Direct neutrino mass measurement with KATRIN

The Future of Neutrino Mass Measurements
INT Workshop, Seattle, February 8-11, 2010

Christian Weinheimer for the KATRIN collaboration

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- The KArlsruhe TRItium Neutrino experiment KATRIN
- Background suppression
- Systematics and sensitivity
- Conclusion

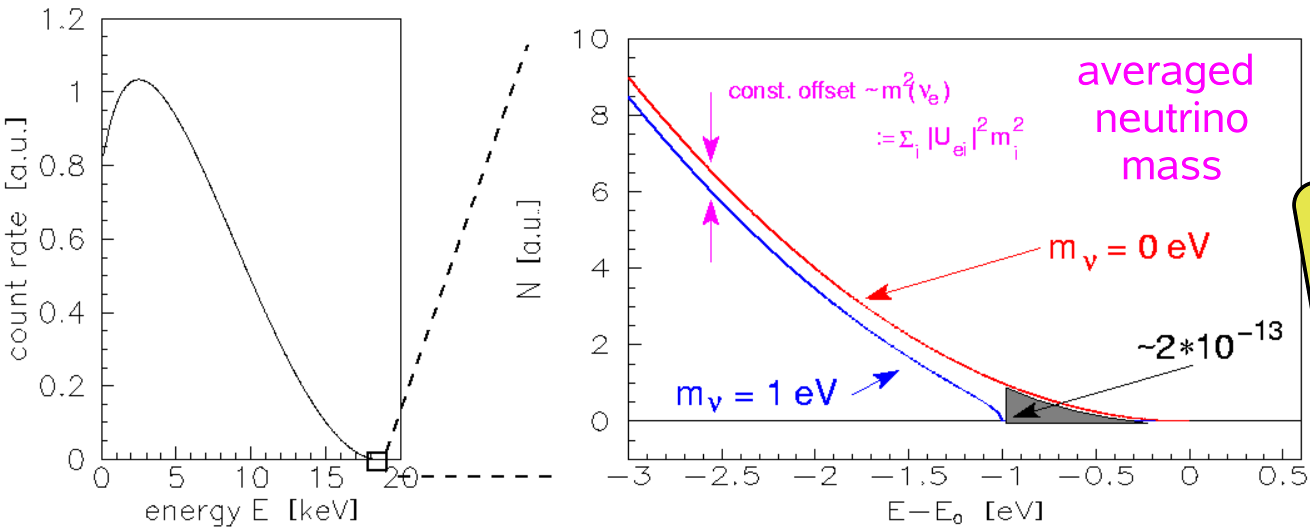
Direct determination of $m(\nu_e)$ from β decay

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

β electron energy spectrum:

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

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

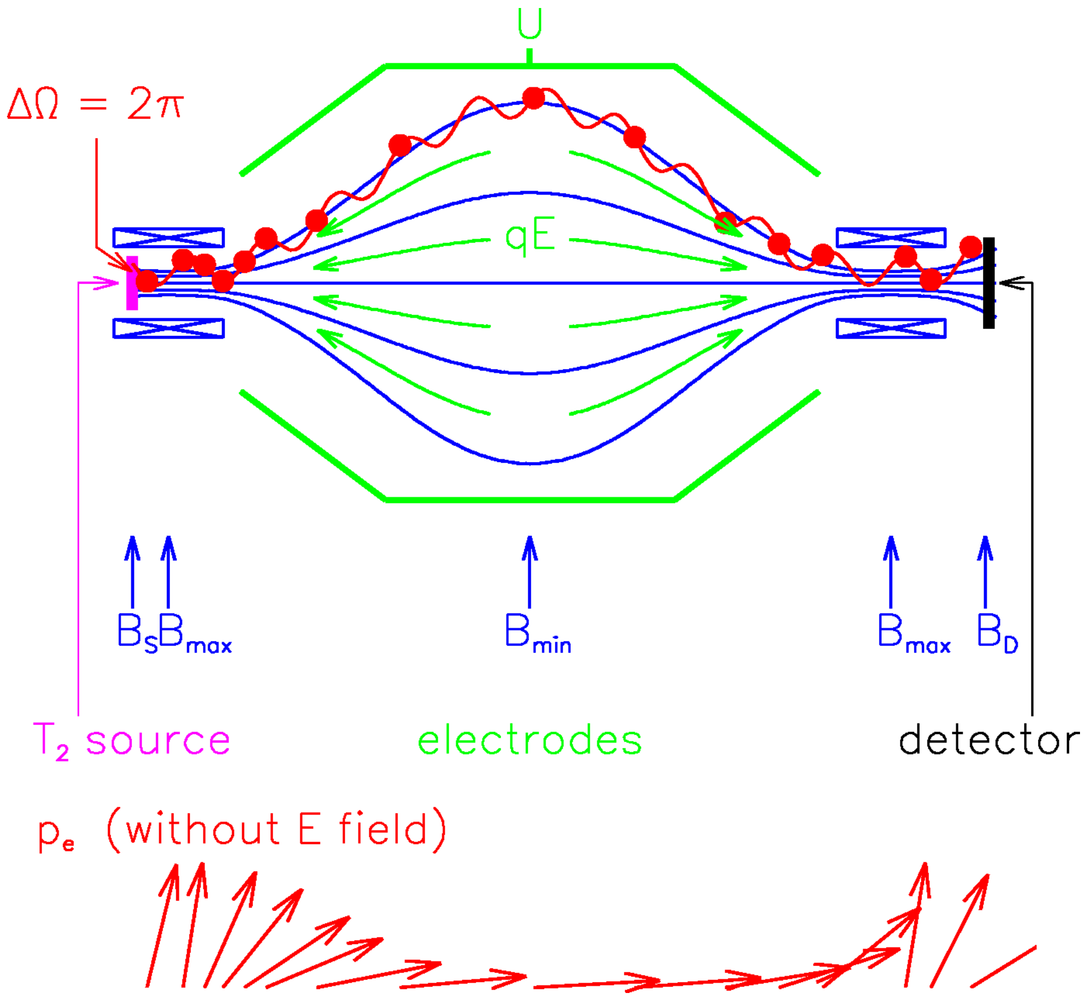


E.W. Otten & C. Weinheimer
Rep. Prog. Phys.
71 (2008) 086201

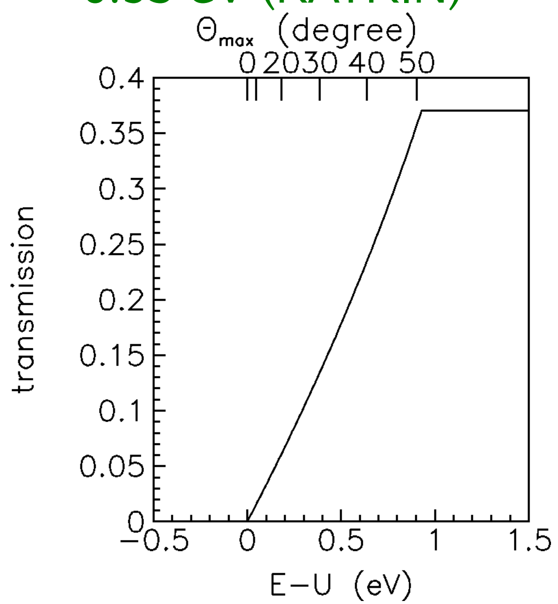
Need: **low endpoint energy** ⇒ **Tritium ^3H, (^{187}Re)**

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

Tritium experiments: source ≠ spectrometer
MAC-E-Filter



- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E_\perp/B = \text{const.}$
  $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)



$\Rightarrow$ sharp integrating transmission function without tails $\rightarrow$

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

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The Karlsruhe Tritium Neutrino experiment KATRIN

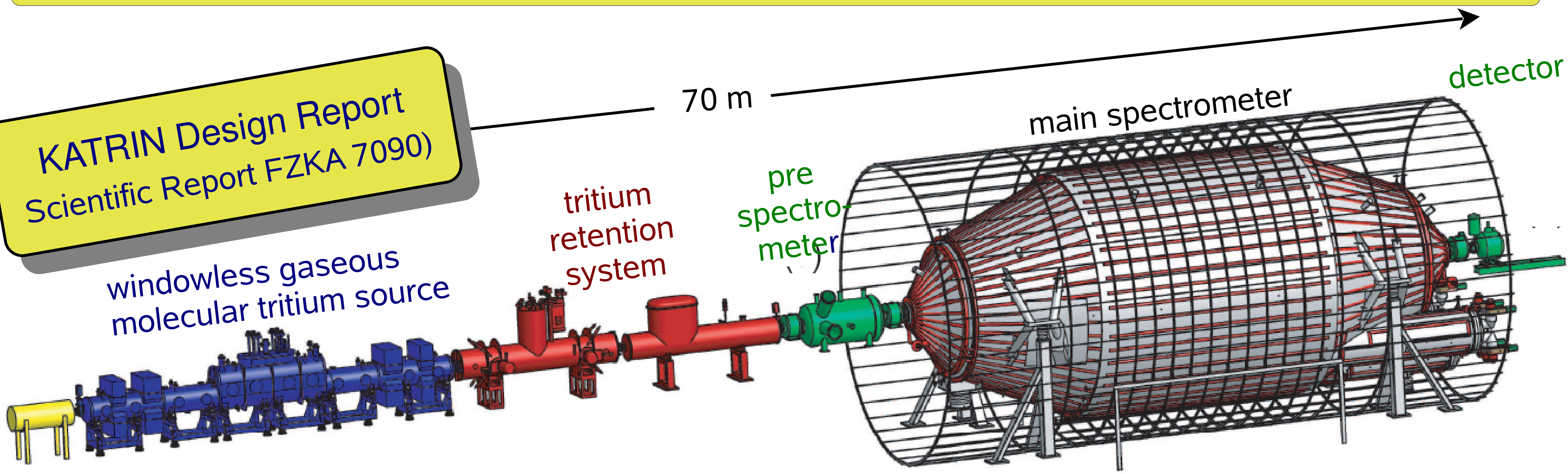
is being set up at the Forschungszentrum Karlsruhe

Aim: $m(\nu_e)$ sensitivity of 0.2 eV (currently 2 eV)

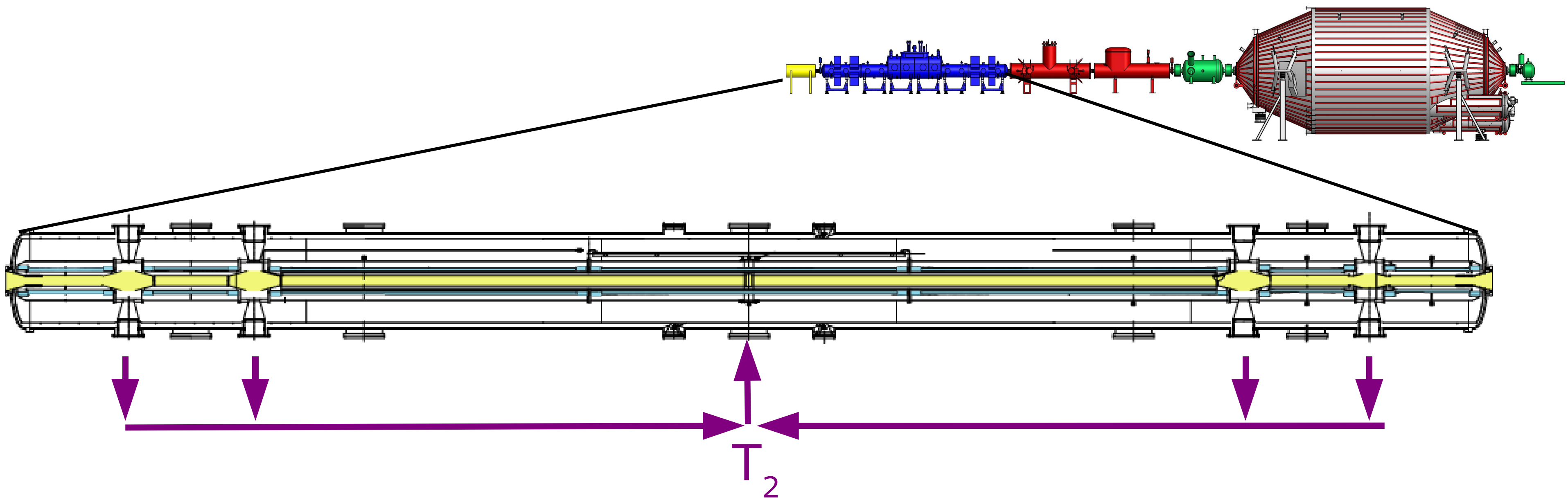
- **very high energy resolution ($\Delta E \leq$ 1eV) $\Rightarrow$ source $\neq$ spectrometer concept**
- **source opaque $\Rightarrow$ $dN/dt \sim A_{source}$**
- **magnetic flux conservation (Liouville) $\Rightarrow$ scaling law:**

$$A_{spectrometer} / A_{source} = B_{source} / B_{spectrometer} = E / \Delta E = 20000 / 1$$

KATRIN Design Report
Scientific Report FZKA 7090)



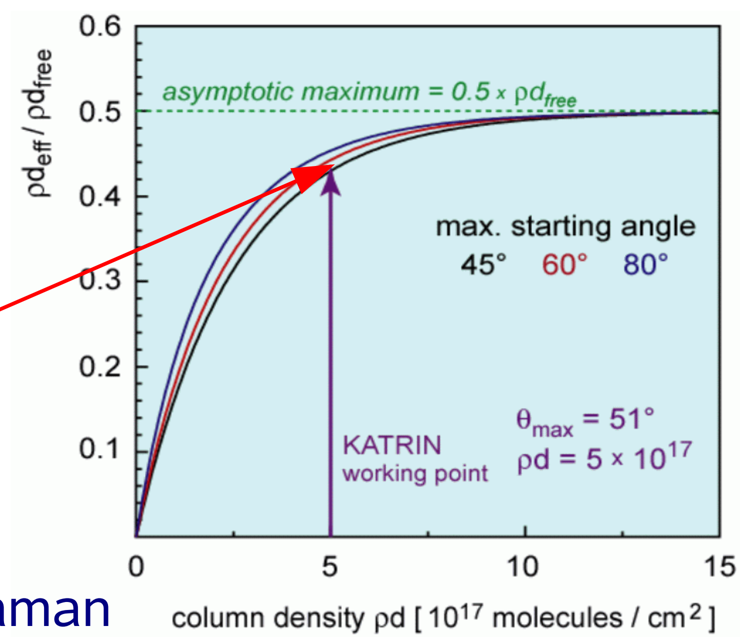
Molecular Windowless Gaseous Tritium Source WGTS



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
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics



check column density by e-gun, T_2 purity by laser Raman

Molecular Windowless Gaseous Tritium Source WGTS

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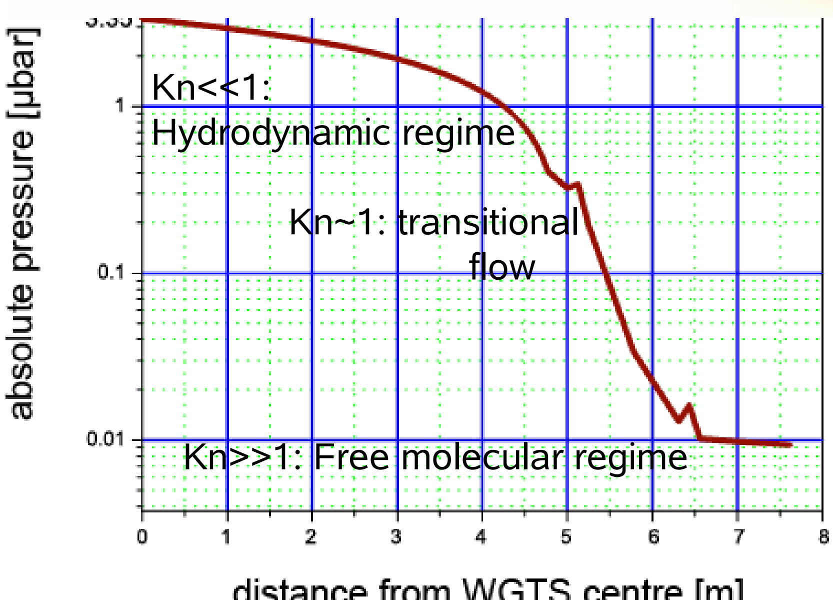
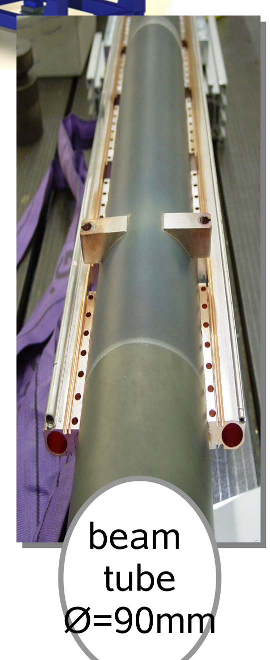
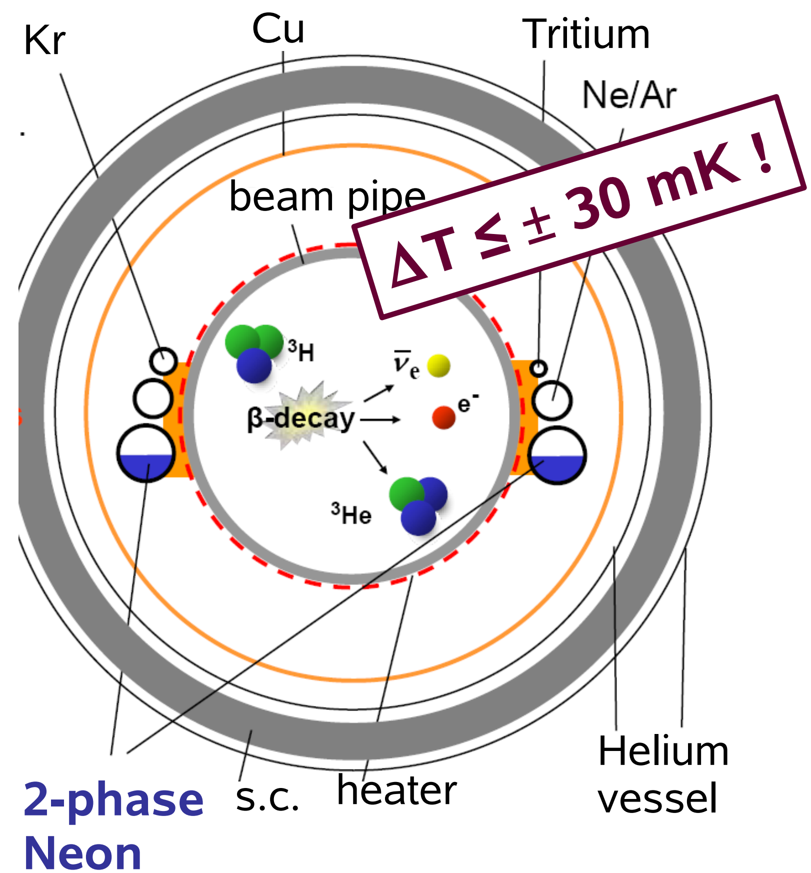
Conceptional design

