KATRIN and Mare:
direct neutrino mass experiments

Launch Workshop, Max-Planck-Institut für Kernphysik, Heidelberg, March 21-23, 2007

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- Introduction
- The ^{187}Re decay experiment MARE
- The Karlsruhe TRItium Neutrino experiment KATRIN
- KATRIN´s background suppression, statistics & systematics
- Summary

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

3 complementary ways to the absolute ν mass scale

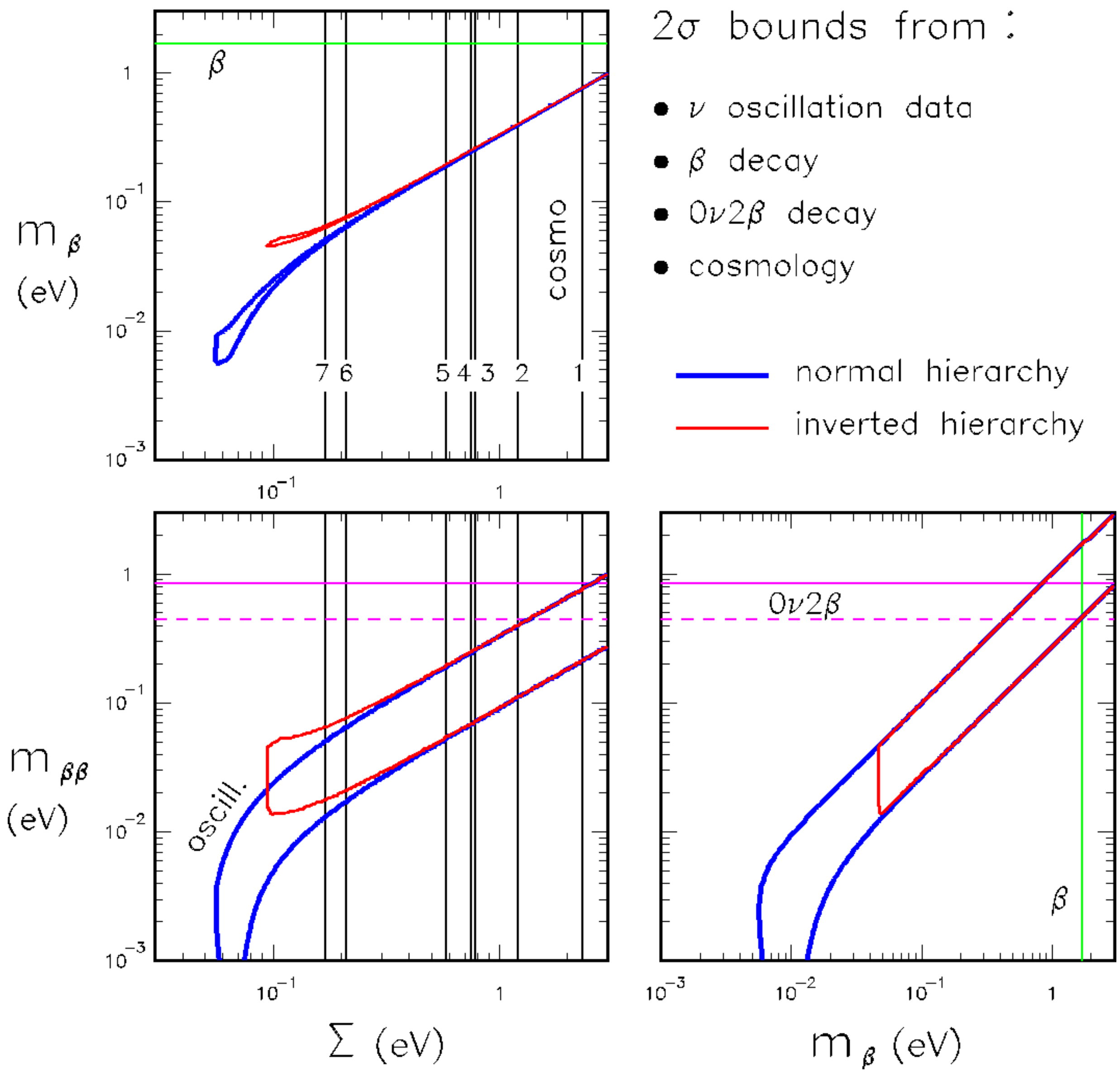
1) cosmology:
very sensitive $\Sigma m(\nu_i)$
but model dependent

2) $0\nu\beta\beta$:
evidence?
Majorana neutrinos

$$m_{ee}(\nu) = | \Sigma |U_{ei}^2| e^{i\alpha(i)} m(\nu_i)|$$

3) direct neutrino mass determination:
no further assumptions
no cancellations:

$$m^2(\nu_e) = \Sigma |U_{ei}^2| m^2(\nu_i)$$



Fogli et al., hep-ph/0608060

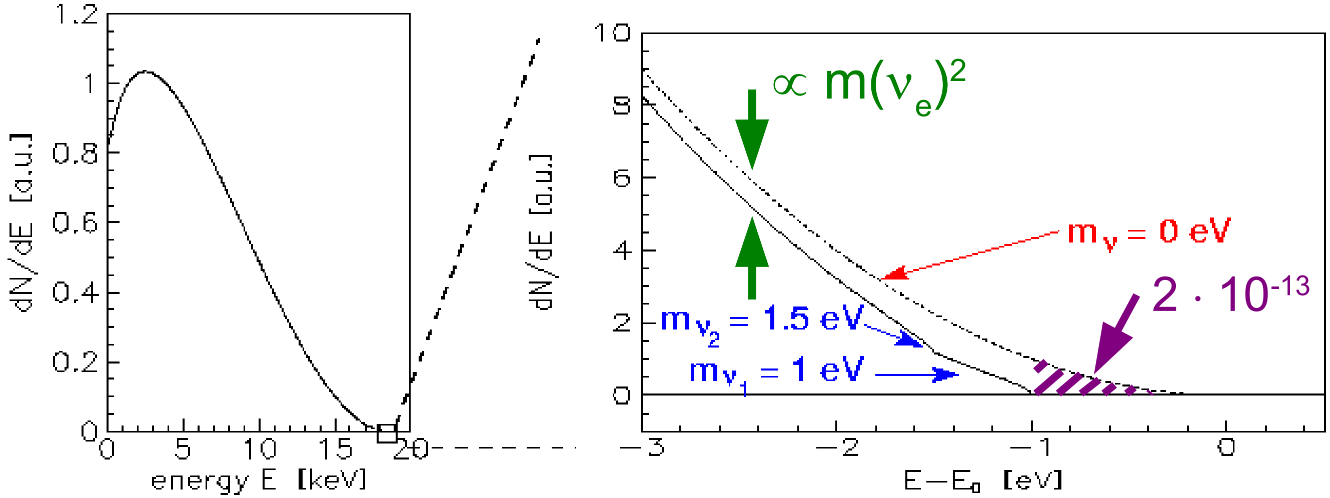
Direct determination of $m(\nu_e)$ from β decay

β decay: $(A,Z) \to (A,Z+1)^+ + \boxed{e^-} + \bar{\nu}_e$

β electron energy spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \Sigma\,|U_{ei}|^2\,[\,(E_0-E_e)^2 - \mathbf{m(\nu_i)^2}\,]^{1/2}$$

(modified by electronic final states, recoil corrections, radiative corrections)



oscillation exp: small Δm_{ij}^2

$\Rightarrow$ see only average neutrino mass squared:

$m(\nu_e)^2 := \Sigma\,|U_{ei}|^2\,\mathbf{m(\nu_i)^2}$

Need: **low endpoint energy** $\Rightarrow$ **Tritium ^{3}H, (^{187}Re)**

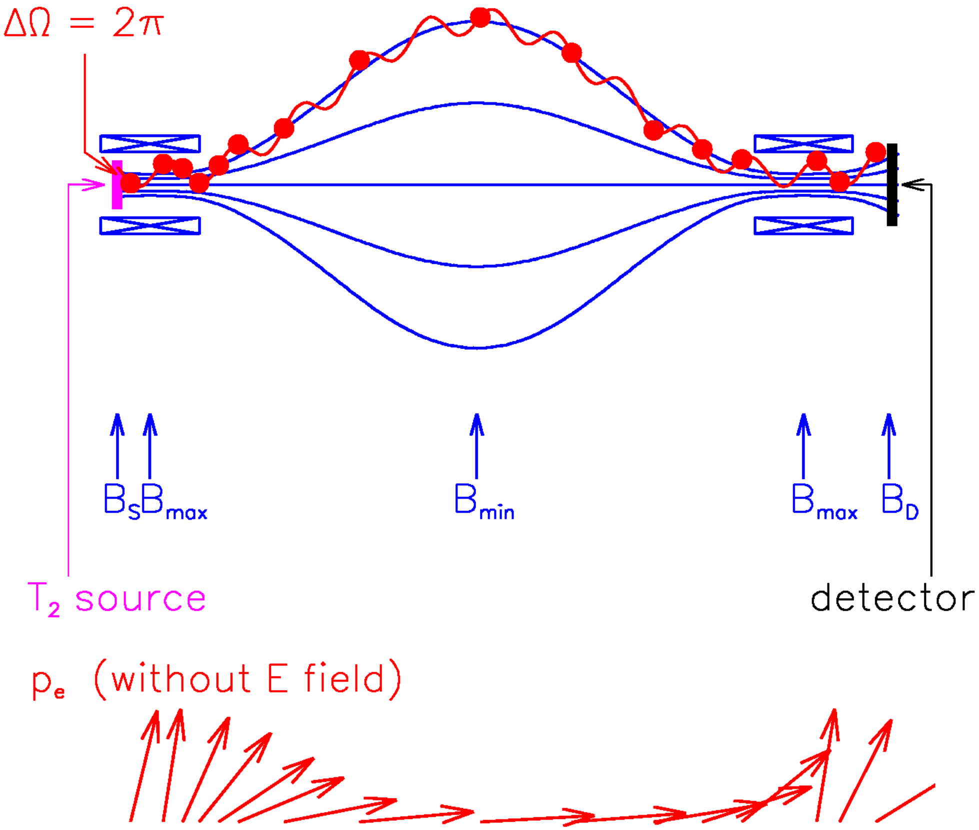
very high energy resolution &
very high luminosity &
very low background
} $\Rightarrow$ **MAC-E-Filter**
(or bolometer for ^{187}Re)

Principle of the MAC-E-Filter

Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

- Two supercond. solenoids compose magnetic guiding field
- Electron source (T_2) in left solenoid
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_\perp / B = \text{const.}$

$\Rightarrow$ parallel e^- beam



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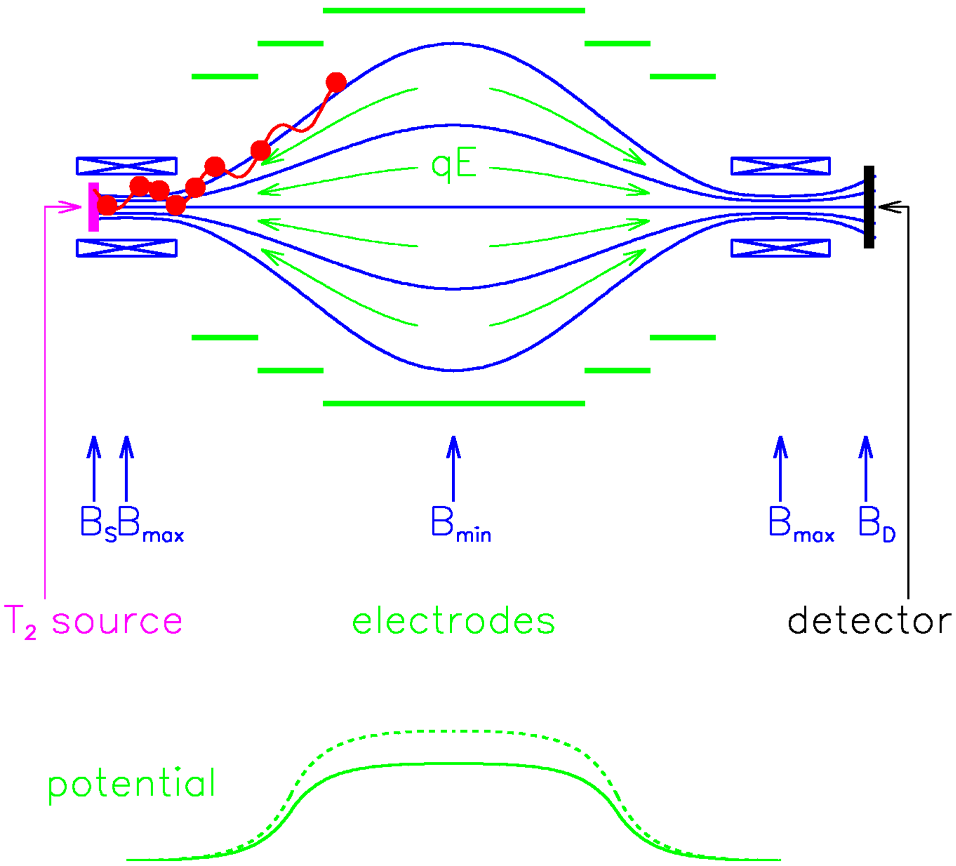
- Energy analysis by electrostat. retarding field



$\Delta E = E \cdot B_{min} / B_{max} = E \cdot A_{s,eff} / A_{analyse}$ ≈ 4.8 eV (Mainz) $= 0.93$ eV (KATRIN)

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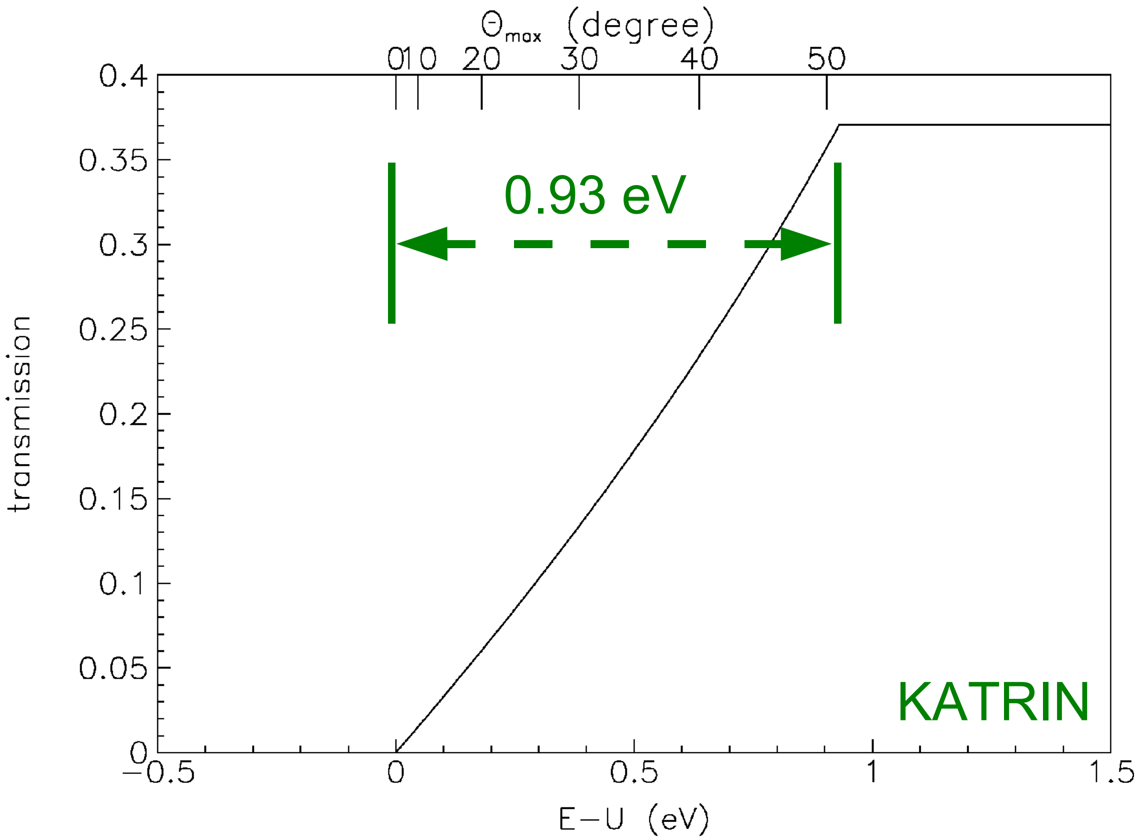
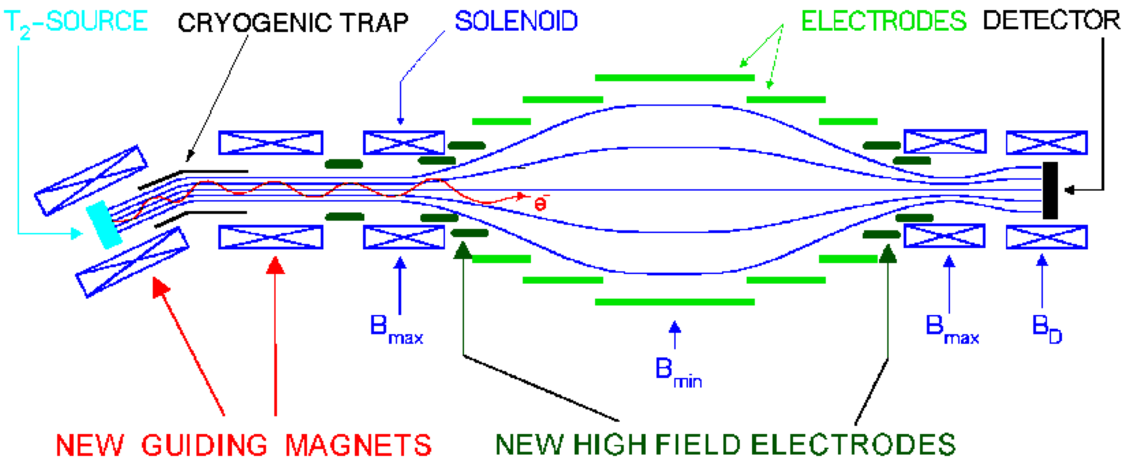
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

