Impact of T_2-βeta-Endpoint and Control of Filter Potential on KATRIN-Result

1.) Correlation of uncertainties of β-endpoint (E_0) and square of neutrino mass $(m_\nu)^2$

2.) High voltage control

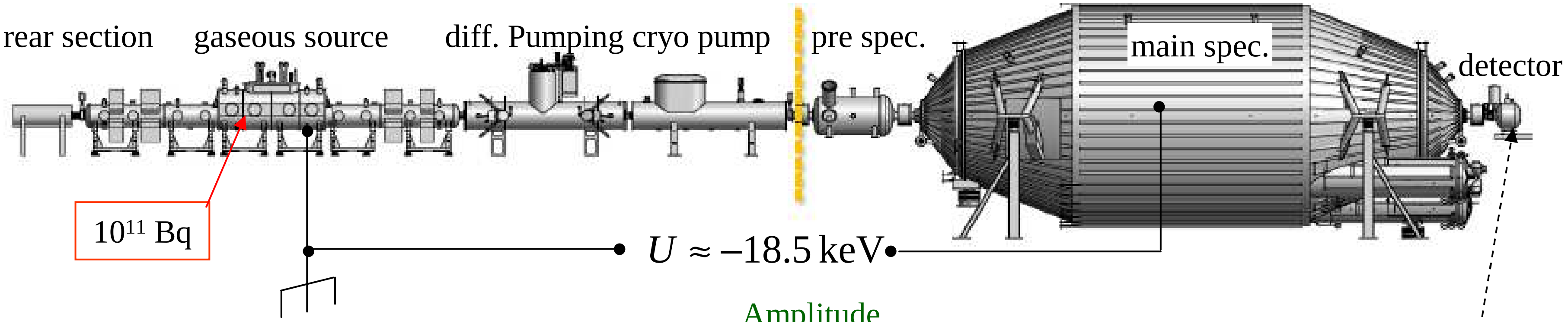
3.) Potential distribution in main KATRIN Spectrometer

4.) Potential distribution in magnetically confined plasma of gaseous tritium source

5.) Outlook into future side experiments for KATRIN

- Absolute high voltage standard by collinear laser spectroscopy
- Improved (T – ^{3}He)-mass difference by ECR in ion trap

Integral β-spectrum and ist Mass - Energy correlation



Amplitude

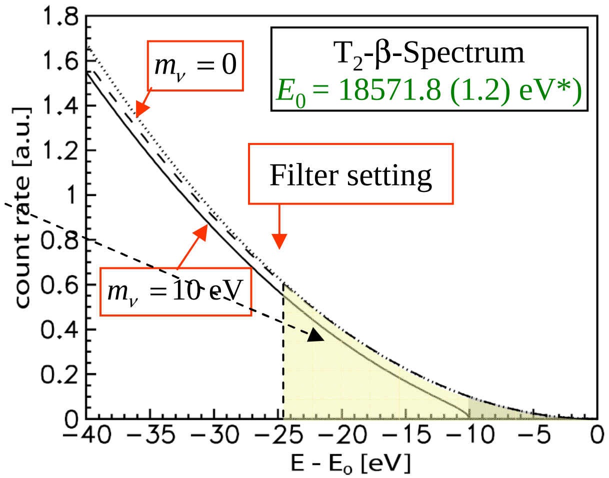
$$R(E) = \int_{E=-eU}^{E_0} S(E')\mathrm{d}E' + B \approx A\left\{(E_0 - E)^3 - (3/2)(E_o - E)m_\nu^2\right\} + B \qquad (1)$$

Signal Background Endpoint (Mass)^2

If $(m_\nu)^2$ is evaluated from a measurement at a setting E its uncertainty is correlated to E_0 by

$$\sigma(m_\nu^2) = \sigma(E_\nu^2) = 2(E_0 - E)\times\sigma(E_0 - E) \qquad (2)$$

Scales with distance from the endpoint!



*) Nagy Sz, Fritioff T, Björkhage M, Bergström I and Schuch R 2006 *Europhys. Lett.* **74** 404

Situation at KATRIN design parameters

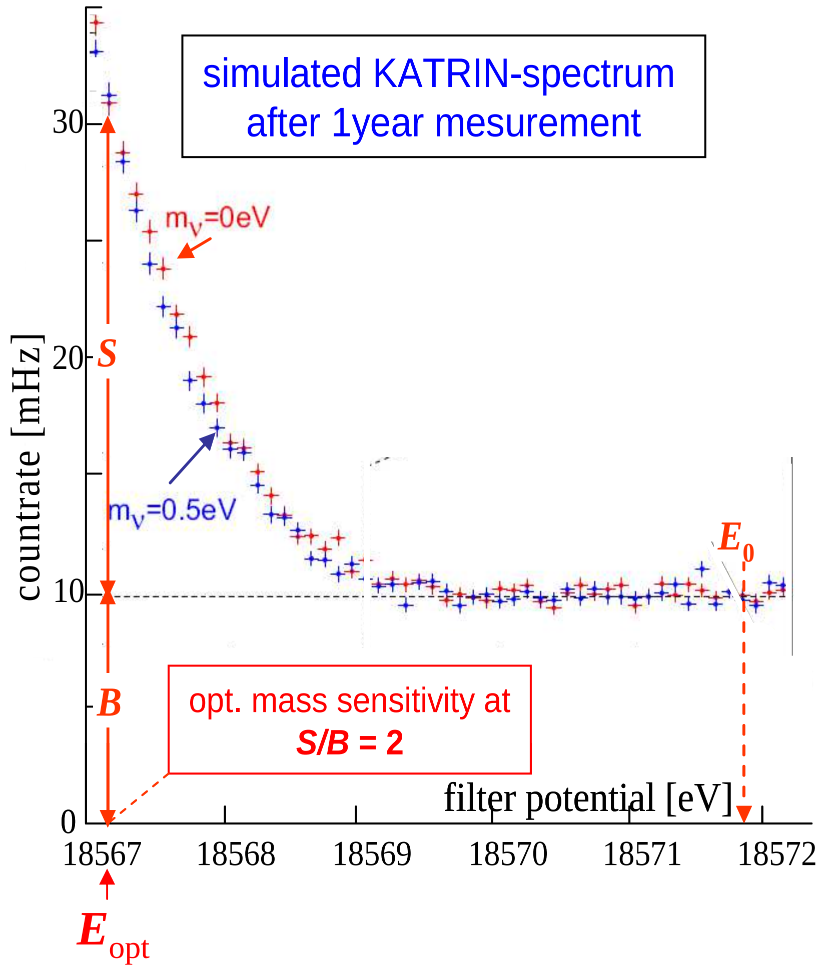
The sensitivity of the integral spectrum on $(m_\nu)^2$ maximizes at a signal to background ratio

$$S / B = 2 \qquad (3)$$

expected to happen at

$$E_0 - E_{opt} \approx 5\ \text{eV} \rightarrow \qquad (4)$$

$$\sigma(m_\nu^2) \approx (10\ \text{eV}) \times \sigma(E_0 - E) \qquad (5)$$



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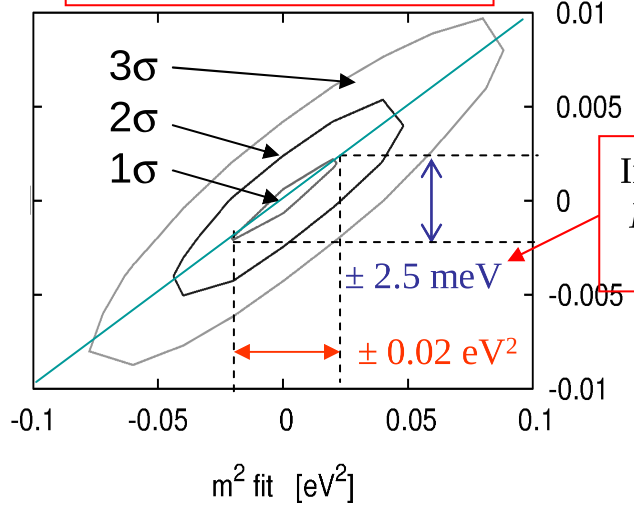
Simulation of 3y measurement at B = 10 mHz predict uncertainty:

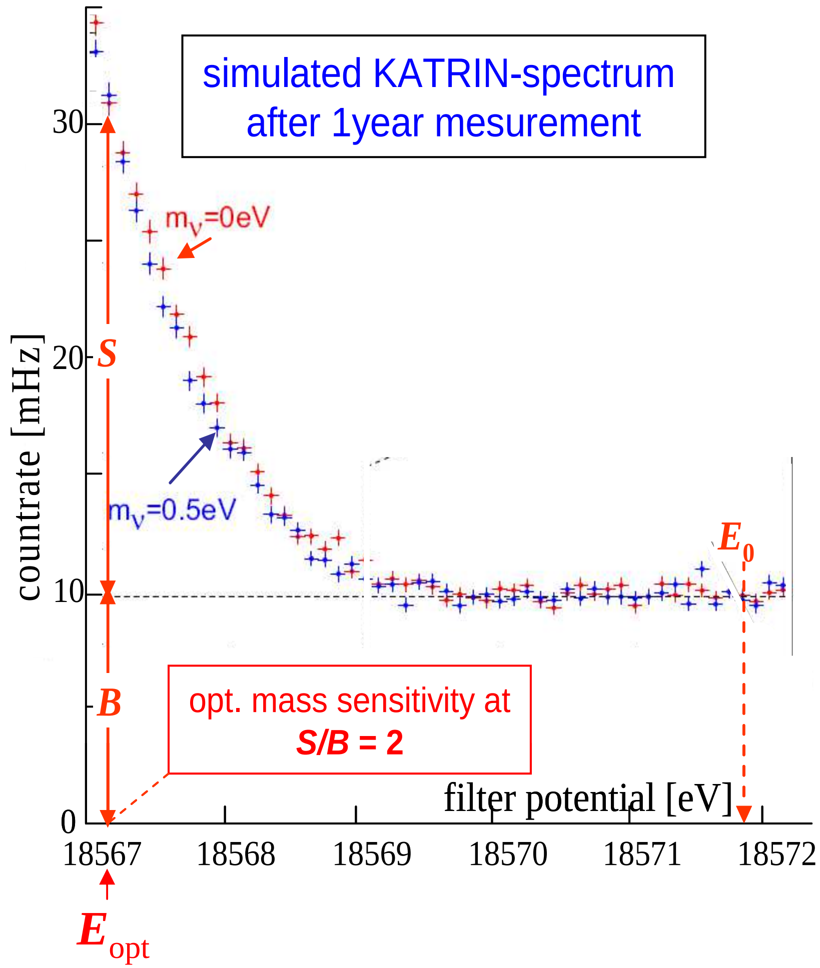
$$\sigma((m_\nu)^2) \approx 0.02\text{ eV}^2 \qquad (6)$$

and $(m_\nu)^2 - E_0$ correlation:

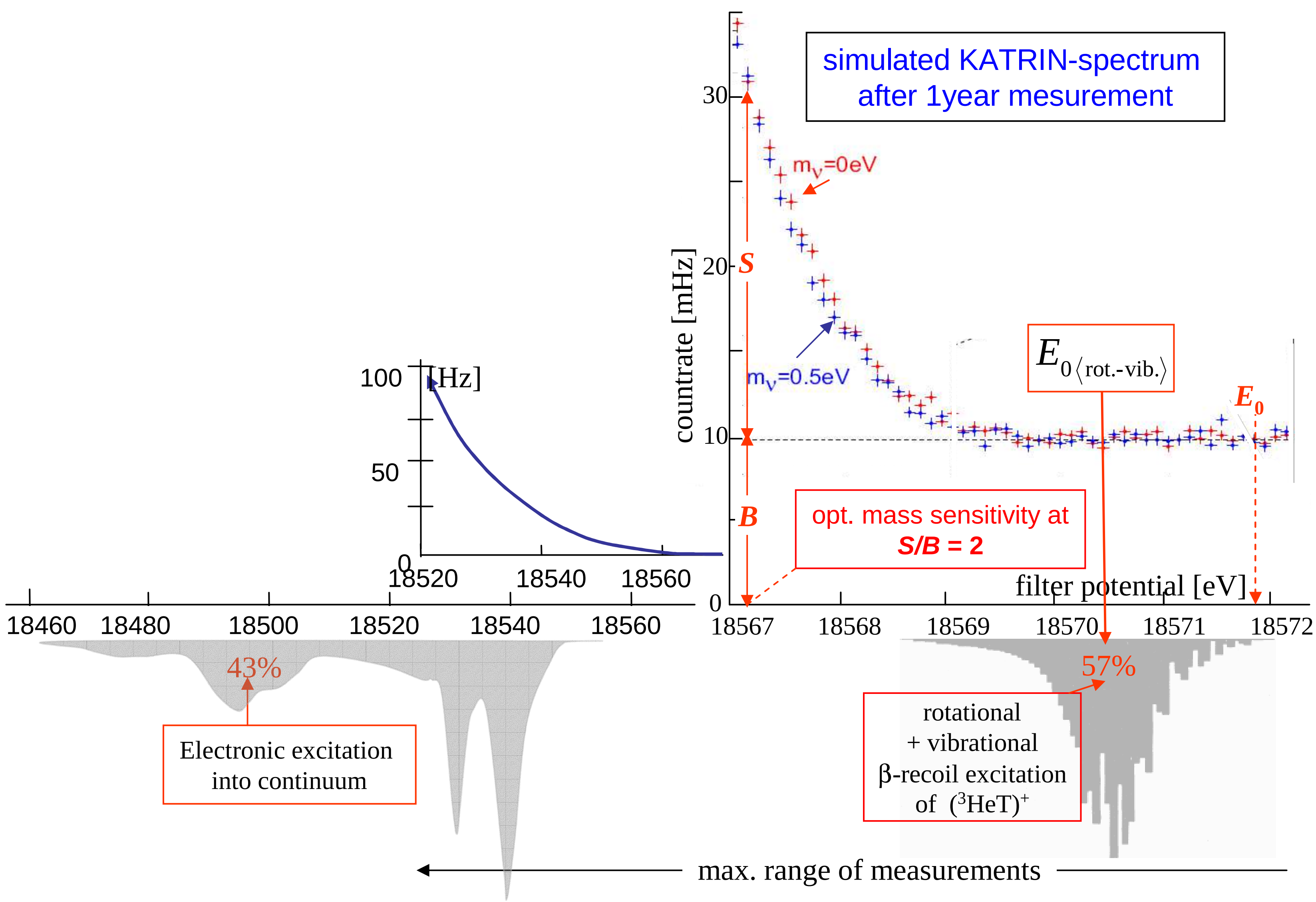
$$\delta(m_\nu^2) \approx (8\,\text{eV}) \times \delta(E_0) \qquad (7)$$



Inserting external E_0 would require this precision!

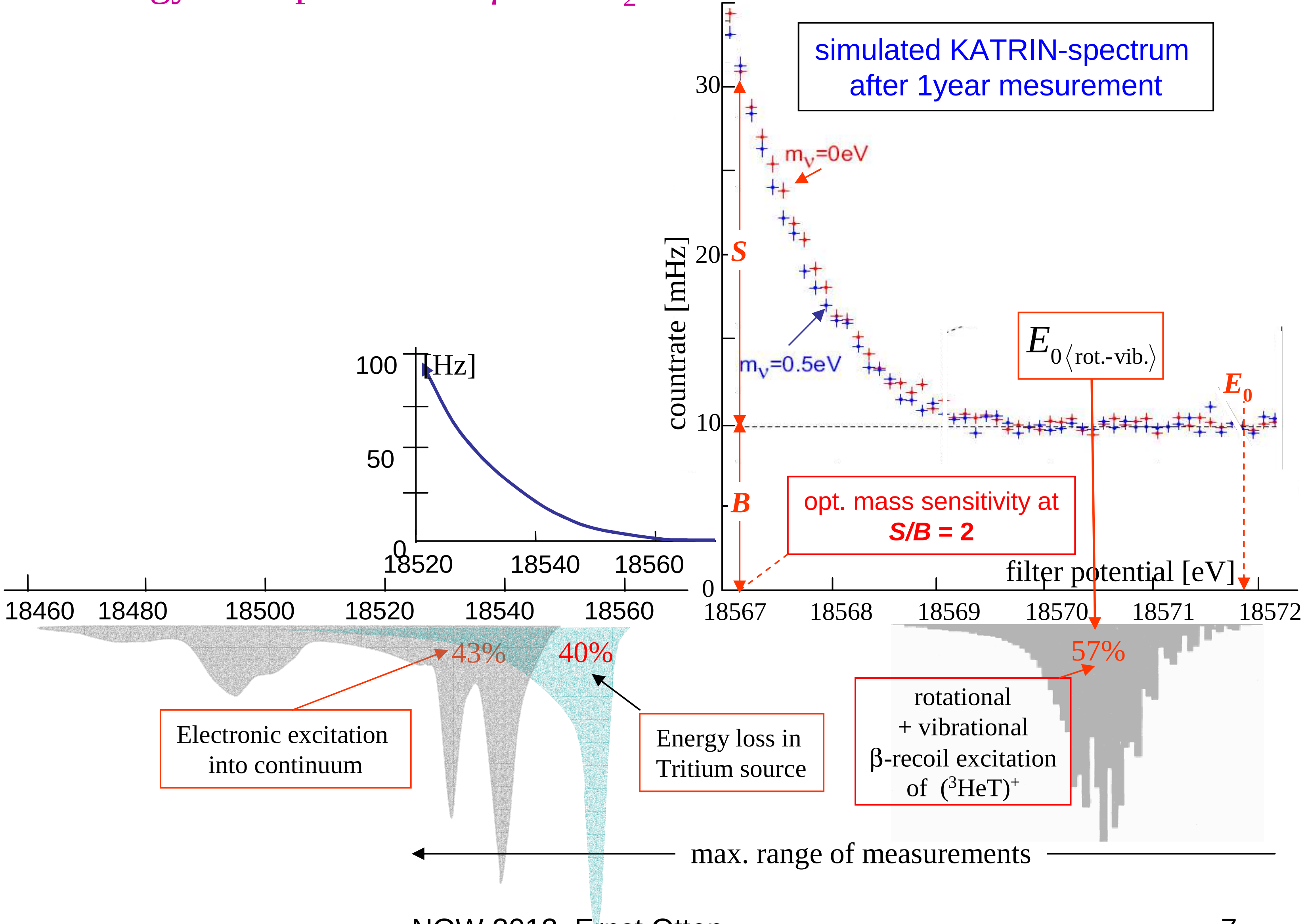


Spectrum od final state distribution of daughter molecular ion $(3HeT)^+$



Spectrum od final state distribution of daughter molecular ion (3HeT)$^+$

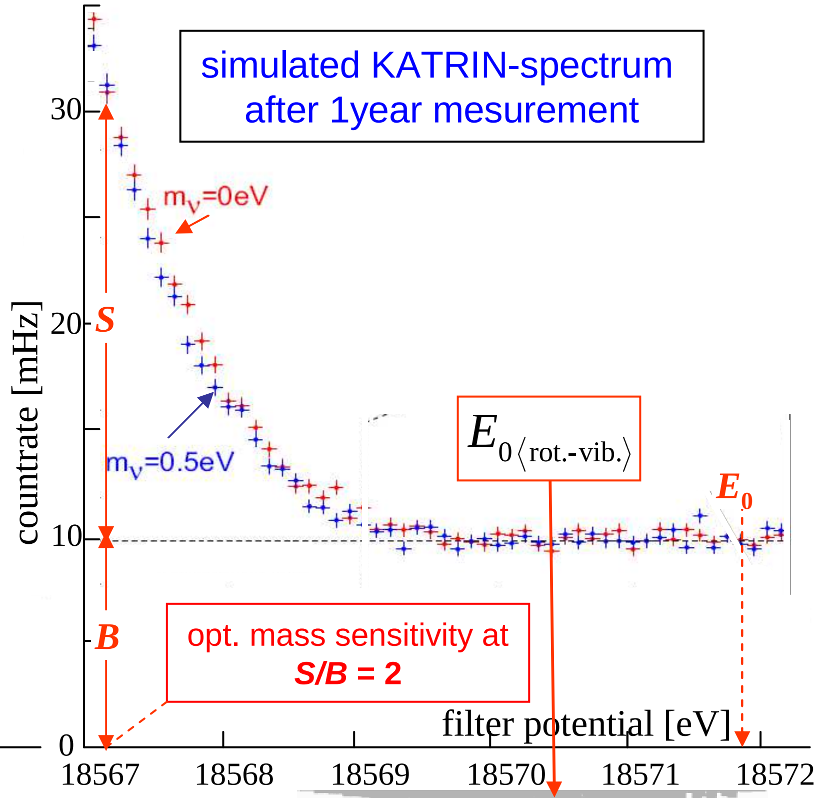
In addition: Energy loss spetcrum of β's in T_2-source

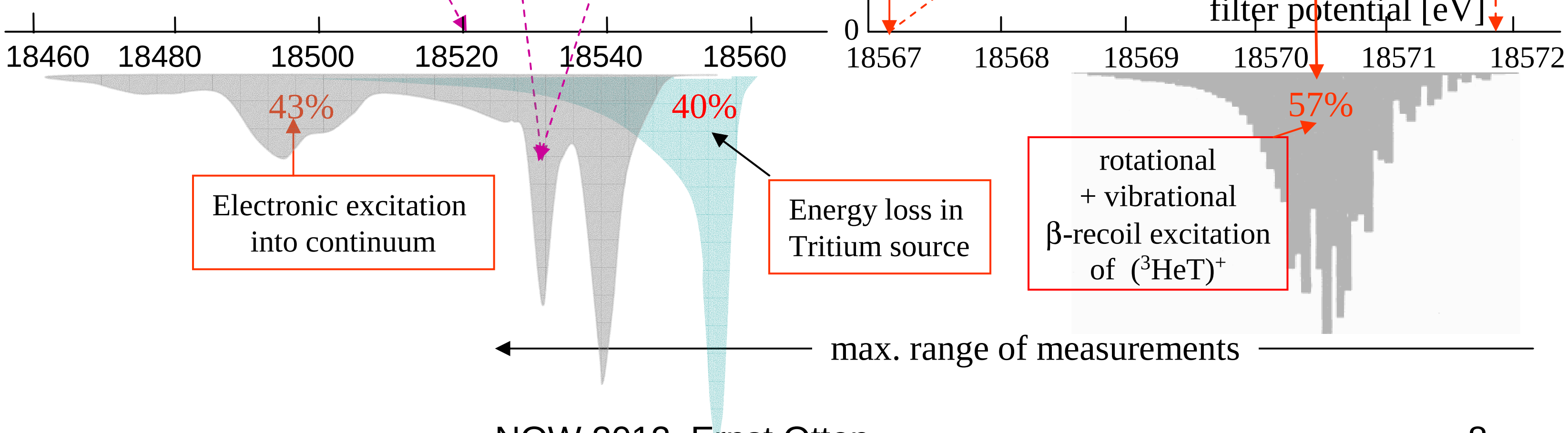


Correlation of final state and energy loss spectrum with endpoint and $(m_\nu)^2$

If, e. g., a particular spectral component with energy E_j and weight P_j would have been missed a measurement at energy $E < E_0 - E_j$ yields systematic correlated down shifts of E_0 and furthermore through (2) and (4) of $(m_\nu)^2$:

$$\delta(m_\nu^2) \approx 2\left(E_0 - E_{opt}\right)\left\{-\frac{1}{3}\left(E_0 - E - \frac{(E_0 - E_j - E)^3}{(E_0 - E)^2}\right)P_j\right\} \quad (8)$$