Neon cooling with
g temperature: 27–28 K
l (homogeneity): ± **0.1%**
(stability/hour): ± **0.1%**

S. Grohmann, Cryogenics 49, No. 8 (2009) 413







WGTS under construction

WGTS-demonatrator will arrive spring 2010

Tritium loops

Inner loop:

stable (±0.1%)

tritium

injection

Outer loop:

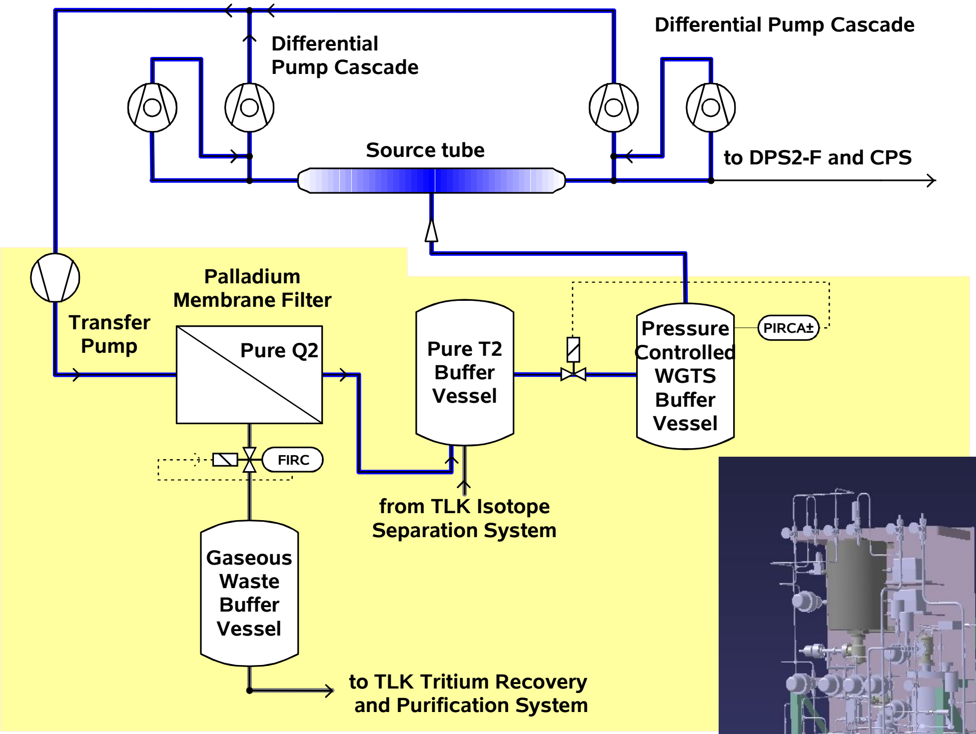
high (>95%)

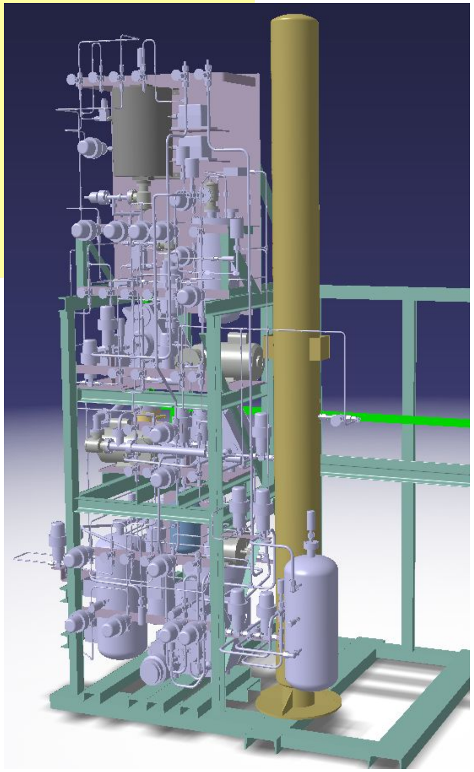
and

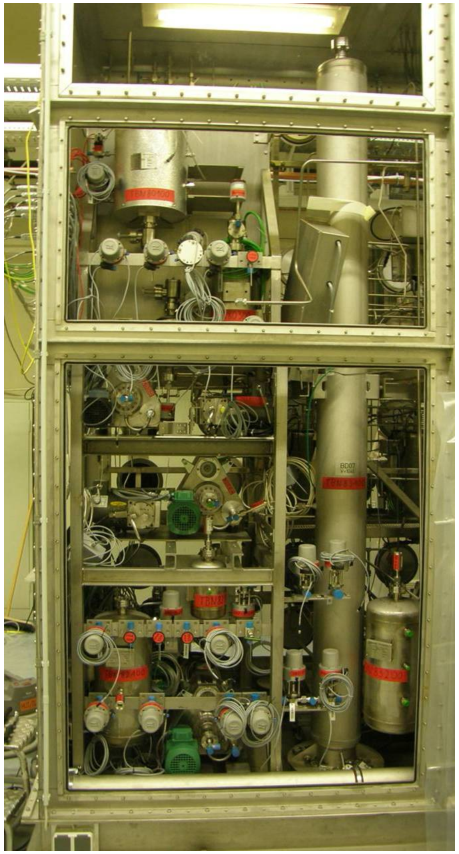
stable (±0.1%)

tritium

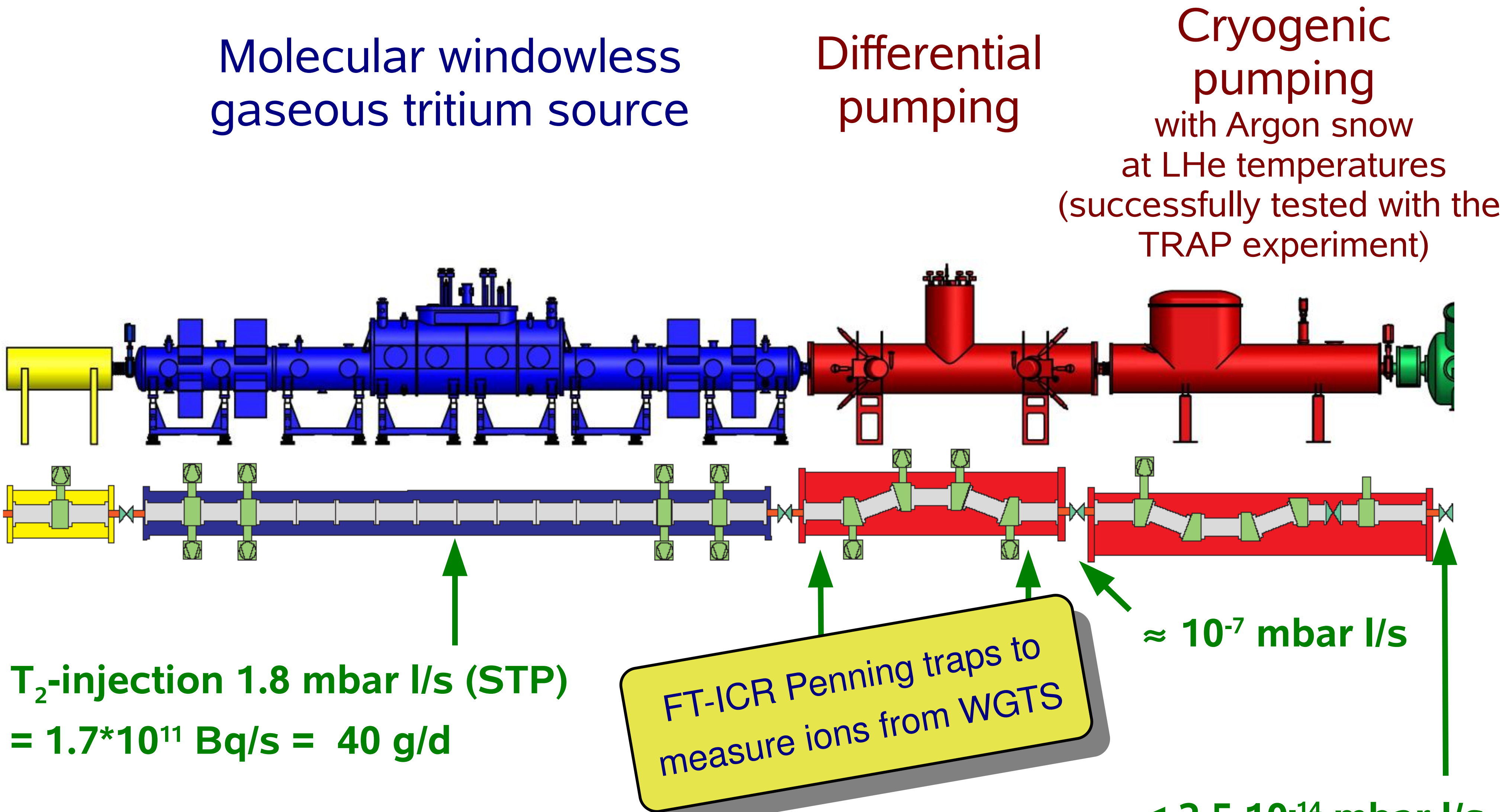
purity







Transport and differential & cryo pumping sections



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

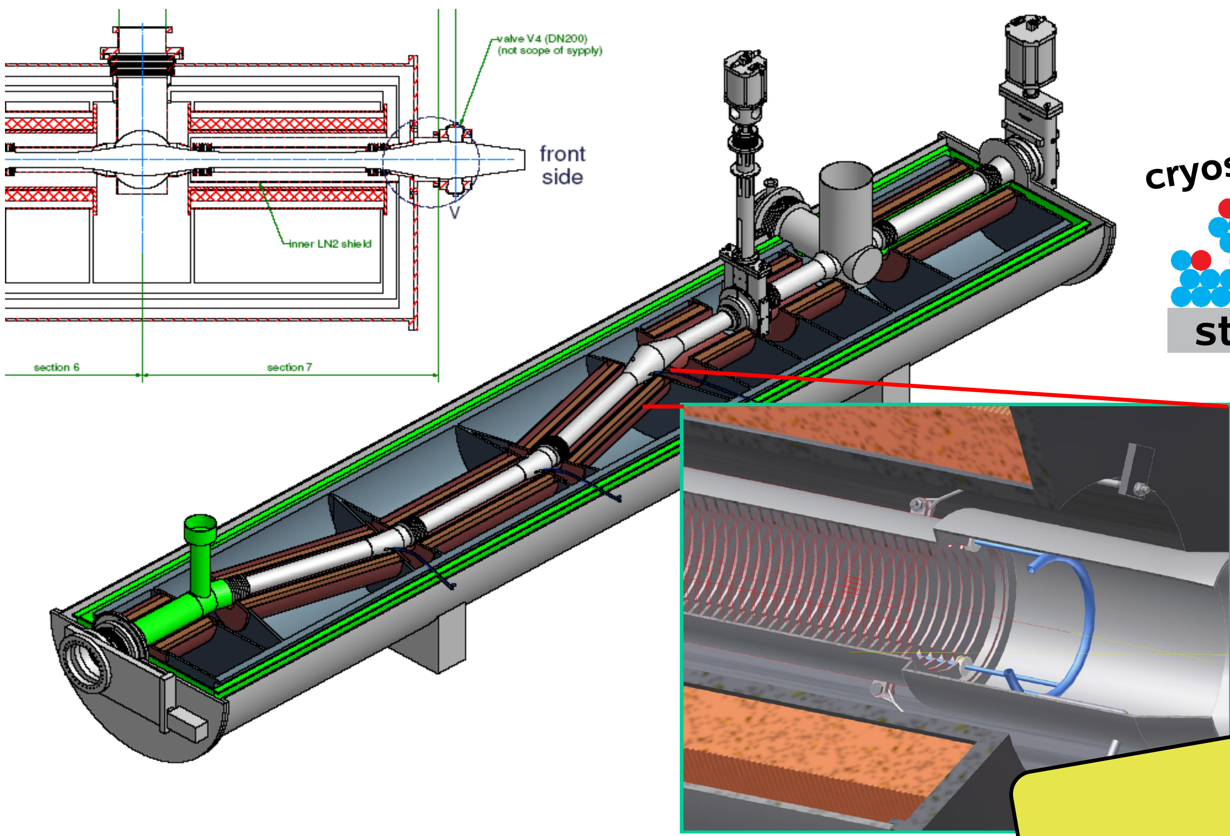
Arrival of DPS2-F at Karlsruhe: July 15, 2009

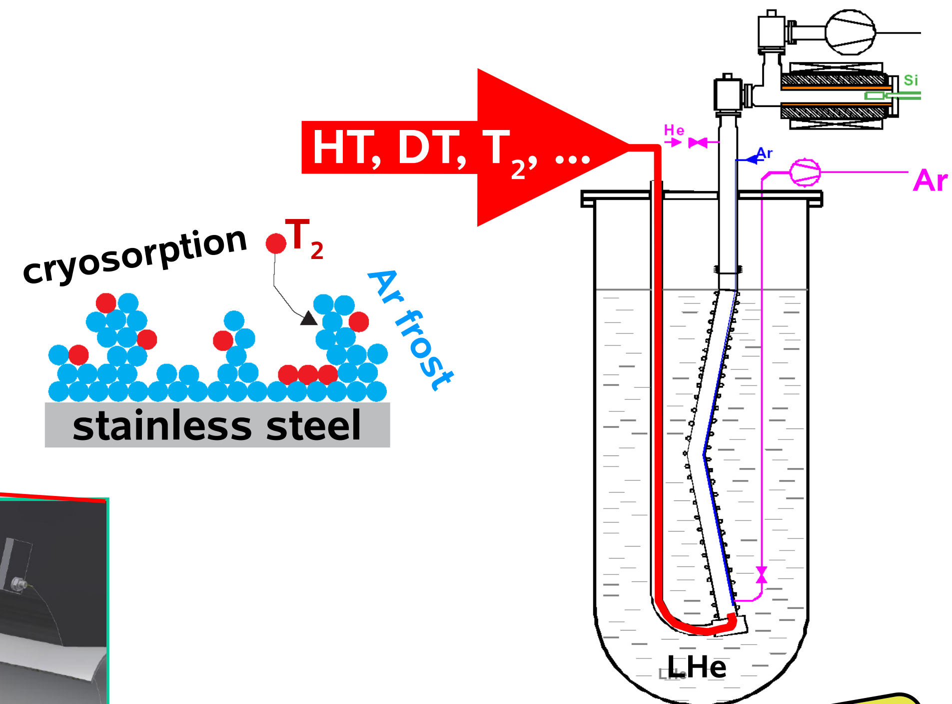
FT-ICR Penning traps:
M. Ubieto-Diaz et al.,
Int. J. Mass. Spectrom.
288 (2009) 1-5

