The electrode system of the KATRIN main spectrometer

- Spectrometer-related background at KATRIN
  - Background reduction by electrostatic screening
- Wire electrode system
  - Design and optimization
  - Construction, assembly and installation
- Status and outlook

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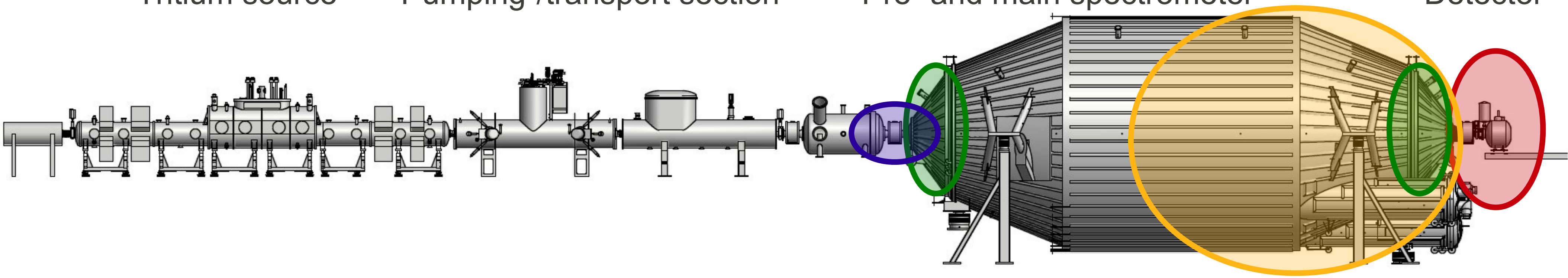
International School on Nuclear Physics
31st course: Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics
Erice, Sicily, Sept. 16 – 24, 2009

Background sources at KATRIN (I)



1. Radioactivity in the **detector system** (aim: **< 1 mHz** in analyzed energy interval!)
→ material selection, shielding (veto), post-acceleration

2. **T_2 β-decay** inside the main spectrometer
→ reduce T_2 partial pressure to $< 10^{-20}$ mbar in the spectrometer section!

3. Trapped charged particles and **ionization** **inside of** or **between** the spectrometers
→ long ionization time scale at UHV conditions ($p < 10^{-11}$ mbar)
→ carefully optimized electromagnetic design (see talk by *S. Mertens*)
→ electric dipole field: ***E*** x ***B*** drift
→ further active measures, e.g. 'electron catcher' sweeping through the trap

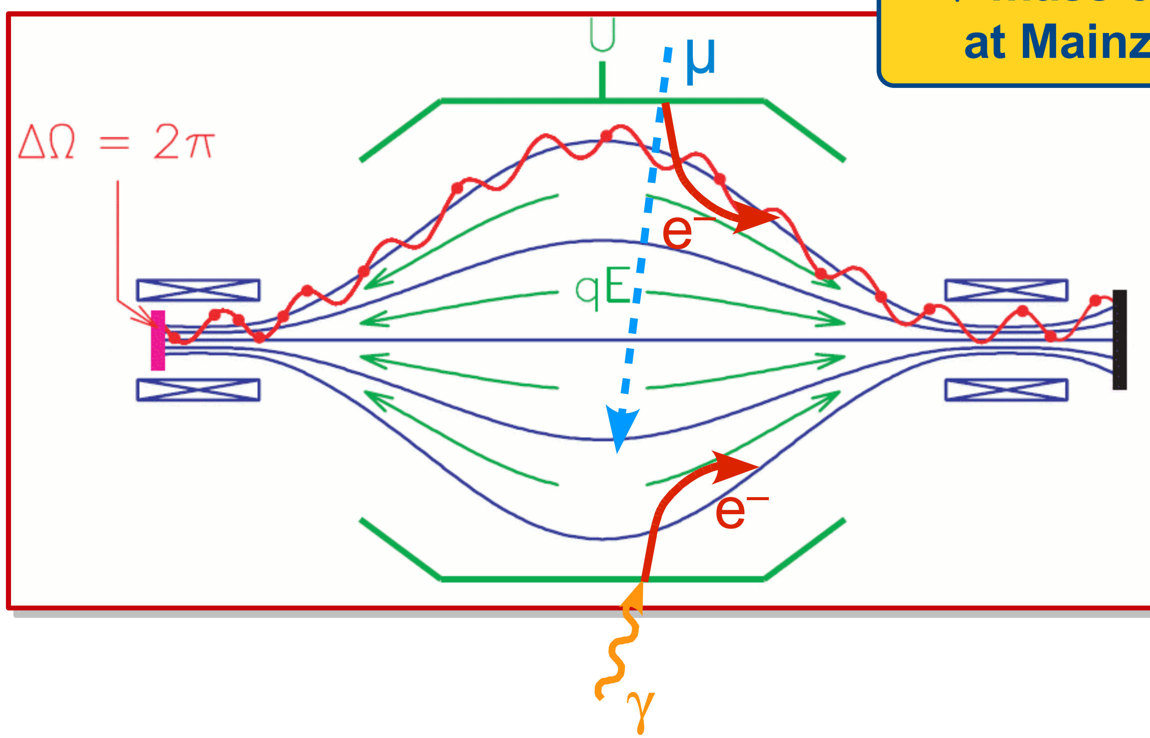
Background sources at KATRIN (II)

4. Emission of **electrons from electrode surfaces** by

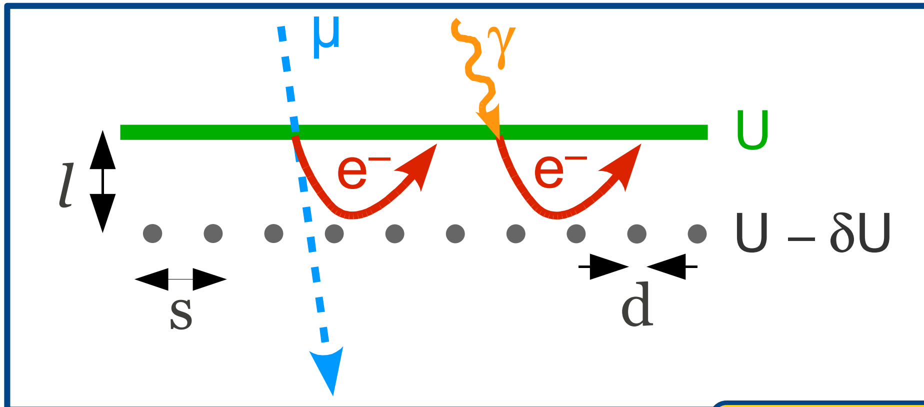
- cosmic muons,
- environmental radioactivity,
- radioactive impurities in material,
- field emission at sharp edges

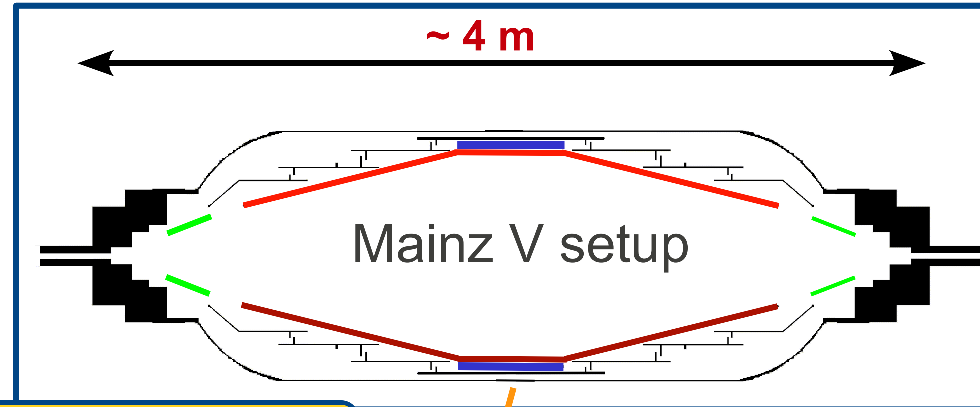
→ background electrons in energy range of β-endpoint (~1 keV resolution of electron detector!)

Principal background in ν-mass experiments at Mainz & Troitsk!

