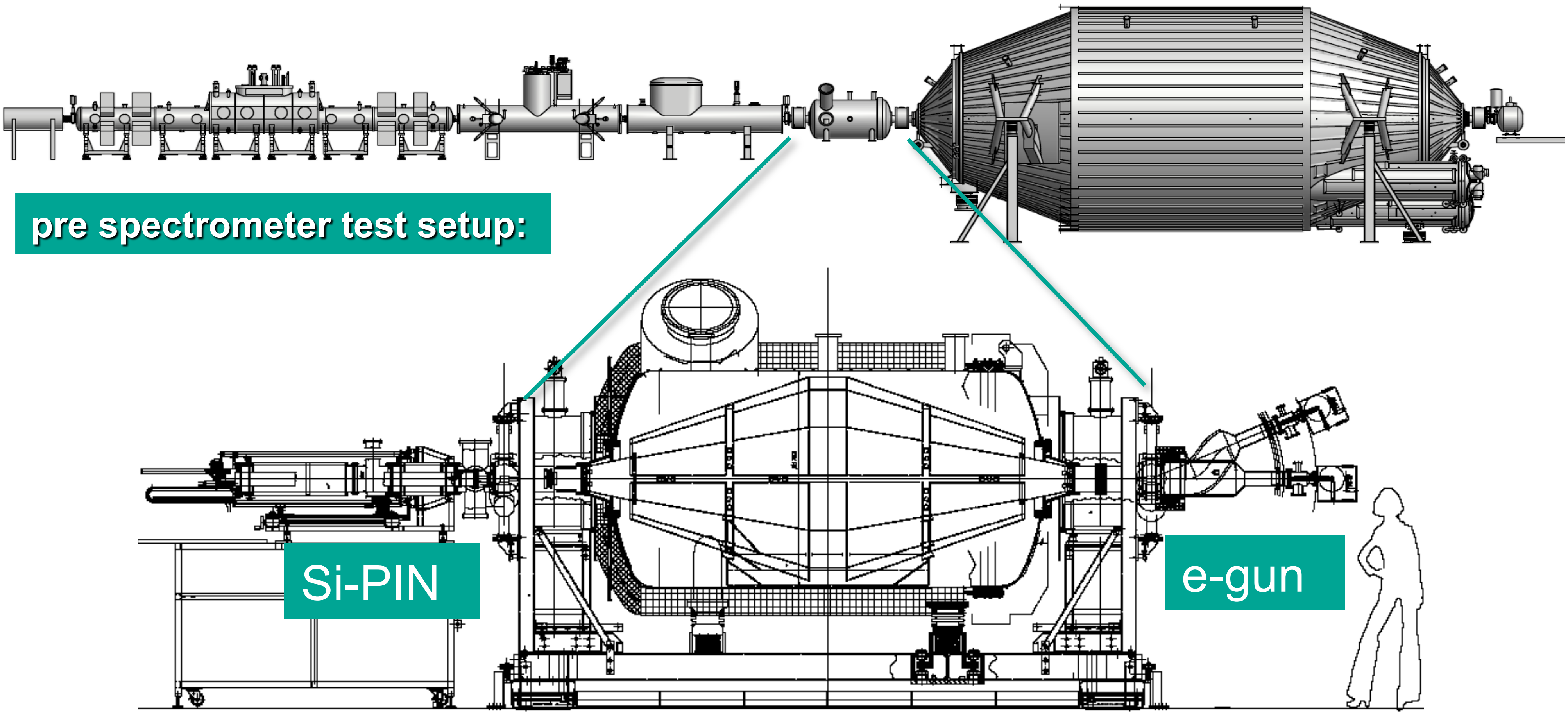
Transport & Pumping Sections



- active pumping, 4 TMPs
- Tritium retention 10^5
- magnetic field: 5.6 T
- on-site since 08/2009, commissioning ongoing

- pumping by cryo-sorption
- Tritium retention $>10^7$
- magnetic field: 5.6 T
- on schedule: delivery end of 2010