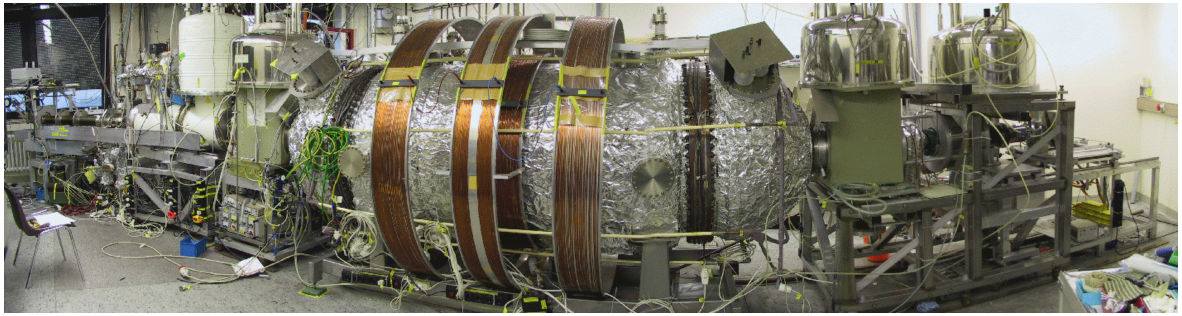


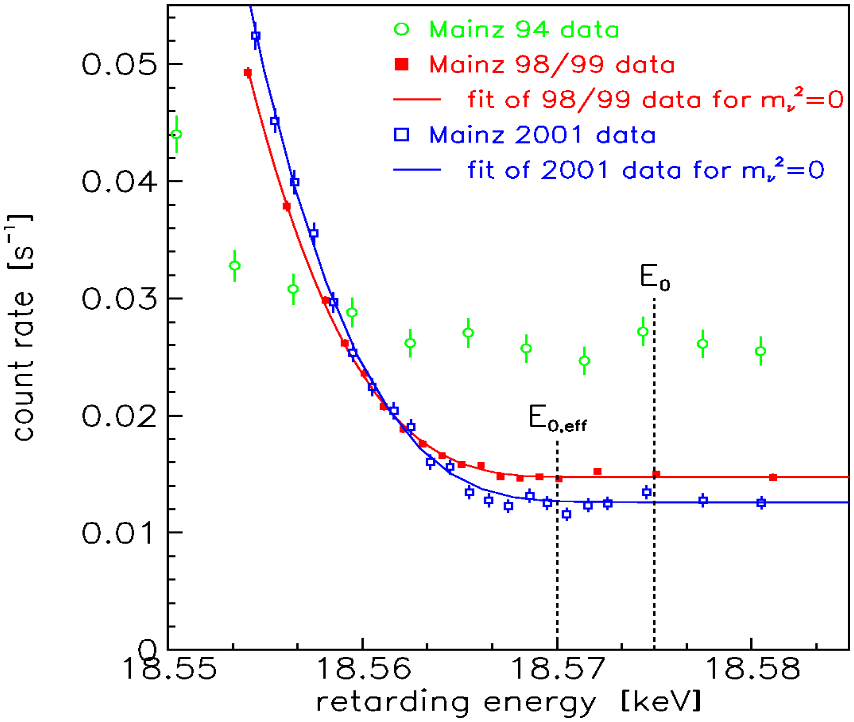
⇒ sharp integrating transmission function without tails:

$\Delta E = E \cdot B_{min}/B_{max} = E \cdot A_{s,eff}/A_{analyse}$ = 0.93 eV, KATRIN (4.8 eV, Mainz)

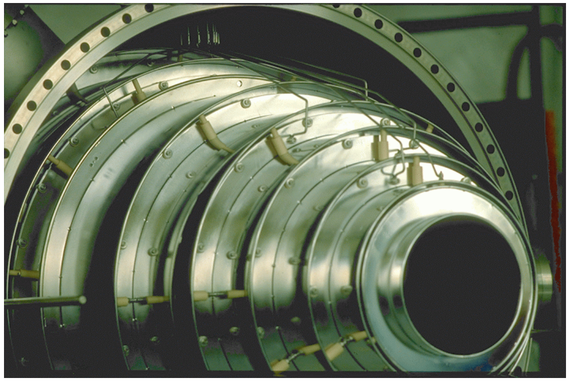
The Mainz Neutrino Mass Experiment
Phase 2: 1997-2001







⇓



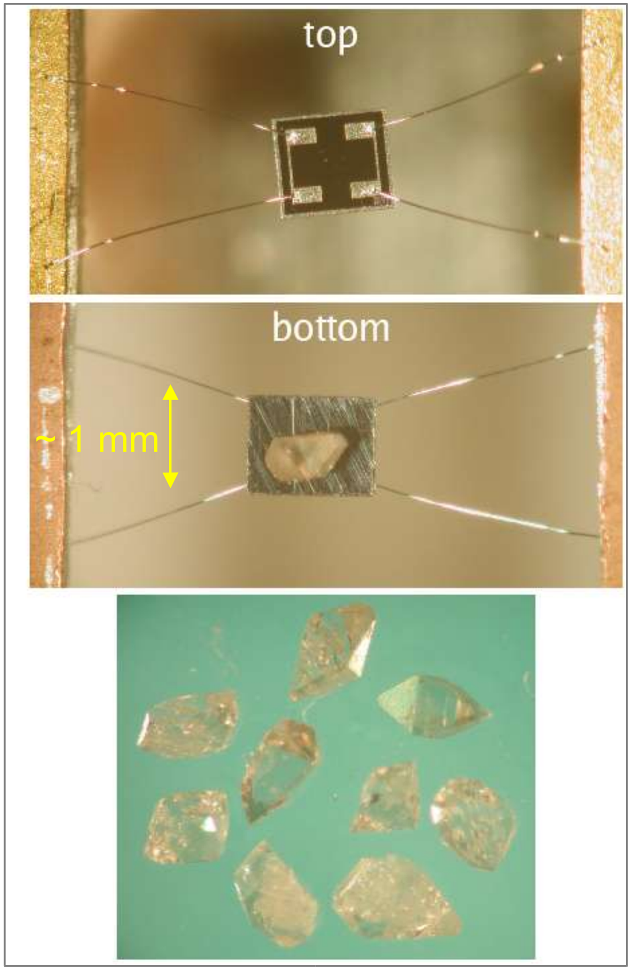
After all critical systematics measured by own experiment (inelastic scattering, self-charging, neighbor excitation):

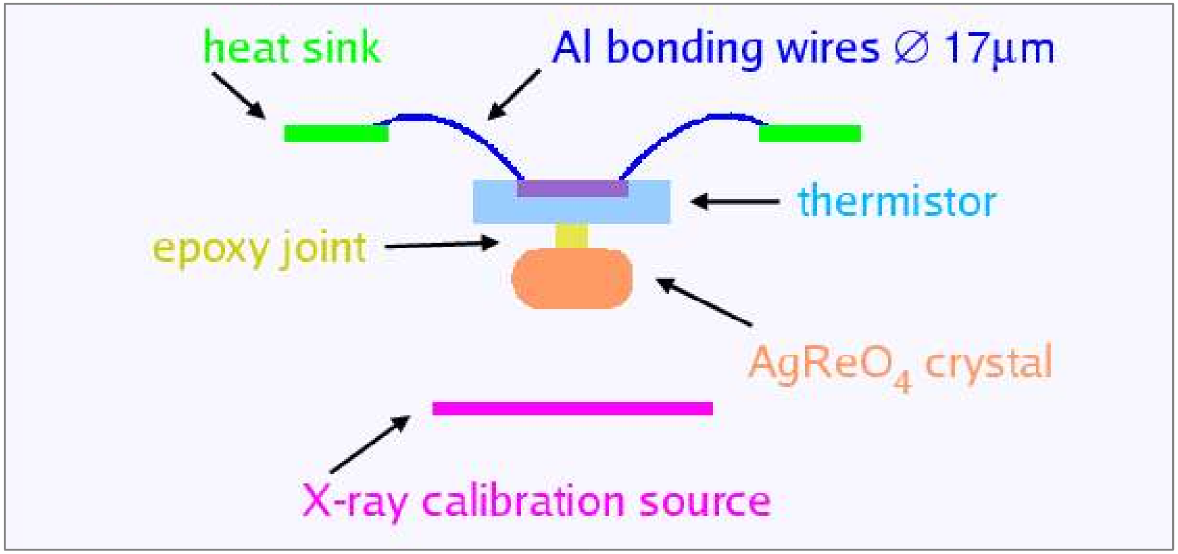
$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1\ \mathrm{eV}^2 \Rightarrow m(\nu) < 2.3\ \mathrm{eV}$ (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

MIBETA (Milano/Como)

$AgReO_4$ (10 * 250 -350 mg)




heat sink

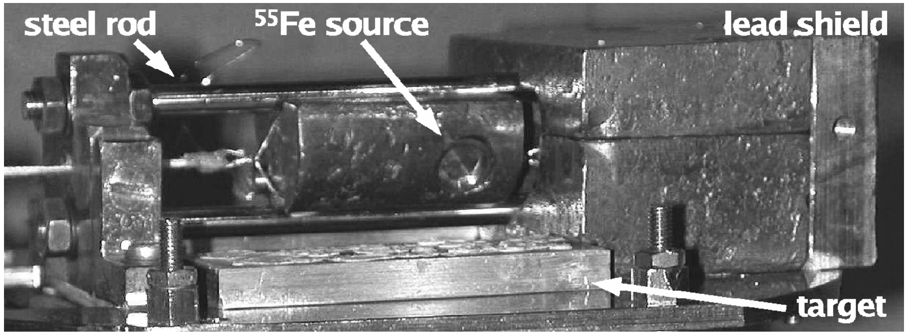
Al bonding wires ∅ 17µm

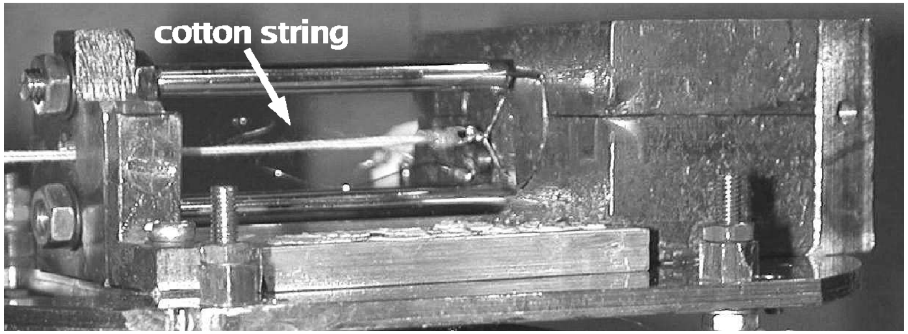
thermistor

epoxy joint

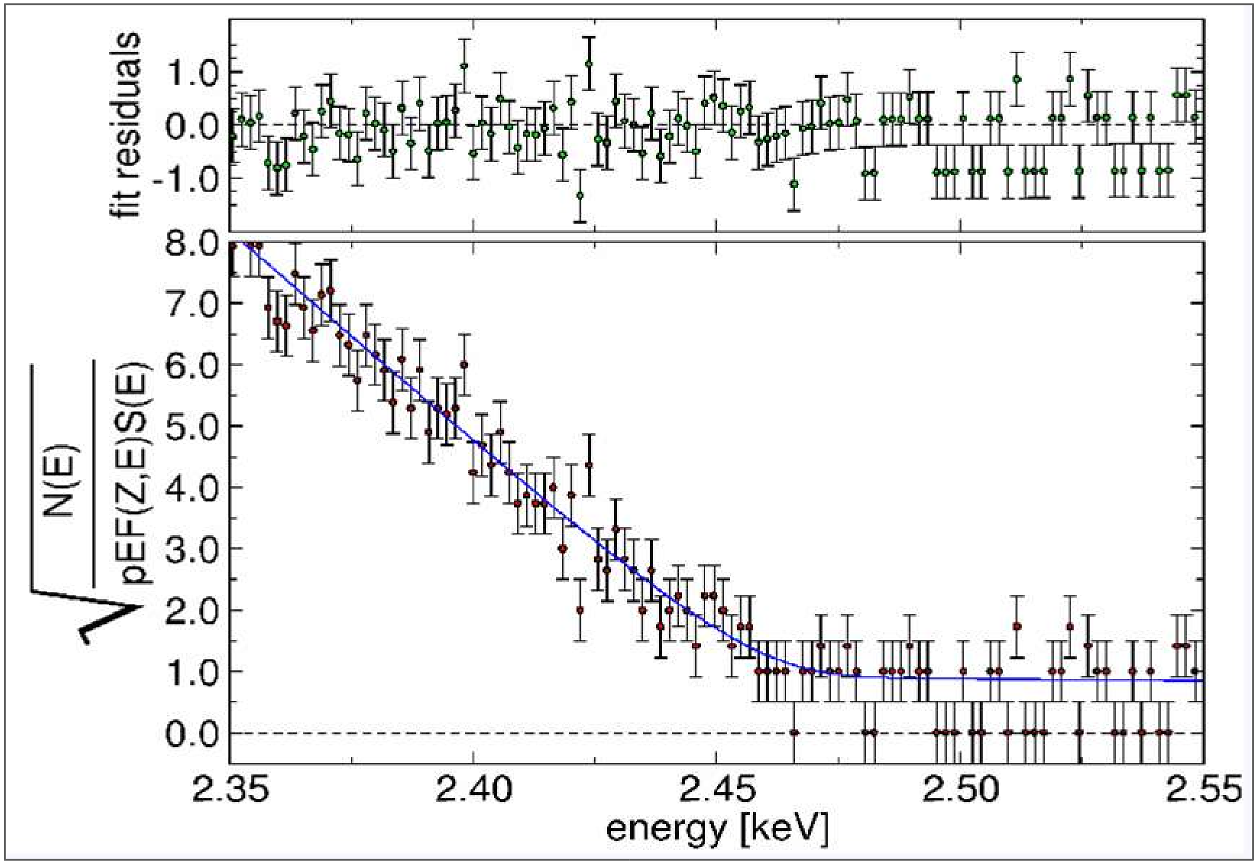
$AgReO_4$ crystal

X-ray calibration source





MIBETA: final result



Parameters

detectors: 10

rate each: 0.13 1/s

energy res.: $\Delta E = 28$ eV

pile-up frac.: $1.7\ 10^{-4}$

$M_\nu^2 = -141 \pm 211_{\text{stat}} \pm 90_{\text{sys}}$ eV^2

$M_\nu < 15.6$ eV (90% c.l.)