Cryogenic pumping section and test of principle

TRAP: TRitium Argon frost Pump

CPS: cryogenic pumping section

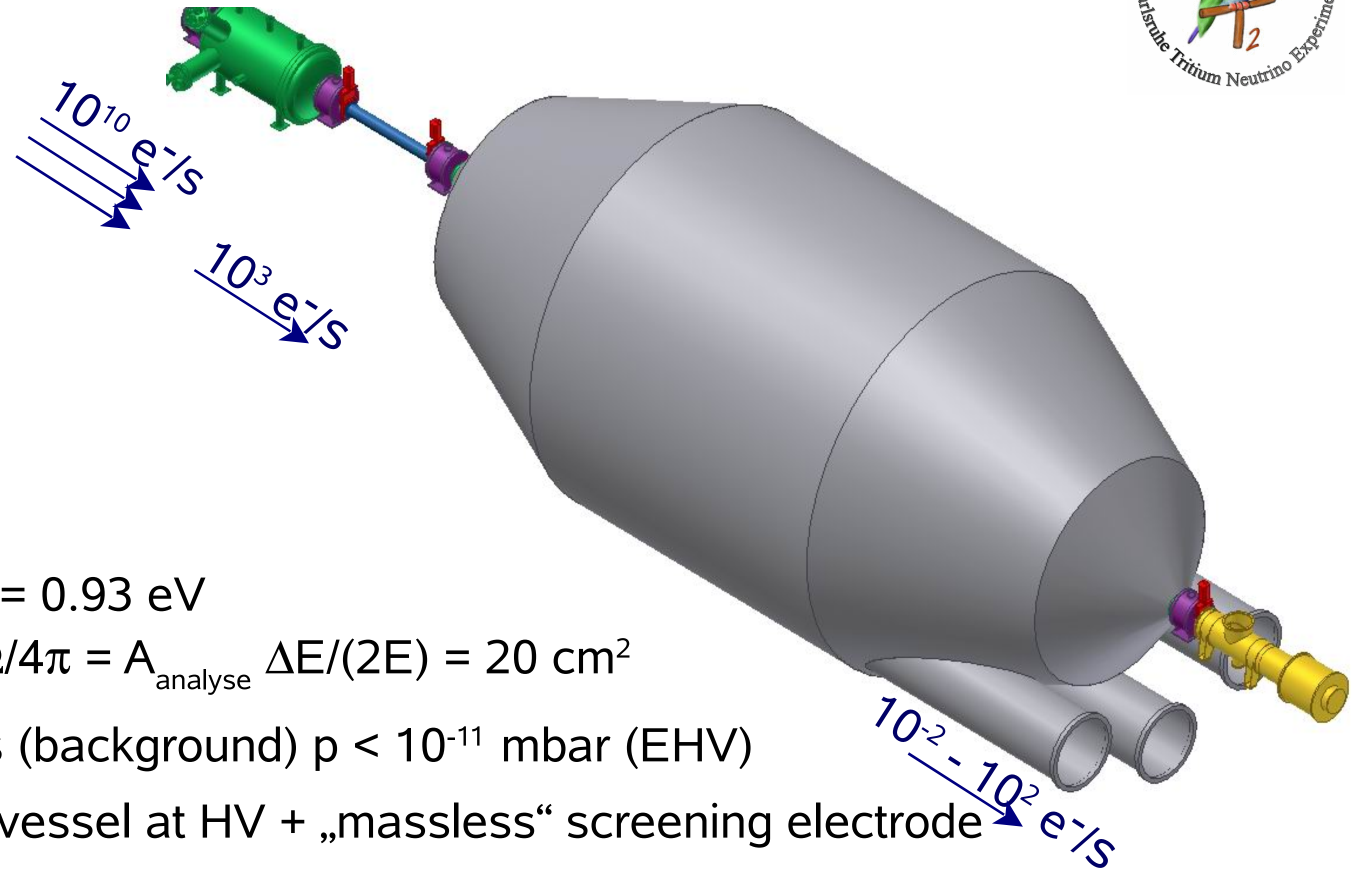




- cryosorption of T_2 by Ar frost
- magnetic guiding field B = 5.6 T
- specification finished
- estimated delivery 2010

O. Kazachenko et al., Nucl. Instr. Meth. A 587 (2008) 136
F. Eichelhardt et al., Fusion Science and Technology 54 (2008) 615

Pre and main spectrometer



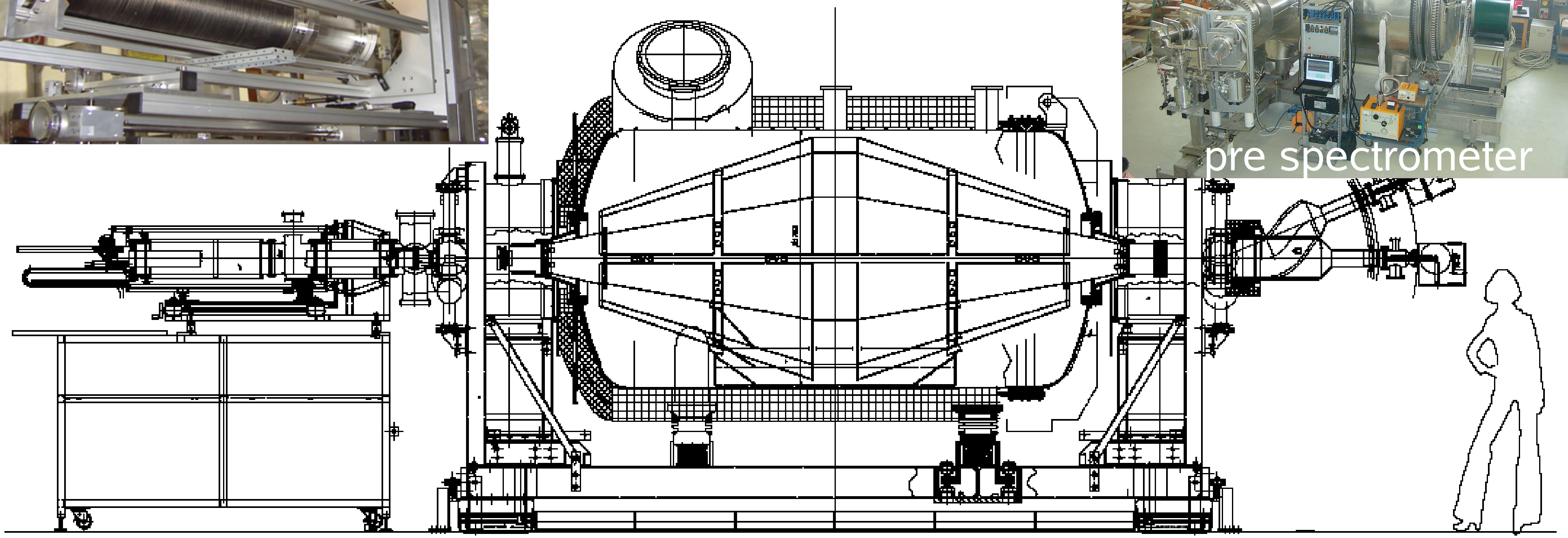
Main spectrometer:

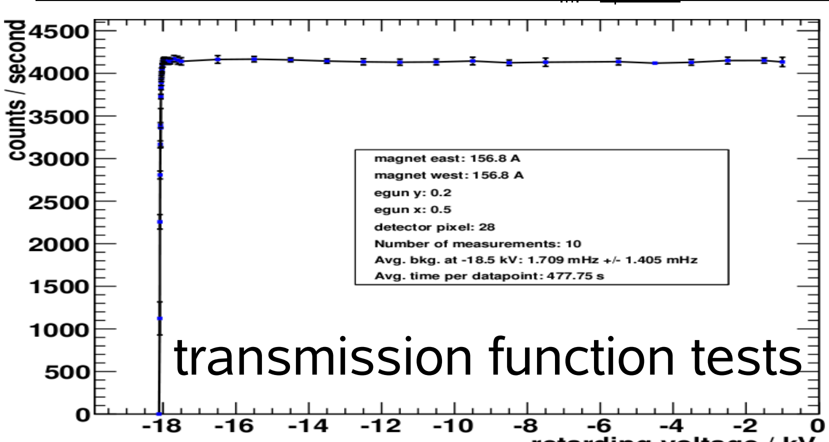
- ∅10m, length 24m
  ⇒ large energy resolution: $\Delta E = 0.93$ eV
  ⇒ high luminosity: $L = A_{Seff}\ \Delta\Omega/4\pi = A_{analyse}\ \Delta E/(2E) = 20\ cm^2$
- ultrahigh vacuum requirements (background) $p < 10^{-11}$ mbar (EHV)
- „simple“ construction: vacuum vessel at HV + „massless“ screening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

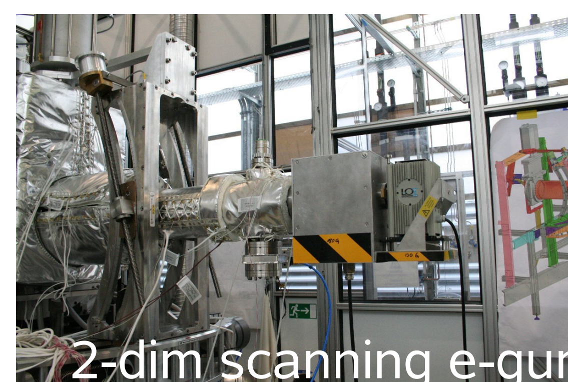
Pre spectrometer

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

Electromagnetic design tests at the pre spectrometer







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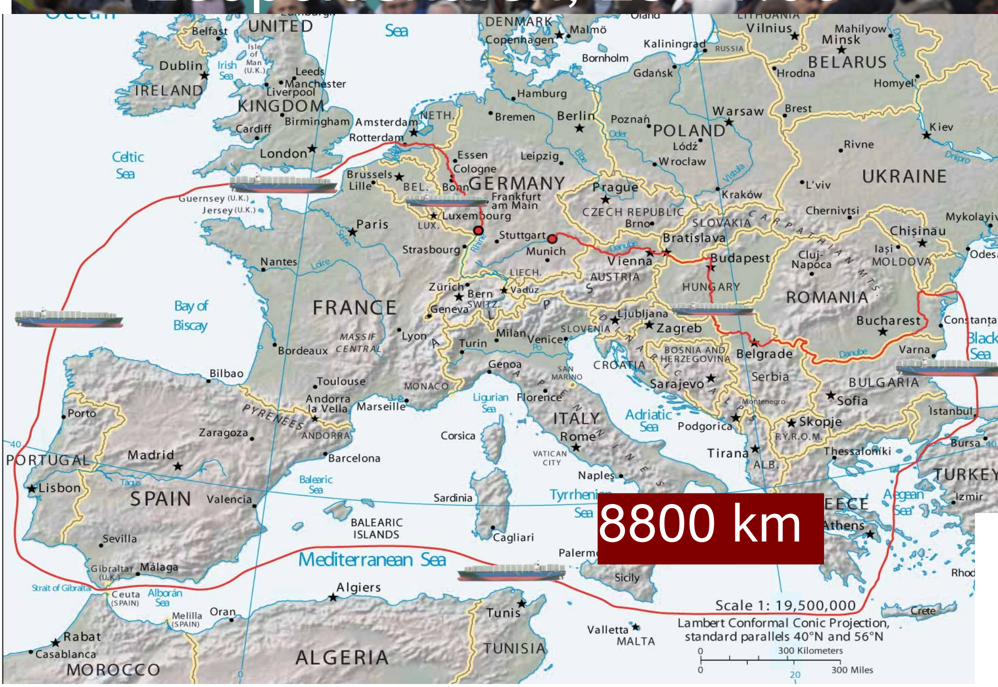
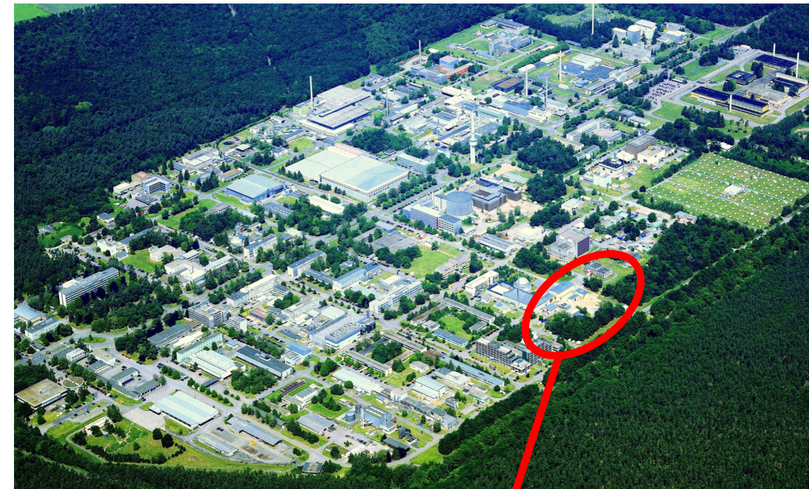
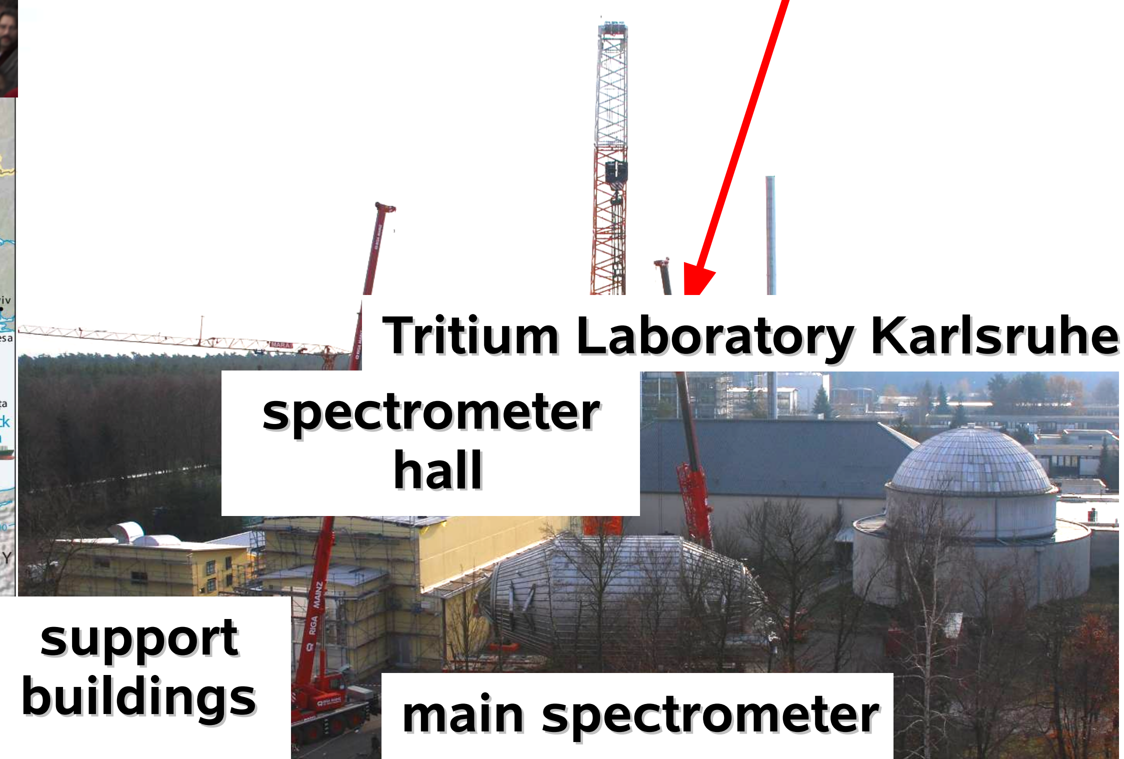
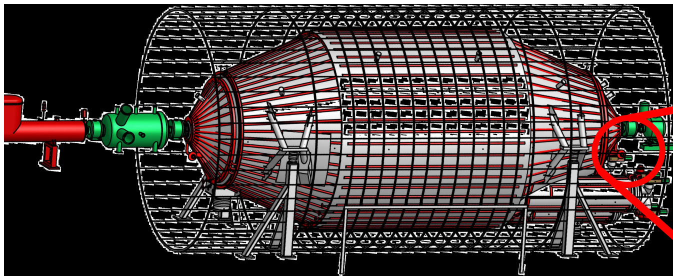
Main Spectrometer – Transport to Forschungszentrum Karlsruhe