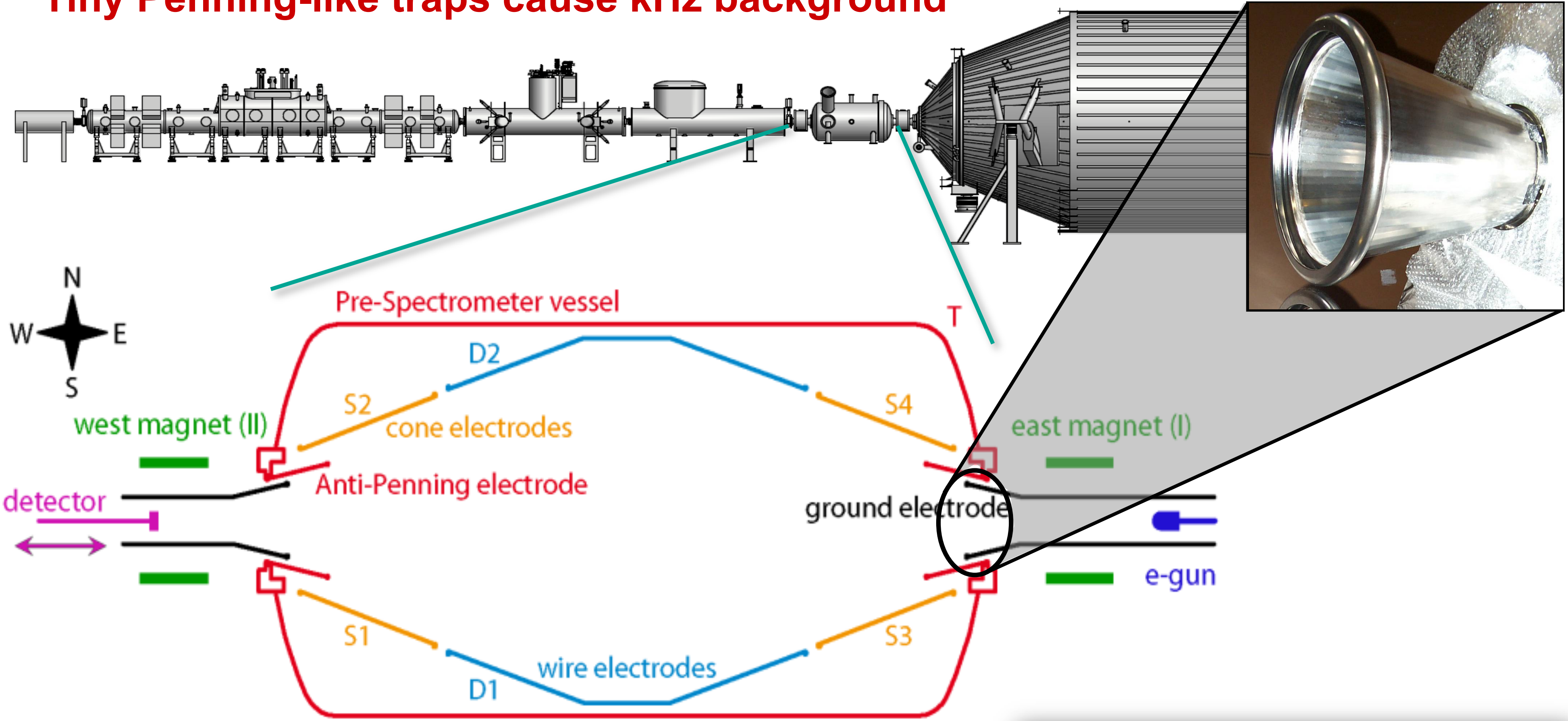
Pre Spectrometer



- tested all major technologies for the Main Spectrometer
- especially electro-magnetic and electron transmission properties

Pre Spectrometer

Tiny Penning-like traps cause kHz background



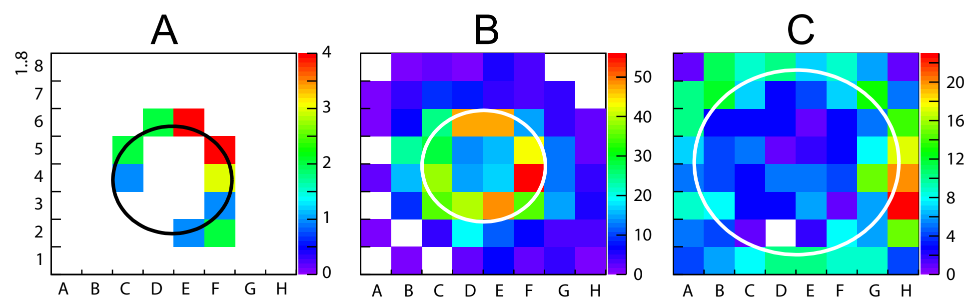
- Tiny cm^3-sized Penning-like traps cause background.
- Carefully refined shape of ground electrode.
- Huge success of em-simulations code.

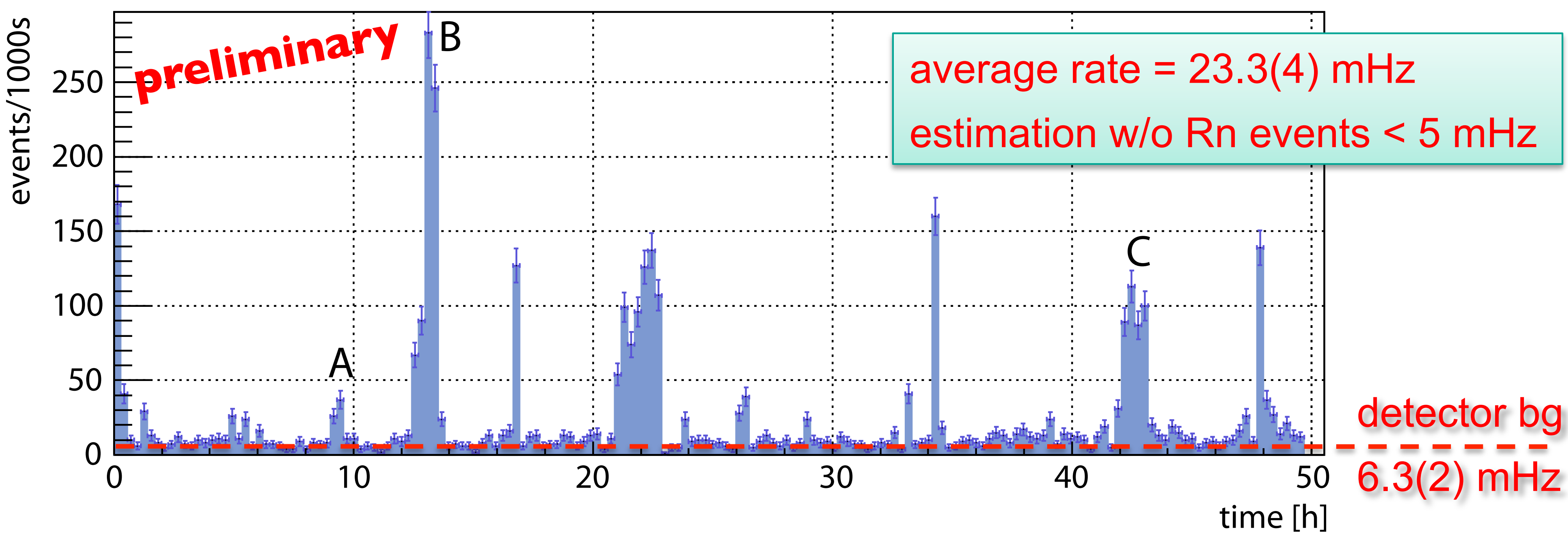
evolution of ground electrodes

Pre Spectrometer Background Tests

- traps avoided – background gone!
- **kHz range in 2009 to few mHz!**
- remaining mHz bg from Rn decay:
  - ➔ single trapped electron stored for hours
  - ➔ create ring shaped event patterns:
- to be completely eliminated by LN_2 baffle!

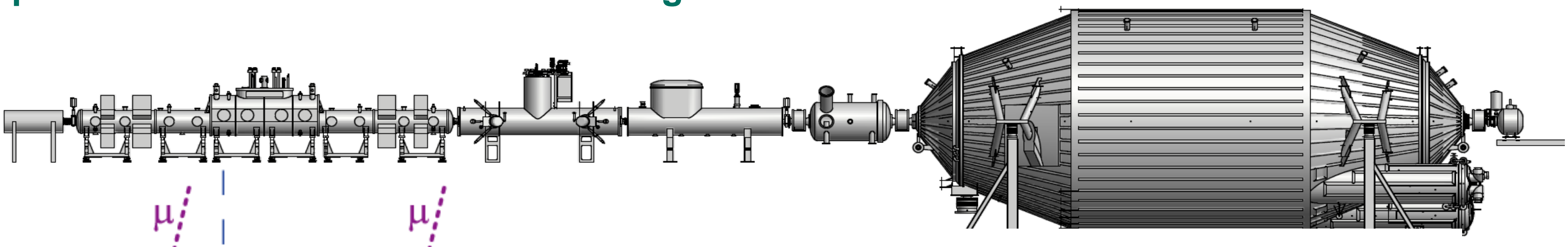
^{219}Rn	7.5 ± 1.8 mBq	getter material
^{220}Rn	33 ± 9 mBq	auxiliary components