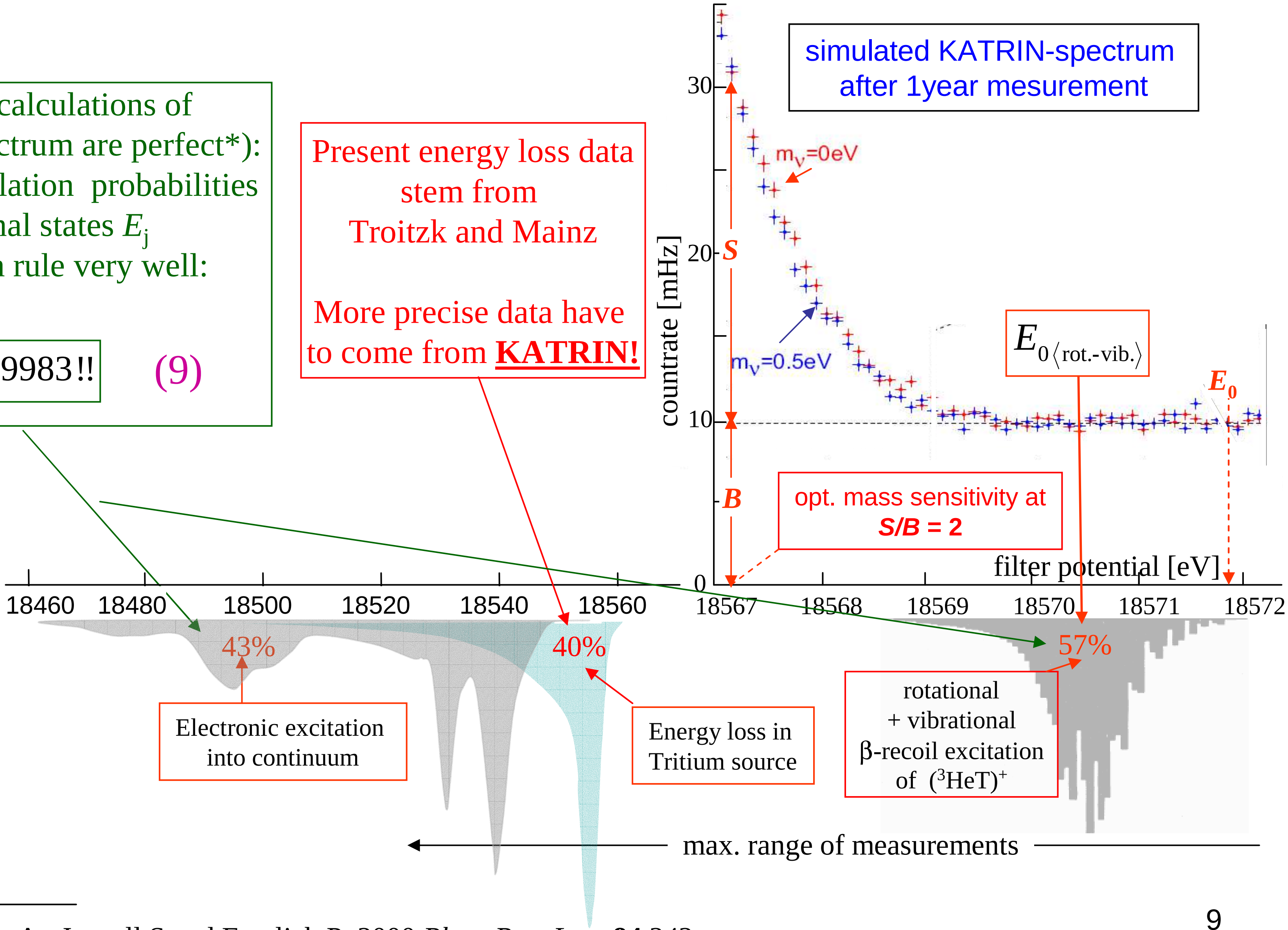




Correlation of final state and energy loss spectrum with endpoint and $(m_\nu)^2$

Fortunately, calculations of daughter spectrum are perfect*): Sum of population probabilities P_j over all final states E_j exhausts sum rule very well:

$$\sum P_j = 0.9983!! \qquad (9)$$

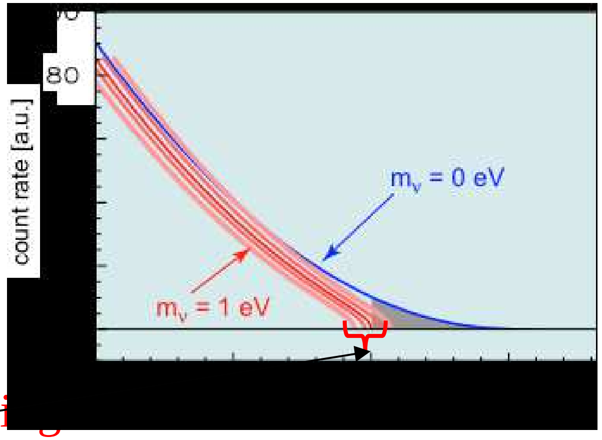


*) Saenz A, Jonsell S and Froelich P 2000 *Phys. Rev. Lett.* **84** 242

2.) High voltage stability and control

In order not to spoil the statistical KATRIN sensitivity of $\sigma((m_\nu)^2) \approx 0.02\ \text{eV}^2$ seriously, any of the known 5 major sources of systematic uncertainty should obey a limit:

$$\sigma(m_\nu^2)_i^{syst} \leq 0.007\ \text{eV}^2 \quad (10)$$



Mind:
Absolute precision of the filter potential plays no role, since we fit E_0 from data

Any potential **fluctuation** in space or time during data taking must be known and controlled precisely!
If undiscovered, systematic downshift of $(m_\nu)^2$ occurs:

$$-\delta(m_\nu^2)_U = 2e^2 \left\langle \left(U - \langle U \rangle\right)^2 \right\rangle < 0.007\ \text{eV}^2 \ \Rightarrow\ \underline{\sigma(U) < 60\ \text{mV}} \quad (11)$$

Precision HV Divider

Built byMünster group in cooperation with Dr. K. Schon and R. Marx, PTB Braunschweig
(R. Marx, IEEE Transactions on Instr. and Meas. Vol. 50, No. 2, 2001)

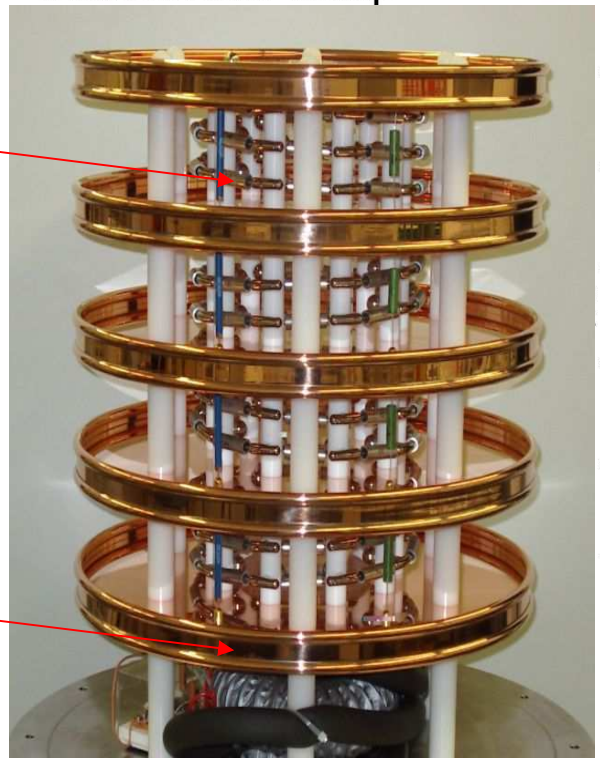
●
recise primary divider:

- 100 precision resistors in helix structure
- total resistance R_1 = 184 MΩ
- screened and matched according to TCR and warm-up
- N_2 as insulation gas (circulating)
- stabilized temperature T = 25 °C (ΔT < 0.1 °C)

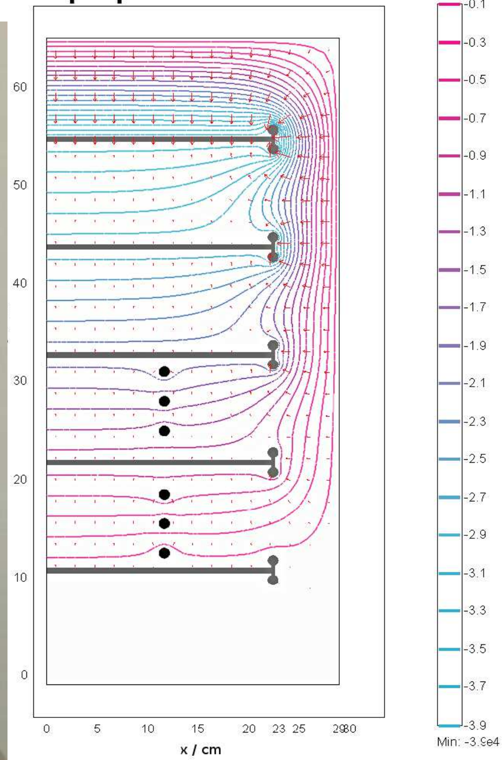
●
econdary divider:

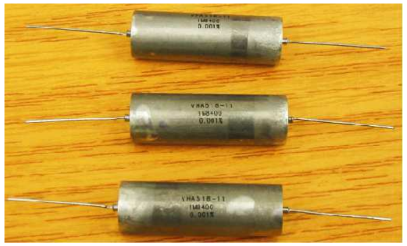
- independent field shaping electrode system
- identical potential drop
- preventing discharges and leak currents
- capacitive divider
- overload protection

main divider setup



equipotential lines

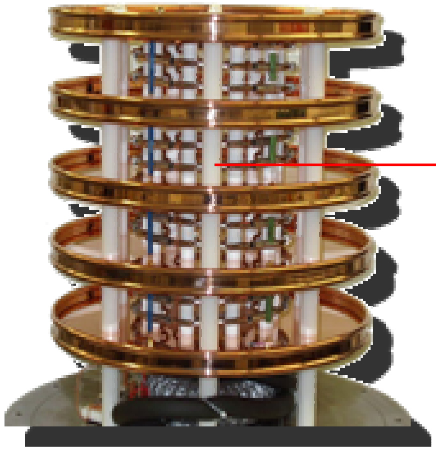




- **Precision Resistors**
  - Vishay Bulk Metal Foil technology
  - R = 1.84 MΩ
  - TCR < 2 ppm / K

Source: Th. Thümmler - Precision HV Monitoring for the KATRIN Experiment

Precision KATRIN Divider, assembly

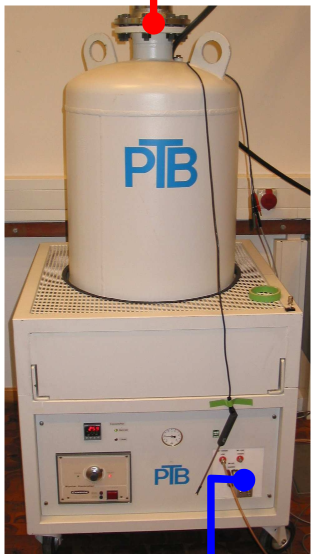


shield

Control units providing
N_2- atmosphere
at constant temperature
inside shield

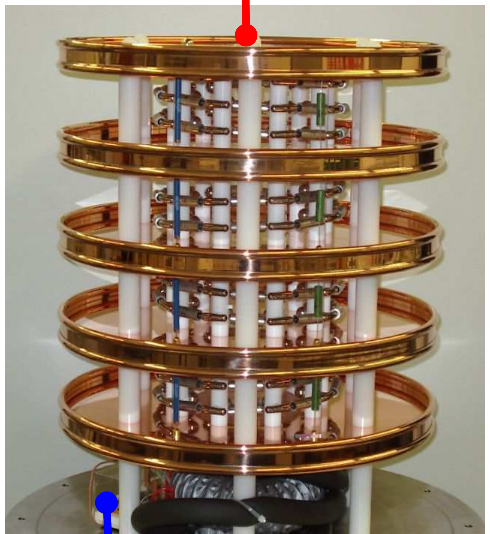
Calibration of KATRIN divider at PTB

FuG 100 kV supply
U = 32 kV



PTB
reference
divider
“MT100”