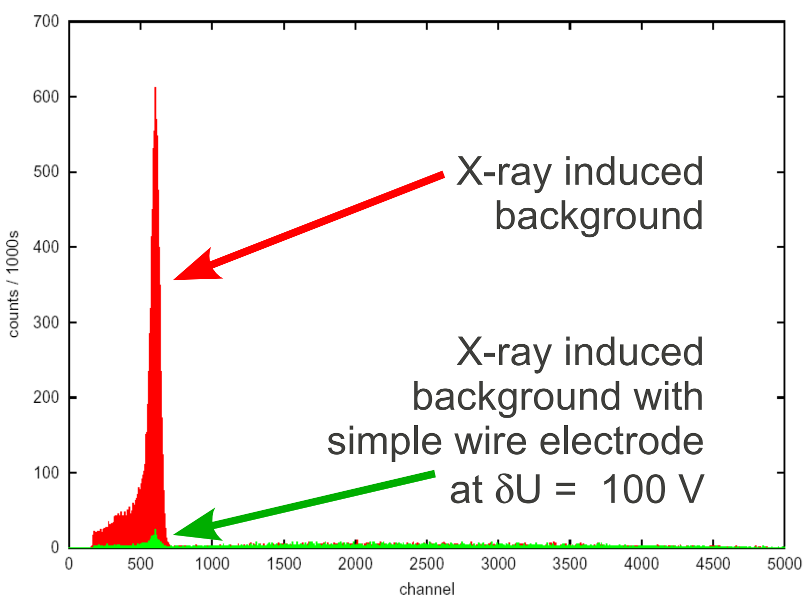


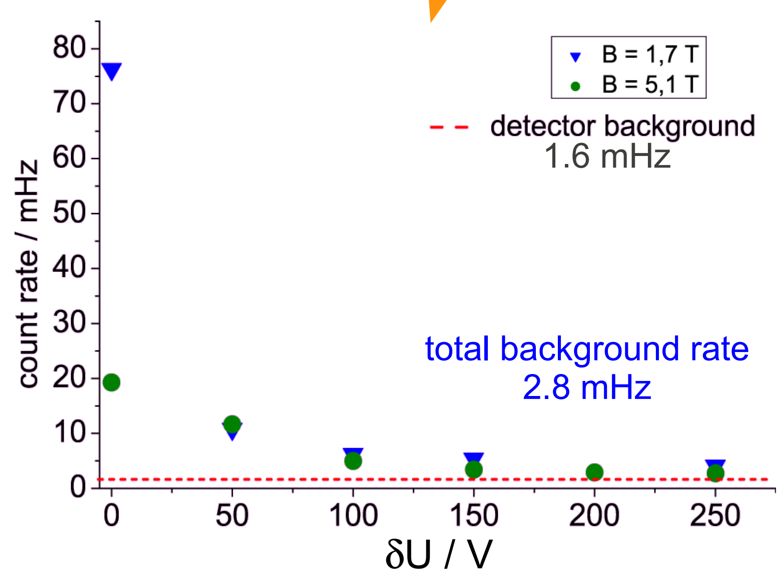
Principle of electrostatic screening (I)





Tested very successfully at the Mainz MAC-E filter



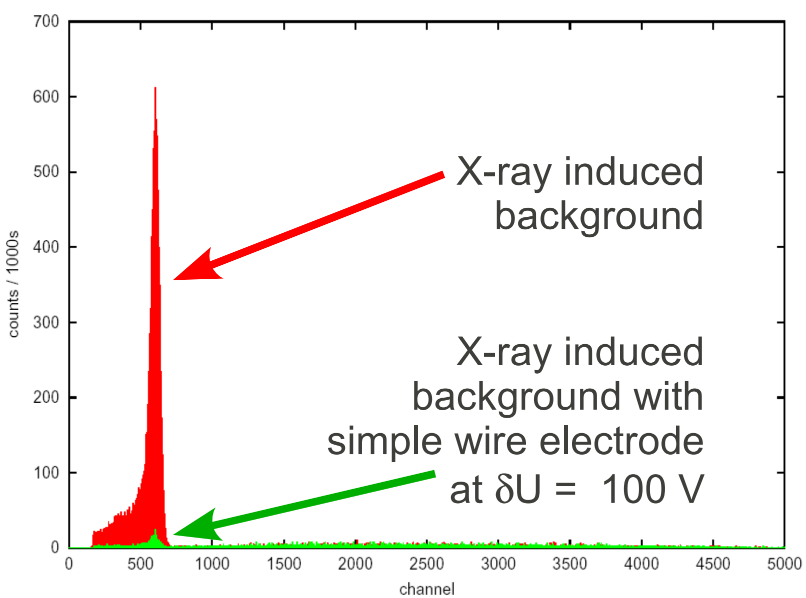


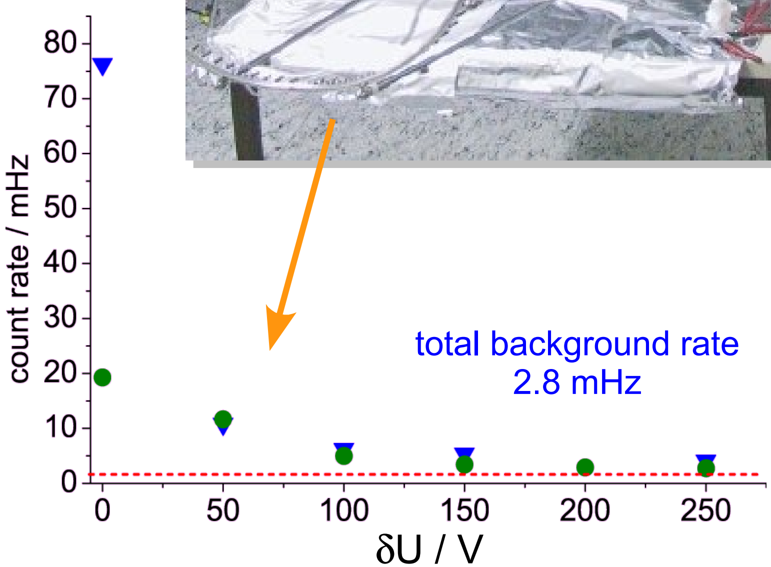
Diploma thesis B. Ostrick (U Mainz, 2002), PhD thesis B. Flatt (U Mainz, 2004)

Principle of electrostatic screening (II)

- Single-layer wire electrode at Mainz MAC-E-Filter with δU ~ 200 V: background suppression **by factor >10**

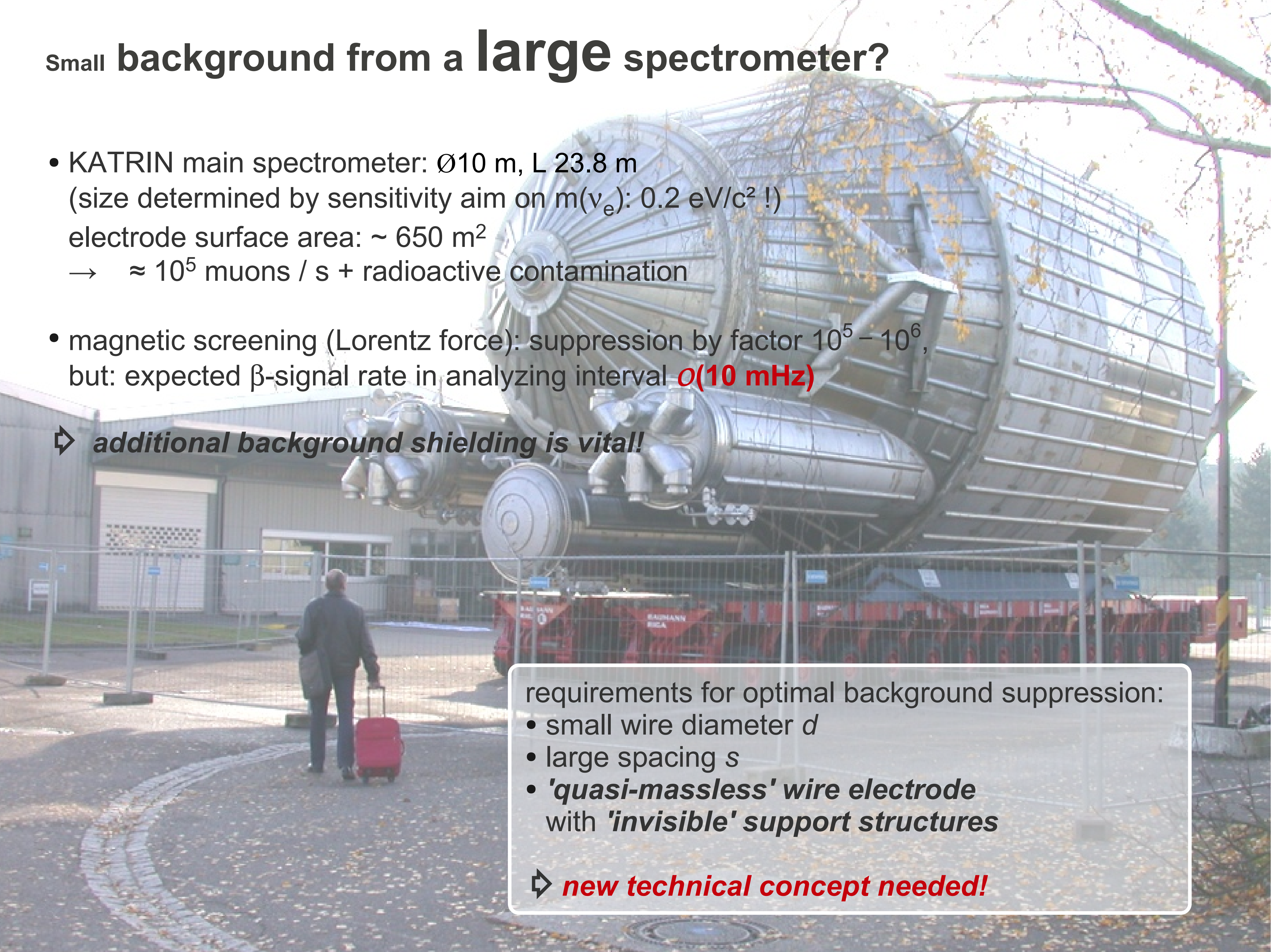
But: How to improve and scale this 'table-top setup' to KATRIN dimensions?