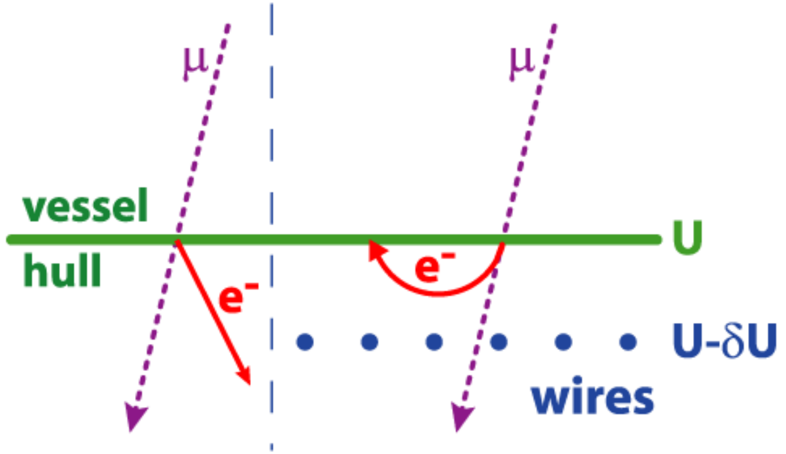


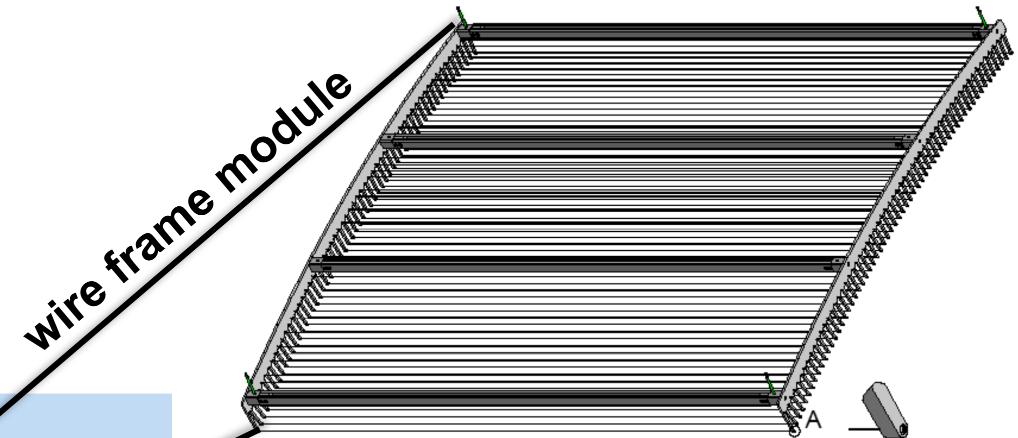


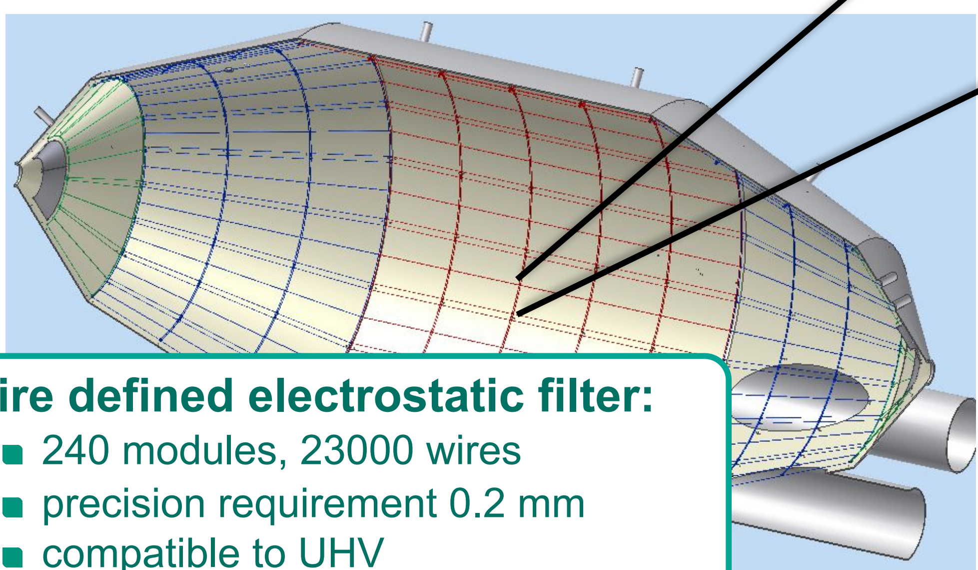
Main Spectrometer

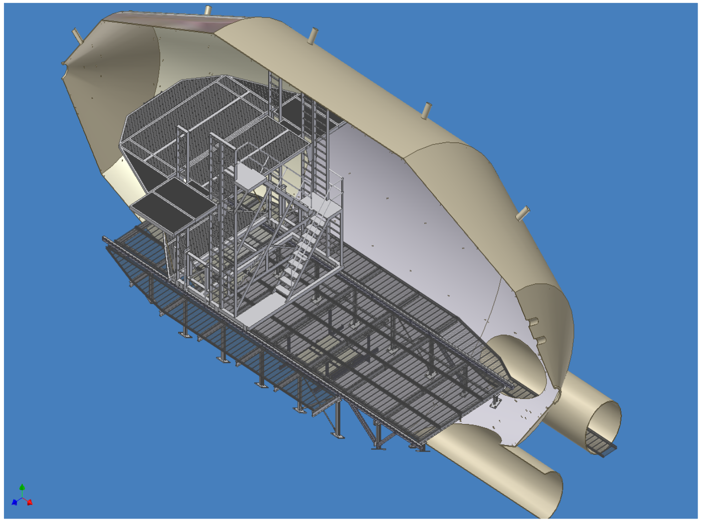
Spectrometer itself is a source of background