(M. Sisti et al., NIMA520 (2004) 125)

MANU (Genova)

- Re metalic crystal (1.5 mg)
- BEFS observed (F.Gatti et al., Nature 397 (1999) 137)
- sensitivity: $m(\nu) < 26$ eV (F.Gatti, Nucl. Phys. B91 (2001) 293)

Proposal: Microcalorimeter Arrays for a Rhenium Experiment (MARE)

Collaboration: Genova, Goddard Space Fligth Center/NASA, Heidelberg, Como, Milano, Trento, U Wisconson

Idea: 2nd and 3rd generation rhenium β decay experiment

MARE I:
300 detectors (MIBETA: 10)
ΔE = 10 eV (MIBETA: 28 eV)
$\tau = 10^{-4}$ s (MIBETA: 10^{-3} s)
with semiconductor sensors (like MIBETA/MANU)

a

expected sensitivity on $m(\nu_e)$: 2-3 eV
(before full start of KATRIN in 2010)

MARE I looks realistic as a first step
really complementary to tritium β experiments

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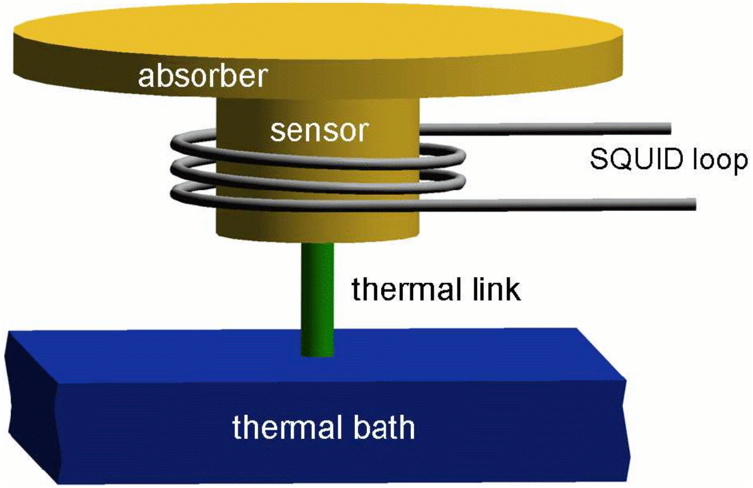
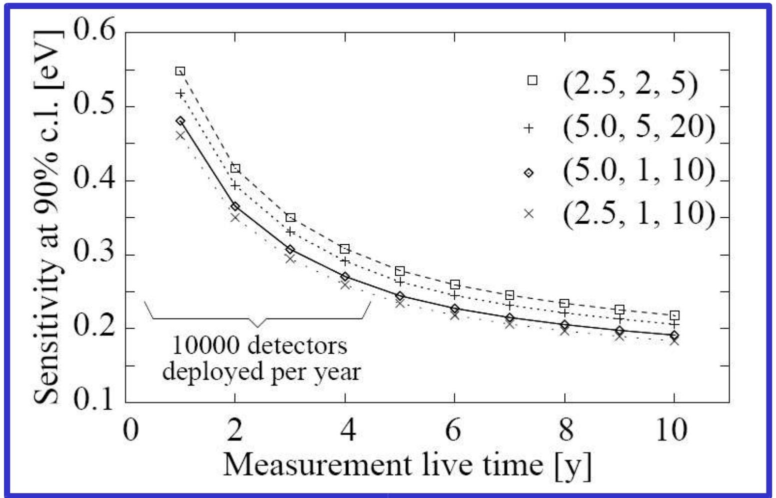
Idea: 2nd and 3rd generation rhenium β decay experiment

MARE II:
5000 – 50000 detectors (MIBETA: 10)
ΔE = 2.5 - 5 eV (MIBETA: 28 eV)
τ = a few 10^{-6} s (MIBETA: 10^{-3} s)
with superconducting transition edge sensors (TES) or
with metallic magnetic temperature sensors (MMC)

a

expected sensitivity on m(ν_e): 0.2 eV





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$\Delta E = 5$ eV (MIBETA: 28 eV)

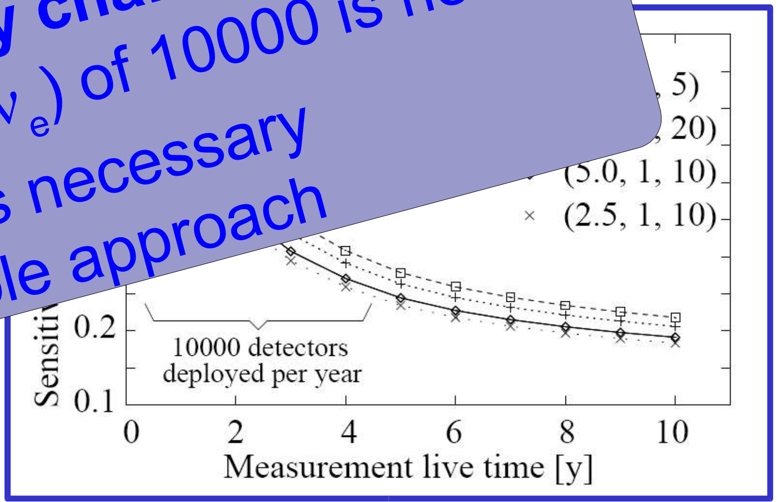
τ = a few 10^{-6} s (MIBETA: 10^{-3} s)

with superconducting transition edge sensors (TES) or

with metallic magnetic temperature senso IC)

a

expected sensitivity on m(



MARE II looks really challenging,

since an improvement in $m^2(\nu_e)$ of 10000 is needed

$\Rightarrow$ a lot of R&D is necessary

but it is a scalable approach

The Karlsruhe Tritium Neutrino experiment KATRIN

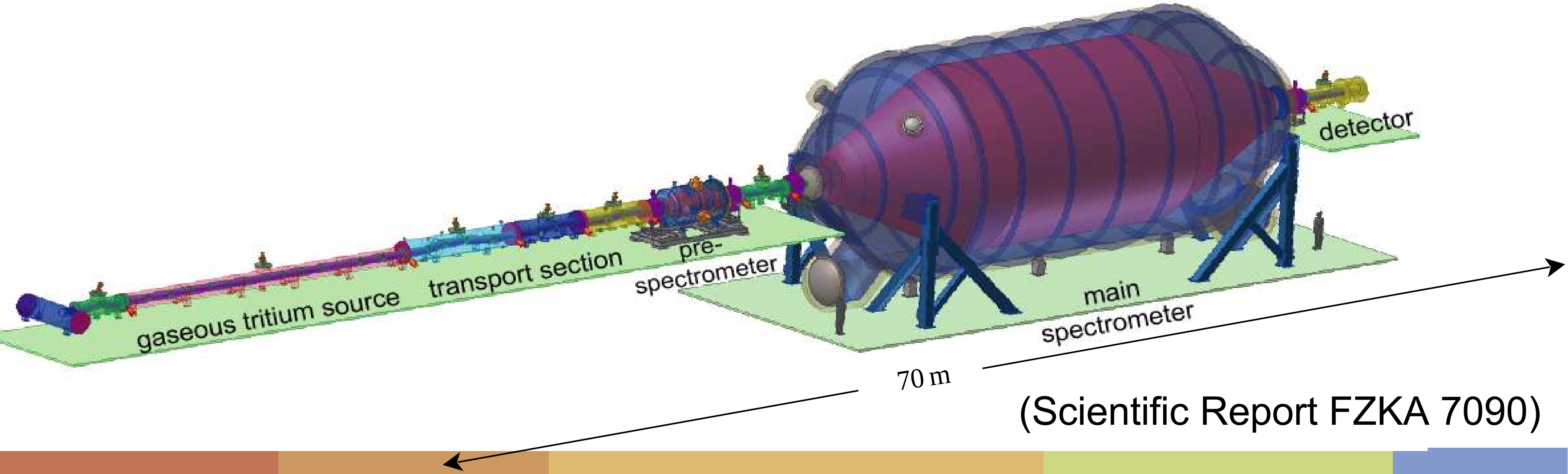
is being set up at the Forschungszentrum Karlsruhe

Physics Aim:

Improvement of sensitivity by 1 order of magnitude: 2.2 eV → 0.2 eV

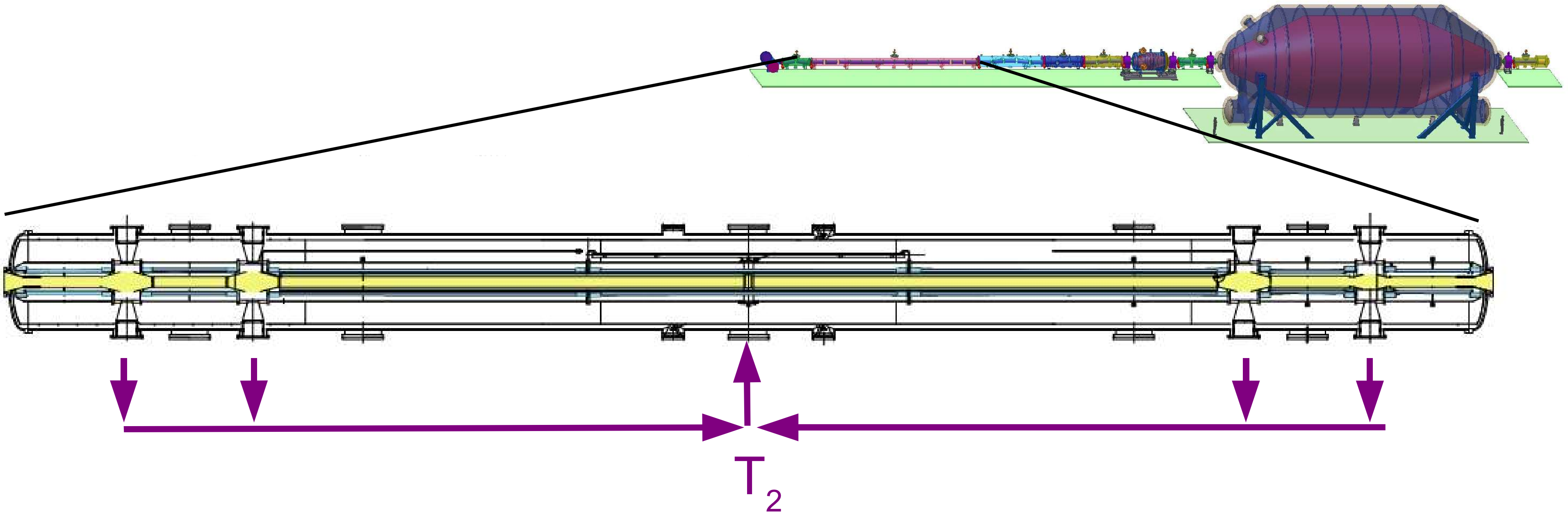
- higher energy resolution: $\Delta E \approx 1\text{eV}$
  since $E/\Delta E \sim A_{\text{spectrometer}}$ $\Rightarrow$ larger spectrometer
- relevant region below endpoint becomes smaller
  even less count rate $dN/dt \sim A_{\text{spectrometer}}$ $\Rightarrow$ larger spectrometer
- much longer measurement time: 100 d → 1000 d

$\}$ $\varnothing$10m



(Scientific Report FZKA 7090)

Molecular Windowless Gaseous Tritium Source WGTS

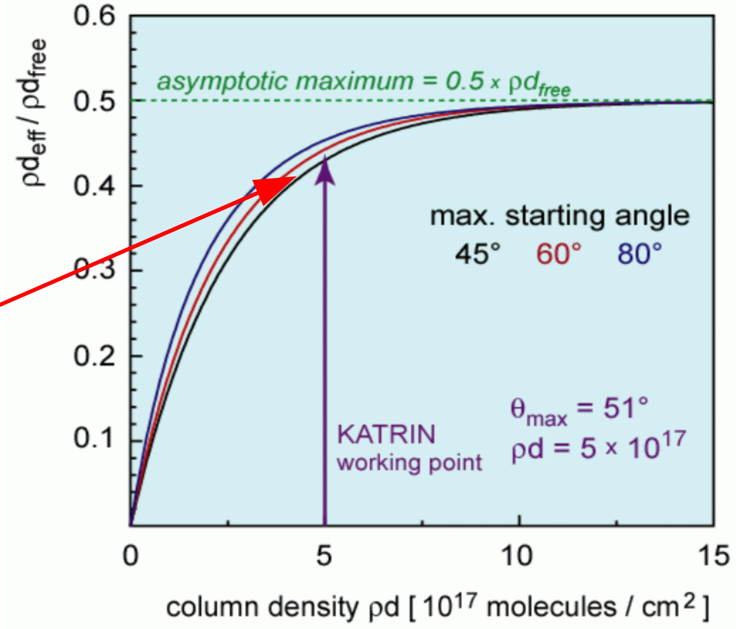


WGTS:

tub in long superconducting solenoids
∅ 9cm, length: 10m, T = 30 K

Tritium recirculation (and purification)
p_{inj} = 0.003 mbar, q_{inj} = 4.7Ci/s

allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/\text{cm}^2$
with small systematics

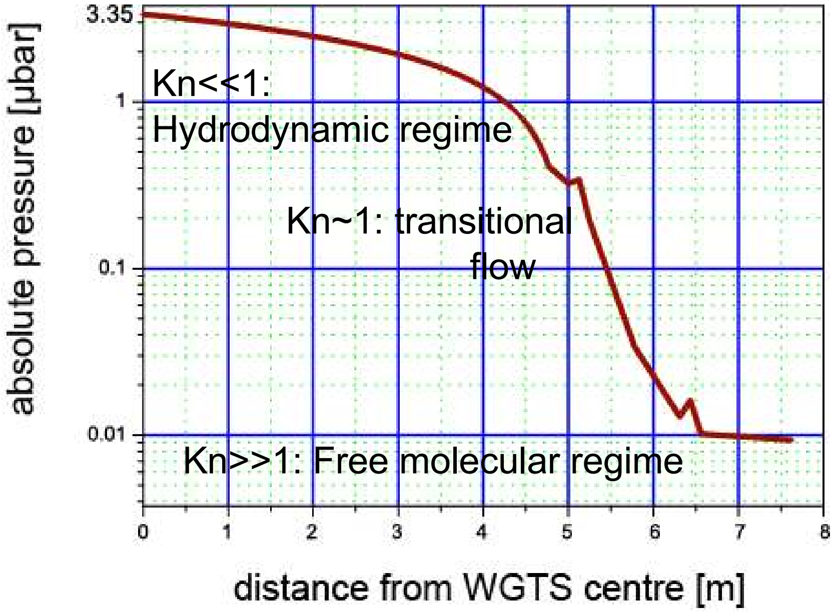


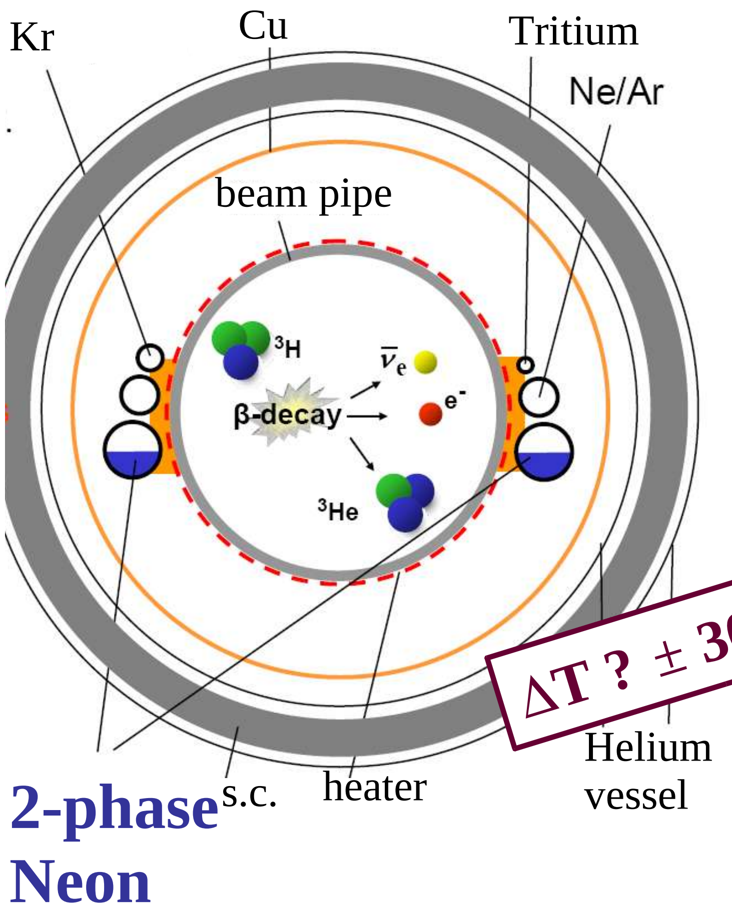
Molecular Windowless Gaseous Tritium Source WGTS

Conceptional design

2 phase Neon cooling with operating temperature: 27–28 K

- **spatial** (homogeneity): ± **0.1%**
- **time** (stability/hour): ± **0.1%**



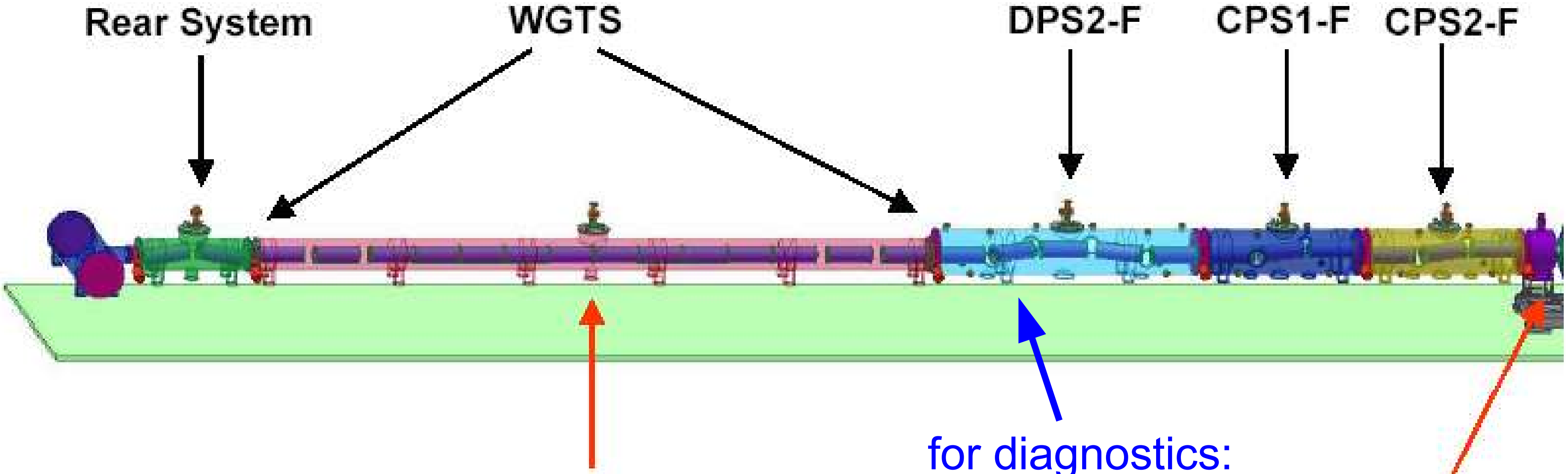


ΔT ? ± 30 mK !

