Neutrino mass measurement with the KATRIN experiment

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(for the KATRIN collaboration)

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Prague ν13, 24 May 2013

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Karlsruhe Tritium Neutrino Experiment

KIT Karlsruhe Institute of Technology

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen
Grundlagenforschung

Neutrino mass:

Particle physics: mass generation mechanism
(fermion mass theory ?)

Cosmology: contribution to matter density, model input

SM:

left-handed and massles neutrinos

Neutrino oscillation experiments (solar, atmospheric, reactor, accelerator):

non-zero mass-squared differences → at least two neutrinos have non-zero masses

No information about absolute mass scale from neutrino oscillation experiments

Indirect neutrino mass determination

Cosmology, neutrinoless double beta decay:

Sensitive to absolute neutrino mass scale (even below 0.1 eV possible in future)
But: model dependent

Example for 00νβ:

It could be that the light massive neutrino mechanism is subdominant.
Dominant mechanism could be f.e.: R-parity violating supersymmetry, right-handed couplings, leptoquark exchange, etc.

In that case neutrinoless double beta decay experiments give only upper limits for the absolute neutrino mass scale.

Also: sensitive to Dirac and Majorana phases → cancellation possibility

Direct neutrino mass experiments

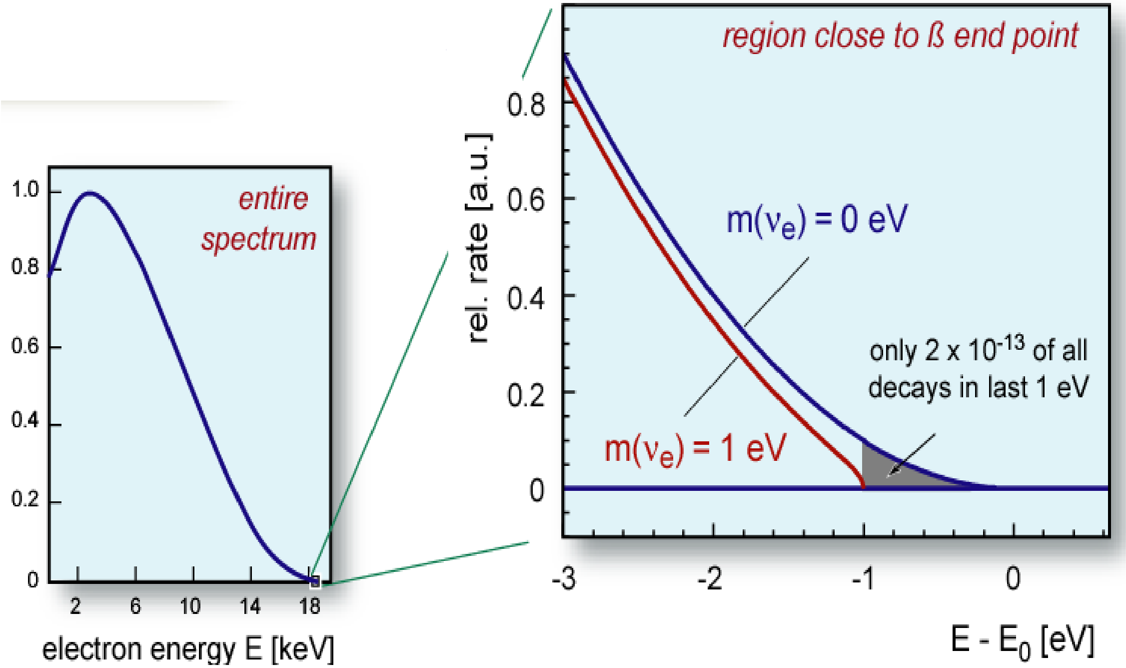
Electron energy spectrum close to endpoint of single beta decay:

$$w(E_e) \sim E_e p_e E_\nu p_\nu$$

$$\sim E_e p_e (E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m_\nu^2}$$

T_2 (E_0=18.6 keV):

KATRIN



Electron energy spectrum with general neutrino mixing:

mass eigenstates

$$\nu_e = \sum_i U_{ei}\,\nu_i$$

$$w(E_e) \sim E_e p_e (E_0 - E_e) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m_{\nu i}^2}\; \Theta(E_0 - E_e - m_{\nu i})$$

lepton mixing matrix elements

3 active neutrinos: small Δm_ν^2

→ effective electron neutrino mass definition:

$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_{\nu i}^2$$

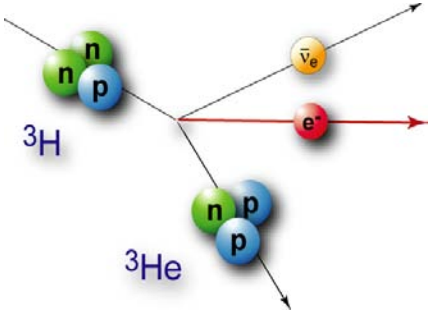
Not sensitive to phases !

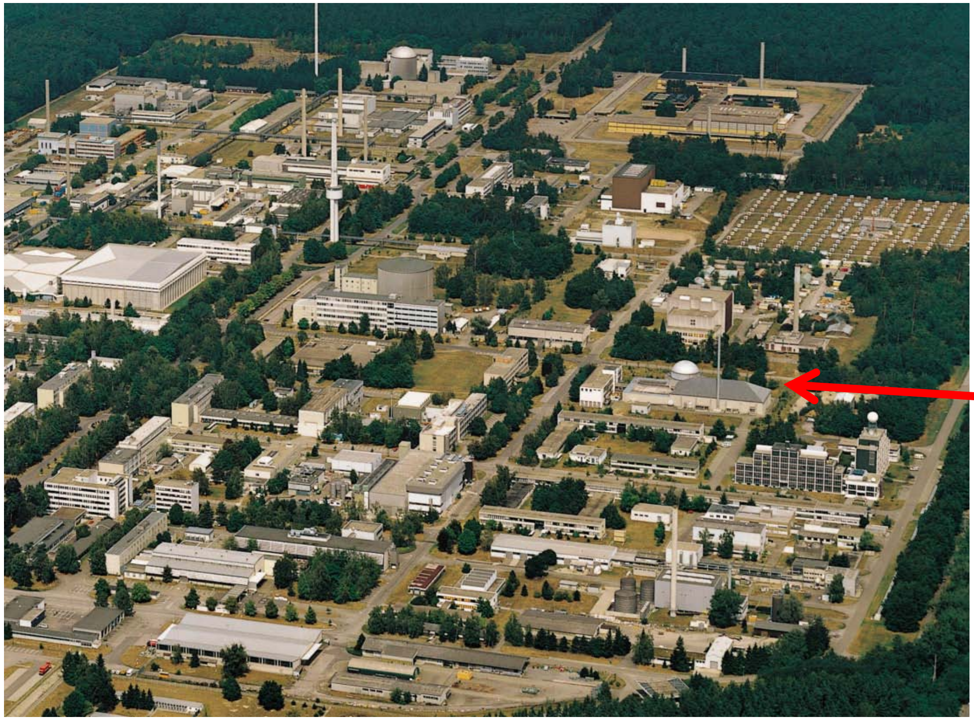
KATRIN experiment

Absolute neutrino mass scale determination down to 0.2 eV, with small model dependence.

Integral electron energy spectrum measurement
(MAC-E filter method),
close to endpoint of molecular tritium beta decay.

^{3}H: super-allowed	
E_0	18.6 keV
$t_{1/2}$	12.3 y





KIT (Karlsruhe Institute of Technology) campus north, Germany

KATRIN: at TLK (Tritium Laboratory Karlsruhe)

Collaboration:
Germany, USA, Russia,
Czech Rebublik, Great Britain

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

universität mainz

Uni Bonn

KATRIN
Karlsruhe Tritium Neutrino Experiment

ASTeC

Institute for Nuclear Research

University of Washington

Fachhochschule Fulda
University of Applied Sciences

UNIVERSITÄT
KARLSRUHE (TH)

Advantages of tritium:

- Superallowed transition: → matrix element M is not energy dependent
- Low endpoint energy: → relative decay fraction at the endpoint is comparatively high
- Short half life: → specific activity is high
  → low amount of source material
  → low fraction of inelastic scattered electrons
- Hydrogen isotope: → simple atomic shell
  → final states precisely calculable

Status of previous tritium experiments

Mainz & Troitsk have reached their intrinsic limit of sensitivity

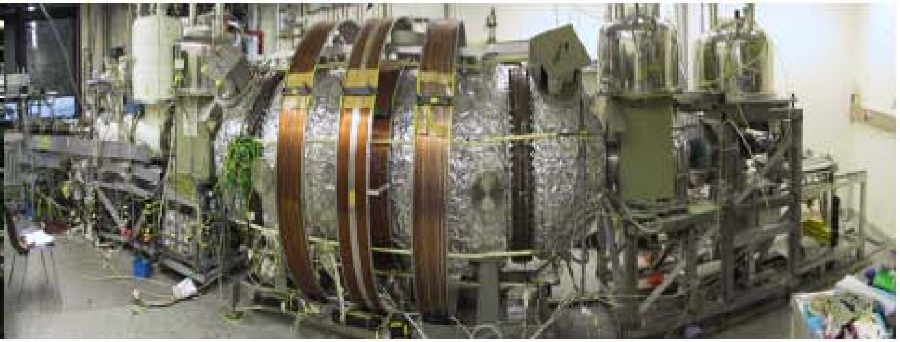
Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0 \ \mathrm{eV}^2$

$m_\nu \leq \quad 2.2 \ \mathrm{eV}$ (95% CL.)



Mainz

quench condensed solid T_2 source

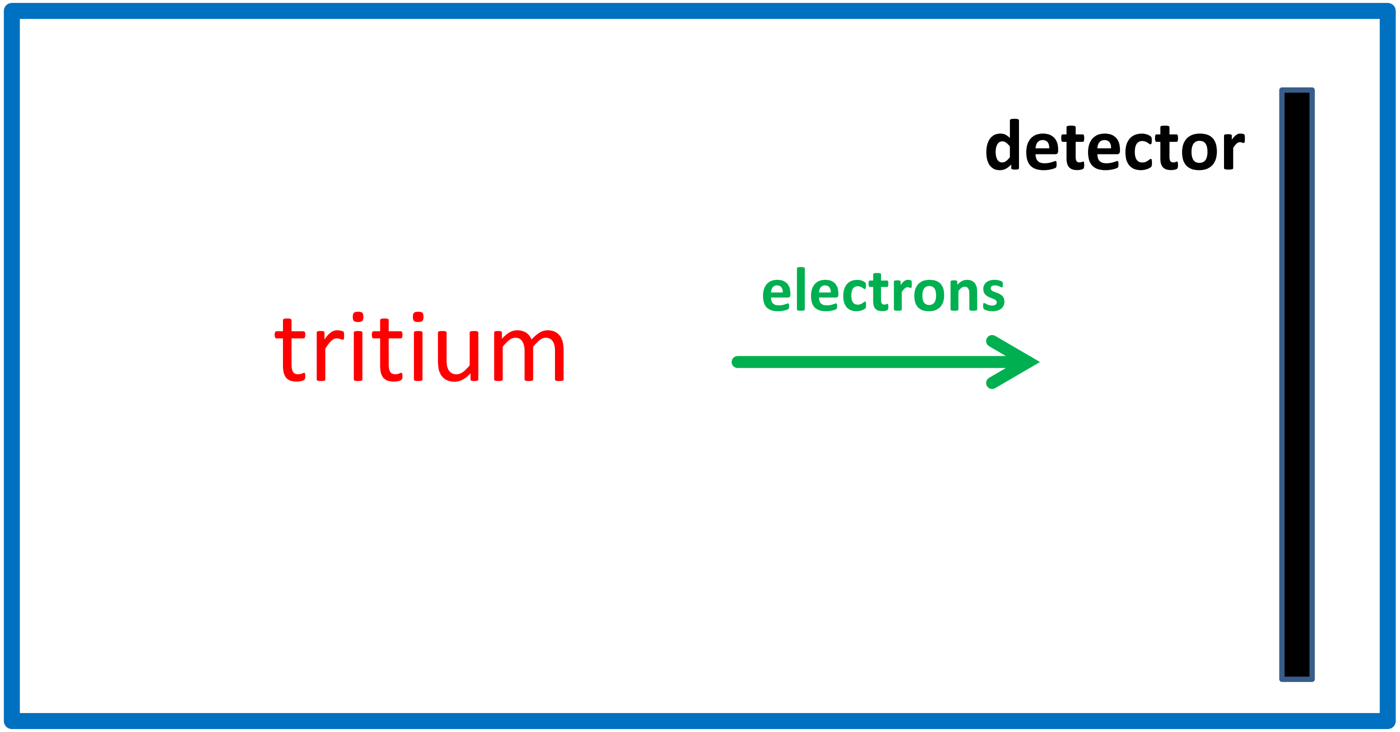
analysis 1998/99, 2001/02

$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1 \ \mathrm{eV}^2$

$m_\nu \leq \quad 2.2 \ \mathrm{eV}$ (95% CL.)

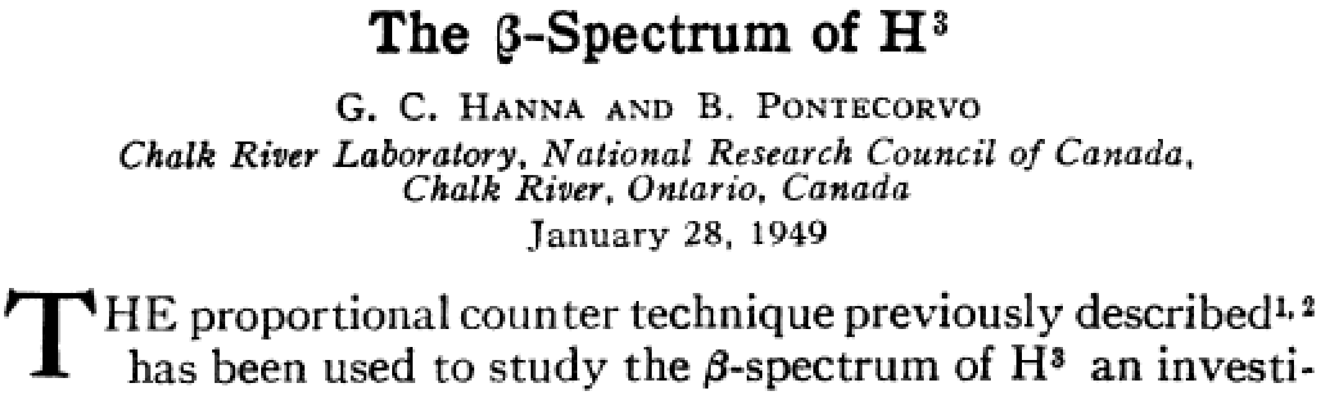
Goal of KATRIN: **factor 10 improvement**

Simple energy spectrum measurement method



Problems:

- no electron detector with 1 eV resolution
- extremely large rate



The β-Spectrum of H^3

G. C. HANNA AND B. PONTECORVO

Chalk River Laboratory, National Research Council of Canada,
Chalk River, Ontario, Canada

January 28, 1949

THE proportional counter technique previously described[1, 2] has been used to study the β-spectrum of H^3 an investi-

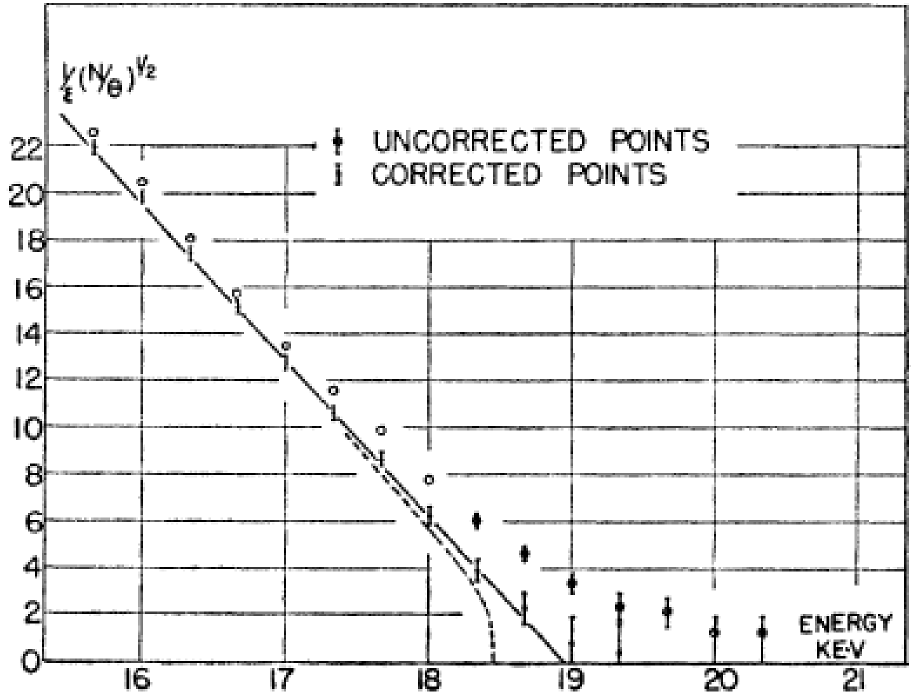
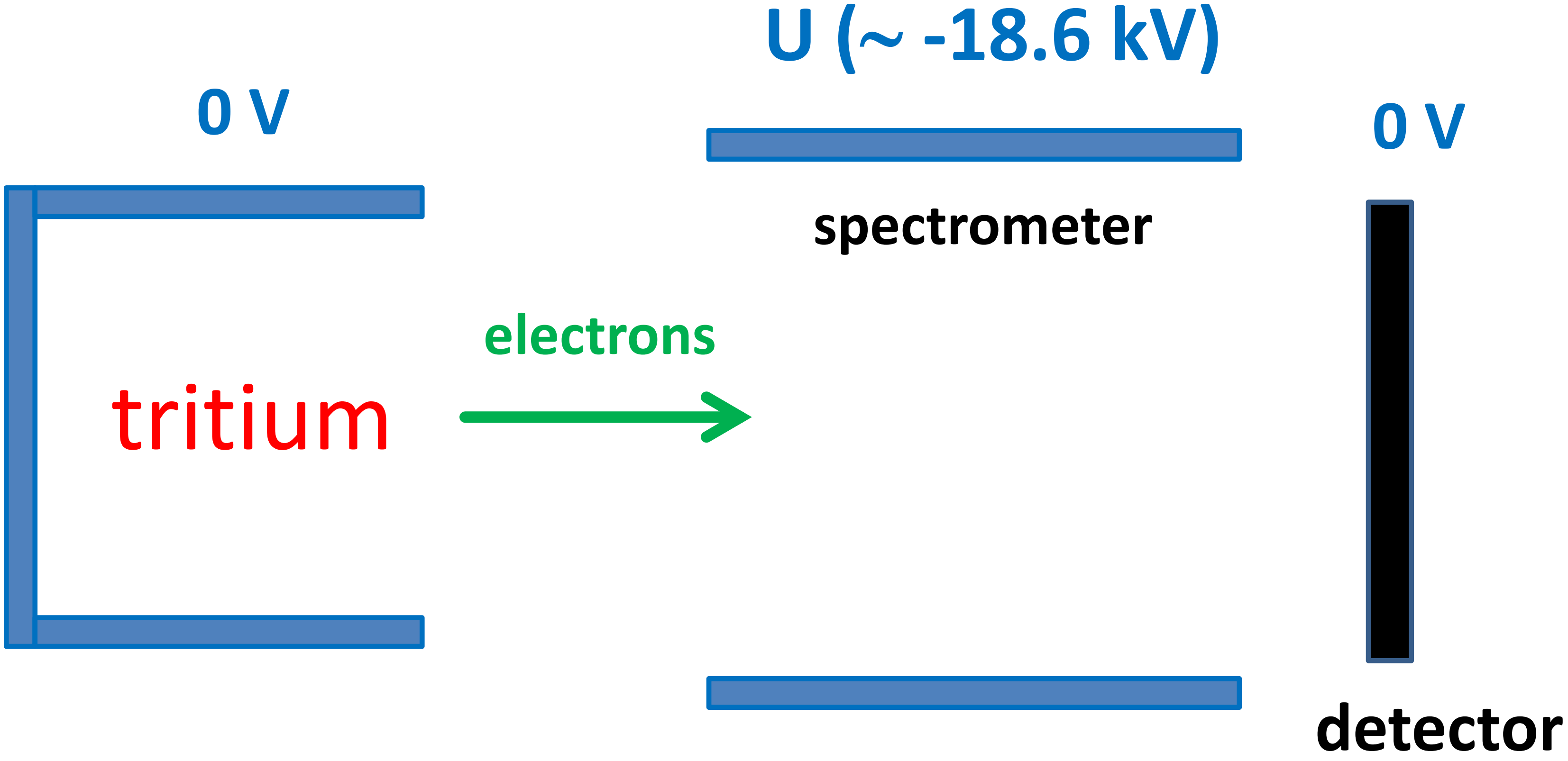
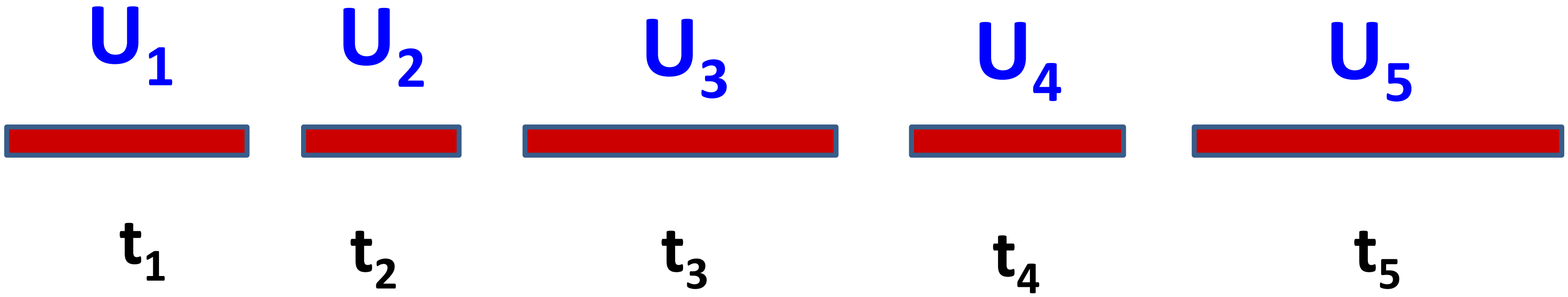
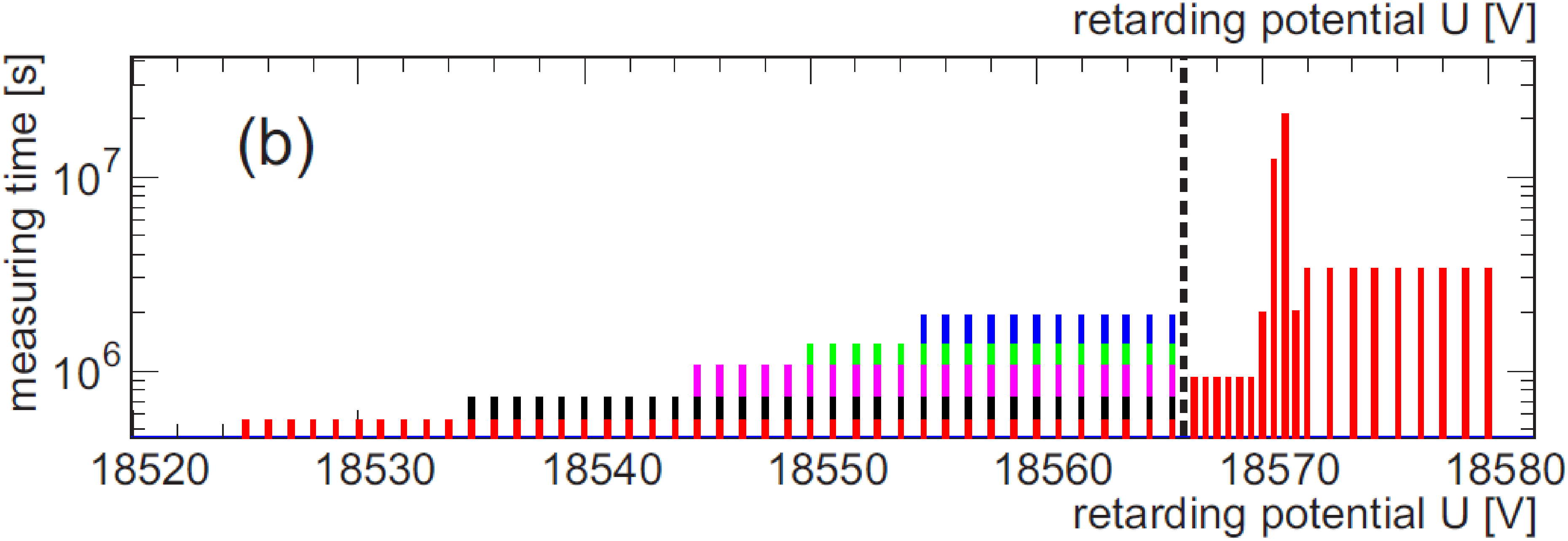


FIG. 2. "Kurie" plot of the end of the H^3 spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.