10000:1
3334:1



KATRIN
divider

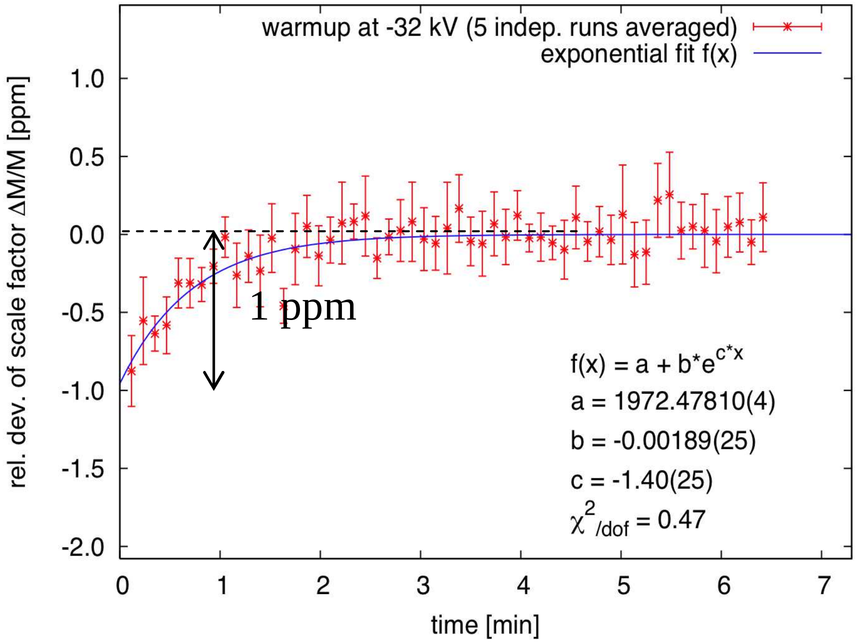
1972:1
3944:1

HP 3458A DVM

Fluke DVM 8508A

Source: Th. Thümmler - Precision HV Monitoring for the KATRIN Experiment

Results



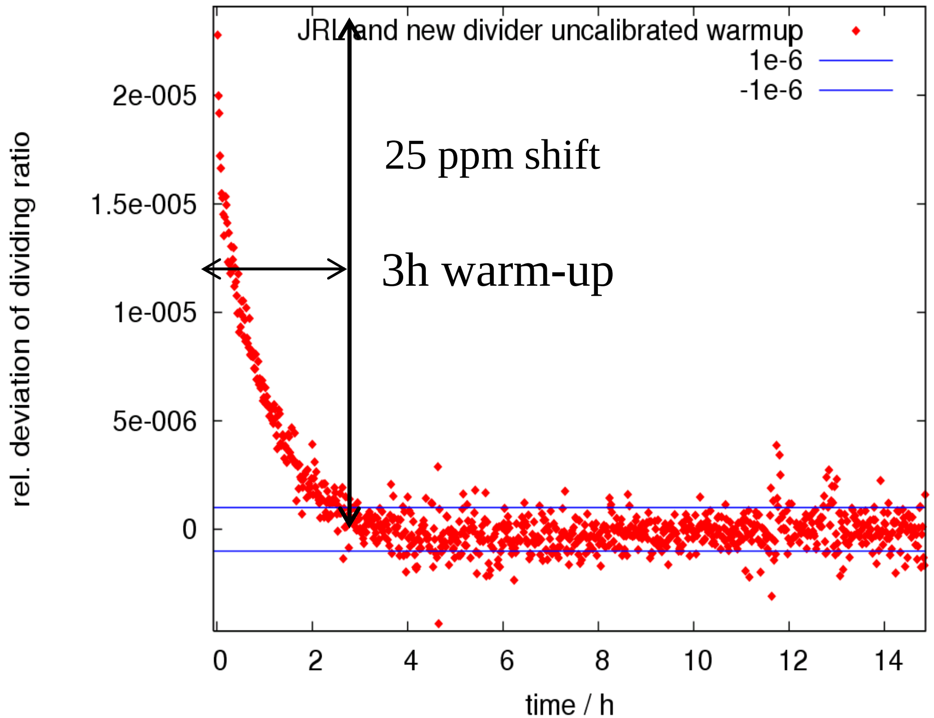
Warm up time: 1 min
Warm up shift: 1 ppm
Long term stability: 0.7 ppm/month

KATRIN Divider

- **x100** faster warm-up
- **x25** less fluctuation

In comparison with:

- one of the most accurate commercial 50 kVdividers

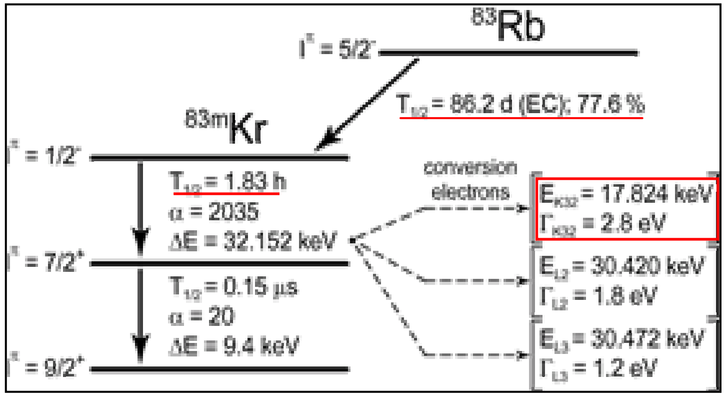


Source: Th. Thümmler - Precision HV Monitoring for the KATRIN Experiment

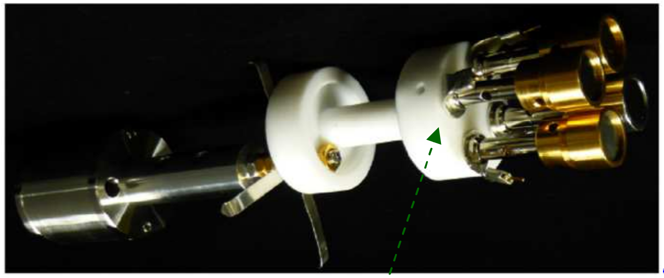
17.8 keV conversion line of ^{83m}Kr as KATRIN- HV monitor

Test measurements at old Mainz Mac-E-Filter, now turned to KATRIN-HV monitor

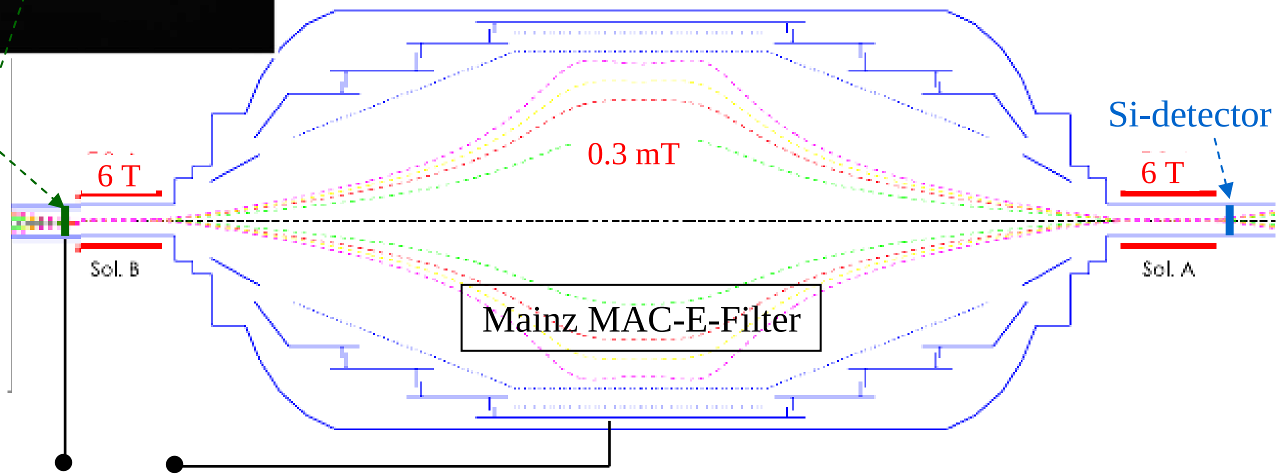
*KIT, Mainz, Münster, Prague**)



^{83}Rb-beam of 15 or 30 keV energy implanted into inert substrates (Pt, Au)



4 ^{83}Rb/Kr-sources mounted on revolver

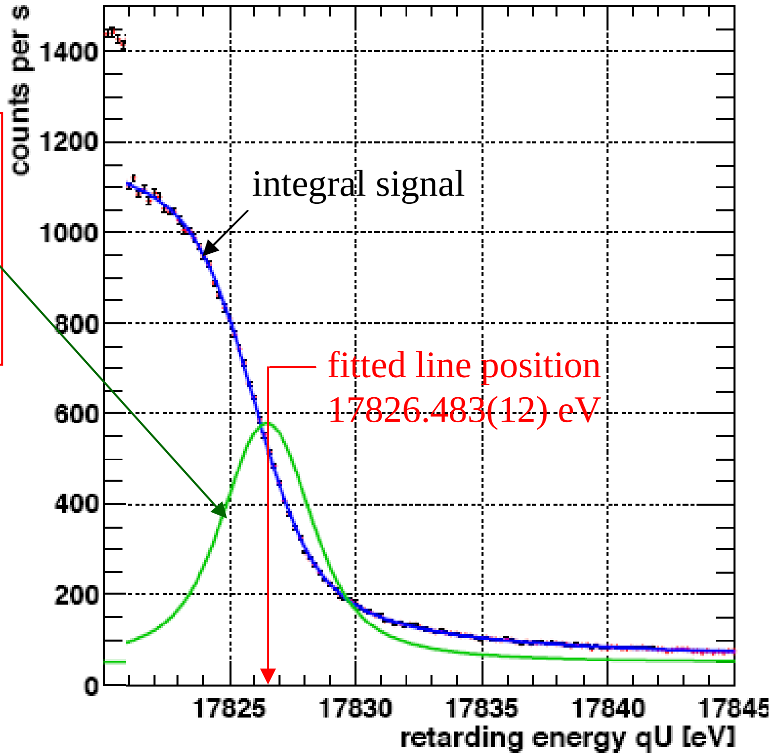


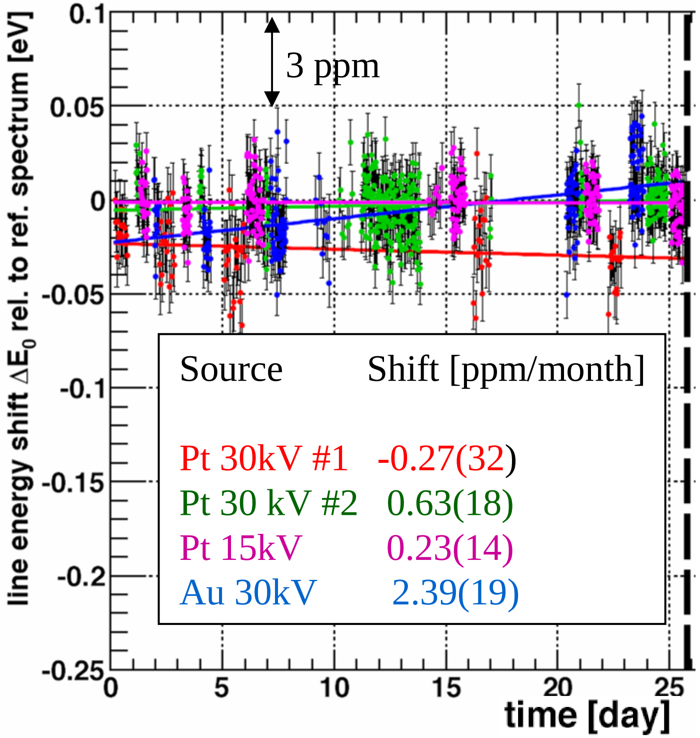
17.8 keV
controlled by precision divider
and calibrated DVM

*) Source: Miroslav Zboril, PHD thesis 2011, Münster/Prague

Results

Zero energy loss component
of ^{83m}Kr conversion line
from implanted ^{83}Rb mother
with small chemical shift (≈ eV)