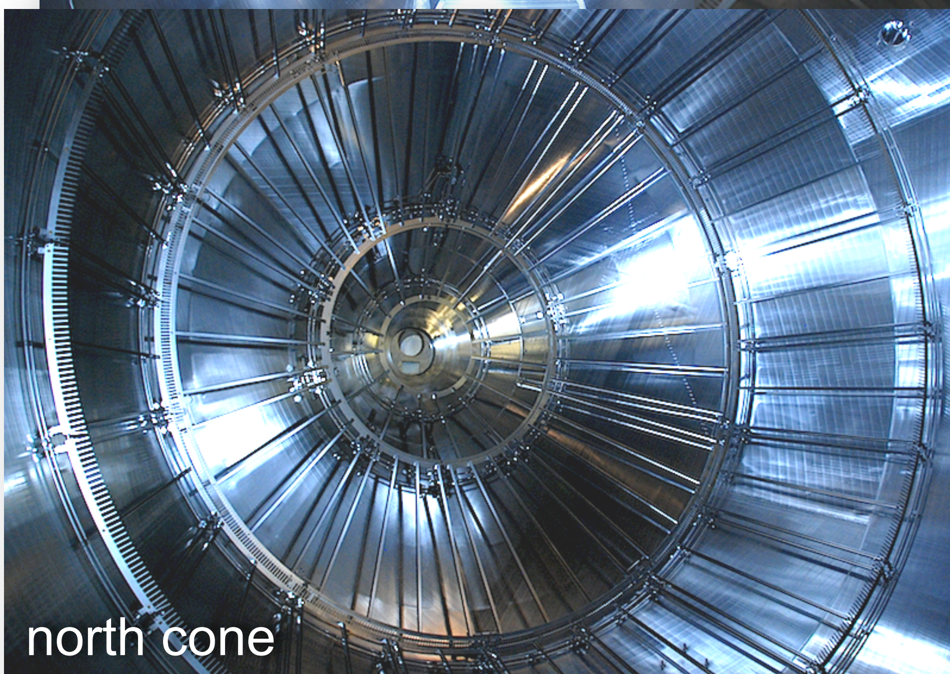
Wire defined electrostatic filter:

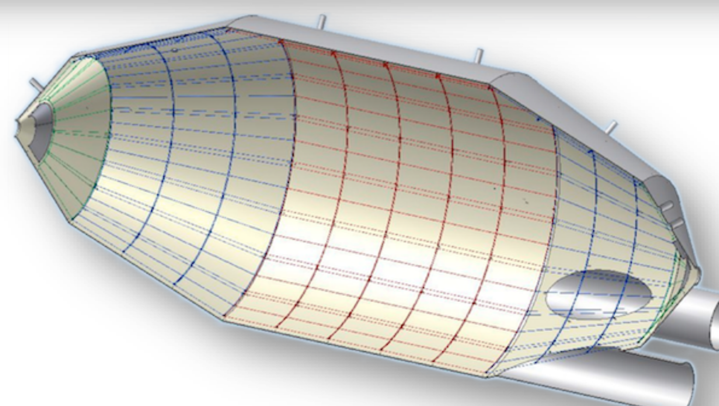
- 240 modules, 23000 wires
- precision requirement 0.2 mm
- compatible to UHV

Wire Electrode System - Mounting

Karlsruhe Institute of Technology

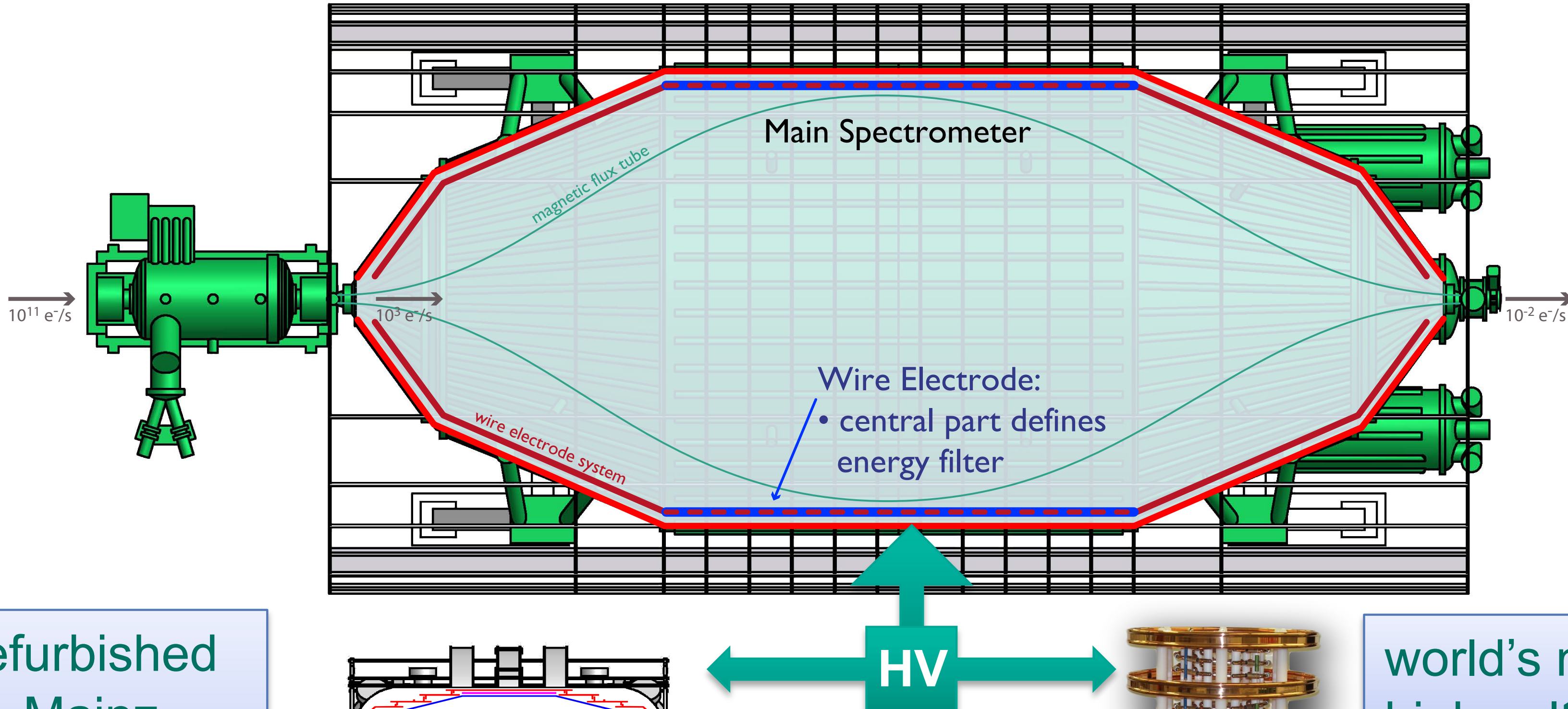
Installation ongoing → finished until end of 2010