Integral energy spectrum measurement with spectrometer at negative potential between source and detector

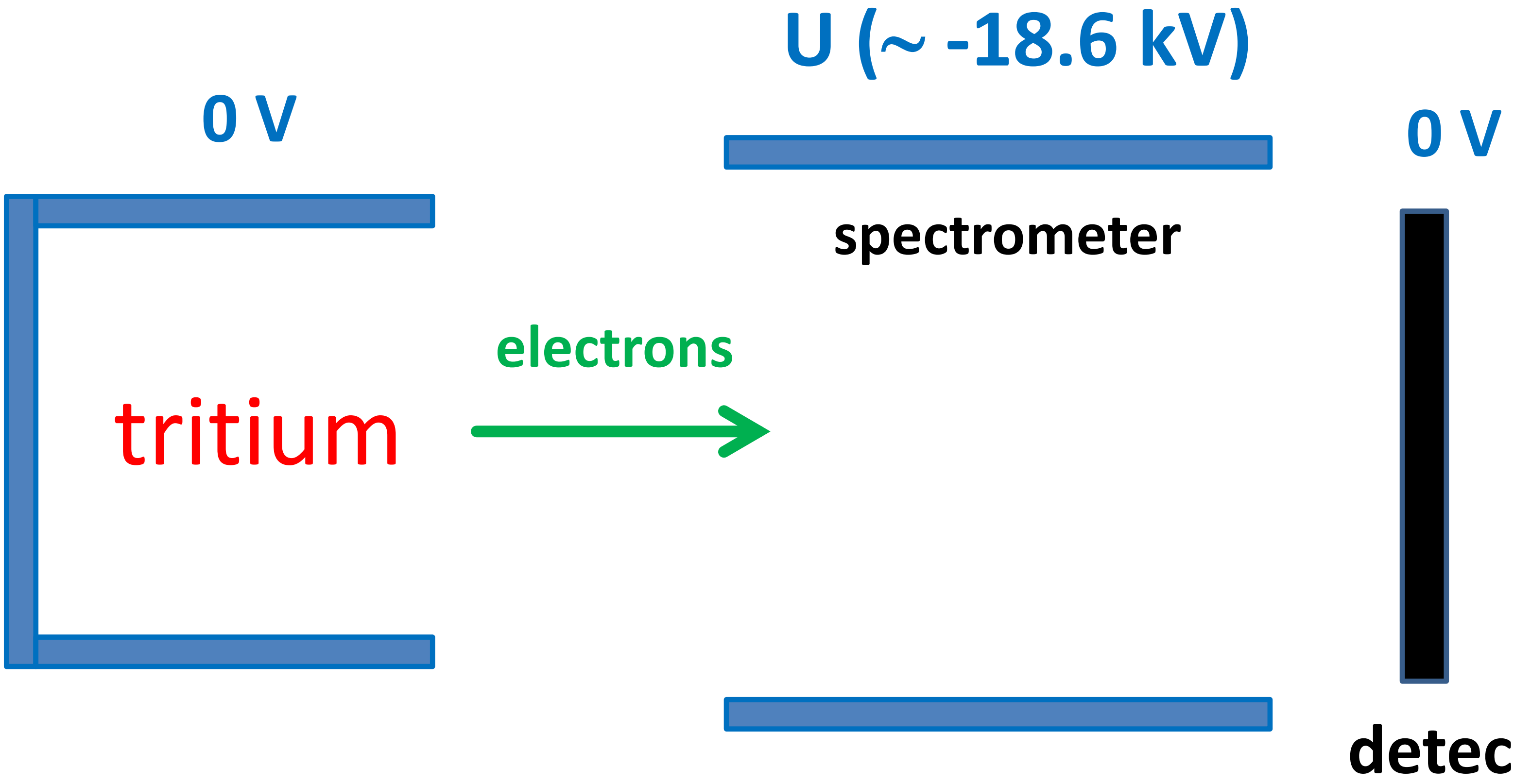






Measured number of events: N_1, N_2, N_3, … → integral spectrum; neutrino mass determination by fit

Integral energy spectrum measurement with spectrometer at negative potential between source and detector



U (~ -18.6 kV)

0 V

0 V

spectrometer

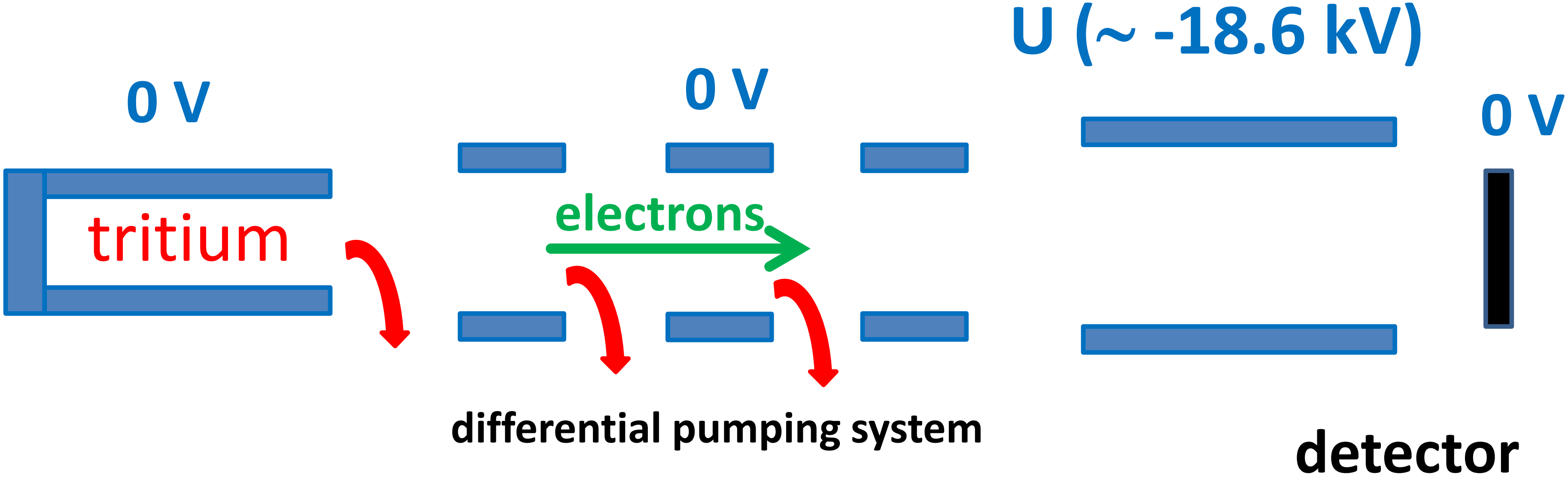
electrons

tritium

detector

Problem: tritium beta decays inside and beyond the negative potential region (no material window allowed between source and spectrometer: energy loss !)

Reducing the tritium flow into the spectrometer by differential pumping system (large distance between source and spectrometer)



U (~ -18.6 kV)

0 V

0 V

0 V

tritium

electrons

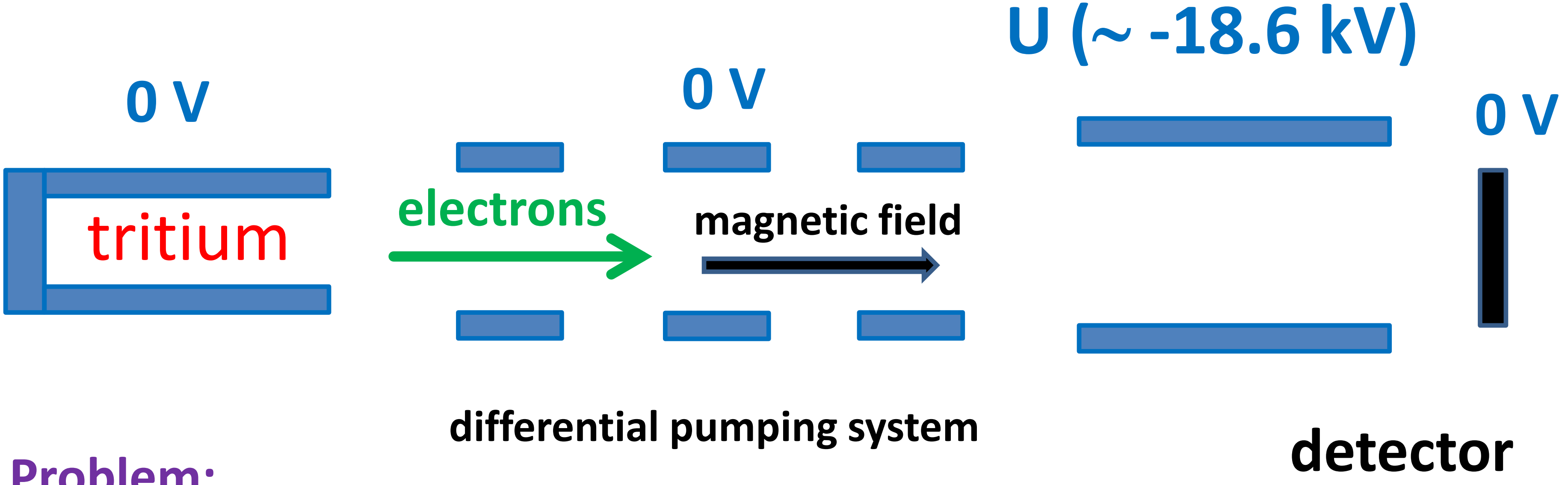
differential pumping system

detector

Problem: Most of the beta decay electrons do not get to detector (small solid angle)

Guiding the beta electrons by magnetic field

Electrons follow the magnetic field lines
(in adiabatic approximation)

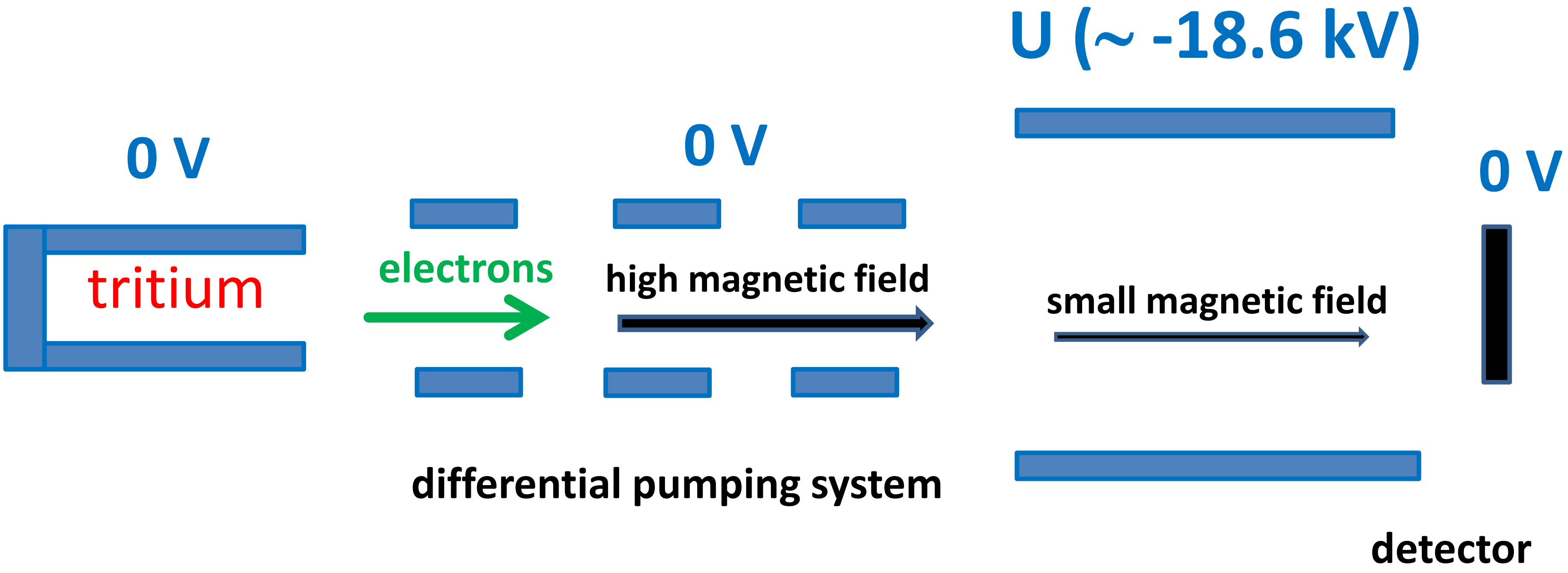


Problem:

Electric field can change only the longitudinal energy
→ most of the electrons with larger transversal energy do not get to detector

Converting the transversal energy into longitudinal energy by inverse magnetic mirror effect

Adiabatic approx.: orbital magnetic moment E_{trans} / B is constant



U (~ -18.6 kV)

0 V

0 V

0 V

tritium

electrons

high magnetic field

small magnetic field

differential pumping system

detector

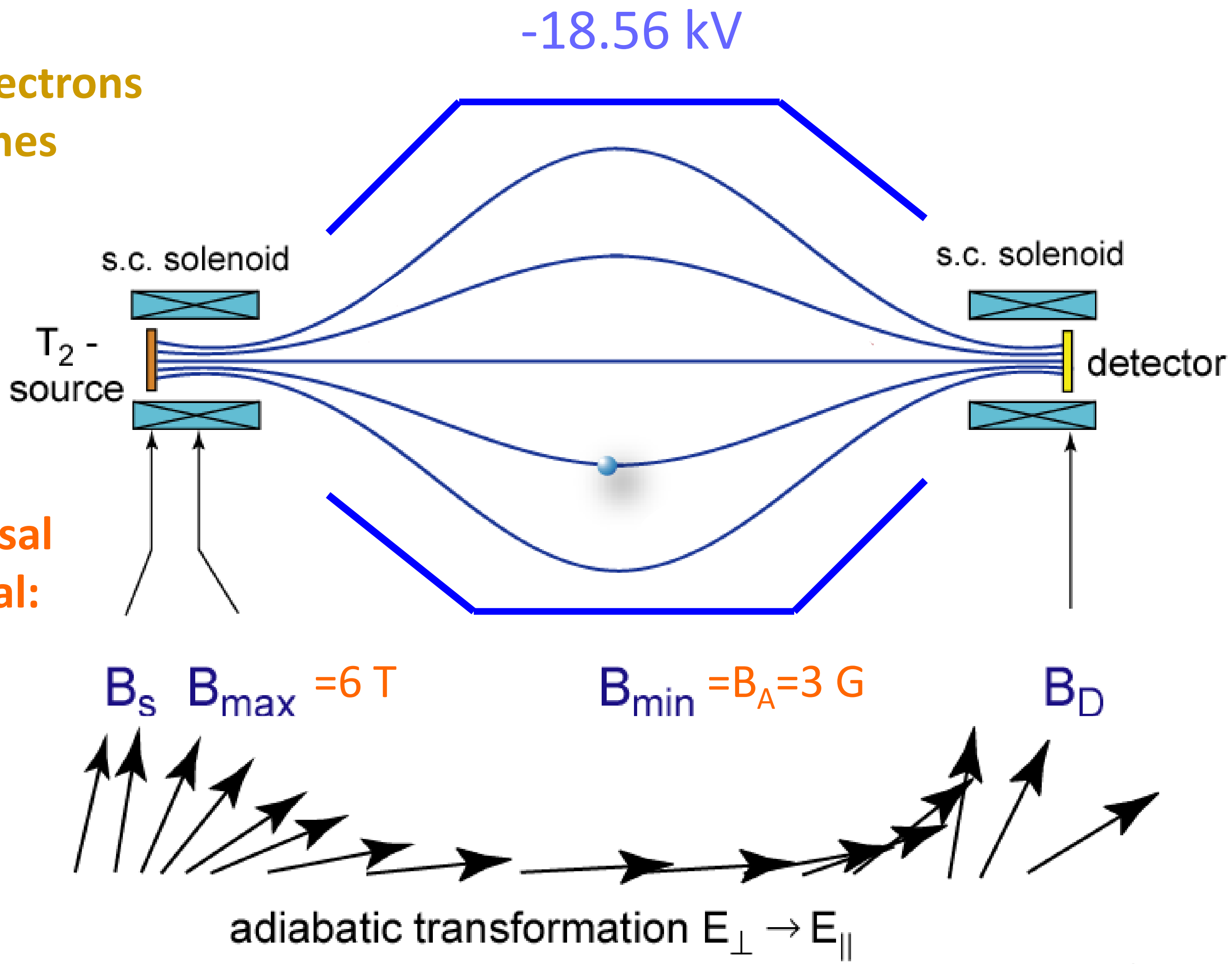
principle of an electrostatic filter with magnetic adiabatic collimation (MAC-E)

Adiabatic guiding of electrons along magnetic field lines

Energy analysis: electric field can change longitudinal energy

Conversion of transversal energy into longitudinal: by inverse magnetic mirror effect

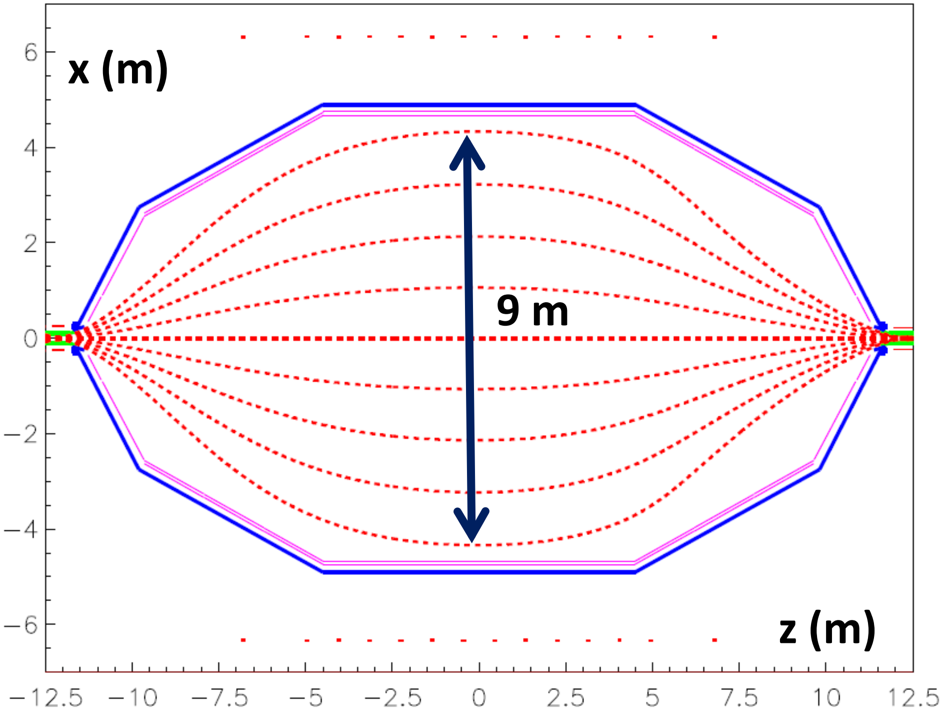
Constant magnetic flux, Bmin small: large spectrometer diameter (10m)



Flux tube : defined by magnetic field lines going through the source

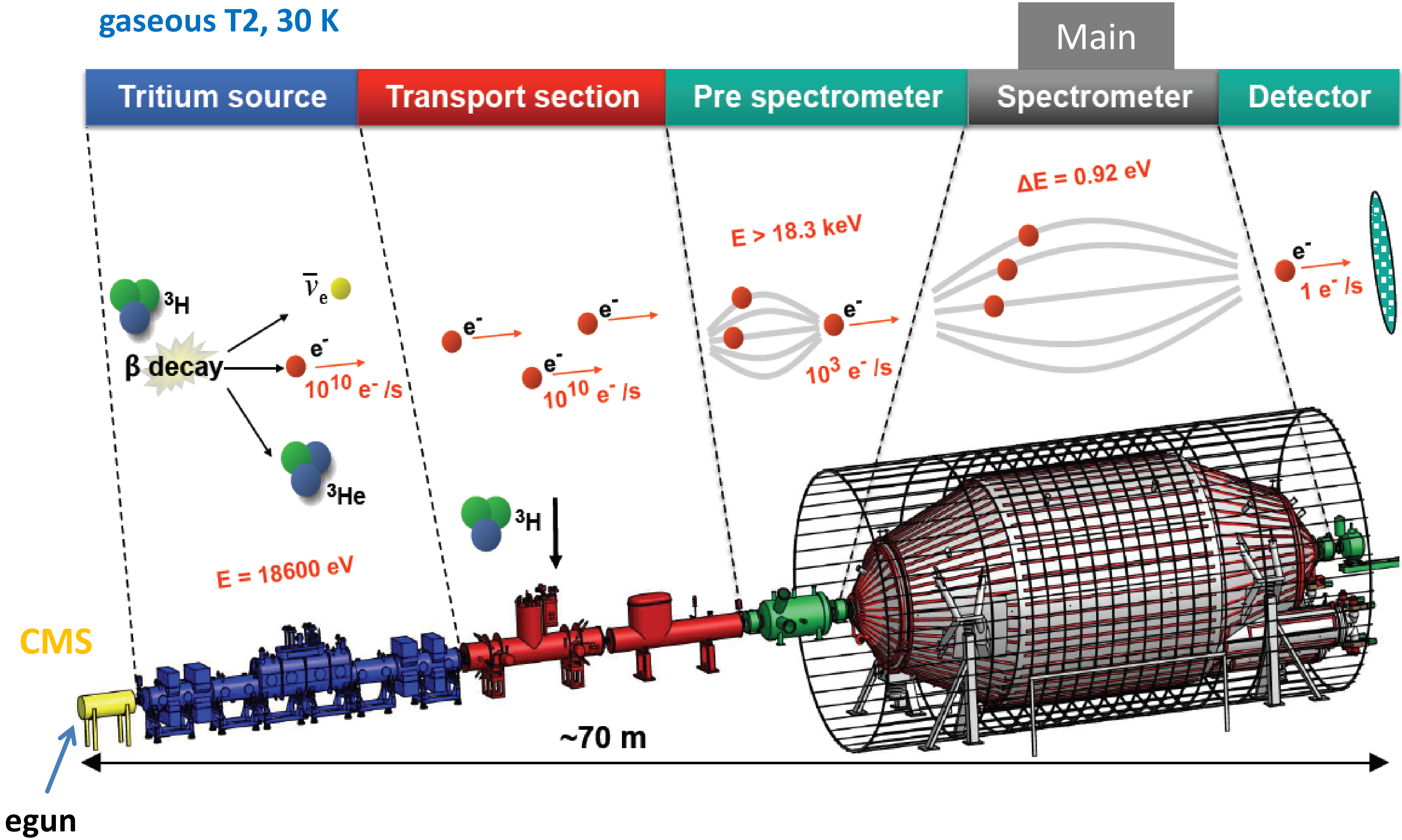
Magnetic flux constant in flux tube: $d_S^2 B_S = d_A^2 B_A$