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

Small background from a **large** spectrometer?



- KATRIN main spectrometer: Ø10 m, L 23.8 m
  (size determined by sensitivity aim on $m(\nu_e)$: 0.2 eV/c² !)
  electrode surface area: ~ 650 m^2
  → ≈ 10^5 muons / s + radioactive contamination

- magnetic screening (Lorentz force): suppression by factor $10^5 - 10^6$,
  but: expected β-signal rate in analyzing interval ***O*(10 mHz)**

⇨ ***additional background shielding is vital!***

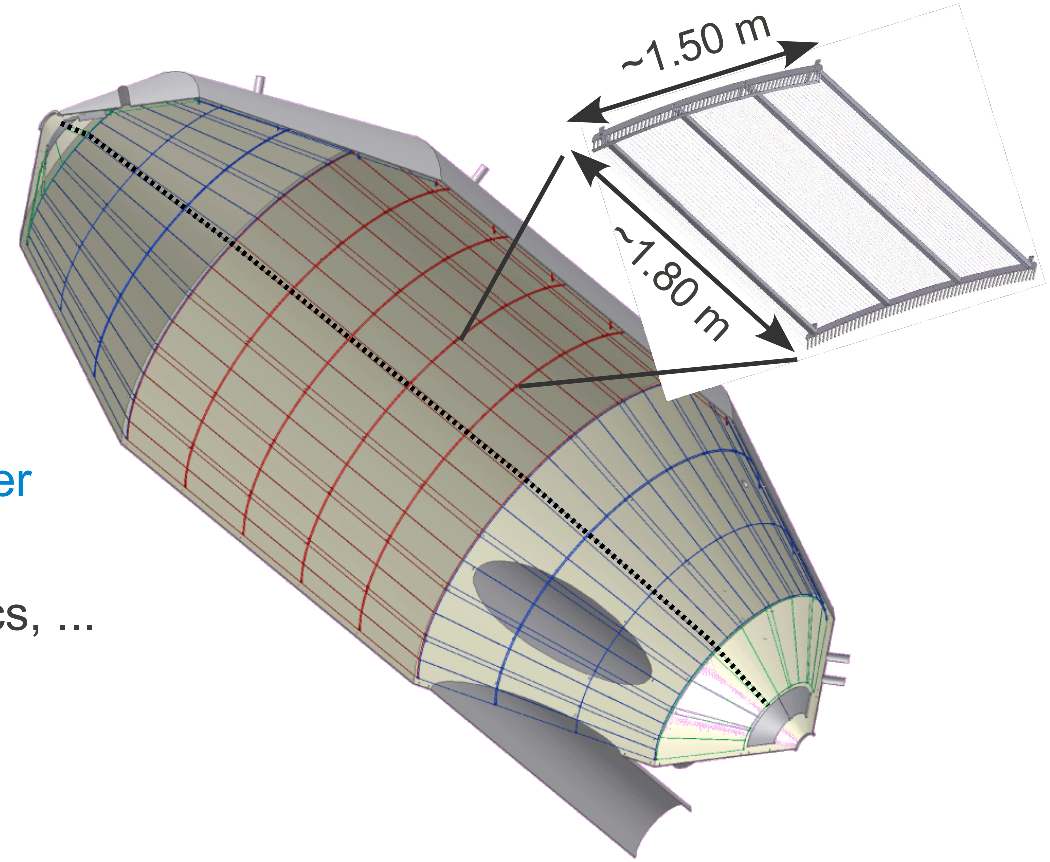
requirements for optimal background suppression:
- small wire diameter *d*
- large spacing *s*
- ***'quasi-massless' wire electrode***
  with ***'invisible' support structures***

⇨ ***new technical concept needed!***

Concept for KATRIN: 2-layer modular wire electrode

Two layers:

- to increase background shielding
- to increase electrical shielding
- to allow mechanical precision

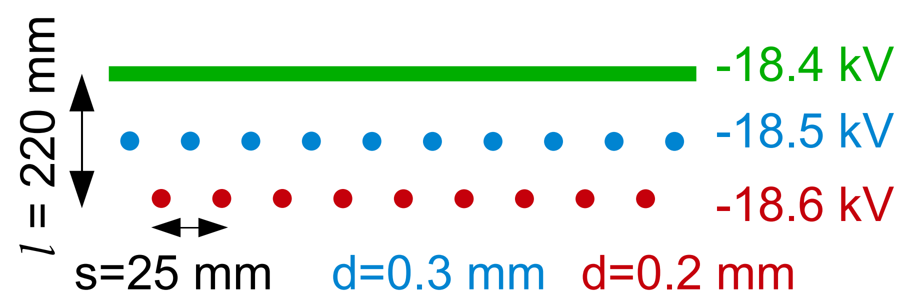


Modular layout to cover full main spectrometer
(A = 650 m^2, V=1240 m^3):

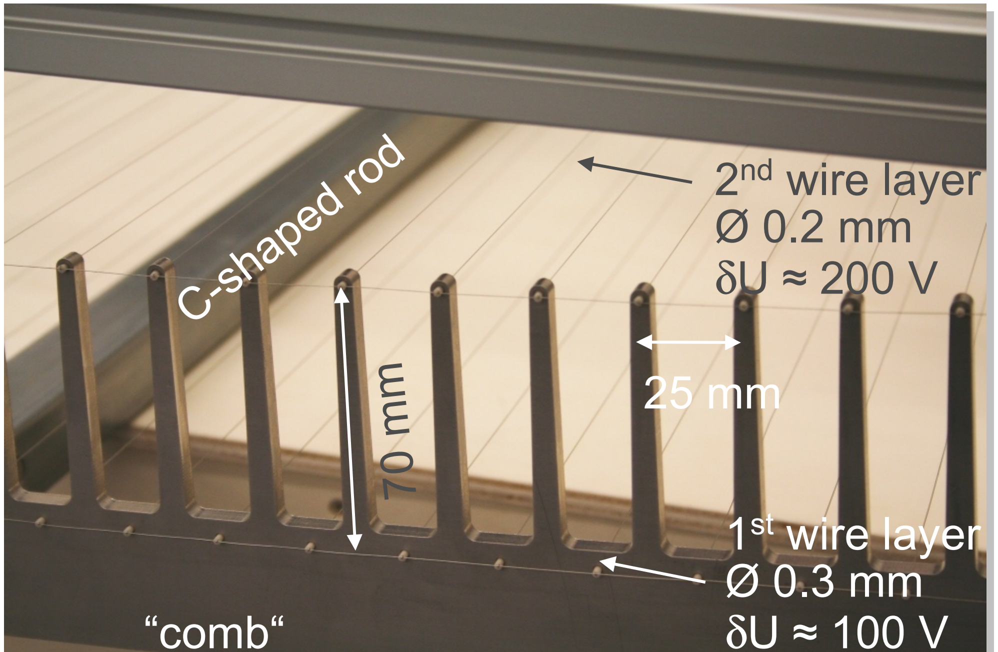
- 248 modules, 23120 wires, 46240 ceramics, ...
- two insulated dipole halves ($\Delta U \approx 1$ kV)

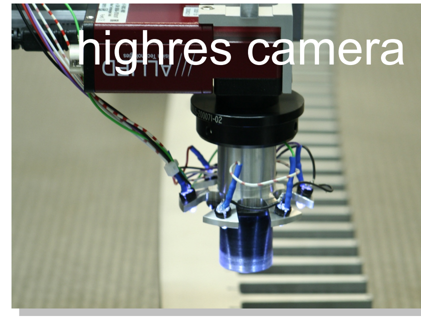
Technical requirements:

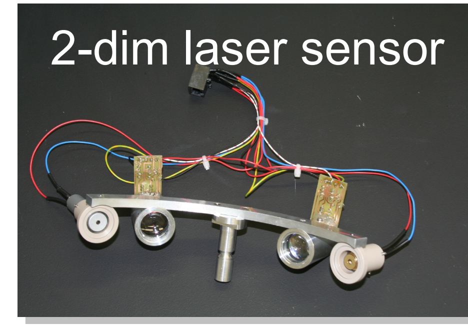
- modules have to withstand bake-out at 350°C
- module design needs to be compatible with UHV requirements (10^{-11} mbar)
- exact relative wire position ($\Delta x = 200\ \mu$m)
- non-magnetic, non-radioactive, ...