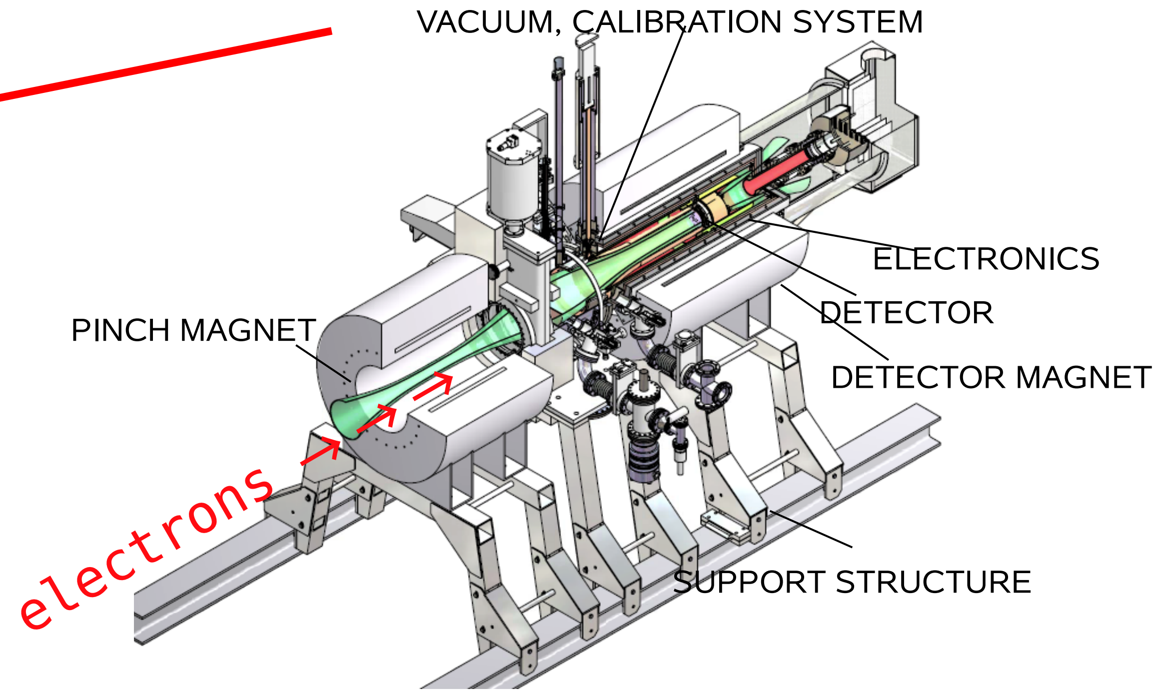


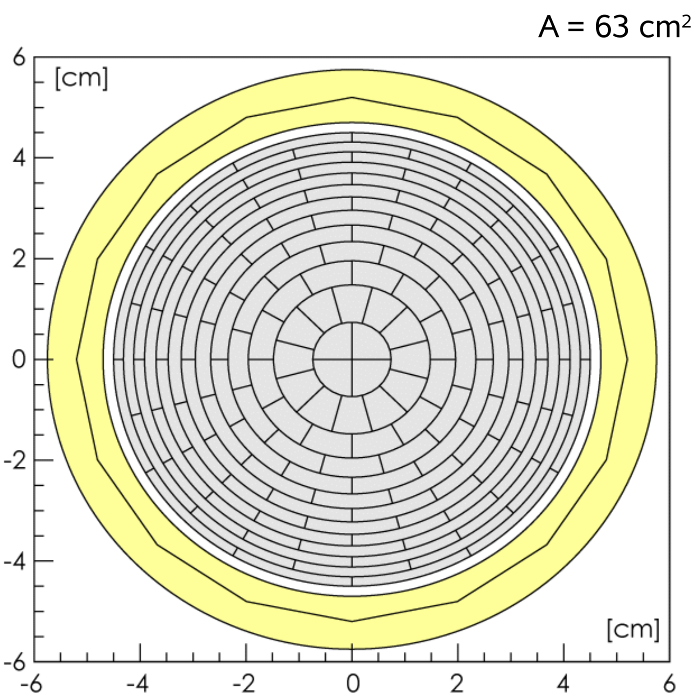




Detector Setup



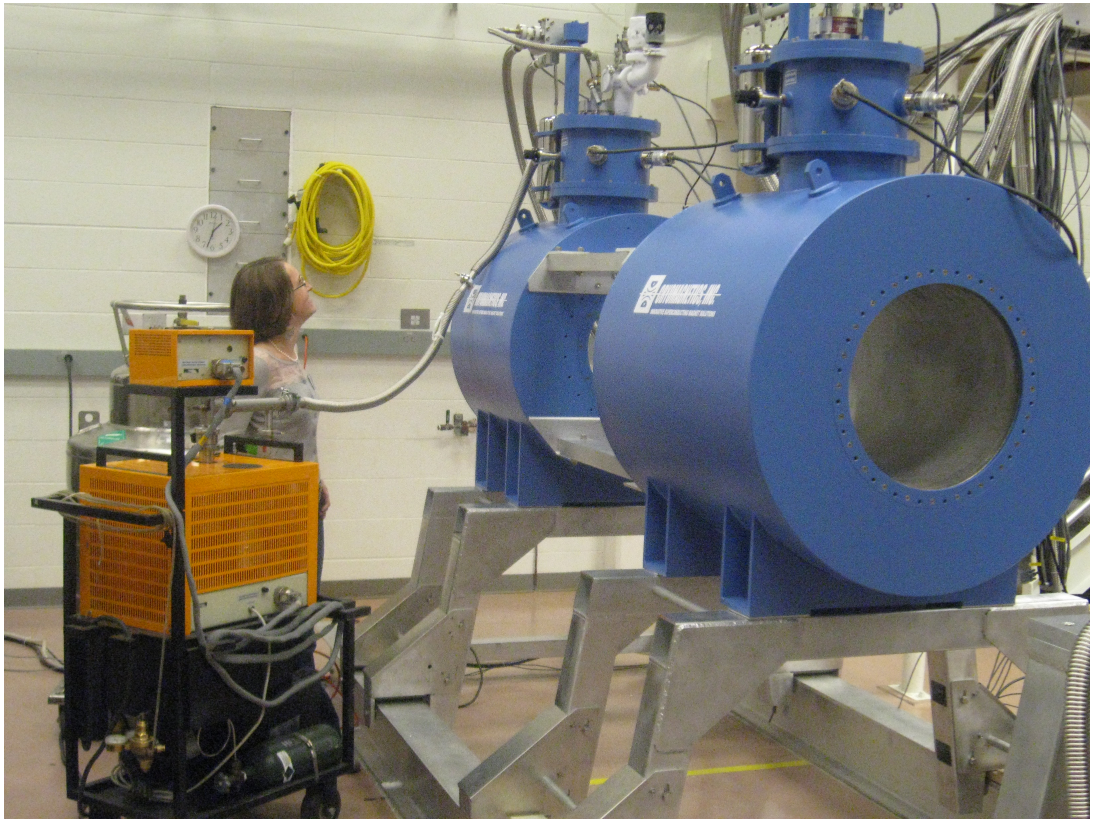




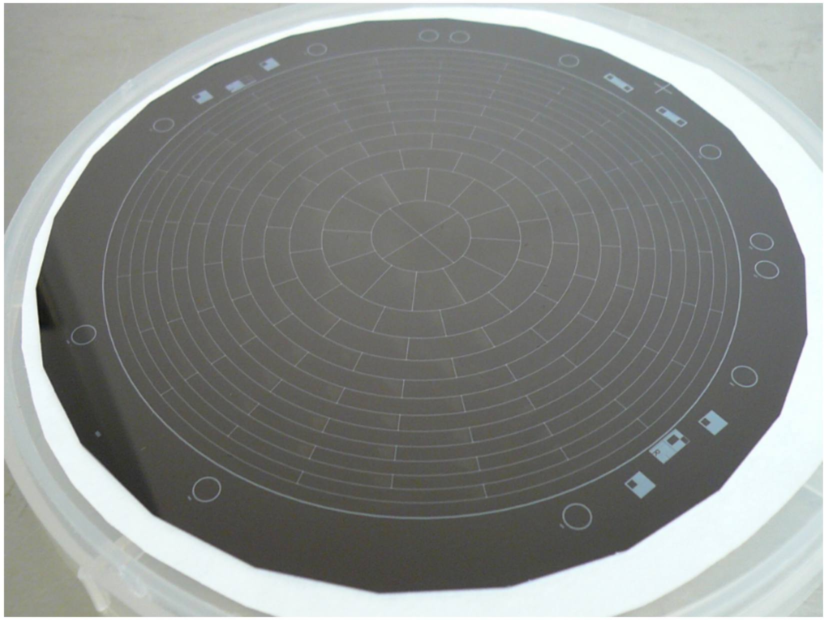
- Si-Pin diode
- Detection of transmitted β-decay electrons (mHz to kHz)
- **Low background for endpoint investigation**
- High energy resolution $\Delta E \approx 1$ keV
- 12 rings with 30° segmentation + 4 fold center = **148 pixels**
  - record azimuthal and radial profile of flux tube
    - minimize background
    - investigate systematic effects
    - compensate field inhomogeneity in analyzing plane

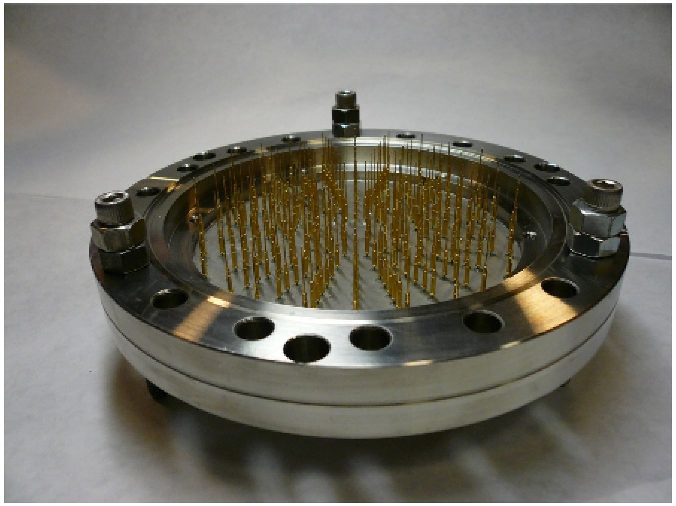
(magn. field of 3 - 6 T, active veto shield, post-accel. mode)

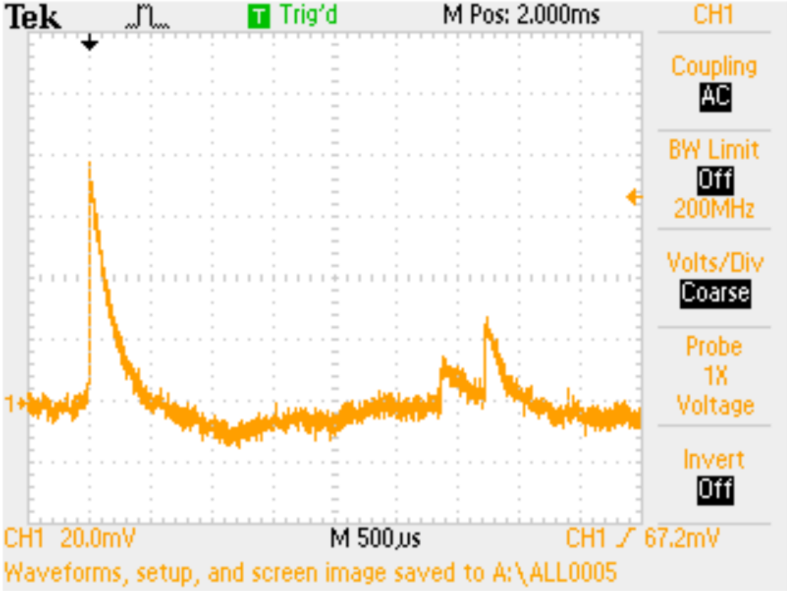
Detector magnets, post-acceleration electrode, passive shield



Detector and cabling





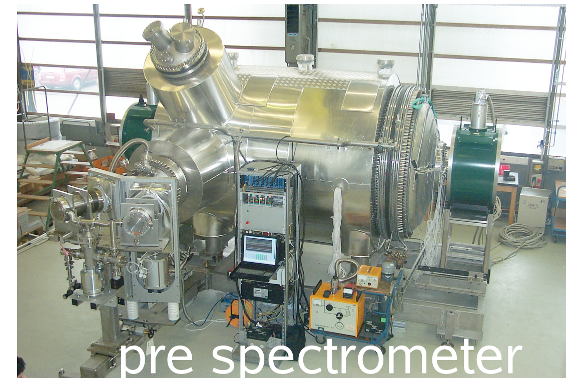


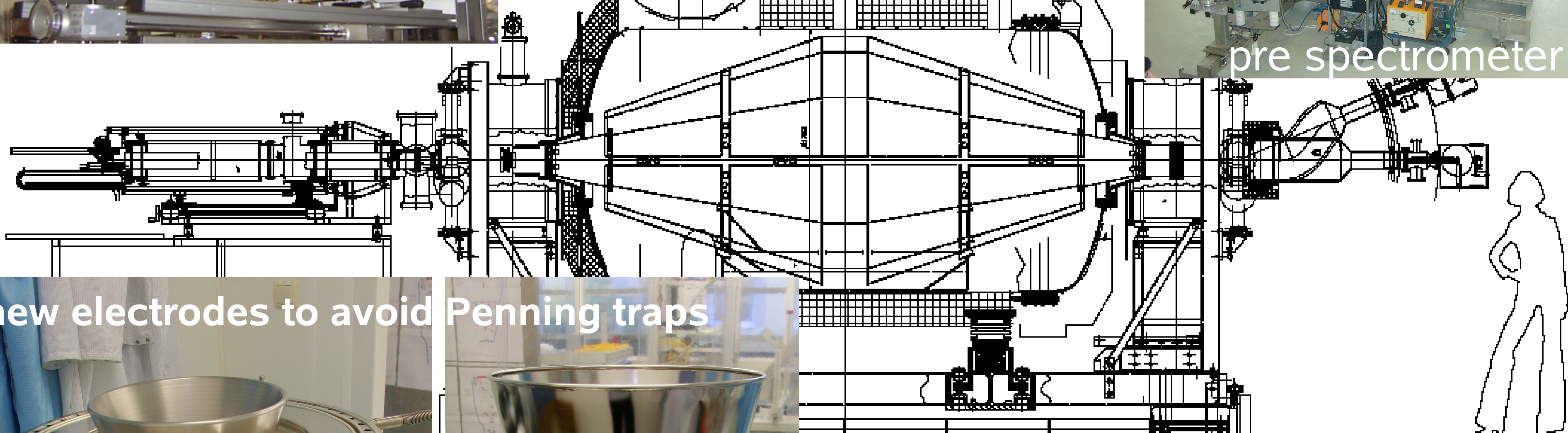
Background

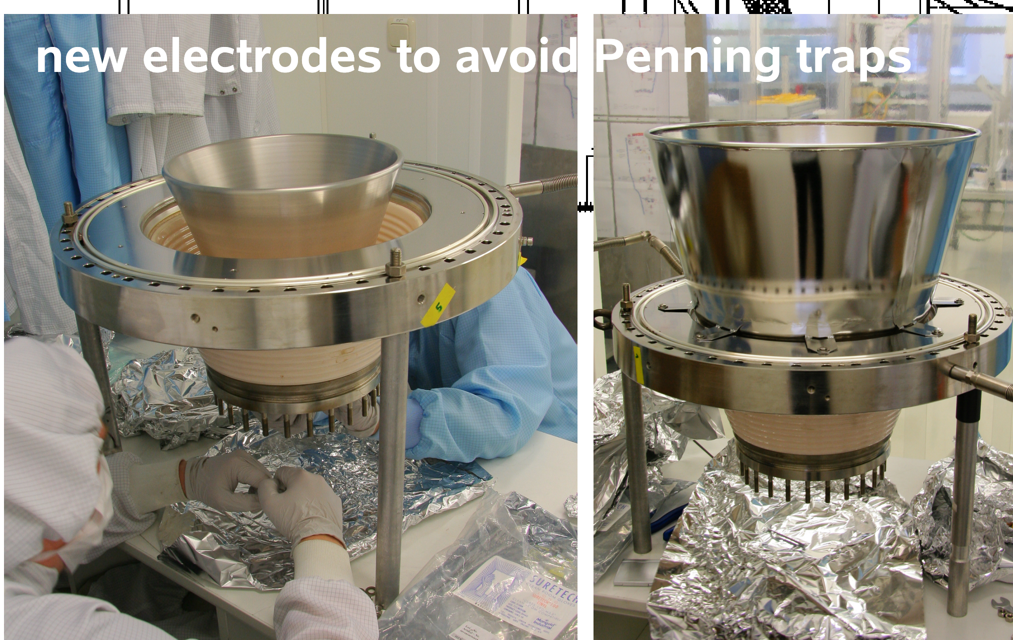
To reach KATRIN's design sensitivity,
the background has to be as low as 0.01 s^{-1}

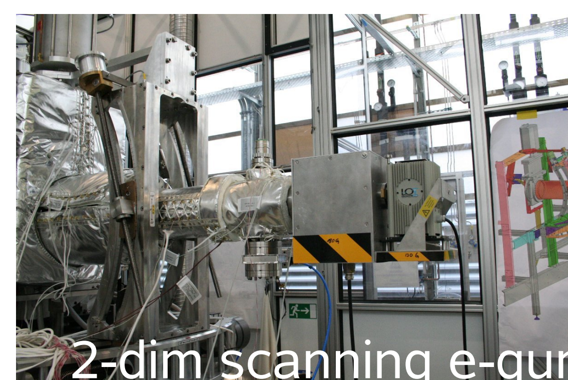
detector:	passive & active shield, post-acceleration
pre spectrometer:	wire electrode system avoiding small Penning traps
main spectrometer:	2-layer wire electrode system vacuum 10^{-11} mbar avoiding small Penning traps