KATRIN: $B_S / B_A \approx 10000$ $d_S =$ 9 cm $d_A =$ 9 m



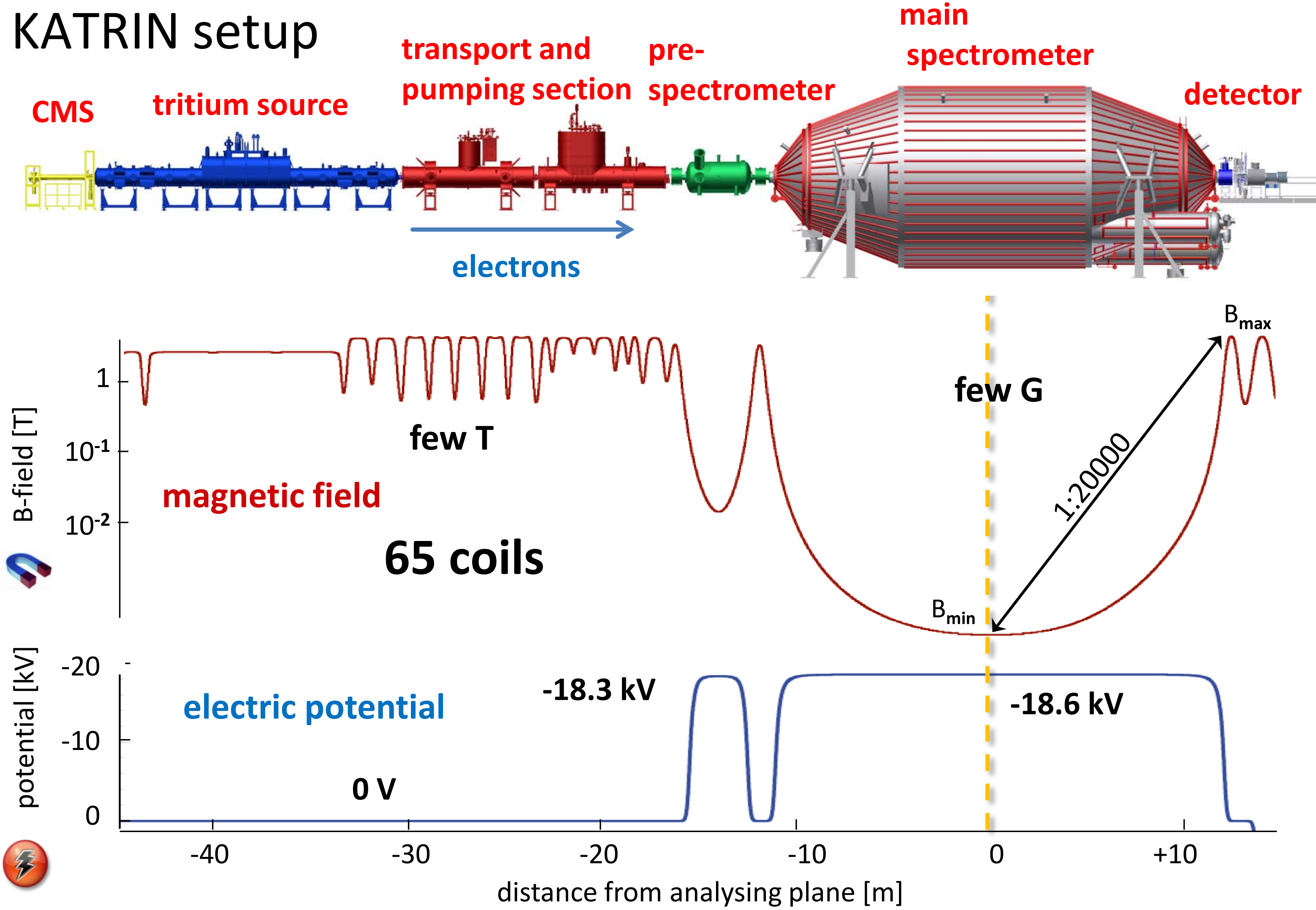
MAC-E filter: **high energy resolution (no tail at the low energy part), high luminosity, low background**

gaseous T2, 30 K



KATRIN system

KATRIN setup

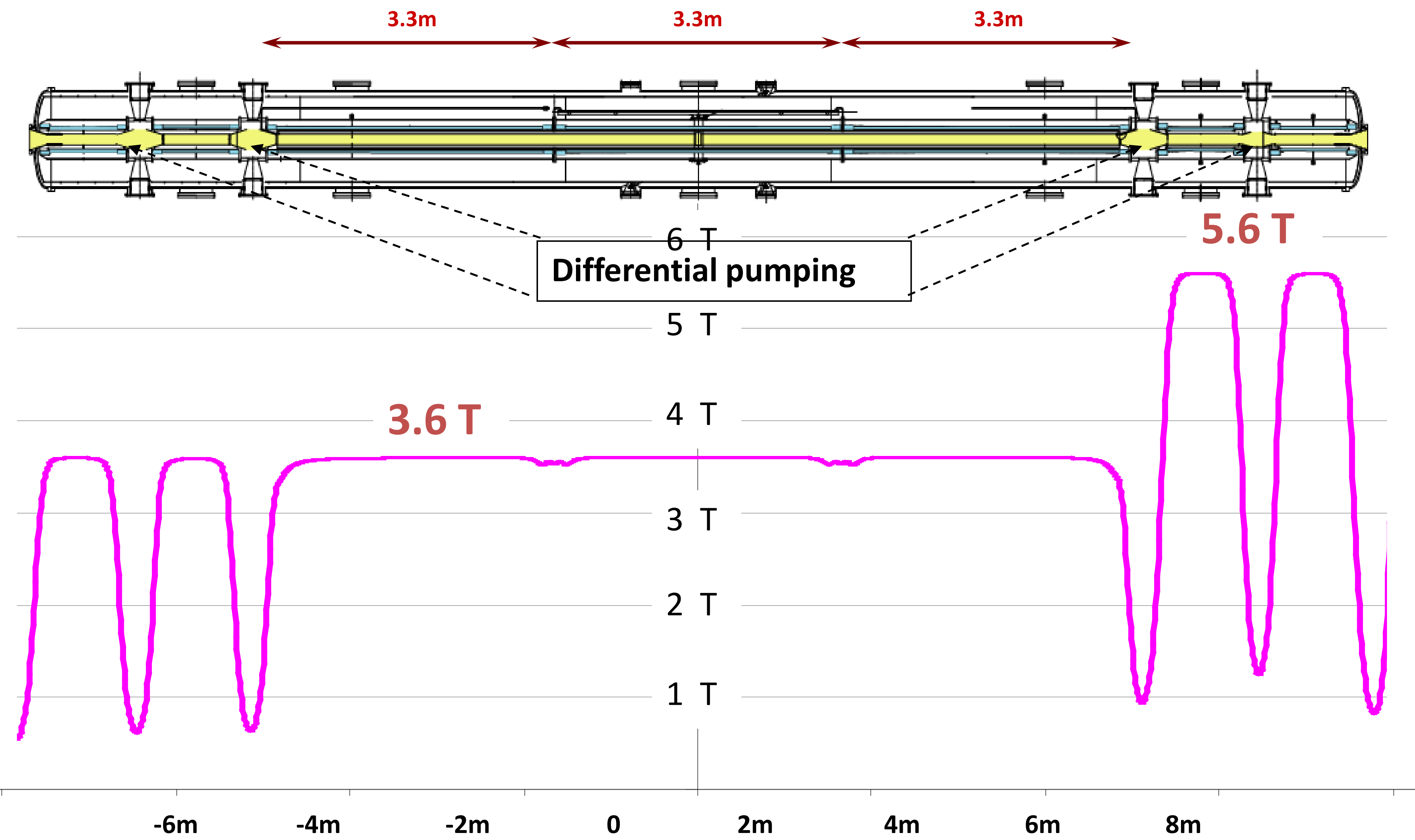


WGTS

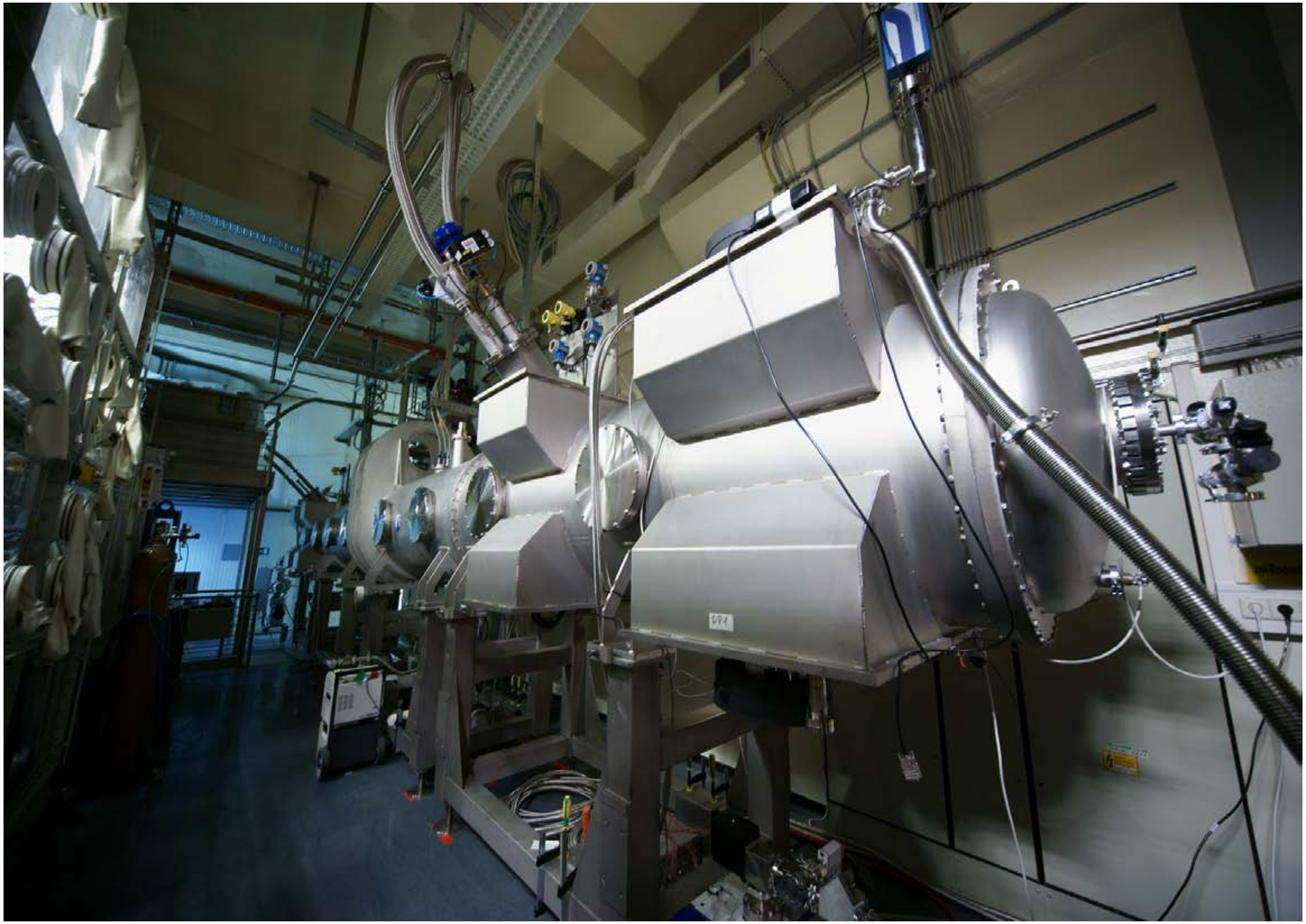
Windowless Gaseous Tritium Source

7 sc. magnet modules (3.6 T, 5.6 T); axisymmetric + dipole coils
12 turbomolecular pumps
Tritium gas temperature: 30 K
Tritium purity: > 95 %
Column density: 5 x 10^{17} mol/cm^2
Beta decay rate: 10^{11}/s

WGTS – magnetic field



F. Glück, KIT Neutrino13, Prague



WGTS Demonstrator at KIT-TLK: to test cooling concept
(without sc magnets)

Temperature stability: 3 mK
(requirement: 30 mK)

Plasma effects

Beta decay and ionization:

$$T_2 \longrightarrow (^3HeT)^+ + e^- + \bar{\nu}_e$$

$$e_p^- + T_2 \rightarrow e_p^- + e_s^- + T_2^+$$

$$e_p^- + T_2 \rightarrow e_p^- + e_s^- + T^+ + T$$

a lot of electrons and
ions in tritium source
→ plasma

From simulation: secondary electrons cool down to gas temperature → average electron energy: few meV → space charge potential cannot be much larger than few mV → systematic effect to neutrino mass probably not significant

Experimental information:

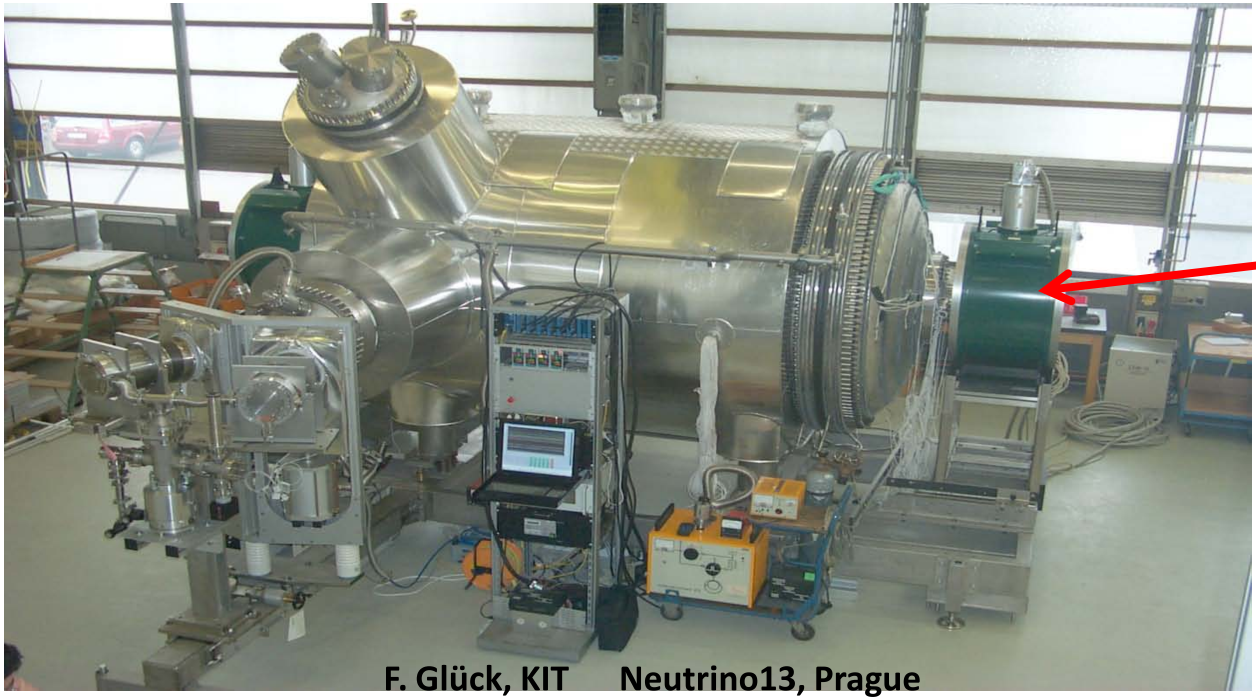
- ^{83m}Kr in tritium source (change of Kr lines due to plasma effects)
- egun electrons through tritium source (change of energy due to plasma instabilities)

Pre-spectrometer

- Optimize the background by its potential
- Additional tritium pump
- Prototype for main spectrometer (important !)

Delivered : 2003
Length: 3.4 m, diameter: 1.5 m

First measurements: 2006



Sc. magnet
max.
4.5 T

First pre-spectrometer measurements:

Strong Penning discharge:
increasing magnetic field →
pressure and leakage current increase, electric breakdown

Caused by deep (few kV) Penning traps

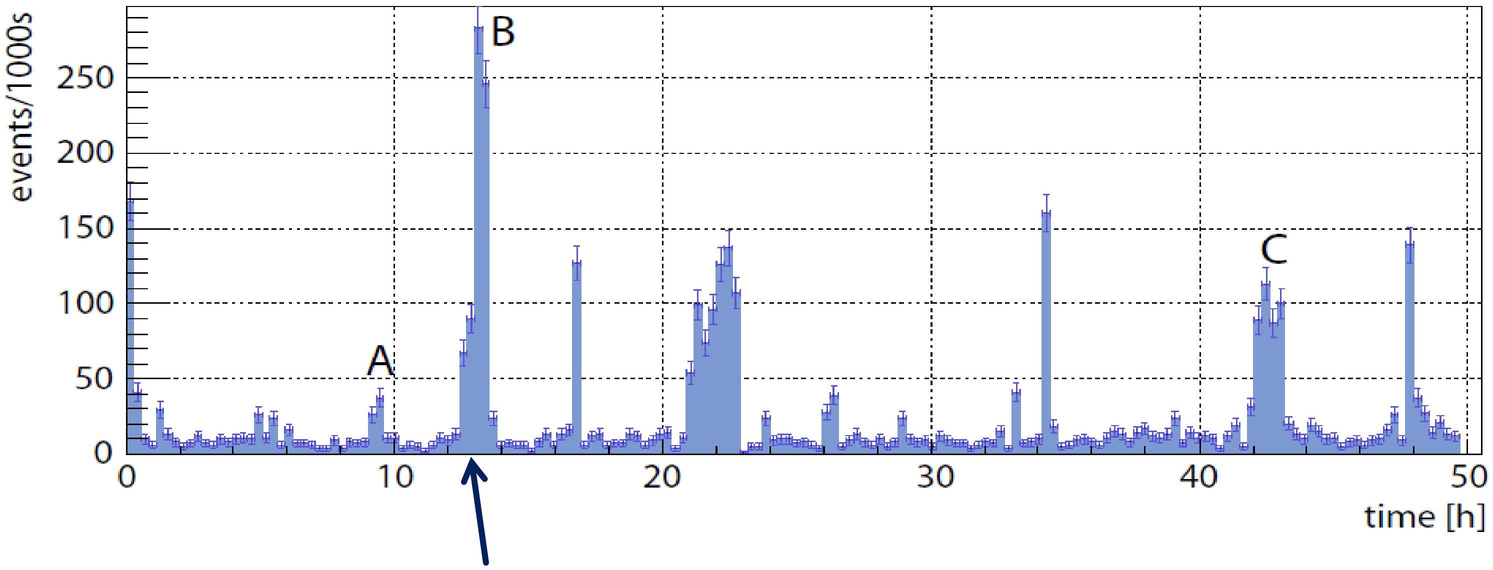
Eliminating the Penning traps (by a new shielding electrode)
→ strong Penning discharge disappeared !

Measurements with detector: large background (few 100 Hz) at high magnetic field

Caused again by Penning traps (at the ground electrode, few mm dimensions)

New ground electrode: no Penning traps → background reduction by factor 100000 !

Background from radon decays



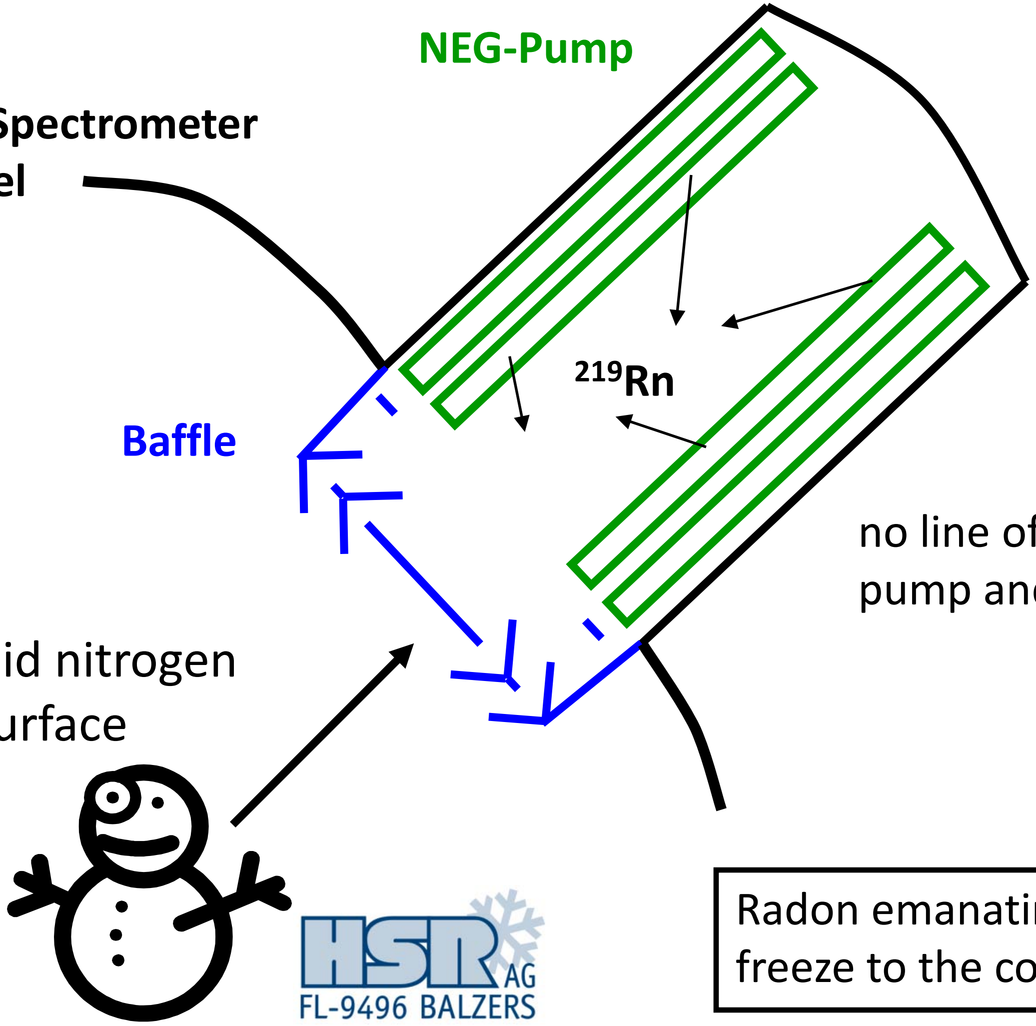
many secondary electrons
from 1 high energy primary electron

- background from high energy stored electrons
- high energy electrons come from Rn decays
- Rn comes from getter

Background reduction
(from few 10 mHz to few mHz):

- removing getter from pump ports
- cooled baffle, preventing radon transport from getter into spectrometer