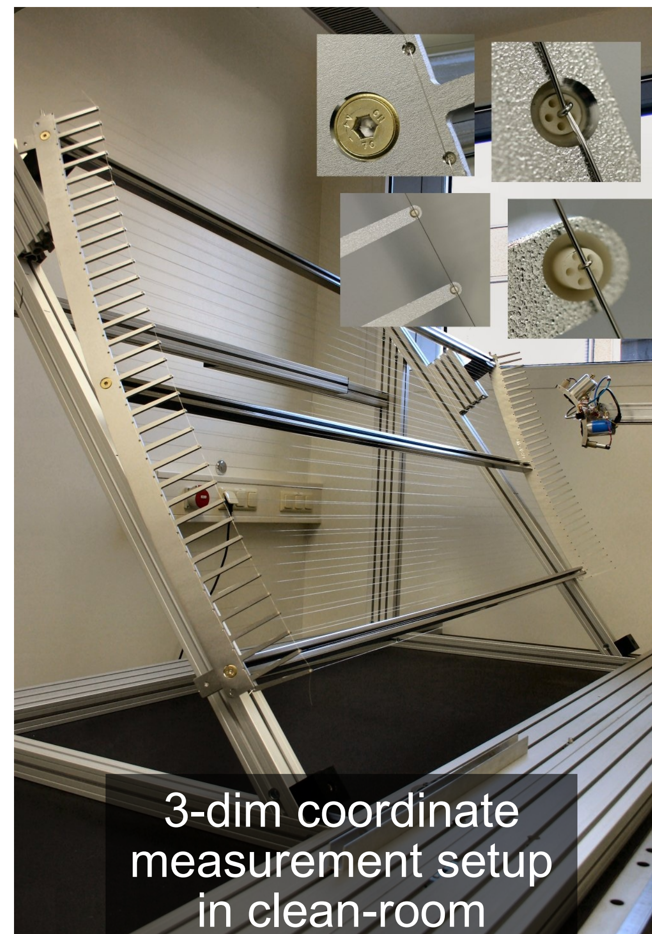


Technical realization



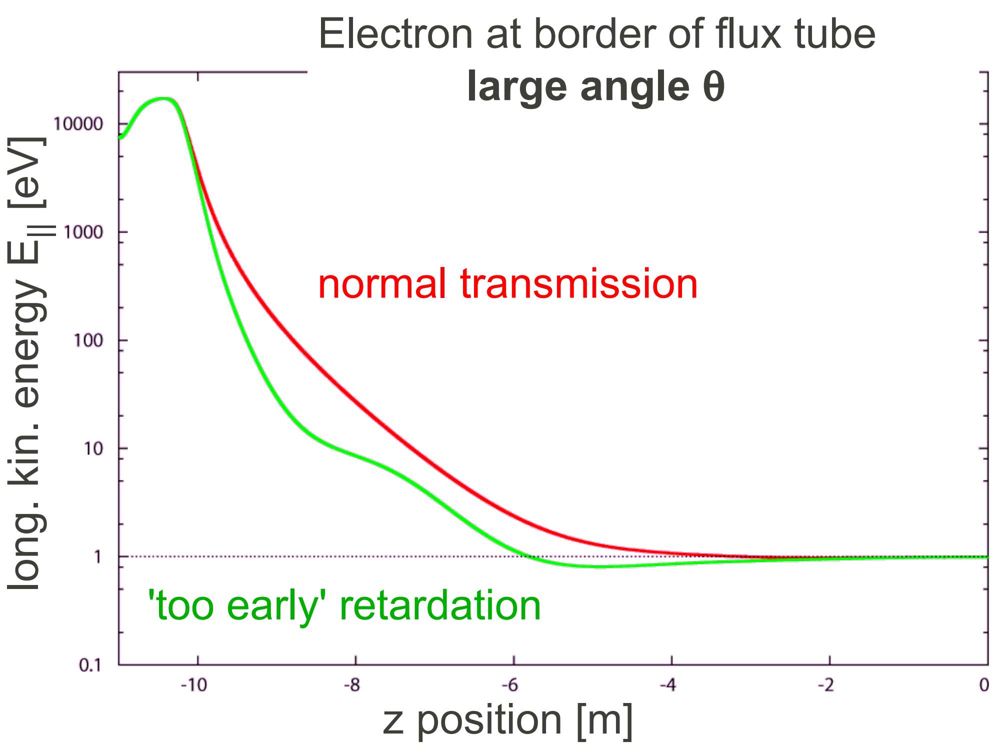




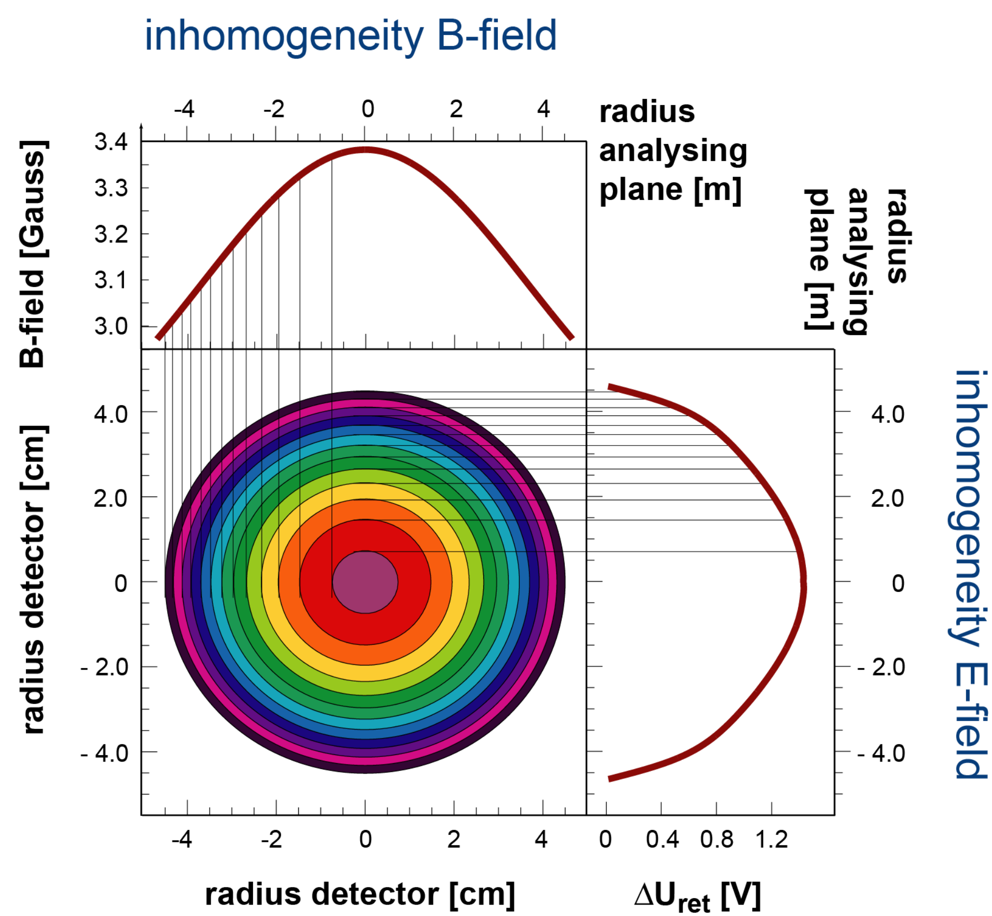


Design criteria for the wire electrode

Problems with transmission:



(in)homogen. fields in analysing plane:

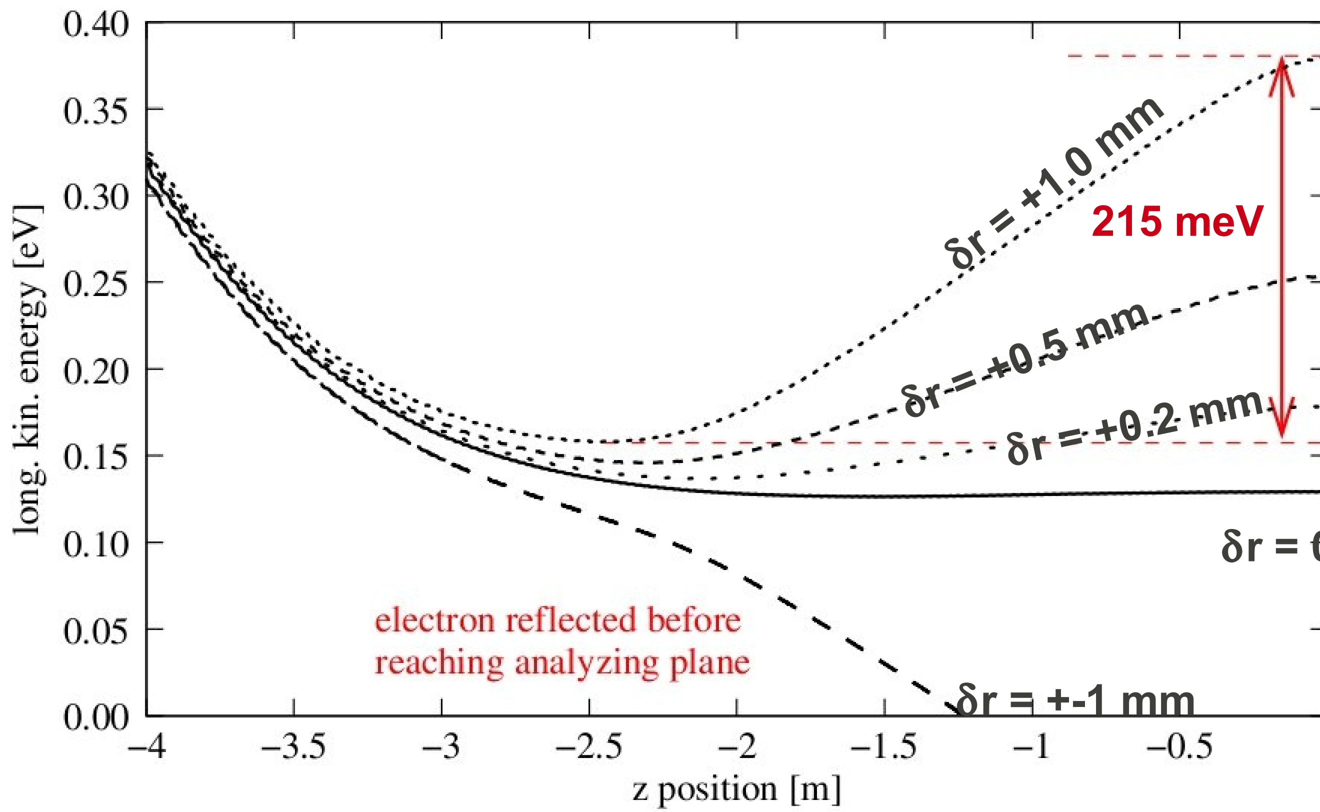


intolerable **broadening and smearing** of sharp transmission function!
→ optimize design
→ use highly segmented detector
→ detailed pixel-by-pixel calibration measurements (see talk by *K. Hugenberg*)

Simulations: construction & mounting tolerances

What happens if …

- ... wires sag due to their weight?
  → δr < 0.2 mm acceptable over L = 1.80 m!
  since $\left|\frac{\partial U_{eff}}{\partial l}\right| \propto \frac{1}{l^2}$
  l = 50 mm → 70 mm



- … wires are misaligned within a module?
  → stringent QA required!