Electromagnetic design tests at the pre spectrometer









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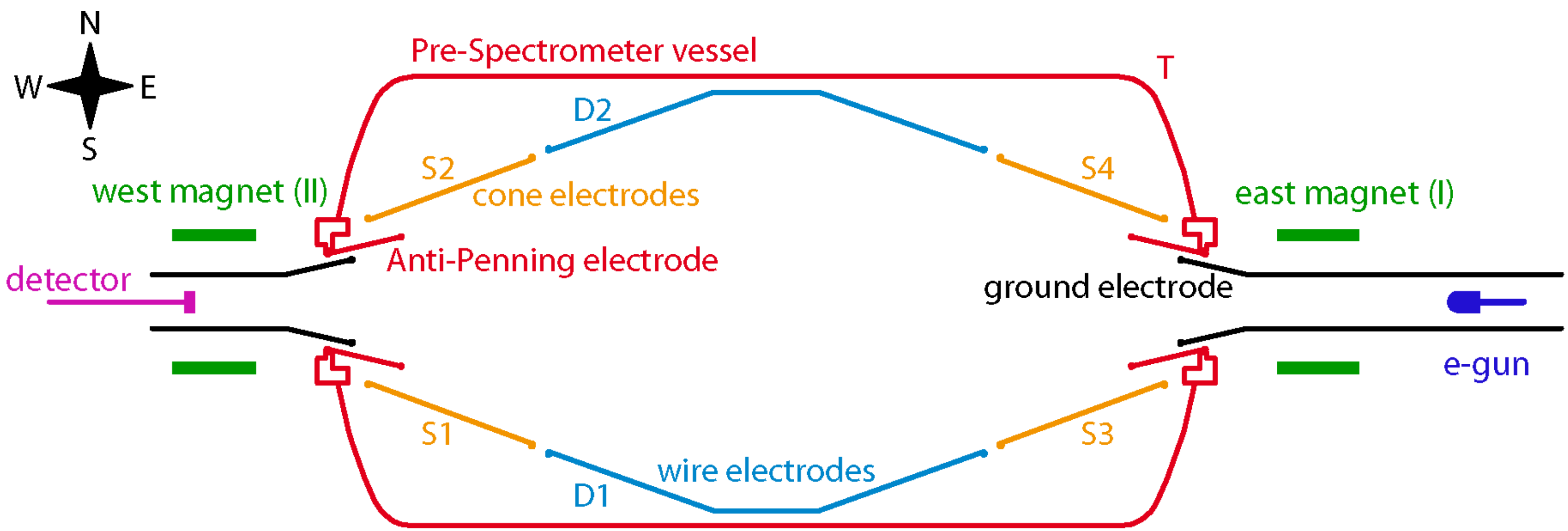
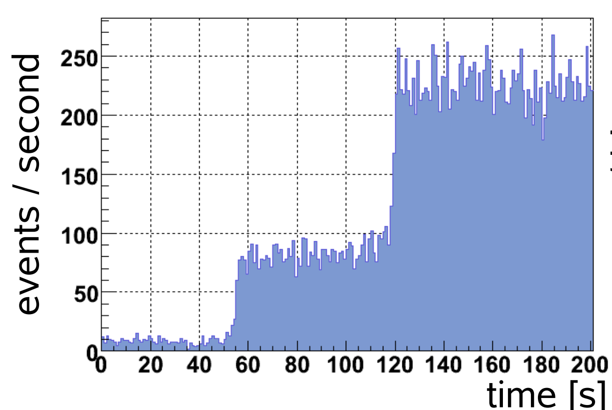
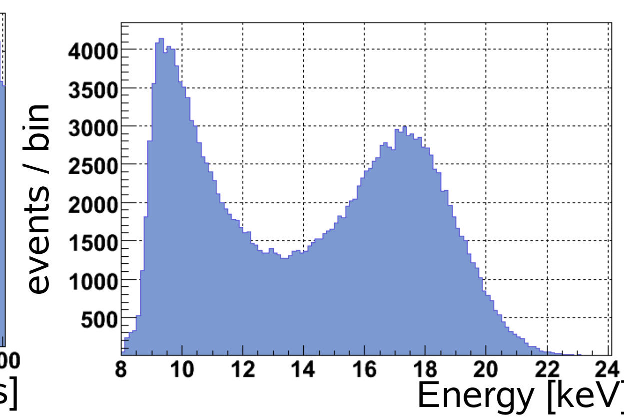
Pre spectrometer background studies I



Background at high B-fields (B_{max} > 2T) (up to sommer 2009)

- strong dependence on B (threshold)
- delayed ignition
- background strongly correlated with p
- strong dependence on voltage

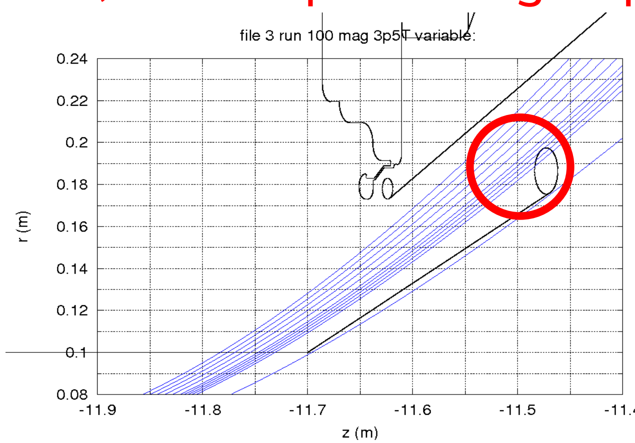


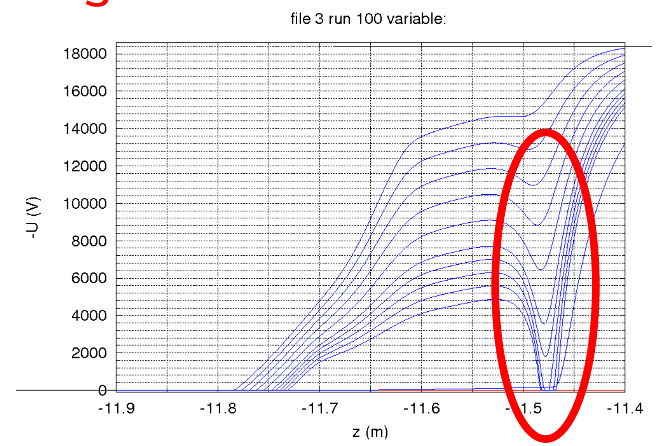


⇒ background caused by trapped particles

Pre spectrometer background studies II

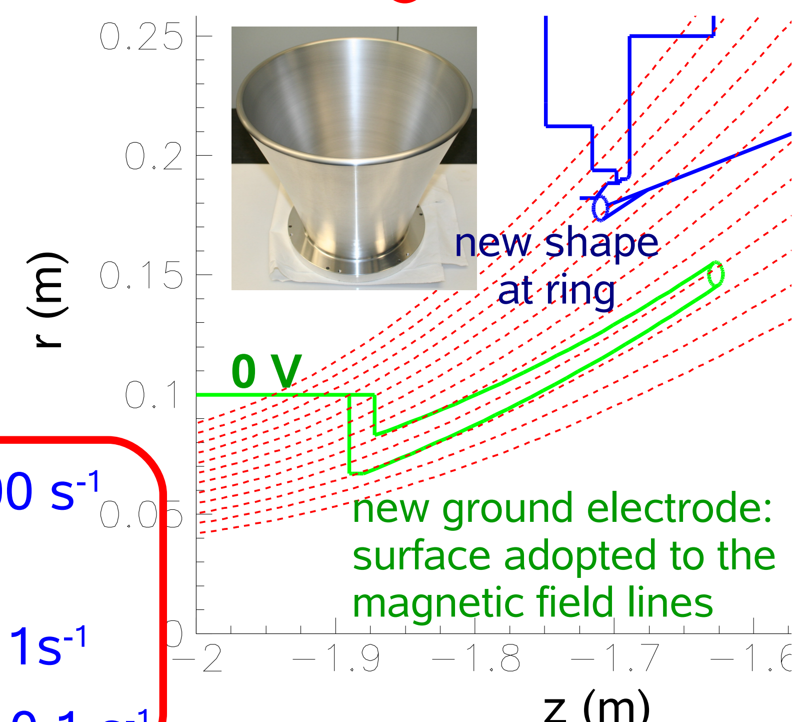
Problem: very small, but deep Penning traps near geometrical corners





Solution: - very precise and very detailed electromagnetic calculations (special codes developed by KATRIN)

- avoid Penning trap by optimally shaped electrodes



Result: Background reduction by 10^4:

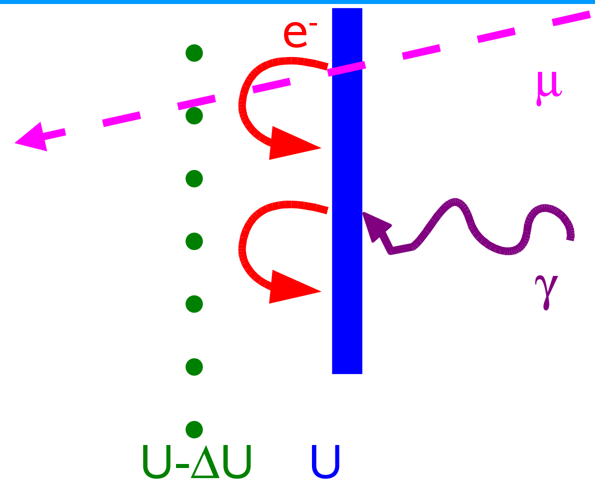
- with small Penning traps: bg ≈ 1000 s^{-1}
- optimally shaped electrodes with residual shallow Penning trap: bg ≈ 1 s^{-1}
- no residual Penning trap: bg ≈ 0.1 s^{-1}

Background reduction: shielding by „massless“ wire electrode

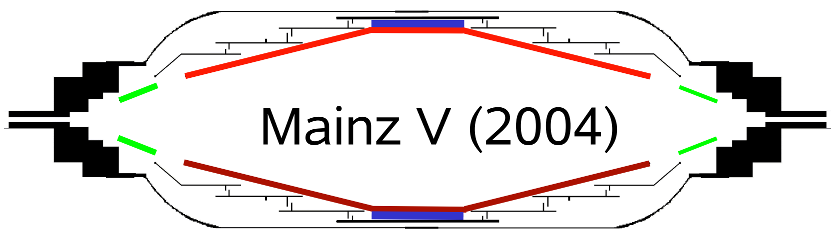
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

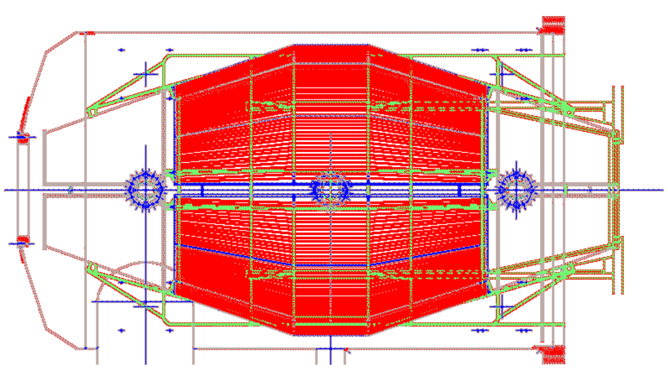
wire electrode on slightly more negative potential



First realisation:
Mainz III

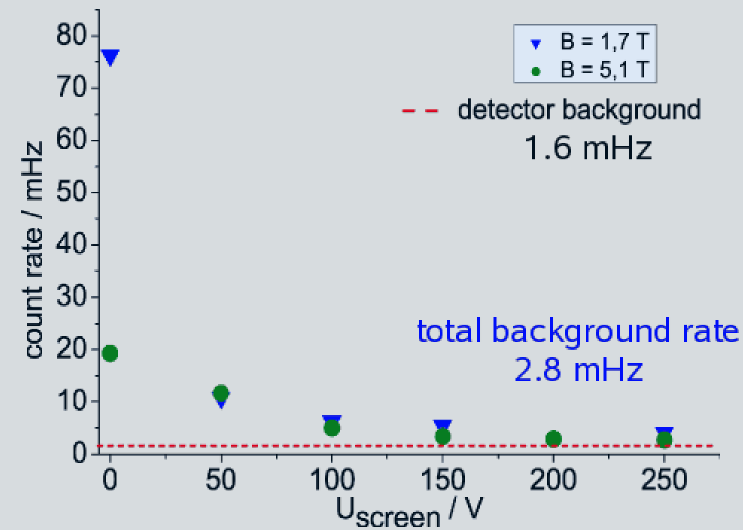


New record !
April 04



KATRIN pre spectrometer

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



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

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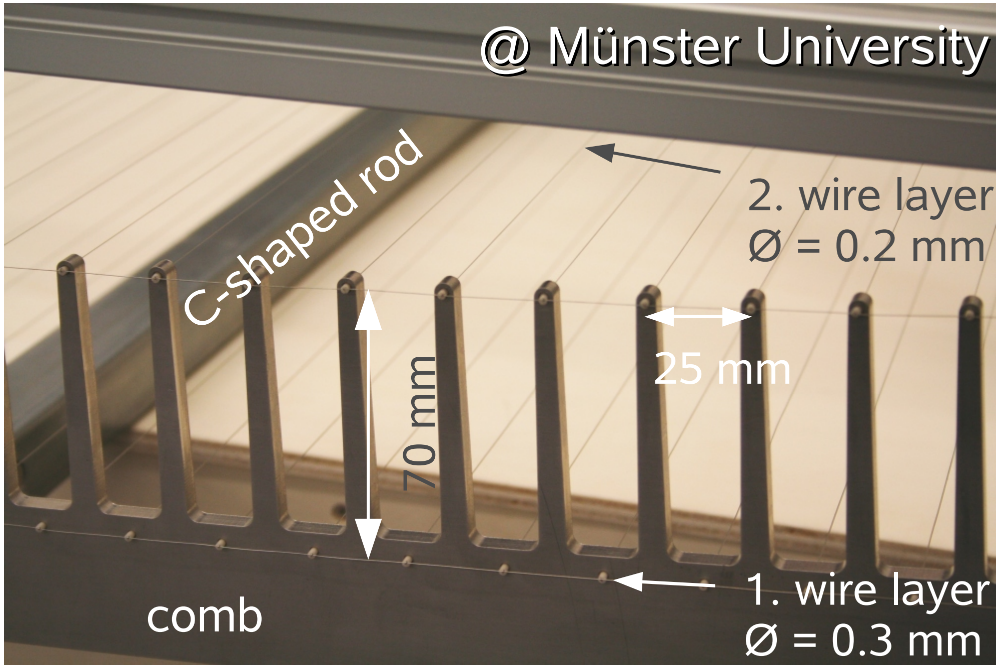
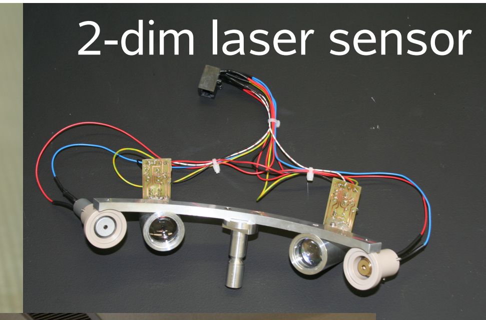
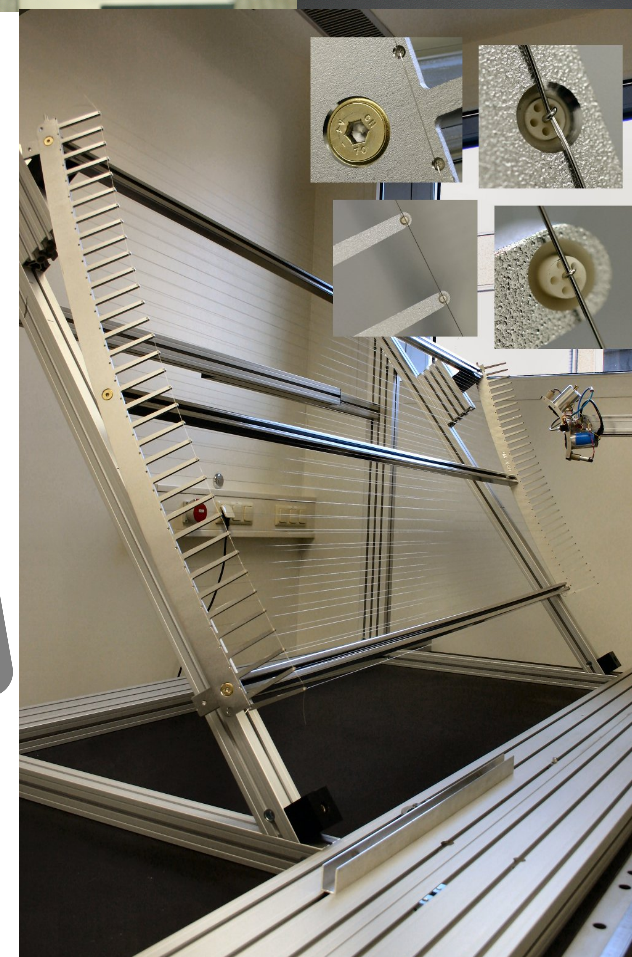
Double-wire layer electrode (690m²) production and quality assurance