Baffle Setup at Pre-Spectrometer



NEG-Pump

Pre-Spectrometer vessel

45° pump port

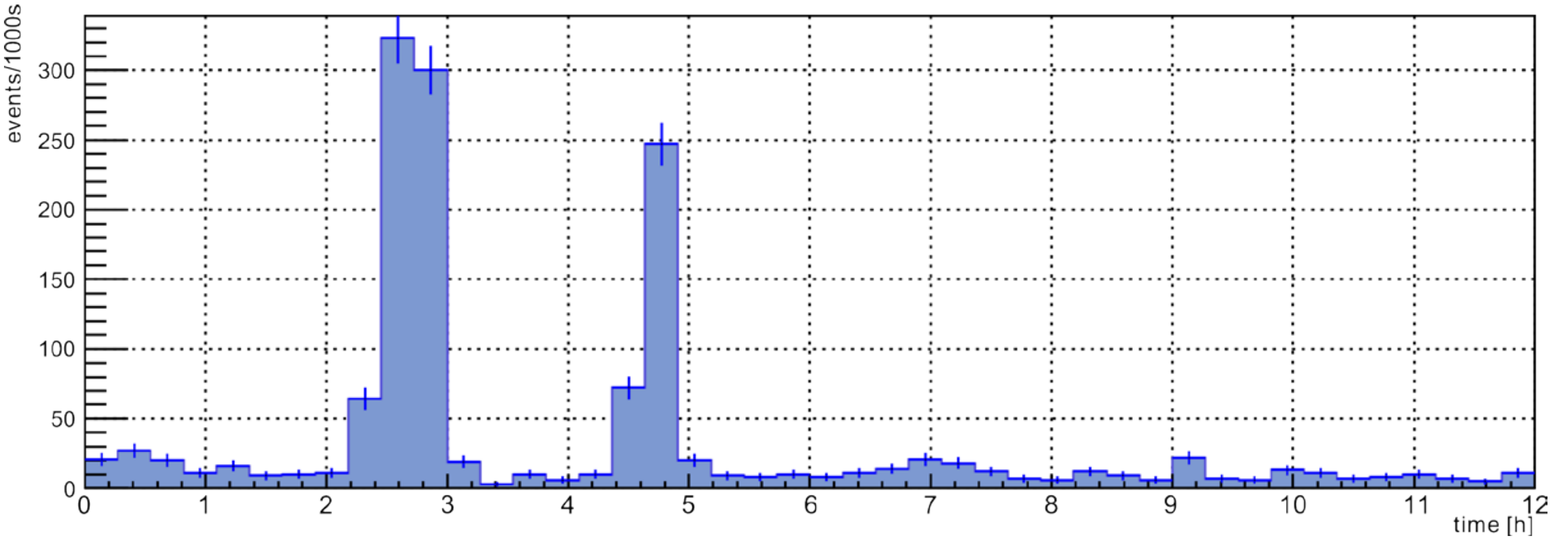
^{219}Rn

Baffle

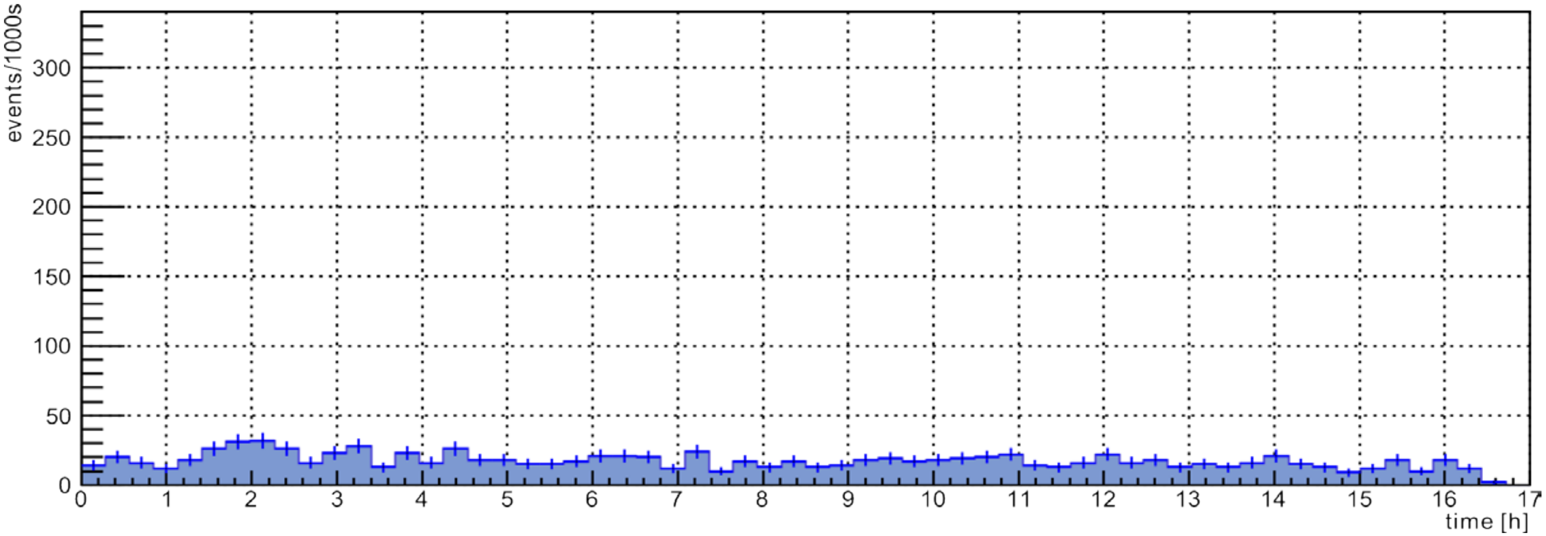
no line of sight between pump and vacuum chamber

with liquid nitrogen cooled surface

Radon emanating from the getter freeze to the cold surface of the Baffle



Background in pre-spectrometer with warm baffle

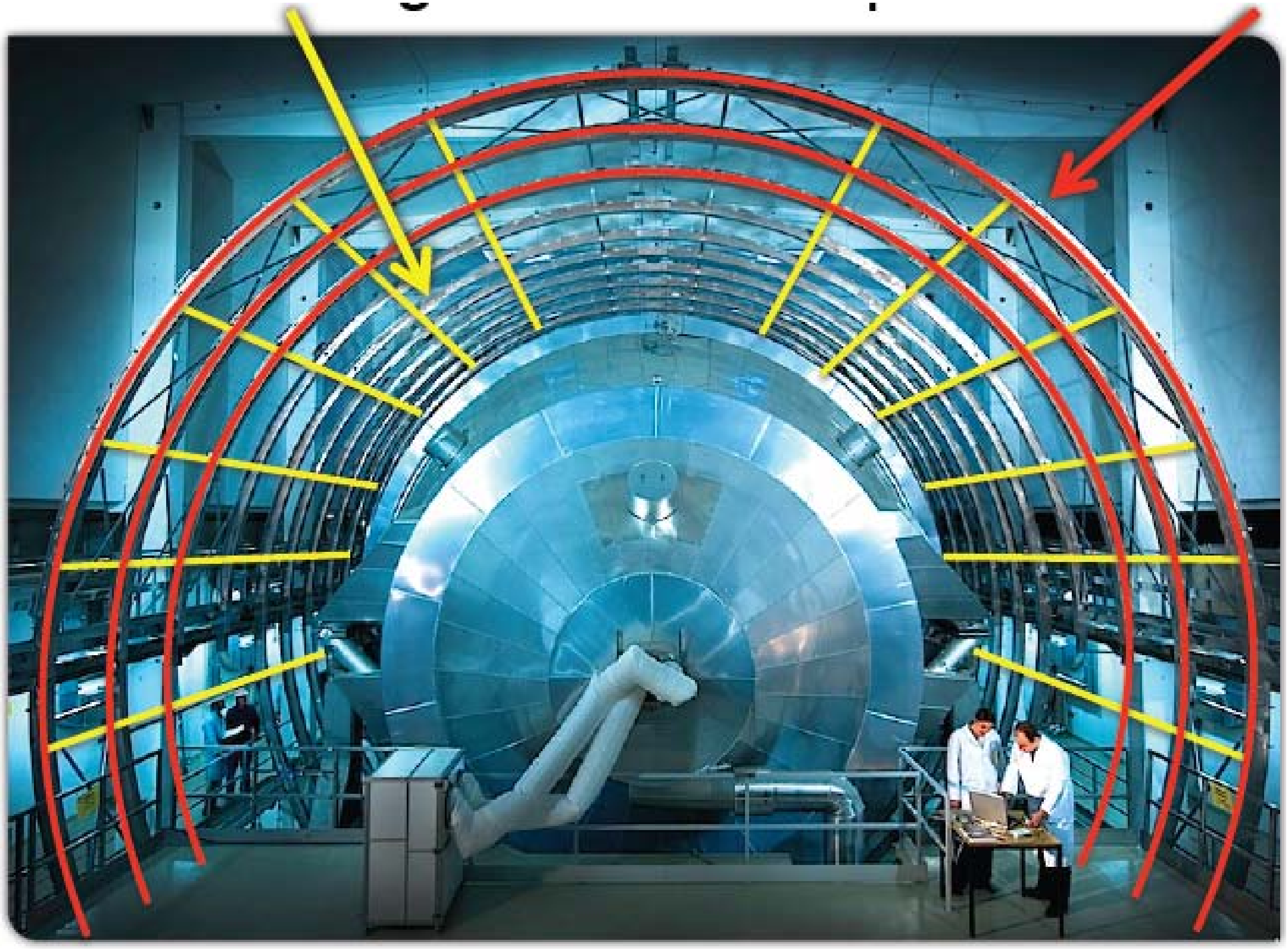


Background in pre-spectrometer with cold baffle

KATRIN main spectrometer

24 m long, 10 m diameter, stainless steel: 3 cm thick, 200 t.
Vacuum inside: 10^{-11} mbar.

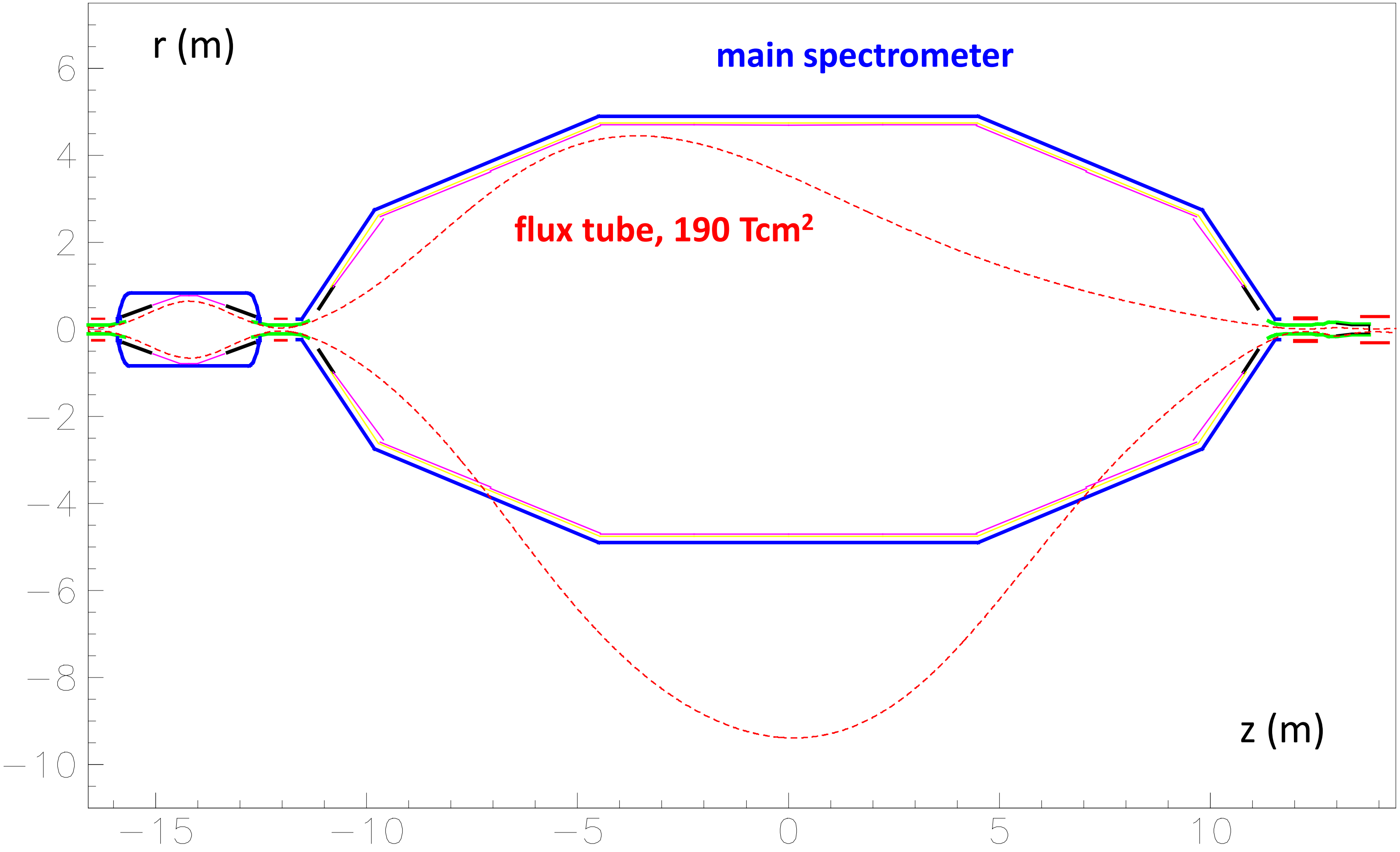
Air coils



earth magnetic field compensation coils

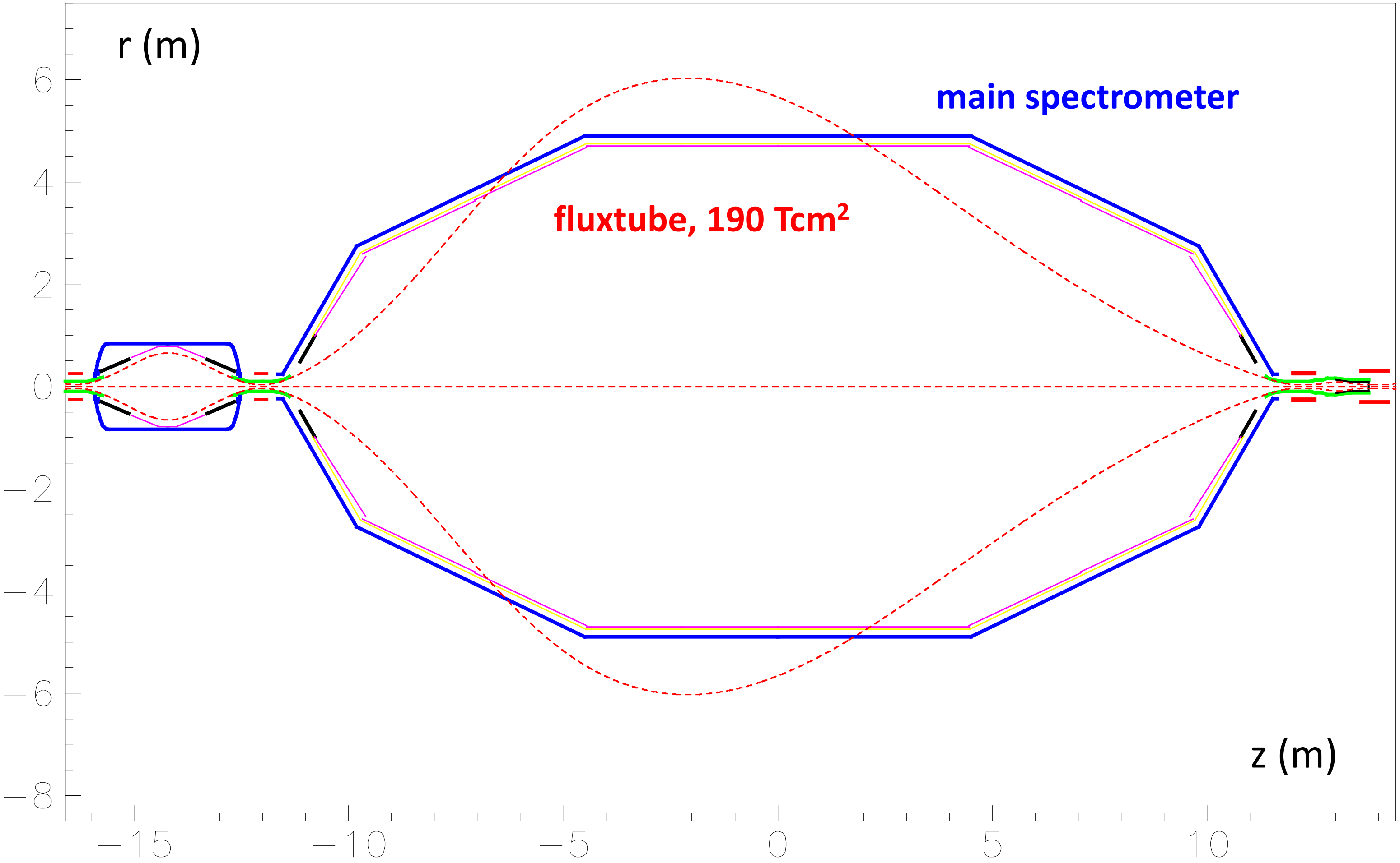
axisymmetric air coils

Flux tube magnetic field lines without air coils:
shift of field lines due to earth magnetic field

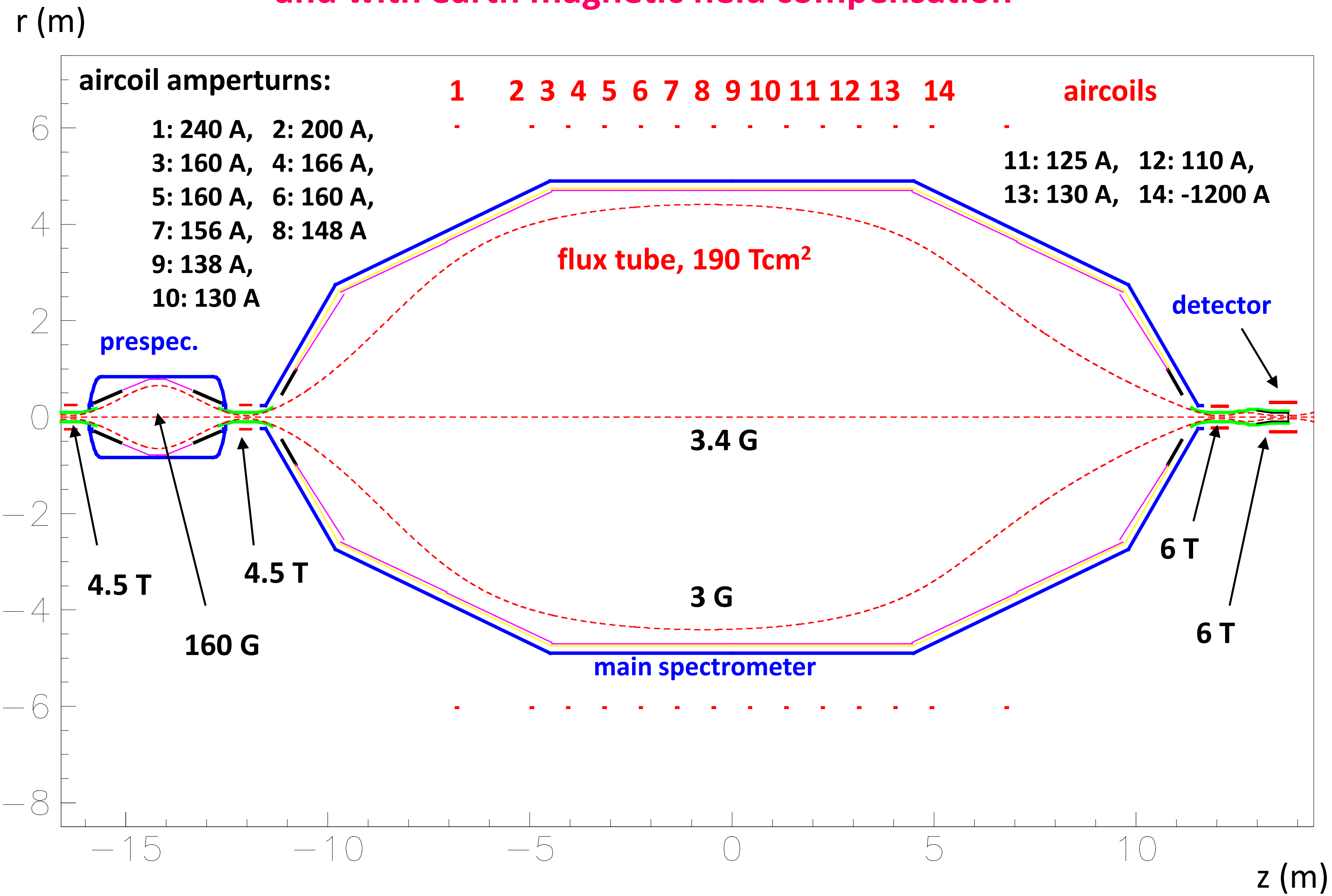


Flux tube magnetic field lines without axisymmetric air coils, but with earth magnetic field compensation:

axisymmetric air coils are also needed



Flux tube magnetic field lines with axisymmetric air coils and with earth magnetic field compensation

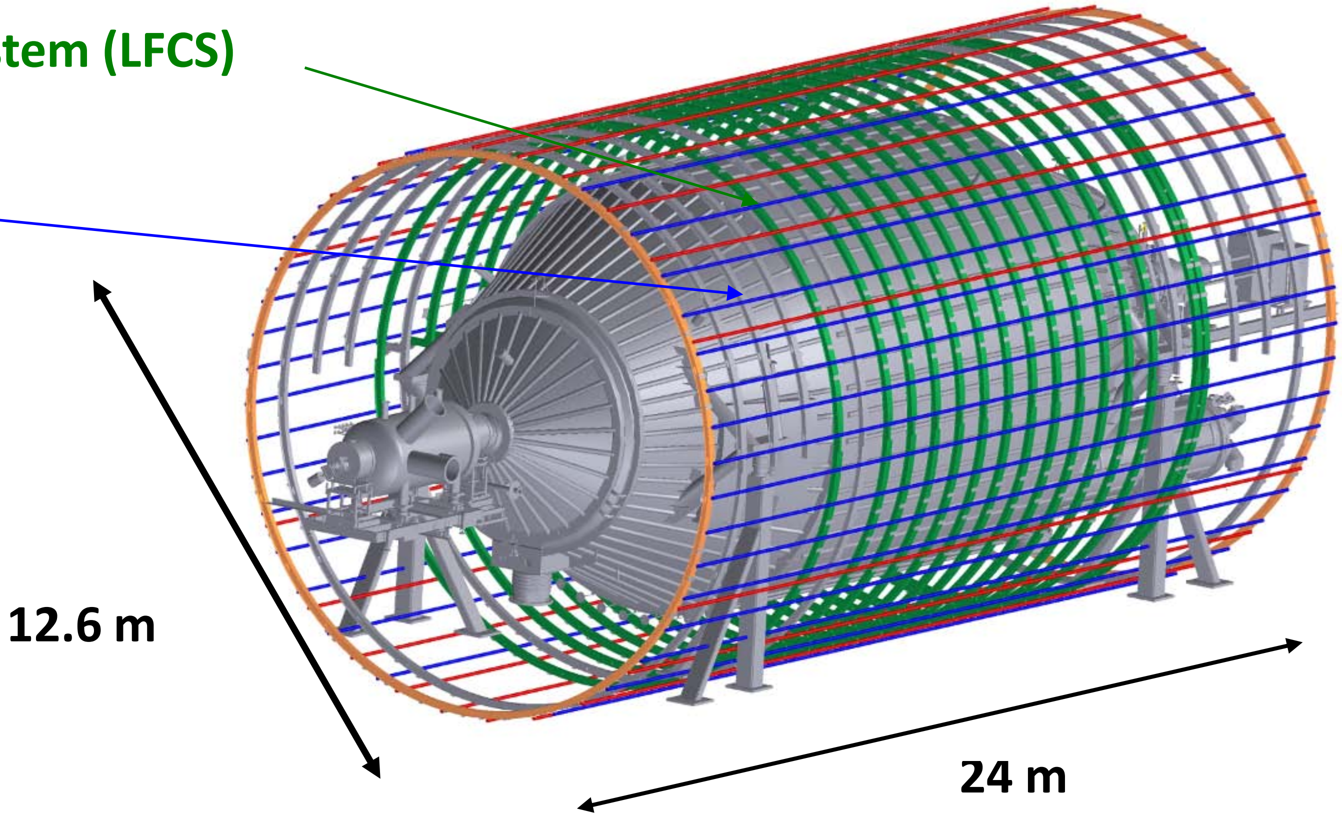


aircoil amperturns:

1: 240 A, 2: 200 A,
3: 160 A, 4: 166 A,
5: 160 A, 6: 160 A,
7: 156 A, 8: 148 A
9: 138 A,
10: 130 A
11: 125 A, 12: 110 A,
13: 130 A, 14: -1200 A

Aim of air coils:

- to optimize the axisymmetric magnetic field inside the tank (field of supercond. coils alone is not optimal for electron transmission)
- to compensate the earth magnetic field

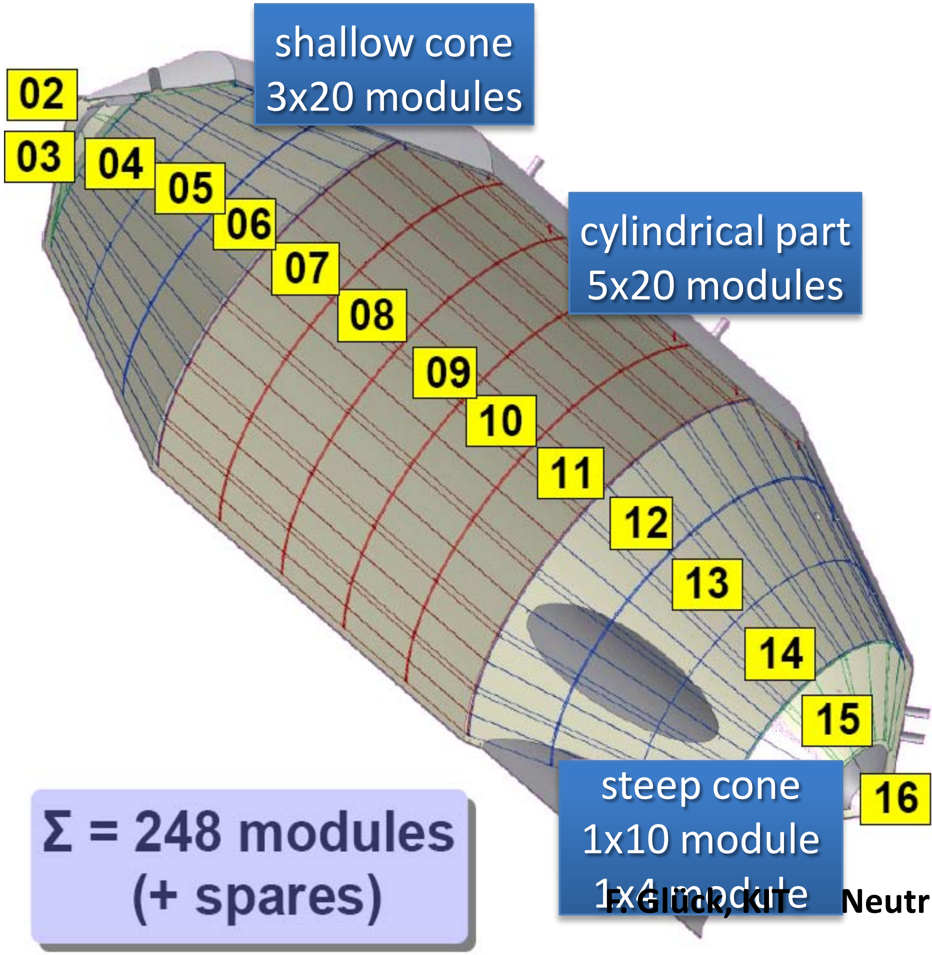


low field coil system (LFCS)

earth magnetic field compensation system (EMCS)
→ cosine coil system

Electric shielding with wire electrodes: background reduction

Wires more negative than tank →
small energy secondary electrons
are reflected by the wires

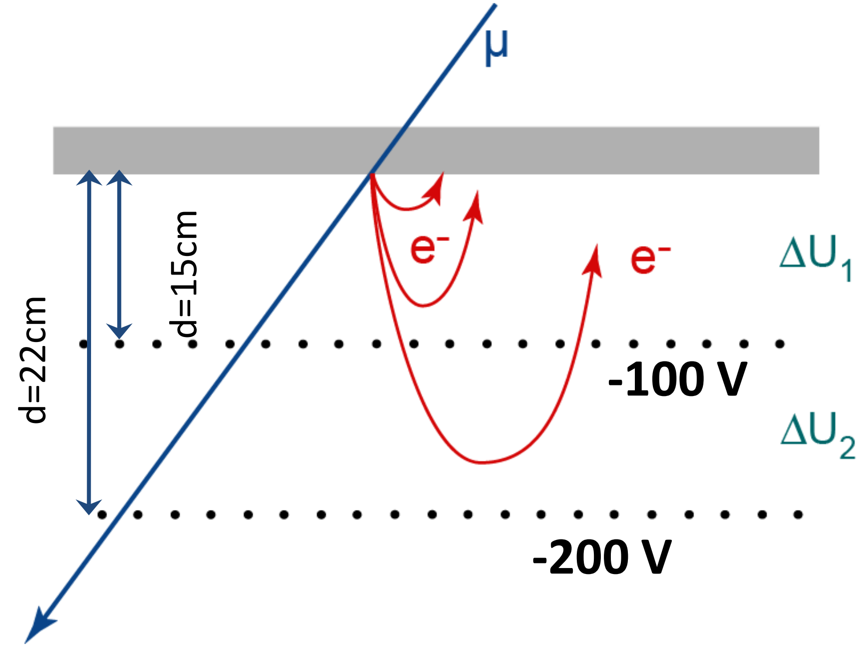


shallow cone
3x20 modules

cylindrical part
5x20 modules

steep cone
1x10 module
1x4 module

Σ = 248 modules
(+ spares)



Wires:

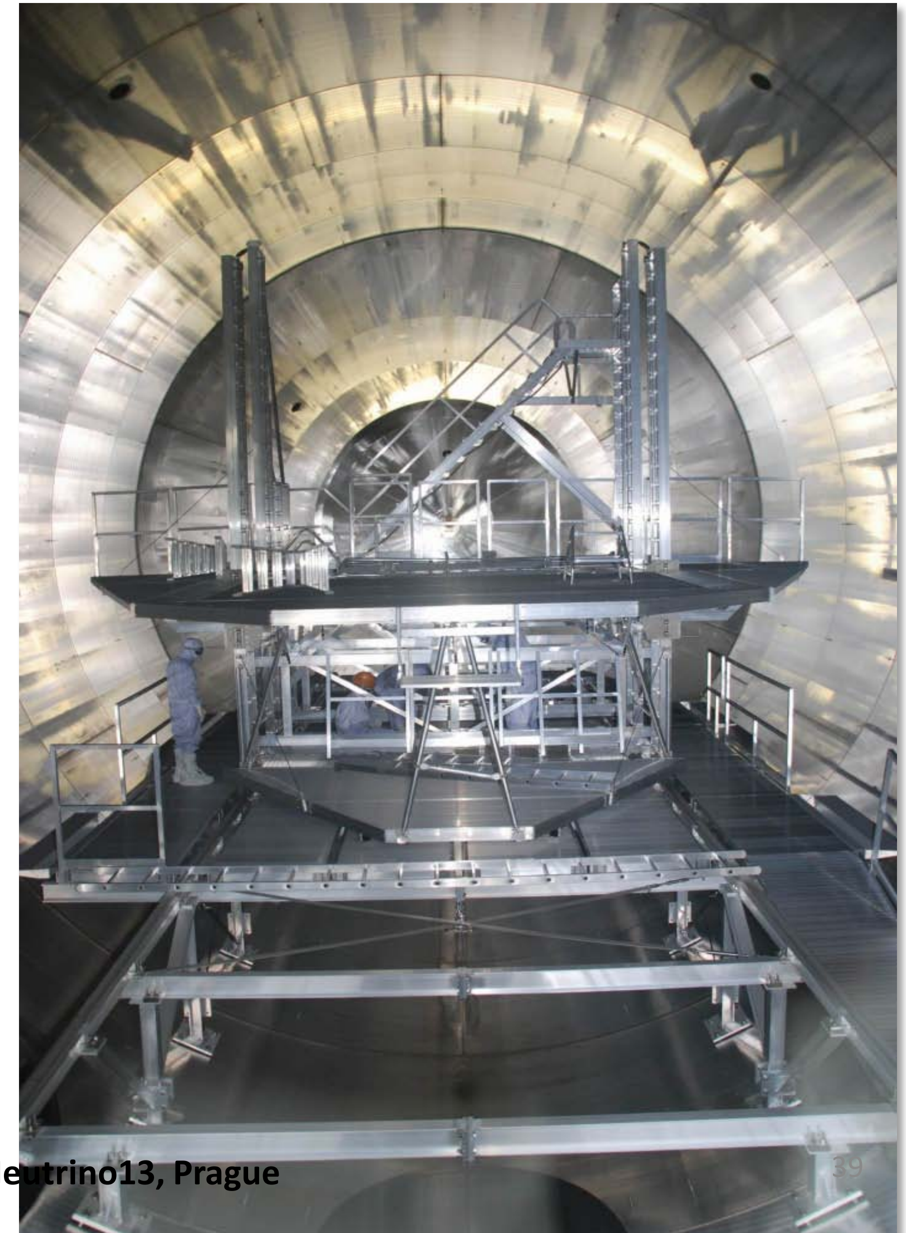
0.2 and 0.3 mm diameter

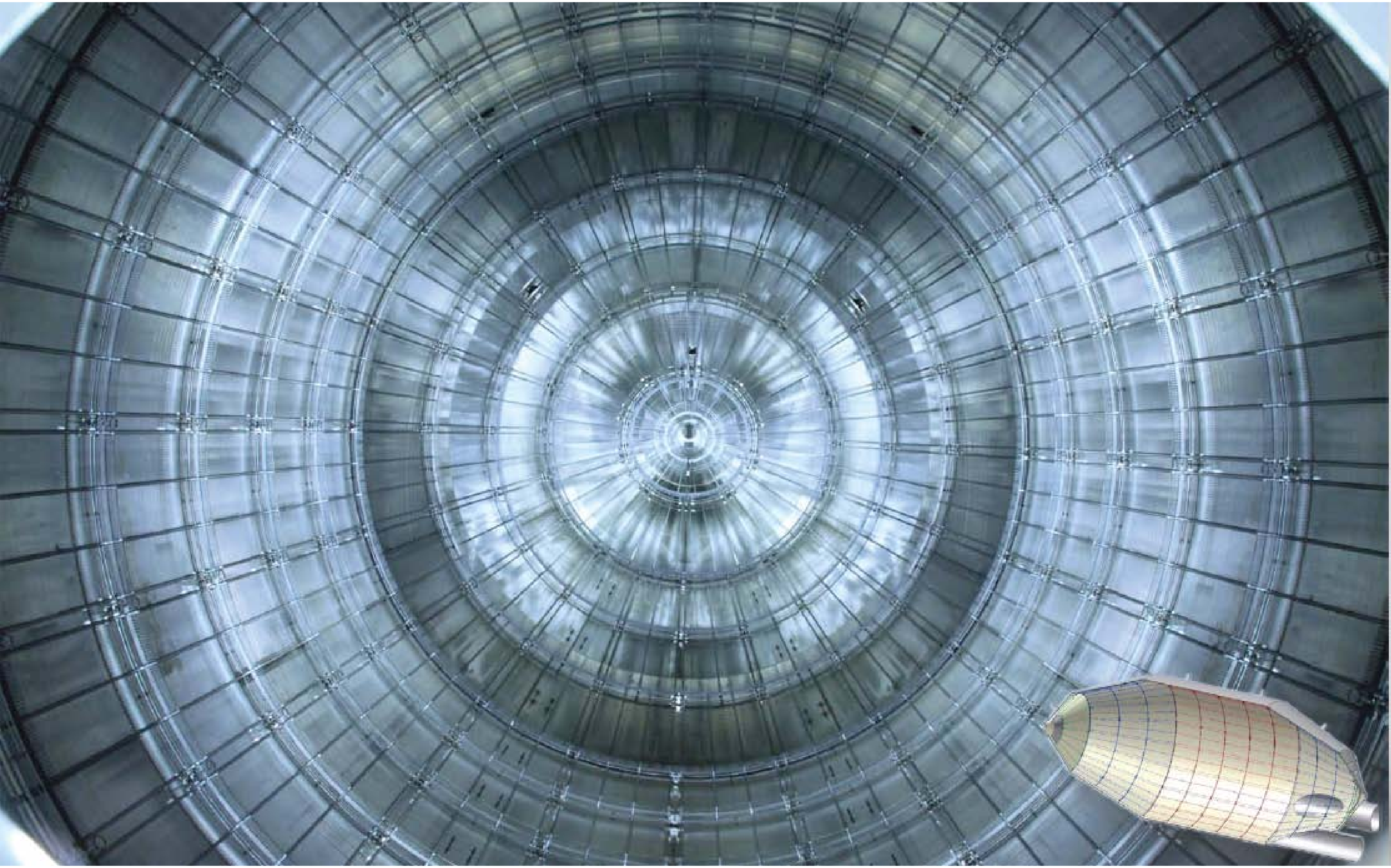
total length: 42 km

tank surface: 700 m²

Wire modules:
University of Münster

Scaffolding:
KIT



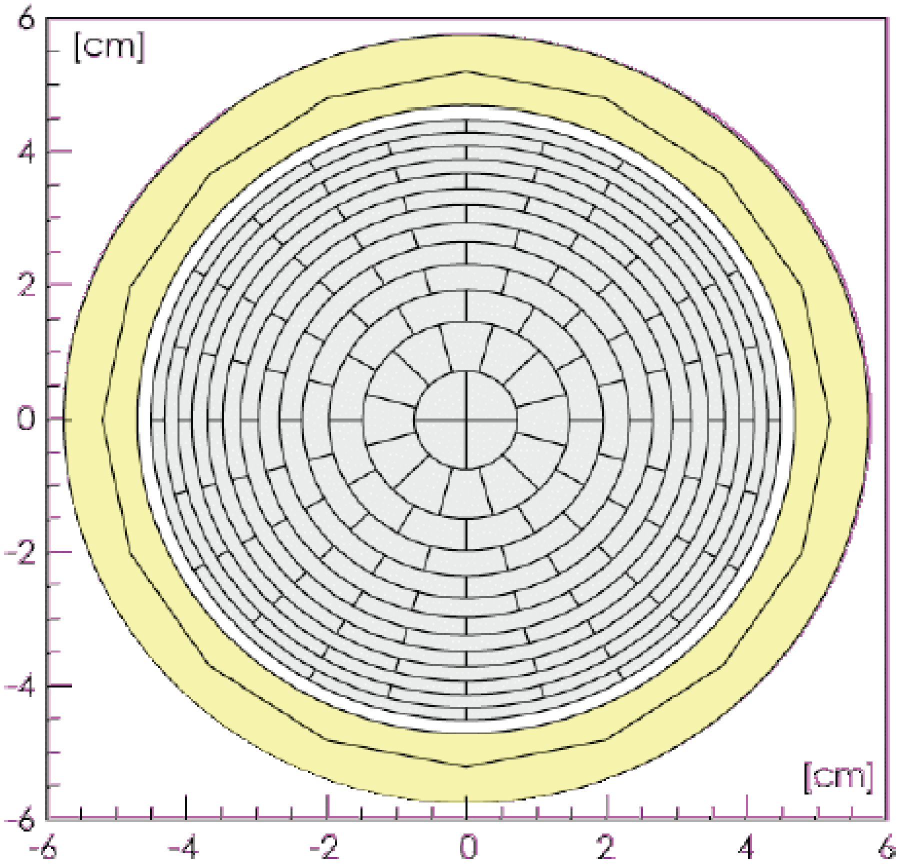


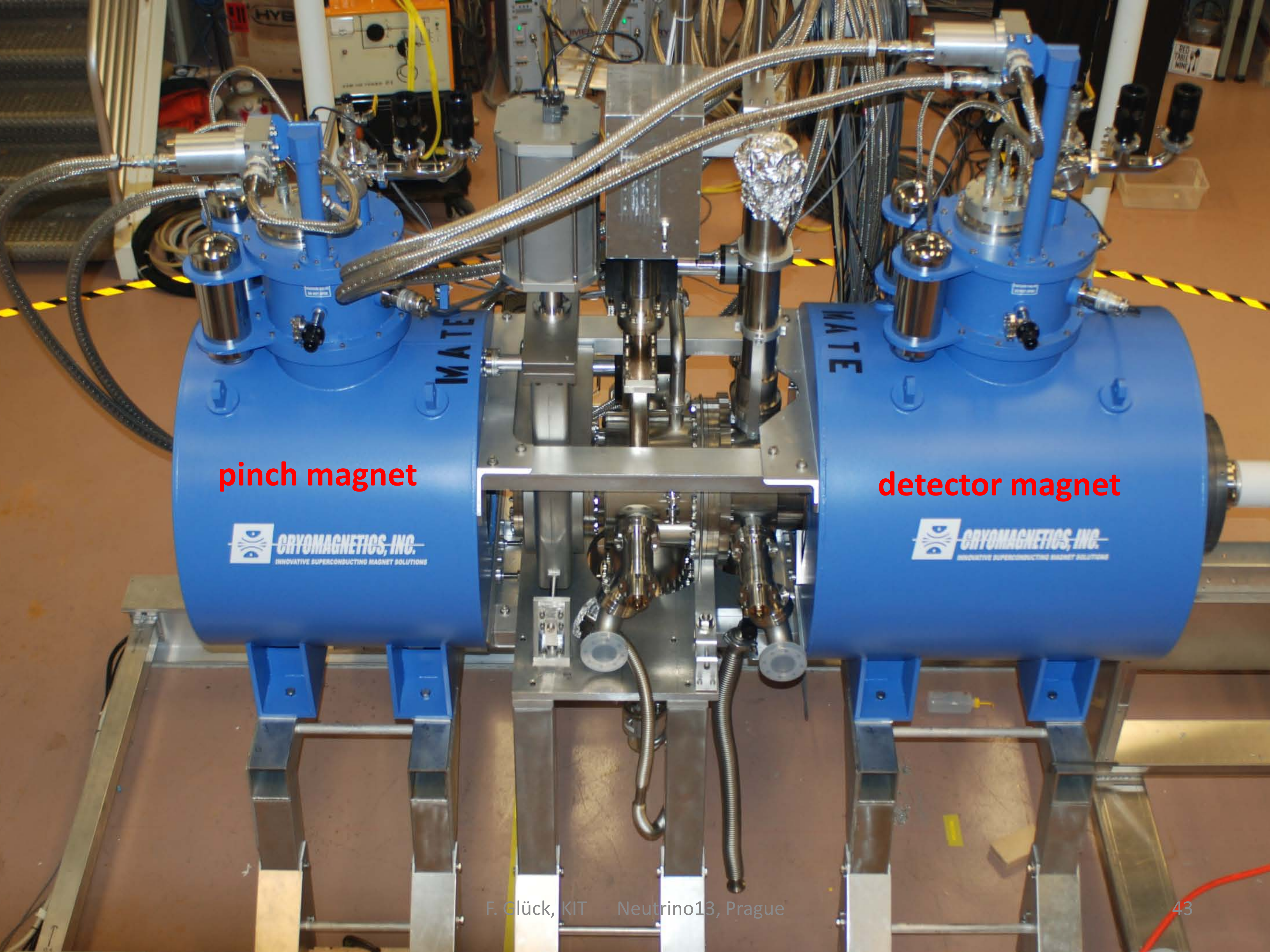
Detector system

Assembled and commissioned:
University of Washington, Seattle

Focal-Plane detector:

- segmented Si-PIN diode array (148 pixels: to record radial and azimuthal profile of signal and background electrons)
- energy resolution: 1.5 keV
- minimal electron energy: 5 keV
- detector region background: few mHz possible (with muon veto: MIT)




pinch magnet
detector magnet
MATE
MATE
CRYOMAGNETICS, INC.
INNOVATIVE SUPERCONDUCTING MAGNET SOLUTIONS
CRYOMAGNETICS, INC.
INNOVATIVE SUPERCONDUCTING MAGNET SOLUTIONS

Detector system installed near main spectrometer

Wire electrode installation ready, main spectrometer vessel was baked up to 300 °C (Jan. 2013).

Main spectrometer commissioning experiments start next week

- first background experiments with low potential
- electron transmission experiments (with egun)
- radon background with warm and cold baffle;
  removing stored electrons by electric dipole field and
  magnetic pulse (fast decrease of magnetic field)
- high voltage experiments
  (field emission, Penning discharge, background from
  secondary electron emission)

Variation of the retarding potential in main spectrometer

Unaccounted variation of the analyzing plane potential in middle of the main spectrometer → shift of measured neutrino mass squared

$$\Delta m_\nu^2 = -2\sigma_{\Delta U}^2 \qquad \Delta U = U_A - U_S$$

$U_A, \quad U_S$: analyzing plane and source potentials

→ better than 60 mV stability of analyzing plane potential is required during spectrum scanning

Absolute value of the analyzing plane potential is not critical (since endpoint is free parameter)

Retarding potential monitoring:

- direct voltage measurement (18 kV → 10 V by high-precision voltage divider)
- direct calibration of analyzing plane potential of main spectrometer, with conversion electrons from ^{83m}Kr or photoelectrons from ^{241}Am/Co source; not possible during data taking
- main spectrometer potential connected to monitor spectrometer; continuous calibration of monitor spectrometer potential by photoelectron or conversion electron sources

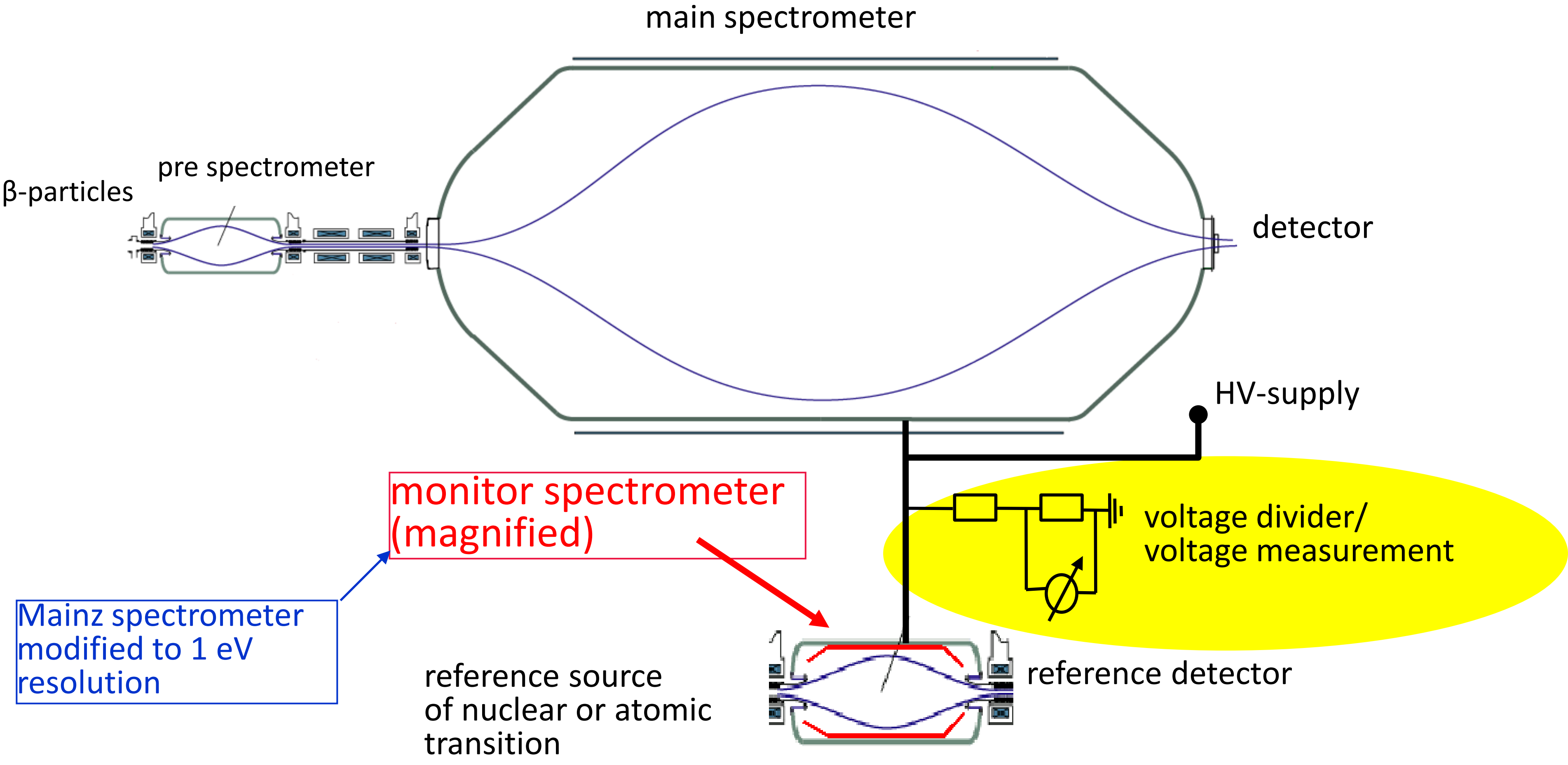
Quench condensed Kr source, high-precision voltage divider:
Münster (group of Ch. Weinheimer)