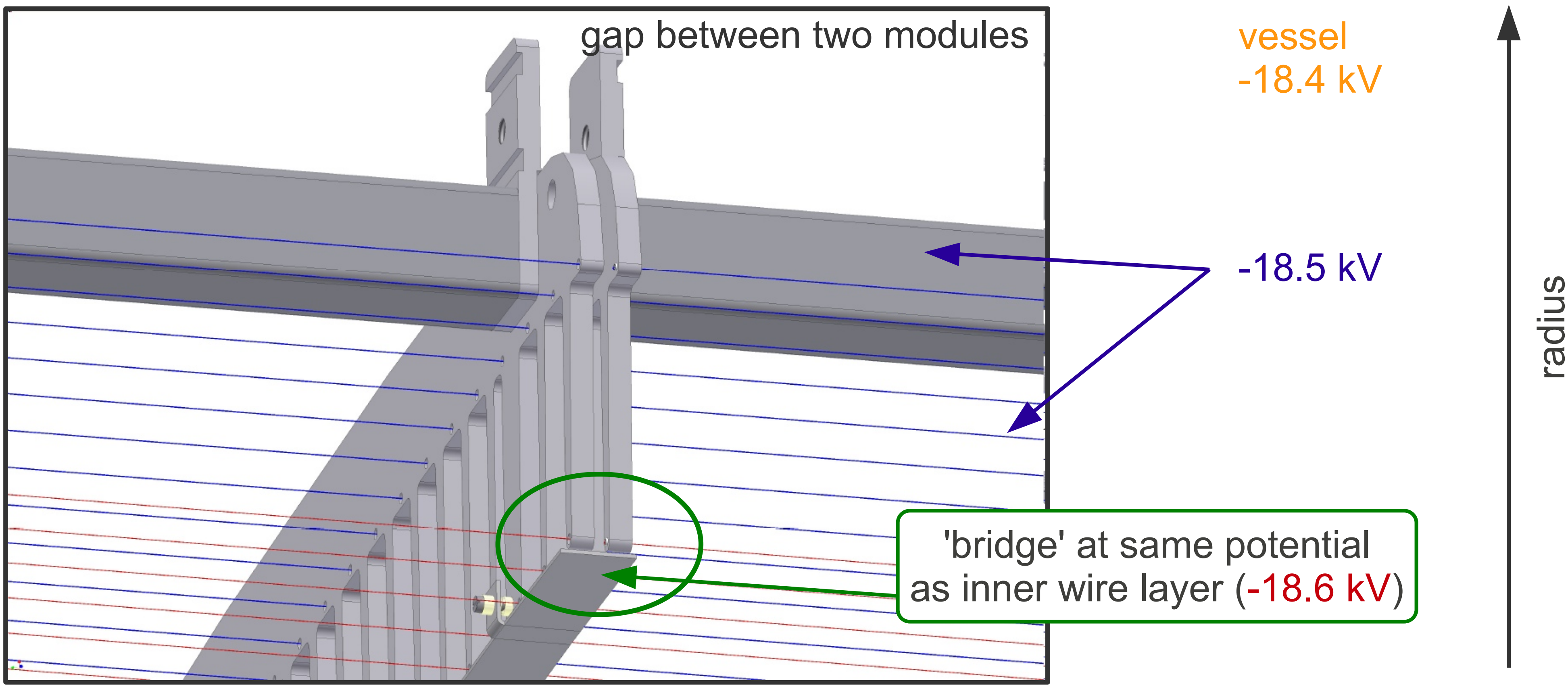
- ... mounting points of the modules are misaligned?
  → compensation by mounting interface!

- ... the steel vessel deviates from the 'ideal shape'?
  → two-layer system helps!
  → mounting interface compensates differences!

Simulations: field homogeneity

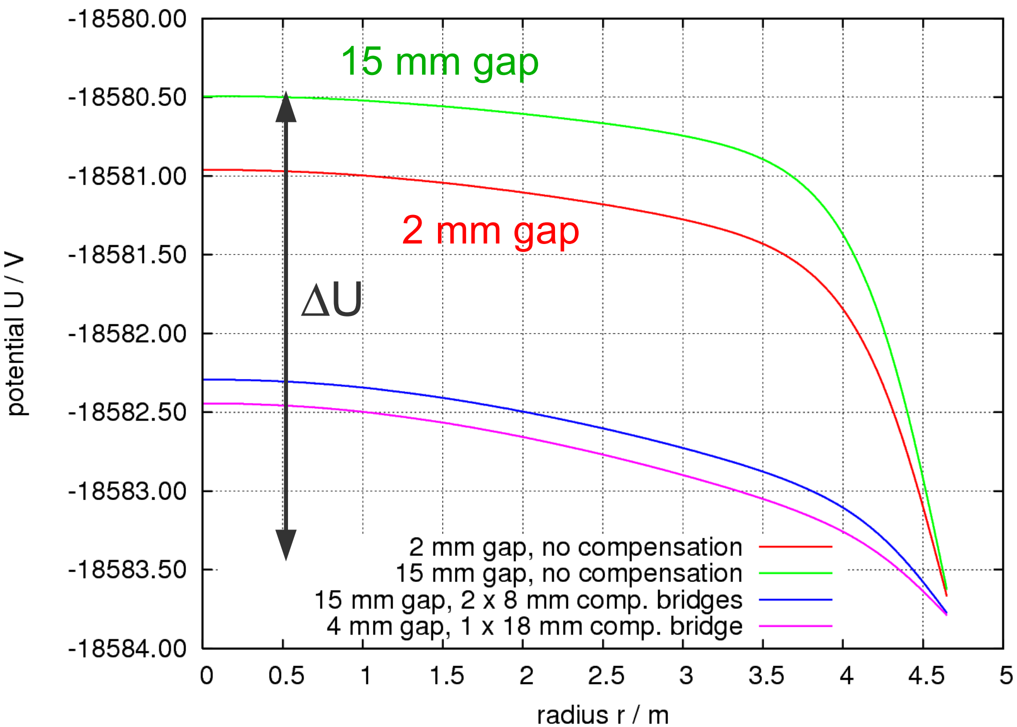
Various origins of distortions of the electric potential:

- **C-shaped rods** at -18.5 kV (+100 V w.r.t. inner wire layer)
  → *screened* by wires at -18.6 kV, only little influence on interior of flux tube
- **Combs** at -18.5 kV, tips *not fully screened* by wires!
- **Gaps between adjacent modules** in axial (z-) direction



Simulations: field homogeneity

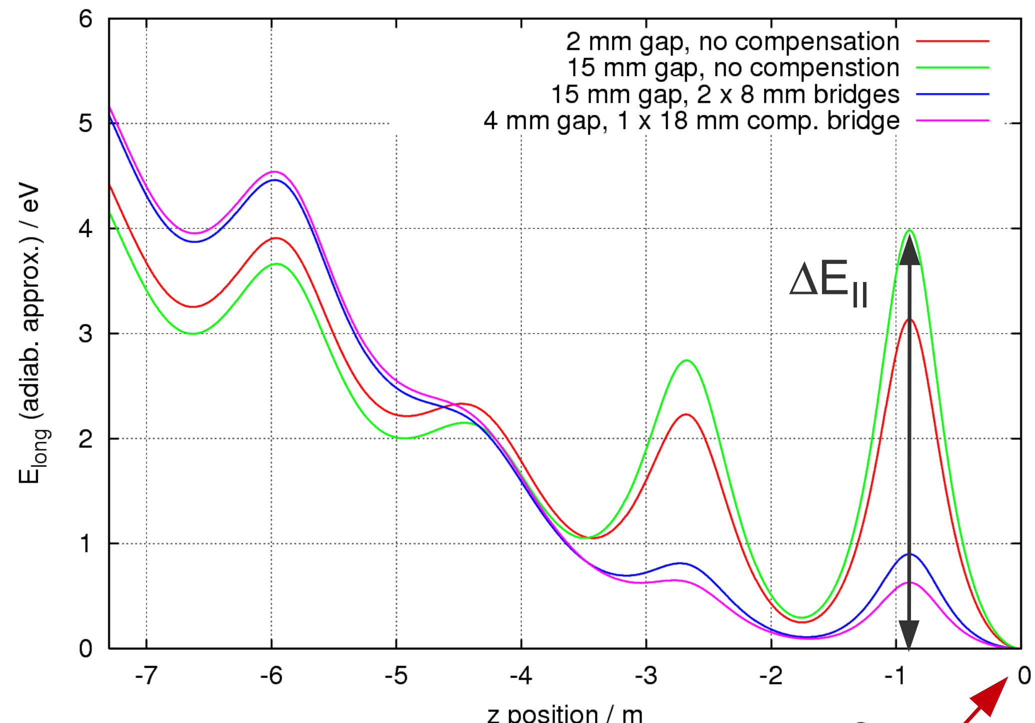
Retardation potential



position along
spectrometer radius (z = 0)

