Status of direct neutrino mass measurements and the KATRIN Project

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on High Energy Physics
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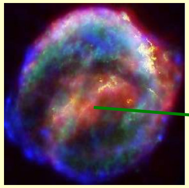
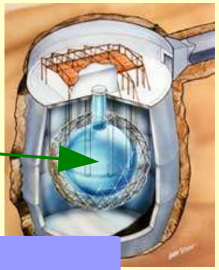
- Introduction
- Direct ν mass measurements:
  - Bolometer experiments using ^{187}Re β-decay
  - Spectrometer experiments using ^{3}H β-decay
  - The KATRIN experiment
- Outlook

How can we fix the absolute neutrino mass scale?



SN 20xx

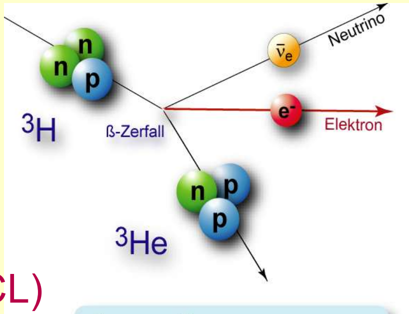
ν



supernova
time of flight
measurements

PDG 2005: SN1987A: $m(\nu_e) < 5.7$ eV

kinematics of
weak decays
(^3H β-decay,
^{187}Re β-decay)



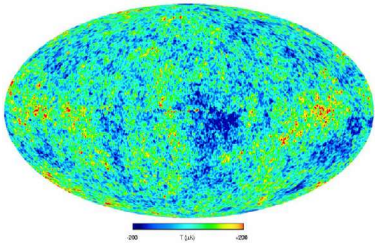
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

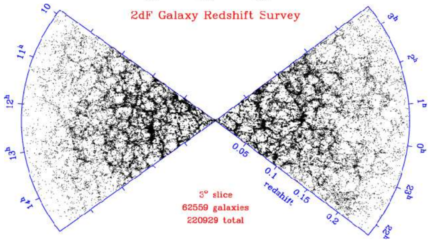
Mainz: $m(\nu_e) < 2.3$ eV (95% CL)

„direct“ neutrino mass measurements

neutrino
masses

astrophysics
& cosmology
(CMB, LSS)



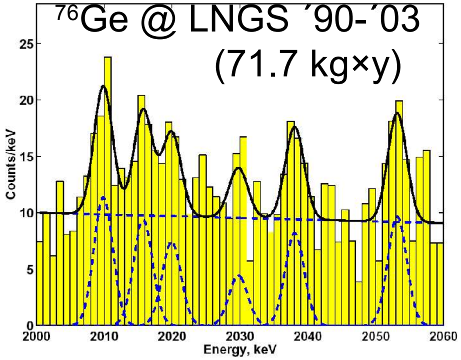


D.N. Spergel et al:
$\Sigma m_\nu < 0.69$ eV (95%CL)
S.W. Allen et al:
$\Sigma m_\nu = 0.56$ eV (best fit)

(see talk S. Pastor in this session)

neutrinoless
double β-decay
($0\nu\beta\beta$)

COBRA,
CUORICINO/CUORE,
GERDA, NEMO3, ...
(this session)
+ others ...



^{76}Ge @ LNGS ´90-´03
(71.7 kg×y)

H.-V. Klapdor-Kleingrothaus et al:
$|m_{ee}| = 0.44^{+0.13}_{-0.2}$ eV

β-decay kinematics

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

transition energy $E_0 = E_e + E_\nu$

measure energy spectrum of charged lepton (electron):

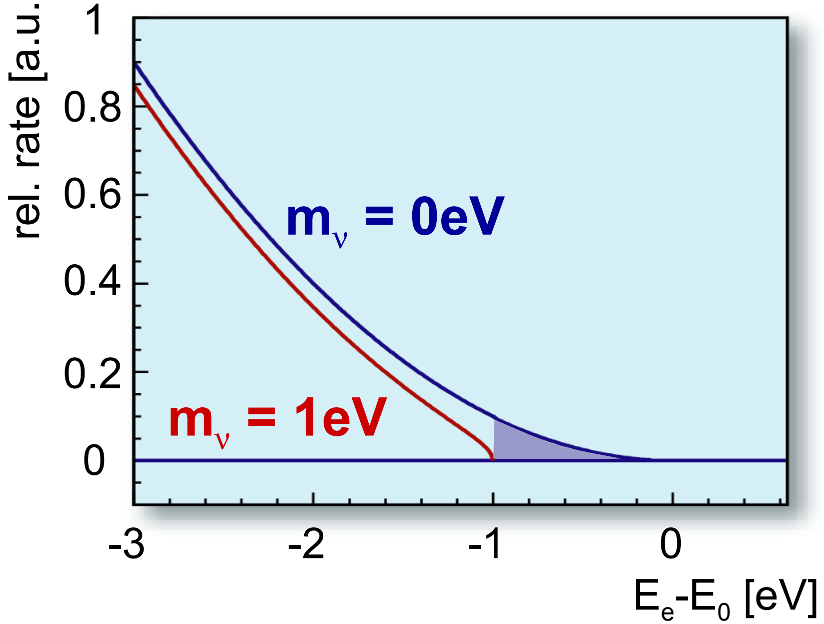
$$\boxed{dN/dE = K \cdot F(E,Z) \cdot p \cdot E_{tot} \cdot (E_0-E_e) \cdot \Sigma\, |U_{ei}|^2 \left[(E_0-E_e)^2 - m(\nu_i)^2 \right]^{1/2}}$$

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

experimental observable:

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

theoretical β spectrum near endpoint



requirements:

- strong source (high count rate near E_0)
- small endpoint energy E_0 → ^{187}Re, ^{3}H
- excellent energy resolution
- long term stability
- low background rate

MAC-E type
spectrometer
or
cryo-bolometer

Investigating ^{187}Re β-decay with cryo-bolometers

Multi-purpose, scalable new detector technology

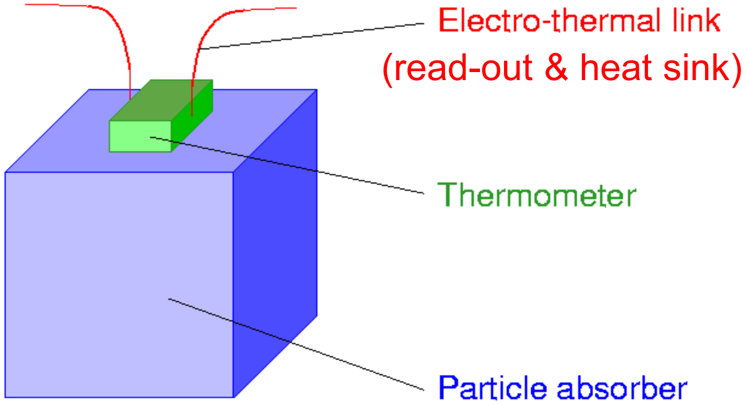
- basic idea: β *emitting crystal = cryo-detector* (absorber)