Transport and differential & cryo pumping sections

Differential pumping

Cryogenic pumping



Injection: 1.8 mbar l/s (STP)

for diagnostics:
FTICR trap
K. Blaum et al.

max 2.5 10^{-14} mbar l/s

requirements:

- adiabatic electron guiding
- T_2 reduction factor of ~10^{14}

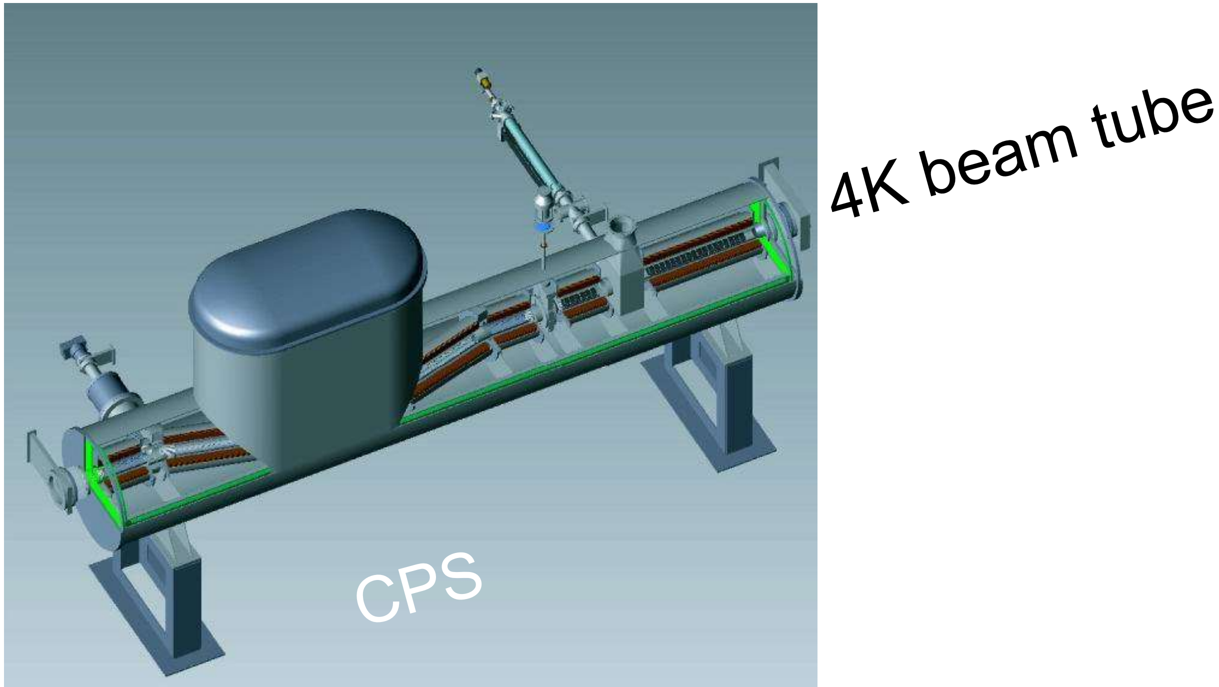
Cryogenic pumping section

Objective: retention of remaining tritium flux, reduction factor 10^7

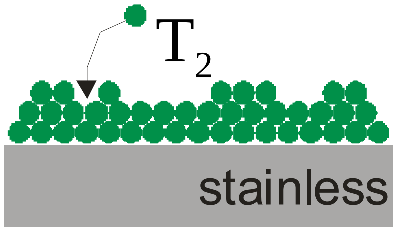
(tritium partial pressure in main spectrometer $p < 10^{-20}$ mbar)

method: cryo-sorption on condensed Ar-frost

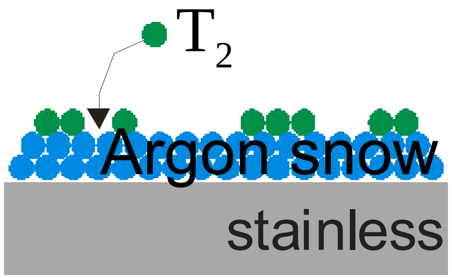
rate: <1 Ci T_2 in 60 days (regeneration with warm He-gas)



Cryocondensation



Cryosorption



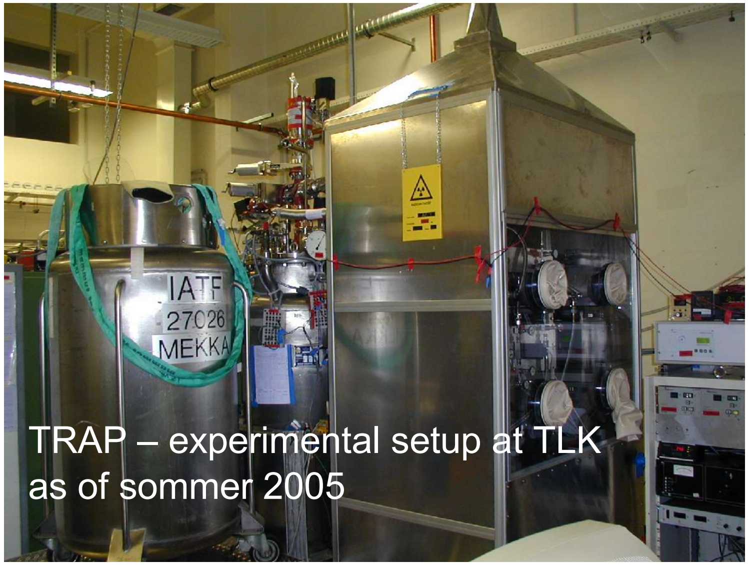
TRAP - TRitium Argon Frost Pump at FZK

Inlet flow rate: ≈ 10^{-6} mbar l/s

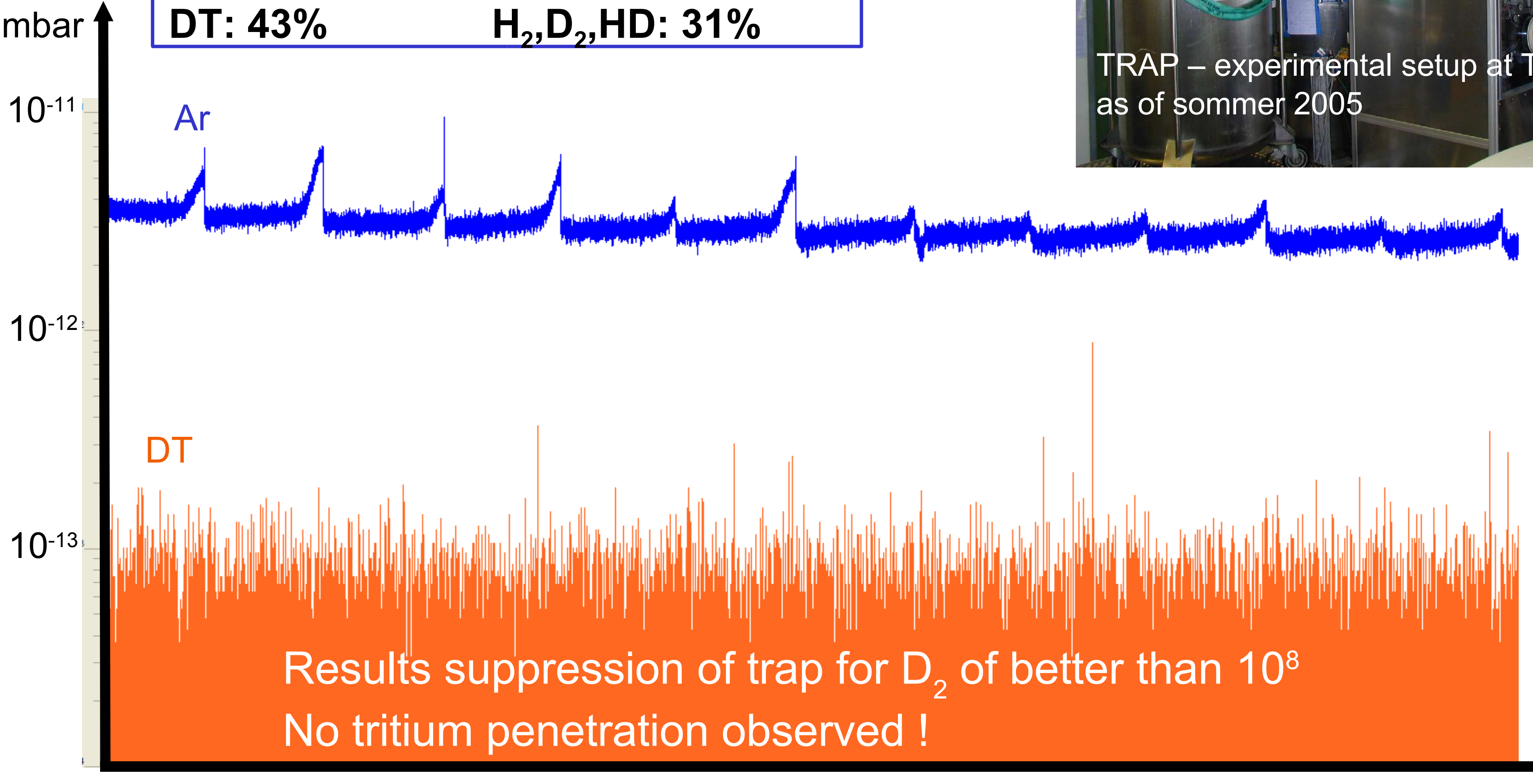
Isotopic composition (CAPER-GC):

HT: 7% **T_2: 19%**

DT: 43% **H_2,D_2,HD: 31%**

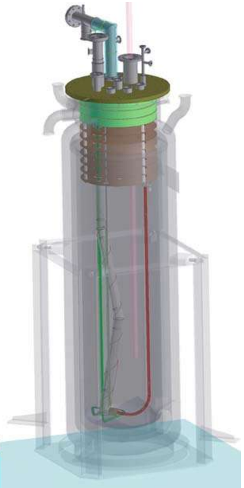


TRAP – experimental setup at TLK as of sommer 2005

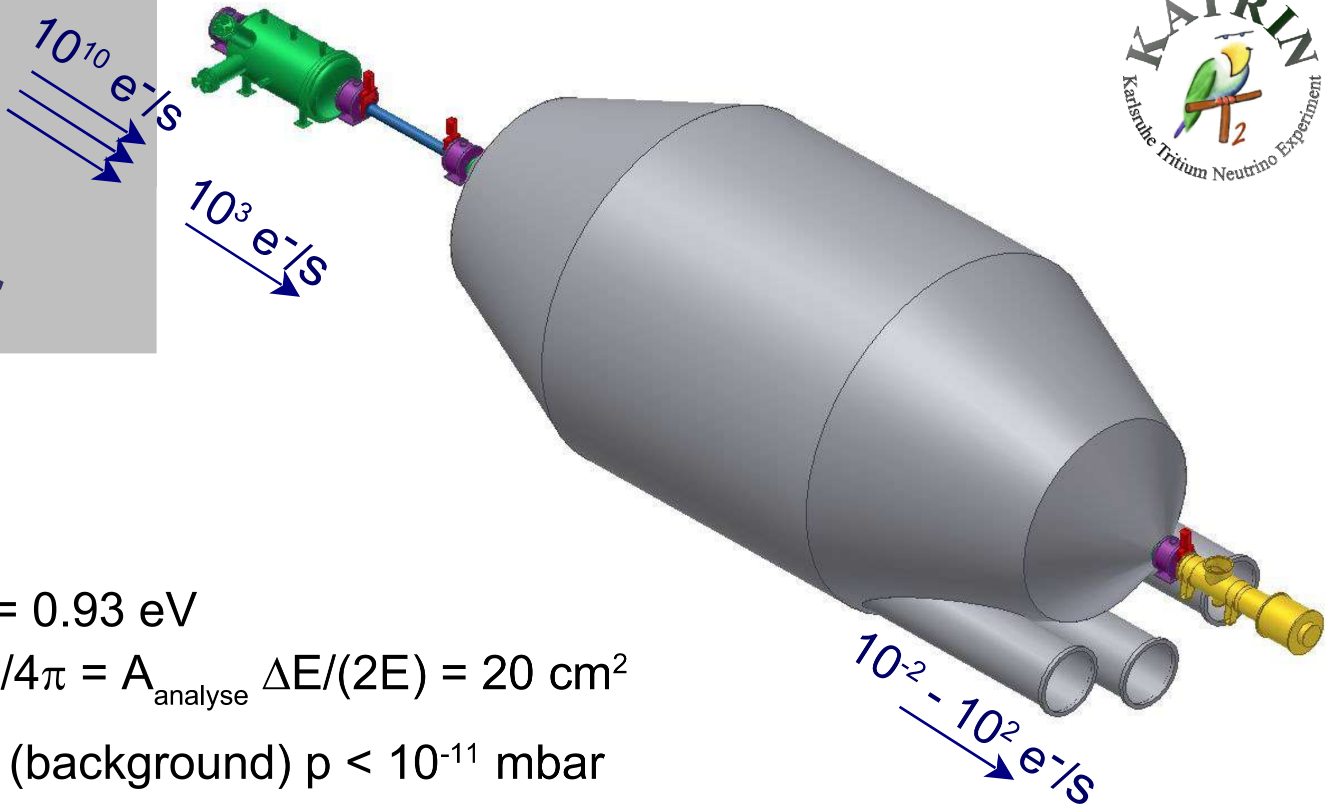


Results suppression of trap for D_2 of better than 10^8

No tritium penetration observed !



Pre and main spectrometer



Main spectrometer:

- $\varnothing$10m, length 24m
  $\Rightarrow$ large energy resolution: $\Delta E = 0.93$ eV
  $\Rightarrow$ high luminosity: $L = A_{Seff}\ \Delta\Omega/4\pi = A_{analyse}\ \Delta E/(2E) = 20\ \mathrm{cm}^2$
- ultrahigh vacuum requirements (background) $p < 10^{-11}$ mbar
- „simple“ construction: vacuum vessel at HV + „massless“ screening electrode

Pre spectrometer

- Transmission of electron with highest energy only
  (10^{-7} part in last 100 eV)
  $\Rightarrow$ Reduction of scattering probaility in main spectrometer
  $\Rightarrow$ Reduction of background
- only moderate energy resolution required: $\Delta E = 80$ eV
- test of new ideas (XHV, shape of electrodes, avoid and remove of trapped particles, ...)

Detector

task: detection of transmitted ß-decay electrons

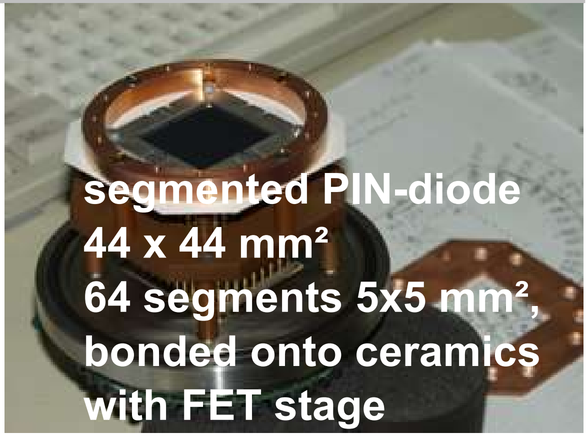
with high energy resolution ($\Delta E = 1$ keV)

record radial profile of flux tube

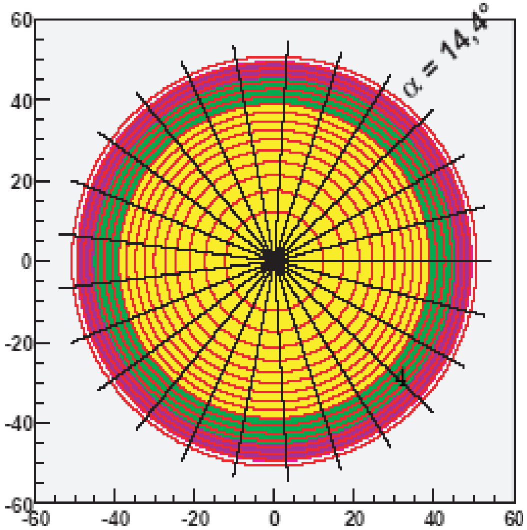
aim: background minimisation, systematic effects

⇒ post-acceleration to place signal line

at lower intrinsic background



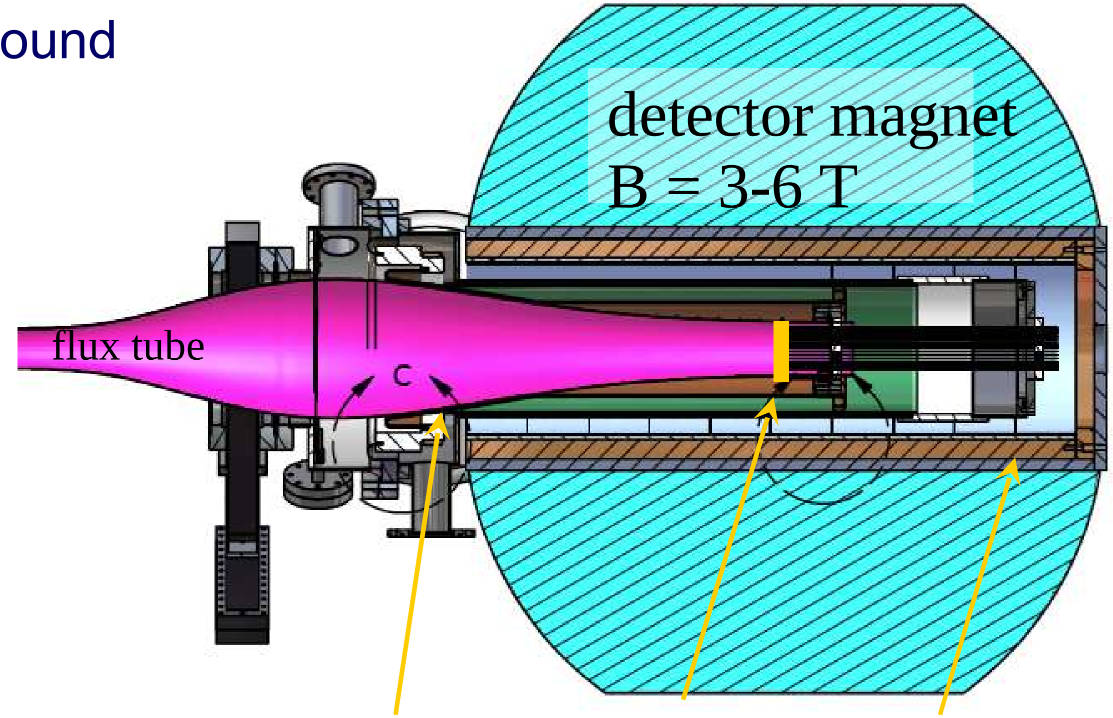
segmented PIN-diode
44 x 44 mm^2
64 segments 5x5 mm^2,
bonded onto ceramics
with FET stage



design: radially segmented

Si-PIN diode array

~150 pixels with A=100 cm^2



electrode
(kV-acceleration)

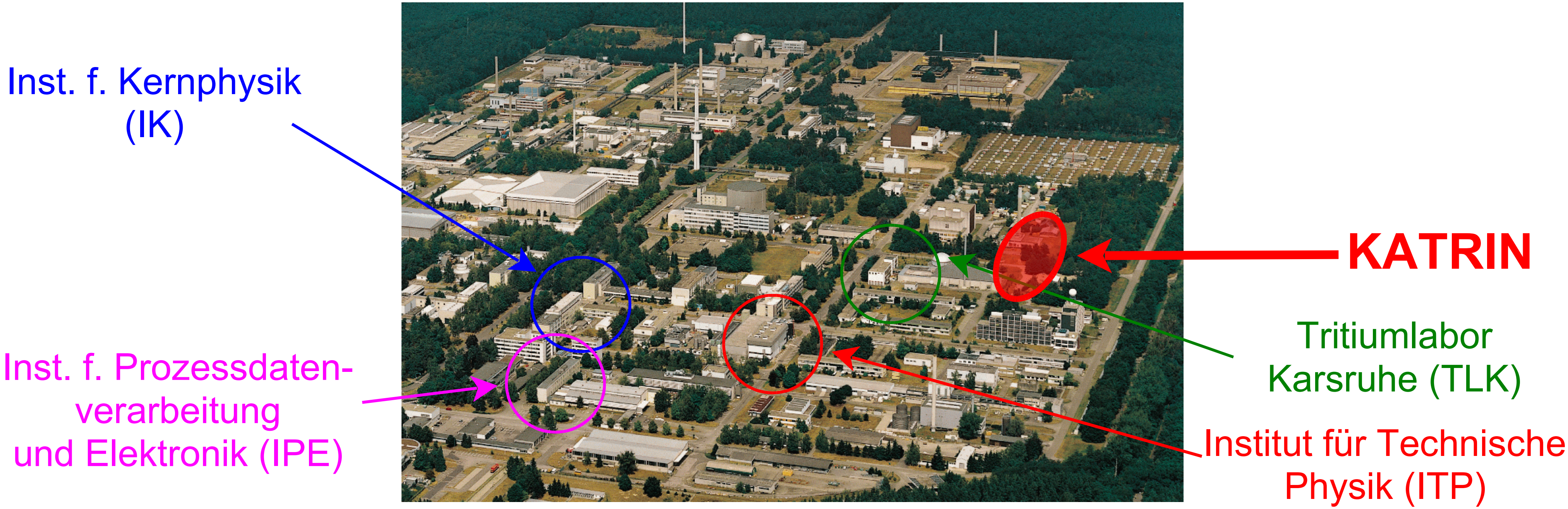
low-level
detector

shielding &
veto

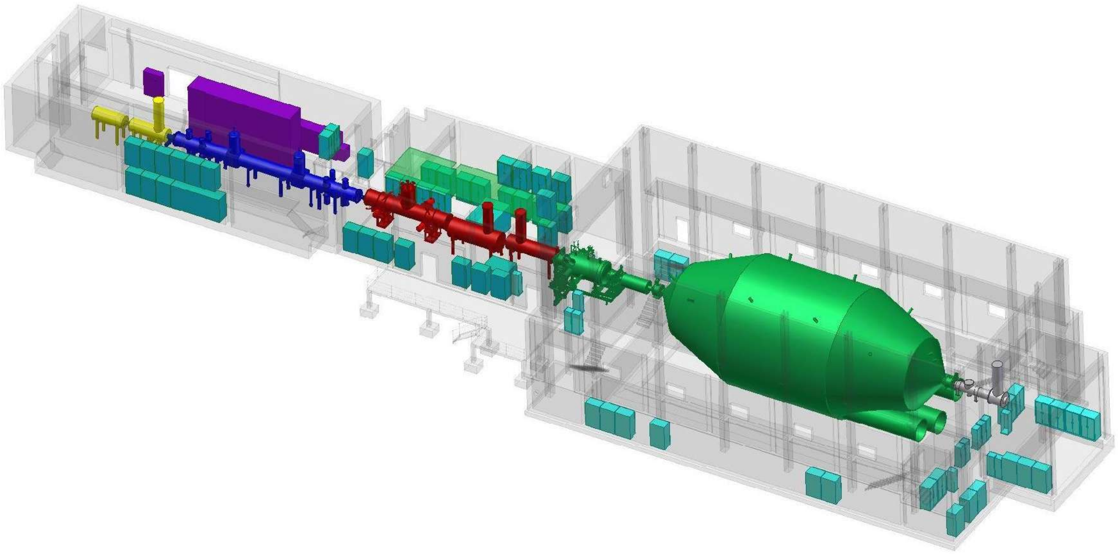
Technical challenges

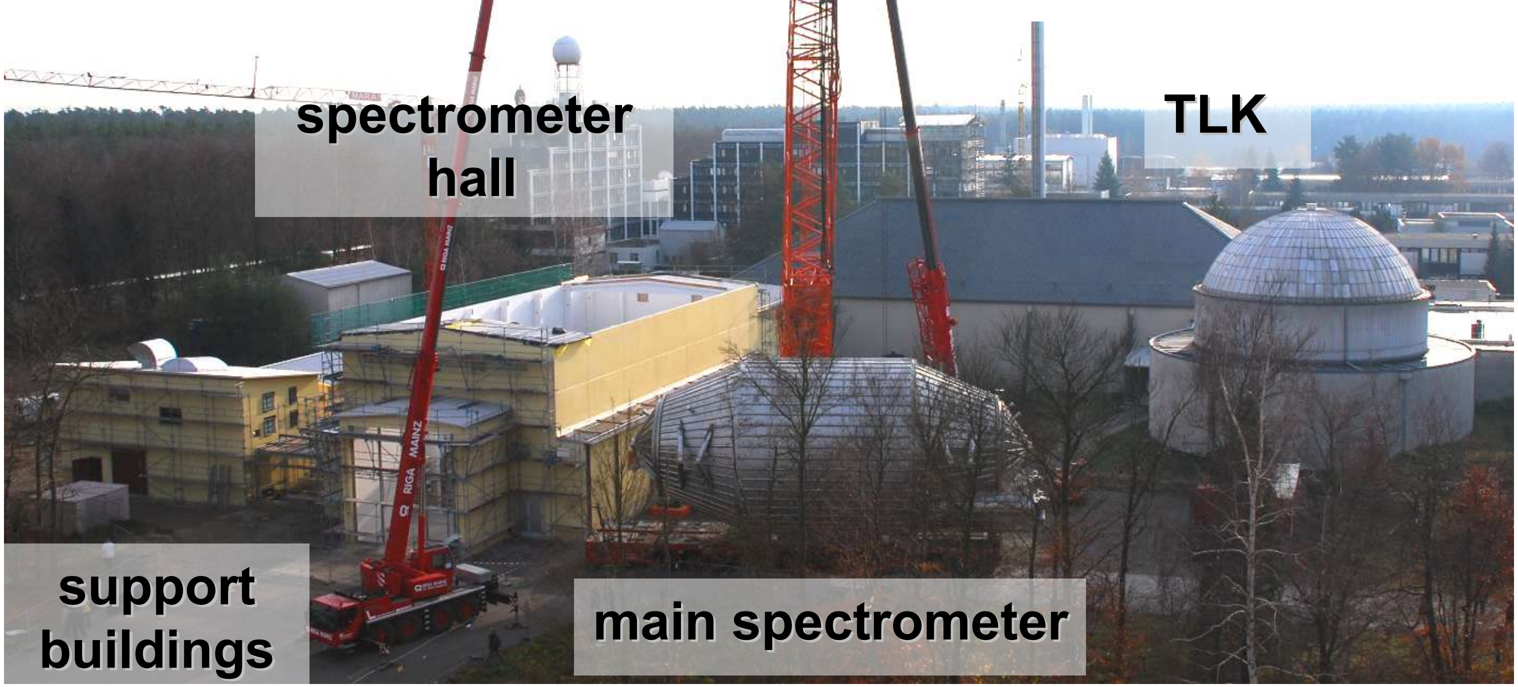
- Recirculation and purification of tritium to a large extent (kCi)
- $\approx$ 30 superconducting solenoids
- UHV (< 10^{-11} mbar) in huge volume ($1000 m^2$)
- HV calibration and stability on ppm level
- High resolution detectors
- ....

$\Rightarrow$ ideal place: Forschungszentrum Karlsruhe/Germany



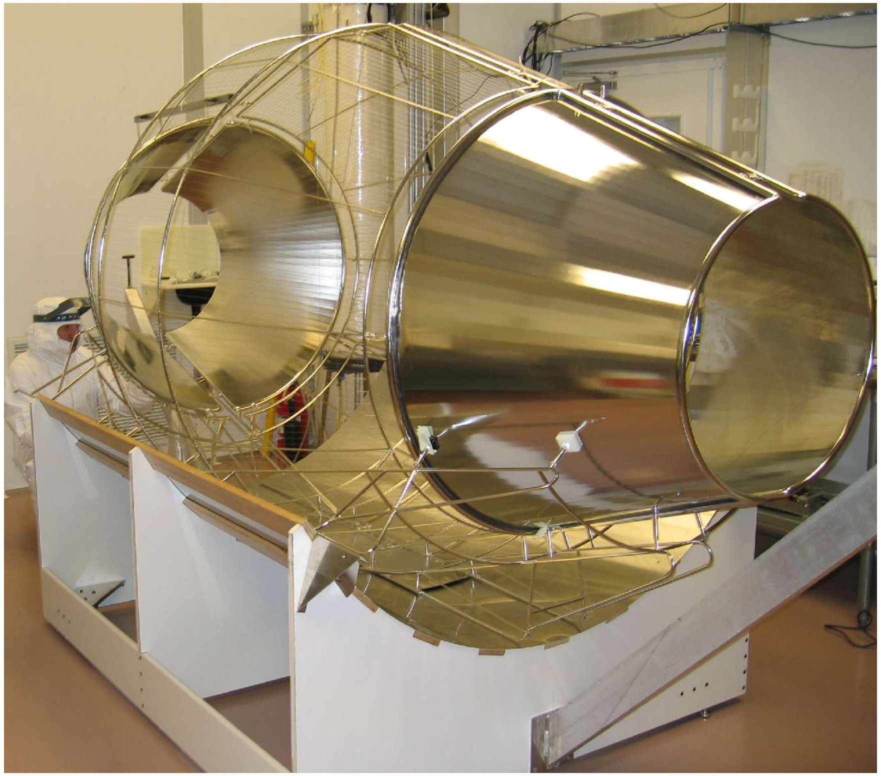
KATRIN`s location at Forschungszentrum Karlsruhe





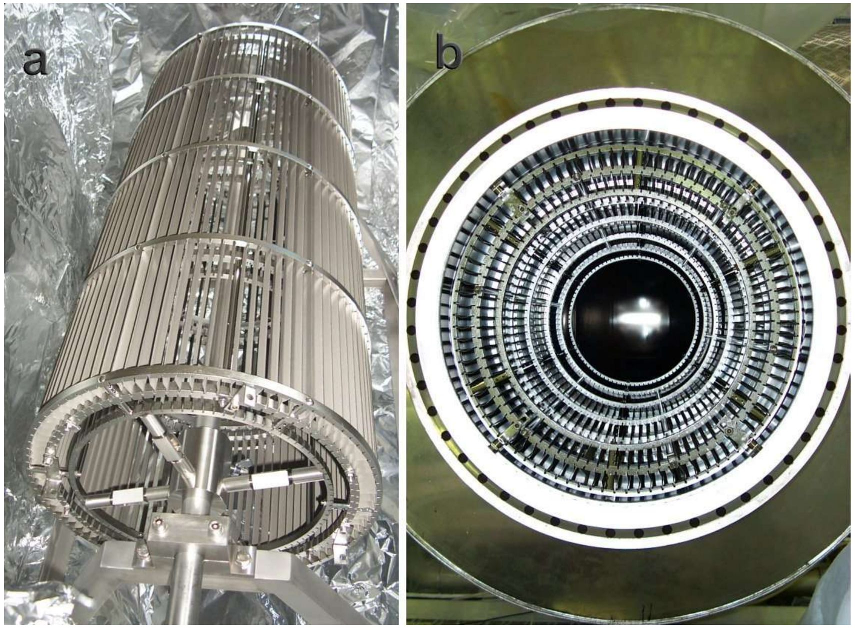
Vacuum tests and inner electrode system of pre spectrometer