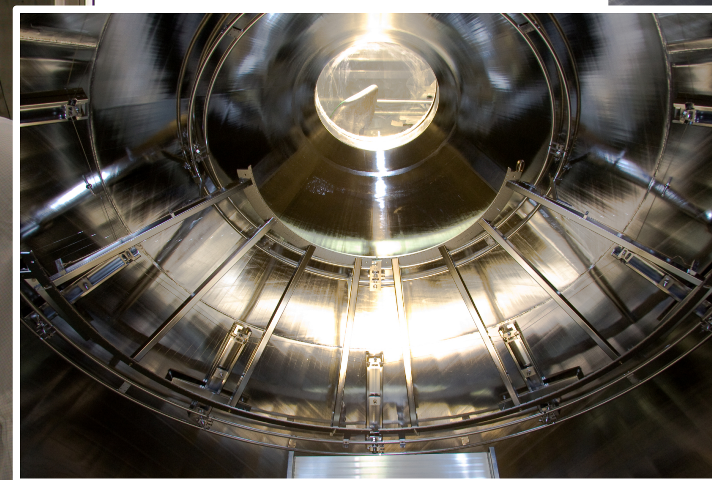


Electrode production finished in Oct. 2009





Electrode module installation at the main spectrometer


Systematic uncertainties

A) As smaller m(ν) as smaller the region of interest below endpoint E_0

B) Any unaccounted 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
   - **dedicated e-gun measurements**, unfolding of 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: ϕ < 20mV)
   - 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 $\Delta m_\nu^2 \leq 0.007\ \mathrm{eV}^2$ each

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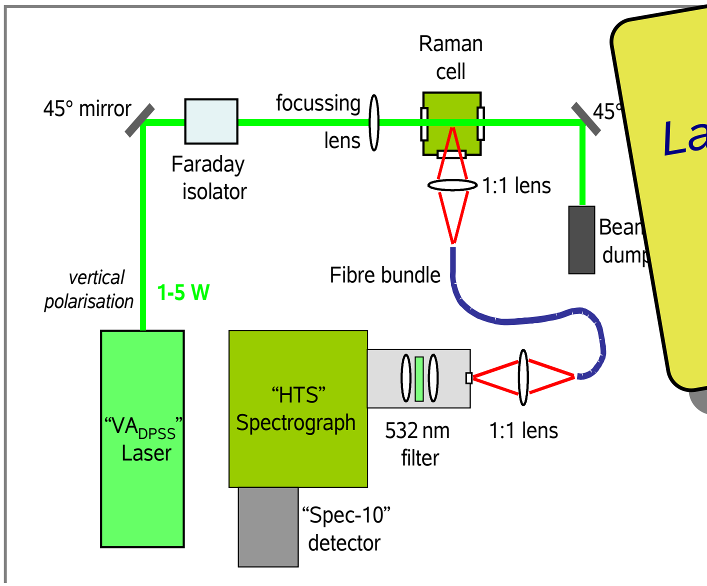
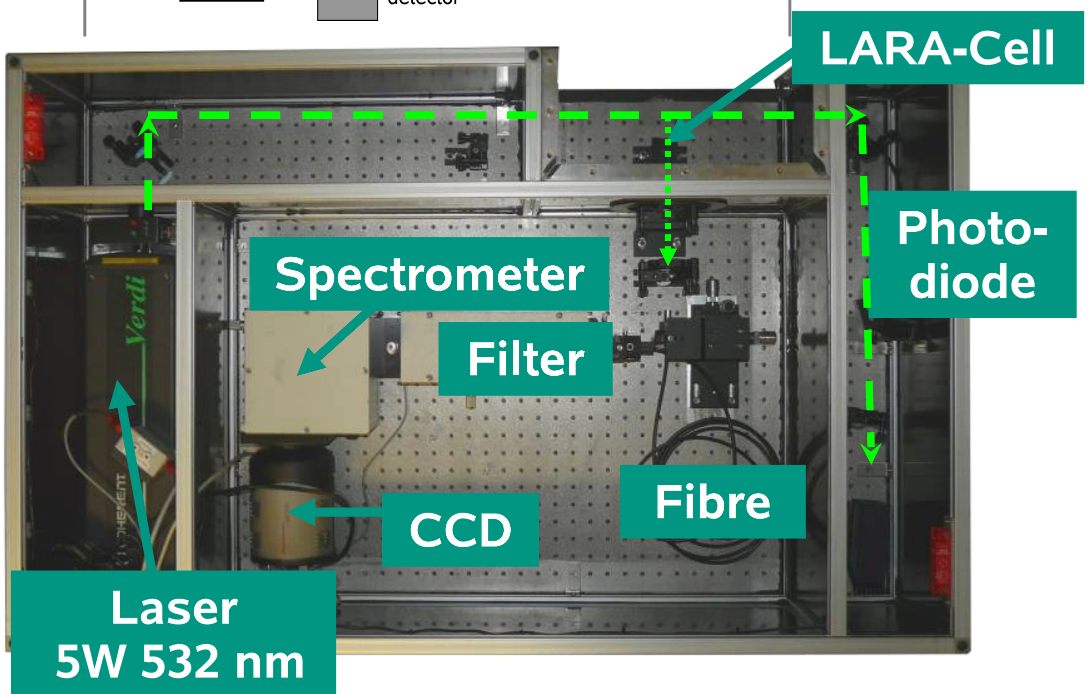
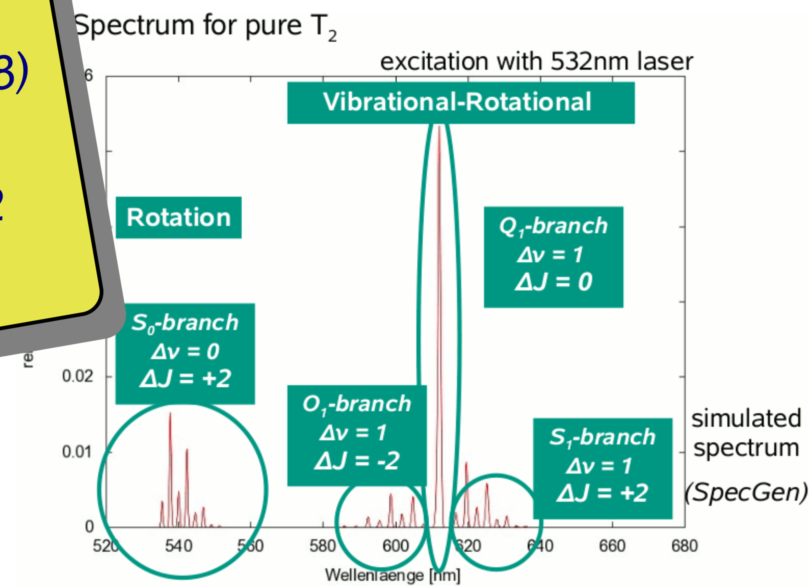
Measurement of tritium concentration by laser Raman spectroscopy

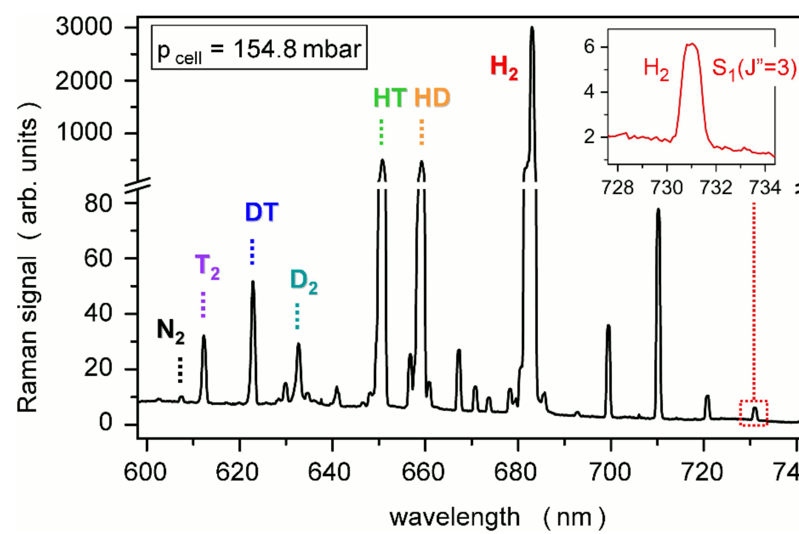
R.J. Lewis et al.,
Las. Phys. Lett.1-10 (2008)
M.Sturm et al,
Las. Phys. 20 (2010) 2
(to be published)





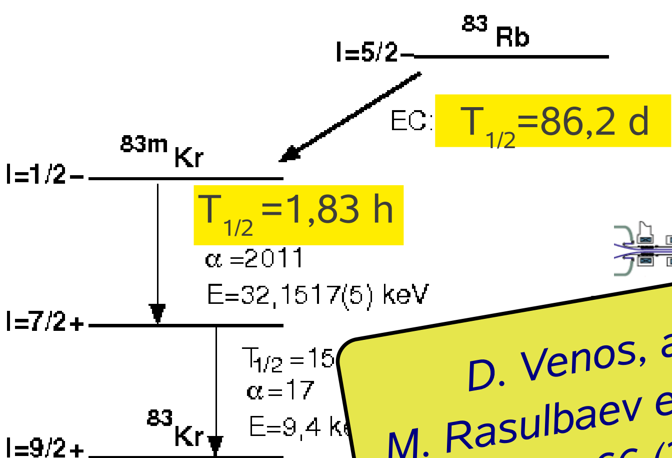


H_2 / HD / T_2 / DT / HT
= 0.820 / 0.083 / 0.003 / 0.005 / 0.085

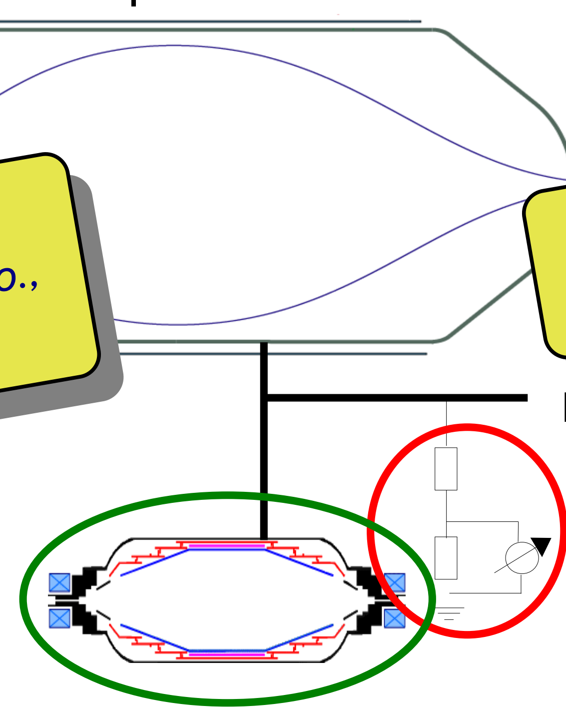


Stability of retarding potential / energy calibration: ppm at 18.6 kV

- Measure HV by precision HV divider
- Lock retarding HV by measuring energetically well-defined electron line with monitor spectrometer



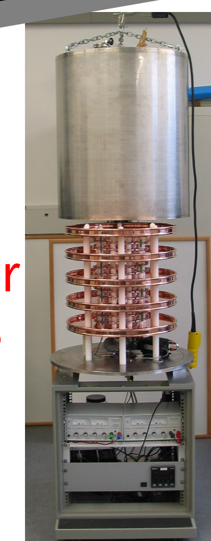
D. Venos, arXiv 0902.0291
M. Rasulbaev et al., Appl. Rad. Iso., 66 (2008) 1838



Th. Thümmler et al., NJP 11 (2009) 103007

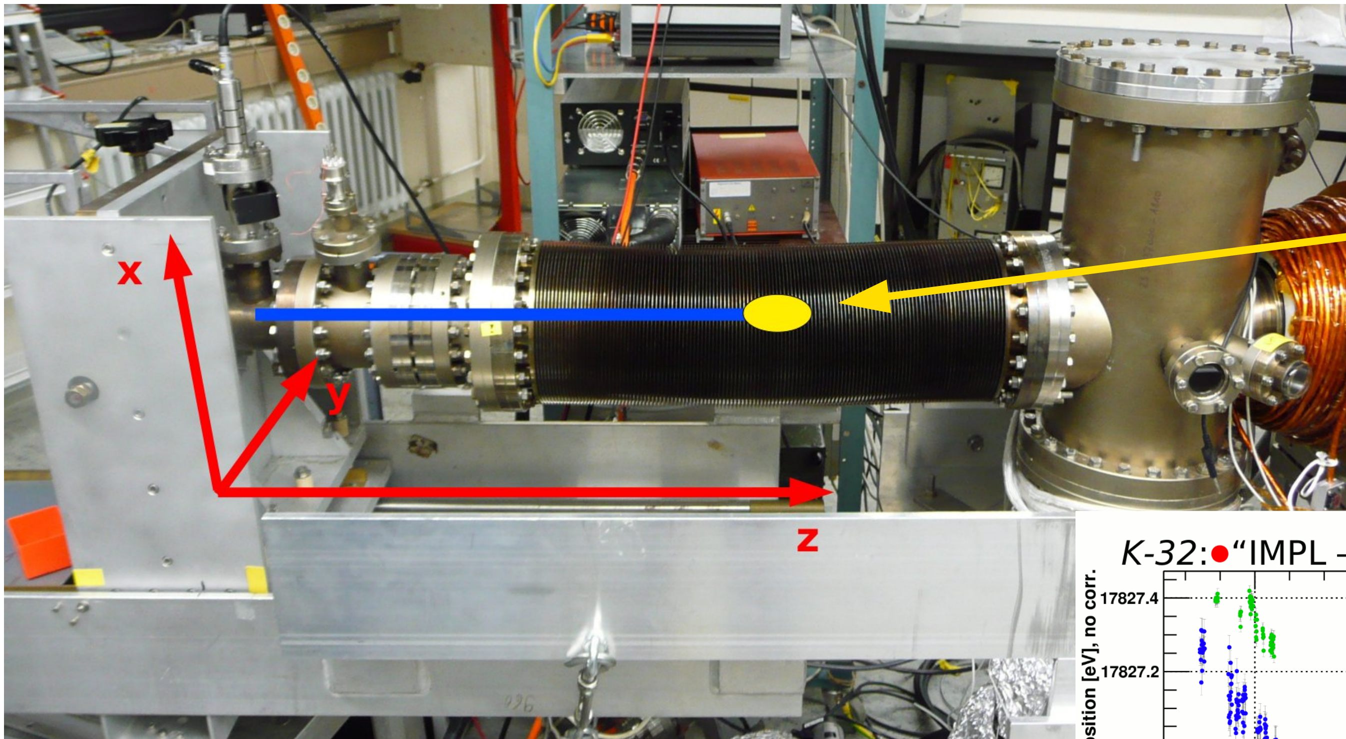
^{83m}Kr conversion electron sources:

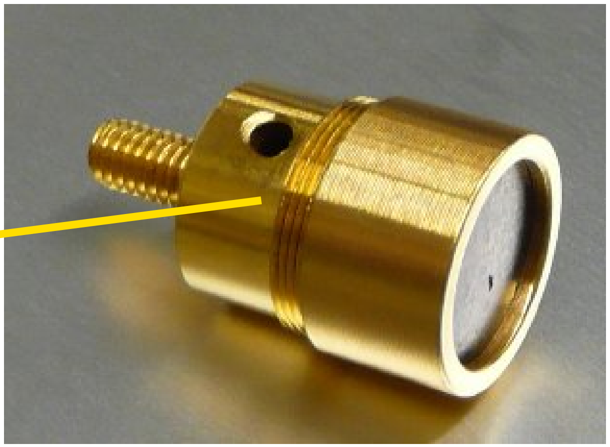
- condensed ^{83m}Kr: Münster/Mainz
- ^{83}Rb/^{83m}Kr: Rez/Mainz/Münster/Karlsruhe
- ^{83}Rb production: Bonn, Rez



monitor spectrometer
= modified Mainz spec.:
ΔE=5eV → 1 eV

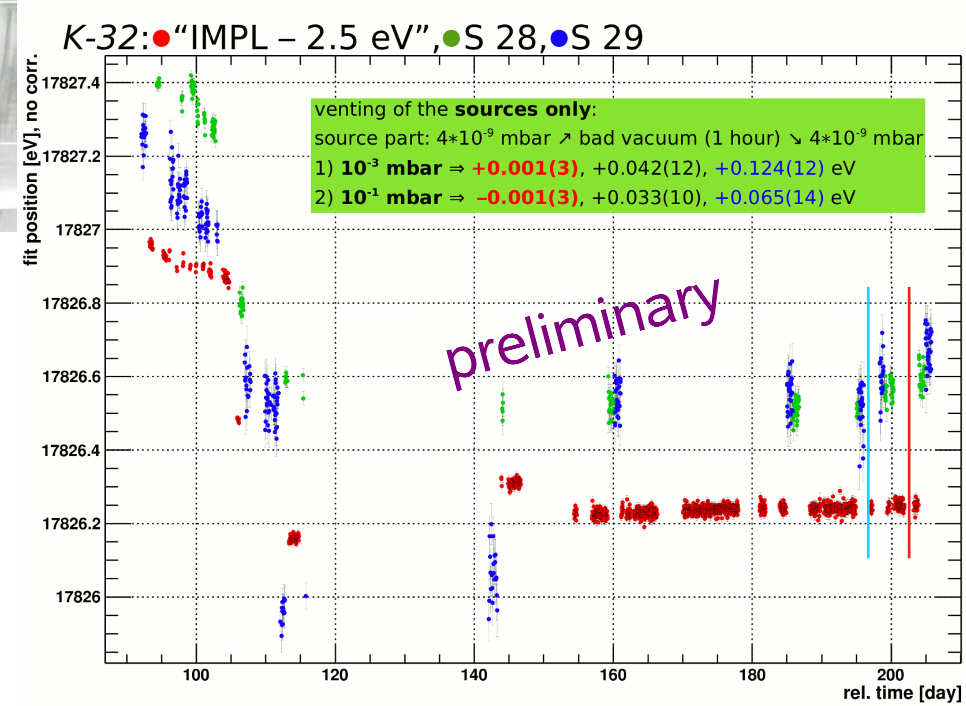
Currently: Investigations of implanted + evaporated ^{83}Rb/^{83m}Kr-source