- advantage: detection of all released energy (including excited final states) except ν part

  disadvantages:
  - record full spectrum, while most sensitive region is small: $\propto (m_\nu/E_0)^3$
  - thermal integration time ~10^{-4} s → limited count rate

- choice of β emitter: ^{187}Re: **E_0 = 2.46 keV** (lowest transition energy in nature), $t_{1/2} \approx 5 \cdot 10^{10}$ y, high natural abundance (≈ 63 %)

$$\boxed{^{187}\mathrm{Re} \longrightarrow {}^{187}\mathrm{Os} + e^- + \overline{\nu}_e}$$



very low heat capacity at operating temperature < 100 mK

Investigating ^{187}Re β-decay with cryo-bolometers

a) MANU2 (F. Gatti et al., Genoa)

- first test experiment: metallic Re single crystal (1.5 mg)

  m(ν) < 26 eV (95% CL) F. Gatti et al., Nucl. Phys. B 143 (2005) 541

- under construction (MANU2): → **1 eV sensitivity** with superconducting metallic Re crystal & Ir transition edge sensors (TES)
- aim: array of 300 detectors (total 0.5 g)

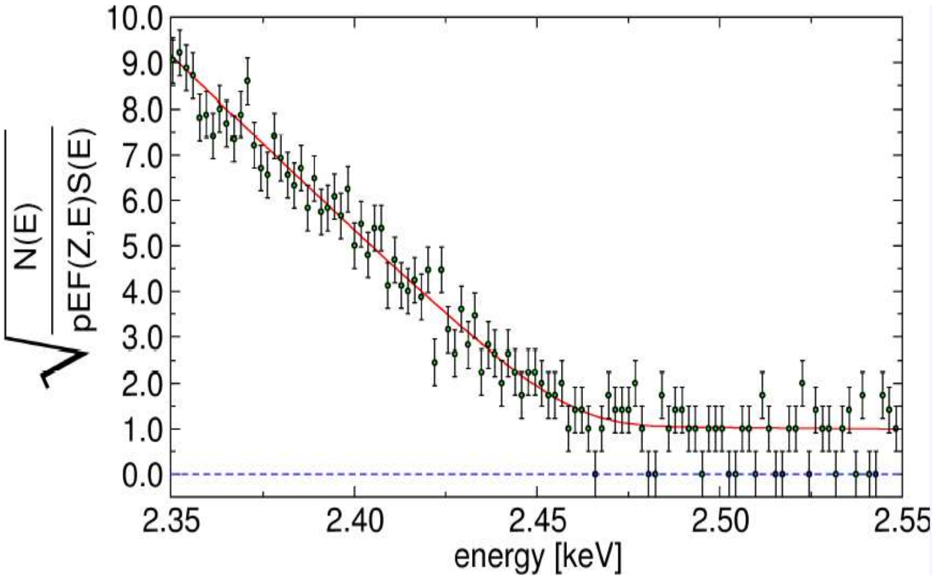
b) MiBeta (E. Fiorini et al., Milan, Como, Trento)

- $AgReO_4$ (array: 10 * 250 - 350 μg)
- Final result after 1 year data taking:

  $m^2(\nu) = -112 \pm 207 \pm 90\ \mathrm{eV}^2$

  ⇒ **m(ν) < 15 eV (90%CL)**

- 2nd phase: aim for m(ν) < 2.5 eV (90% CL) after 3 years running with 200 detectors, ΔE=10-15 eV



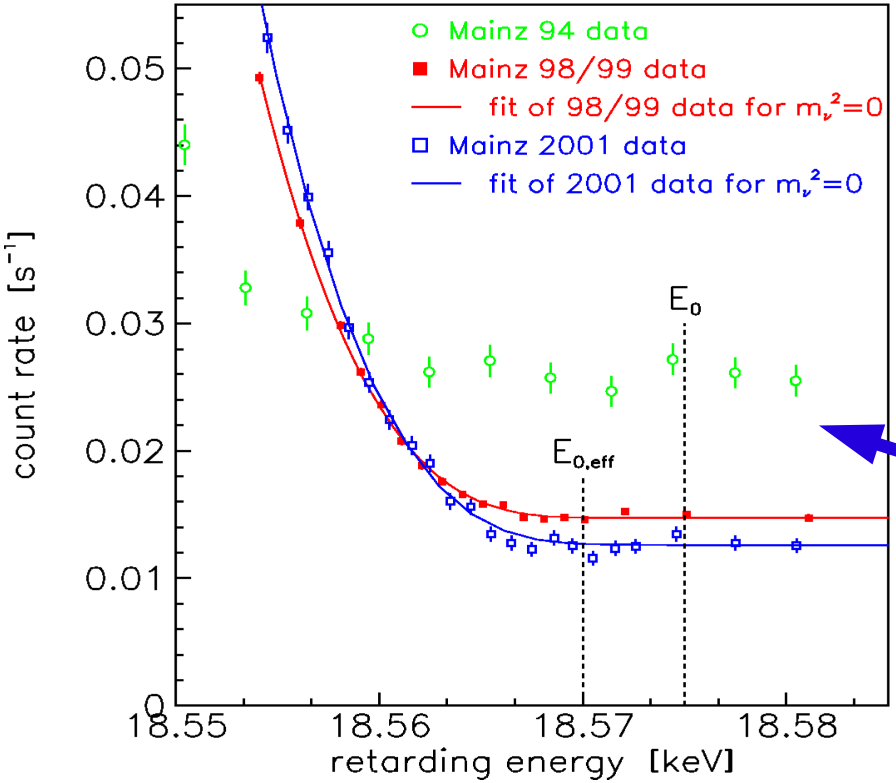
A. Nucciotti et al., NIM A520 (2004) 148

Results from the Mainz and Troitsk ^{3}H β-decay experiments

both MAC-E type spectrometers, energy res. ΔE = 4.8 eV (3.7 eV)

molecular tritium (T_2) β sources: $t_{1/2}$ = 12.3 y, **E_0=18.6 keV**

quench-condensed solid T_2 film (M) vs. windowless gaseous tritium source (T)



no Troitsk anomaly seen

- Troitsk 1994-1999,2001 data:

  $m^2(\nu)$ = -2.3 ± 2.5 ± 2.0 eV^2

  $m(\nu)$< 2.05 eV (95% C.L.)