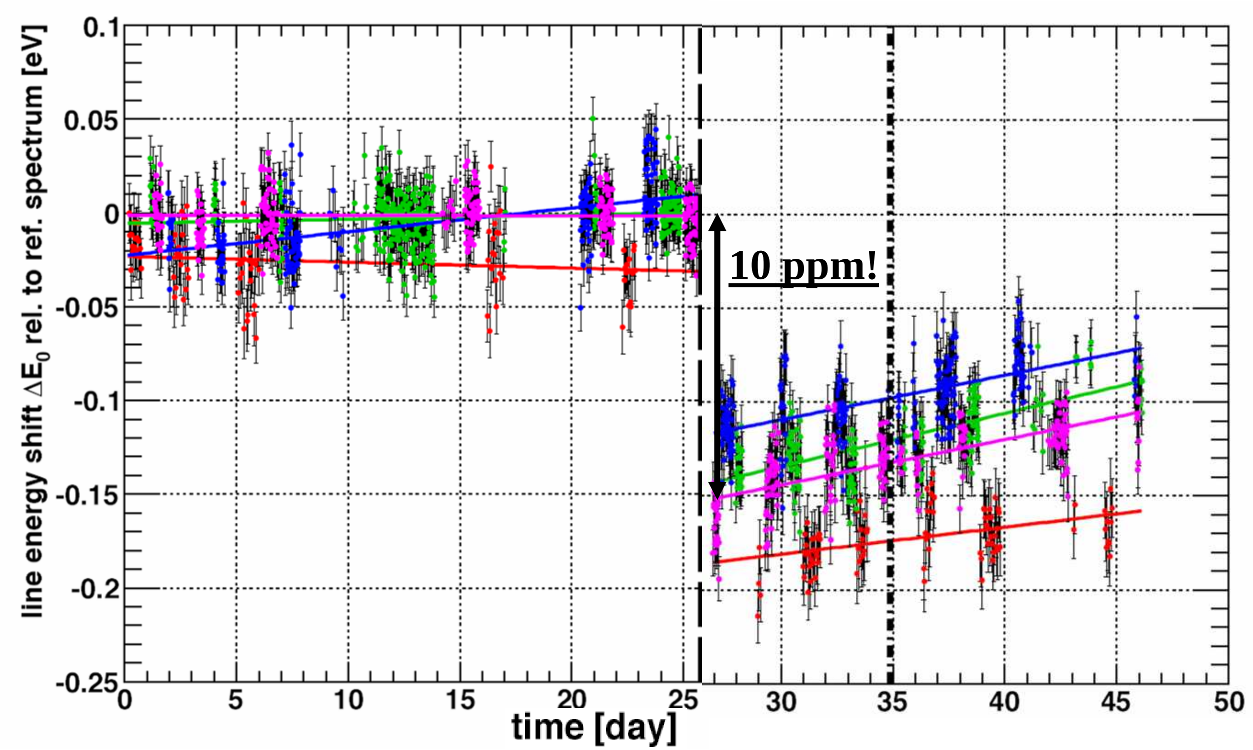




Implantation into inert substrate
seeems to guarantee
excellent long term stability!

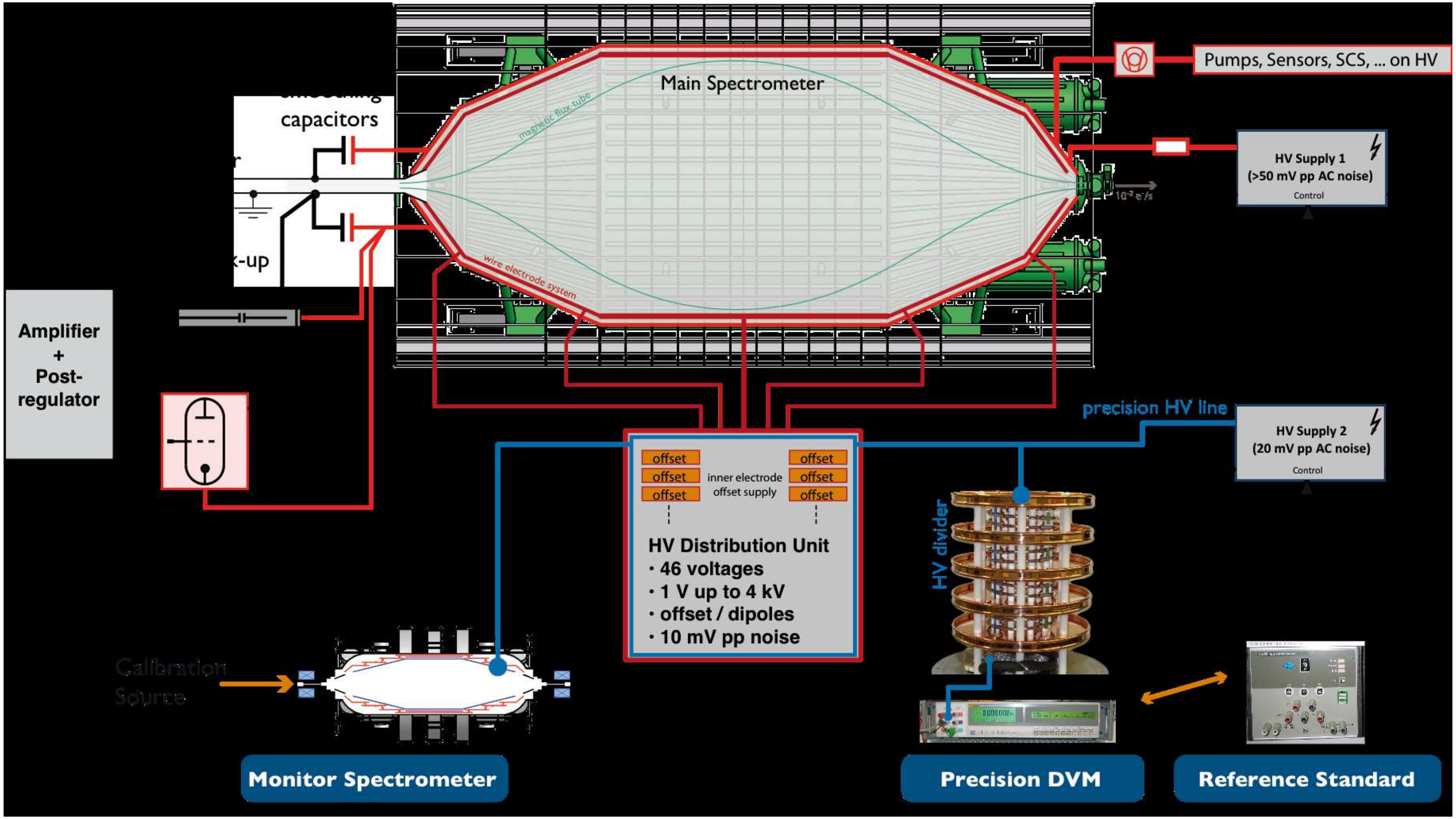
Source: Miroslav Zboril, PHD thesis 2011, Münster/Prague

But on day 26 vacuum in spectrometer deteriotated →
Work function of electrodes changed by rest gas adsorption
Thereafter slow recovery (without baking)



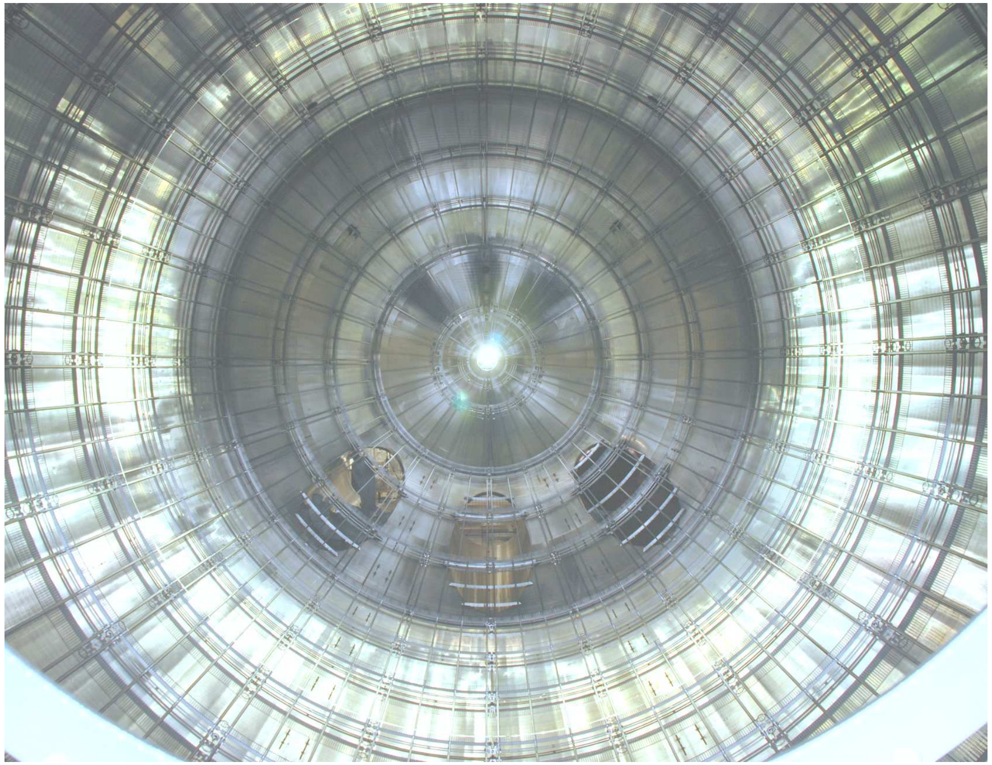
Source: Miroslav Zboril, PHD thesis 2011, Münster/Prague

KATRIN Monitoring Concept



Source: Th. Thümmler - Precision HV Monitoring for the KATRIN Experiment

3.) Potential distribution in KATRIN Spectrometer

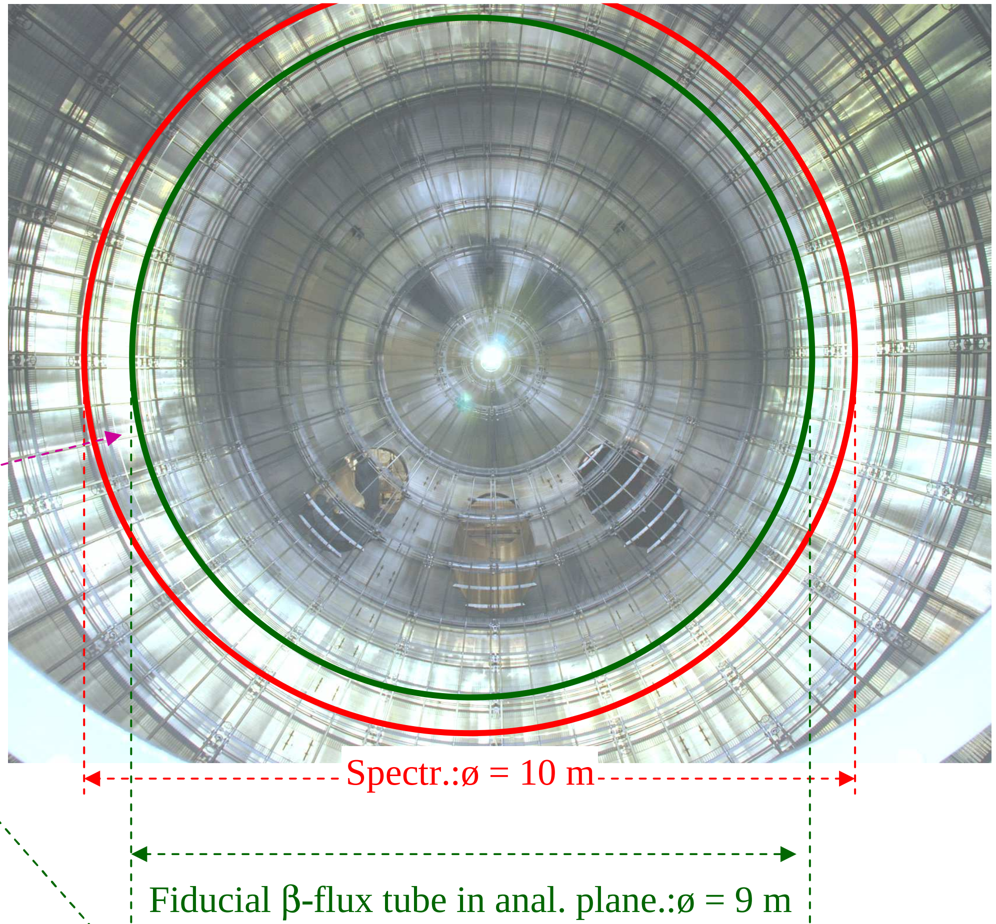


Inner spectrometer wall is lined completely with fine grids repelling by -100 V backgound electrons, emitted from wall