Longitudinal kinet. energy $E_{||}$

- electron with small surplus $\varepsilon = E_{kin} - qU_0$
- outermost field line guided onto detector

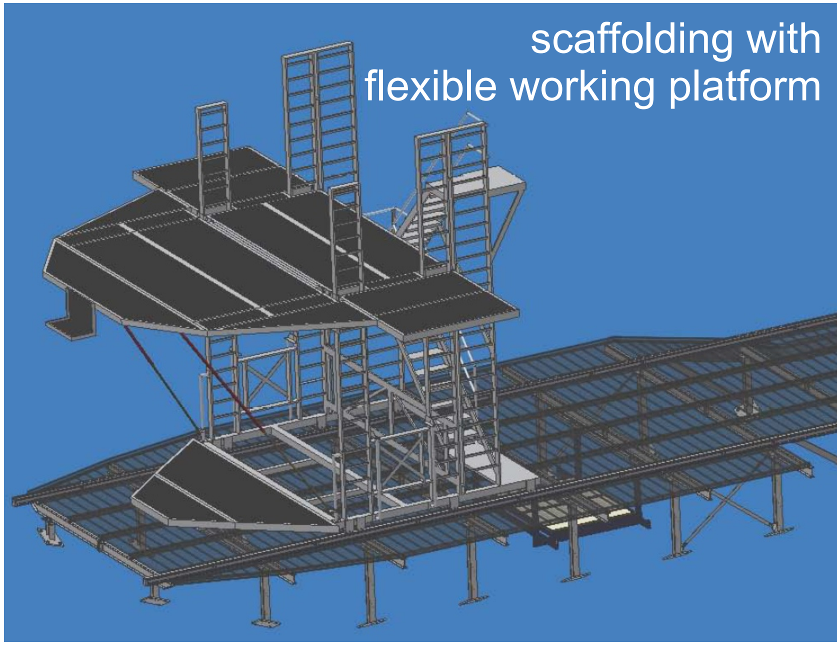


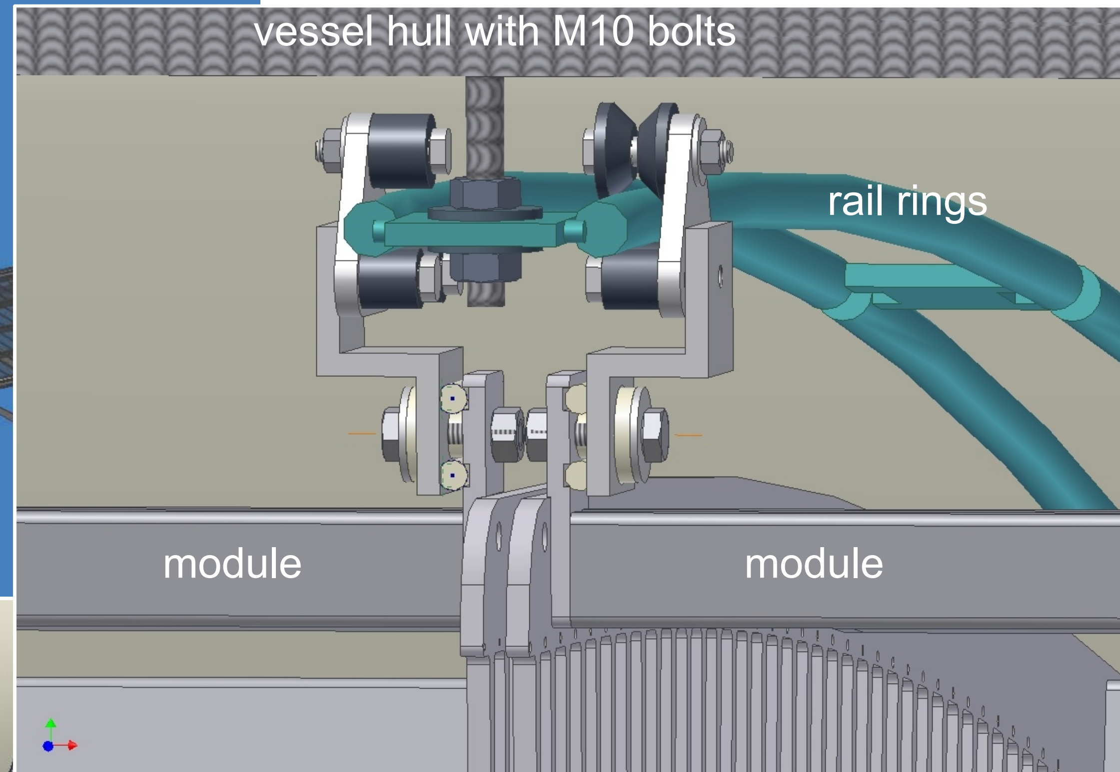
position along
z-axis

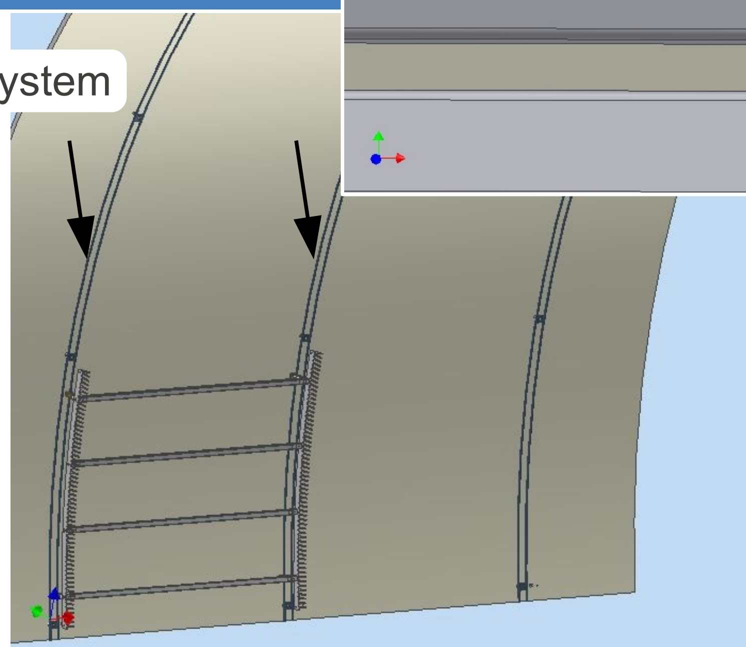
z = 0:
analysing-
plane

Gap not covered:	$\Delta U > 3$ V	$\Delta E_{||} \approx 4$ eV
Gap covered by 'bridge':	$\Delta U \approx 1.3$ V	$\Delta E_{||} < 1$ eV