^{241}Am/Co source: Rez, group of O. Dragoun

Monitor Spectrometer

Precise monitoring of the main spectrometer energy scale:

precise measurement of retarding potential
+ comparison to reference energy



main spectrometer

β-particles

pre spectrometer

detector

HV-supply

voltage divider/
voltage measurement

monitor spectrometer
(magnified)

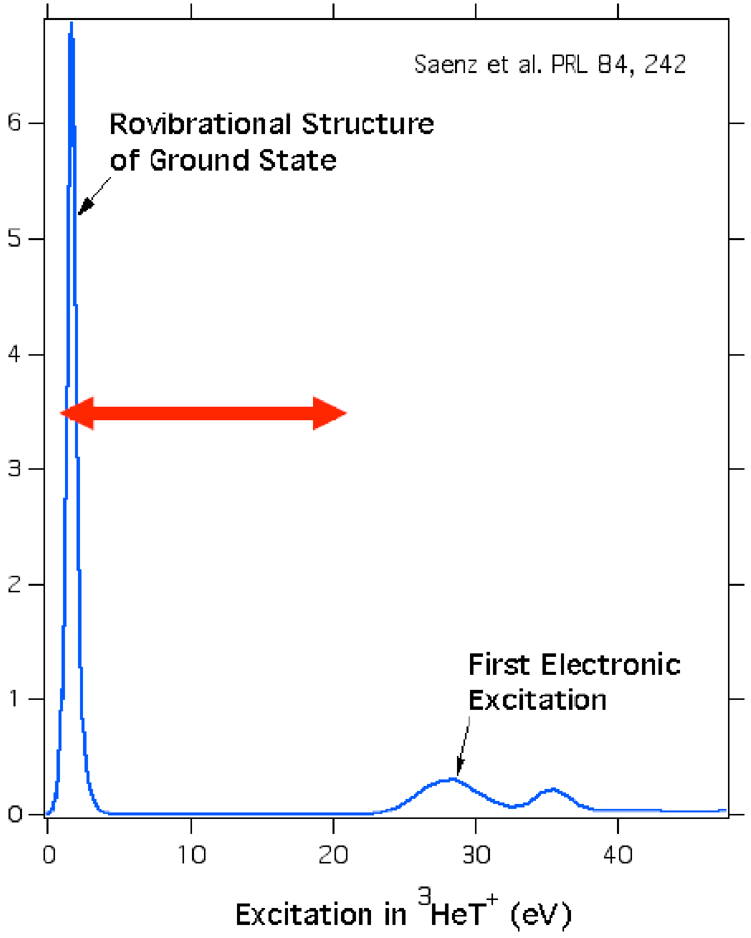
Mainz spectrometer
modified to 1 eV
resolution

reference source
of nuclear or atomic
transition

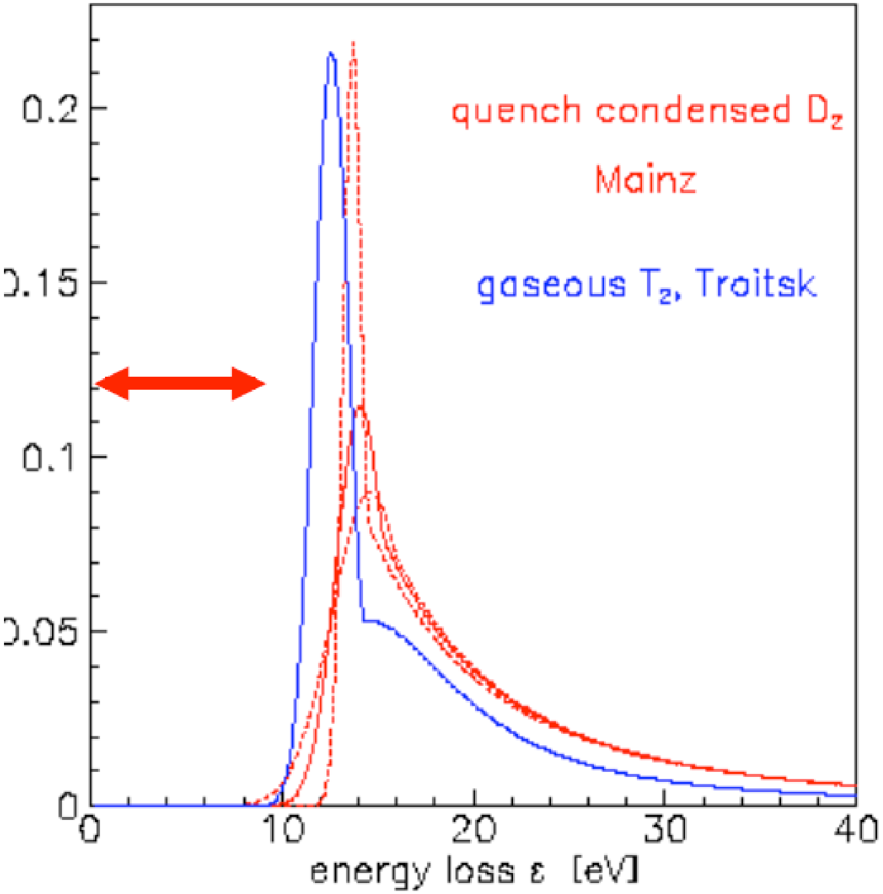
reference detector

A window to work in

Molecular Excitations



Energy loss function



Simulation codes

Various C and C++ codes

Standard C++ simulation package of KATRIN: KASSIOPEIA

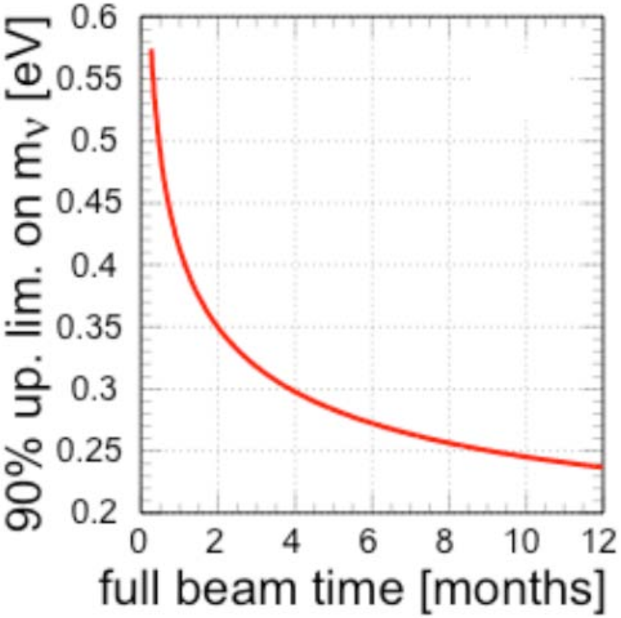
- **relativistic charged particle tracking: 8th order Runge-Kutta**
- **electric field calculations: BEM, direct and iterative solvers, zonal harmonic expansion**
- **magnetic field: zonal harmonic expansion, elliptic integrals, integrated Biot-Savart**
- **e-H_2 scattering : elastic, excitation, ionization, total and differential cross sections. Electron scattering in silicon.**
- **gas flow**
- **various statistical simulation methods**

After 3 years data (5y realtime):

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

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

Planned start of data taking with tritium: 2015



KATRIN and sterile neutrinos

Sterile neutrinos: chiral right-handed singlets, no weak interaction

But they can mix with left-handed active neutrinos (if massive)

LSND anomaly: short-baseline $\bar{\nu}_e$ appearence from $\bar{\nu}_\mu$ beam

Reactor antineutrino anomaly: short-baseline detected $\bar{\nu}_e$ rate smaller than calculated rate

Gallium anomaly: detected $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$ rate from artificial ν_e EC sources (^{51}Cr, ^{37}Ar) smaller than calculated rate

large mixing: $\sin^2(2\theta) \approx 0.1$

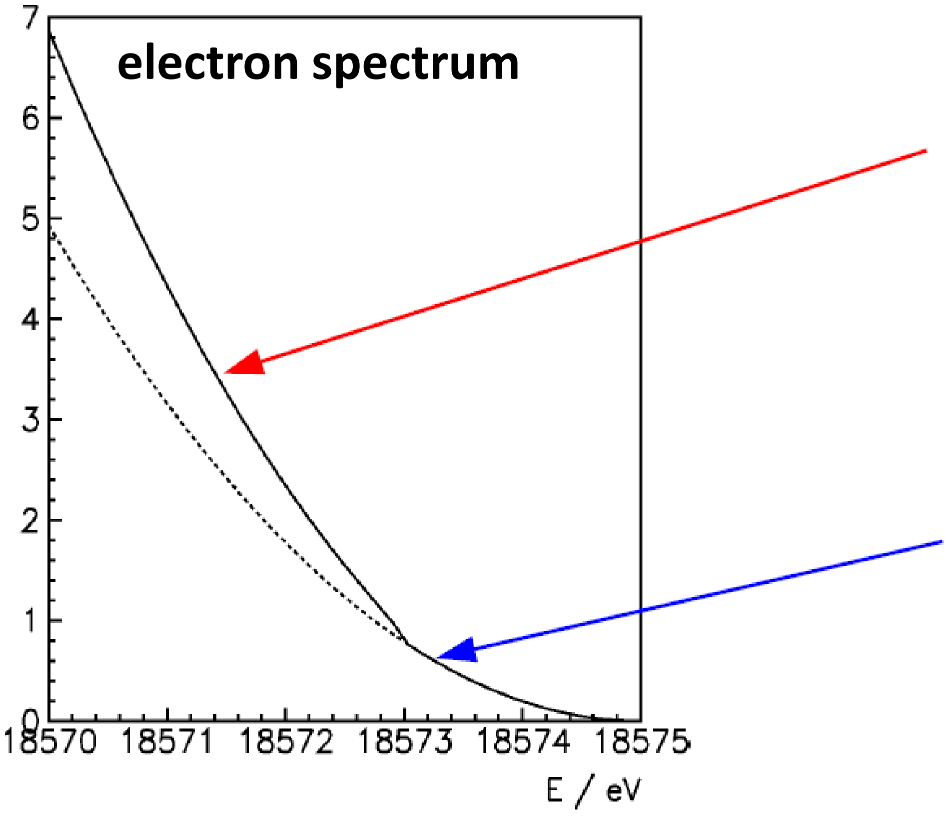
large masses: $\Delta m^2 > 1$ eV^2

$$\nu_e = \sum_{i=1}^{3} U_{ei}\,\nu_i + U_{e4}\,\nu_4$$

$$\sum_{i=1}^{3} |U_{ei}|^2 = \cos^2(\theta)$$

$$|U_{e4}|^2 = \sin^2(\theta)$$

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_4)^2}\right)$$



e.g. **sterile neutrino**

$m(\nu_4) = 2$ eV

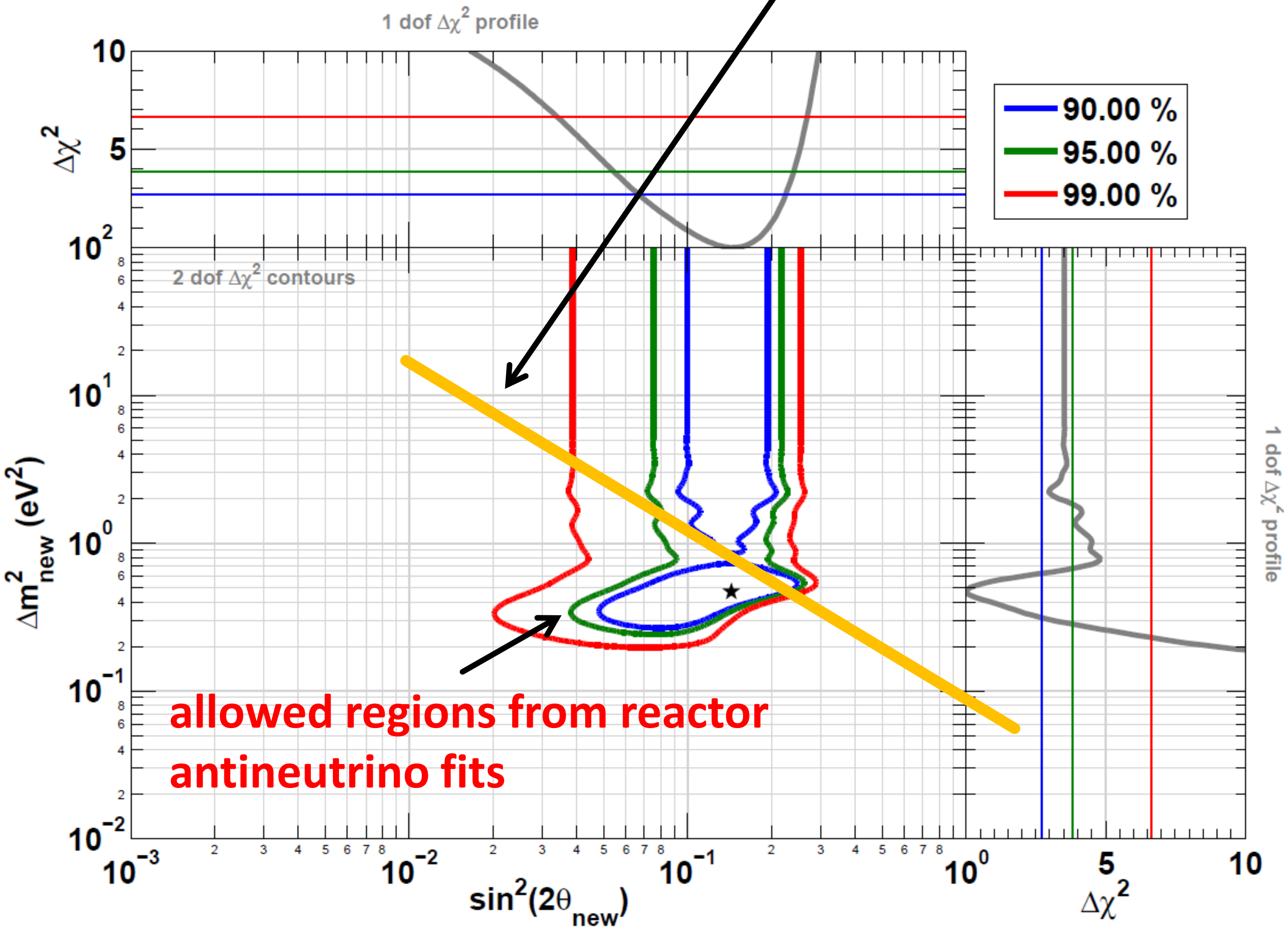
$\sin^2(\theta) = 0.3$

e.g. **active neutrinos**

$m(\nu_{123}) \approx 0$ eV

$\cos^2(\theta) = 0.7$

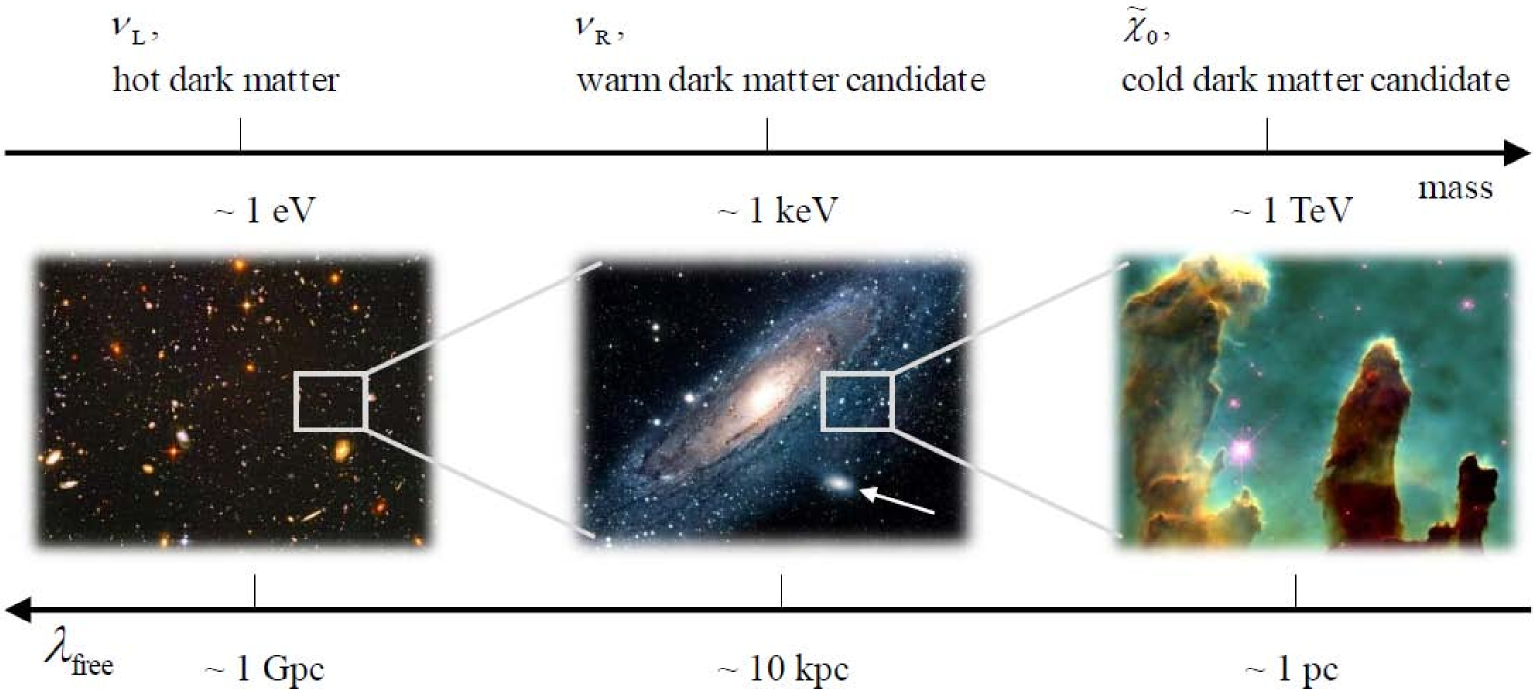
KATRIN 90 % exclusion possibility for light steril neutrino above the yellow line



allowed regions from reactor antineutrino fits

Riis, Hannerstad, JCAP 1102 (2011) 011
Formaggio, Barrett, PLB 706 (2011) 68
Esmaili, Peres, arXiv 1203.2632

Warm dark matter (WDM) and keV sterile neutrinos



ν_L,
hot dark matter

ν_R,
warm dark matter candidate

$\tilde{\chi}_0$,
cold dark matter candidate

mass

~ 1 eV

~ 1 keV

~ 1 TeV

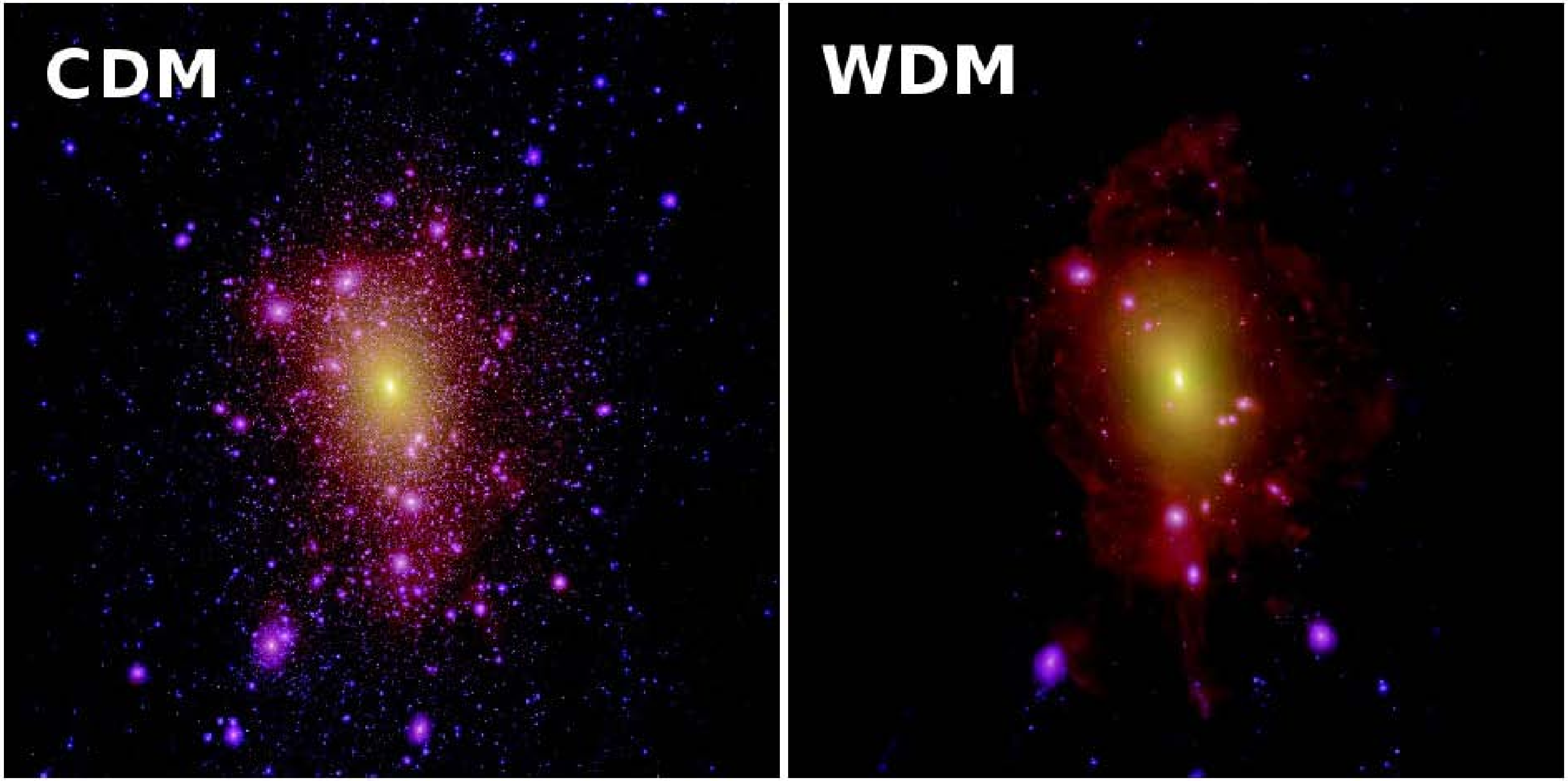
λ_{free}

~ 1 Gpc

~ 10 kpc

~ 1 pc

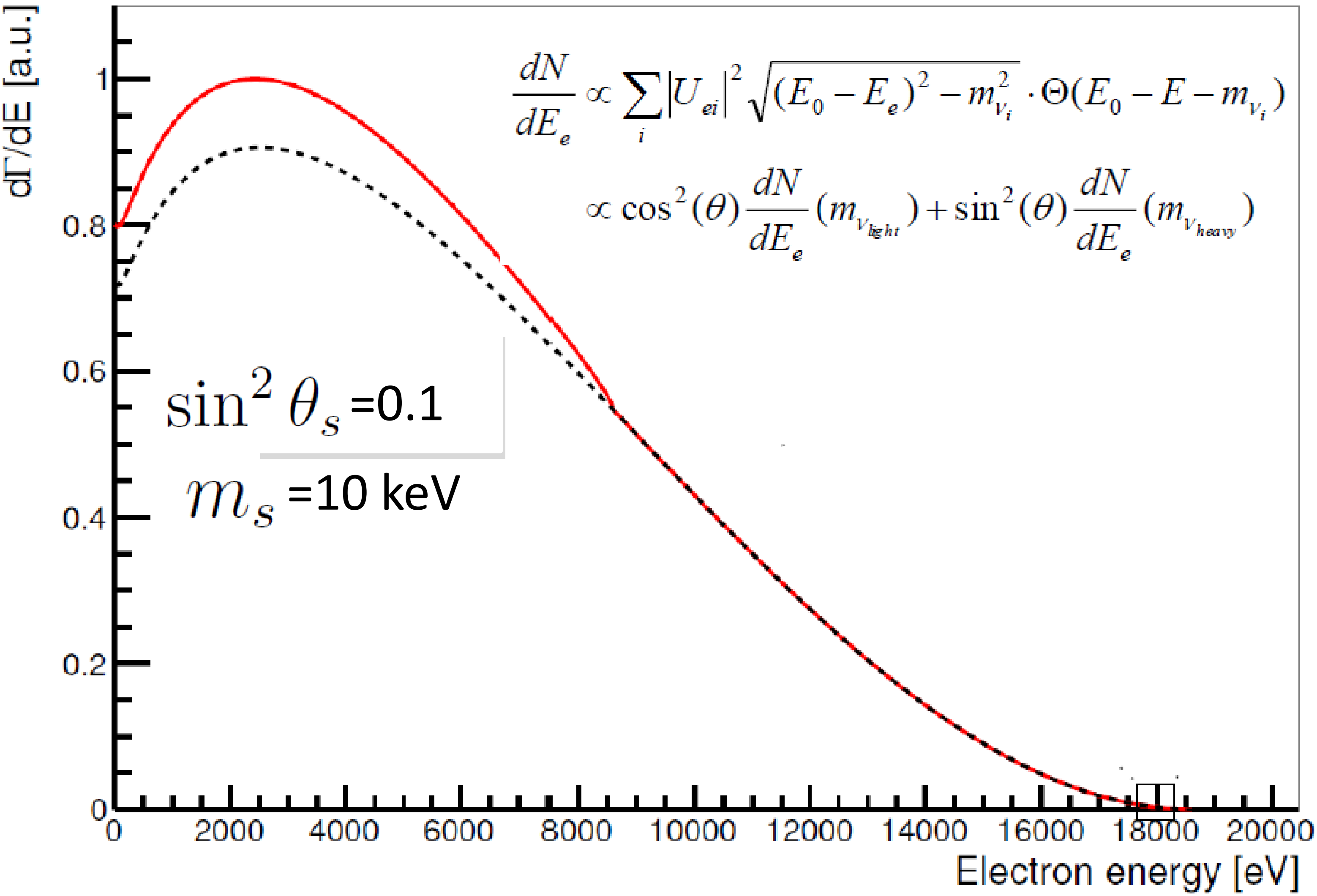
Some problems with CDM (e.g.: too many satellite dwarf galaxies predicted)



keV mass sterile neutrinos: possible WDM candidates

Predictions: **mass: 1-15 keV,** **mixing angle:** $\sin^2\Theta_s < 10^{-7}$

Tritium beta decay spectrum with sterile neutrino (example)



$$\frac{dN}{dE_e} \propto \sum_i |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m_{\nu_i}^2} \cdot \Theta(E_0 - E - m_{\nu_i})$$