3.) Potential distribution in KATRIN Spectrometer

Inner spectrometer wall is lined completely
with grids repelling by -100 V
background electrons, emitted from wall

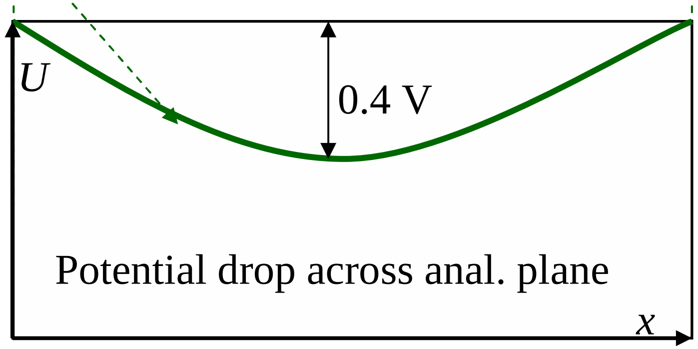
Potential varations stemming from
grid fine sructure die out on the way
to the β-flux tube, slimmer by 1 m



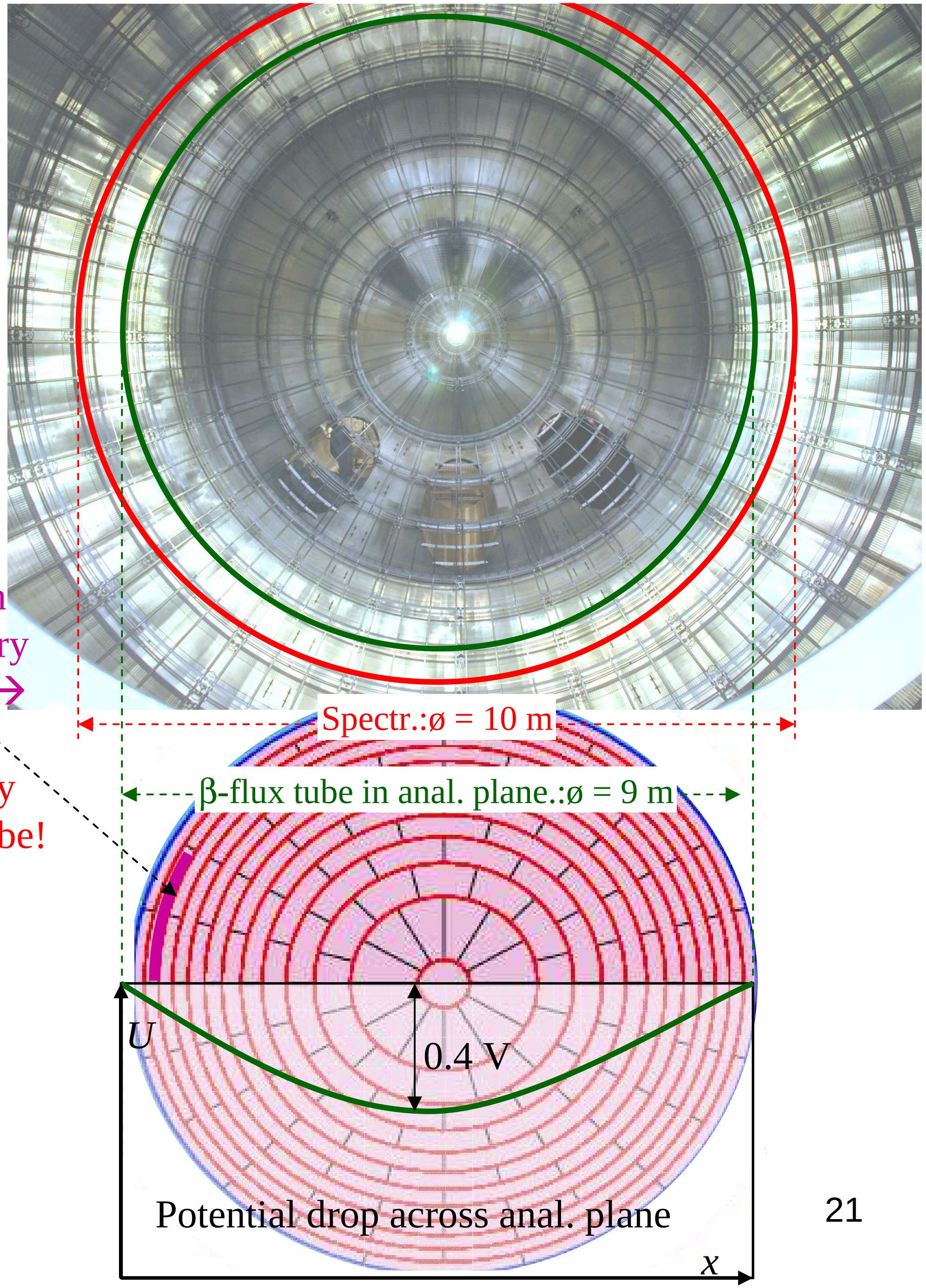
Potential drop towards centre of analysing plane
can be simulated perfectly,
provided wall has uniform work function

.

However, work function
may vary locally up to 1 eV
due to various surface contaminations



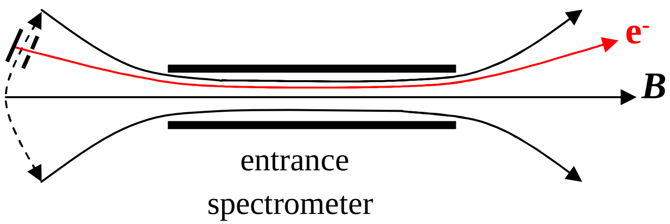
3.) Potential distribution in KATRIN Spectrometer



Inner spectrometer wall is lined completely with fine grids repelling by -100 V background electrons, emitted from wall

145 Pixel β-detector
projected from downstream
into analysing plane
Outer pixel projection covers arc of 2.4 m length
Analysing potential along pixel projection may vary considerably due to fluctuation of work function →

Analysing potential has to be measured ***locally*** by scanning e^-- beam from electron gun across flux tube!



Pilot experimentat performed at Mainz Spectrometer*)
Measurements at KATRIN will start soon!

---

*) K.Valerius et al. 2011 *JINST* **6** P01002

4.) Potential distribution in magnetically confined plasma of window less gaseous tritium source (WGTS)

The concept of WGTS with strong *longitudinal* magnetic guiding field
was pioneered in the Los Alamos ν-mass experiment [1])
and further used in the Troitzk experiment [3])

Later on it was recognized that β-decay in WGTS forms thermal plasma
through ionisation of T_2-gas with
Strong transverse magnetic confinement of charged particles by 3.5 T guiding field

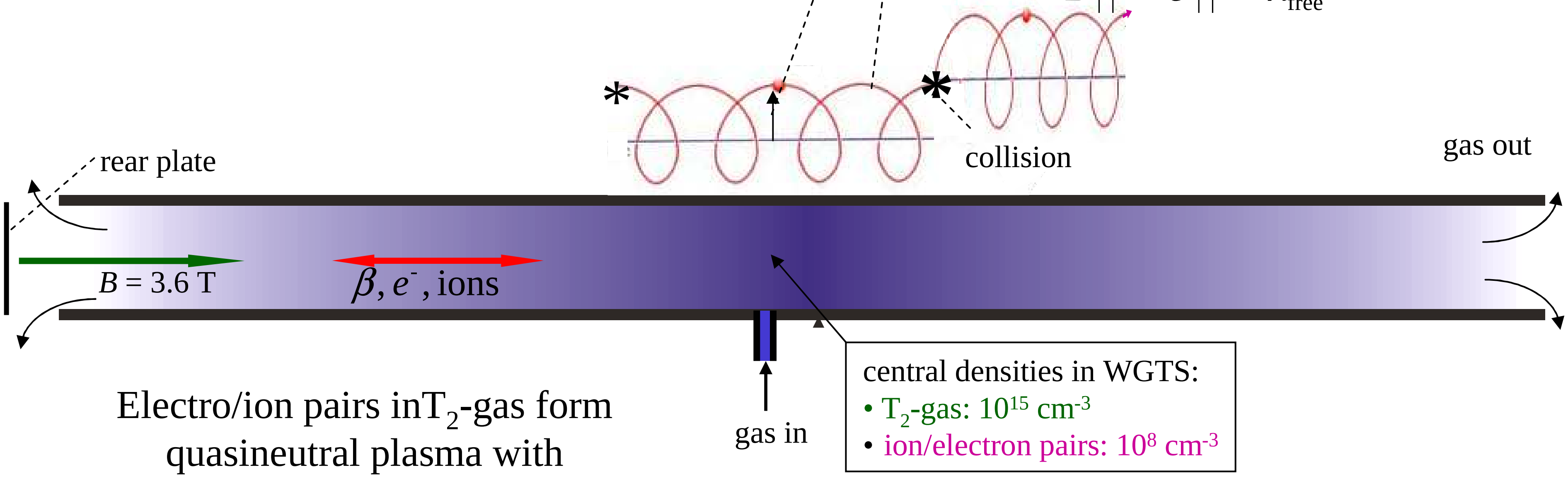
The scenario raises a number of tricky problems [3)]

---

1)Wilkerson J F, Bowles T J, Browne J C, Maley M P, Robertson R G H, Cohen J S, Martin R L, Knapp D A and Helffrich J A 1987 *Phys. Rev. Lett.* **58** 2023
2) Belesev A I *et al.* 1995 *Physics Letters* **B 350** *263*
3) **Effects of Plasma Phenomena on Neutrino Mass Measurements Process Using a Gaseous Tritium Beta Source**
Anatoly F. Nastoyashchii, Nikita A. Titov, Igor N. Morozov, Ferenc Glück, Ernst W. Otten
Fusion Science and Technology (ANS), Vol. 48 (2005) 743-746

Mechanism and consequences of magnetic confinement in WGTS

$$R_c / \lambda_{free} \ll 1 \Rightarrow \frac{D_\perp}{D_{\uparrow\uparrow}} = \frac{\sigma_\perp}{\sigma_{\uparrow\uparrow}} \approx \frac{R_c^2}{\lambda_{free}^2} \approx 10^{-7}$$

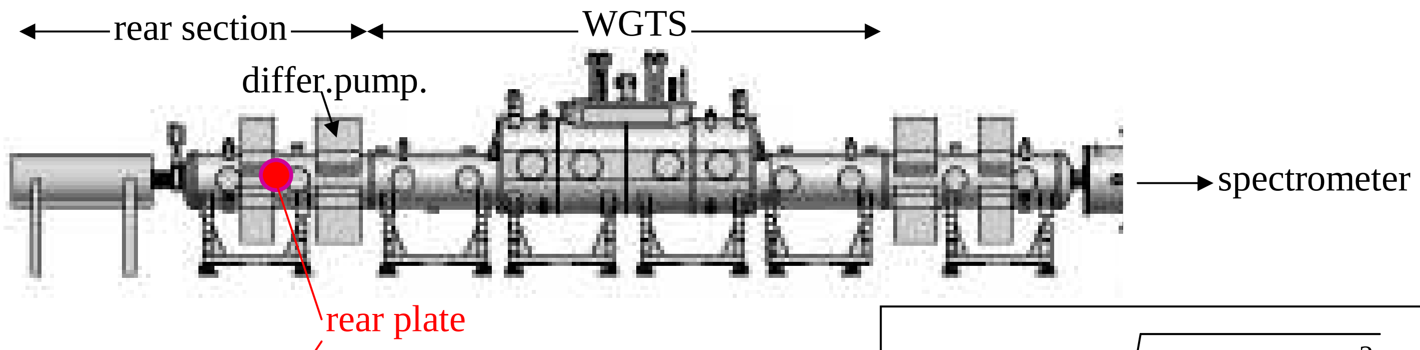


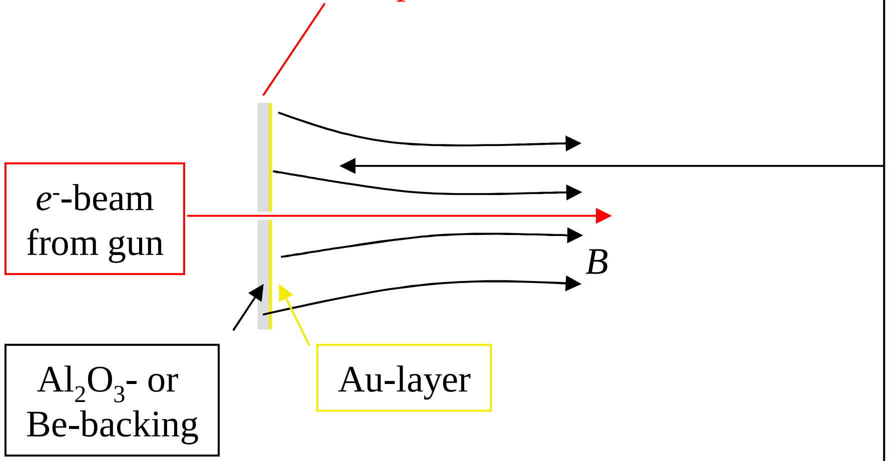
Electro/ion pairs inT_2-gas form quasineutral plasma with
high longitudinal conductivity: $\sigma_{\uparrow\uparrow}$
very low transverse conductivity: $\sigma_\perp \approx 10^{-7}\sigma_{\uparrow\uparrow}$