  V.M. Lobashev, Nucl. Phys. A719 (2003) 153c

  „anomaly": step in integrated spectrum, can be described as additional line → *fit line run by run*

- Mainz 1998-2001 data:
  systematic uncertainties now well understood:
  - surface roughening
  - self-charging of T_2 film
  - inelastic scattering
  - T_2 condensate: neighbour excitation effects

final publication: C. Kraus et al.,
Eur. Phys. J. C40 (2005) 447, hep-ex/0412056:

$m^2(\nu)$ = -0.6 ± 2.2 ± 2.1 eV^2

$m(\nu)$< 2.3 eV (95% C.L.)

The Karlsruhe Tritium Neutrino experiment

Design Report 2005:
FZKA Scientific Report 7090

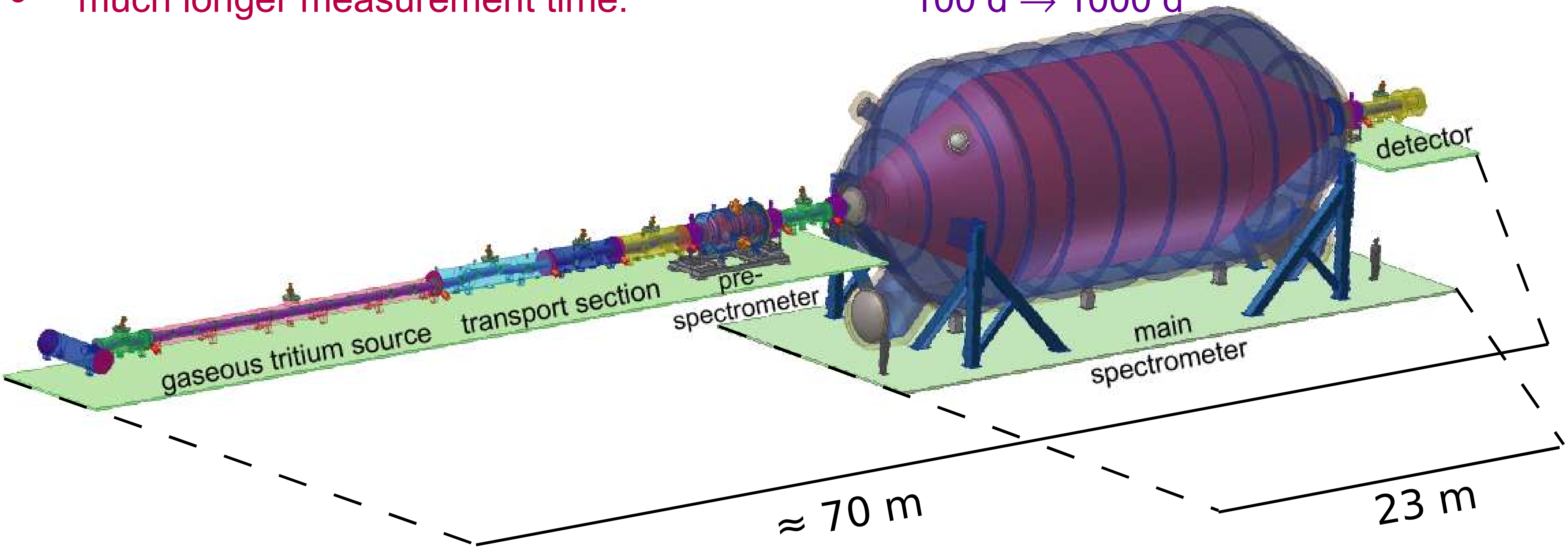
Physics Aim:

Improvement of sensitivity by 1 order of magnitude: ~2 eV → 0.2 eV

- higher energy resolution: $\Delta E \approx 1\text{eV}$
  since $E/\Delta E \sim A_{\text{spectrometer}}$ ⇒ larger spectrometer
- relevant region below endpoint becomes smaller
  even smaller count rate $dN/dt \sim A_{\text{spectrometer}}$ ⇒ larger spectrometer

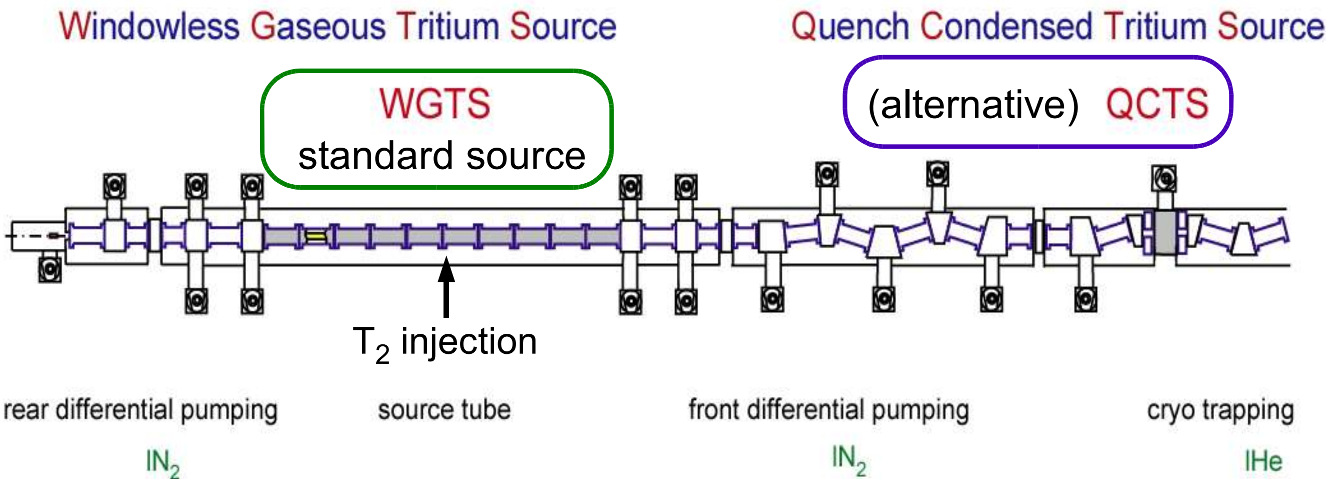
} $\varnothing = 10$ m

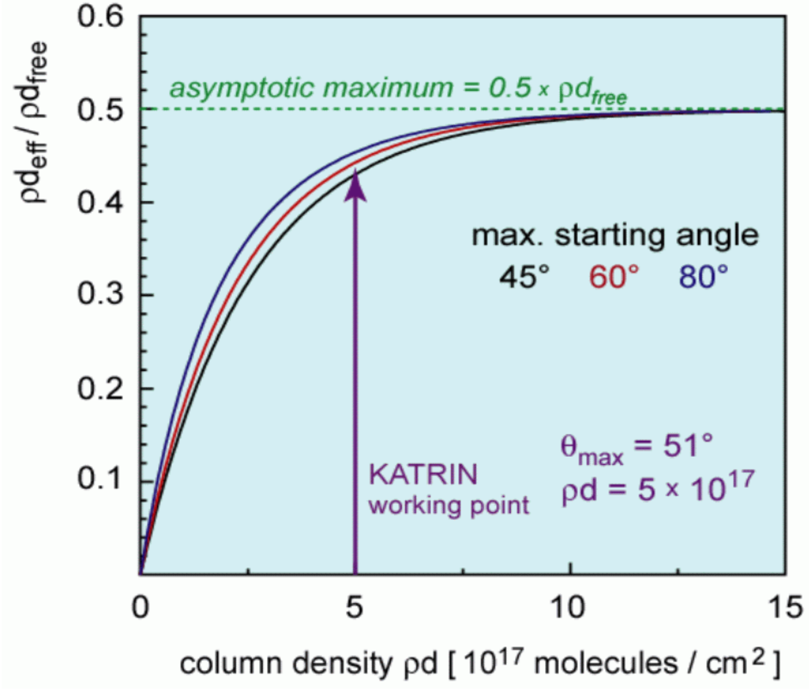
- much longer measurement time: 100 d → 1000 d



KATRIN main components I: molecular tritium sources

two sources : independent measurements with different systematic effects





WGTS characteristics:

- ∅ 9 cm, length: 10 m, T = 27 K
- column density $\rho d = 5 \cdot 10^{17}/cm^2$ optimized for large count rate and small systematics
- p_{inj} = 0.003 mbar, q_{inj} = 4.7 Ci/s ~ 40 g T_2 throughput per day:

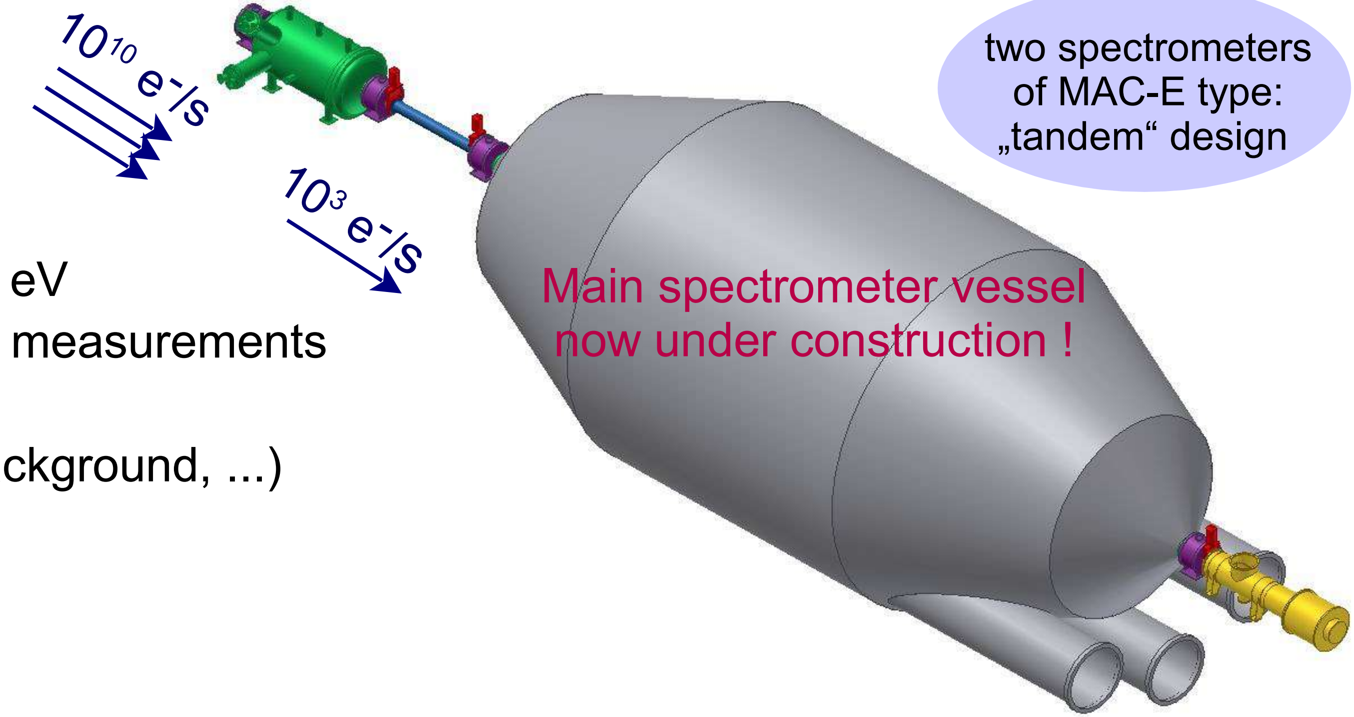
  need closed T_2 loop!
- high isotopic purity > 95% T_2
- magn. guiding field B_{source} = 3.6 T

QCTS characteristics:

- ∅ 8 cm, T= 1.6 K, d = 35 nm
- presently limited by self-charging

Windowless Gaseous Tritium Source
and front diff. pumping section
under construction !

KATRIN main components II: electrostatic spectrometers



two spectrometers of MAC-E type: „tandem“ design

Main spectrometer vessel now under construction !

Pre-spectrometer:

- pre-filter transmitting highest electron energies only
- moderate energy res. $\Delta E \approx 80$ eV
- on site since end of 2003, test measurements
- testbed for main spectrometer (vacuum, electrode design, background, ...)

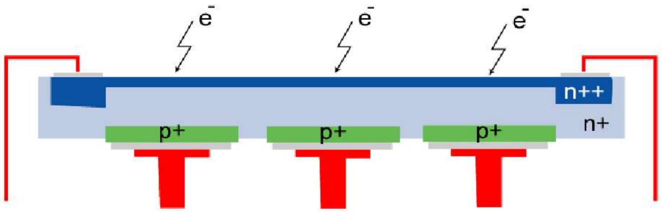
Main spectrometer

- 23 m length, 10 m diameter:
  $\Rightarrow$ energy resolution $\Delta E = 0.93$ eV at 18.6 keV
  $\Rightarrow$ high luminosity
- XHV of $p < 10^{-11}$ mbar required (low background), volume to pump ≈ 1500 m³ !
- vessel electrode + inner screening electrode (made of thin wires)

ongoing design works, > 200 modules covering surface of 650 m² !

KATRIN main components III: detector design, calibration

the prespectrometer detector:
prototype of KATRIN main detector



multipixel PIN diode from
Canberra SemiConductors

board for 64 pre-amps
on UHV flange

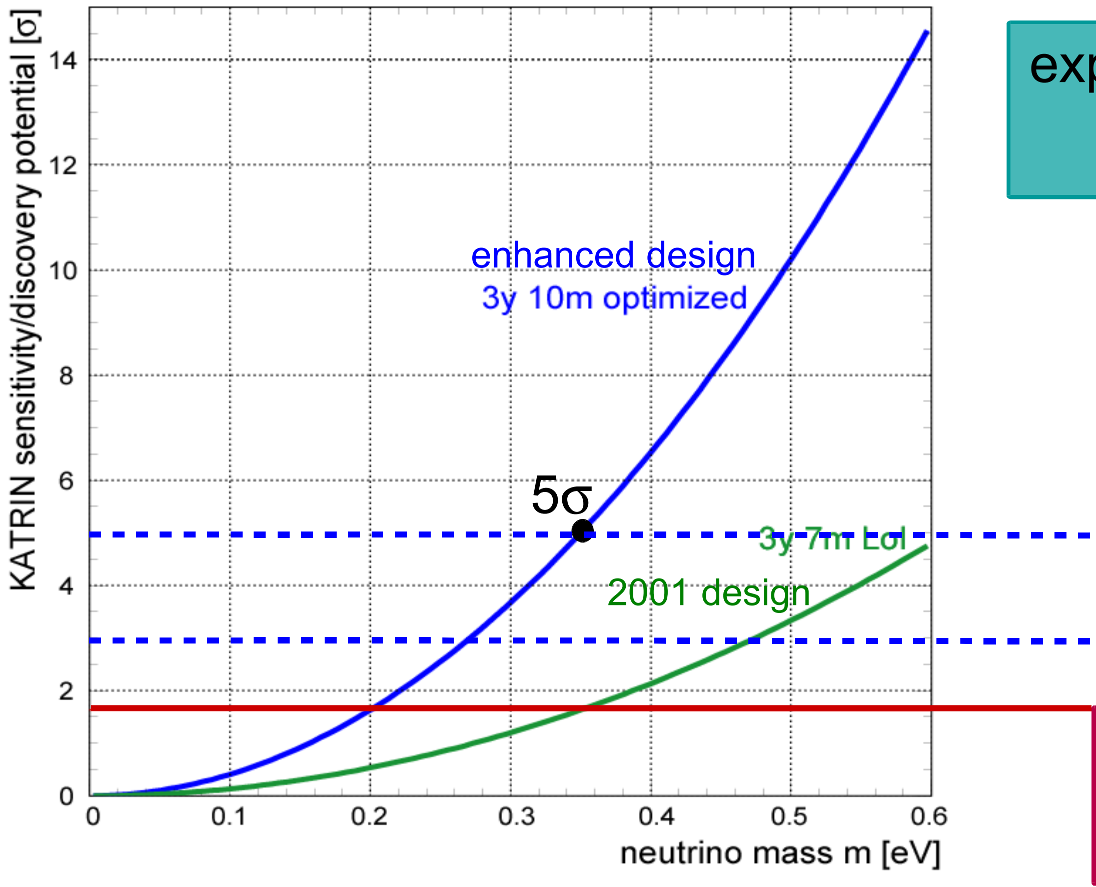
- 64 segments 5x5 mm^2
- KATRIN main detector: need larger number of pixels

- need high precision calibration of energy filter (main spectr.): reproducible/stable over 3 y!

- concept 1:
  small monitor spectrometer sharing same HV
- electron sources @ monitor spectr.:
  - ^{241}Am /Co photoelectron source
  - ^{83m}Kr source: K shell conversion electron

- concept 2:
  direct measurement of retarding voltage using new precision high voltage divider and digital voltmeter

KATRIN sensitivity & discovery potential



expectation for 3 full beam years:

$\sigma_{syst} \sim \sigma_{stat}$

discovery potential

m_ν = 0.35 eV (5σ)

m_ν = 0.30 eV (3σ)

sensitivity

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

Systematic uncertainties:

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

6 contributions of about $\Delta m_\nu^2 \leq 0.007$ eV^2 each:

1. inelastic scattering of β inside WGTS,
2. fluctuations of WGTS column density
3. spectrometer transmission function,
4. HV stability of retarding potential,
5. WGTS charging due to remaining ions,
6. final state distribution

Status of KATRIN (I)

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Uni Bonn

University of Washington

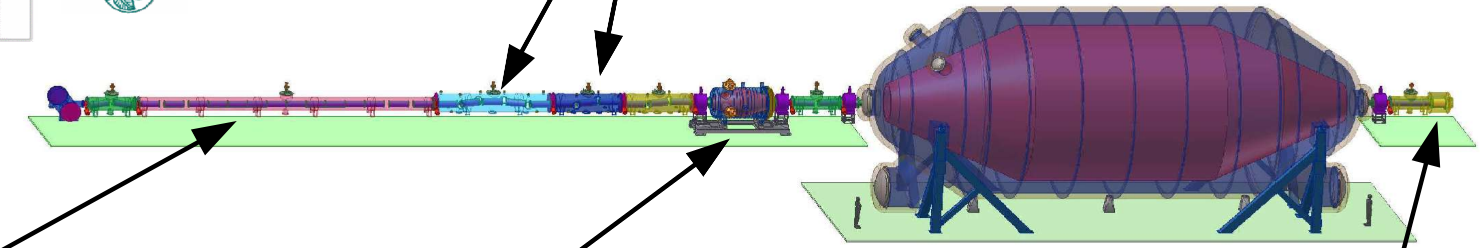
Fachhochschule Fulda
University of Applied Sciences

UNIVERSITÄT
KARLSRUHE (TH)

ASTeC

cryo trapping:
test experiment TRAP
general cryo supply:
He liquefier ordered

diff. pumping section:
ordered



tritium source:
test setup of gas inlet system/constancy T_2 loop,
WGTS ordered

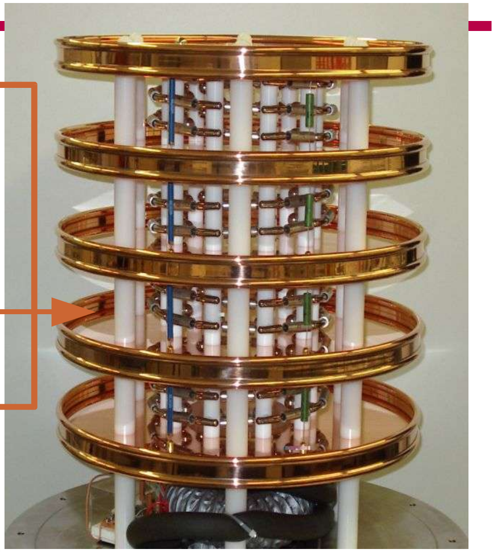
pre-spectrometer:
on-site,
vacuum properties successfully tested,
better than KATRIN specfications

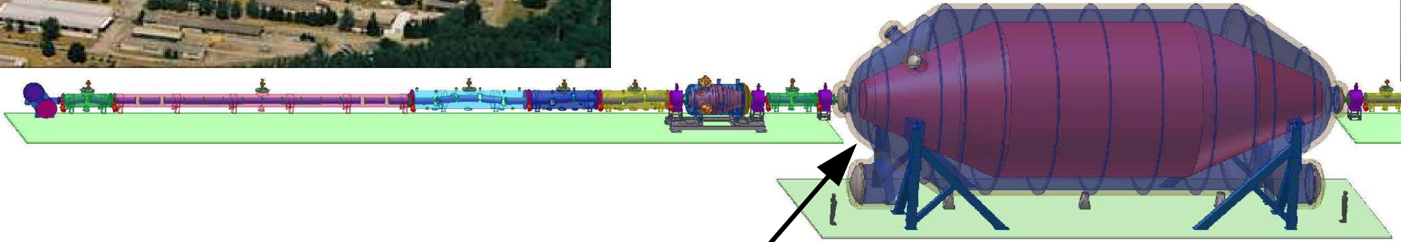
detector design:
setup of pre-spec detector

Status of KATRIN (II)


new **KATRIN halls** at FZ Karlsruhe: groundbreaking in **Sept. 2005**

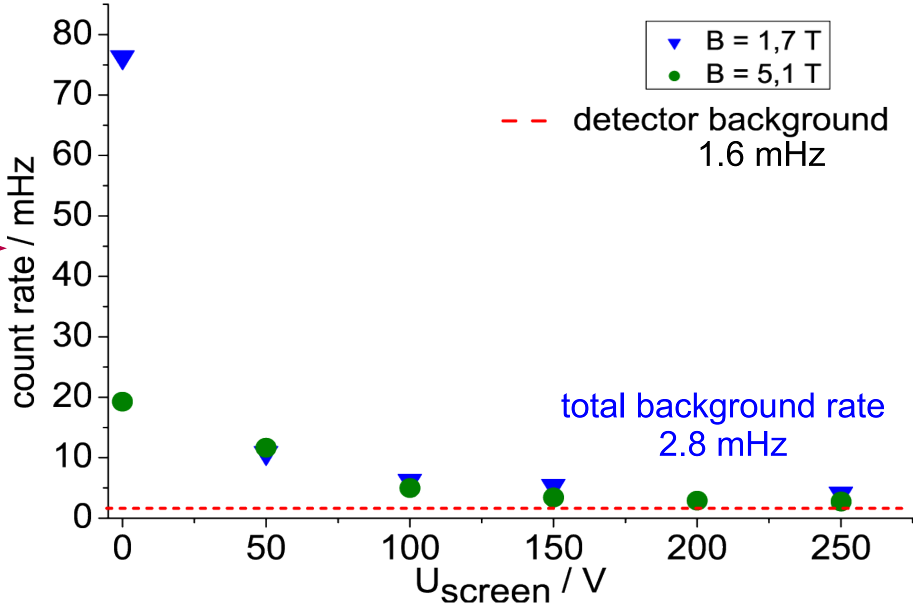
calibration:
- Am/Co source first successful tests
- Kr source ready to be tested
- HV divider setup finished, ongoing tests





main spectrometer:
UHV vessel under construction,
ongoing design studies for inner screening electrode
→ method successfully tested at Mainz spectr.
→ significant background suppression achieved!

April '04



2008: commissioning of full setup & start of data taking

Summary and Outlook

- absolute scale of ν masses important input for particle physics & astrophysics/cosmology

- direct ν mass searches: present limits from β decay

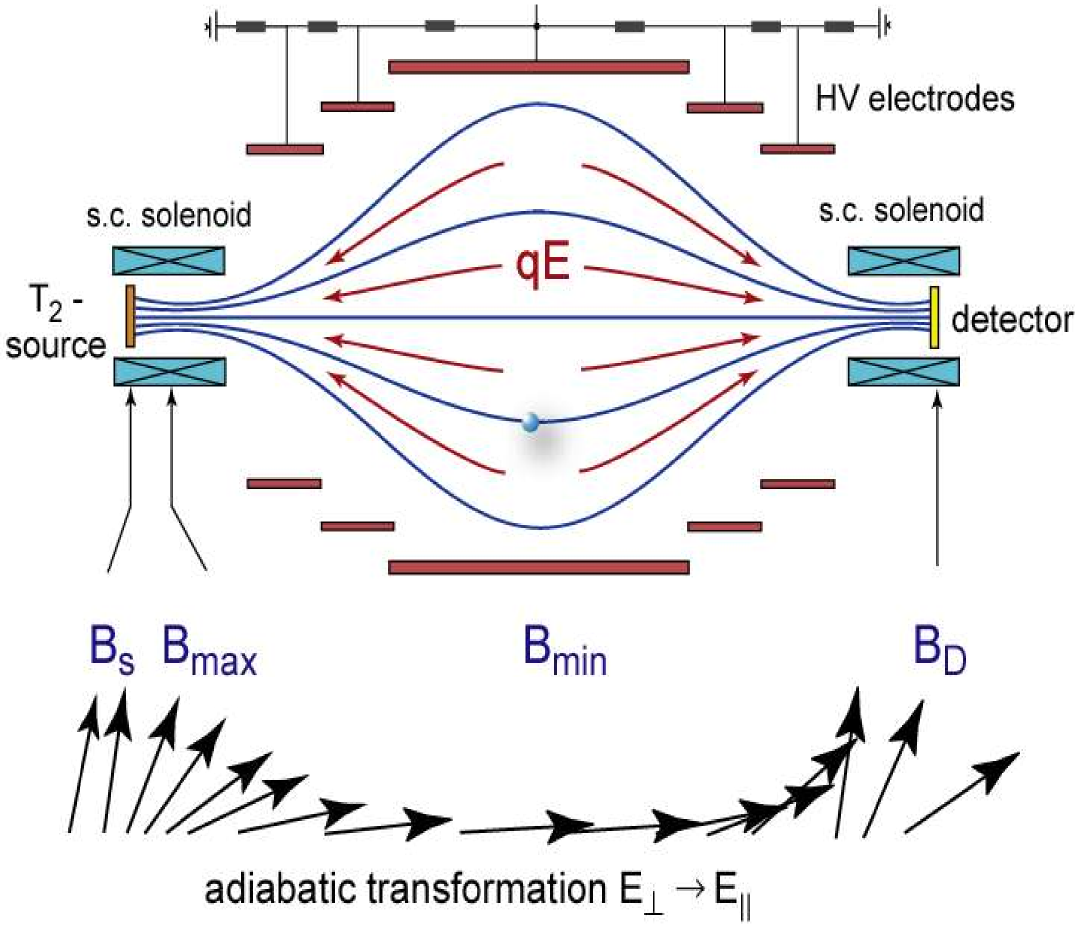
  - ^{187}Re (MiBeta): $m(\nu) < 15$ eV (90% CL)
    heading for 1-2 eV sensitivity

  - ^{3}H (Mainz): $m(\nu) < 2.3$ eV (95% CL)
    next-generation: KATRIN → sensitivity 0.2 eV

- KATRIN status:
  - first components already on site
  - successful tests of vacuum concept, background suppression
  - major components under construction (WGTS, main spectrometer)
  - new KATRIN buildings, groundbreaking: Sept. 2005
  - commissioning & start of data taking: 2008

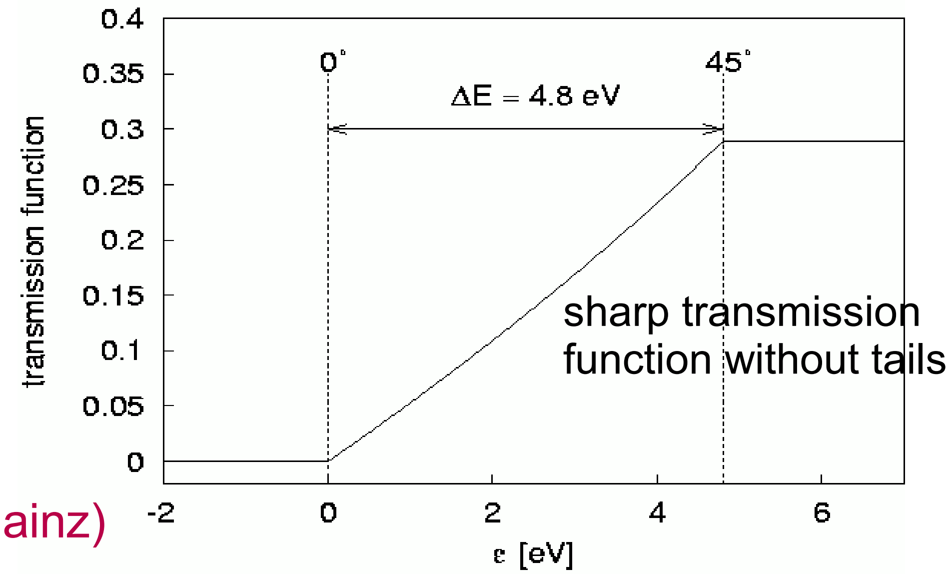
Principle of the MAC-E-Filter

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



- adiabatic magnetic guiding of β´s along field lines in stray B-field of s.c. solenoids
- energy analysis by static retarding E-field with varying strength:

high pass filter with integral transmission for E>qU

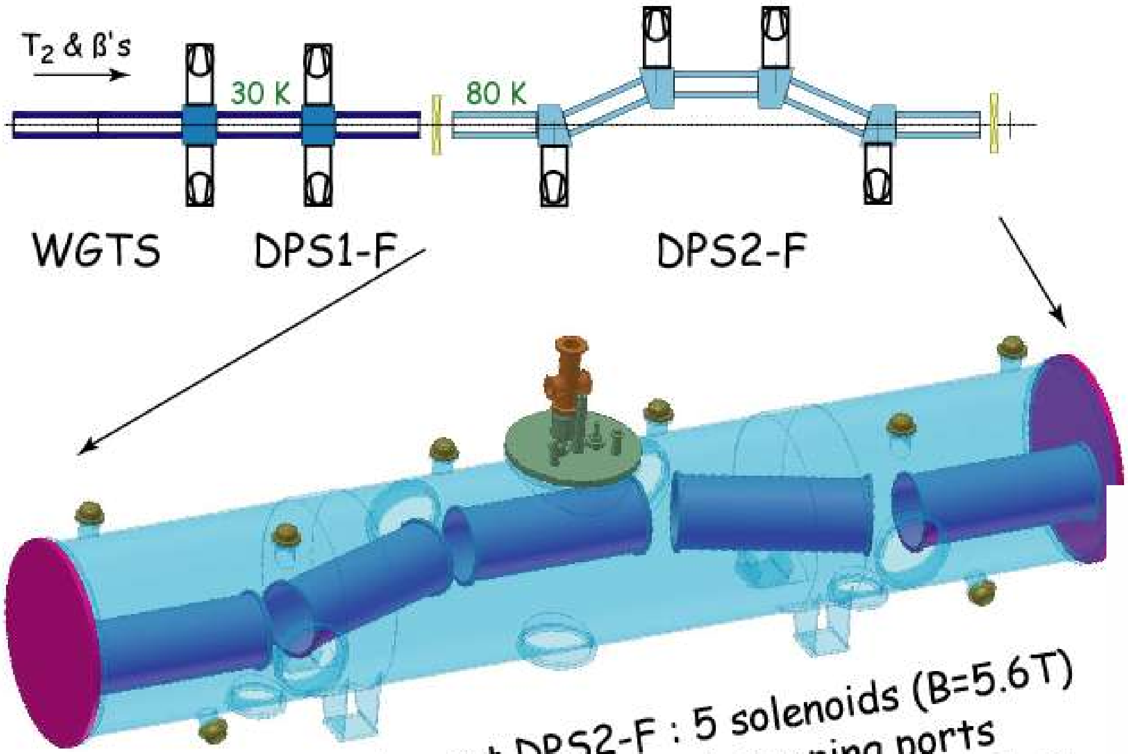


sharp transmission function without tails

$\Delta E = E \cdot B_{min}/B_{max} \approx 0.9$ eV KATRIN (= 4.8 eV Mainz)

differential pumping section - DPS

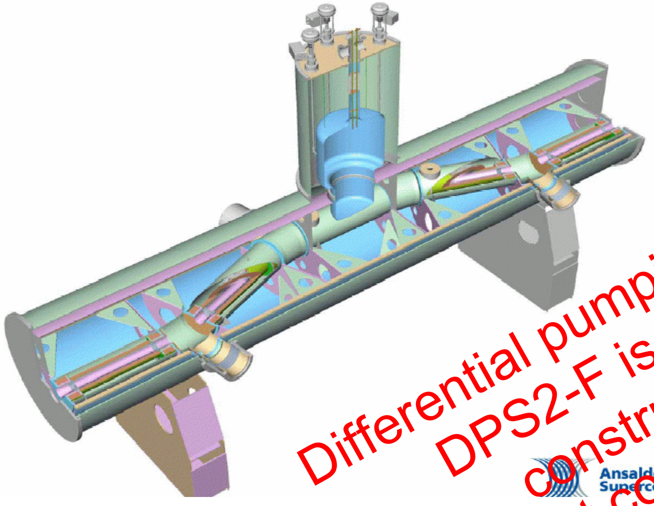
- active pumping of T_2 molecules by TMP's (8 pumping ports)
  suppression factor of T_2 flow ~ 2×10^8 , closed tritium loop
- electron transport (7 s.c. solenoids, each l=1m)



transport element DPS2-F : 5 solenoids (B=5.6T)
4 pumping ports
beam tube Ø=75mm
elements tilted by 2

- **DPS1-F:** recirculate T_2 via inner loop to WGTS
- **DPS2-F:** transfer T_2 via outer loop to TLK for isotope separation & T_2 recovery

pumping port layout

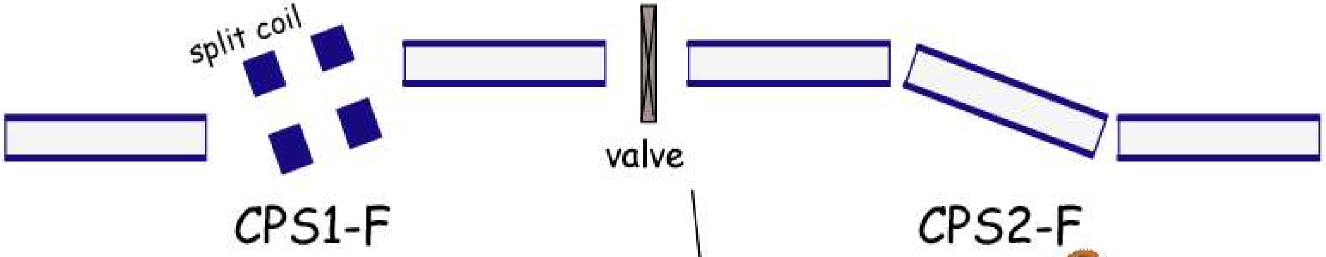


Differential pumping section DPS2-F is under construction at company

Cryo-pumping section

- trap remaining molecular T_2 flow onto lHe cold surfaces to keep spectrometer T_2 partial pressure at ~ 10^{-20} mbar

6 s.c. magnets (5 solenoids, 1 split coil for QCTS or other ß-sources)



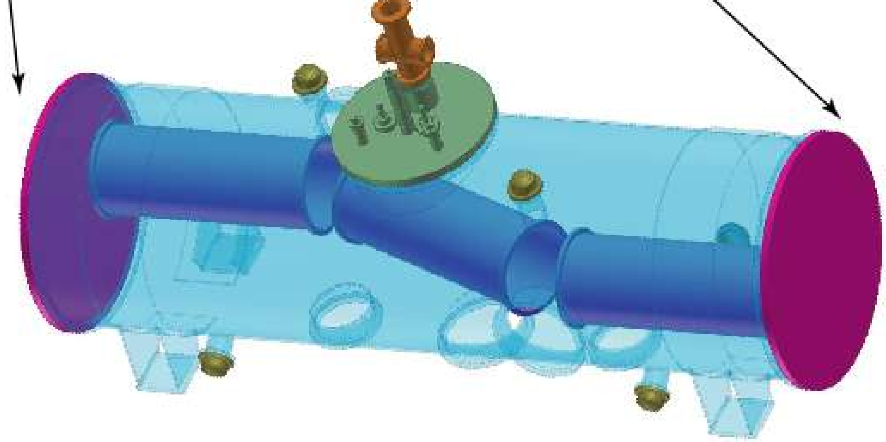
lHe-cold bore (4.5K) magnets:

condensation of T_2 & residual gases

- cryosorption on condensed Ar-frost/charcoal (inner wall)
- cryogettering on condensing Ar

CPS regeneration by warm He-flow

max. allowed: 1 Ci of T_2 after 60 days



transport element CPS2-F

T_2-tube: Ø=75mm B=5.6 T

Systematic error contributions

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

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

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

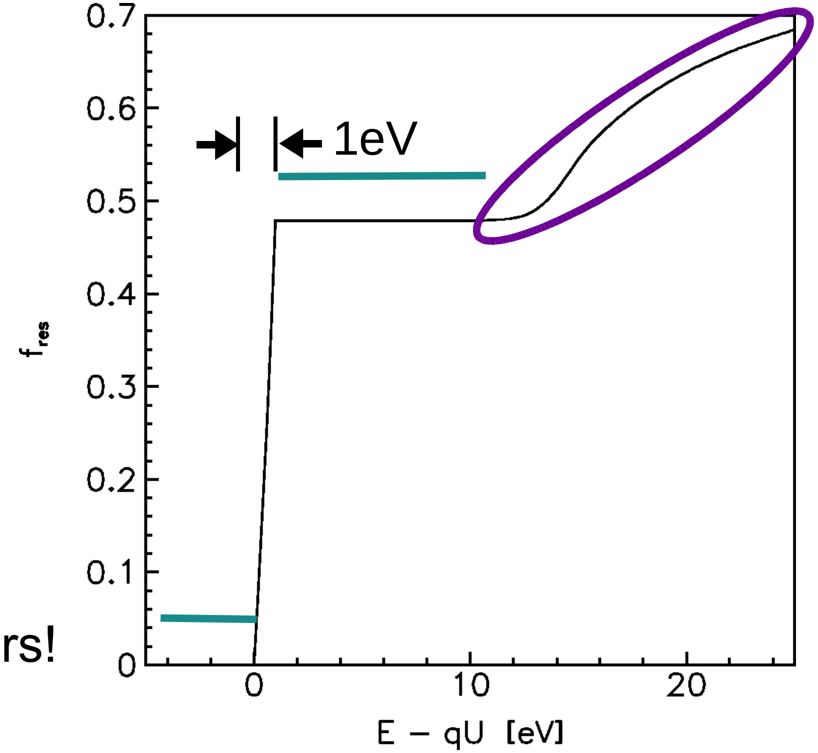
Systematic uncertainties

For smaller m(ν):
⇒ *smaller region of interest below endpoint* E_0

- **Excited electronic final states**
  do not play a role (ΔE_{exc} > 27 eV)

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

⇒ One well-defined final state similiar to cryo-detectors!



Only true because MAC-E-Filter response function has ***no tails!***