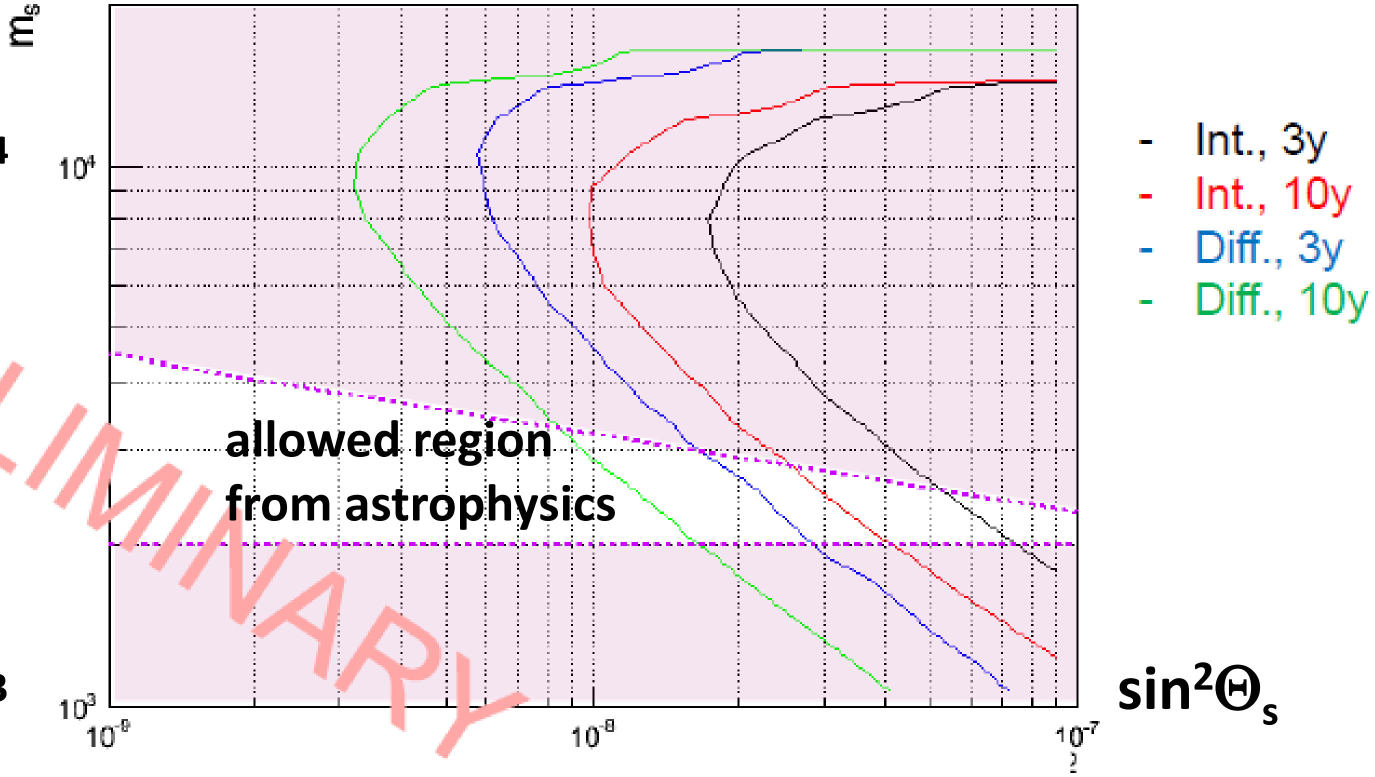
$$\propto \cos^2(\theta) \frac{dN}{dE_e}(m_{\nu_{light}}) + \sin^2(\theta) \frac{dN}{dE_e}(m_{\nu_{heavy}})$$

$\sin^2 \theta_s$ =0.1

m_s =10 keV

KATRIN statistical 90 % exclusion possibility for WDM sterile neutrino

Sterile neutrino mass (eV)



allowed region
from astrophysics

10^4

10^3

$\sin^2\Theta_s$

10^{-9} 10^{-8} 10^{-7}

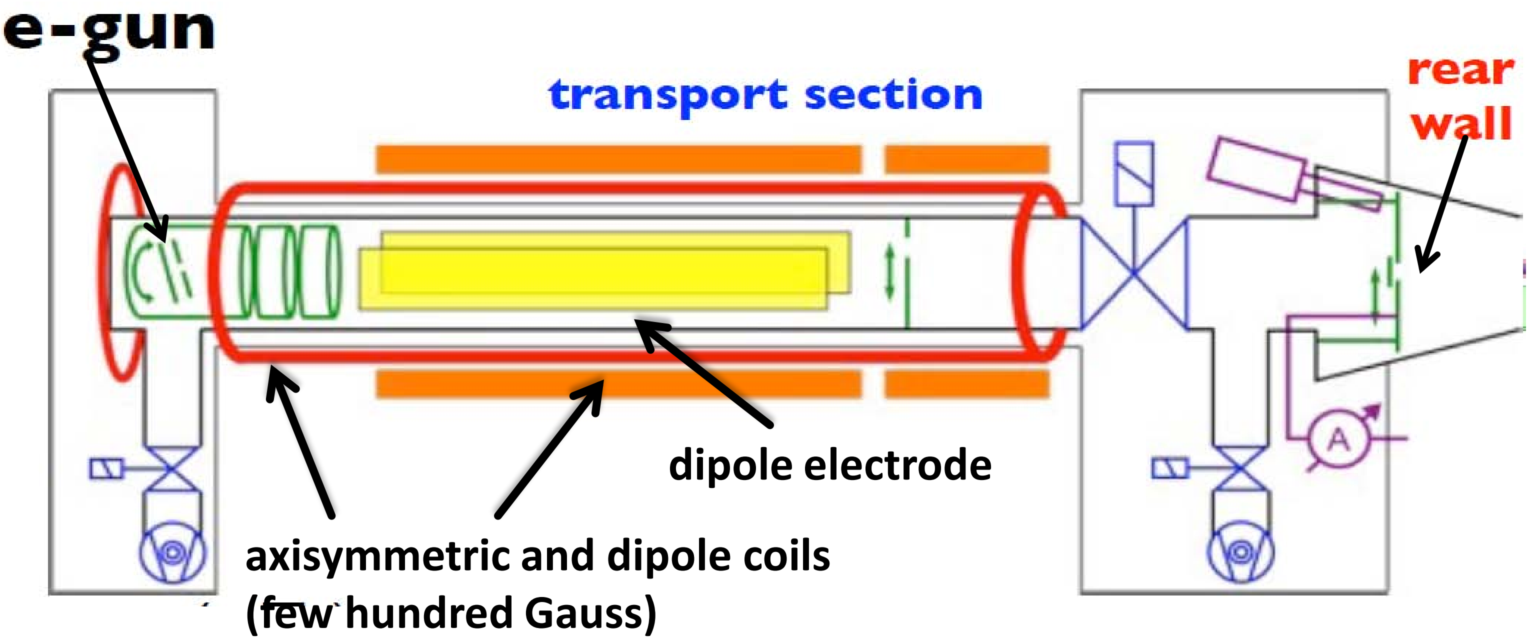
Systematics ???

Summary

- absolute neutrino mass scale determination: important task for particle physics and cosmology
- KATRIN: direct , model independent absolute neutrino mass scale determinatio by electron energy spectrum measurement of tritium β decay
- Spectrometer method; gaseous tritium source far from detector; magnetic guiding; integral spectrum (MAC-E filter); high statistics, high resolution, small background; complicated system; data taking start: not before 2015
- goal: 0.2 eV neutrino mass limit (90 % CL)
- possibility of light and WDM keV sterile neutrino detection

CMS

Calibration and Monitoring Section



e-gun

transport section

rear wall

dipole electrode

axisymmetric and dipole coils
(few hundred Gauss)

Egun:

- electrons with sharp energy and angular distribution
- transmission function measurements
- source thickness monitoring
- plasma effects

Rear wall:

- source potential definition and stabilization
- source activity monitoring
- gold-plated

Advantages of tritium:

- **Superallowed transition:** ➔ matrix element M is not energy dependent
- **Low endpoint energy:** ➔ relative decay fraction at the endpoint is comparatively high
- **Short half life:**
  - ➔ specific activity is high
  - ➔ low amount of source material
  - ➔ low fraction of inelastic scattered electrons
- **Hydrogen isotope:**
  - ➔ simple atomic shell
  - ➔ final states precisely calculable

Final state distribution calculation is needed for differential spectrum of T_2 decay:

$$w_{diff}(E) = \sum_j W_j \cdot E_{\nu j}\sqrt{E_{\nu j}^2 - m_\nu^2}$$

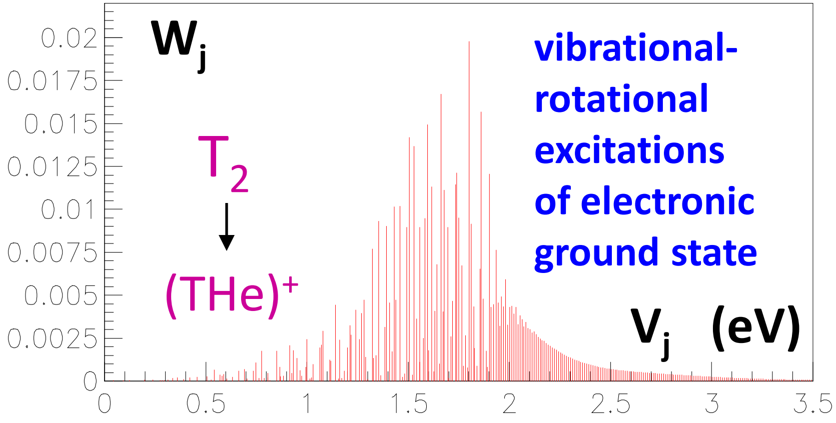
$$E_{\nu j} = E_0 - V_j - E$$

(assuming degenerate neutrino masses)

Ground state probability: 0.57

mean: 1.7 eV

$$\sigma = 0.4\ \mathrm{eV}$$



E_0 : endpoint

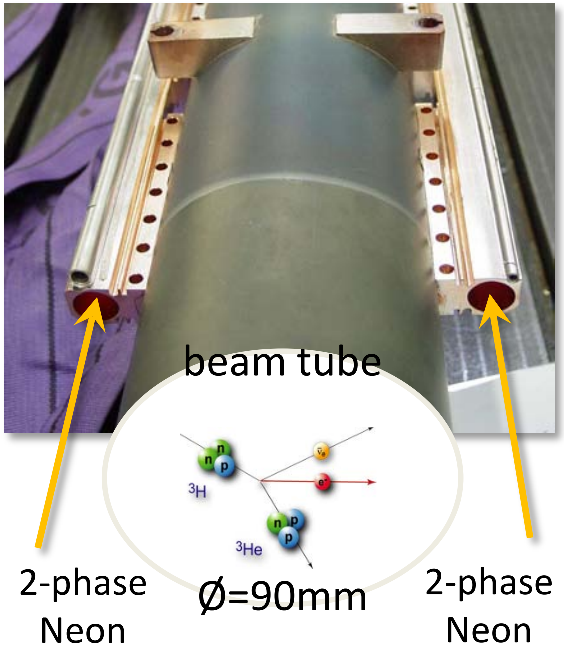
WGTS demonstrator

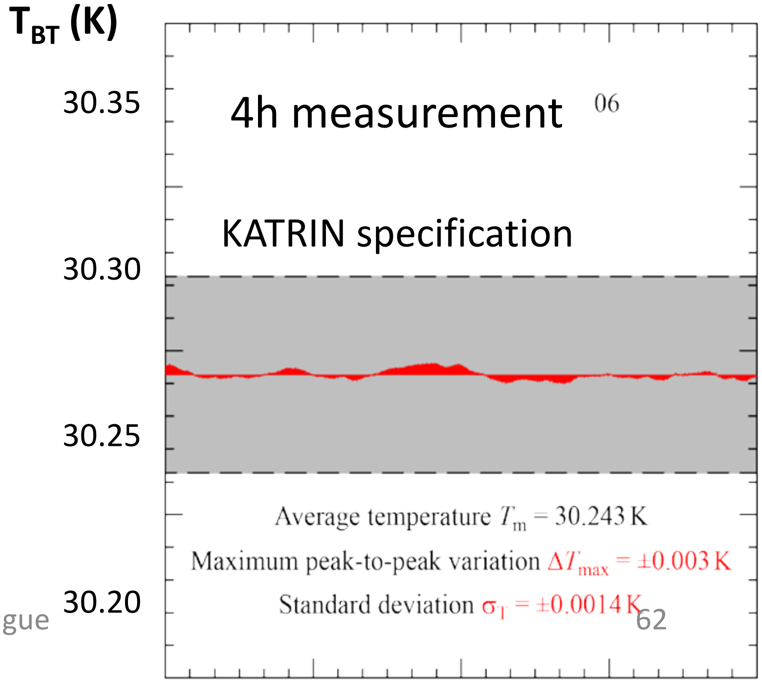
- beam tube cooling system: T_{BT} = 28-32 K
  $\Delta T = \pm$ **30 mK** - stability (1h) &
  homogeneity

- initial stability results: **proof-of-principle ☑**

Parameter	ΔT (4h)	ΔT (24h)
peak-to-peak variation	3 mK	9 mK
standard deviation σ_t	**1.4 mK**	3.6 mK

- implications: $\Delta T_{BT} \ll 10^{-3}$, $\Delta p_{in} < 10^{-3}$
  ↳ **super-stable ß-emitting source**
  ↳ **reduced systematics from source**
  ↳ demonstrator ⇨ WGTS cryostat (2013)





Average temperature T_m = 30.243 K
Maximum peak-to-peak variation ΔT_{max} = ±0.003 K
Standard deviation σ_T = ±0.0014 K

WGTS

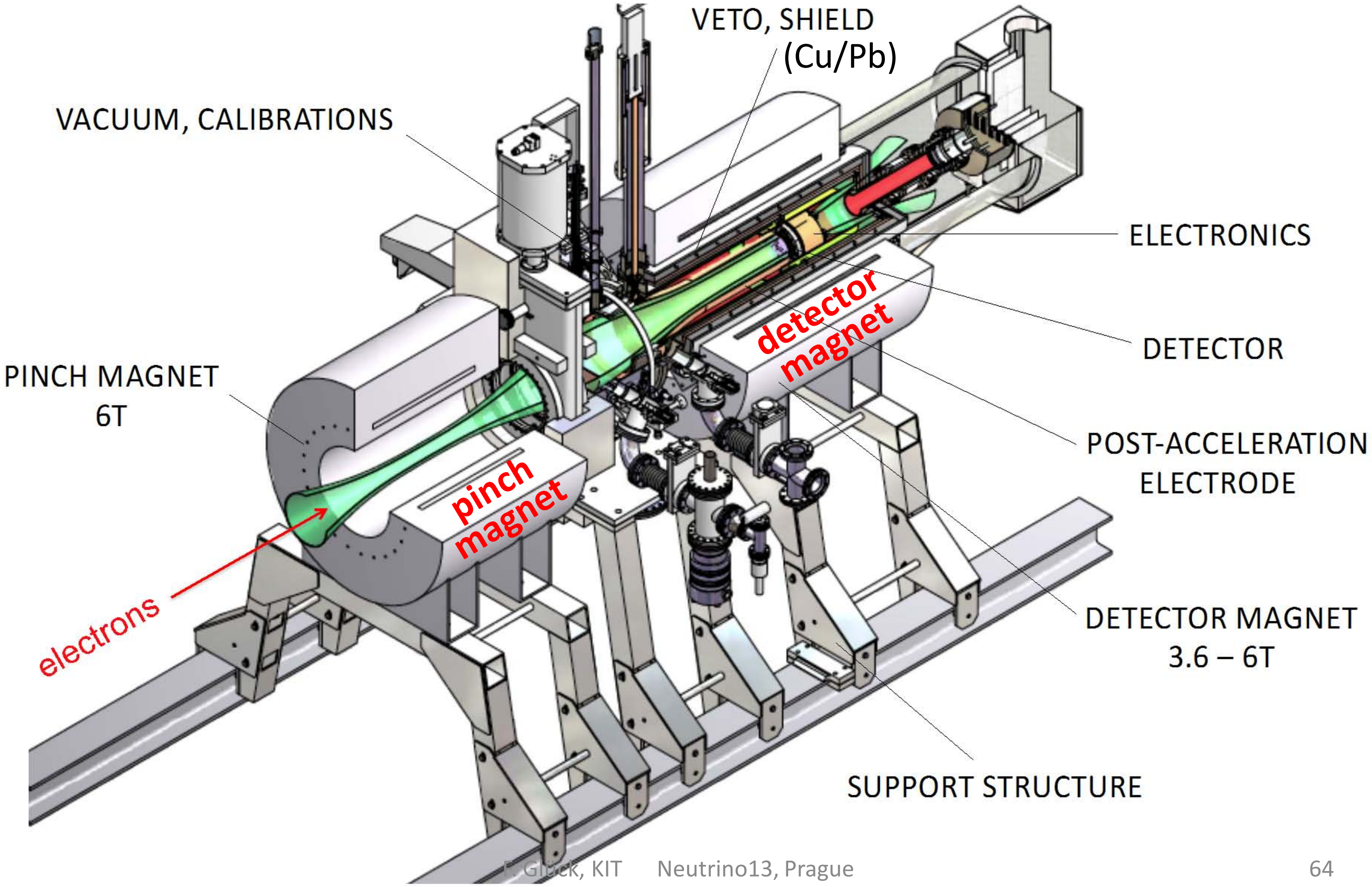
Windowless Gaseous Tritium Source

- T2 gas:
  - high luminosity and high stability
  - differential pumping (TMPs); closed tritium loop
  - high tritium purity; measurement of T_2, DT etc. isotopic composition (with Laser Raman spectroscopy)

- Homogeneous magnetic field and adiabatic guiding of electrons

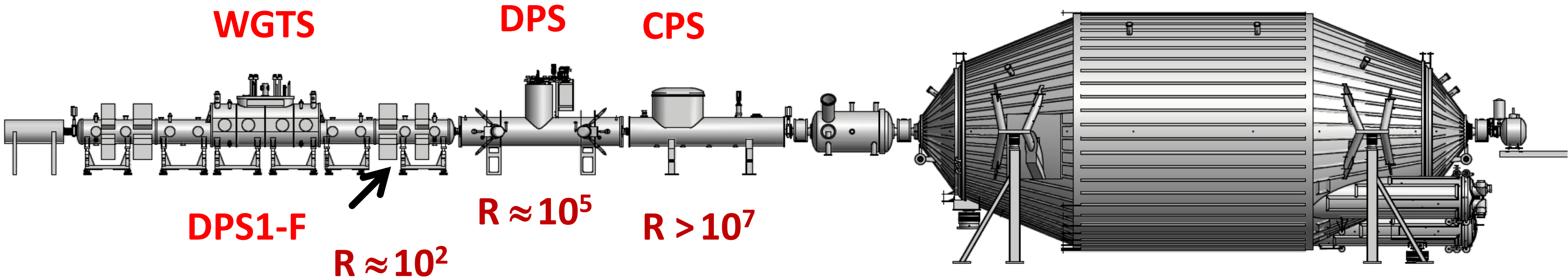
- Systematic effects for neutrino mass: as small as possible

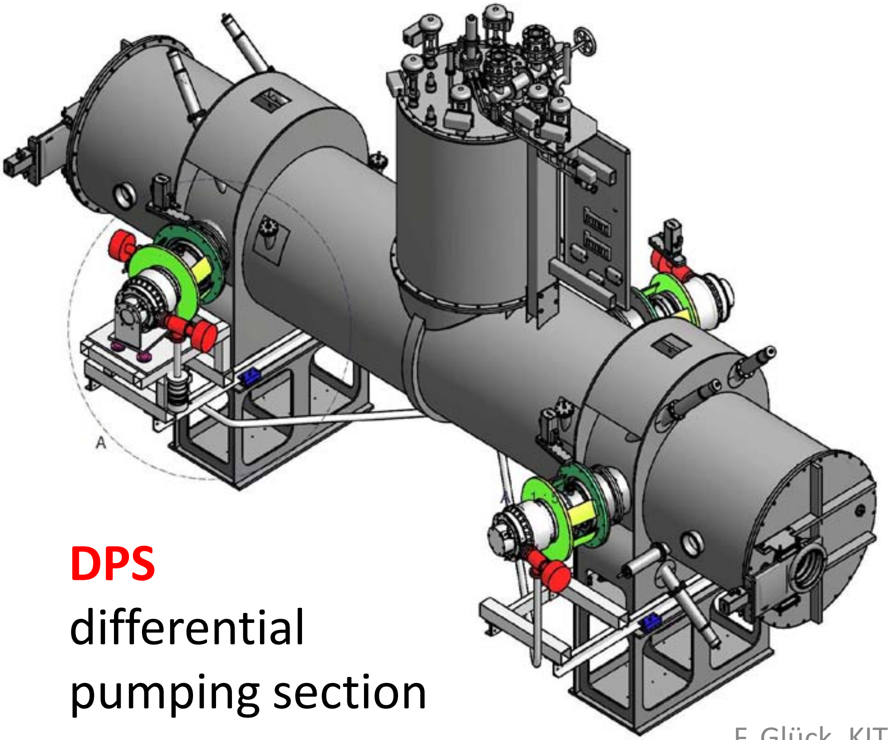
Focal Plane Detector System



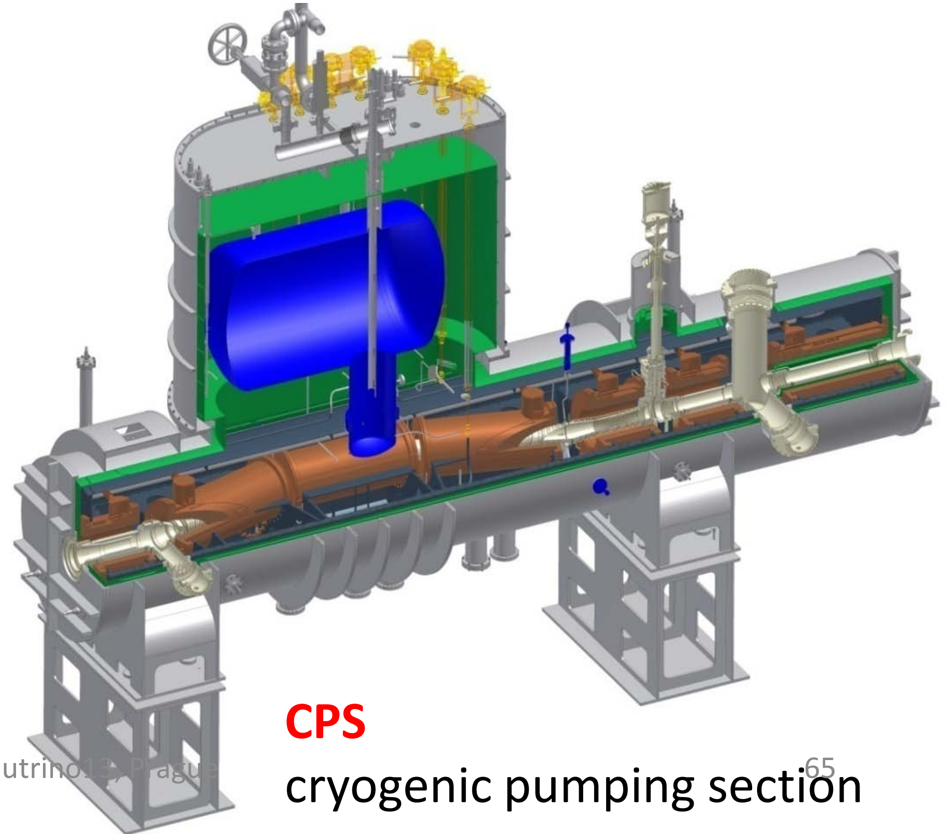
Tritium retention: DPS1-F, DPS2-F and CPS

Only very small amount of tritium allowed to enter the main spectrometer (background !)