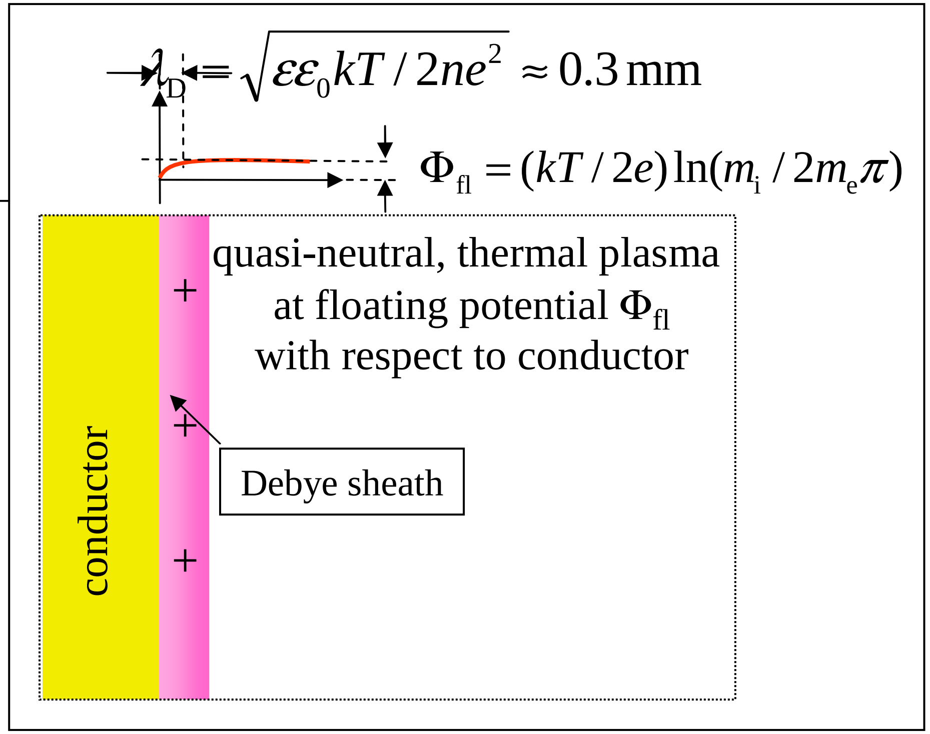
→ charged particles leave the source along magnetic field lines!

→ electric potential is constant along magnetic fild lines and can be defined by a conductive plate which crosses the flux tube at the rear end of WGTS !

Rear plate and plasma potential



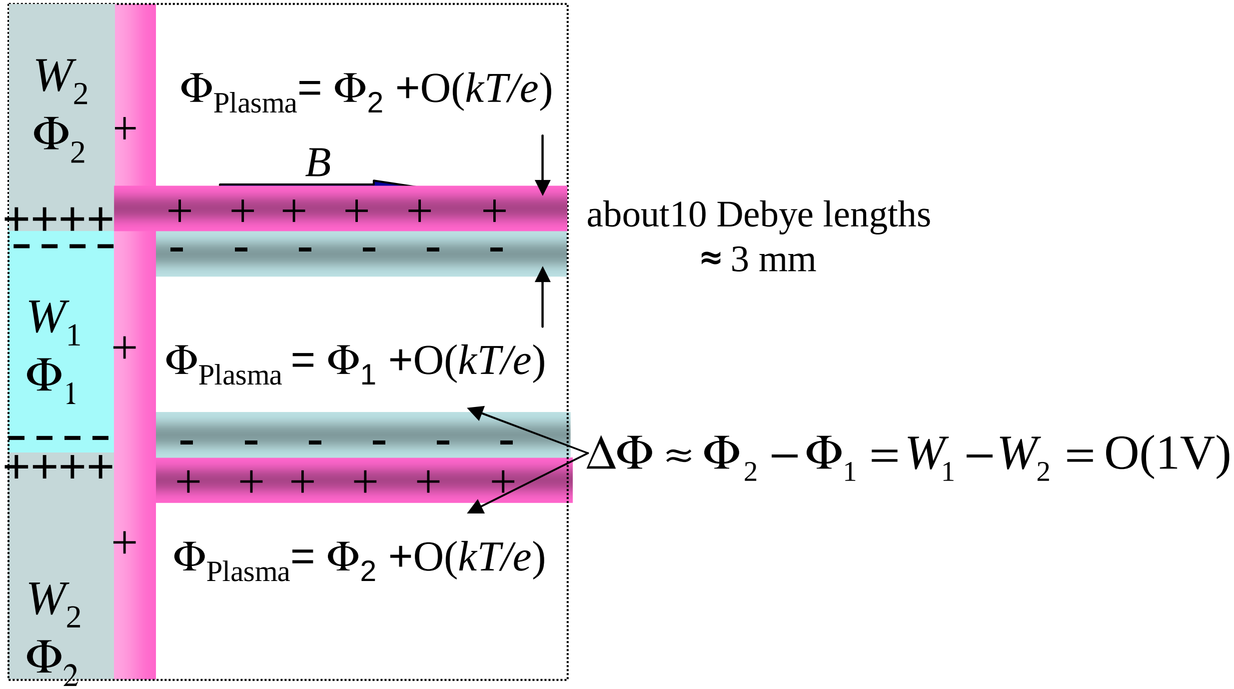




Gold surface is preferred for its inertness
In particular it does not adsorb T_2

In case of perfect magnetic confinement ($B \rightarrow \infty$)

the *local* surface potential Φ_i in front of the rear plate propagates along *B throughout* the WGTS!



But mind: The potential step between different Φ_i-domains is built up by a few mm wide double layer of 2 oppositely charged Debye sheaths

If the domains are much slimmer than the double layer the step is averaged off!

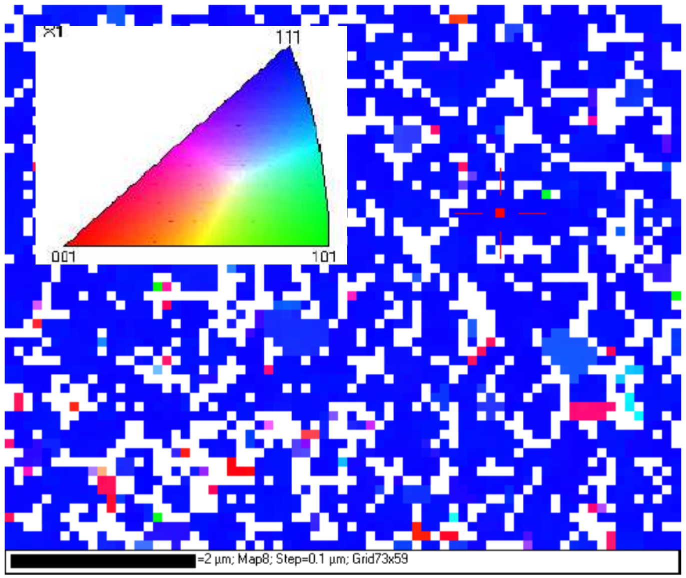
First rear plate test samples measured

Santa Barbara, Mainz

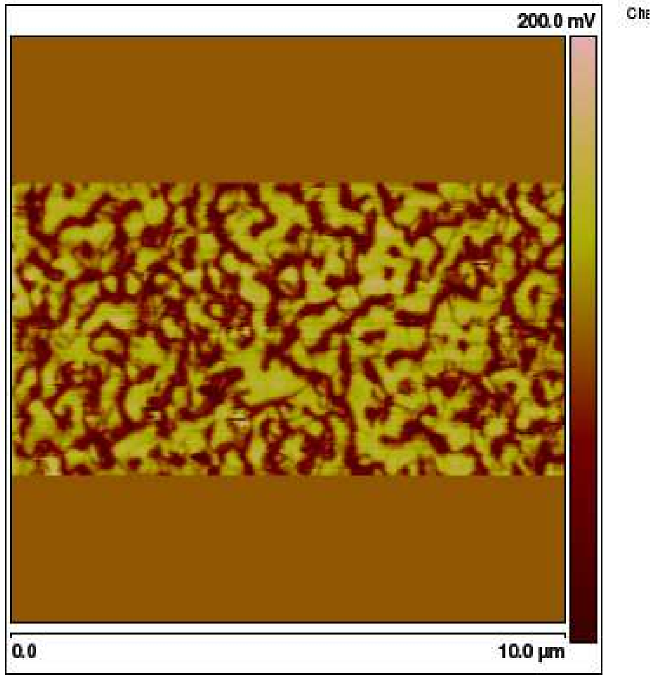
Which backing for the gold layer?

Epitaxial Au-growth on Sapphire preferred
Since imonocrystalline domains show
always 111-plane up →
same work function!

Scanning Electron Diffraction Pattern
111-plane up: > 99% !
But forming 1 µm sized domains
with different azimuthal orientation
At boundaries (white) no diffraction pattern

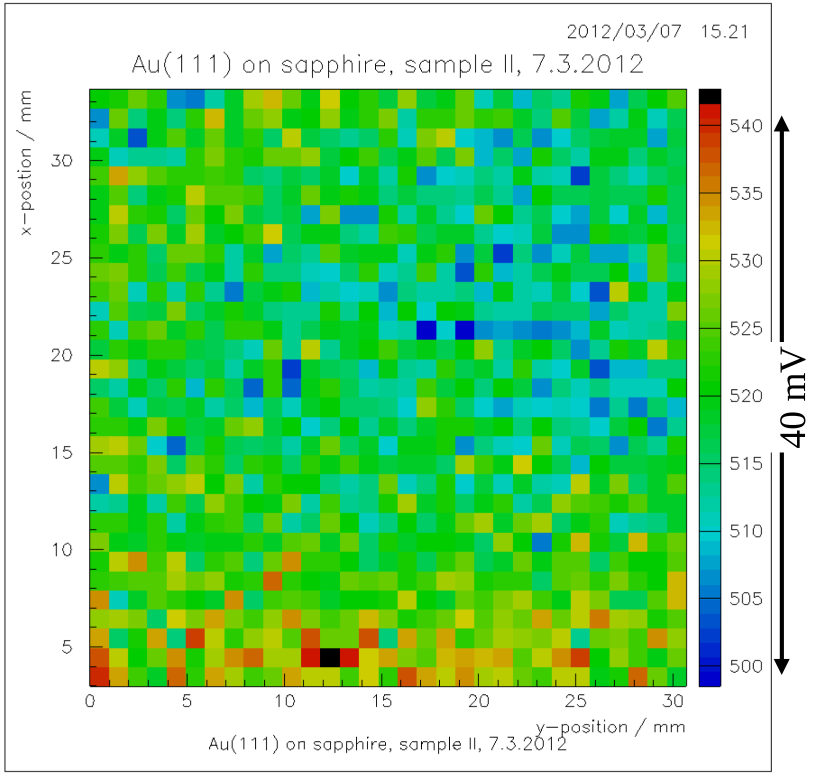


Microscopic false color image of work function
taken with scanning tunnel microscope
(full scale 200 mV)
Identical for all domains since 111 plane always up!