Rez/Prague, Mainz, Münster, Karlsruhe
evaporated source by Rez/Prague
implanted source by ISOLDE@CERN

⇒ implanted source fulfills KATRIN requirements final test in July/August 2009



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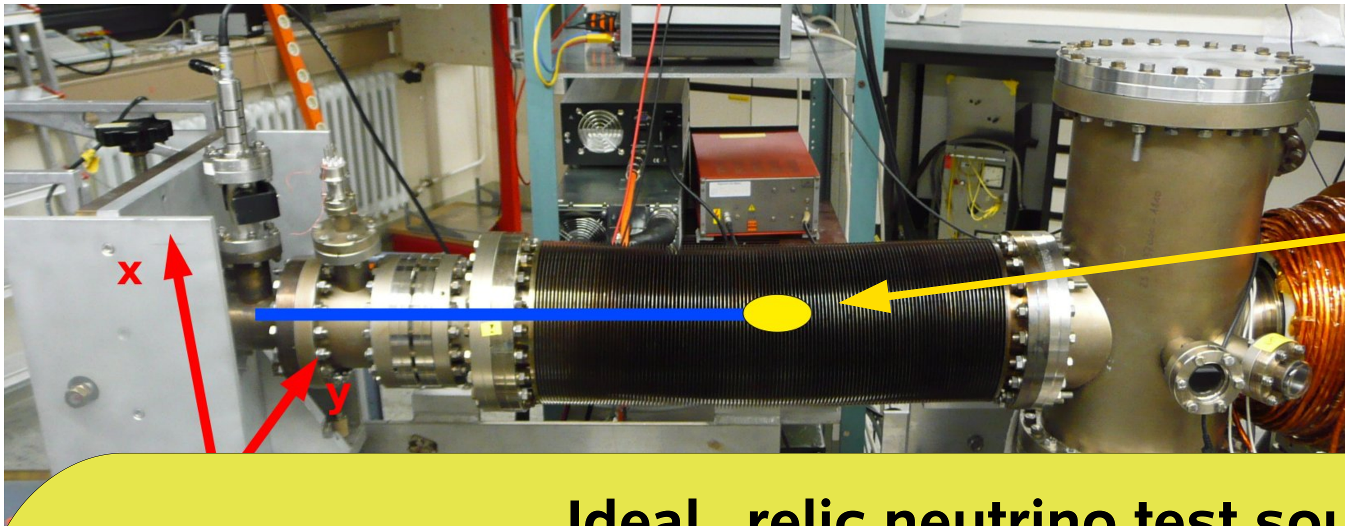
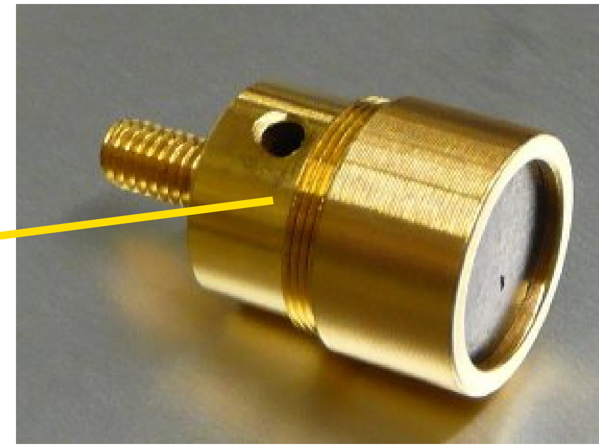
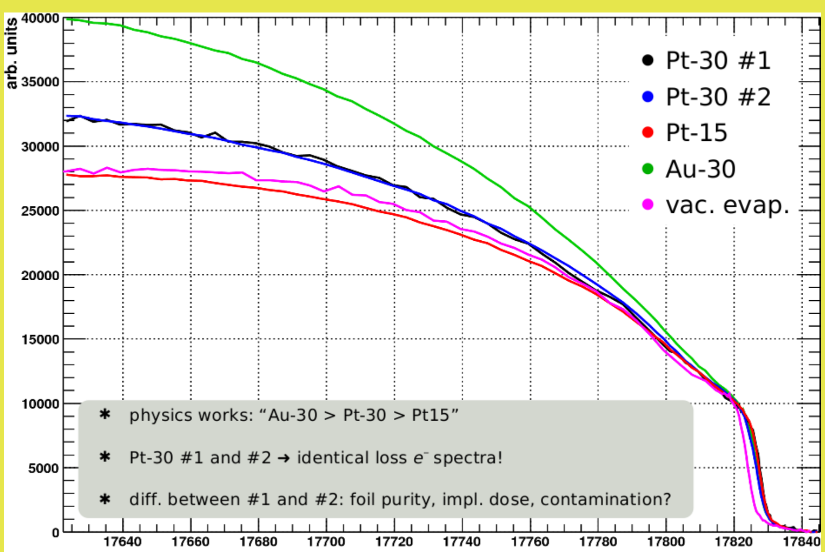
Currently: Investigations of implanted + evaporated $^{83}Rb/^{83m}Kr$-source



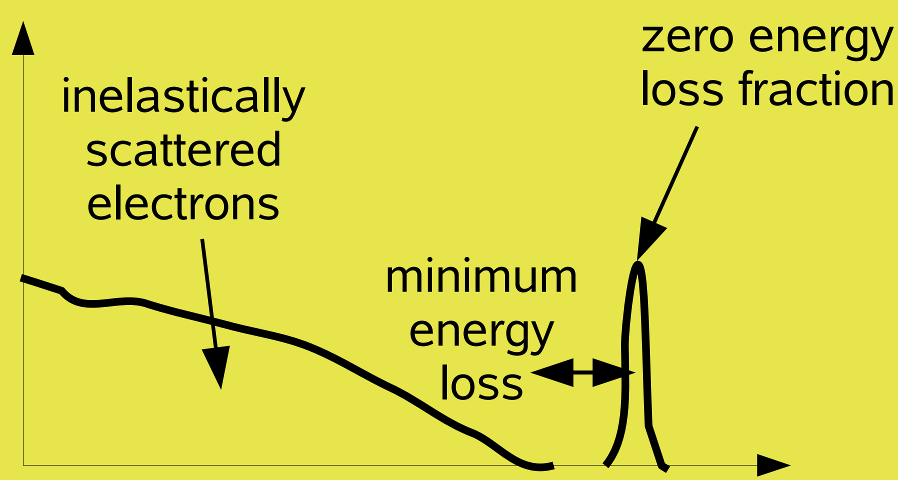


Ideal „relic neutrino test source"

Integral spectrum



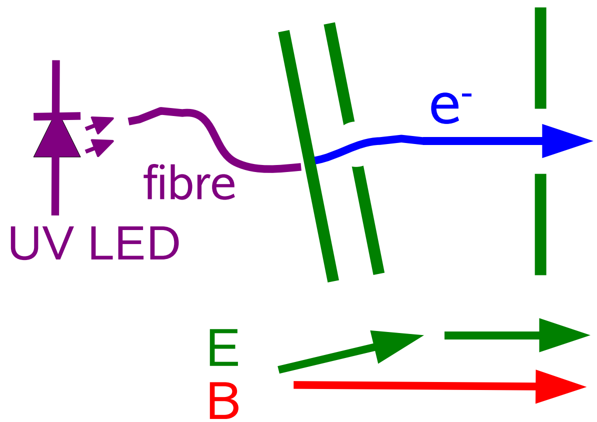
primary energy spectrum

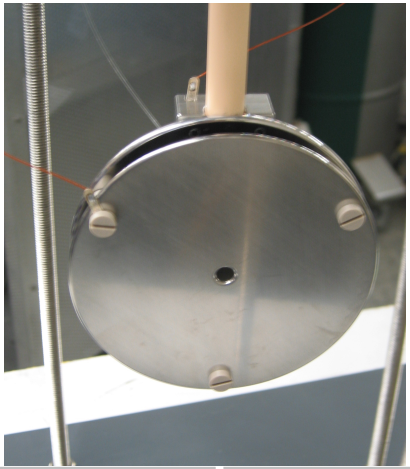


A new pulsed angular-defined UV LED photoelectron source

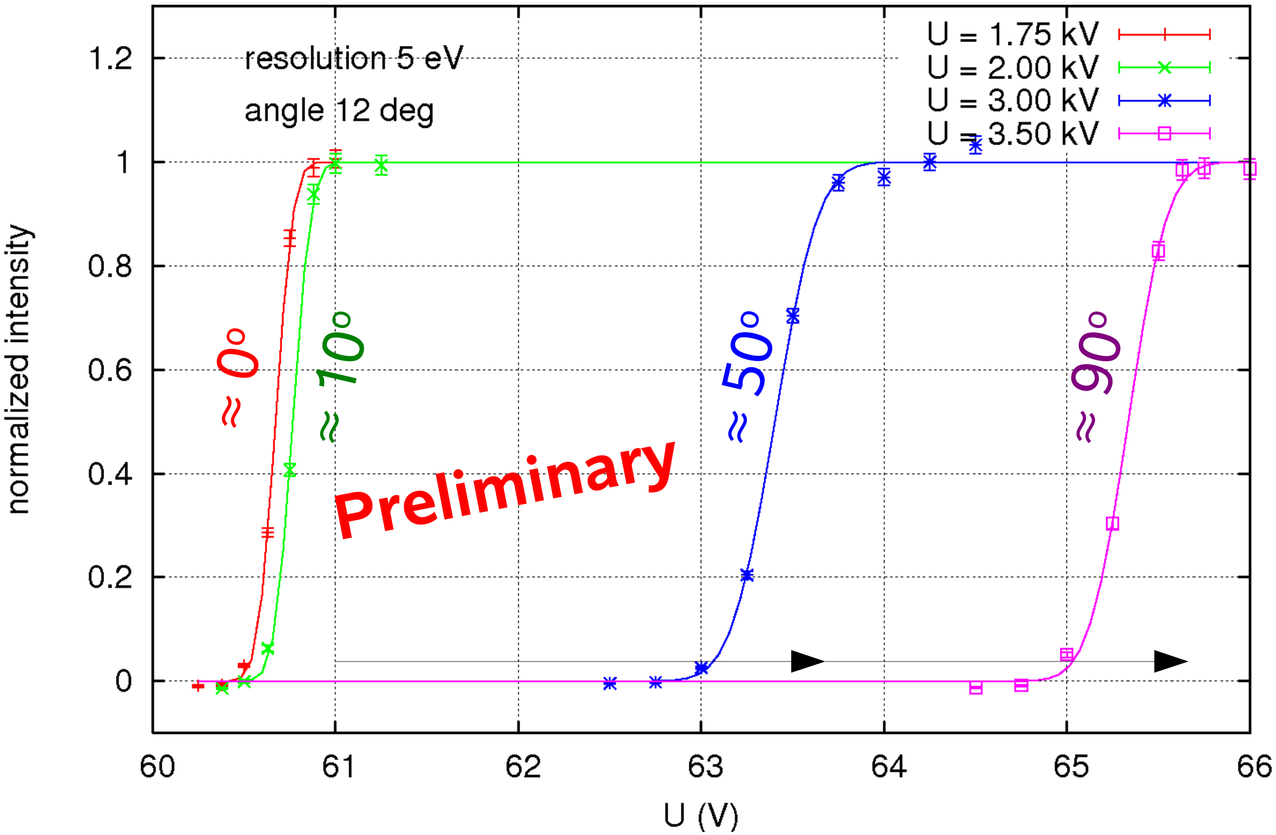
K. Valerius et al., NJP 11 (2009) 063018 (without angular-definition)

Idea:
fast non-adiabatic acceleration with adjustable non-parallel E and B fields





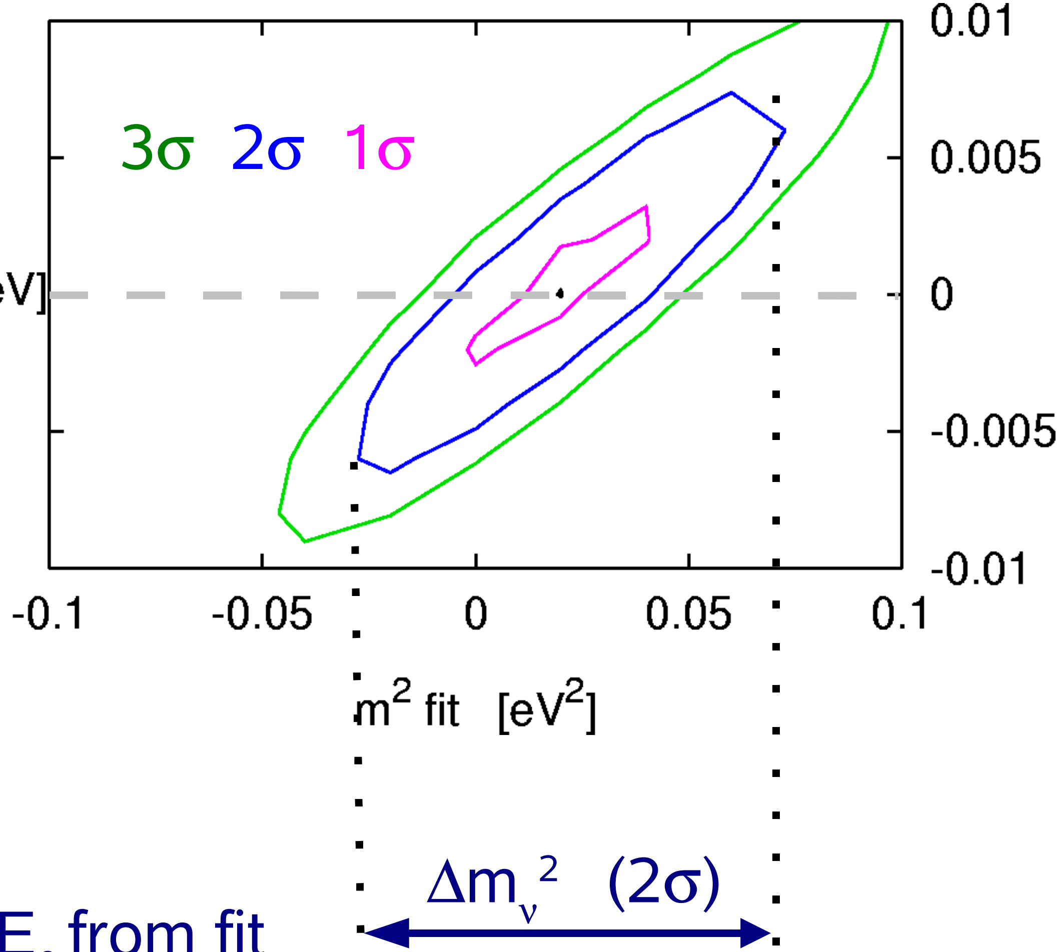
Angle at
electron source: 0° 3.3°
pinch magnet: 0° 90°