Installation and mounting of the modules

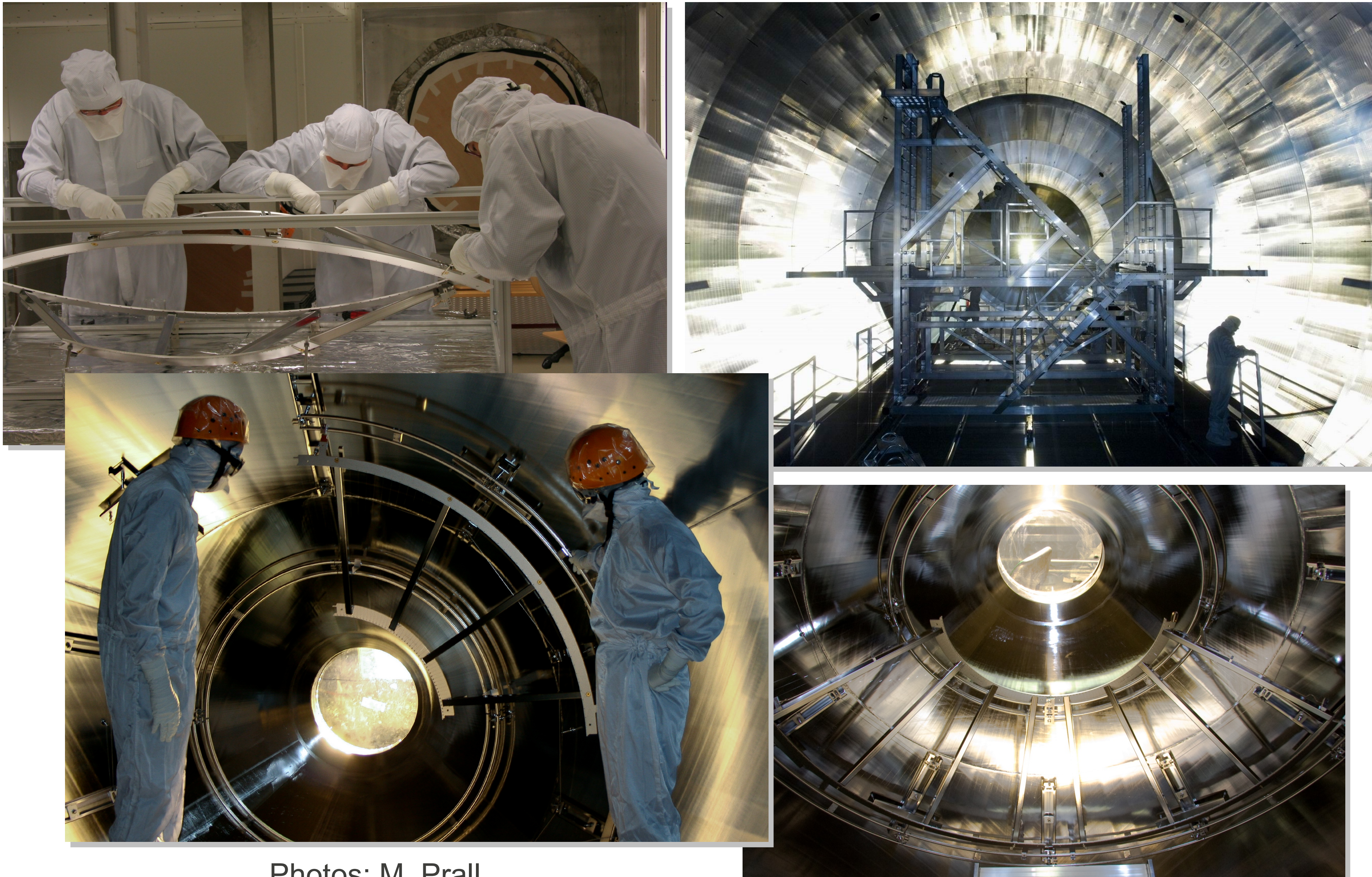






Mounting and intervention system:
FZ Karlsruhe

Status: Installation of the modules has started ...



Photos: M. Prall

Summary and outlook

Sensitivity on neutrino mass $m(\nu_e)$:

2 eV/c^2 (Mainz/Troitsk) → **0.2 eV/c^2 (KATRIN)**

→ need background rate ***< 10 mHz***

Suppression of spectrometer-related background:

- Electrostatic shielding by two-layer **wire electrode system**
- Detailed computer simulations: optimized design, mechanical tolerances
- Assembly of 248 modules (plus spares) in Münster: almost completed
- Installation of the wire electrode system has started, expected to be finished in spring 2010
- Followed by calibration measurements and commissioning of the main spectrometer

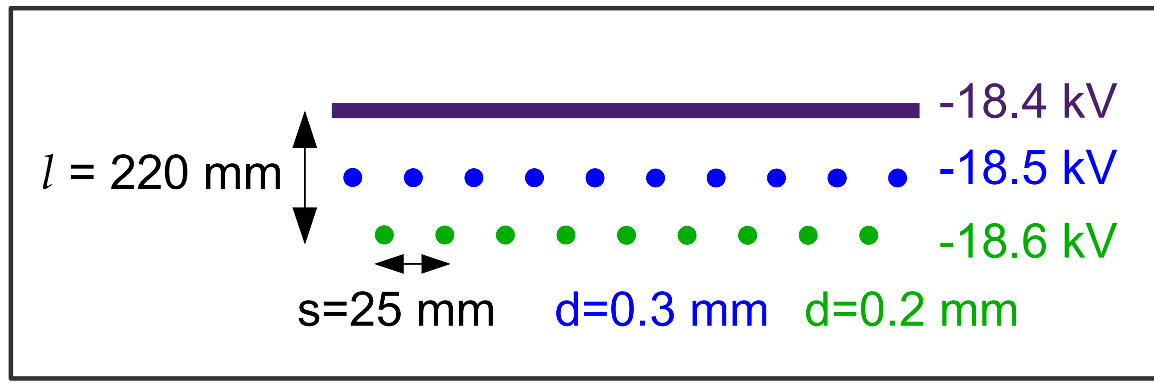
Constraints on the parameters of a 2-layer wire electrode

Aim: **Background suppression** by factor ≈100:

→ need *thin* wires: low geometrical coverage $f_{gc} = \frac{d}{s} \approx 0.01$

but: el. Field strength $E_{draht} = \frac{\Delta U}{l} \frac{s}{\pi d}$ (dipole operation) → *thick* wires

Solution: **two-layer system:**



- additionally allows better electrostatic screening:

$$\Delta U_{eff} = \left(1 - \frac{1}{S}\right) \Delta U_{wire} + \frac{1}{S} \Delta U_{hull}, \qquad S = 1 + \frac{2\pi l}{s \ln\left(\frac{s}{\pi d}\right)}$$

Fluctuation of analysing potential (ΔU_{eff})

Fluctuation of vessel potential (ΔU_{hull})

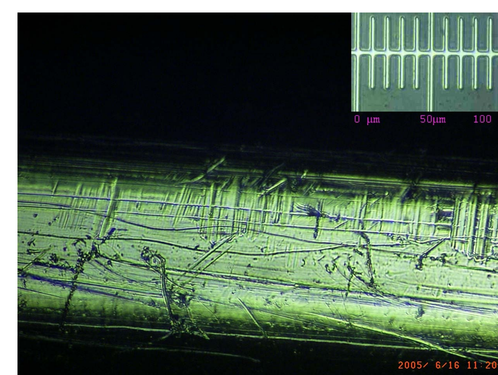
- facilitates observation of mechanical tolerances

Anforderungen an ein Drahtelektrodensystem für das KATRIN-Hauptspektrometer

- **Vakuumtauglichkeit:** Spektrometersektion p < 10^{-11} mbar
  - ➔ zugelassene Materialien: z.B. Edelstahl, Gold, Keramik (Frialit), *keine* Kleber
  - ➔ Reinigung aller Bauteile nach fester Prozedur, Ultraschallbad-Anlage
  - ➔ Fertigung und Handhabung im Reinraum

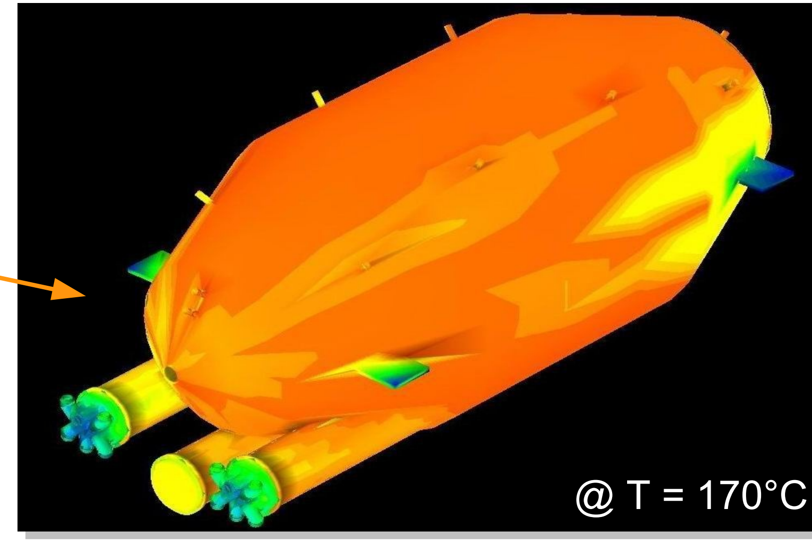
- Nur **nicht-magnetische** Materialien, geringe spezifische **Aktivität**

- **Hochspannungsfestigkeit**
  - ➔ Drähte 1. und 2. Lage elektrisch isoliert gg. Tank/Halterung
  - ➔ Entgraten von scharfen Kanten (Elektropolieren), Oberflächenqualität der Drähte (Vermeidung von Feldstärkeüberhöhung durch Mikrospitzen)
  - Dipol-Modus: hohe el. Feldstärke entlang Trennlinie

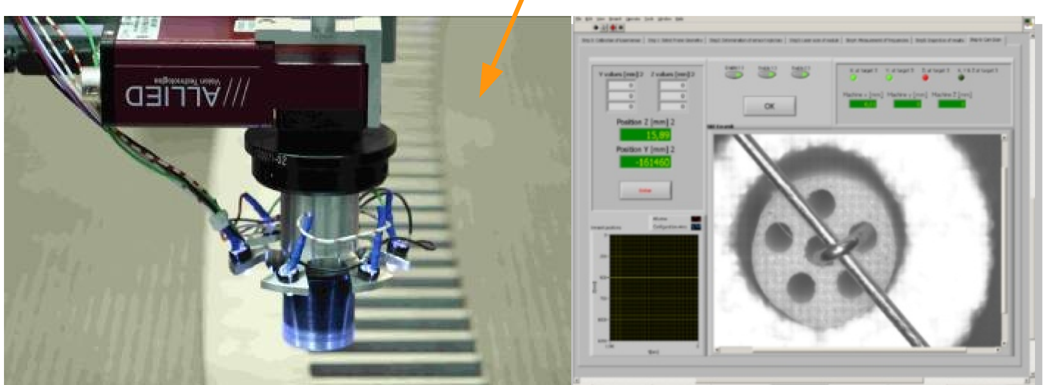


Anforderungen an ein Drahtelektrodensystem für das KATRIN-Hauptspektrometer

- **Belastbarkeit, Langzeitstabilität**
  - ➔ Kein Draht darf reißen! (Gesamtmesszeit 5 Jahre)
  - ➔ Hohe mechan. Stabilität der Haltestrukturen, aber möglichst wenig Material
  - ➔ Ausheizen des ganzen Hauptspektrometers incl. Innenelektrode <u>bis T = 350°C</u>
    - ➔ Anpassung des therm. Ausdehnungskoeffizienten