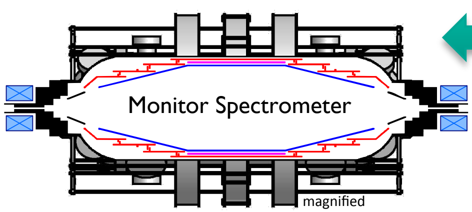


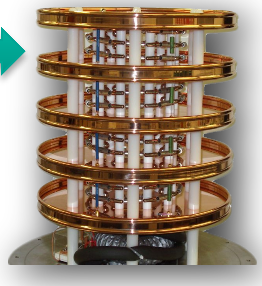
HV Monitoring of Main Spectrometer Energy Filter

- **KATRIN sensitivity goal requires: 60 mV (3×10^{-6}) at 18.6 kV**
- non-trivial, not state-of-the-art and of serious importance for KATRIN



refurbished Mainz spectrometer for monitoring





world's most precise high voltage dividers

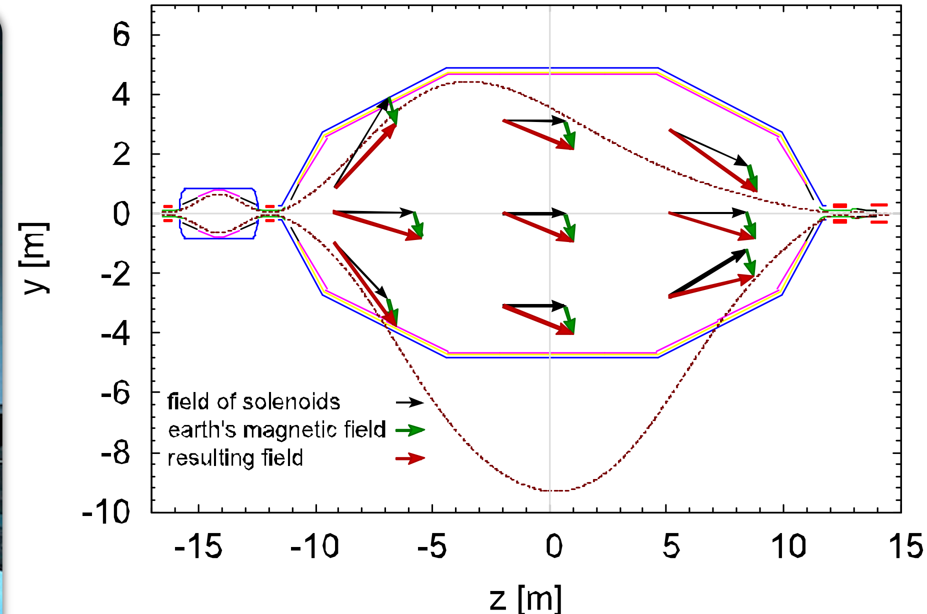
Th Thümmler et al
New J. Phys. 11 103007 (2009)

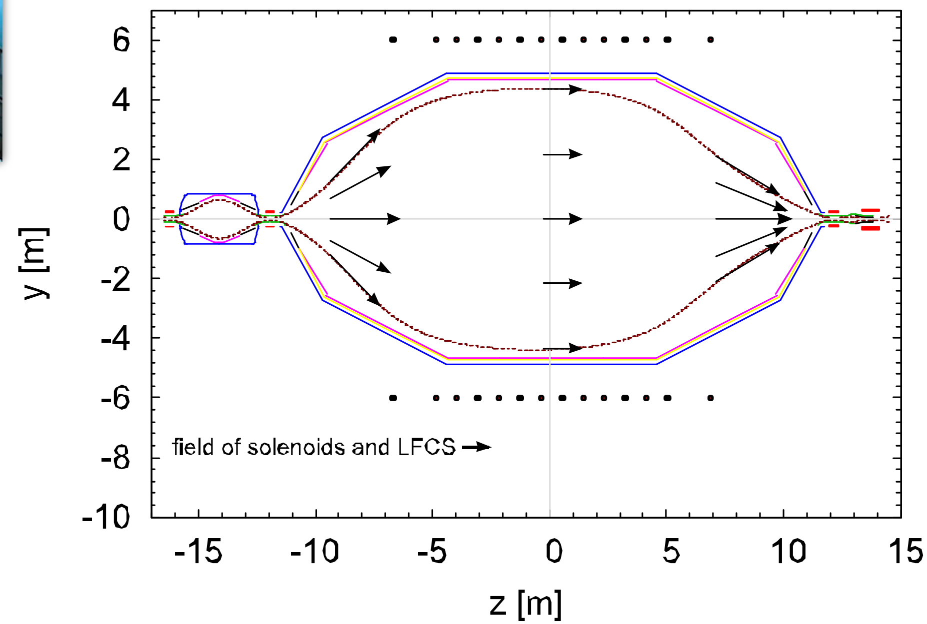
Monitoring of the analyzing potential in the main spectrometer:

- verification with ^{83m}Kr reference source at monitor spectrometer
- online monitoring with precision HV divider