DPS
differential
pumping section



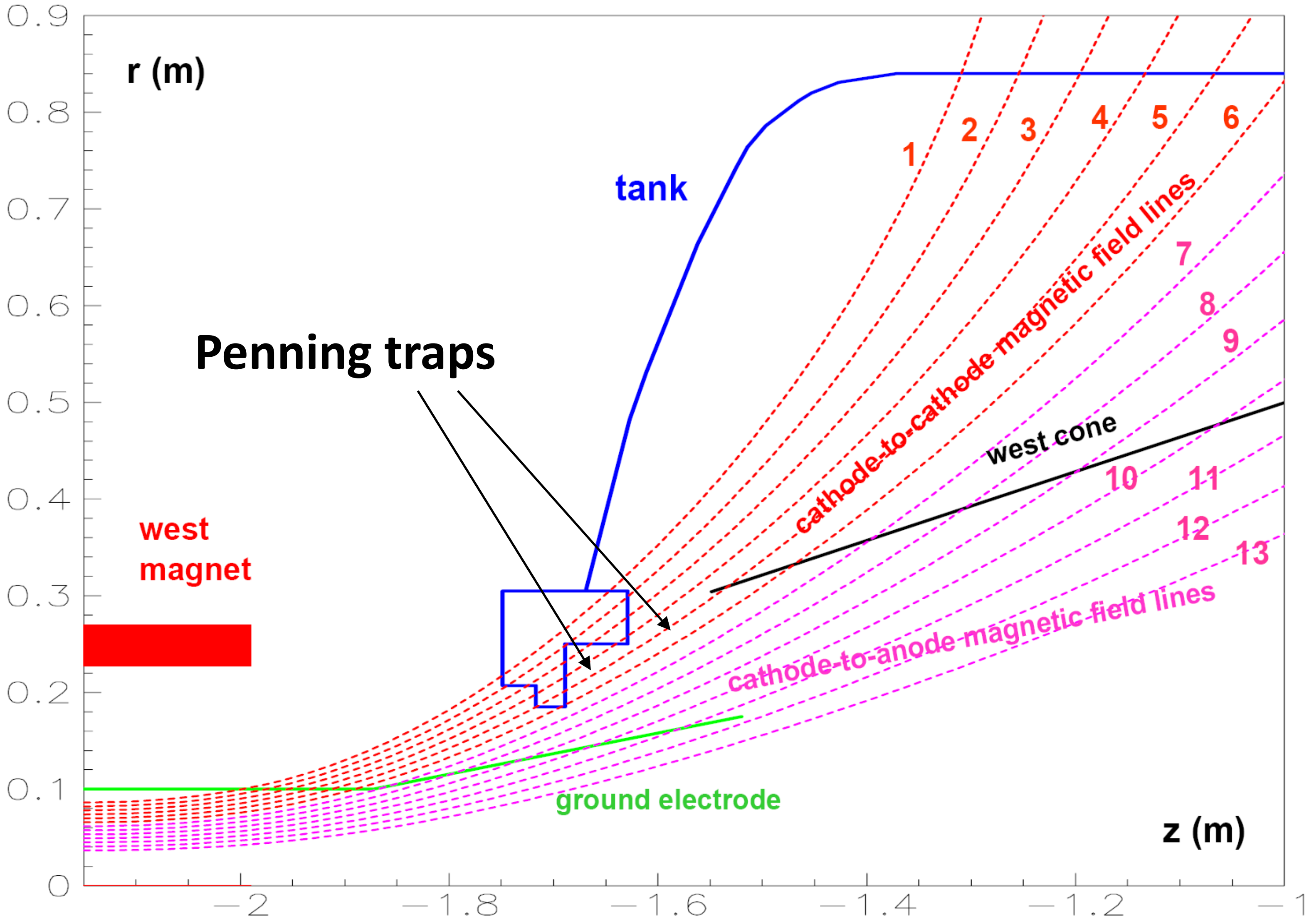
CPS
cryogenic pumping section

First test experiments at KATRIN pre-spectrometer (end of 2006):

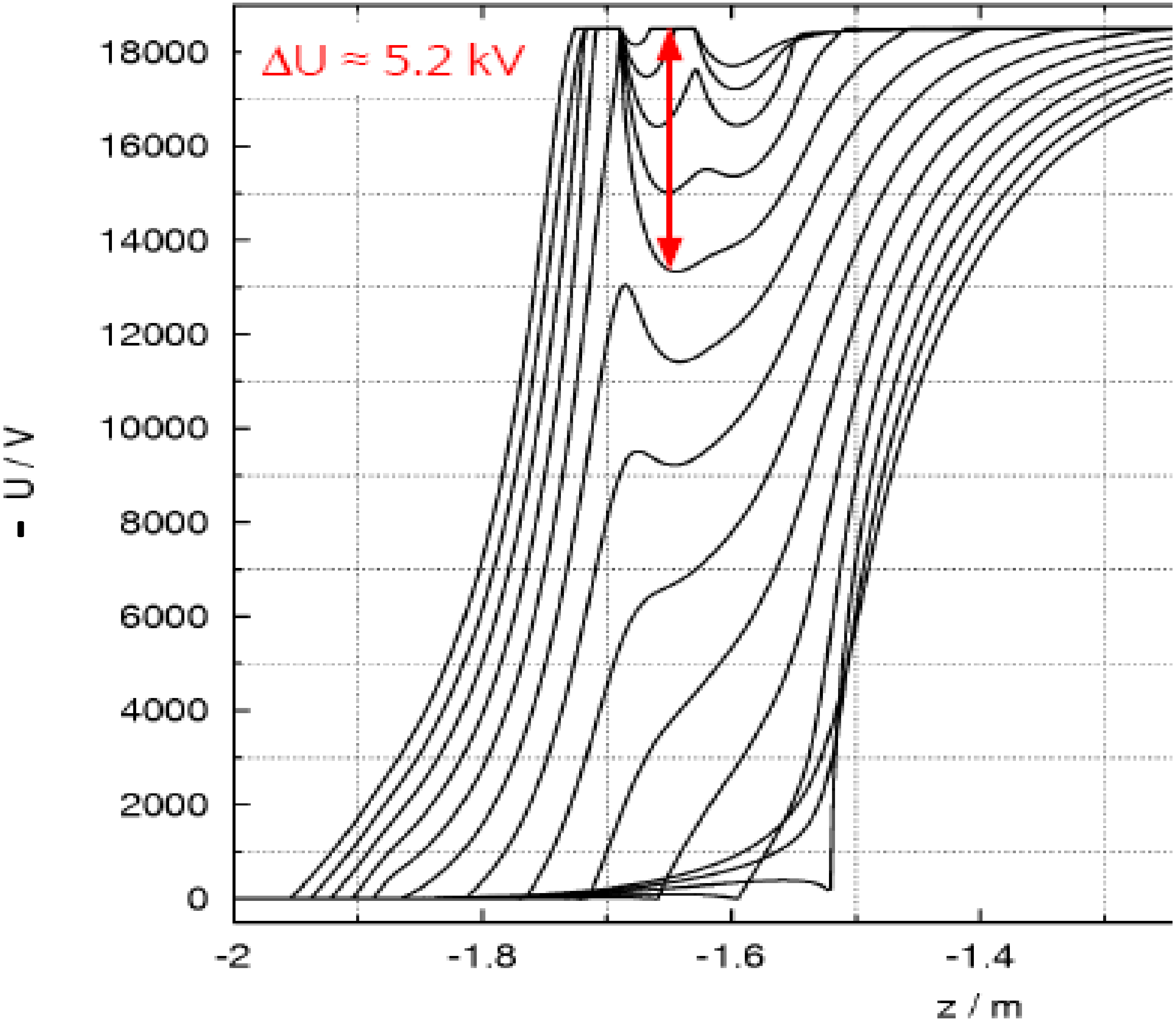
Tank and electrodes at -18 kV, increase of magnetic field; at 0.15 T

- increase of vacuum pressure from 10^{-9} mbar to 10^{-6} mbar
- increase of leakage current from 0.2 μA to few mA (limit of power supply)
- drop of high voltage from -18 kV down to -3 kV (electric breakdown)

Penning discharge !



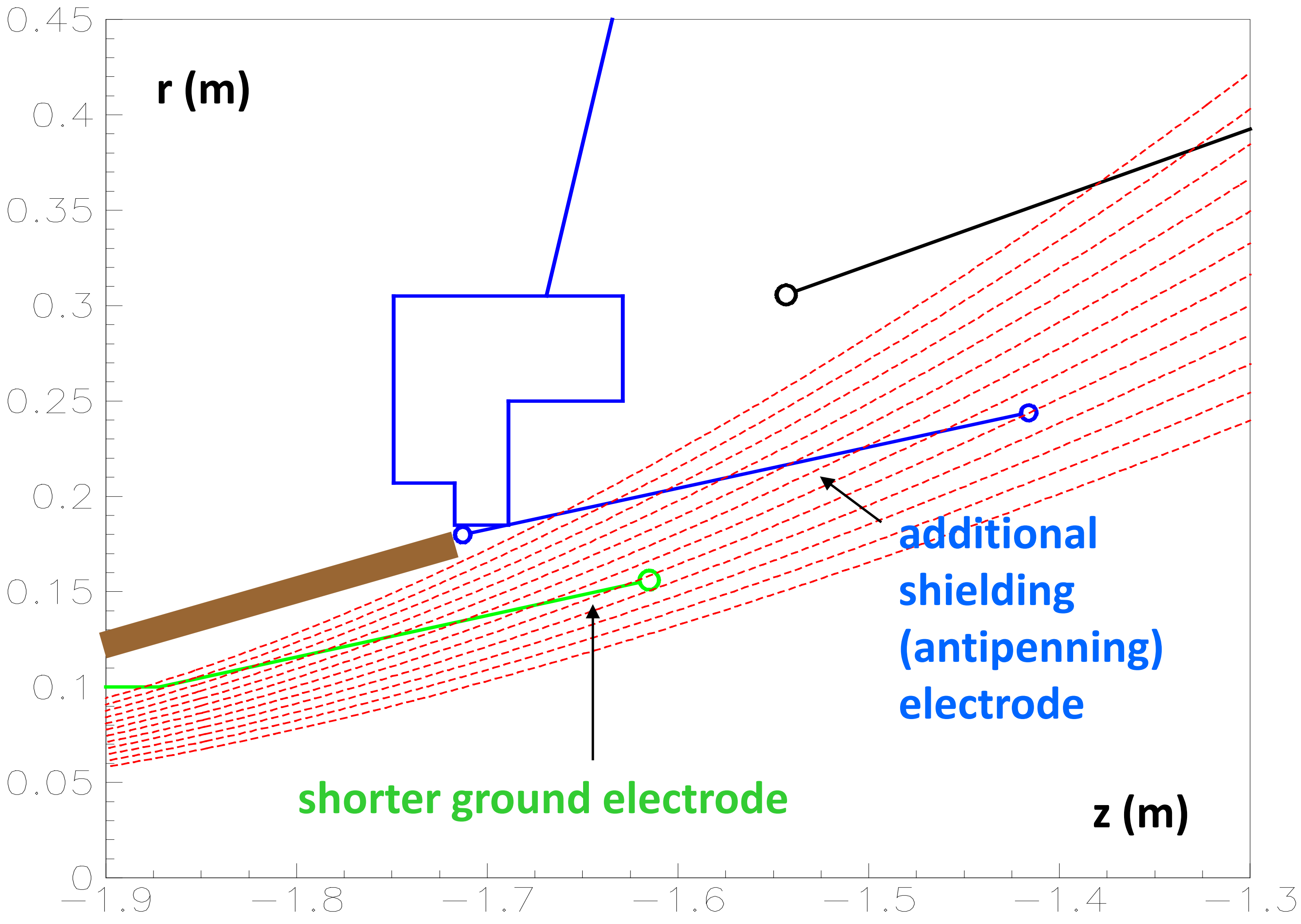
Cathode-to-cathode magnetic field lines, potential penetration from anode (ground electrode)



Electric potential on various magnetic field lines at the entrance of pre-spectrometer

Solution of the Penning discharge problem in the pre-spectrometer

by shielding the Penning trap region against potential penetration from the anode by an additional electrode → no deep Penning traps



additional shielding (antipenning) electrode

shorter ground electrode

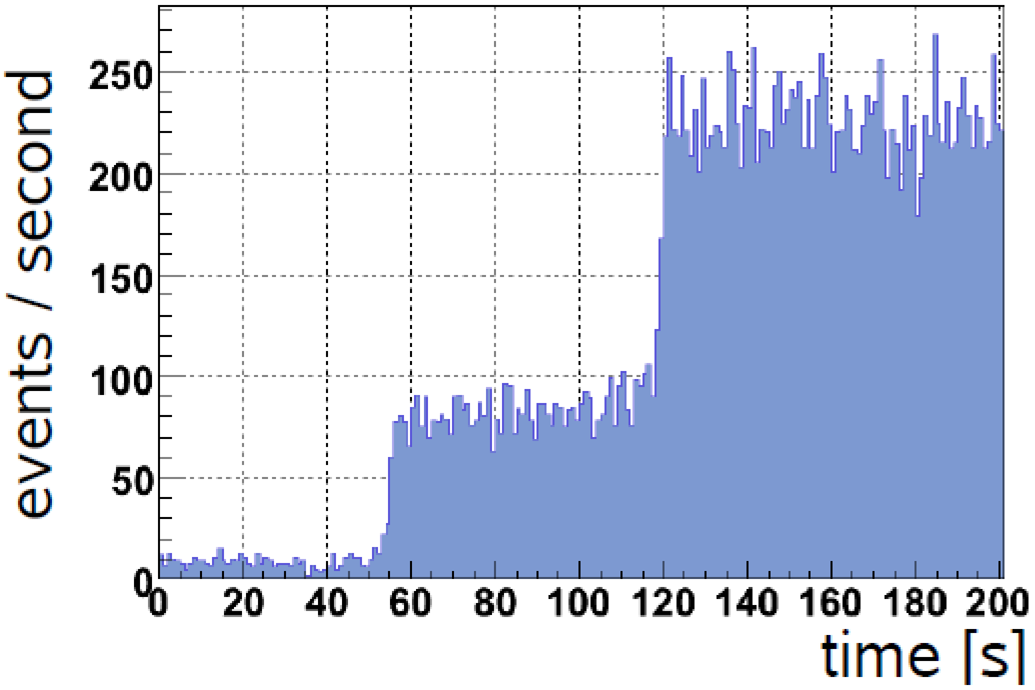
After installation of the new electrodes (Sept 2007):

No pressure and leakage current increase, no electric breakdown (up to -30 kV, 4.5 T)

→ large Penning discharge disappeared !

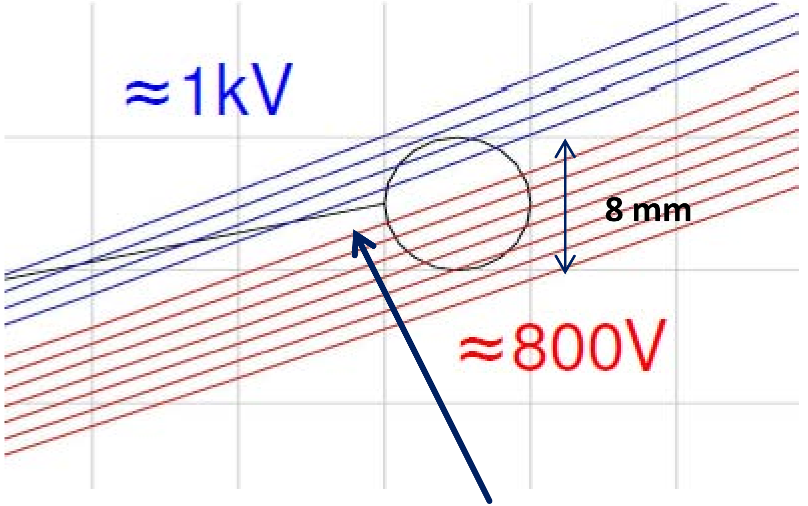
It was then possible to start background measurements with the segmented PIN-diode detector.

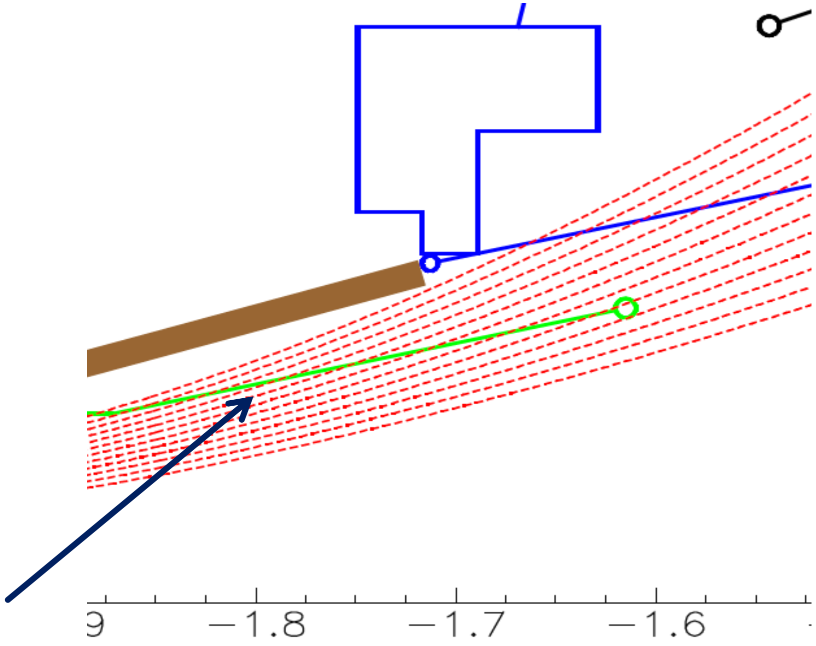
Measurements at high (>2 T) magnetic field:



background:
order of few 100 Hz

Again Penning traps:
at the end ring of the
ground electrode,
small dimensions (few mm)

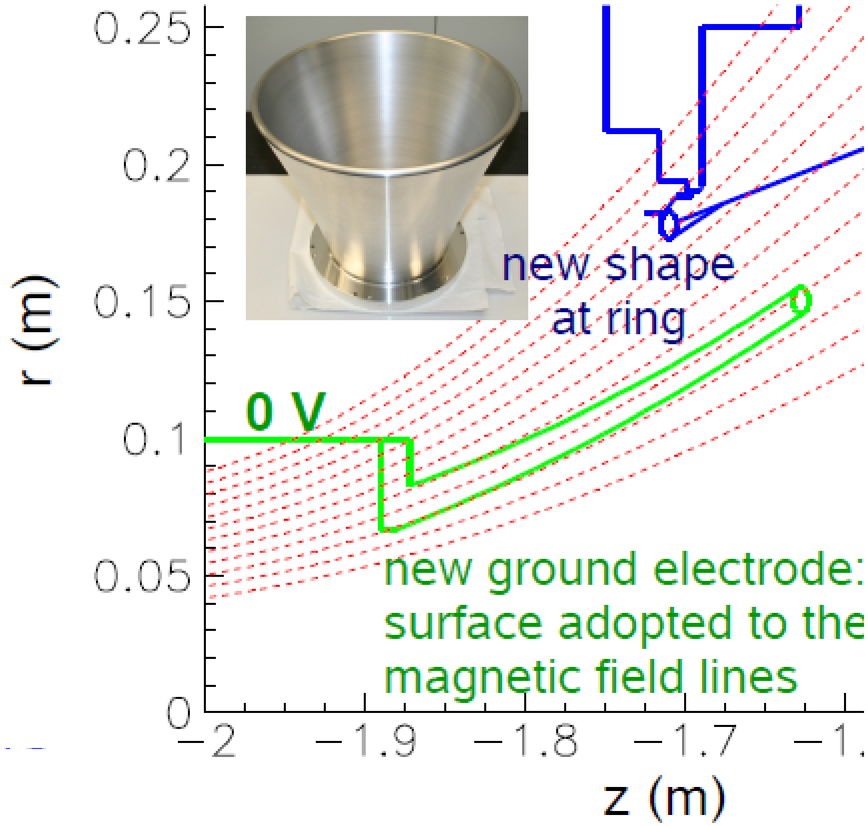




ground electrode

Solution:

new ground electrode design, with detailed simulations,
Penning traps eliminated



new ground electrode: surface adopted to the magnetic field lines

Using the new ground electrode:

Background decreased from few 100 Hz to few 10 mHz (factor 10000)

After reducing background from radon decays:

Background: few mHz
(reduction factor of new ground electrode: 100000)