Statistical limitations due to correlation with endpoint

Strong correlation between m_ν^2 and endpoint E_0

10 m spectrometer
3 years
last 20 eV



with E_0 from fit

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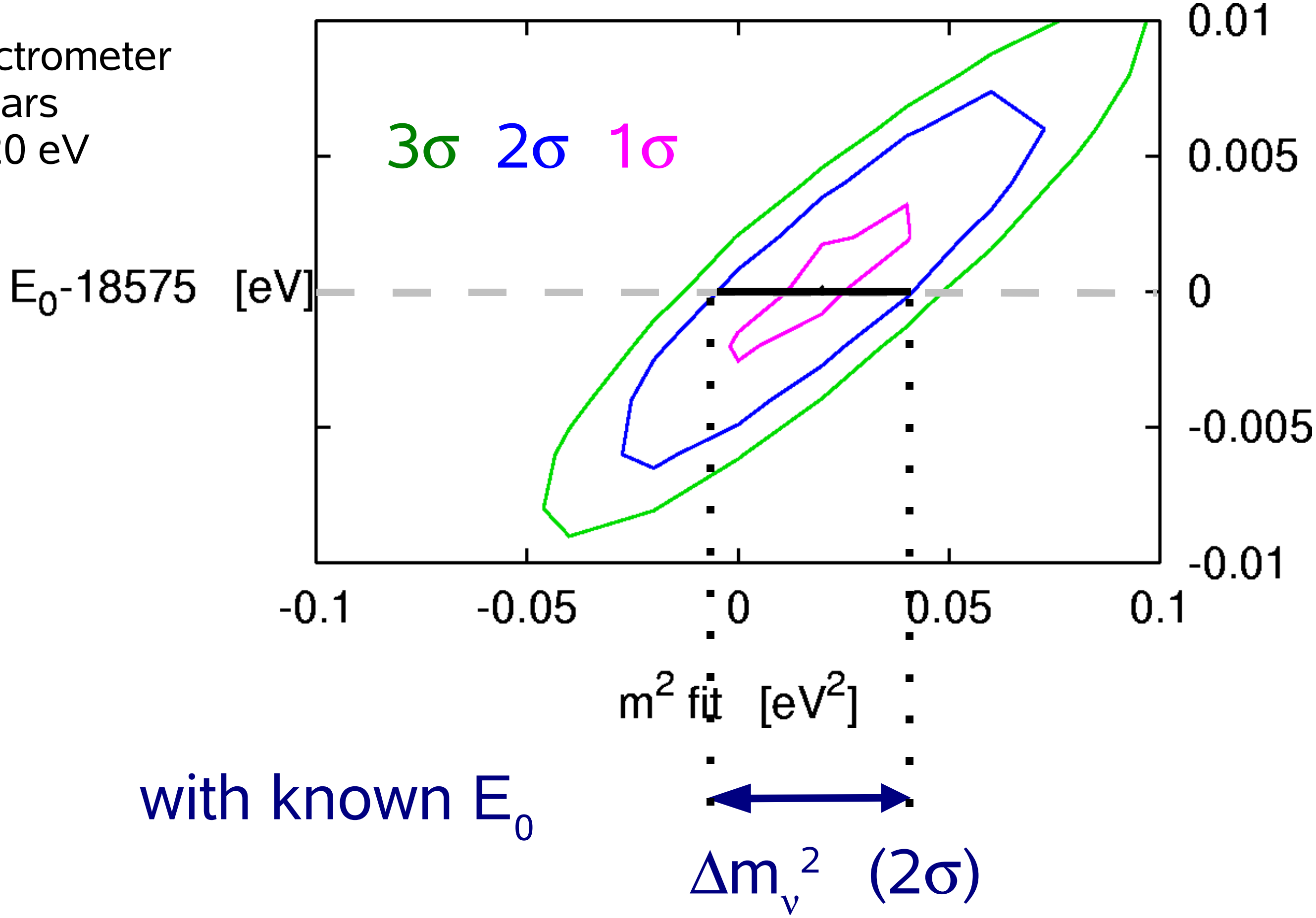
Statistical limitations due to correlation with endpoint

Strong correlation between m_ν^2 and endpoint E_0

10 m spectrometer
3 years
last 20 eV



⇒ more than a factor 2 of sensitivity on m_ν^2 is lost by unknown E_0

Importance of external endpoint

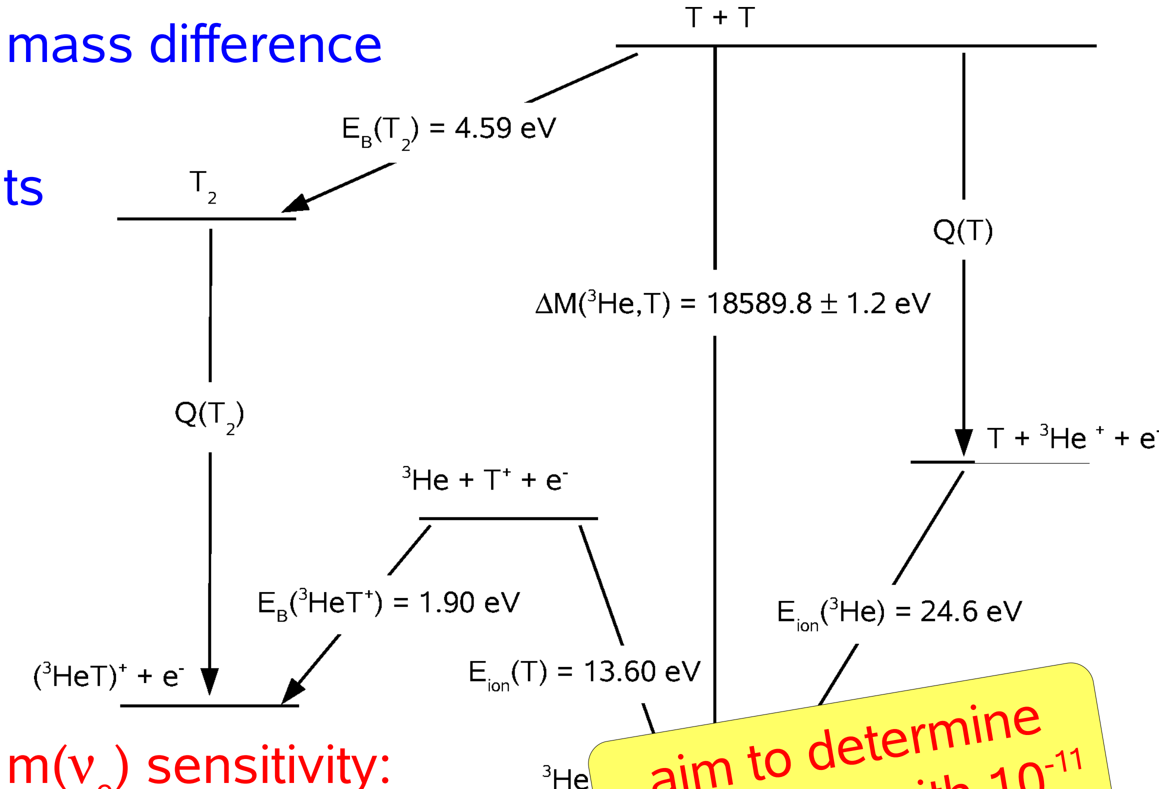
Endpoint/Q-value is related to ^{3}He-T mass difference

Precision Penning trap measurements

$\Rightarrow \Delta M(^3\mathrm{He},\mathrm{T}) = 18589.8 \pm 1.2$ eV

(Nagy et al., Eur. Phys. Lett. 74 (2006) 404)

Improved precision expected by 1 (2) orders of magnitude using state-of-the-art (new) techniques



aim to determine $\Delta M(^3\mathrm{He},\mathrm{T})$ with 10^{-11} precision on single masses (K. Blaum et al. MPIK Heidelberg with Van Dyck/Seattle`s setup)

Required precision to really improve $m(\nu_e)$ sensitivity:

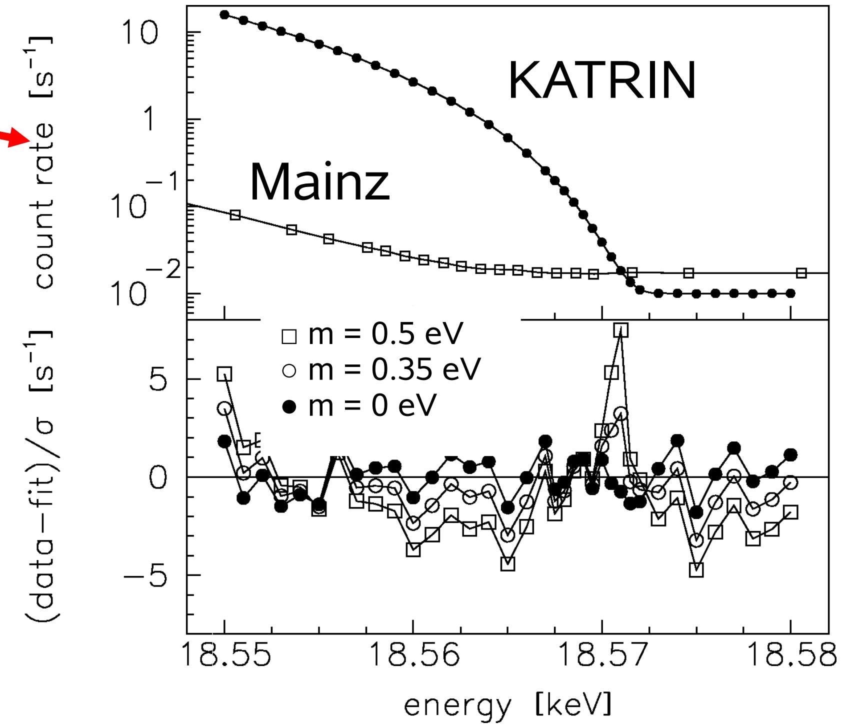
$\Delta E_0 = 5$ meV $\Rightarrow$ unrealistic for Penning traps

but it is also very difficult to calibrate KATRIN to this level

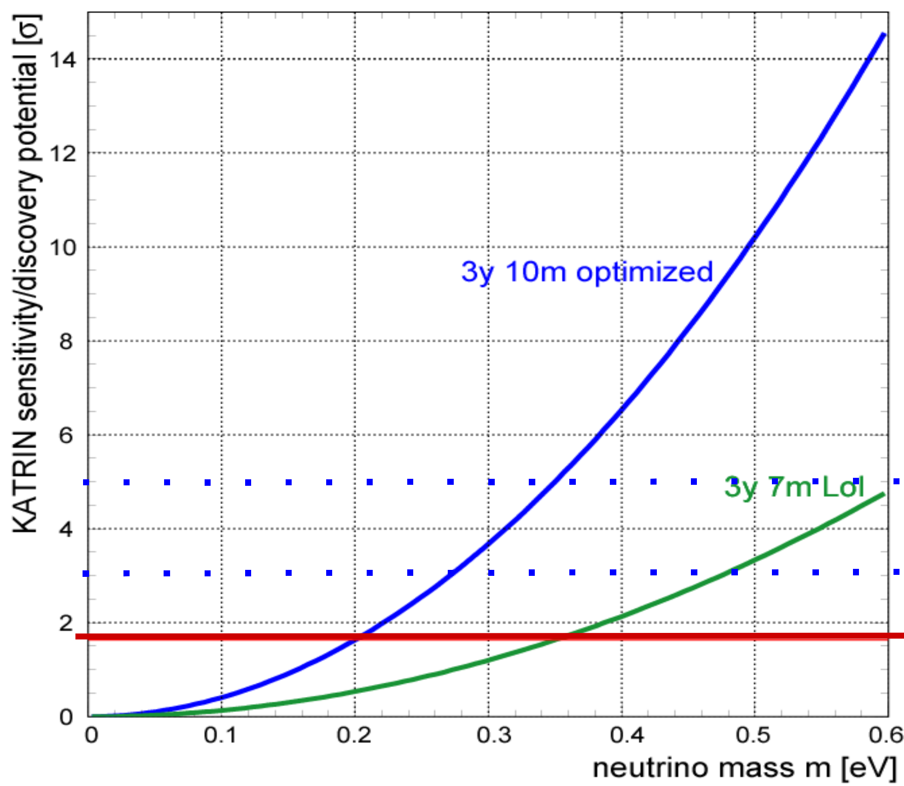
But it would be very helpful to cross-check the systematic uncertainties at the 50-100 mV level !

KATRIN´s sensitivity

Example of KATRIN simulation & fit
(last 25eV below endpoint, reference):



Expectation for 3 full beam years: $\sigma_{syst} \sim \sigma_{stat}$



discovery potential:

m_ν = 0.35eV (5σ)

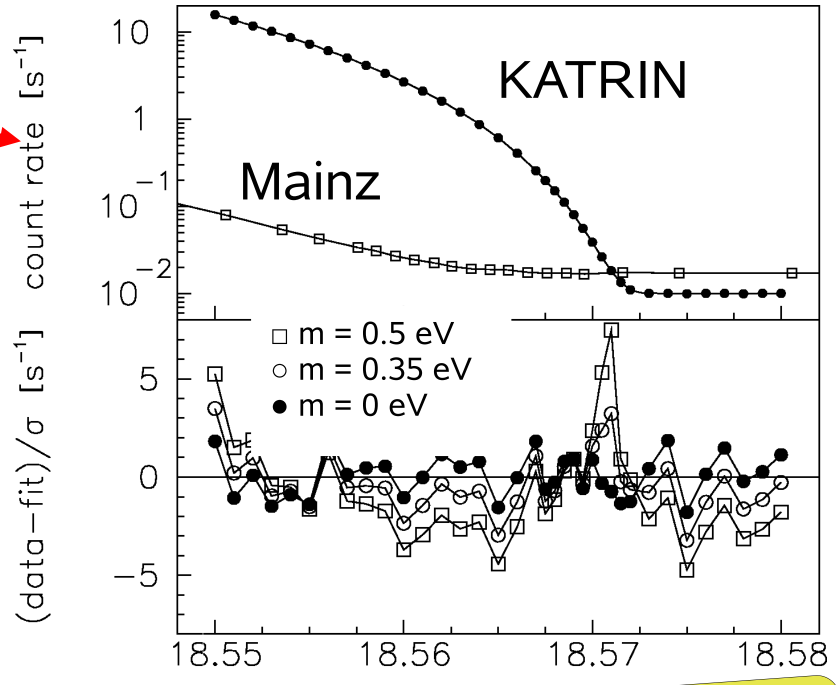
m_ν = 0.3eV (3σ)

sensitivity:

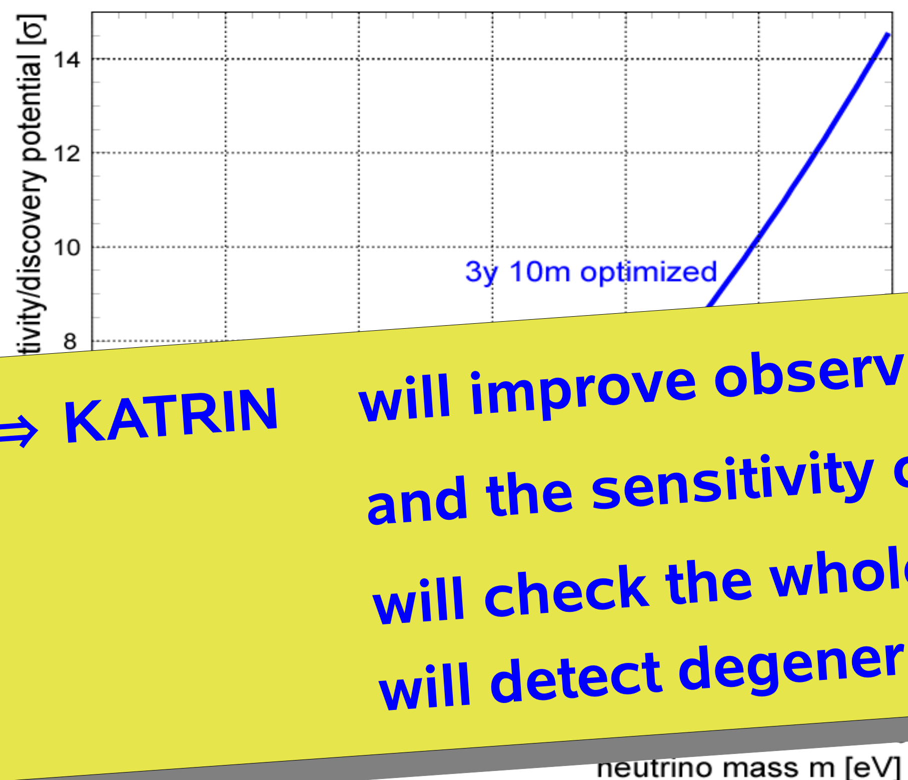
m_ν < 0.2eV (90%CL)

KATRIN´s statistical uncertainty

Example of KATRIN simulation & fit
(last 25eV below endpoint, reference):



Expectation for 3 full beam years: $\sigma_{syst} \sim \sigma_{stat}$



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

⇒ KATRIN will improve observable $m^2(\nu_e)$ by 2 orders of magnitude
and the sensitivity on $m(\nu_e)$ by 1 order of magnitude
will check the whole cosmological relevant mass range
will detect degenerate neutrinos (if they are degen.)

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Conclusion

KATRIN is a model-independent direct neutrino mass experiment complementary to cosmology and $0\nu\beta\beta$ searches

KATRIN is based on well-proven technology pushing it to the frontiers

KATRIN`s sensitivity $m(\nu_e)$ of 0.2 eV will allow to
check the full cosmological relevant neutrino mass range &
to measure $m(\nu_e)$ if the degenerate mass scenario is true

KATRIN`s timeline:

souce:	demonstrator: 2010, full WGTS: 2010-2012
tritium elimination line	DPS2-F: 2010, CPS: 2011-2012
main spectrometer	2010-2011
detector	2010
regular data taking	2012-2018 (3 full-beam-years)

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung