Status of Tritium-based Neutrino Mass Measurements

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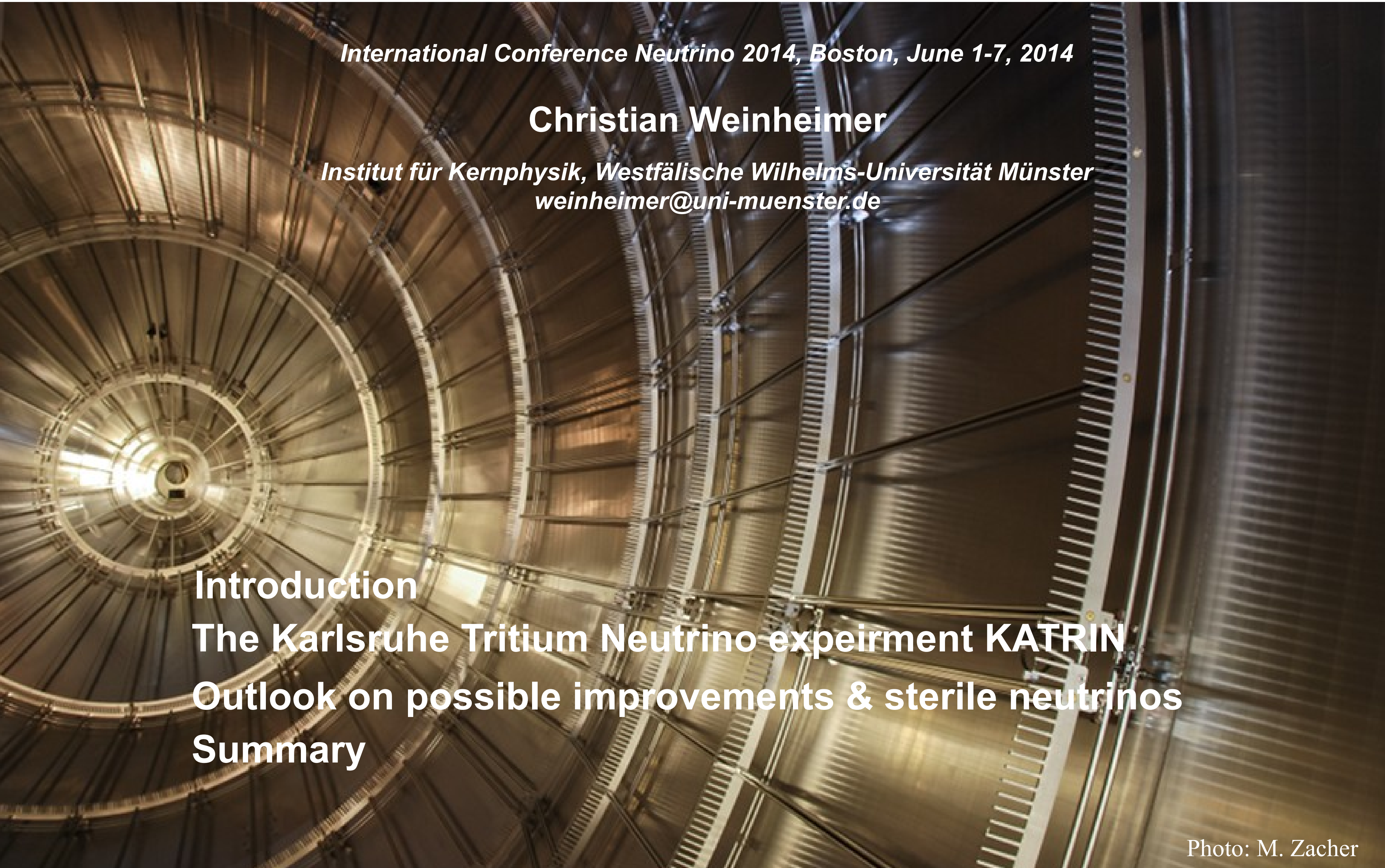

- Introduction
- The Karlsruhe Tritium Neutrino expeirment KATRIN
- Outlook on possible improvements & sterile neutrinos
- Summary

Photo: M. Zacher

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

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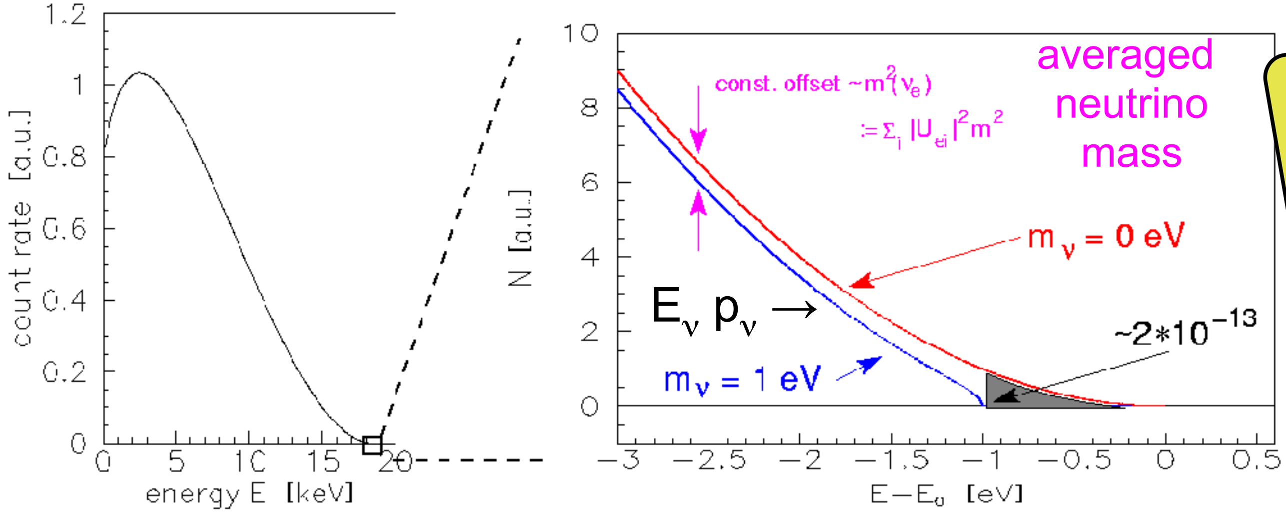
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

Complementary to $0\nu\beta\beta$ and cosmology

$$\beta: dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \sqrt{(E_0-E_e)^2 - \text{"}m(\nu_e)\text{"}^2}$$

phase space: p_e E_e E_ν p_ν

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



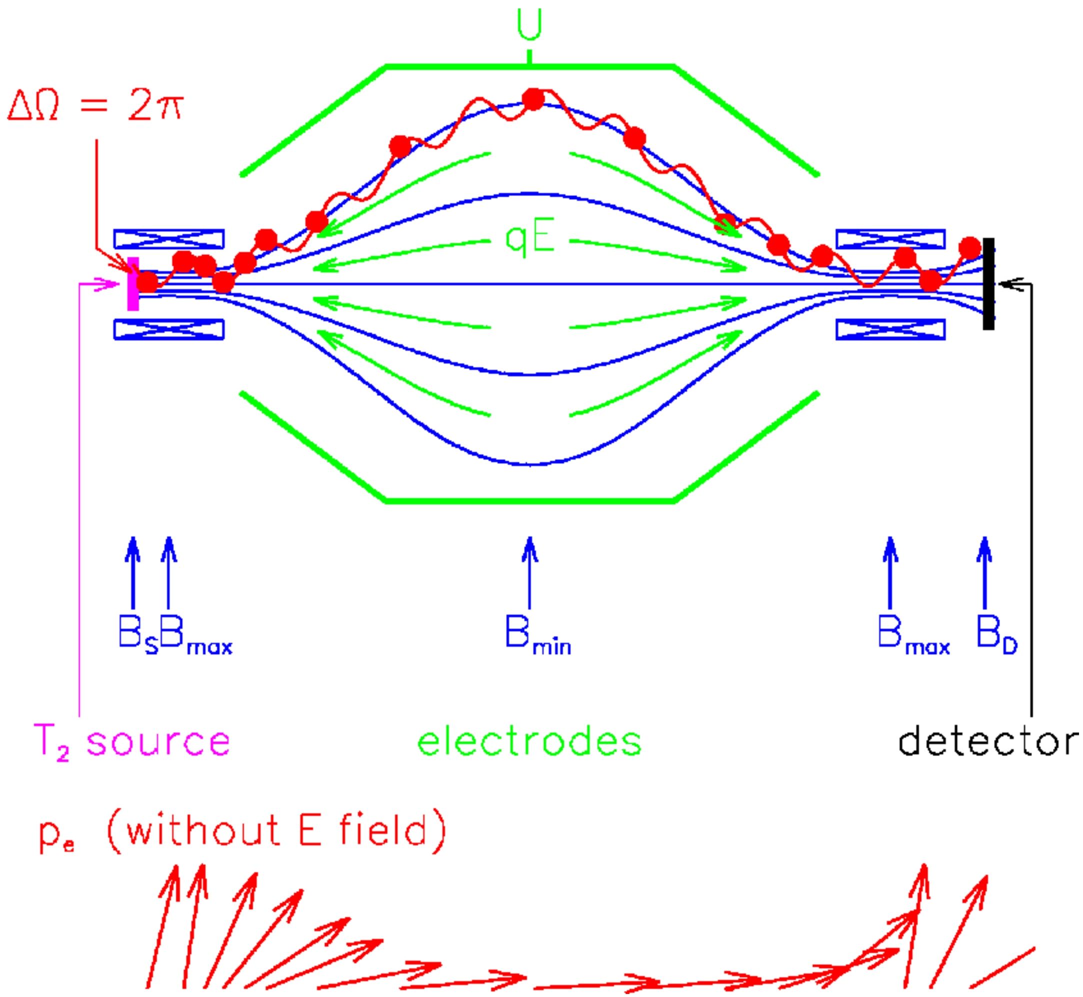
E.W. Otten & C. Weinheimer Rep. Prog. Phys. 71 (2008) 086201

G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, Adv. High Energy Phys., 2013 (2013) 293986

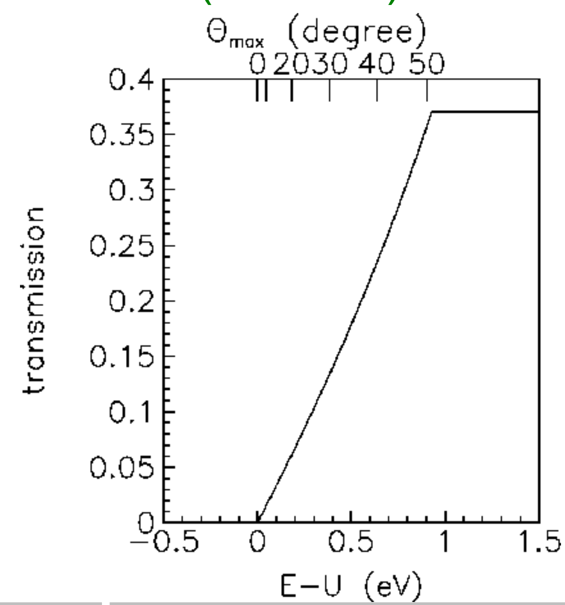
Need: **low endpoint energy** $\Rightarrow$ **Tritium ^3H, (^{187}Re, ^{163}Ho)**

very high energy resolution &
very high luminosity &
very low background
$\Rightarrow$ **MAC-E-Filter (or bolometer for ^{187}Re, ^{163}Ho)**

The classical way:
Tritium β-spectroscopy with a MAC-E-Filter



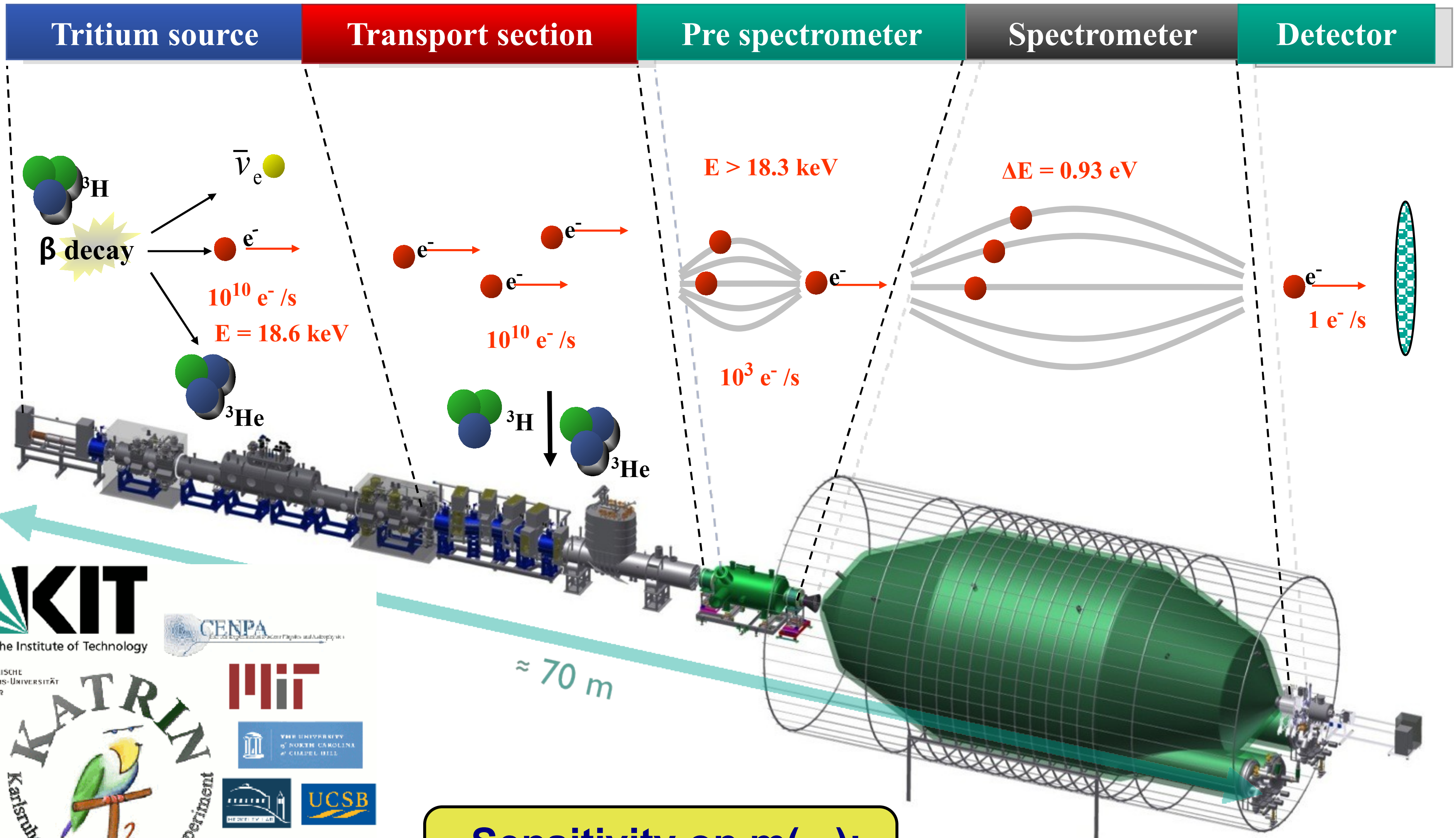
- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E_\perp / B = \text{const.}$
  ⇒ parallel e⁻ beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)



⇒ sharp integrating transmission function without tails →

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

The Karlsruhe Tritium Neutrino Experiment KATRIN - overview

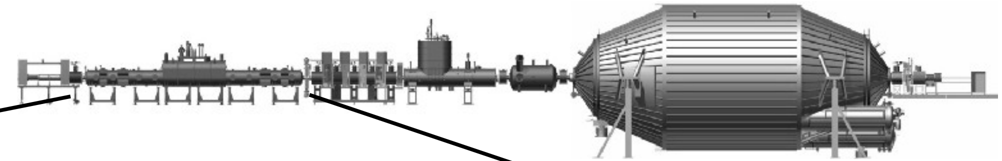


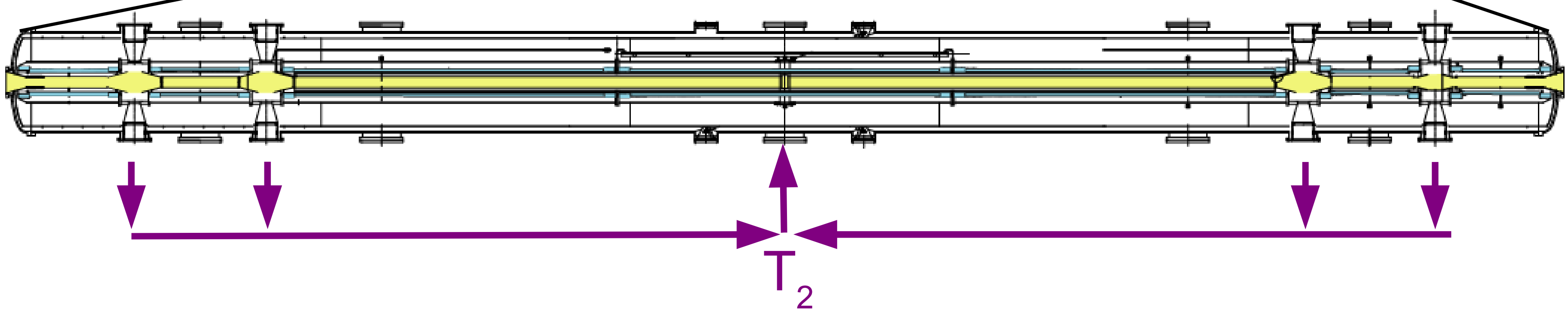
Sensitivity on $m(\nu_e)$:

$2\ eV/c^2 \rightarrow 200\ meV/c^2$

Molecular Windowless Gaseous Tritium Source WGTS

per mill stability source strength request:
$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p\, V / R\, T$
tritium fraction f_T & ideal gas law

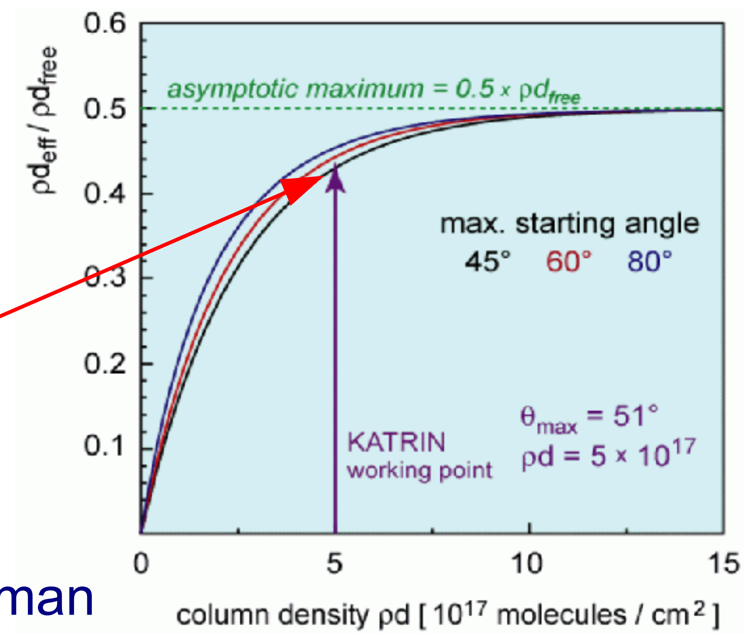




WGTS: tub in long superconducting solenoids
⊘ 9cm, length: 10m, T = 30 K

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

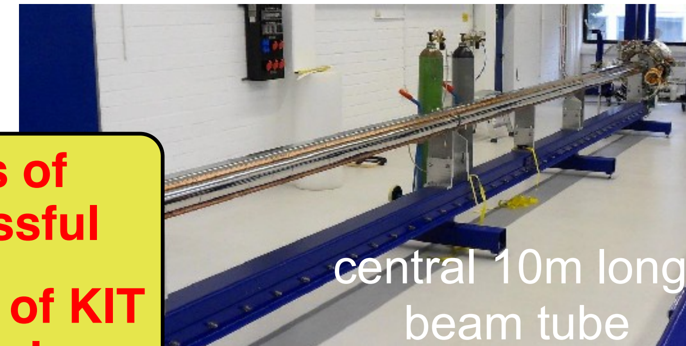
Status of Windowless Gaseous molecular Tritium Source WGTS

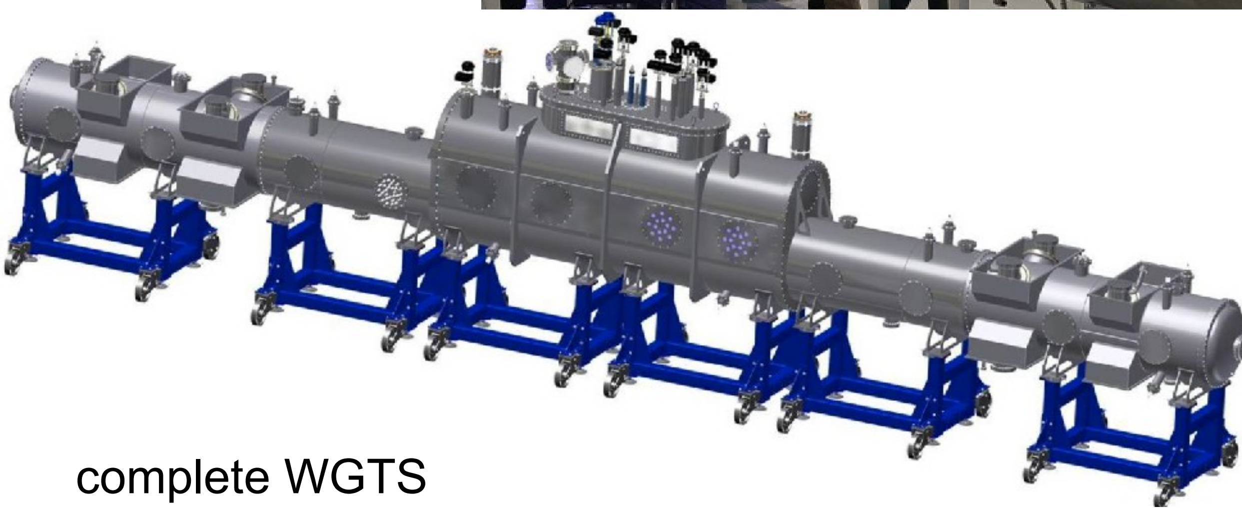
Assembly of beam tube, magnets and cryostat:

Temperature stability tests of „demonstrator“ very successful

Management now in the hand of KIT progress according schedule

Arrival at KIT in 2015





complete WGTS

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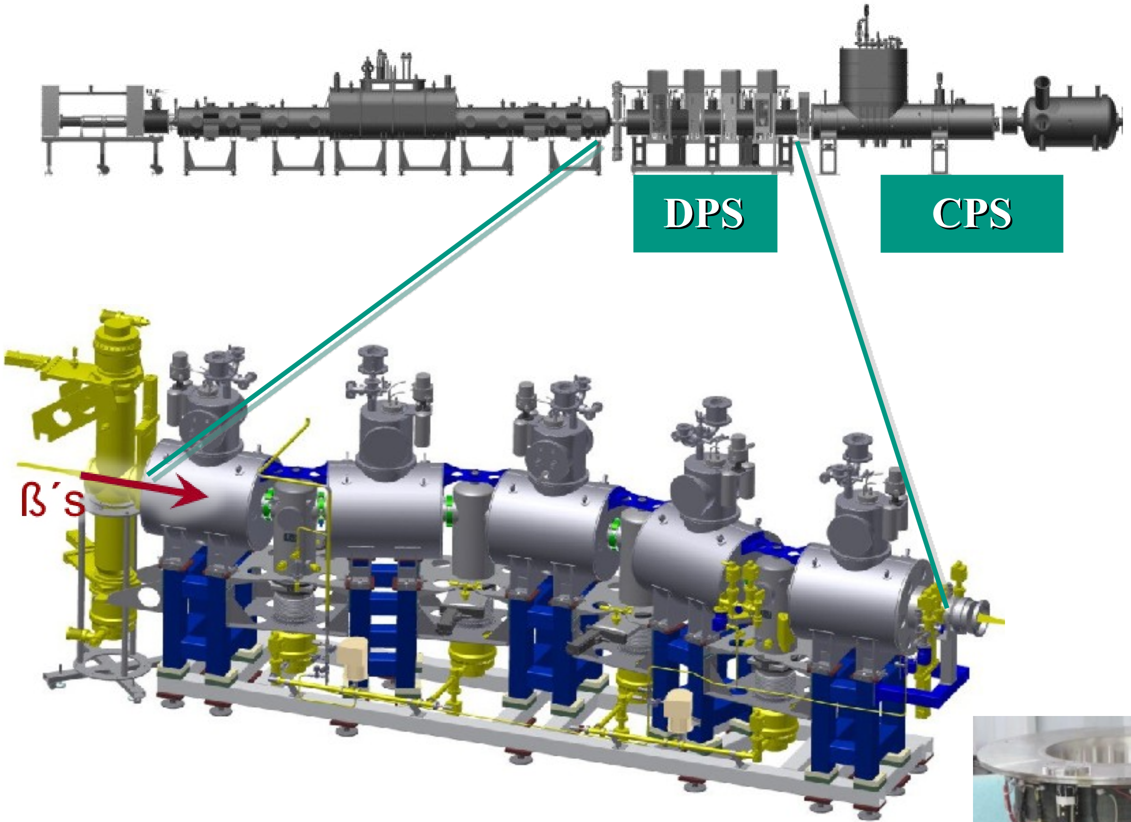
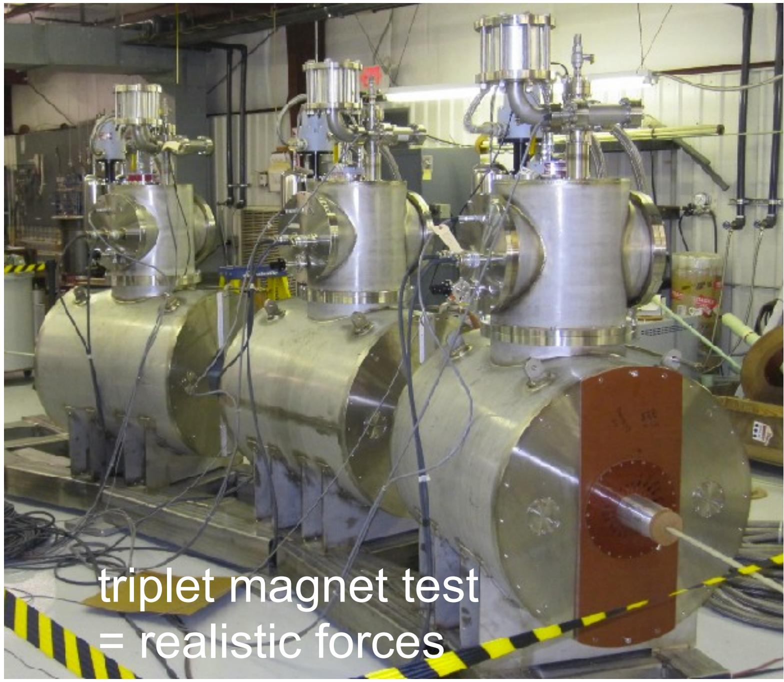
Transport and differential & cryo pumping sections



- old cryostate safety system failed
  → had to build new differential pumping section
- based on simple warm beam-tube and pump port design surrounded by superconducting warm-bore magnets
- S. Lukic et al., Vacuum 86 (2012) 1126

- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- **under construction, full delivery mid 2014**



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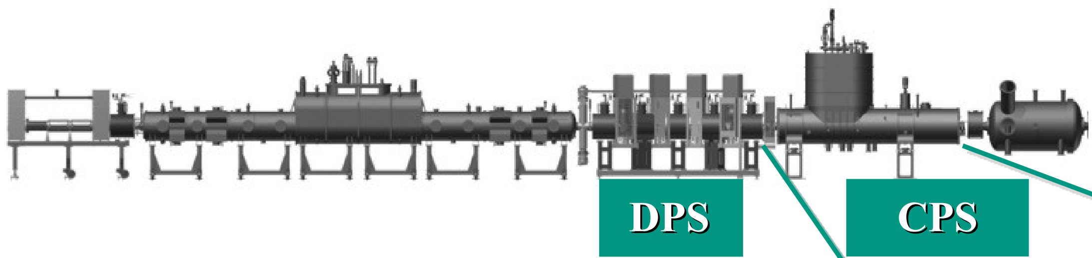
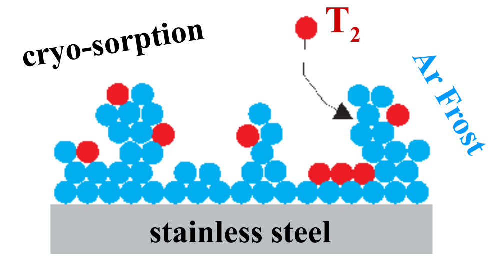
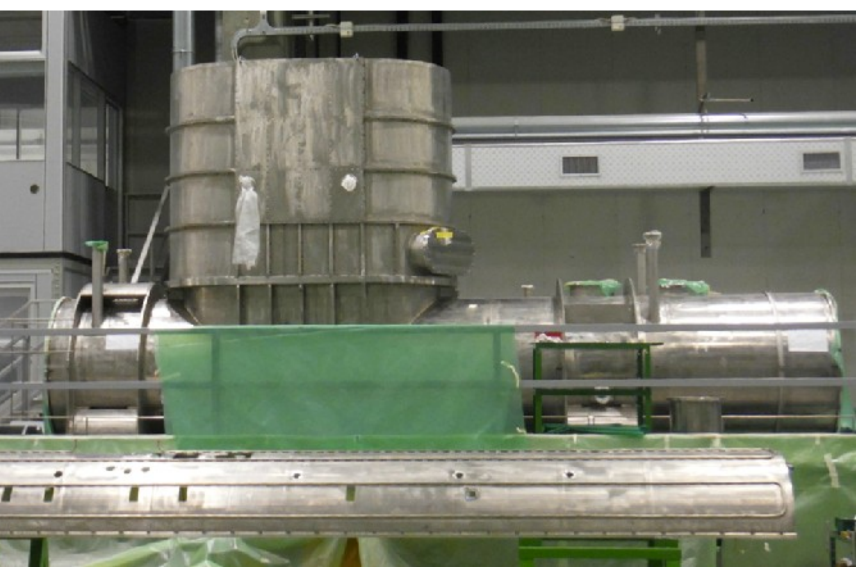
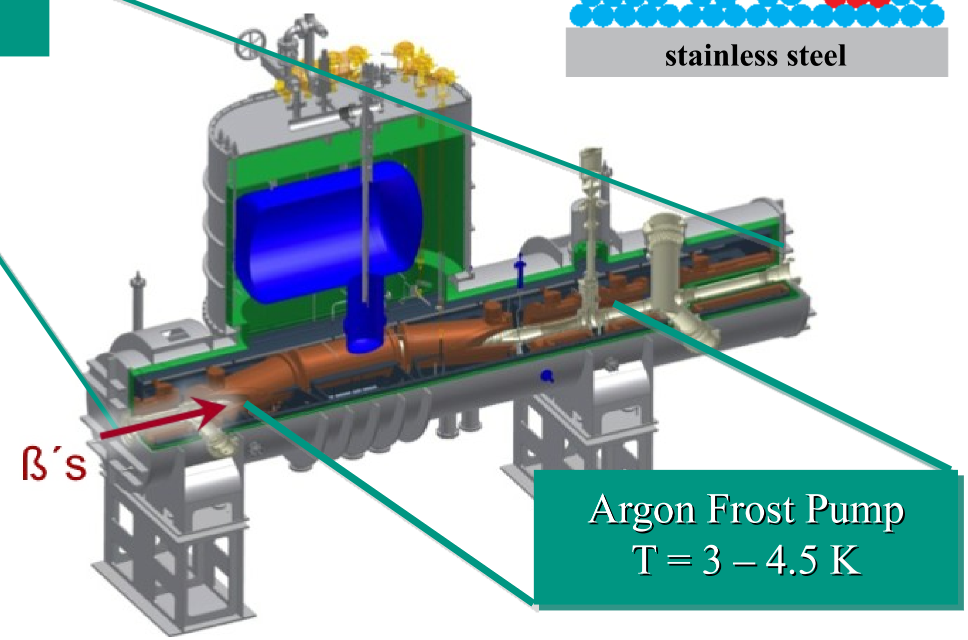
Transport and differential & cryo pumping sections









- based on by cryo-sorption
- Tritium retention: $>10^7$
- magnetic field: 5.6 T
- **delivery end of 2014**

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

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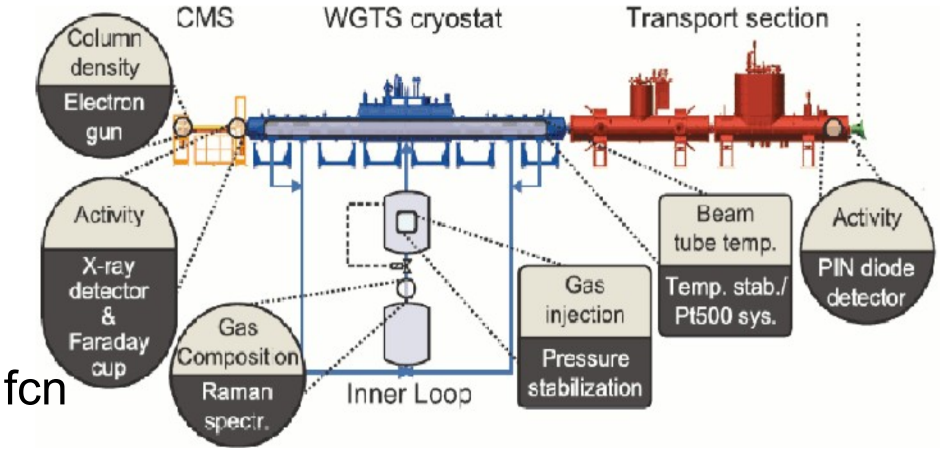
Tritium source systematics



Sensors & calibration:

Tritium activity: x-ray detector

Tritium purity: Laser Raman spectroscopy LARA

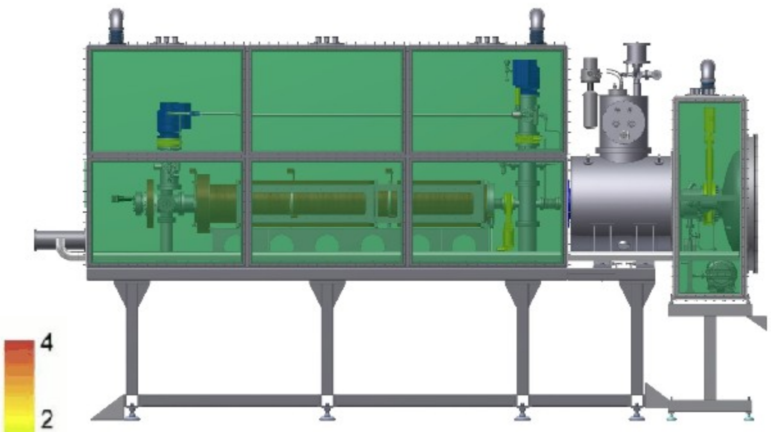
WGTS stabilization: temperature & pressure stab.

Potential stabilization: rear wall with well-defined work fcn

Column density: energy loss measurement with e-gun

Beam intensity: forward beam monitor

Energy loss and response function: e-gun, ^{83m}Kr source



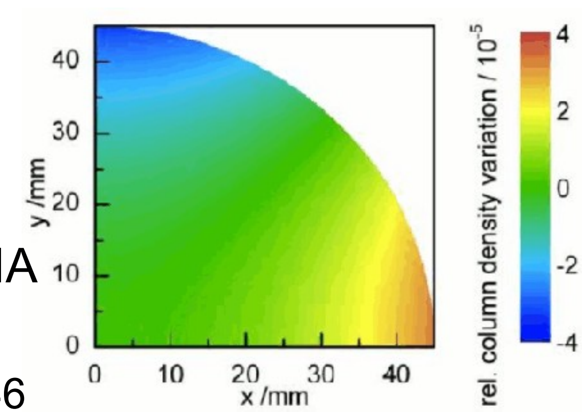
calibration & monitoring rear system

Simulations:

Gas dynamics

Beta spectrum

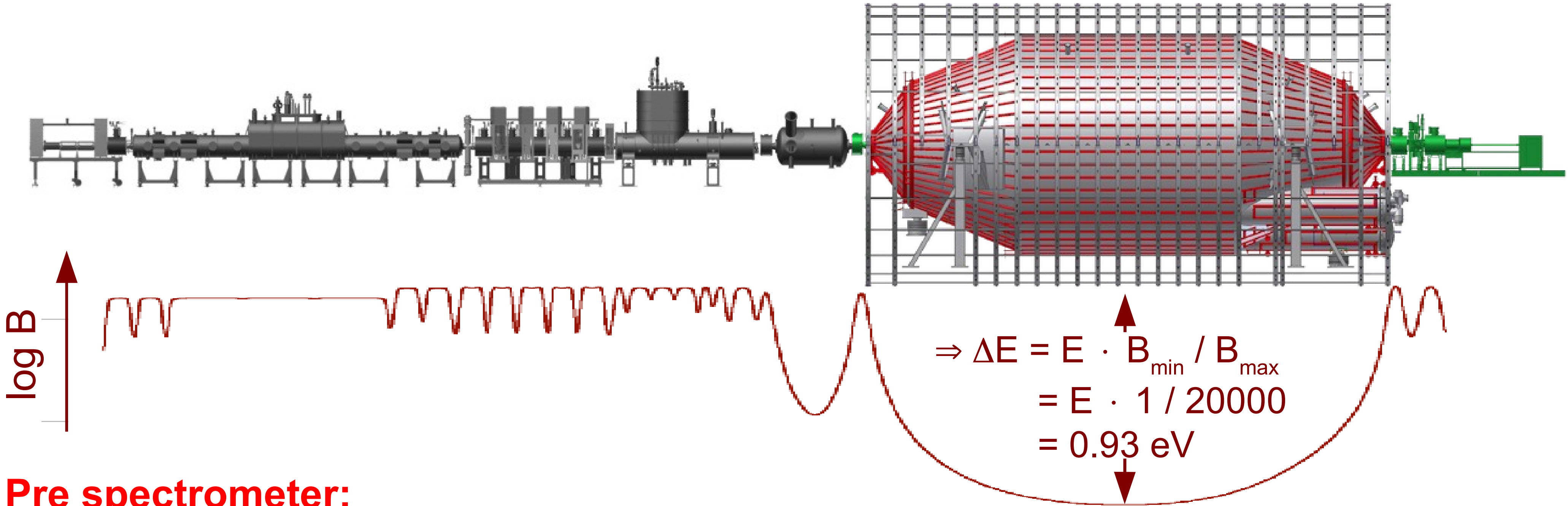
ray-tracing of betas with KASSEIPEIA



M. Babutzka et al., NJP 14 (2012) 103046
M. Schlösser et al., Anal. Chem., 85 (2013) 2739
S. Grohmann et al., Cryogenics 55 (2013) 5

more details on the posters:
Kassiopeia (D. Furse)
WGTS (L. Kuckert)
Calibration & Montoring System
(F. Heizmann et al.)

KATRIN spectrometers



Pre spectrometer:

- successful tests & developments of new concepts

Main spectrometer:

- huge size: 10m diameter, 24m length
  1240 m^3 volume, 690 m^2 inner surface

- ultra-high vacuum: $p = O(10^{-11}$ mbar)
- ultra-high energy resolution: $\Delta E = 0.93$eV
- vacuum vessel on precise high voltage (ppm precision)

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The detector

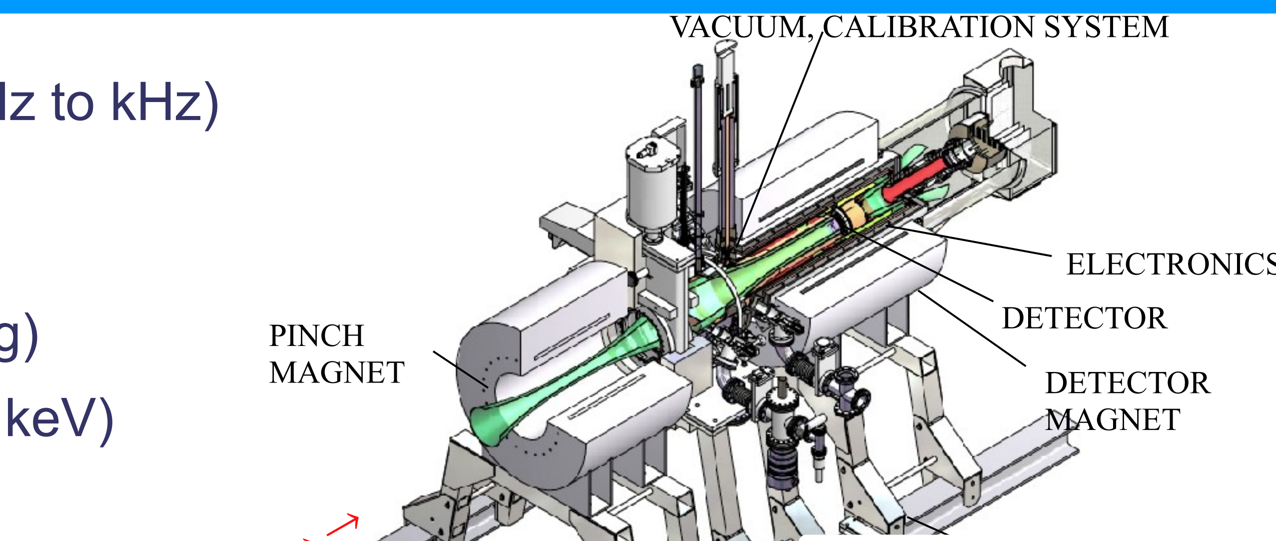
Requirements

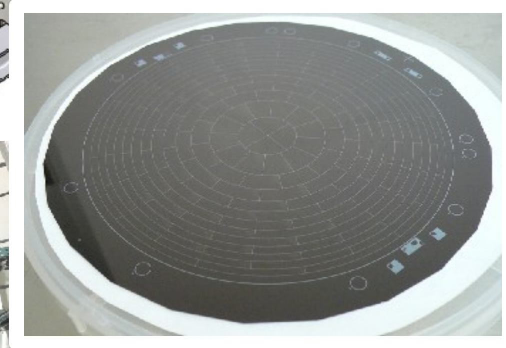
- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
  (passive and active shielding)
- good energy resolution (< 1 keV)

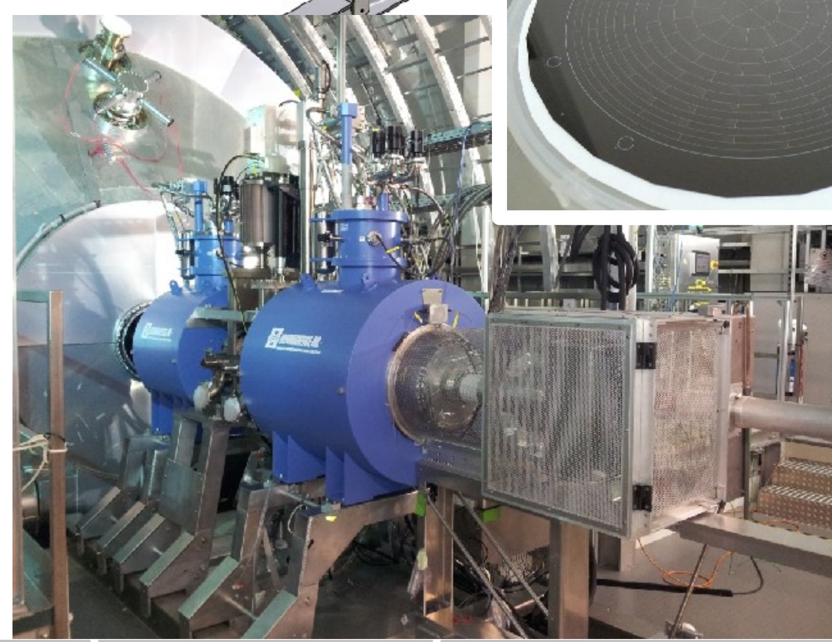
Properties

- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV)
  (to lower background in signal region)
- segmented wafer (148 pixels)

  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities







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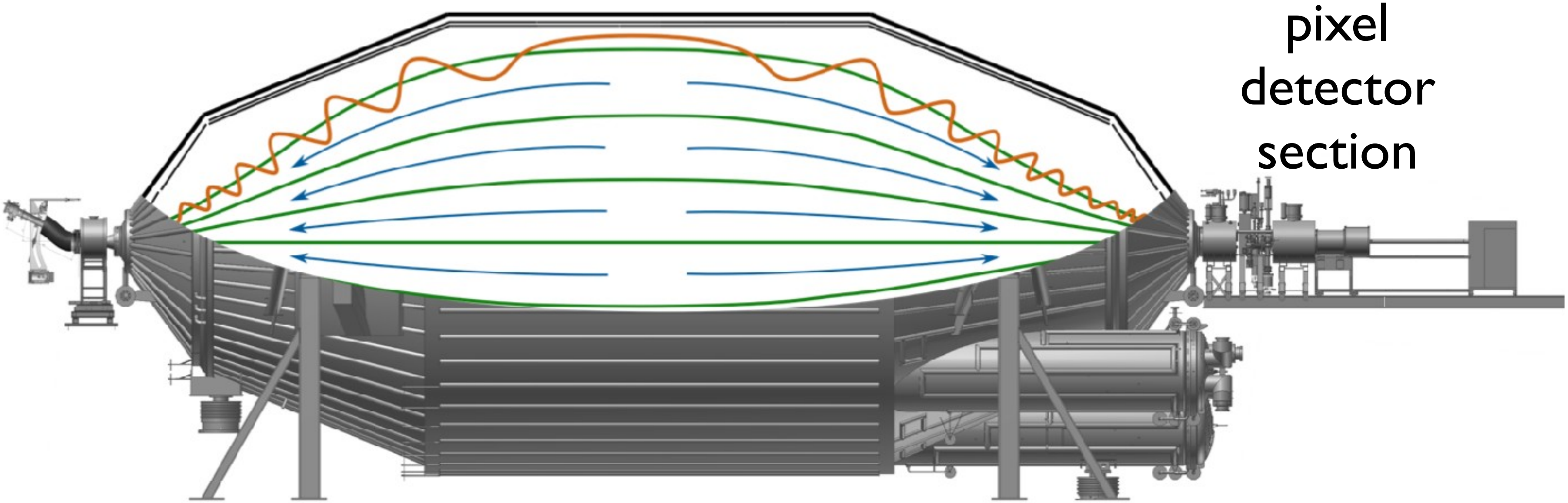
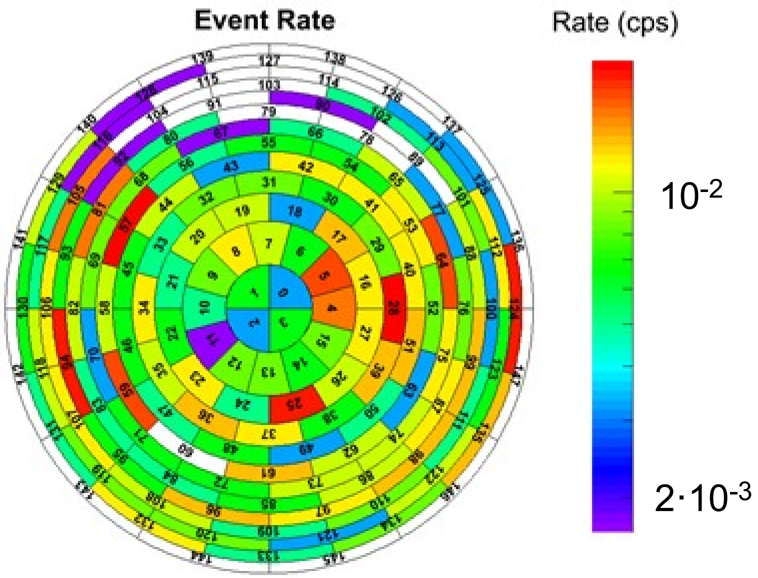
Main spectrometer and detector commissioning – objectives

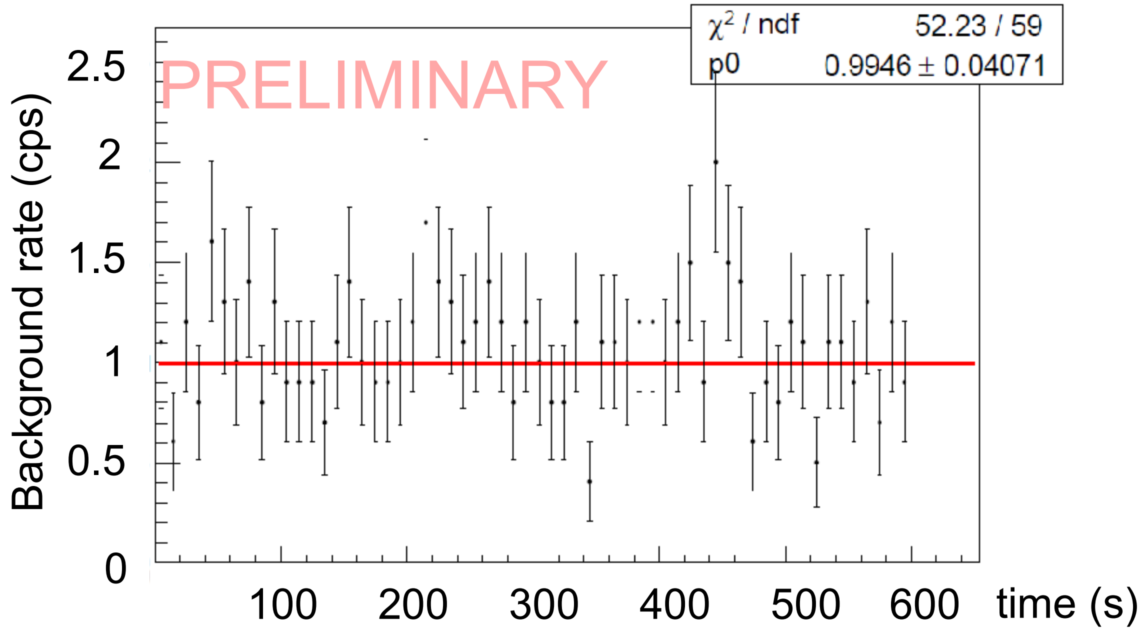


Primary objectives:

- test of individual hardware, software and slow control components
- provide ultra high vacuum conditions at the $p \approx 10^{-11}$ mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter ($E = 18.6$ keV with $\Delta E = 0.93$ eV resolution) and compare to simulation with Kasseiopeia
- detailed understanding and passive & active control of background processes

First switch on with full high voltage on August 13/14, 2013





Could switch on main spectrometer without large background rate

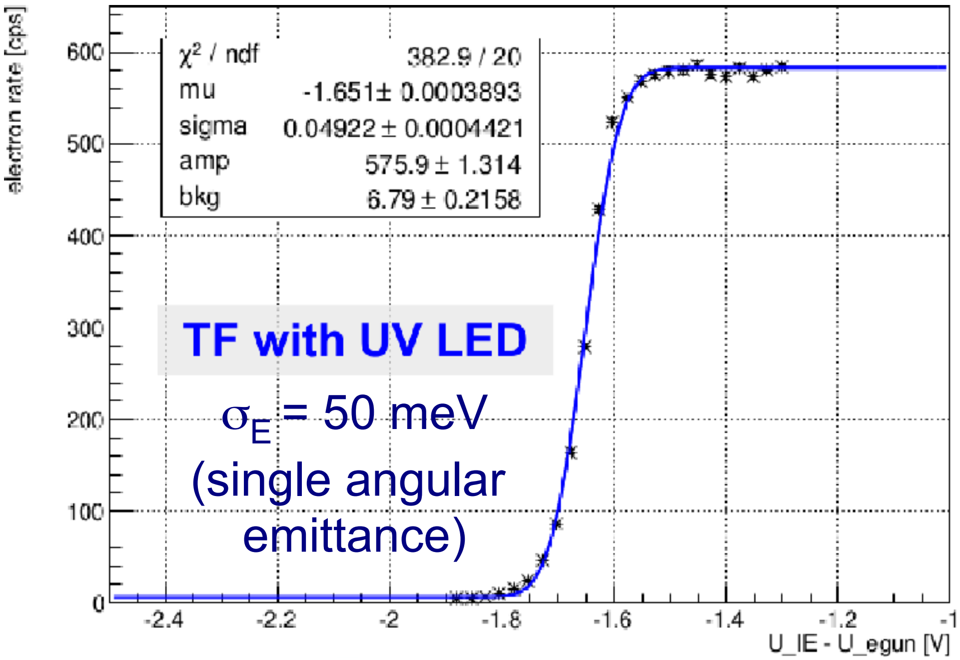
all other MAC-E-Filters (Troitsk, Mainz, KATRIN pre spectrometer) exhibited rates > 10^5 cps when switched on for the first time

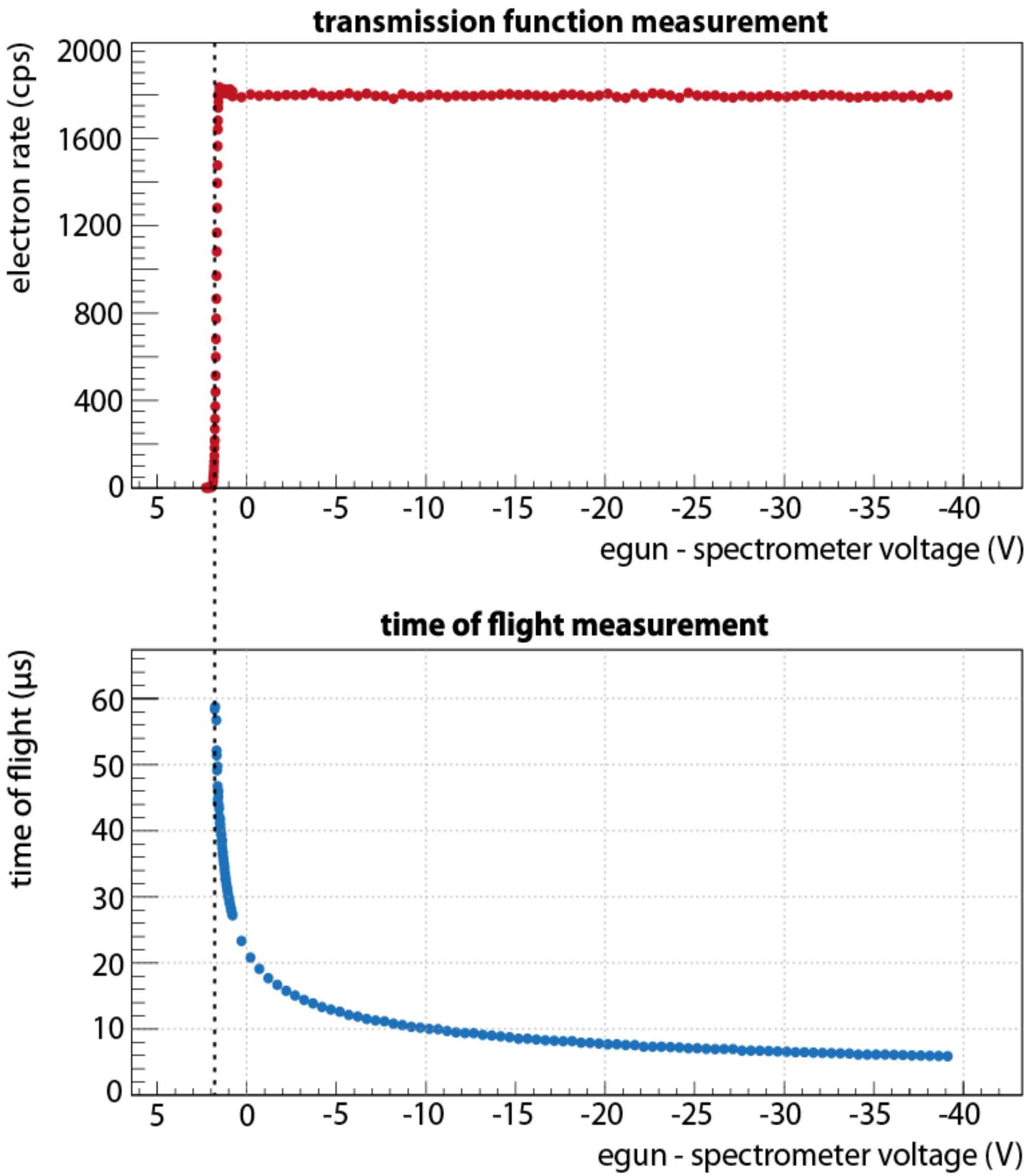
→ **No large Penning traps (advanced KATRIN design works)**

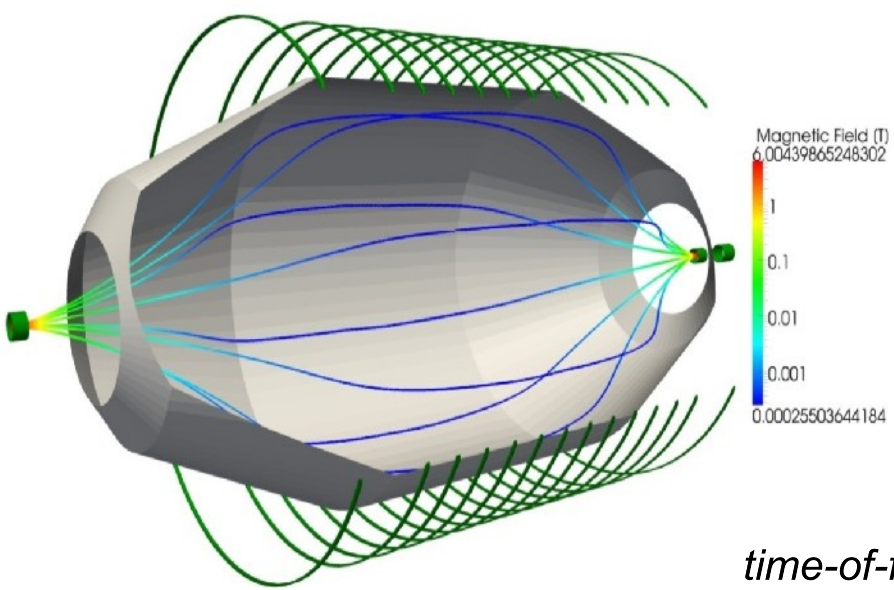
This first measurement without wire electrode on screening potential, LN_2 baffles cold and active counter measures against stored electrons

But still KATRIN requires a background rate of **10^{-2} cps**

Commissioning of main spectrometer and detector







time-of-flight, see also N. Steinbrink et al., NJP 15 (2013) 113020

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Suppress secondary electron background from walls on high potential

Secondary electrons from wall/electrode

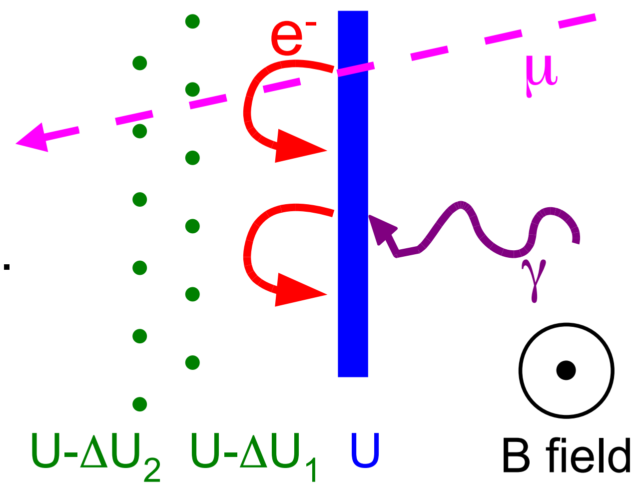
by cosmic rays, environmental radioactivity, ...

Excellent magnetic shielding by nearly perfect axial sym.

Additionally double layer wire electrode

on slightly more negative potential

(ca. 23,000 wires, 200 μm precision, UHV compatible)



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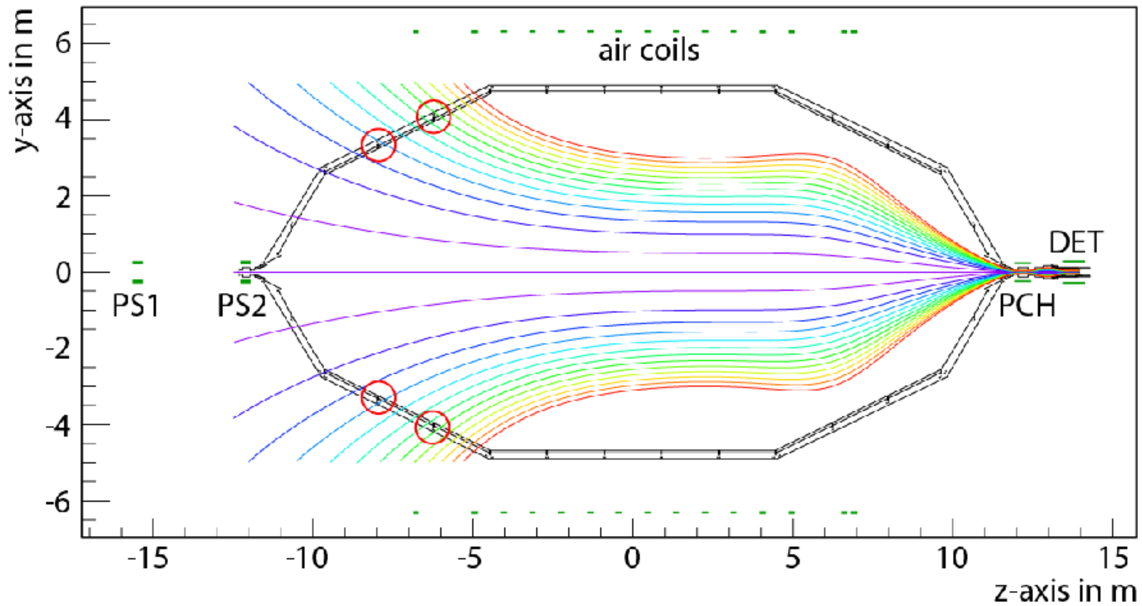
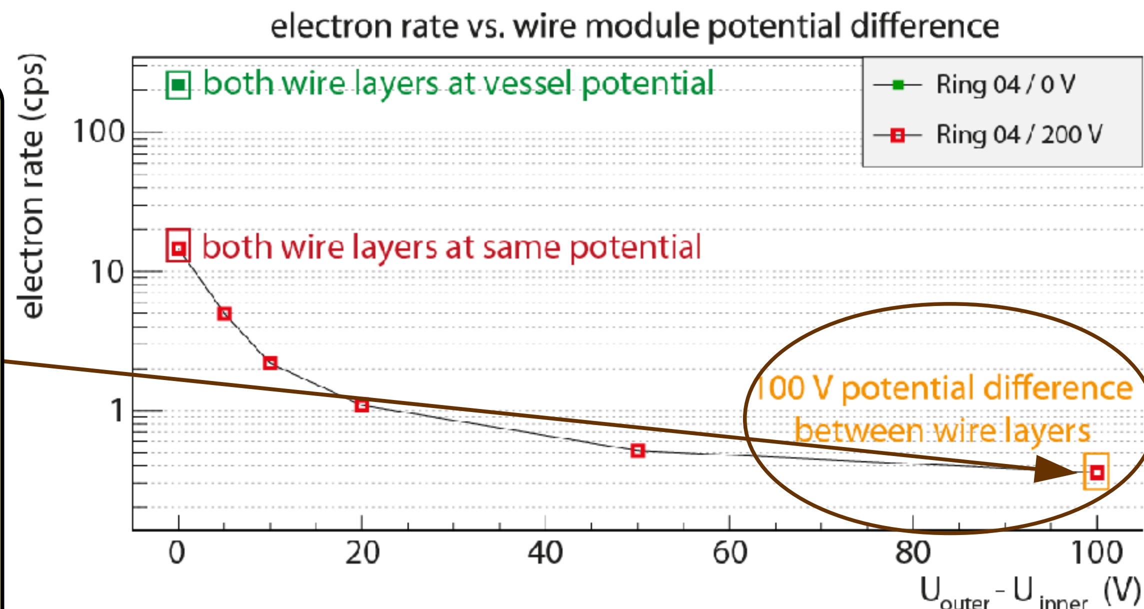
Background suppression by dual layer wire electrode

6 electric shorts between layer 1 and layer 2 of electrode system due to out-baking

→ test wire electrode shielding
by applying asymmetric B-fields
switching off magnetic shielding



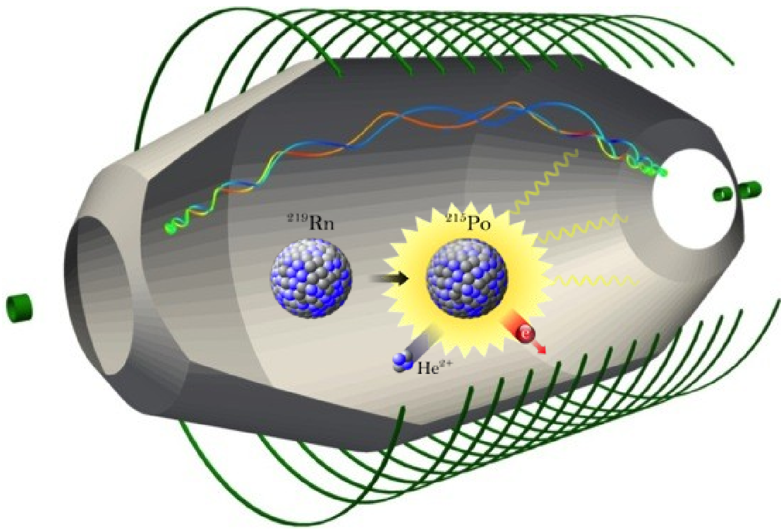


Secondary electrons from wall
- a lot, but screend by wire electrode
- dual wire electrode system is
order of magnitude more efficient

April 2014:
electric shorts in central cylindrical part of wire electrode removed !

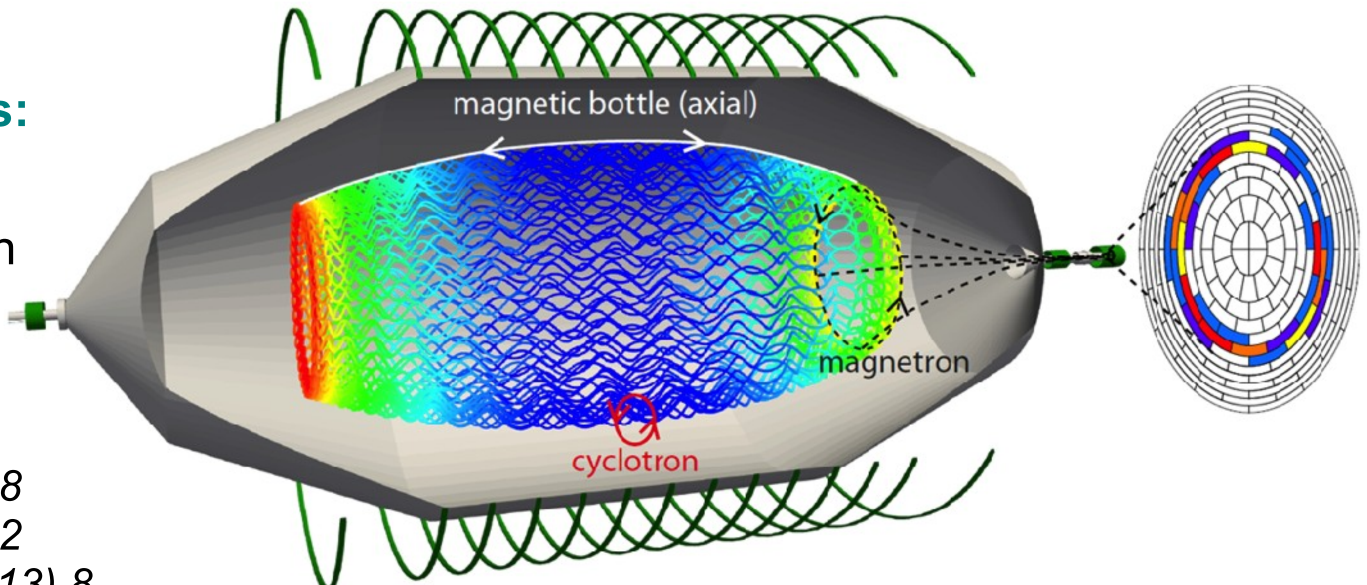
Secondary electron background from radon decays in the volume

- ^{219,220}**Rn emanation** mainly from SAES getter pumps (zirconium vanadium iron alloy)
  conversion, Auger, shake-off electrons can get stored
  my magnetic mirror effect



- **background process continues:**
  - ionization of residual gas → secondary electrons
  - primary electron energies: 100 eV < E < 500 keV
  - up to 5000 secondary electrons per stored primary
  - significant background increase for hours

- **stored multi-keV electrons:**
  rapid cyclotron motion
  intermediate axial oscillation
  slow magnetron drift



F. Fränkle et al., APP 35 (2011) 128
S. Mertens et al., APP 41 (2012) 52
N. Wandkowsky et al., NJP 15 (2013) 8

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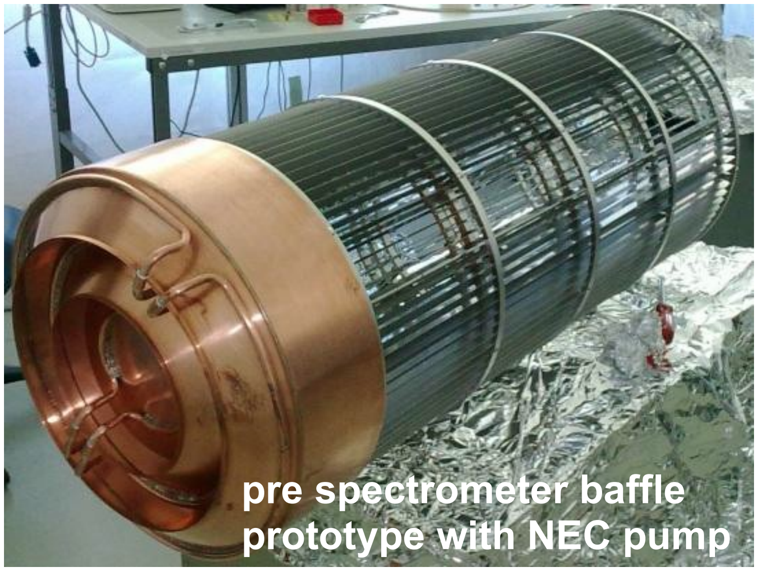
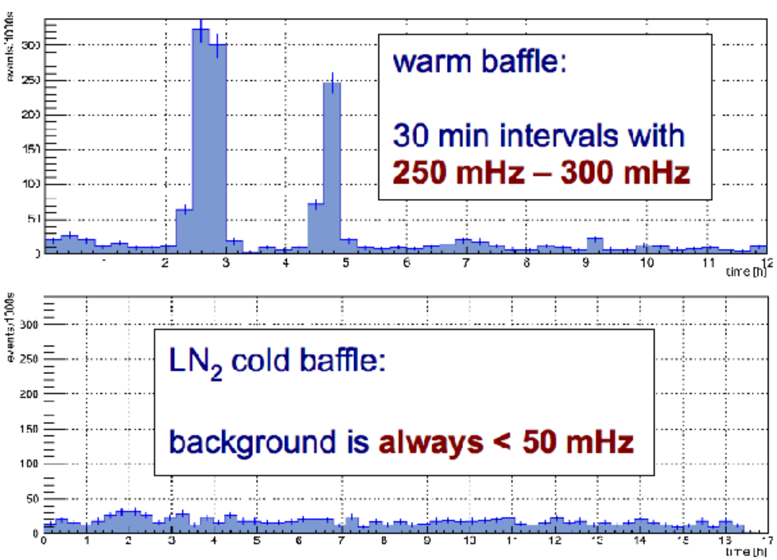
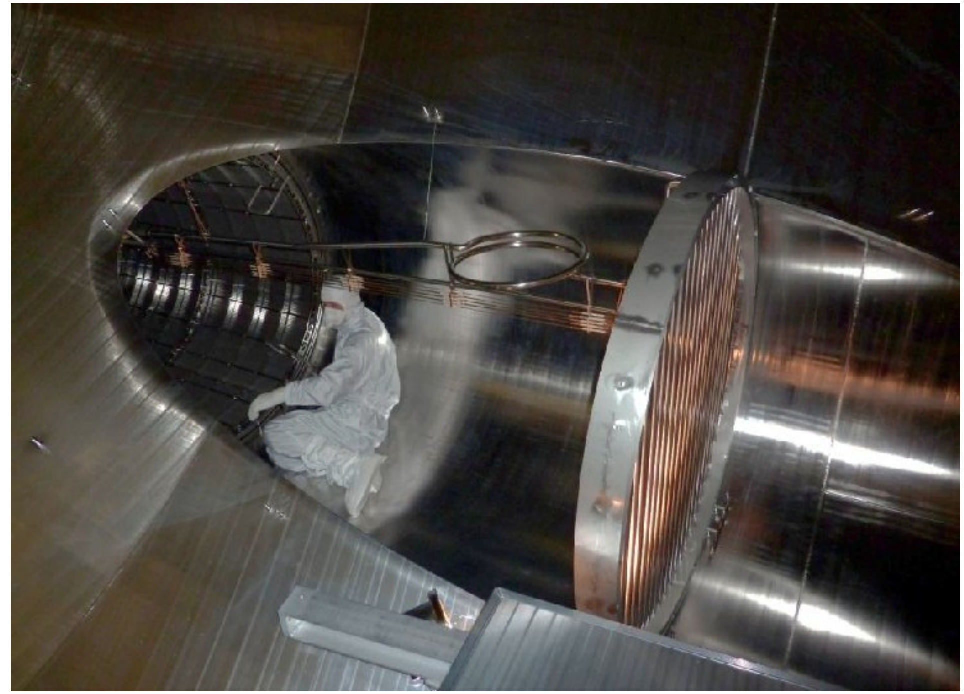
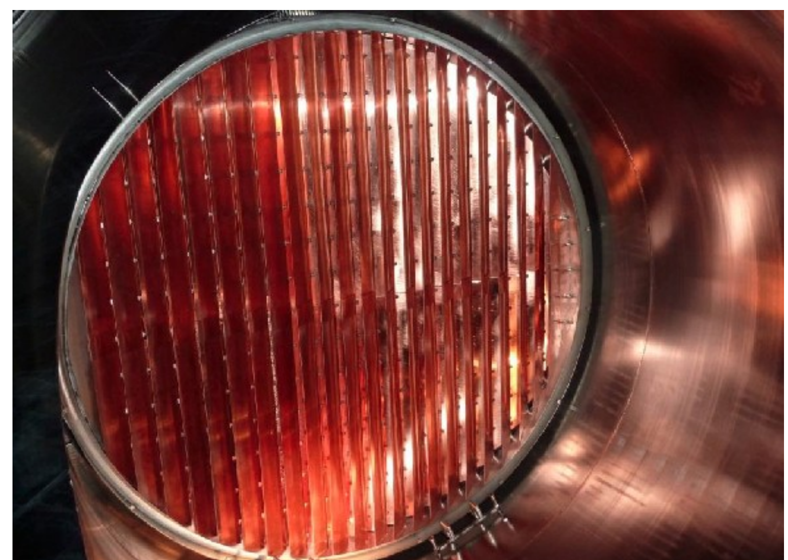
Radon elimination by LN_2-cooled baffles in the pre & main spectrometer



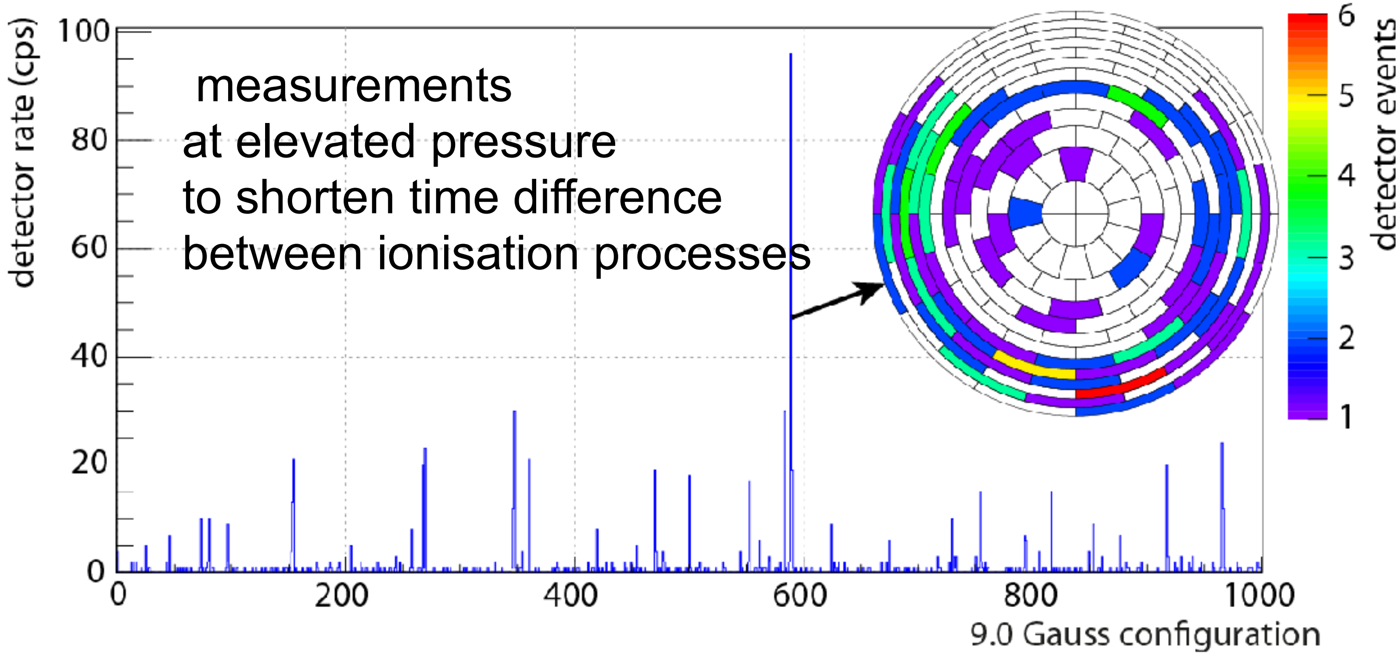


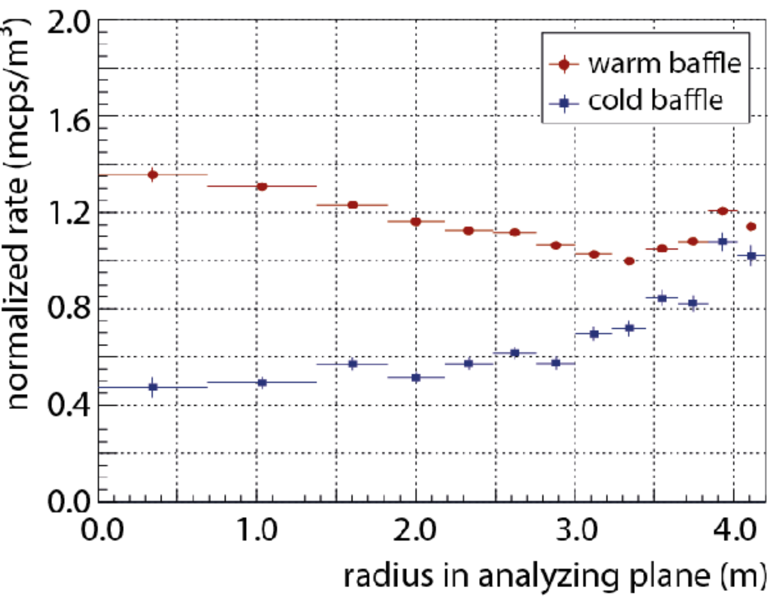


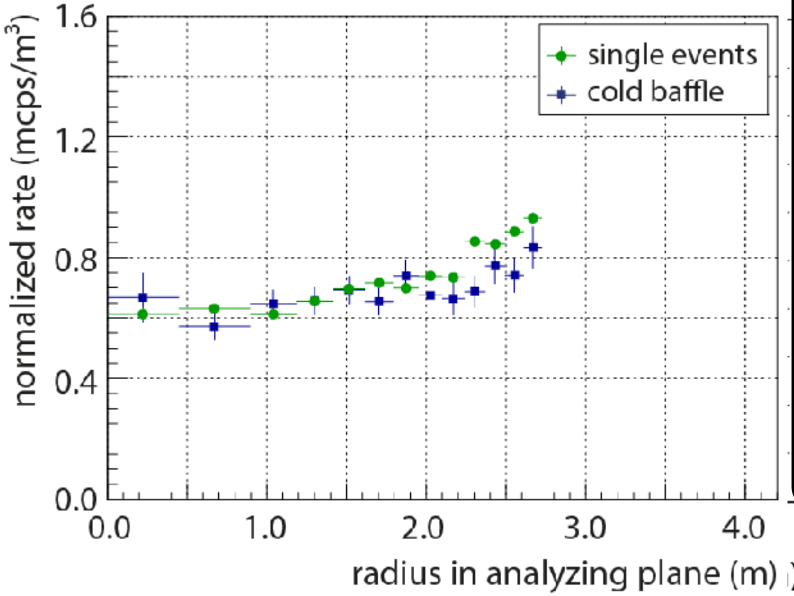


successful application at pre spectrometer

Understanding the background: Radon and other background sources







Very good background understanding:

spike pulses can also be removed by LN2 baffle

→ indeed stored electrons by radon decays

Active stored particle removal by electric dipole and magnetic zeroing

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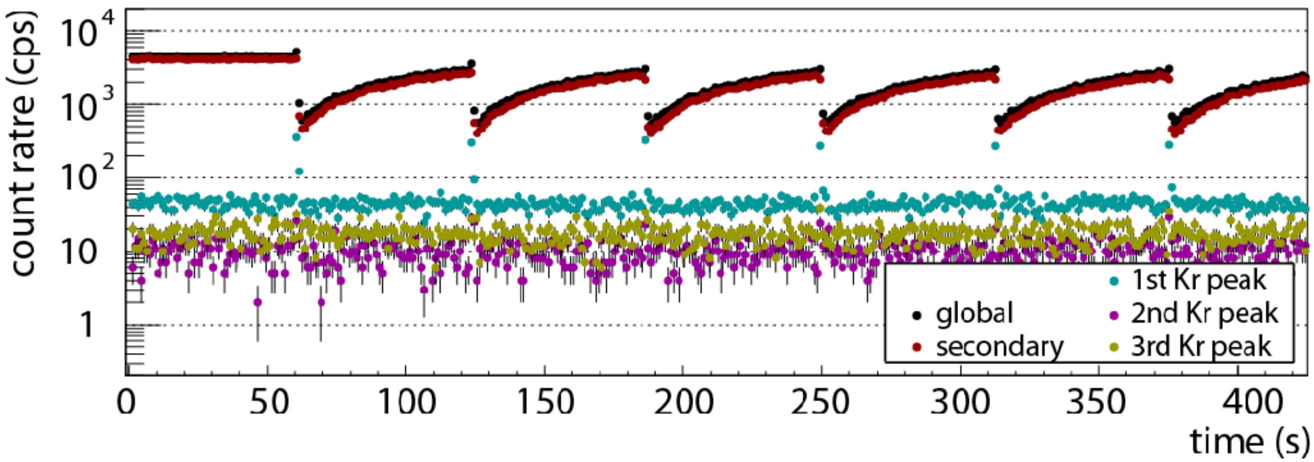
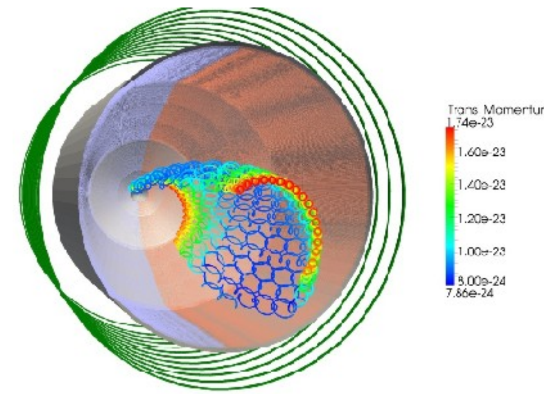
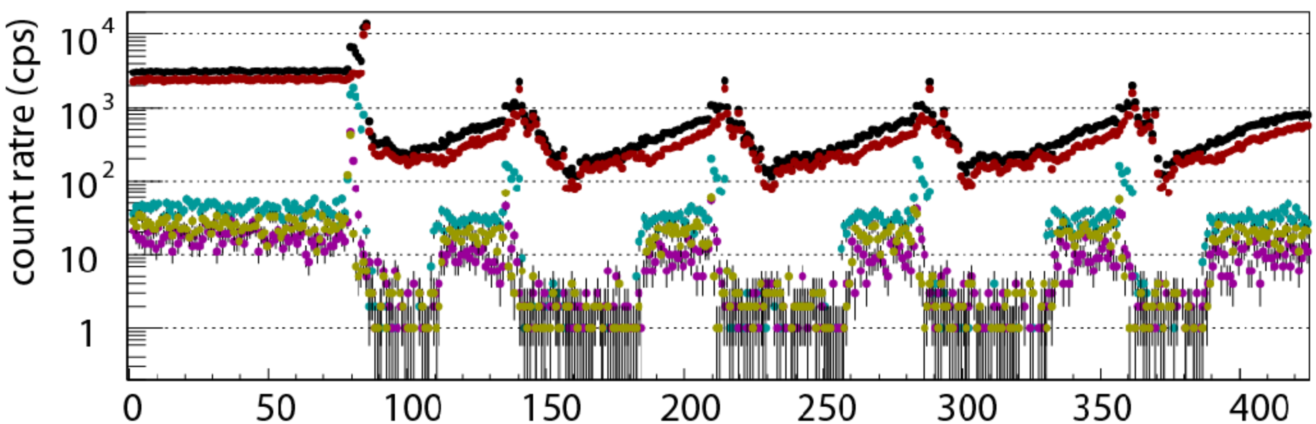
electric dipole

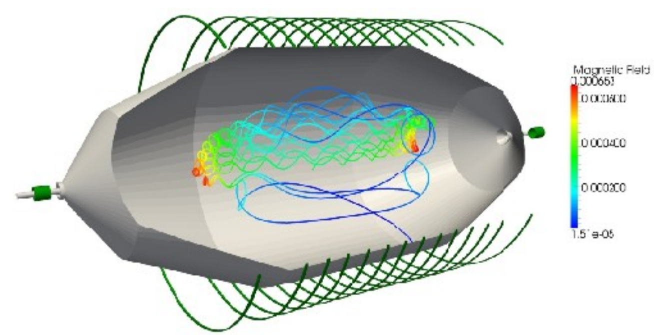




$\boldsymbol{v}_D = \mathbf{E} \times \mathbf{B} / B^2$

magnetic pulse





loss of magnetic guidance

^{83m}Kr injected to enhance no of stored particles

more details on the posters:

Monitoring of the KATRIN HV (M. Slezak, M. Erhard)
Active background reduction (D. Hilk, J. Behrens)
Main spectrometer commissioning (M. Kraus, T. Thümmler)
First spectrometer & detector measurements (S. Groh, N. Wandkowsky)

Systematic uncertainties

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

→ quantum mechanical thresholds help a lot !

A few contributions with $\Delta m_\nu^2 \leq$ 0.007 eV² each:

1. inelastic scatterings of β´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. WGTS charging due to remaining ions (MC: φ < 20mV)
   - **monocrystaline rear plate short-cuts potential differences**
4. final state distribution
   - **reliable quantum chem. calculations**

} tritium source

5. transmission function
   - detailed simulations, **angular-selective e-gun measurements**
6. HV stability of retarding potential on ~3ppm level required
   - **precision HV divider (with PTB)**, **monitor spectrometer beamline**

} spectrometer

Systematic uncertainties

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

→ quantum mechanical thresholds help a lot !

A few contributions with $\Delta m_\nu^2 \leq$ 0.007 eV² e

Measuring the last 25 or 30 eV only
KATRIN becomes nearly
a „single final state" experiment
as cryo-bolometers

1. inelastic scatterings of β´s inside WGTS
   - **dedicated e-gun measurements**, unfolding
2. fluctuations of WGTS column density (required < 0
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, **e-gun measurements**
3. WGTS charging due to r
   - **monocrystaline rea**
4. final state distribution
   - **reliable quantum ch**
5. transmission function
   - detailed simulations
6. HV stability of retarding
   - **precision HV divider (with PTB), monitor spectrometer beamline**

tritium source (1.–4.)

spectrometer (5.–6.)

sensitivity:

m_ν < 0.2eV (90%CL)

discovery potential:

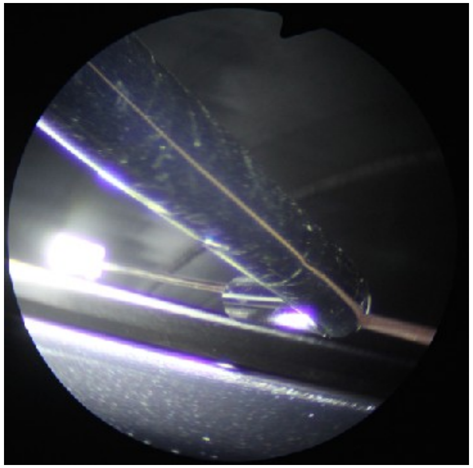
m_ν = 0.3eV (3σ)

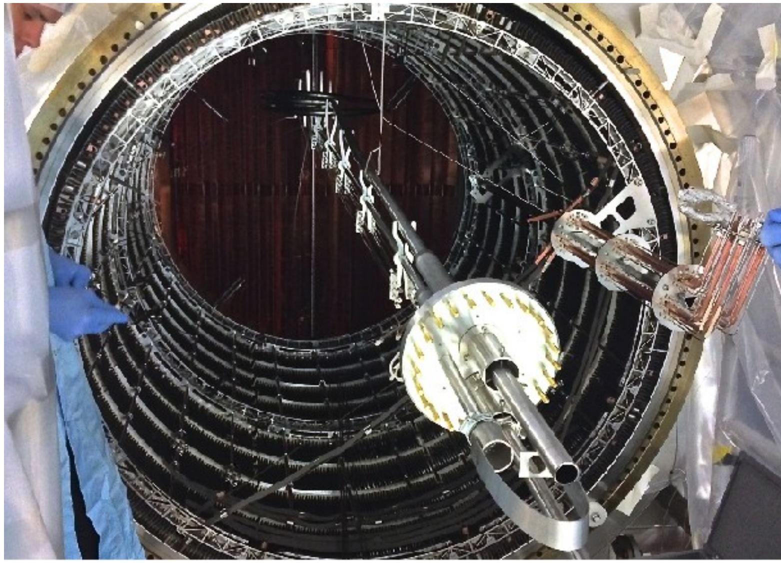
m_ν = 0.35eV (5σ)

KATRIN time line

- Commissioning spectrometer & detector phase 2 — Q3+4/2014

* dual layer wire electrode (in central part at least)
* better egun
* better alignment
* better high voltage settings
* full magnetic zeroing
* full operational LN_2 baffles
* electrical heated NEG pumps





- Tritium retention units DPS and CPS functional — Q2/2015

- Tritium source WGTS final mounting completed — mid-2015

- Spectrometer upgrade completed — Q3/2015

- All source elements & tritium loops integrated — Q4/2015

- First tritium in source, ramp up to nominal ρd — Q1-Q2/2016

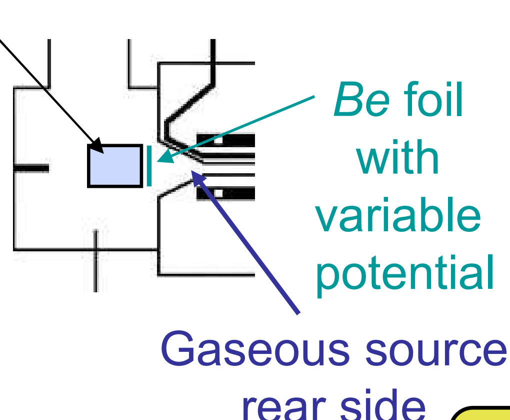
- First tritium data with entire beam line — mid-2016

Upgraded Troitsk nu mass setup and sterile neutrinos search

Upgrade of Troitsk exp.
aim to investigate KATRIN systematics and keV neutrinos

For KATRIN:

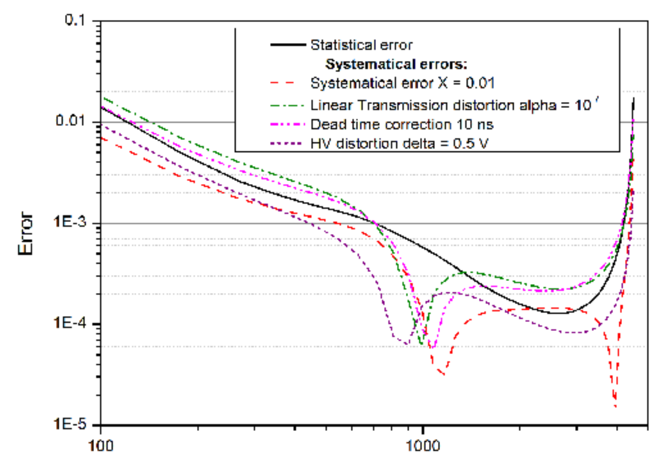
energy loss measurements
space charge experiment
E-gun



Sterile neutrino search up to m(ν_4) = 5 keV

with 1% of original source strength of 10^{17}cm^{-2}

Troitsk sensitivity



more details on the poster by V. Pantuev

eV sterile neutrino search with KATRIN (maybe also keV νs)

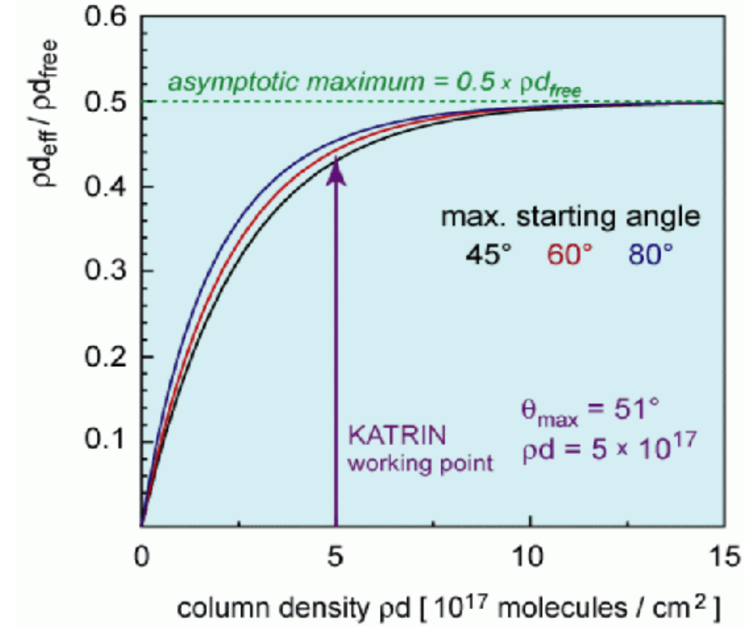
J. A. Formaggio, J. Barret, PLB 706 (2011) 68

A. Sejersen Riis, S. Hannestad, JCAP 02 (2011) 011

more details on the poster by S. Mertens

Can KATRIN be largely improved ?
Problems to be solved

1) The source is already opaque
   → need to increase size transversally
   magnetic flux tube conservation
   requests larger spectrometer too
   but a Ø100m spectrometer is not feasible

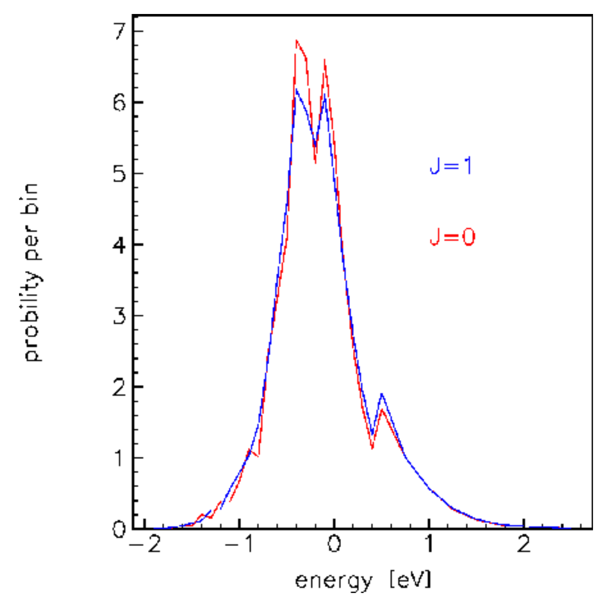


Three possible ways out:

a) source inside detector
using cryogenic bolometers (ECHo, HOLMES)
(see talk by L. Gastaldo)

b) hand-over energy information of β electron
to other particle (radio photon),
which can escape tritium source (Project 8)

c) make better use of the electrons
→ time-of-flight spectroscopy



2) Resolution is limited to $\sigma = 0.34$ eV
   when using molecular tritium by the
   excitation of ro-vibrational states in the final state

Project 8's goal: Measure coherent cyclotron radiation of tritium β electrons

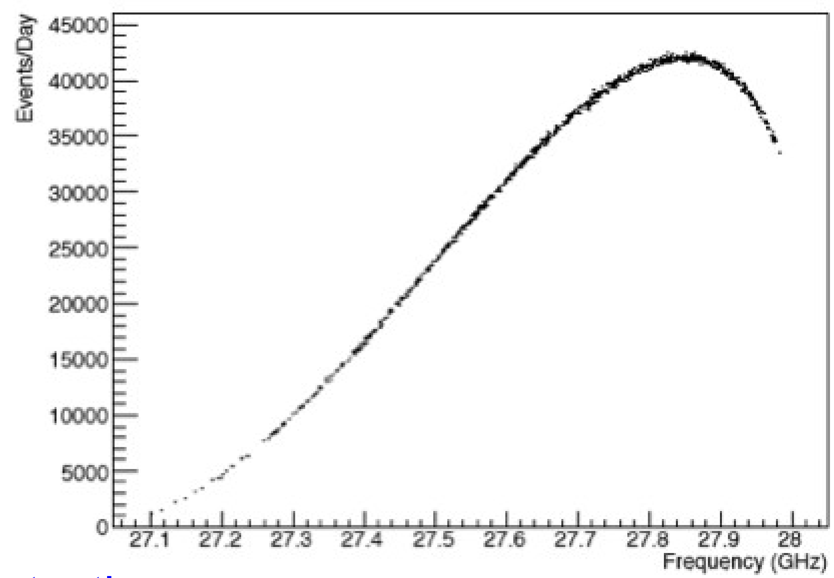
General idea: *B. Monreal and J. Formaggio, PRD 80 (2009) 051301*

- Source = KATRIN tritium source technology :

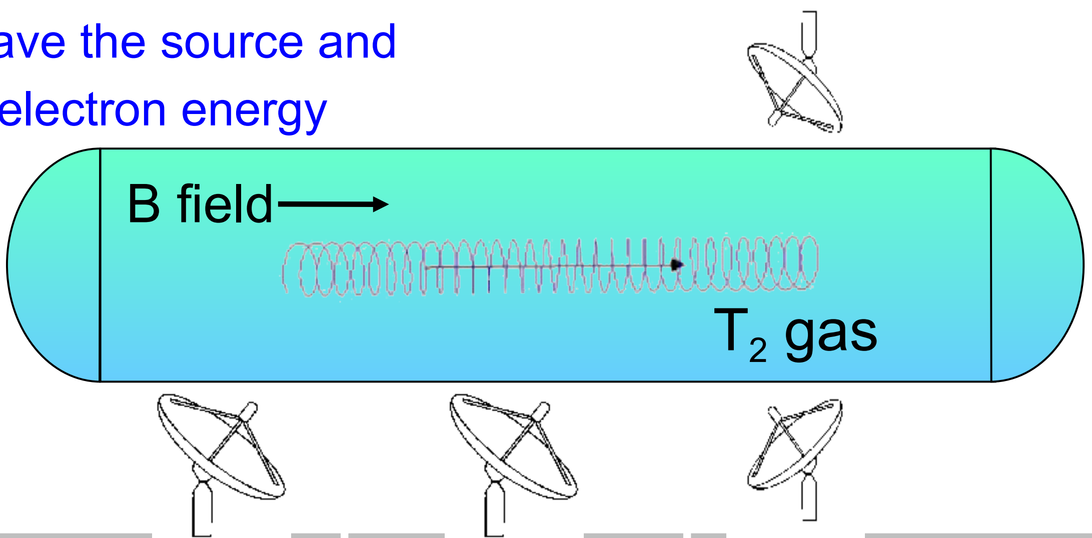
uniform B field + low pressure T_2 gas

β electron radiates coherent cyclotron radiation

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and
  carries the information of the β-electron energy



Westfälische Wilhelms-Universität Münster

Project 8's phase 1 goal: Detect single electrons from ^{83m}Kr

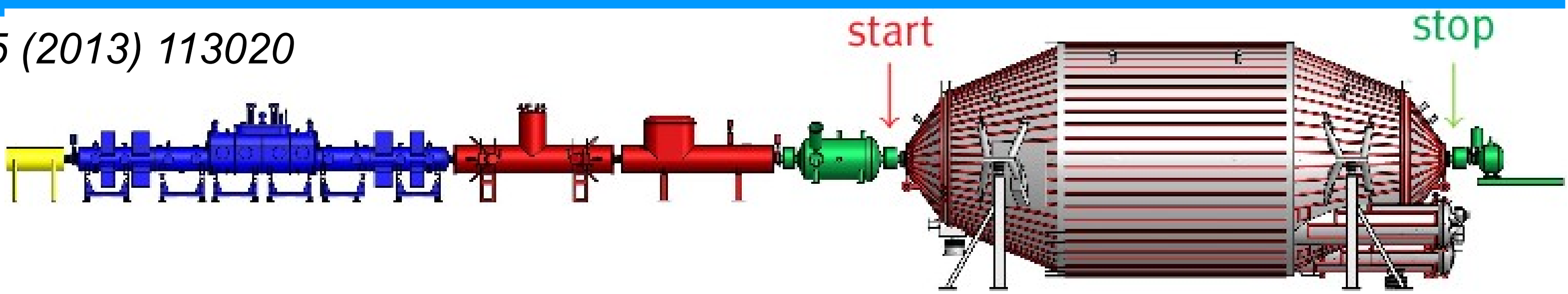
	Timeline	Scientific Goal	Source	R&D Milestone
Phase I	2010-2014	Proof of principle; Kr spectrum	^{83m}Kr	Single electron detection
Phase II	2014-2016	T-He mass difference	T_2	Tritium spectrum; calibration and error studies
Phase III	2016-2018	0.2 eV scale	T_2	
Phase IV	2018+	0.05 eV scale	T	High rate sensitivity

A lot of R&D necessary
- Is it really possible ?
- What are the systematic uncertainties & other limitations?

more details on the poster 134 by N. Oblath

Alternative spectroscopy: measure time-of-flight through KATRIN spectrometer

N. Steinbrink et al., NJP 15 (2013) 113020

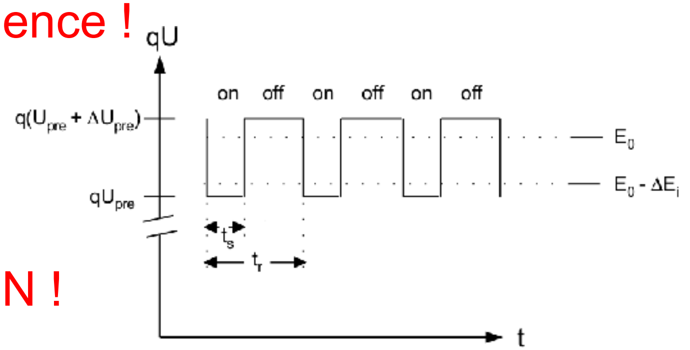


Advantage: measure full β-spectrum by time-of-flight at one (a few) retarding potential

Stop: Can measure time-of-arrival with KATRIN detector with Δt = 50 ns → ok

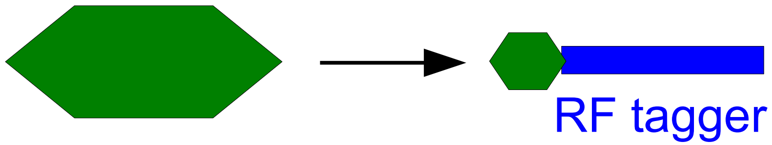
Start: e^--tagger: Need to determine time-of-passing-by of e^- before main spectrometer without disturbing energy and momentum by more than 10 meV:
→ Need „detector“ with 10 meV threshold
seems not to be forbidden but unrealistic for the near future !
Added value: significant background reduction by coincidence !

→ factor 5 in $\Delta m(\nu)^2_{stat}$ under ideal cond.



or: Use pre spectrometer as a „gated-filter“
by switching fast the retarding voltage
→ As sensitive on the neutrino mass as standard KATRIN !

or: Reduce pre spectrometer to a minimal small one,
add a Project 8-type tagger within a long solenoid



Summary

KATRIN is the next generation direct neutrino mass experiment

with a neutrino mass sensitivity of 200 meV

it looks also to sterile eV neutrinos (and maybe to keV neutrinos)

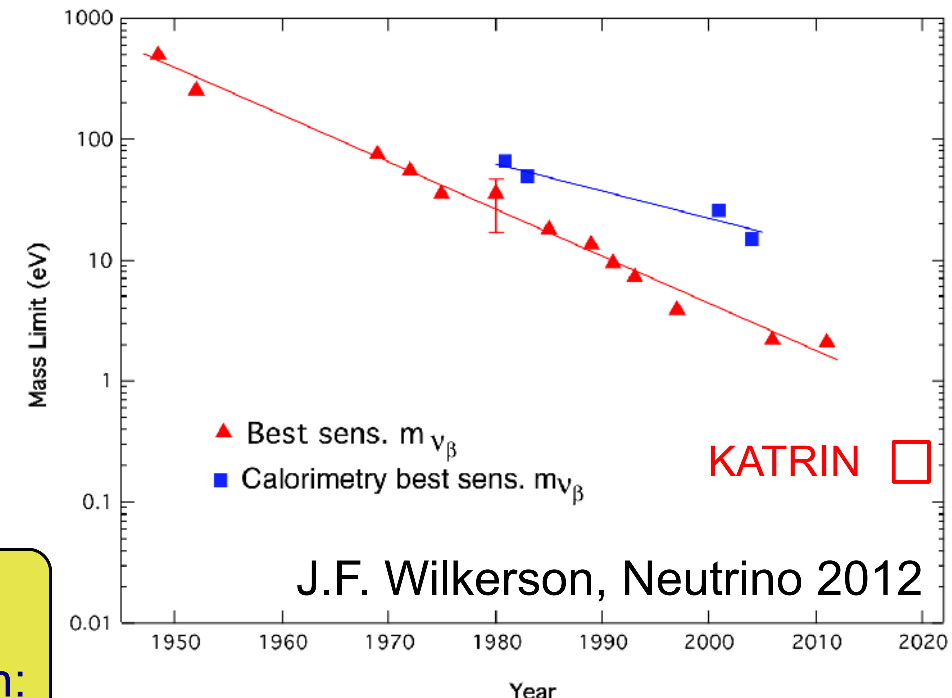
Main spectrometer & detector successfully commissioned (phase 1)

Tritium source and electron transport/tritium retention system on a good way

Start regular data taking in 2016 !

Troitsk nu mass setup upgraded:
- helps KATRIN, own keV ν program

Outlook to further improvements:
- Project 8: does it work ?
- Time-of-flight: how to realize e^- tagging ?



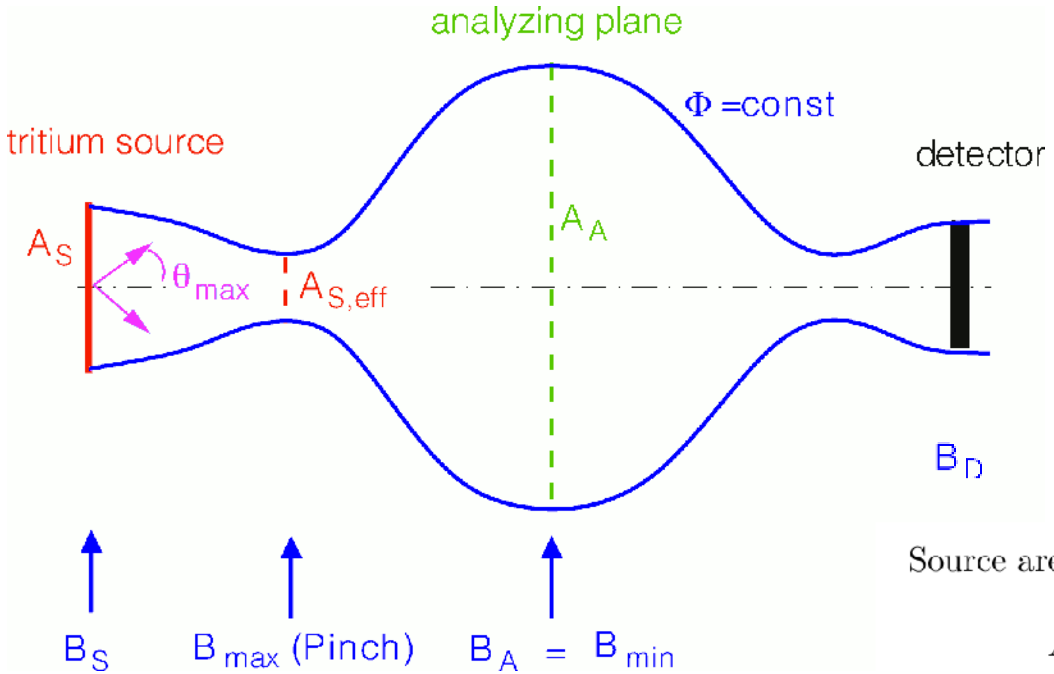
THANK YOU FOR YOUR ATTENTION !

Many thanks to those who provided me information:
G. Drexlin, J. Formaggio, N. Oblath,
T. Thümmler, V. Pantuev, N. Titov

EXTRA SLIDES

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

Enlarging the strength of the KATRIN tritium source ?



→ max. count rate near E_0 is limited:

$S \propto A_A \, \Delta E / \sigma_{inelastic}$

cannot make source thinkness larger

source area transversally limited by $A_A \cdot \Delta E$

Adiabatic constant (local magnetic flux conservation):

$$const. = \gamma \cdot \mu = \frac{p_\perp^2}{2mB} \overset{non-rel.}{\approx} \frac{E_\perp}{B}$$

Magnetic flux conservation:

$$\Phi = \int B \, dA = B_S \cdot A_S = B_{max} \cdot A_{S,eff} = B_A \cdot A_A$$

Magnetic pinch effect:

$$\theta_{max} = \arcsin \sqrt{B_S / B_{max}}$$

Accepted solid angle:

$$\frac{\Delta\Omega}{2\pi} = 1 - \cos\theta_{max}$$

Source area:

$$A_S = A_{S,eff} \cdot \frac{B_{max}}{B_S} = A_A \cdot \frac{B_A}{B_{max}} \cdot \frac{B_{max}}{B_S} = A_A \cdot \frac{\Delta E}{E} \cdot \frac{1}{\sin^2\theta_{max}}$$

Source area times acceptance solid angle:

$$A_S \cdot \frac{\Delta\Omega}{2\pi} = A_A \cdot \frac{\Delta E}{E} \cdot \frac{1 - \cos\theta_{max}}{\sin^2\theta_{max}} = A_A \cdot \frac{\Delta E}{E} \cdot \frac{1}{1 + \cos\theta_{max}} \overset{A_S \to \infty}{\longrightarrow} A_A \cdot \frac{\Delta E}{E} \cdot \frac{1}{2}$$

Count rate near endpoint (no inelastic scattering):

$$\begin{aligned} S &= A_S \cdot \frac{\Delta\Omega}{2\pi} \cdot a \cdot \varepsilon_T \cdot \rho d \cdot P_0(\rho d, \theta_{max}) \\ &= A_A \cdot \frac{\Delta E}{E} \cdot a \cdot \varepsilon_T \cdot \underbrace{\frac{\rho d \cdot P_0(\rho d, \theta_{max})}{1 + \cos\theta_{max}}}_{:= (\rho d)_{eff}} \end{aligned}$$

$$\overset{A_S,\ d \to \infty}{\longrightarrow} \underbrace{A_A}_{cross\ section\ of\ spectrometer} \cdot \underbrace{\frac{\Delta E}{E}}_{energy\ resolution} \cdot a \cdot \varepsilon_T \cdot \underbrace{\frac{\rho d_{free}}{2}}_{1/(2\sigma_{inelastic})}$$

Summary: β-spectrum incl. electronic final states + ν mixing

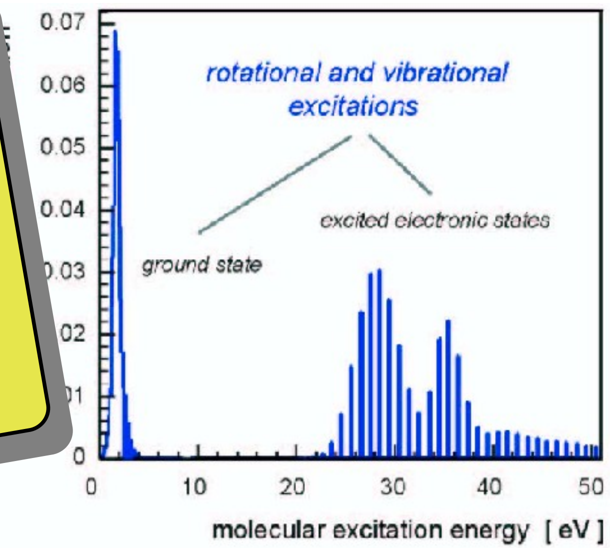
Including electronic excited final states of excitation energy V_j with probability W_j

$$W_j = |\langle \Psi_0 | \Psi_{f,j} \rangle|^2$$

⇒ **electronic final states are important**

Using $\varepsilon_j = E_0 - V_j - E$

$$\frac{d^2N}{dt\,dE} = A \cdot F(E, Z+1) \cdot p \cdot (E+m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \sqrt{\varepsilon_j^2 - m^2(\nu_c)} \cdot \Theta(\varepsilon_j - m(\nu_c))$$



Final states c...

A. Saenz et al. P...

N. Doss et al., P...

The electron spectrum coming out of a β-source is even more complicate due to inelastic scattering, backscattering. ...

Including neutrino mixing

$$\frac{d^2N}{dt\,dE} = A \cdot F(E, Z + \ldots$$

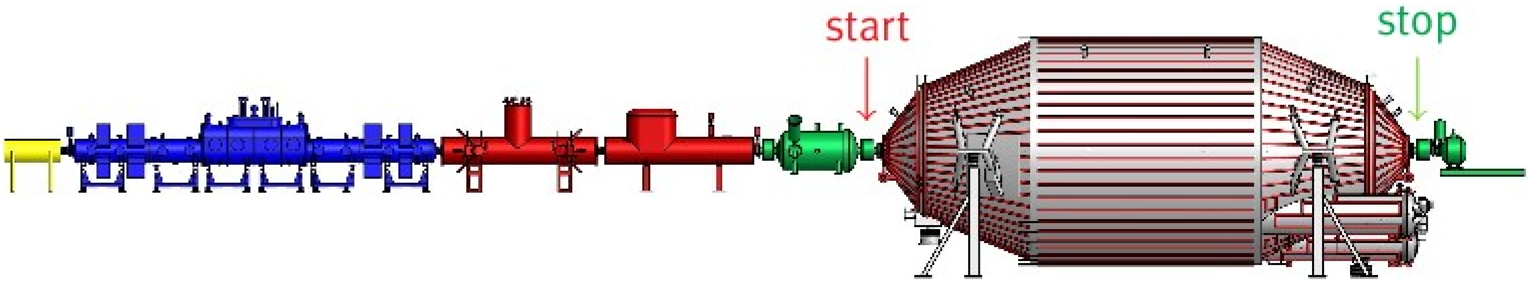
$$\cdot \sum_j W_j \cdot \varepsilon_j \cdot \left(\sum_i |U_{ci}|^2 \sqrt{\varepsilon_j^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i)) \right)$$

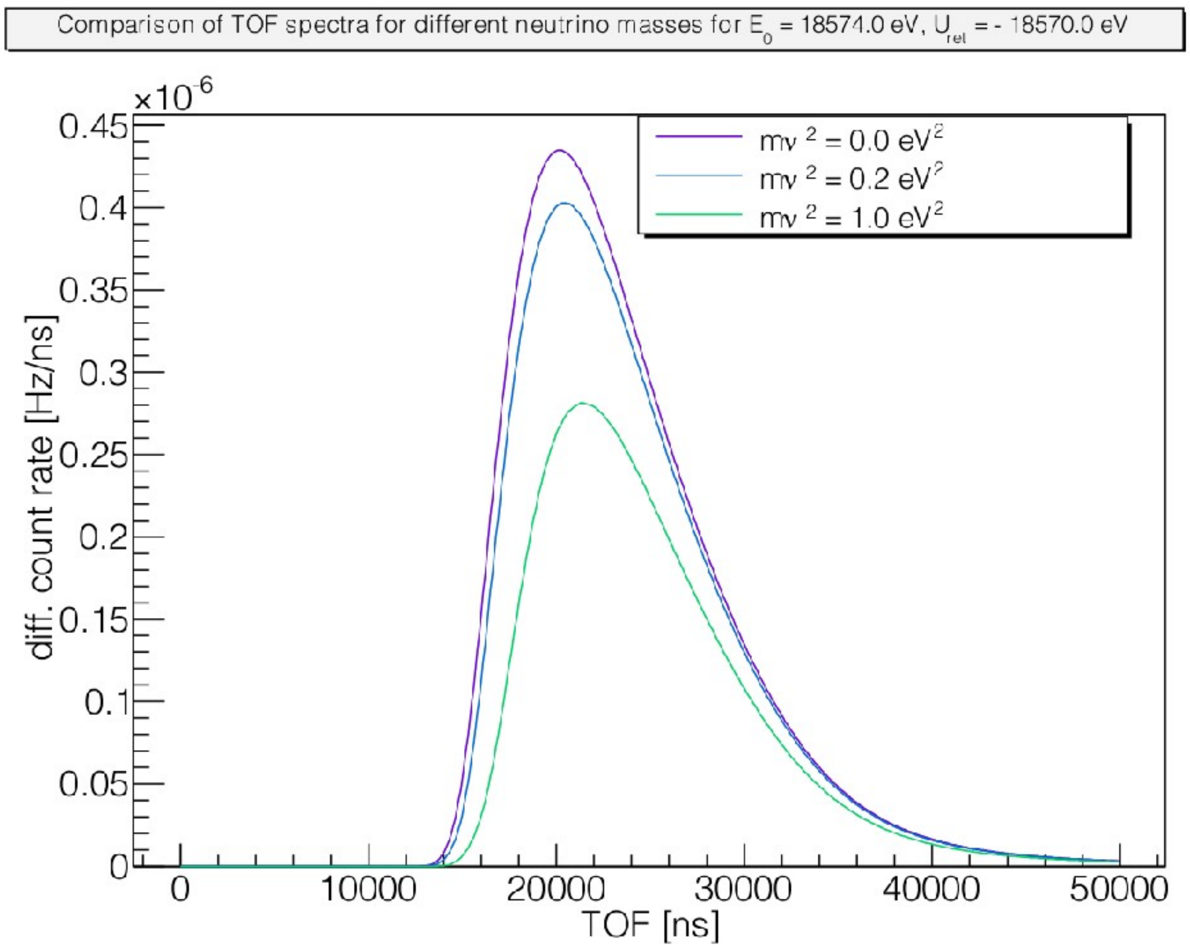
⇒ **the different $m(\nu_i)$ are not important at present precision**

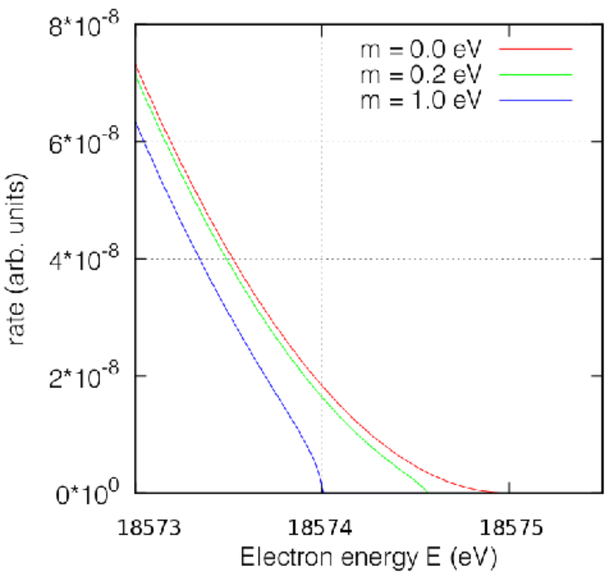
⇒ "Electron neutrino mass"

$$m^2(\nu_c) := \sum_i |U_{ci}|^2 \cdot m^2(\nu_i)$$

Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer





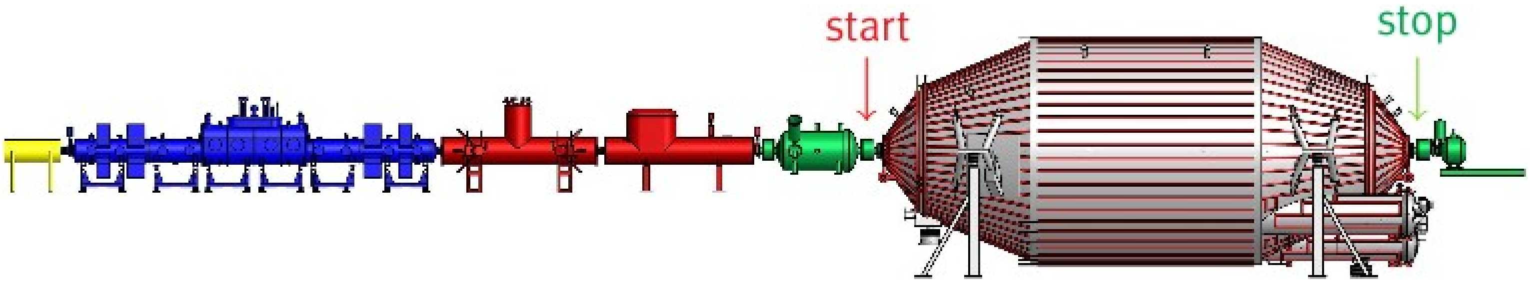


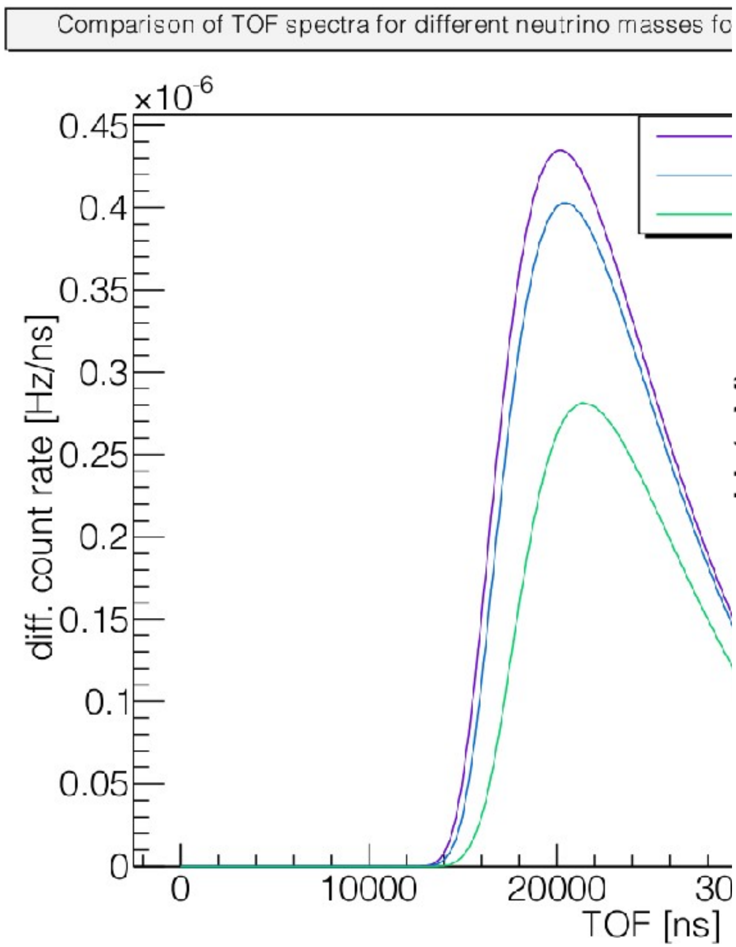
Time-of-flight spectrum is sensitive to the neutrino mass

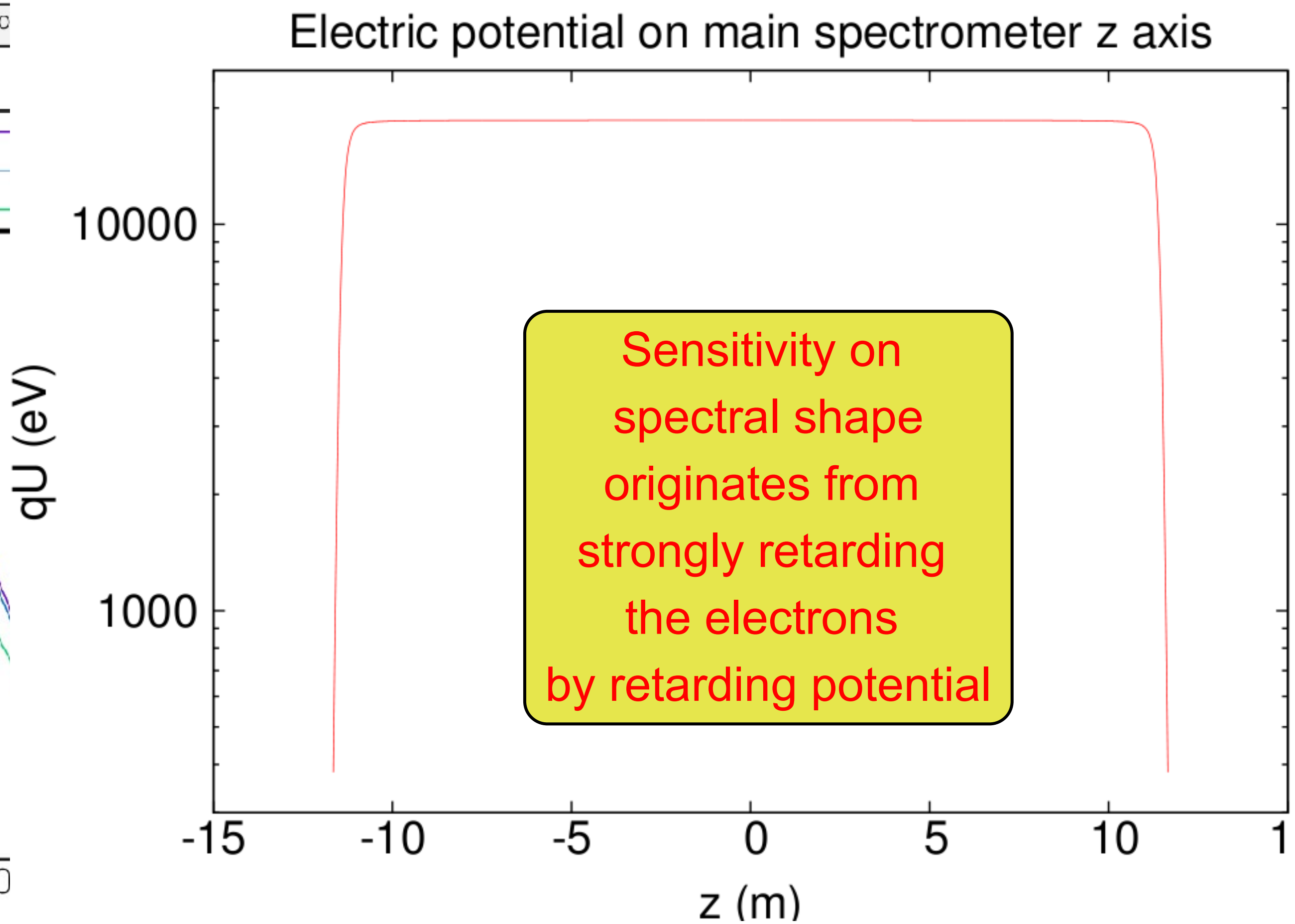
require one retardation potential only

not integral but differential β-spectrum

Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer







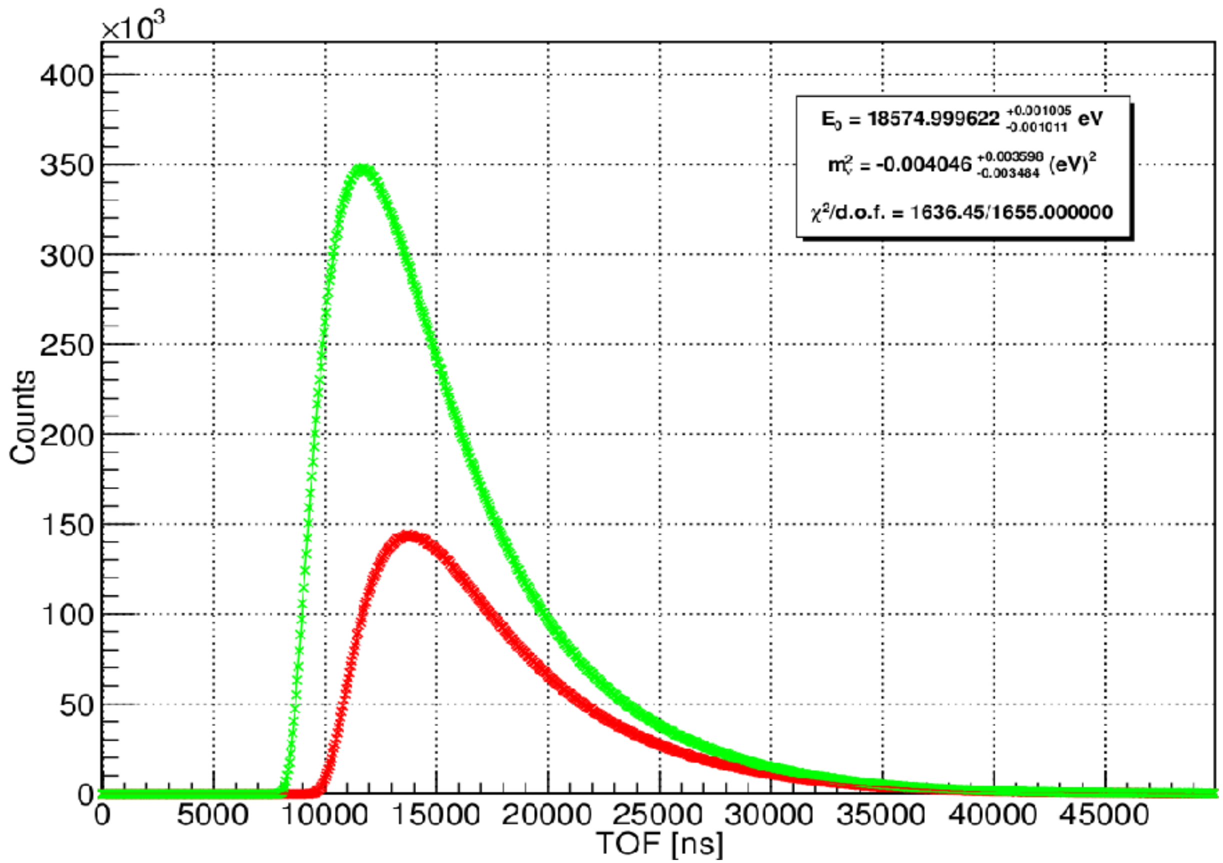
Sensitivity on spectral shape originates from strongly retarding the electrons by retarding potential

Sensitvity improvement on $m^2(\nu_e)$ by ideal TOF determination

Measure at 2 (instead of ≈30) different retarding potentials since TOF spectra contain all the information

Coincidence request between start and stop signal → nice background suppression

→ Factor 5 improvement in m_ν^2 w.r.t. standard KATRIN, but ideal case !



N. Steinbrink et al.
NJP 15 (2013) 113020

Very successful cool-down and stability tests of the WGTS demonstrator

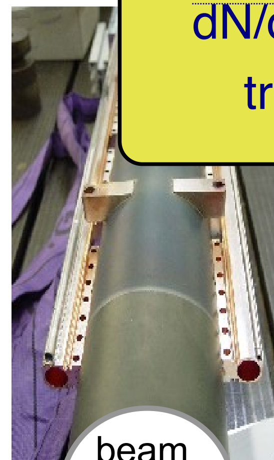
Westfälische Wilhelms-Universität Münster

arrival of WGTS demonstrator at KIT: April 2010

per mill stability source strength request:

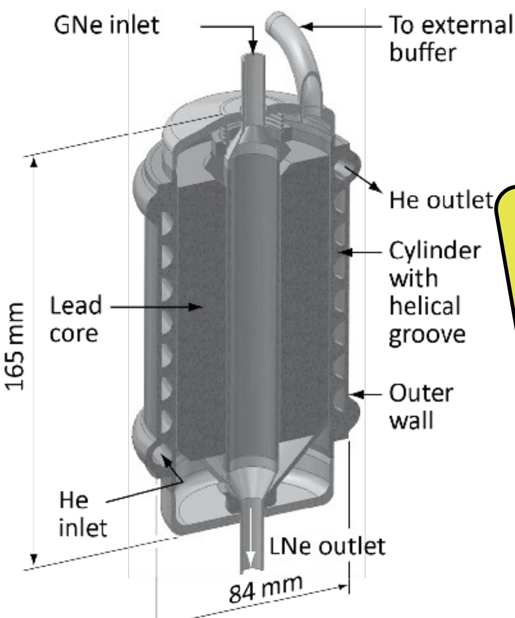
$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p \cdot V / R\, T$

tritium fraction f_T & ideal gas law

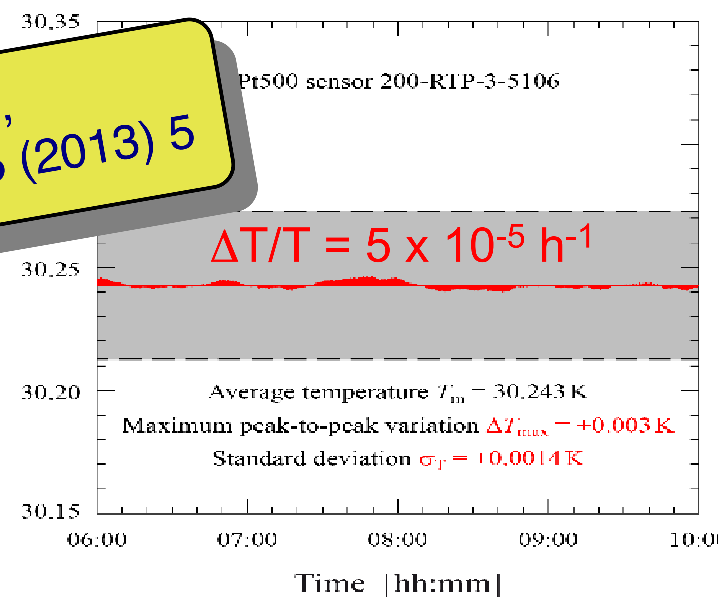


beam tube Ø=90mm

cooling concept of WGTS: pressurized 2-phase Ne



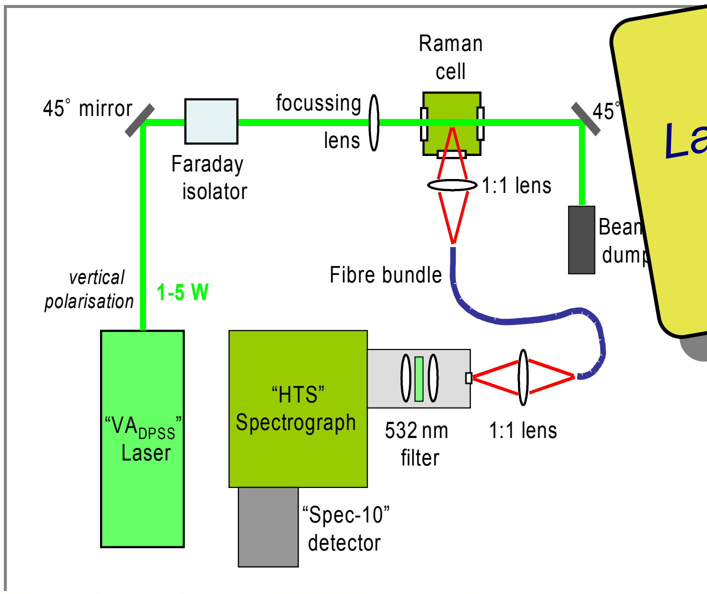
S. Grohmann et al., Cryogenics, Cryogenics 55 (2013) 5



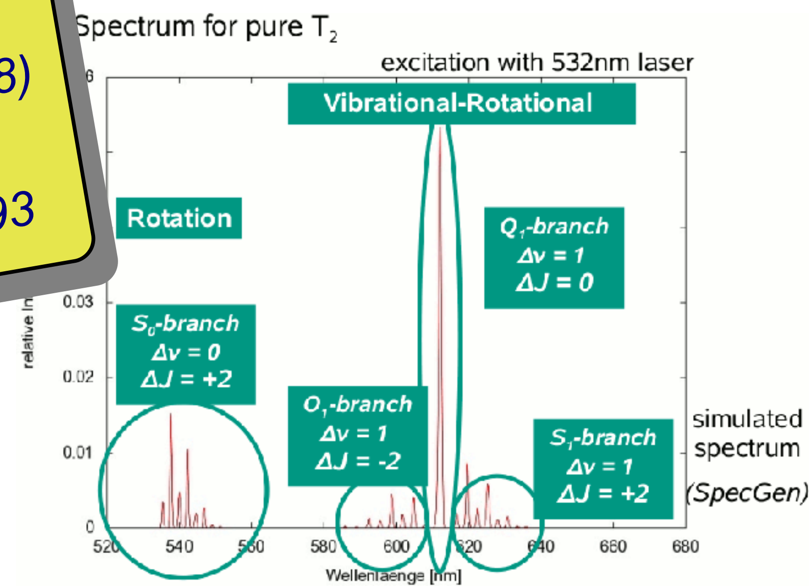
Currently: constructing of WGTS out of demonstrator

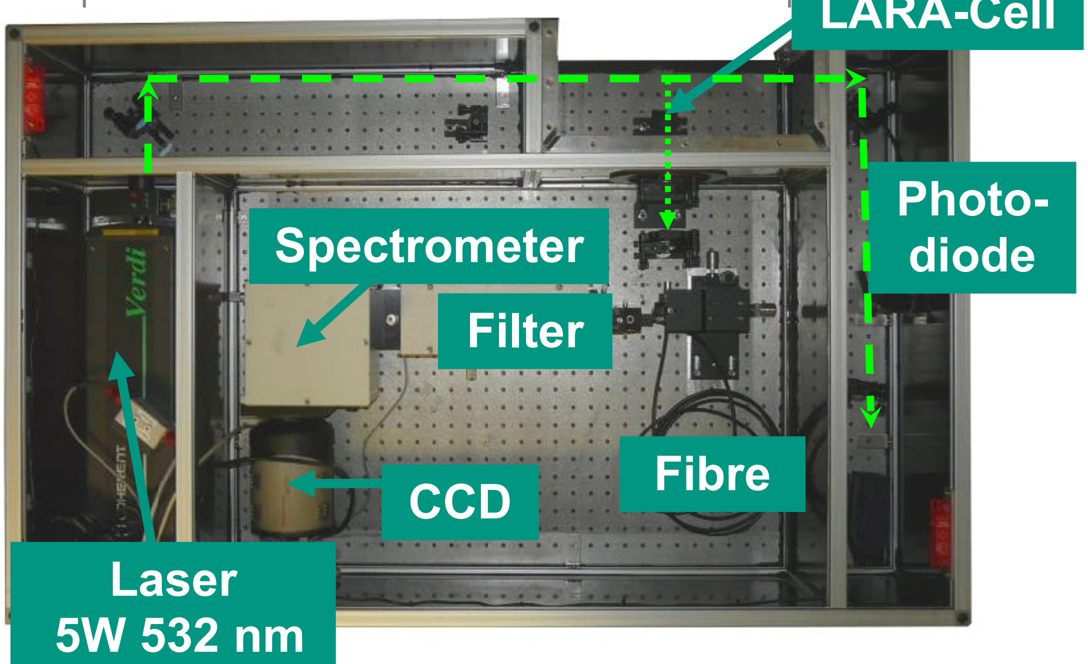
Westfälische Wilhelms-Universität Münster

Measurement of tritium concentration by laser Raman spectroscopy

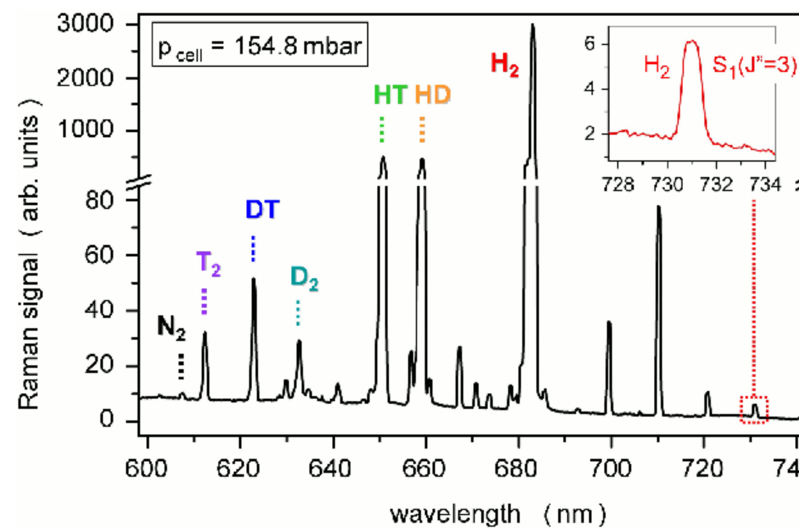


R.J. Lewis et al.,
Las. Phys. Lett.1-10 (2008)
M.Sturm et al,
Las. Phys. 20 (2010) 493



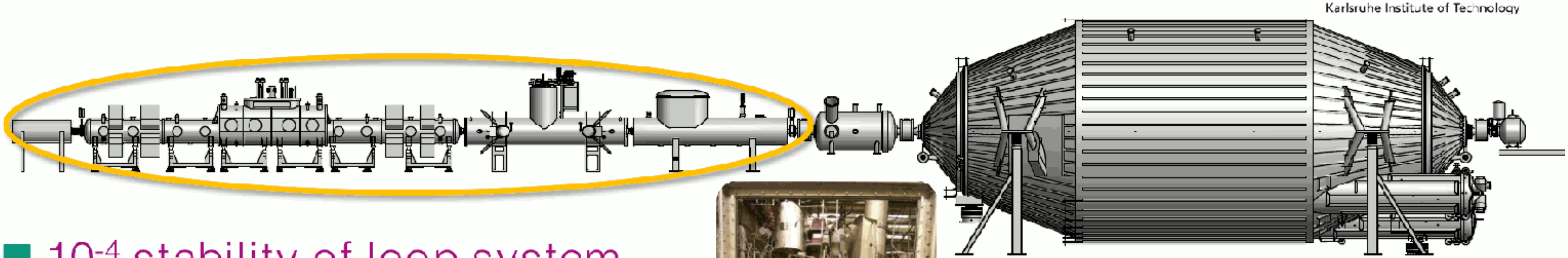


H_2 / HD / T_2 / DT / HT
= 0.820 / 0.083 / 0.003 / 0.005 / 0.085

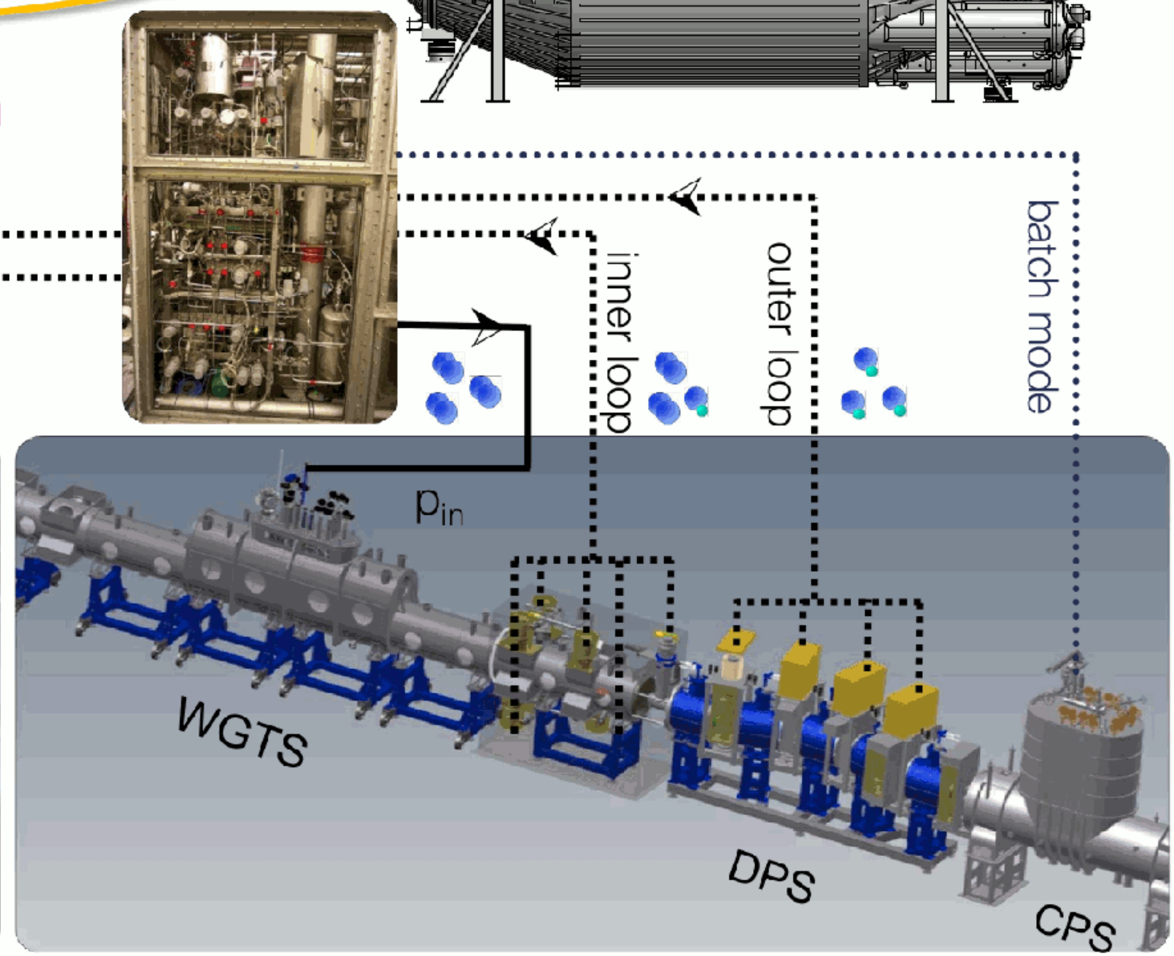


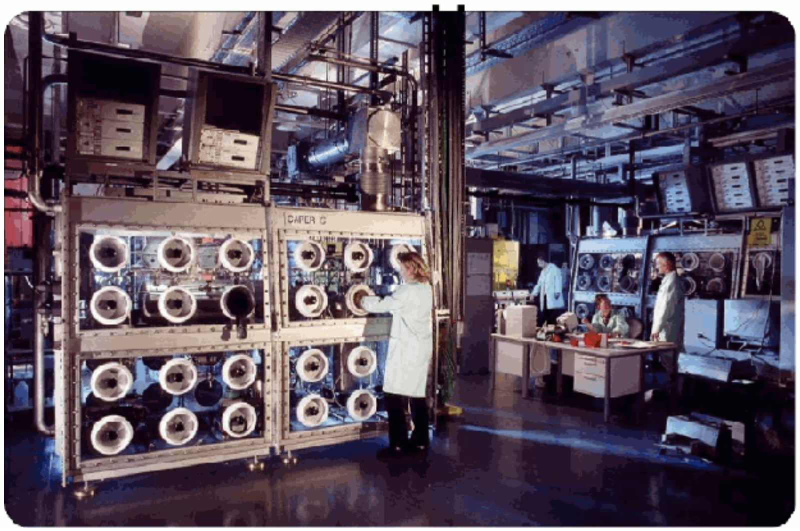
Tritium loops at Tritium Laboratory Karlsruhe

tritium source: loop system



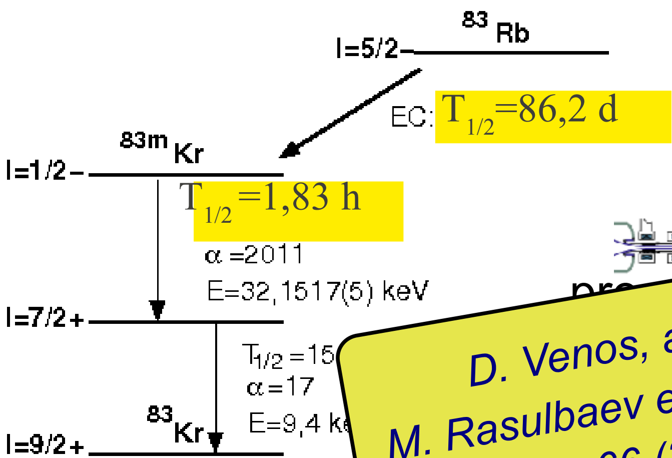
- 10^{-4} stability of loop system achieved for p_{in} in test set-up





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

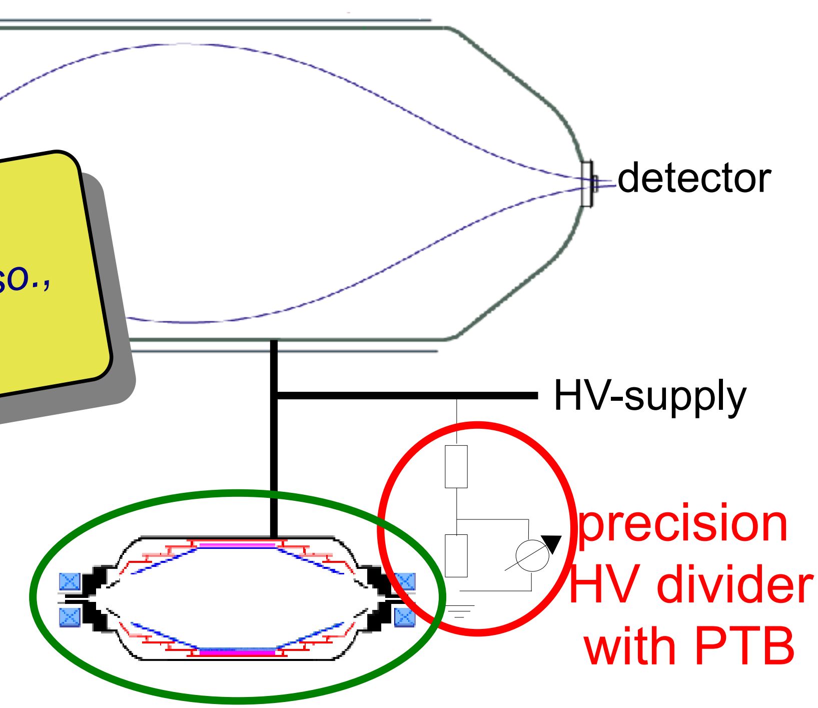
- Measure HV by precision HV divider
- Lock retarding HV by measuring energetically well-defined electron line with monitor spectrometer



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

^{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

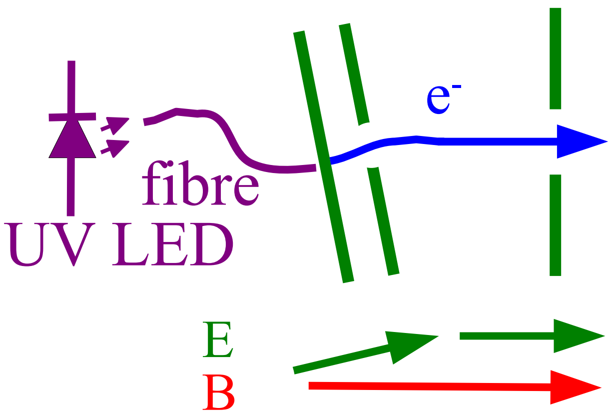
A new pulsed angular-defined UV LED photoelectron source

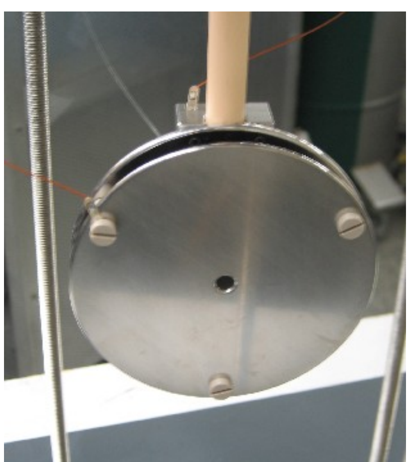
K. Valerius et al., NJP 11 (2009) 063018
K. Valerius et al., JINST 6 (2011) P01002
K. Hugenberg, Prog. Part. Nucl. Phys. 64 (2010) 288

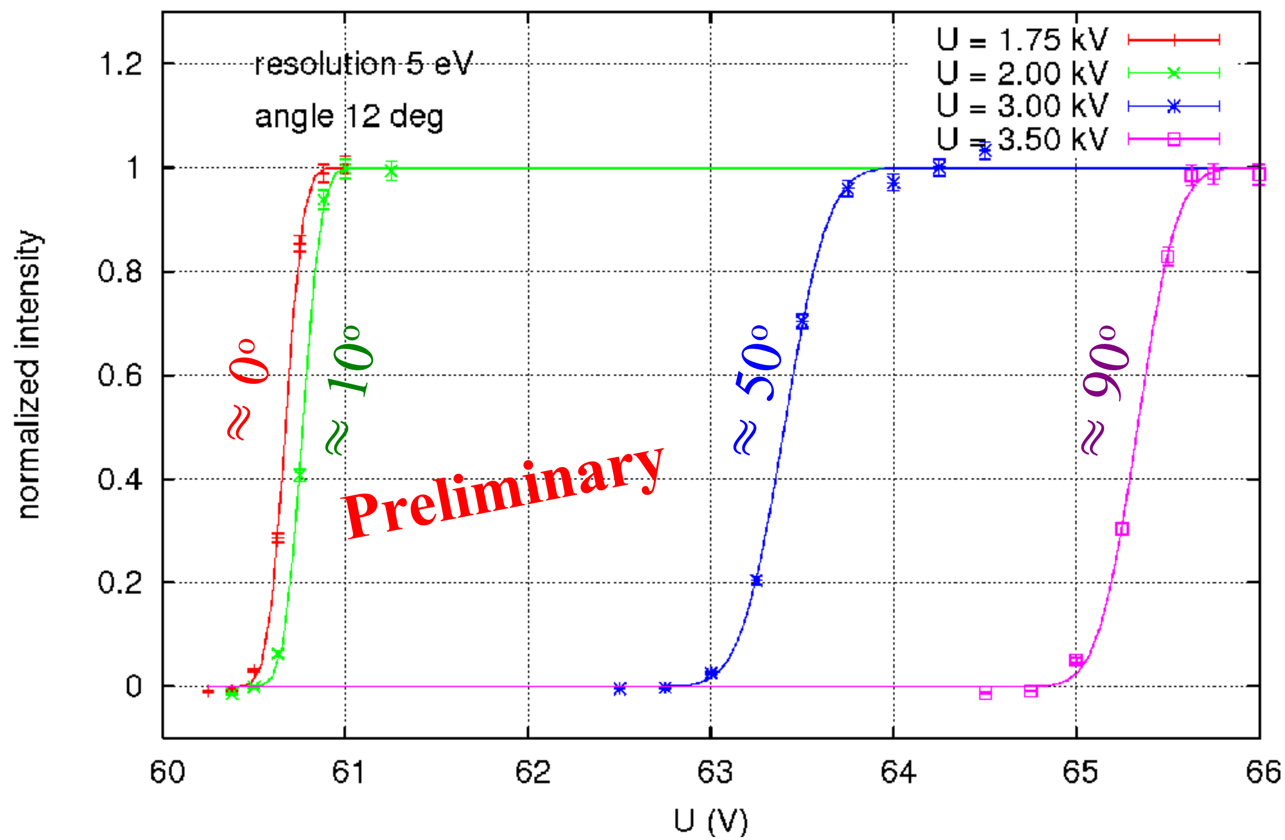
Idea:
fast non-adiabatic acceleration with adjustable non-parallel E and B fields

Angle at

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







UV LED photoelectron source for the main spectrometer