Air Coil System

- Earth magnetic field compensation & low field correction

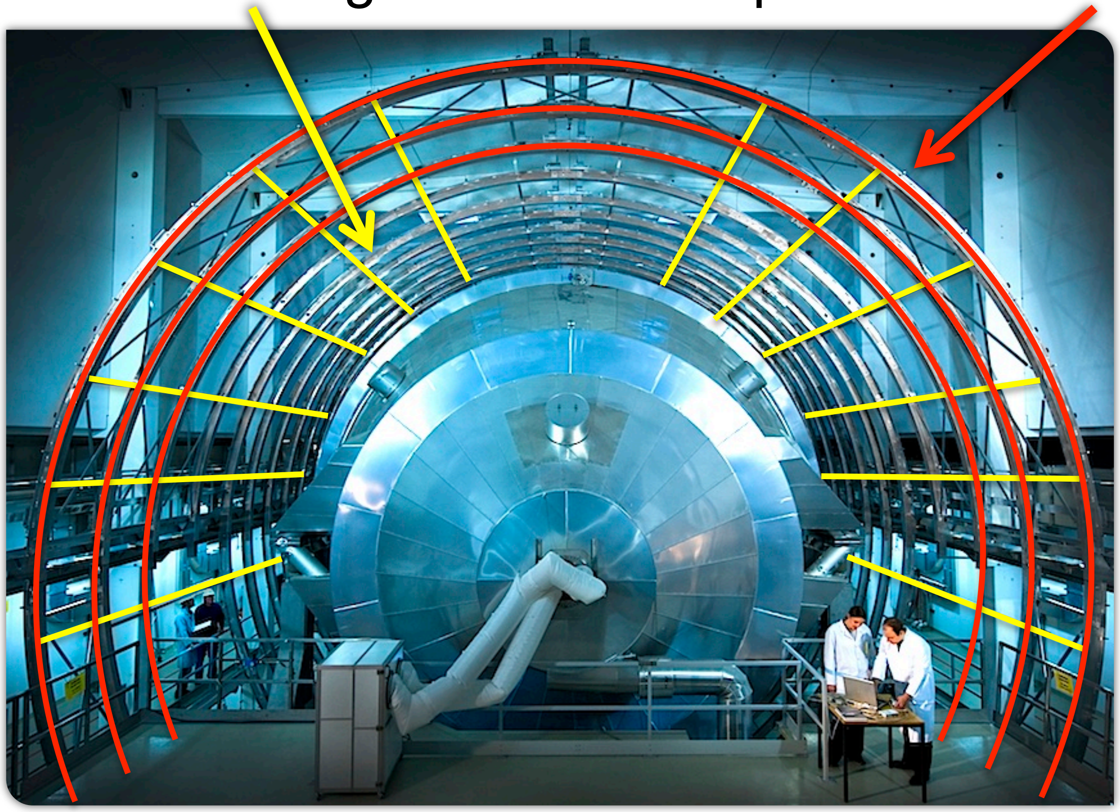


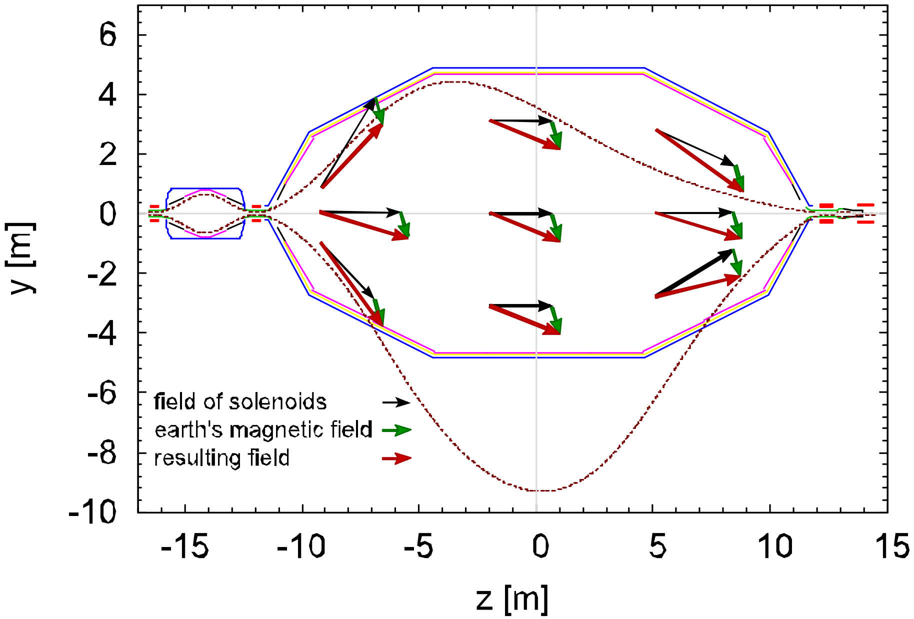


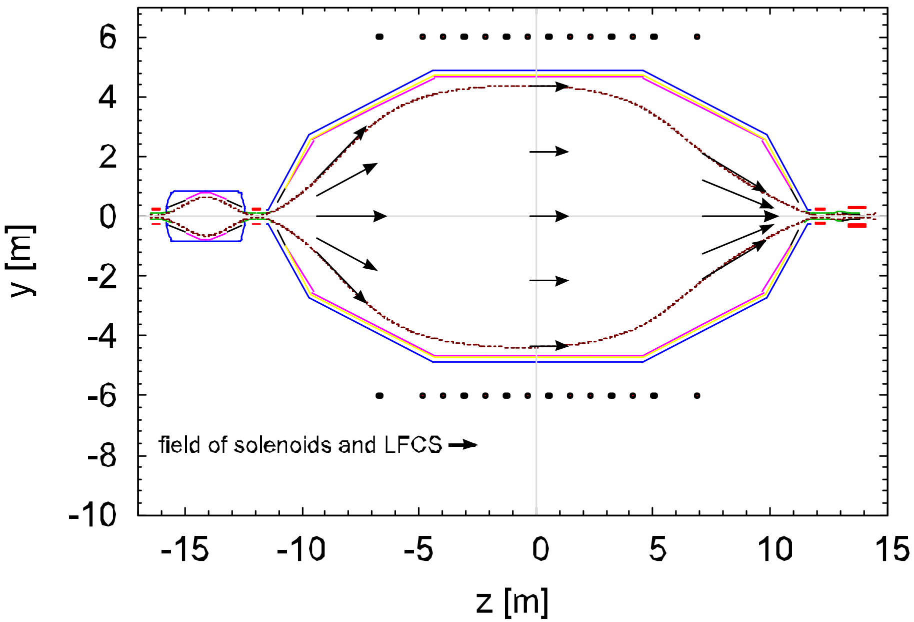
- earth magnetic/environmental fields distort magn. flux tube in low field region (0.3 mT)
- needs to be compensated!
- low field correction:
  - optimize flux tube
  - fine tune transmission and resolution.

Air Coil System

- Earth magnetic field compensation & low field correction

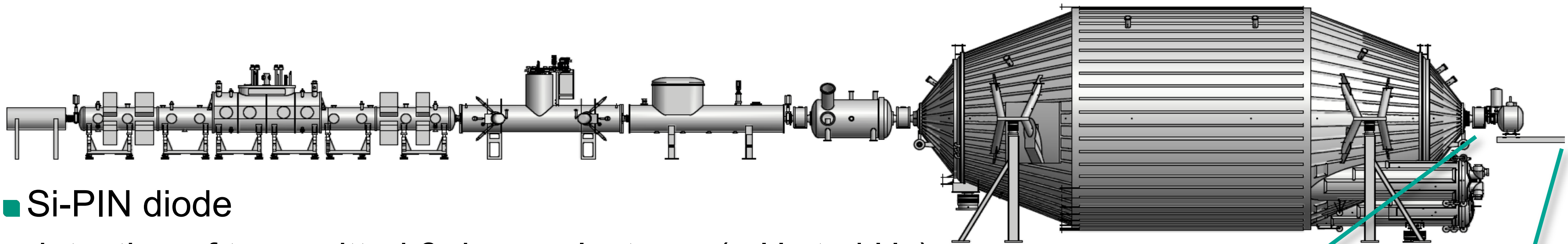




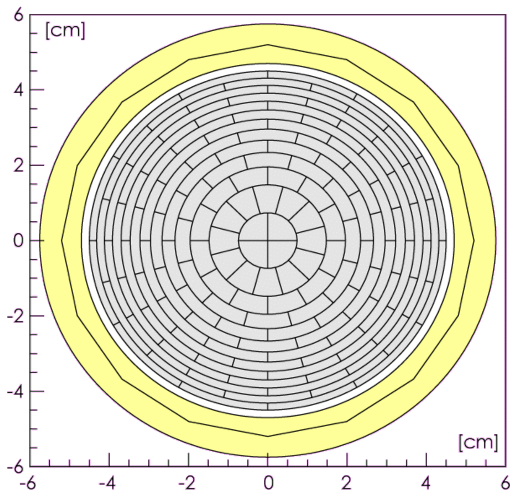


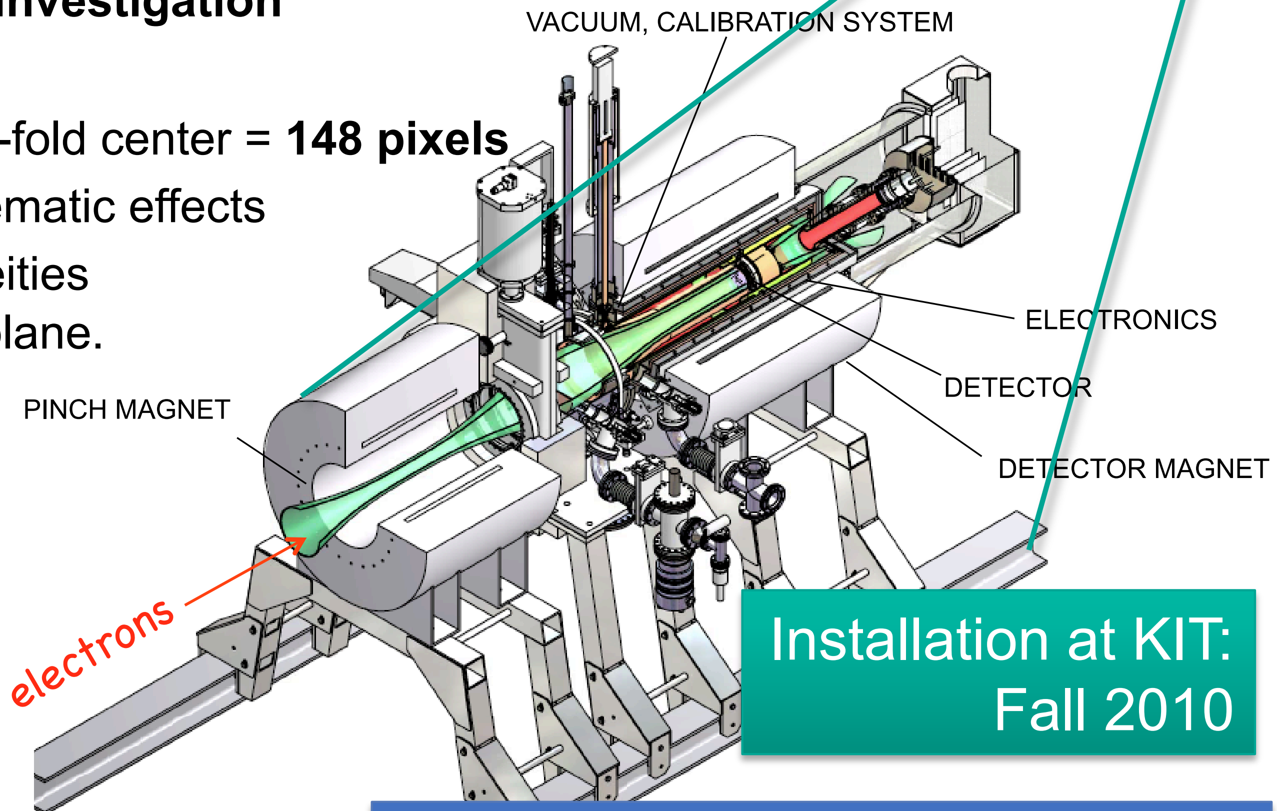
- earth magnetic/environmental fields distort magn. flux tube in low field region (0.3 mT)
- needs to be compensated!
- low field correction:
  - optimize flux tube
  - fine tune transmission and resolution.

Main Detector



- Si-PIN diode
- detection of transmitted β decay electrons (mHz to kHz)
- **low background for T_2 endpoint investigation**
- high energy resolution $\Delta E \approx 1$ keV
- 12 rings with 30° segmentation + 4-fold center = **148 pixels**
  - minimize bg, investigate systematic effects
  - compensate field inhomogeneities of spectrometer's analyzing plane.



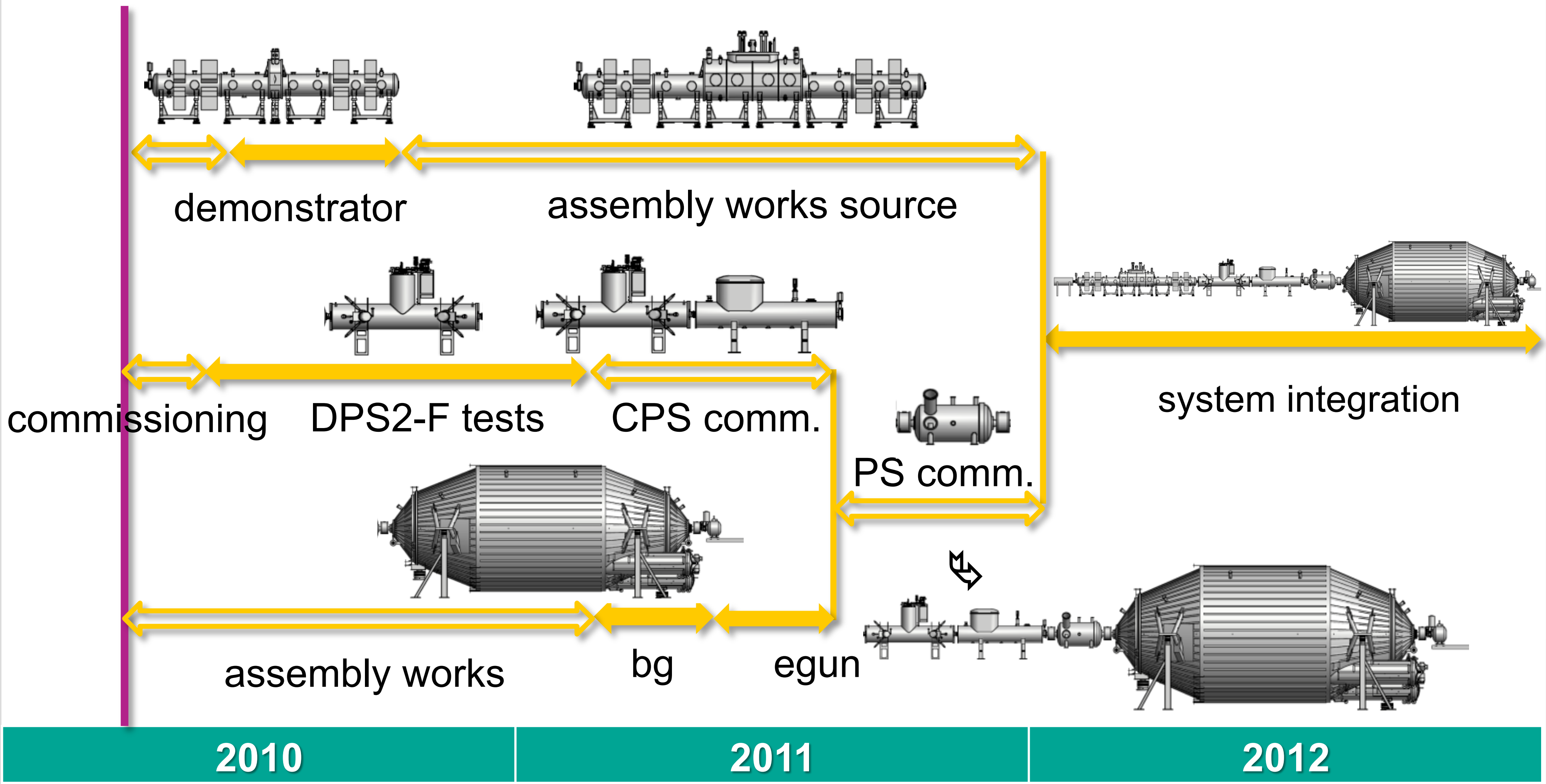


Installation at KIT: Fall 2010

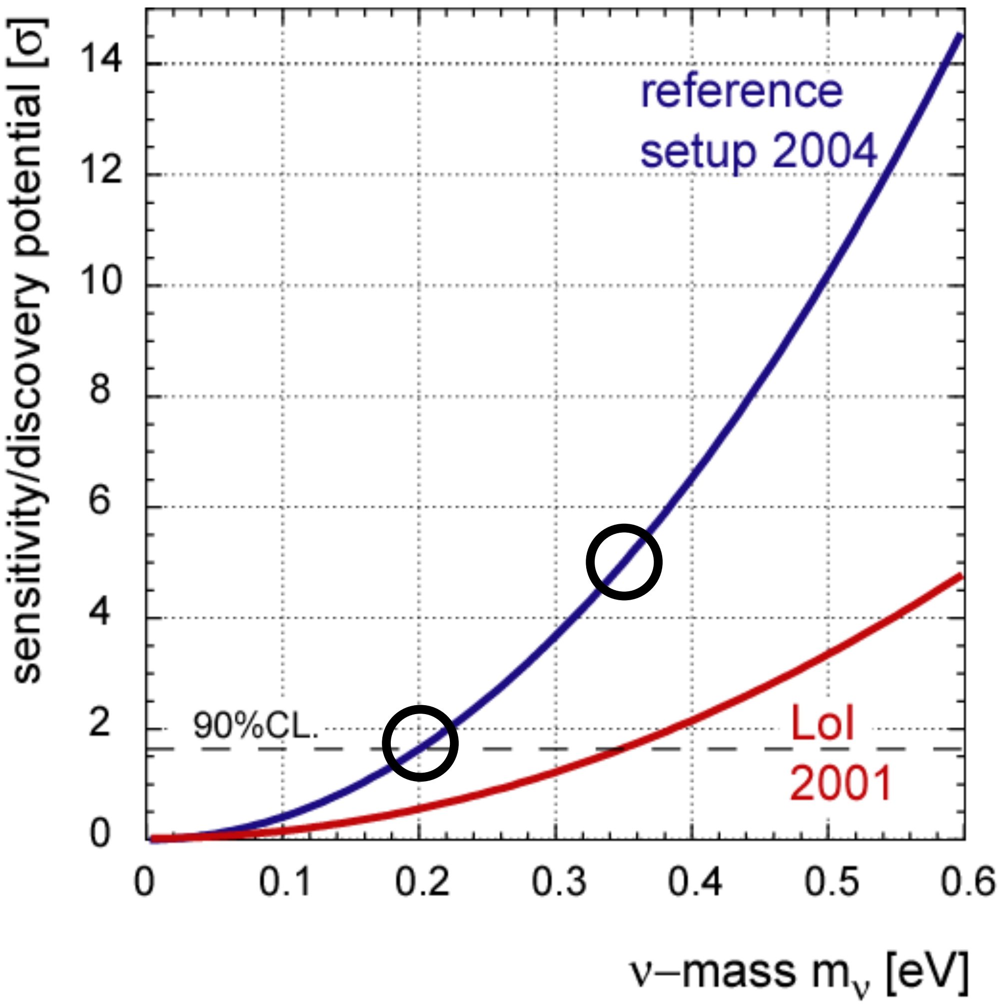
poster: A. Kaboth, P. Renschler, B. Wall

KATRIN Schedule

Goal: Commissioning of completed set-up in 2012



KATRIN Sensitivity



After 3 years data (5y realtime):

discovery potential
$m(\nu) = 0.35$ eV (5σ)

sensitivity (90% CL)
$m(\nu) < 0.2$ eV

$\Delta m_{tot}^2 = (\Delta m_{stat}^4 + \Delta m_{sys,tot}^4)^{½}$

$\Delta m_{tot}^2 \approx 0.025\ eV^2/c^4$

and

$\Delta m_{stat} = \Delta m_{sys,tot}$

$\Delta m_{stat}^2 = 0.018\ eV^2/c^4$

$\Delta m_{sys,tot}^2 \leq 0.017\ eV^2/c^4$

Summary and Outlook

- motivation for neutrino mass meas. from particle and astroparticle physics
- β decay offers a model-independent method to determine m_ν
- Re-based MARE is going to check present limits (Phase I) and KATRIN in future (Phase II)
- Project 8 proposes a new method for future experiments
- T_2-based KATRIN will reach a sensitivity of 0.2 eV on m_ν
- construction of KATRIN is going on and is on time for:
  - start of main spectrometer test program in 2011
  - complete system integration in 2012