Macroscopic pattern of surface potential of epitaxial gold layer on sapphire

False color plot (30 x30) mm^2
Full scale 40 mV
Taken with Kelvin probe (in Lab atmosphere)
Scatter < fluctuation limit of 60 mV!



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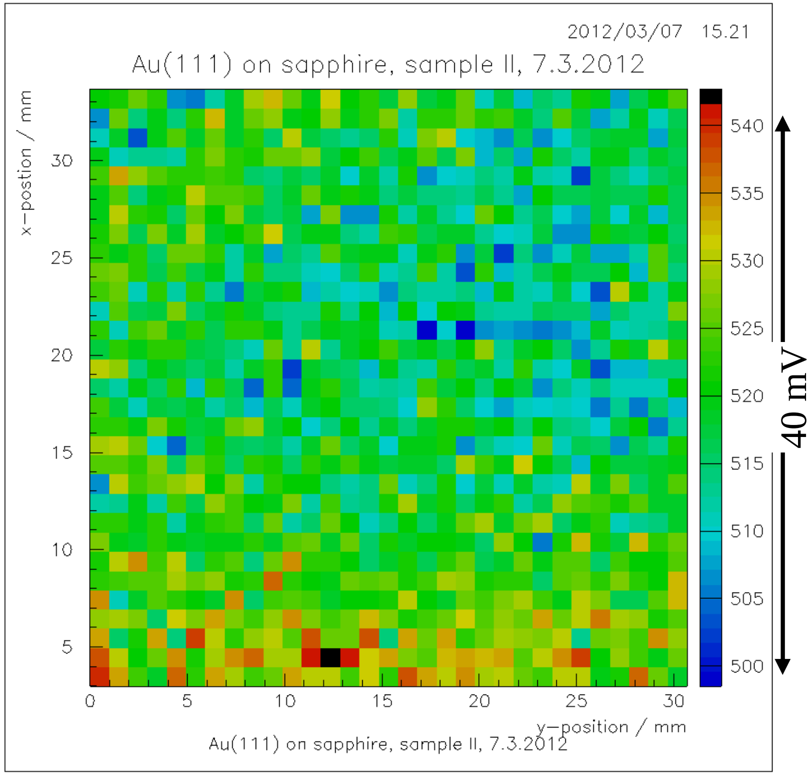
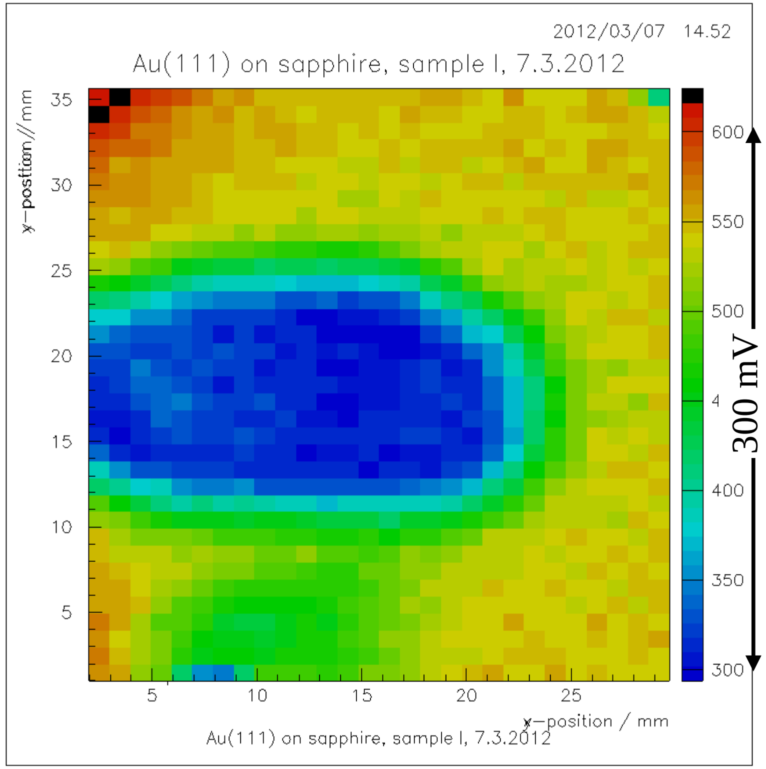


300 mV deep finger print
on the surface potential of gold
Obtained by a slightly careless experimentalist!



Fazit
KATRIN is not only a huge set-up
It also requires subtle expertise and care in many fine details!

5.)0utlook into future side experiments for KATRIN

A) Towards an Absolute High Voltage Standard

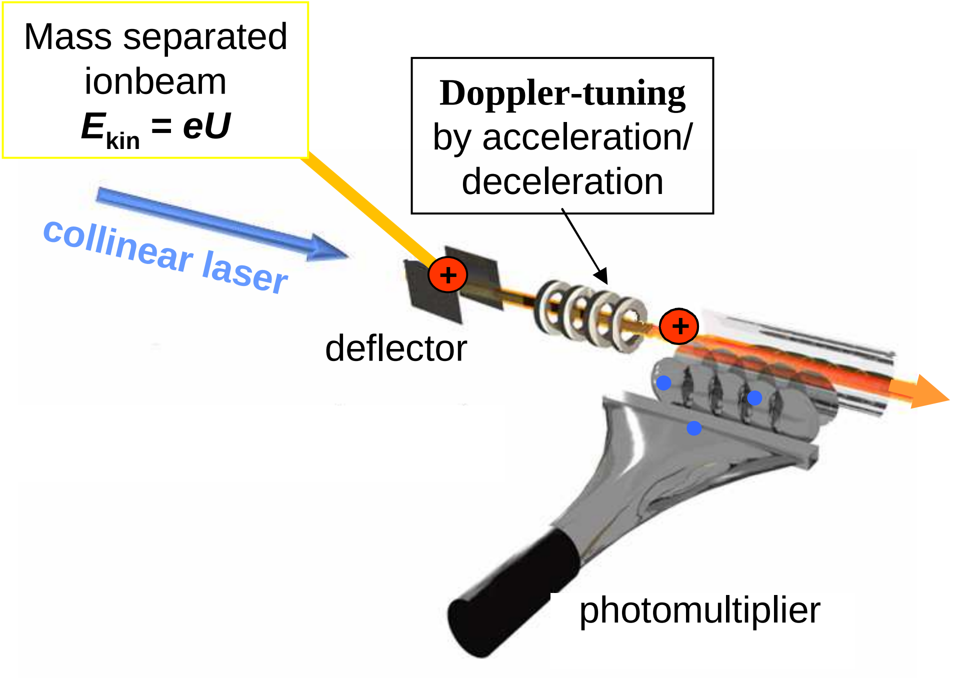
Rabi's Golden Rule for Metrology:
Never measure anything but a frequency!

How to turn high voltage into frequency?

Answer:
Accelerate ion beam by potential difference ***U***
and measure Doppler shift of resonance line
(Revival of old principle by modern methods of laserspectroscopy)

Tool: Collinear laser spectroscopy

developed at Mainz in late 70th for on-line spectroscopy on massed separated beams short lived isotopes at CERN-ISOLDE



Simplest version:
Detection of resonance fluorescence
by photomultiplier viewing the collinear excitation region

Dopplershift

$$\Delta\nu = \nu_0 \gamma\beta \approx \nu_0 \sqrt{2eU/mc^2}$$

Doppler width σ_ν
shrinks reciprocal to Dopplershift

Since initial energy spread σ_E
is constant of motion

$$\sigma(E) = \sigma_{mv^2/2} \approx m v \sigma_v$$

$$= mc^2 \frac{\Delta\nu \cdot \sigma_\nu}{\nu_0^2} \approx kT = \text{const.}$$

Advancced, dedicated version planned by Darmstadt/Mainz collaboration
W. Nörtershäuser et al.
Resolution = (nat. line width / doppler shift) ≈ 10^{-7} seems feasible

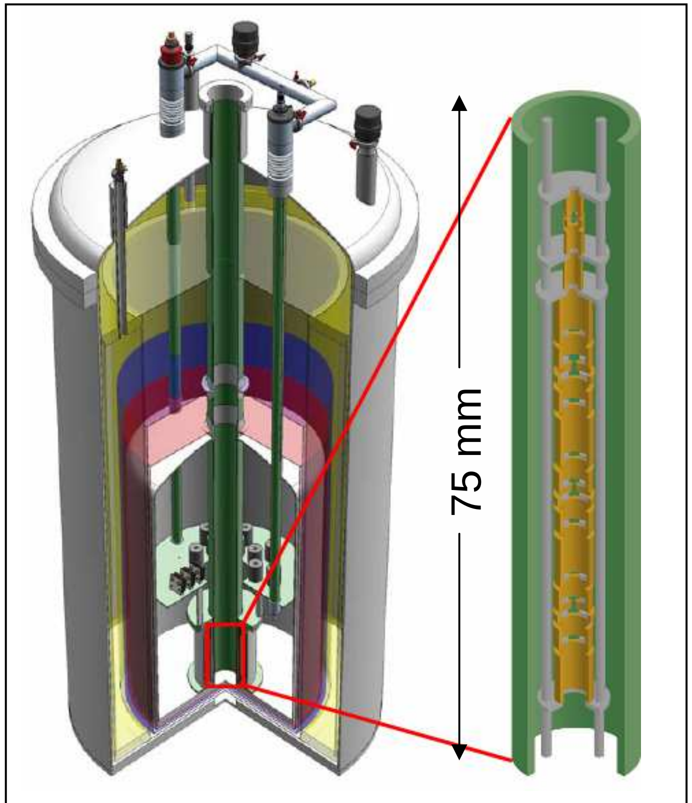
B) Proposal for precision spectroscopy of (T – ^{3}He) mass difference simultaneously and non destrucively in single ion traps at 4K

(K. Blaum et al., MPI Heidelberg)

Present value: $Q(\mathrm{T} \rightarrow {}^3\mathrm{He}) = (18590.1 \pm 1.7)$ eV

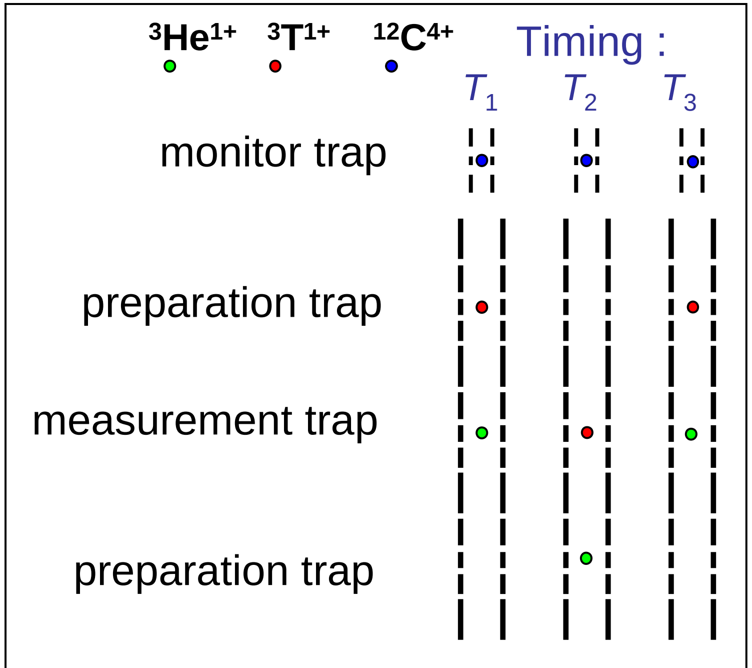
New experiment aims at rel. precision of 10^{-11} corresponding to $\delta Q \approx 0.03$ eV

(in the range of minimal neutrino mass!)



Apparatus

4 traps in a raw
at 4 K
within a solenoid



Procedure