ground electrode
wire electrode + solid cones

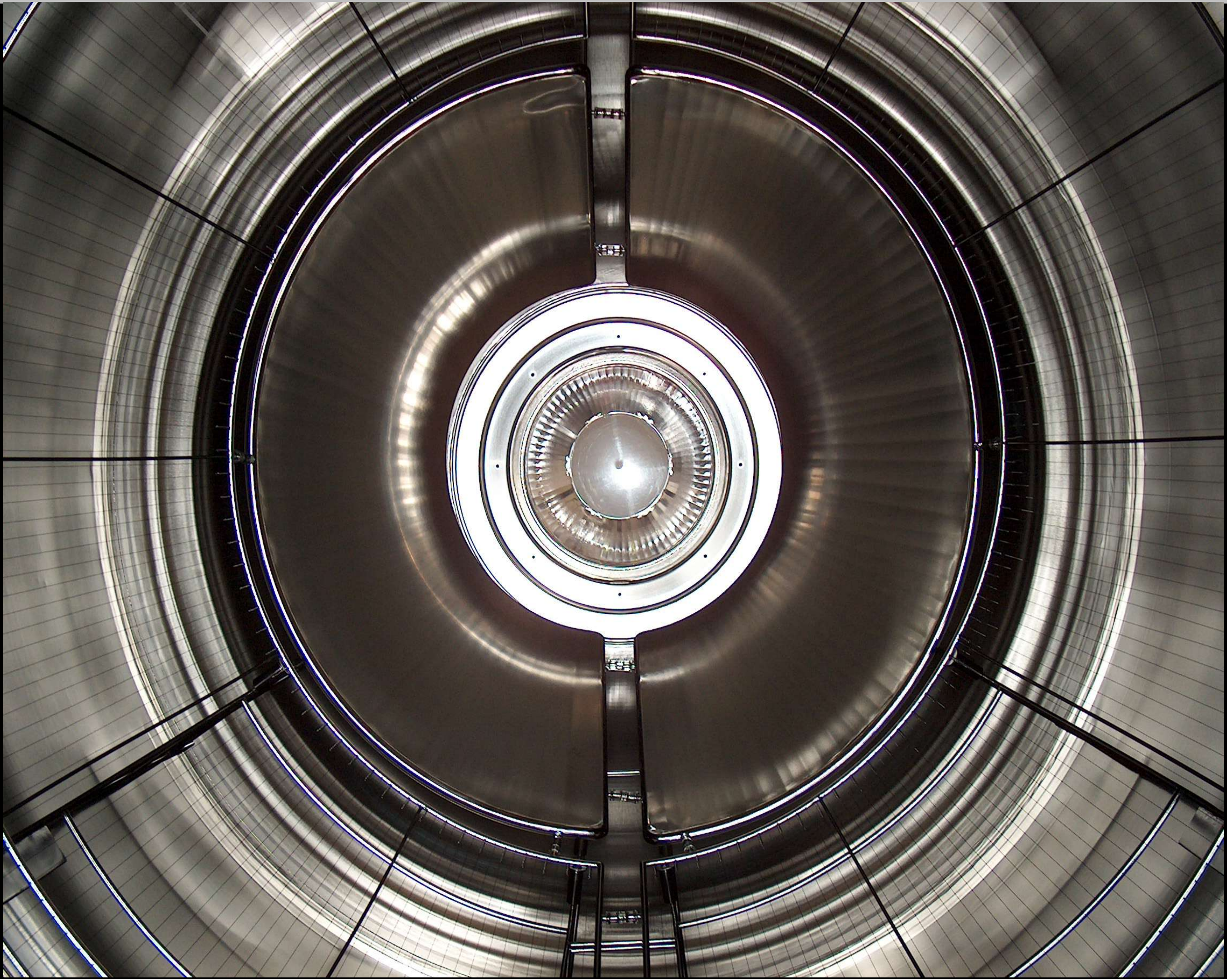


dry air compartment to allow cooling

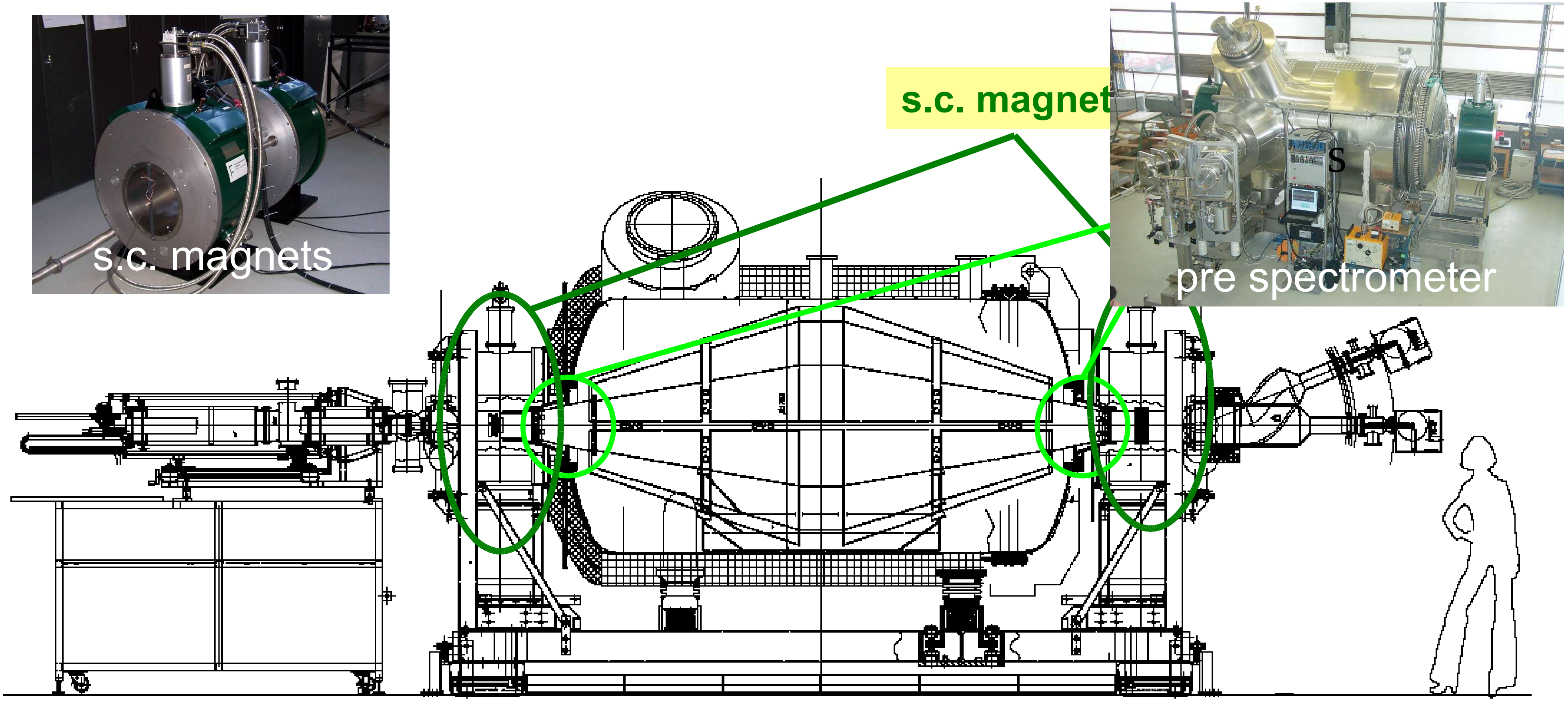
at -20^{o}C: outgasing rate < 10^{-13} mbar l/s cm^{2}
with getter pumps (NEG, 25000 l/s): p< 10^{-11}mbar
⇒ better than KATRIN requirements

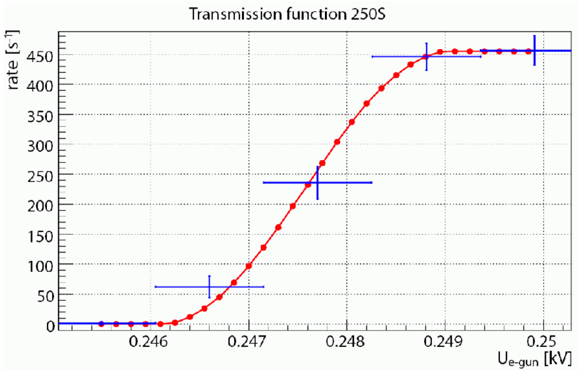


Wire electrode in pre spectrometer

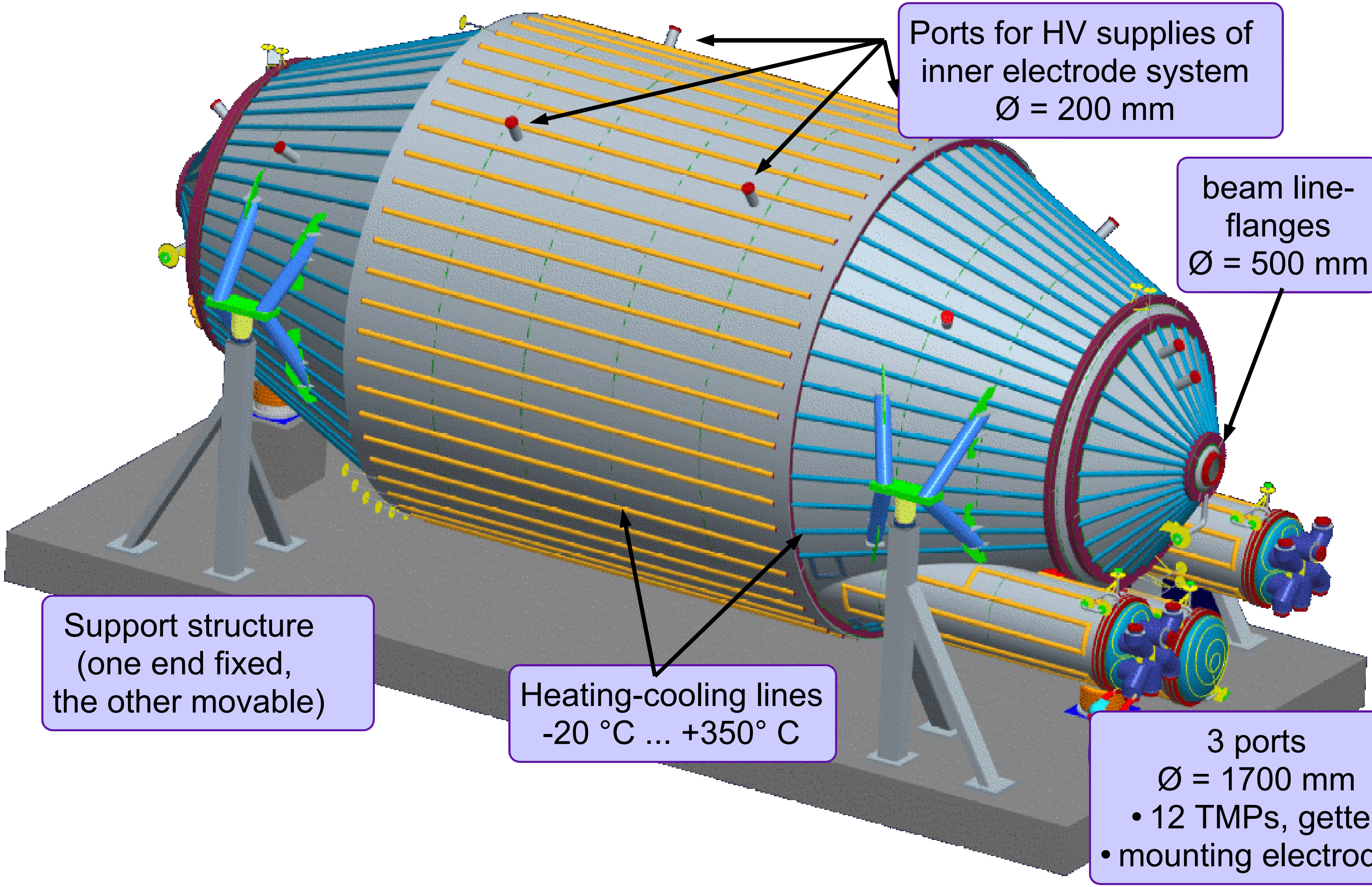


Electromagnetic design tests at the pre spectrometer have just started





Main spectrometer 3dim model with heating-cooling system



Ports for HV supplies of inner electrode system
Ø = 200 mm

beam line-flanges
Ø = 500 mm

Support structure
(one end fixed,
the other movable)

Heating-cooling lines
-20 °C ... +350° C

3 ports
Ø = 1700 mm
- 12 TMPs, getter
- mounting electrodes

Main spectrometer vessel construction at MAN DWE

Main spectrometer vessel construction at MAN DWE

21/07/2006

Main spectrometer vessel construction at MAN DWE

August 2006:
- construction of main spectrometer vessel has been finished
- vessel has passed leak test successfully !

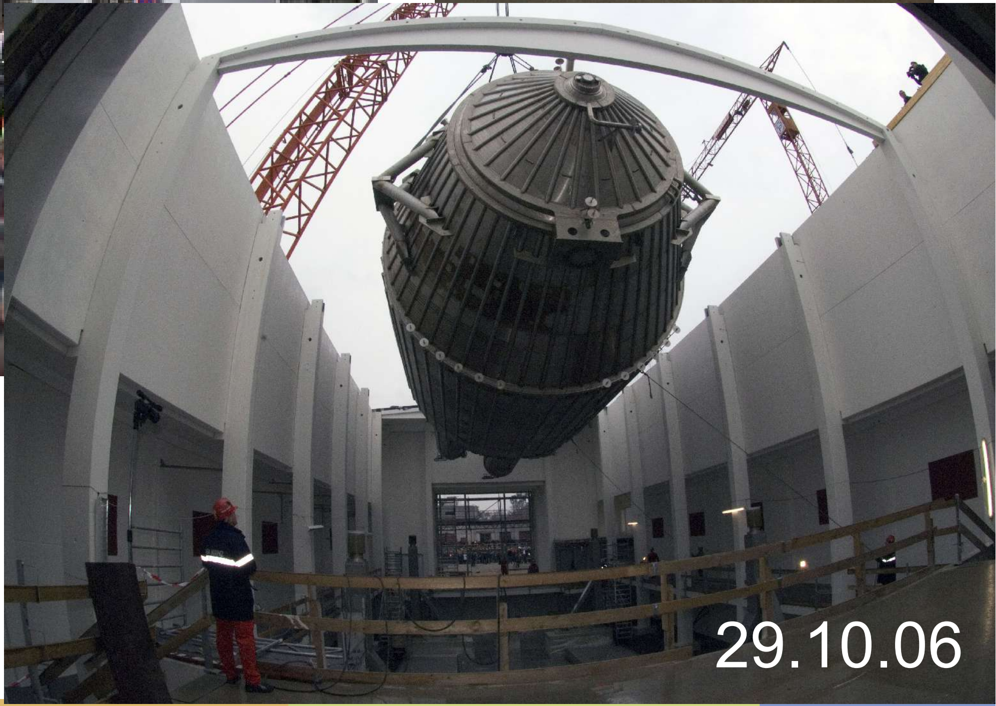
⇒ world`s biggest XHV vessel ever been build !

It is very big and heavy ...
⇒ a 8500 km long detour

Arrival of the Main Spectrometer Vessel: October 2006

Leopoldshafen, 25.10.06

29.10.06



29.10.06

Sensitivity requirements for KATRIN:

1) Low background: Mainz experiment:

most background from spectrometer

but KATRIN spectrometer is much bigger!

⇒ need something new !

2) Huge statistics: optimized source &

large spectrometer

3) Systematic uncertainties:

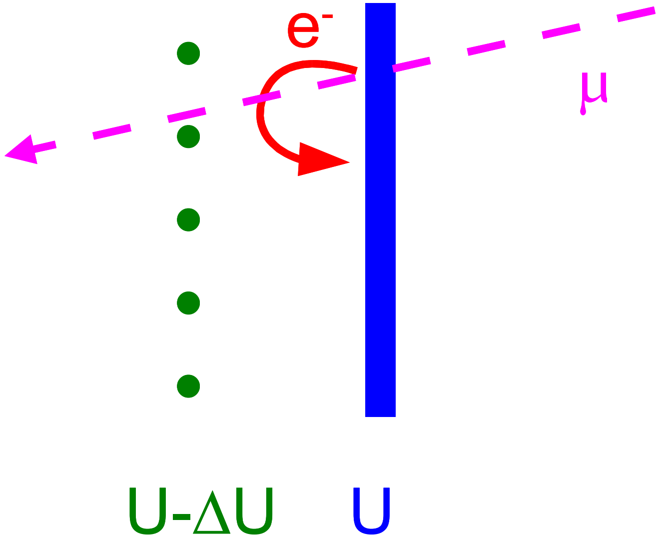
need to be very small !