- **Fertigungs- und Einbautoleranzen**
  - ➔ Durchhängen durch ausreichende Drahtspannung vermeiden:
    $\delta r < 200\ \mu m \Rightarrow$ 10 N (1. Lage)
    bzw. 5 N (2. Lage)
  - ➔ strenge Qualitätssicherungsmaßnahmen, lückenlose Dokumentation (Datenbank)

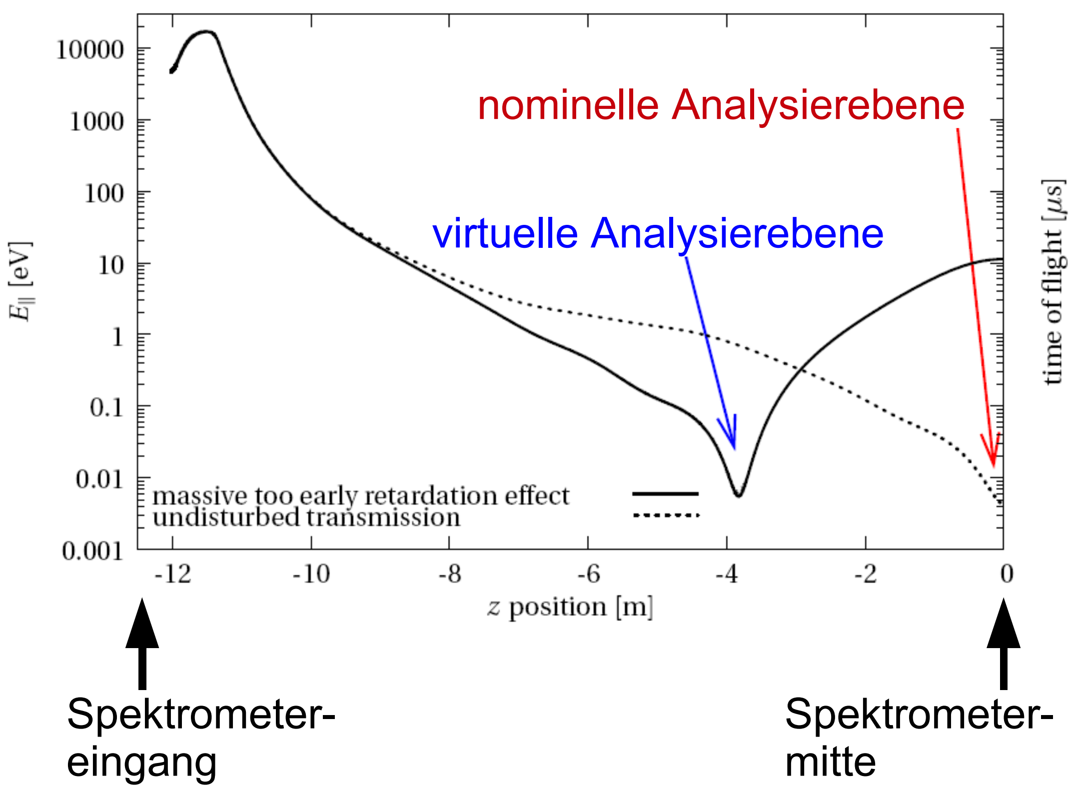


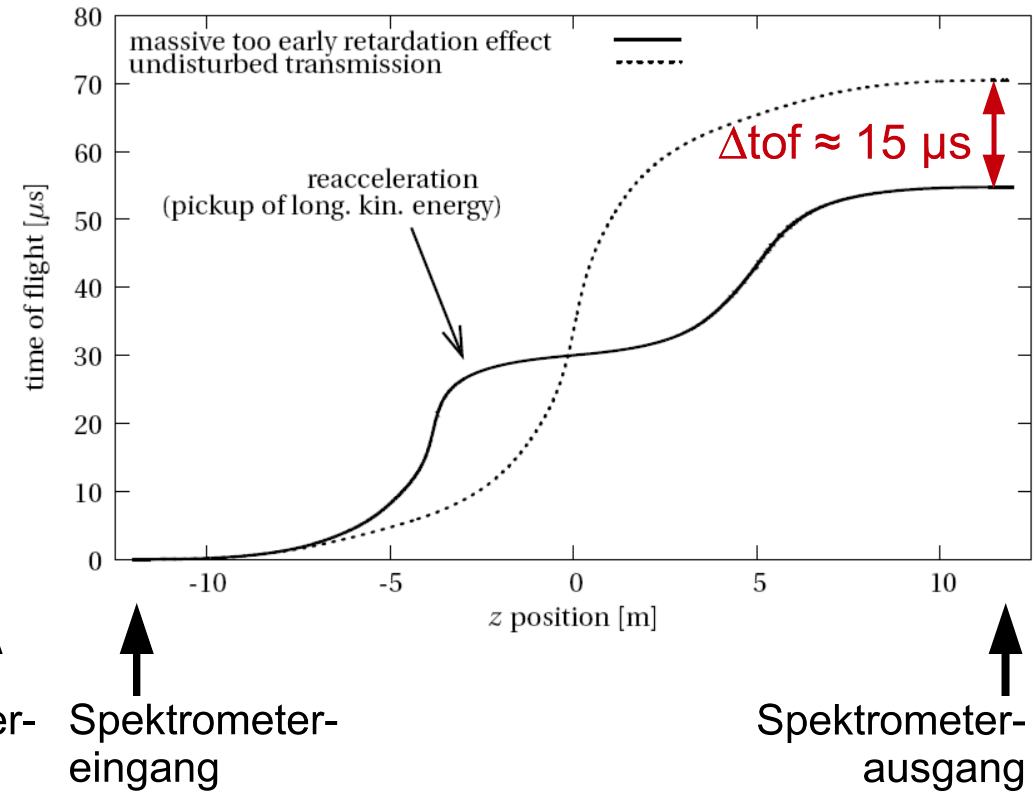
Flugzeitmodus „MAC-E-ToF“

- Idee (Mainzer ν-Massenexperiment: J. Bonn *et al.*, NIM A421 (1999) 256):
  Hochpass-Filter wird zu Bandpass-Filter $qU_{filter} \rightarrow E_{low}$, ToF $\rightarrow E_{up}$
  auch (niederenergetische) Details im Energiespektrum werden sichtbar

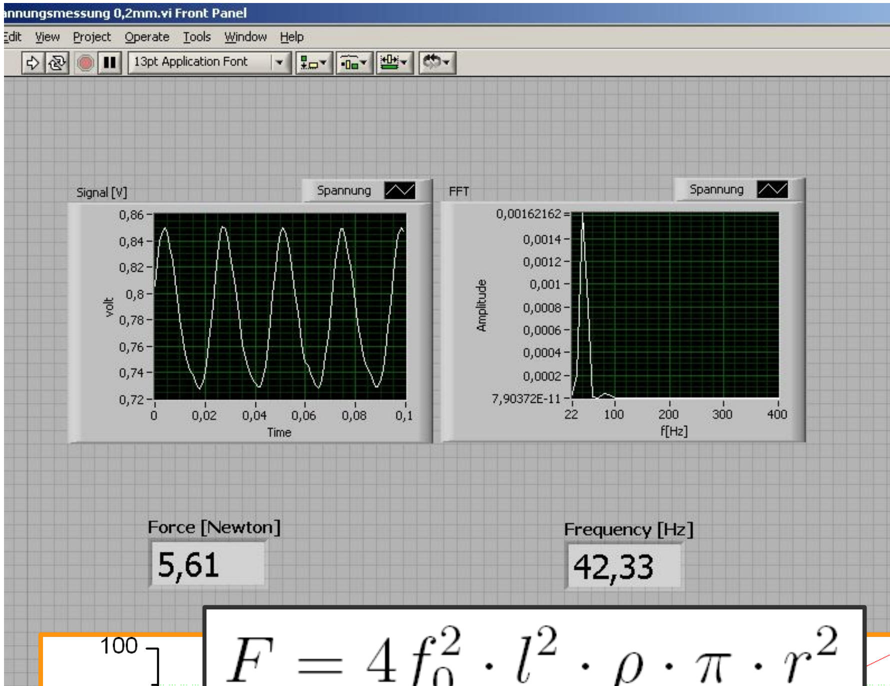
- Zusätzlich: Diagnose von Spektrometereigenschaften

  hier: Simulationen für das KATRIN-Hauptspektrometer





Wire tension measurement



$$F = 4 f_0^2 \cdot l^2 \cdot \rho \cdot \pi \cdot r^2$$