Electric screening by a „massless“ wire electrode

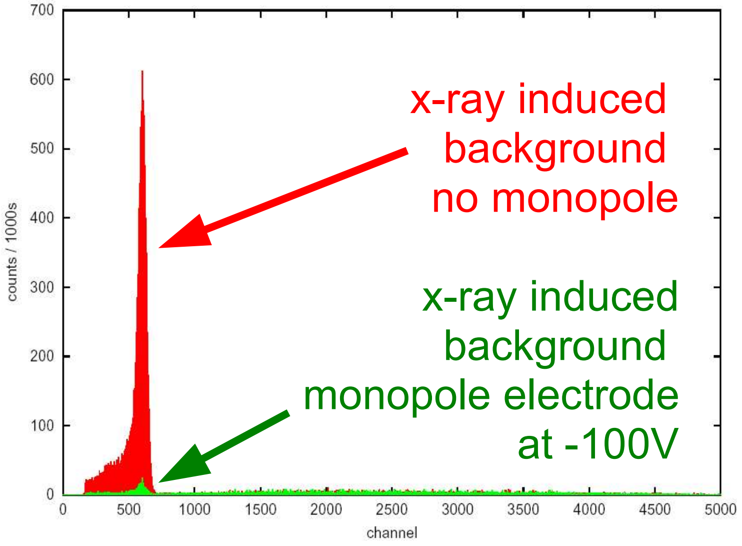
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

wire electrode on slightly more negative potential



First realisation:
Mainz III
(diploma thesis
Beatrix Müller/Ostrick)

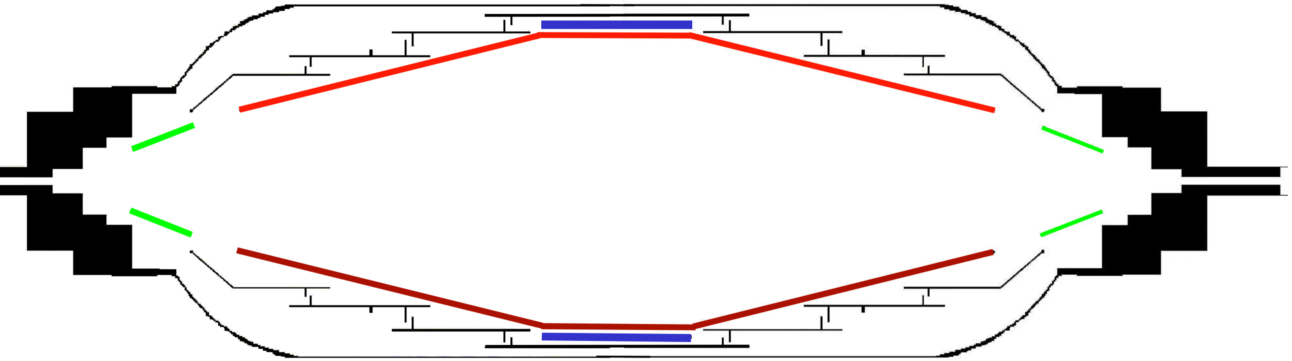


x-ray induced
background
no monopole

x-ray induced
background
monopole electrode
at -100V

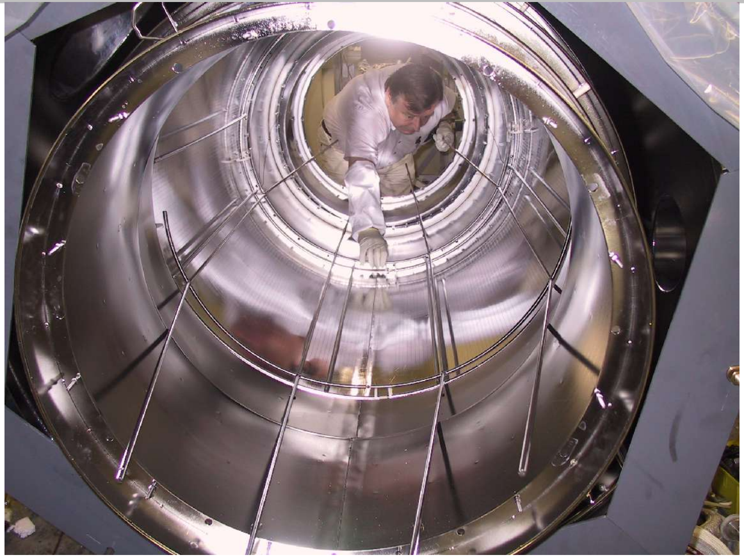
⇒ background suppression by factor 3

Even more progress with „massless“ wire electrode

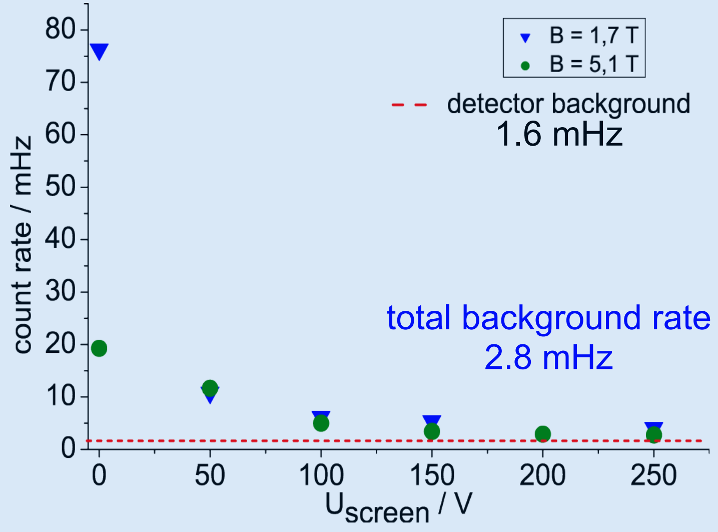


Mainz V (2004)
(PhD thesis Björn Flatt/Mainz

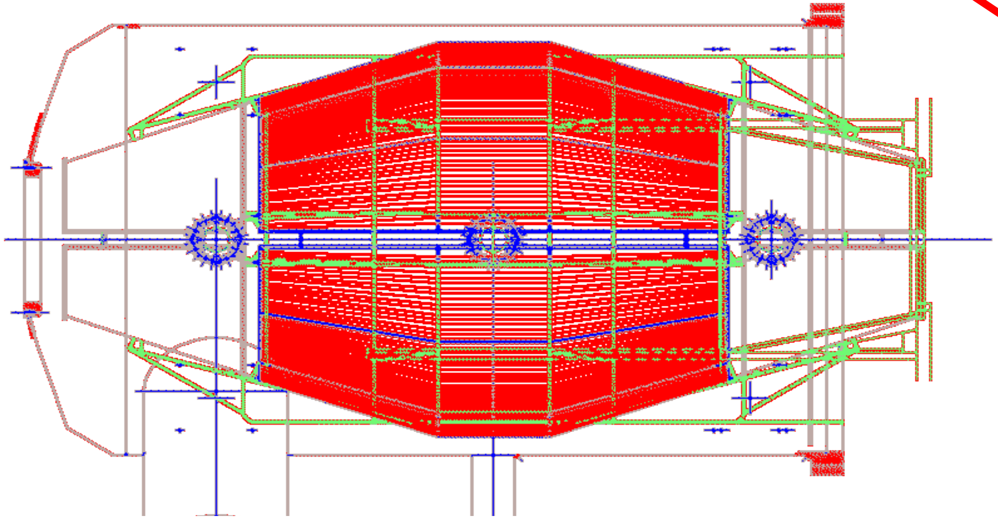
New record !
April 04



Background suppression successfully tested at the Mainz MAC-E filter:

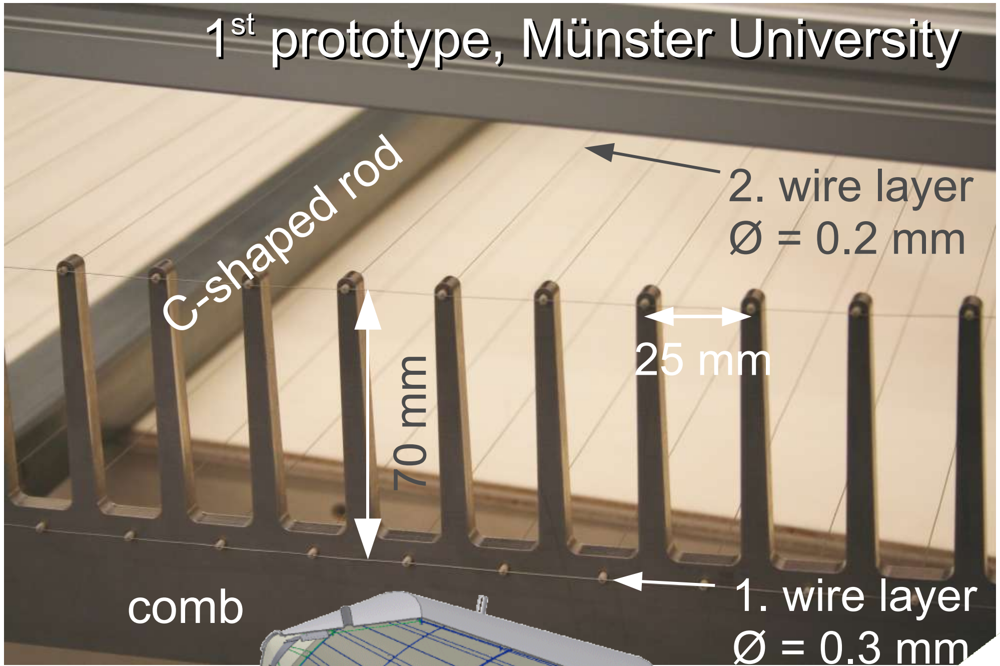


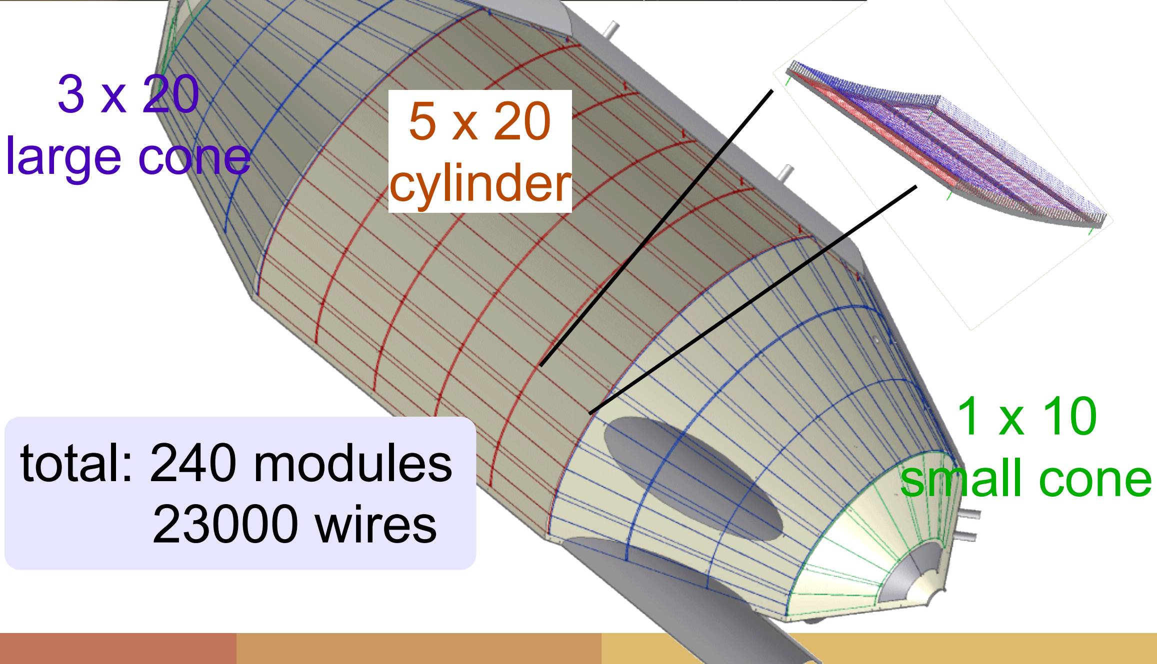
Dipl. thesis B. Ostrick (U Mainz, 2002),
PhD thesis B. Flatt (U Mainz, 2004)

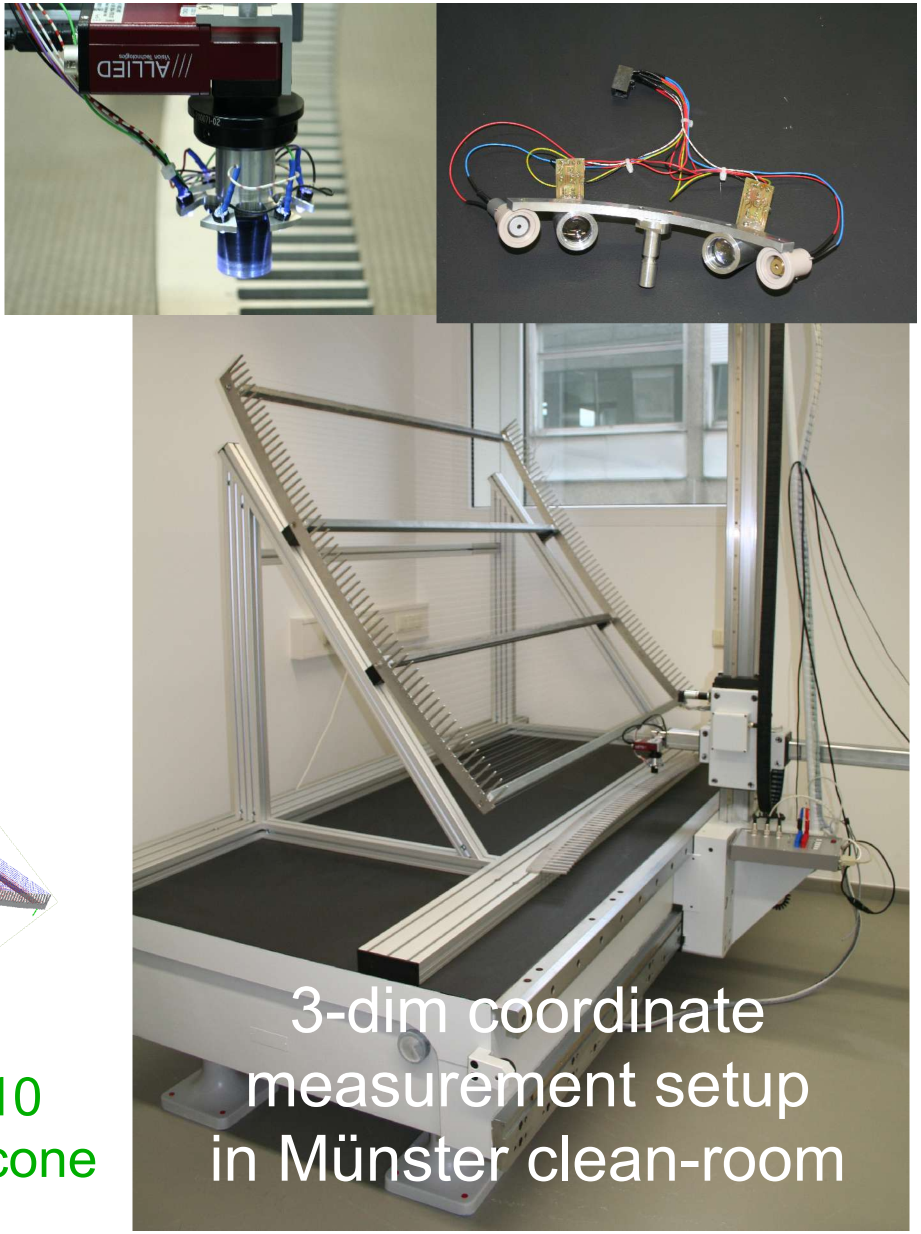


KATRIN pre spectrometer

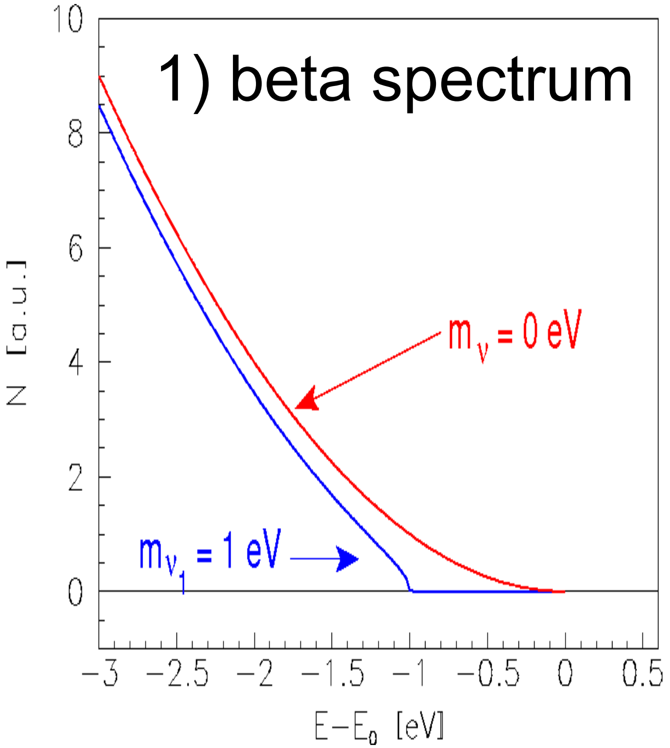
KATRIN: ≈ 240 double layer wire electrode modules

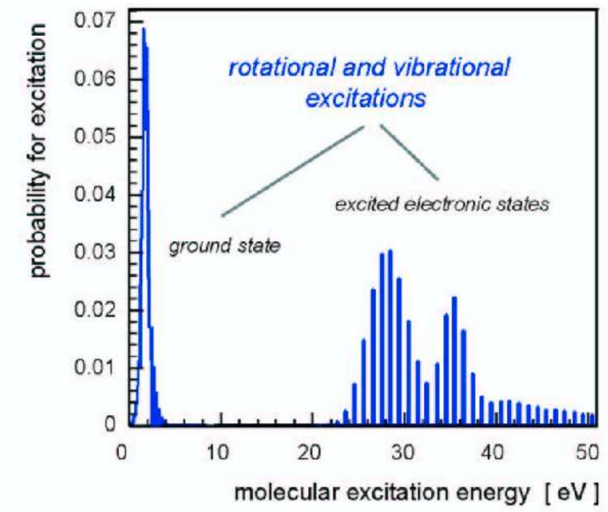


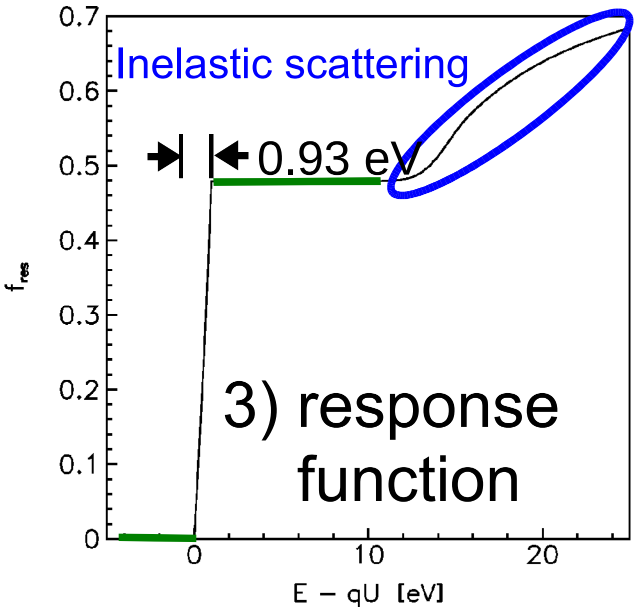




2) Statistics

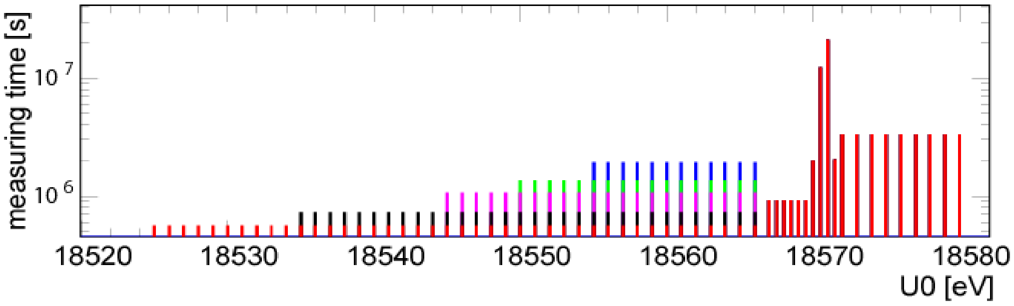

1) beta spectrum


2) final states

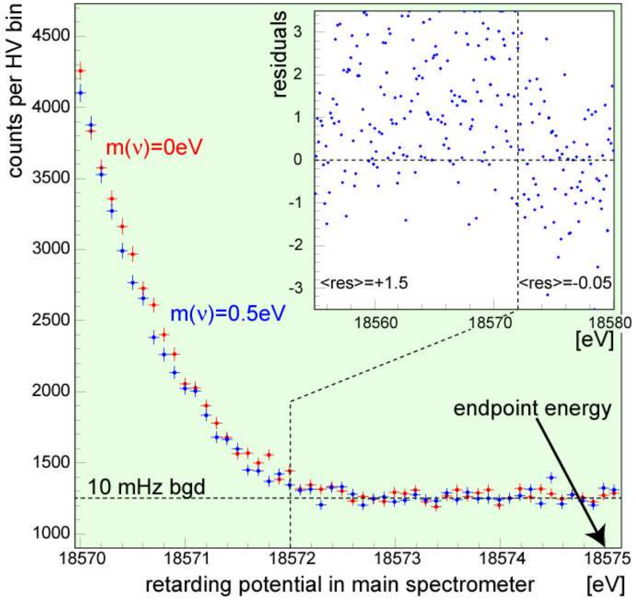

Inelastic scattering

3) response function

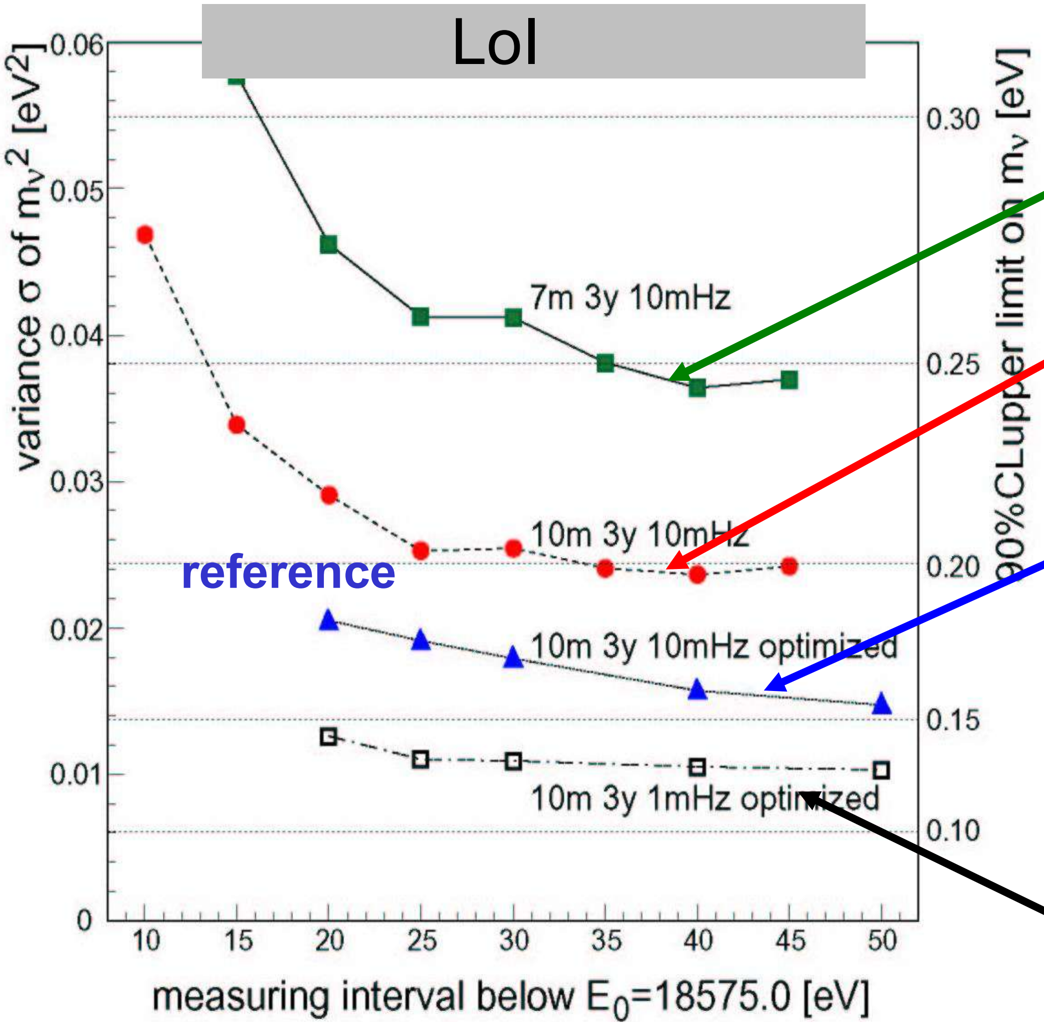
4) measurement point distrib.



⇒ MC data



KATRIN´s statistical uncertainty



design optimisation ´01 -´03

- tritium purity by tritium laboratory (>95%)

2× stronger gaseous source
(Ø=75mm → Ø=90mm)
requires Ø=10m spectrometer)

optimised measuring point
distribution (~5 eV below E_0)

- active background reduction by
inner electrode system, low
background detector
(needs further detailed tests)

3) Systematic uncertainties

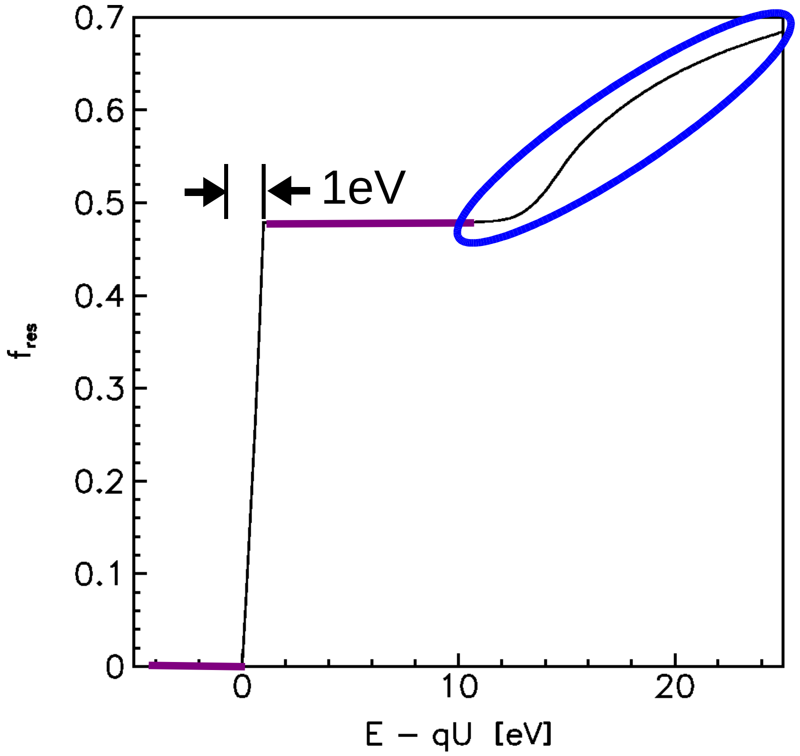
As smaller $m(\nu)$

as smaller the region of interest below endpoint E_0

⇒ Excited electronic final states does not play a role ($\Delta E_{exc} > 27$ eV)

⇒ Inelastic scattering in T_2 is small ($\Delta E_{inel.} > 12$eV ⇒ largest interval 25eV: 2%)

⇒ One well-defined final state (similiar to cryo detectors)



Is only true, since MAC-E-Filter response function has no tails

3) Systematic uncertainties

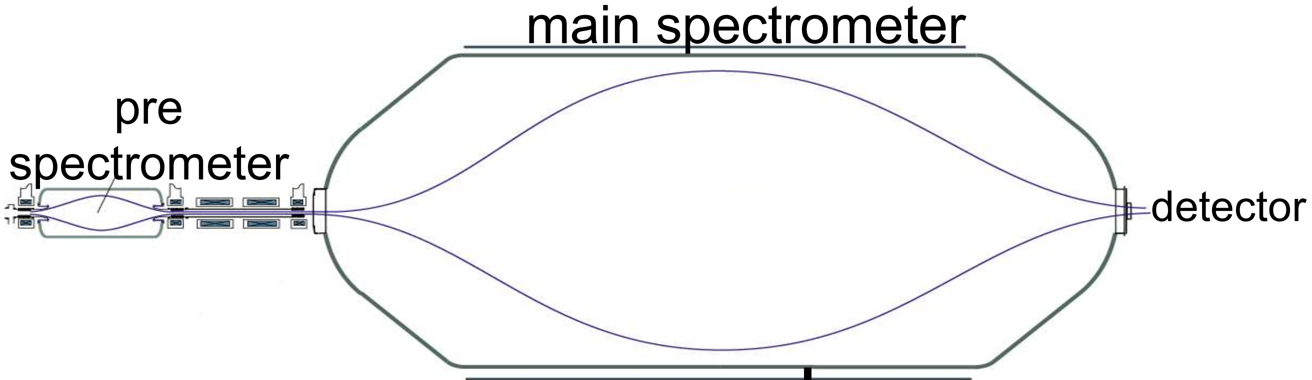
any not accounted variance σ^2 leads to negative shift of m_ν^2: $\Delta m_\nu^2 = -2\sigma^2$

1. inelastic scatterings of ß´s inside WGTS
   - requires dedicated e-gun measurements, unfolding techniques for response fct.
2. fluctuations of WGTS column density (required < 0.1%)
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, e-gun measurements
3. transmission function
   - spatial resolved e-gun measurements
4. WGTS charging due to remaining ions (MC: $\phi < 20\text{mV}$)
   - inject low energy meV electrons from rear side, diagnostic tools available
5. final state distribution
   - reliable quantum chem. calculations
6. HV stability of retarding potential on ~3ppm level required
   - precision HV divider (PTB), monitor spectrometer beamline

a few contributions with each: $\Delta m_\nu^2 \leq 0.007\ \text{eV}^2$

Long term stability of the retarding HV

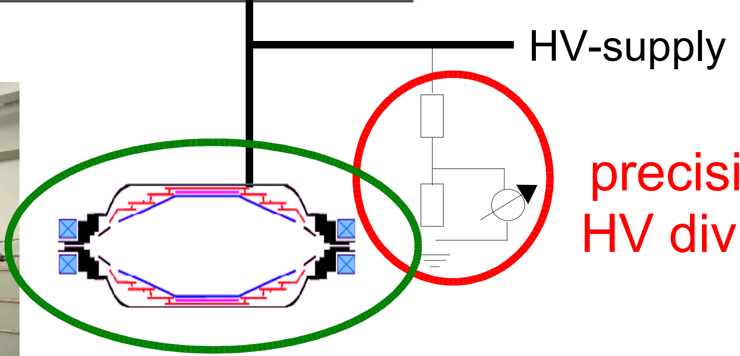
- Measure HV by precision HV divider
- Lock retarding HV by measuring energetically well-defined (atomic/nuclear standard) and sharp electron line with monitor spectrometer



tritium source
or alternately
calibration
source

continuously
calibration source:
^{83m}Kr,
^{241}Am/Co

condensed ^{83m}Kr
source at Münster



monitor spectrometer
= modified Mainz spec.:
$\Delta E=5$eV → 1 eV

precision
HV divider

KATRIN precision high voltage divider (in cooperation with PTB Braunschweig)

KATRIN's sensitivity:

- higher T2 purity
- larger statistics
- optimized measurement point distribution
- smaller systematic uncertainties

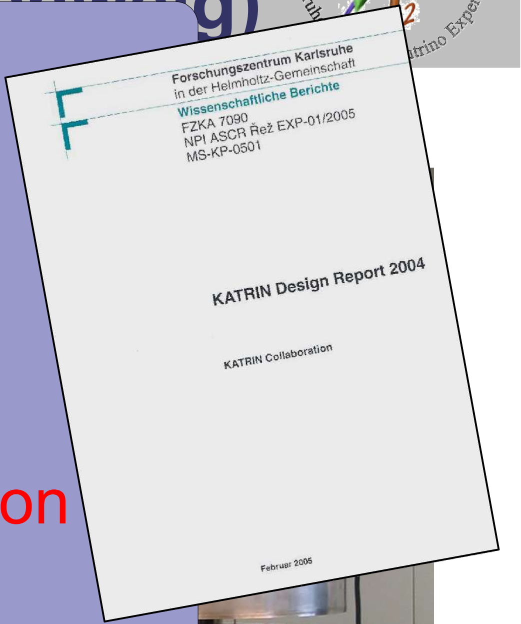
$\Rightarrow$ sensitivity on $m(\nu_e)$

$\approx 0.20\ \mathrm{eV/c^2}$

(about equal contribution from stat. and syst. uncertainties)
(90% C.L. upper limit for $m(\nu_e) = 0$)

$m(\nu_e) = 0.30\mathrm{eV}$ observable with 3σ

$m(\nu_e) = 0.35\mathrm{eV}$ observable with 5σ

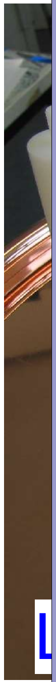


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft
Wissenschaftliche Berichte
FZKA 7090
NPI ASCR Řež EXP-01/2005
MS-KP-0501

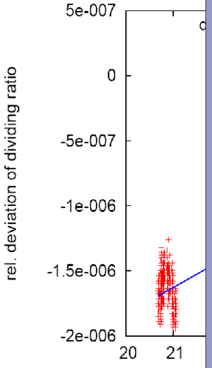
KATRIN Design Report 2004

KATRIN Collaboration

Februar 2005



tempera



⇒ TO

Measurements at PTB Braunschweig

Summary & Outlook

Absolute neutrino mass scale is needed

for particle physics and astrophysics/cosmology

by direct neutrino mass measurement (less model dependent & complementary)

Direct ν mass measurement from tritium β decay:

- Mainz experiment finished (all problems solved): $m(\nu_e) < 2.3$ eV (95% C.L.)
- KATRIN: A large tritium β neutrino mass experiment with sub-eV sensitivity

  $m(\nu_e) < 0.2$ eV or $m(\nu_e) > 0$ eV: for $m(\nu_e) \geq 0.30$ eV @ 3σ

  start of data taking in 2010 ...


the KATRIN collaboration as of 2006

Direct ν mass measurement from rhenium β decay:

- Mibeta, Manu2 (1^{st} generation of exp.): $m(\nu_e) < 15.6$ eV (90% C.L.)
- MARE: Proposal for a large array of improved rhenium micro calorimeters,

  how far can they go?