Direct Neutrino Mass Measurement

Westfälische Wilhelms-Universität Münster

V International Pontecorvo Neutrino Physics School
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- Introduction
- Direct Neutrino Mass determination
  - supernova tof measurements
  - Rhenium β decay experiments
  - Tritium β decay experiments
- The Karlsruhe Tritium Neutrino expeirment KATRIN
- Summary and Outlook

Photo: M. Zacher

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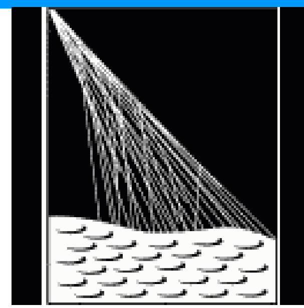
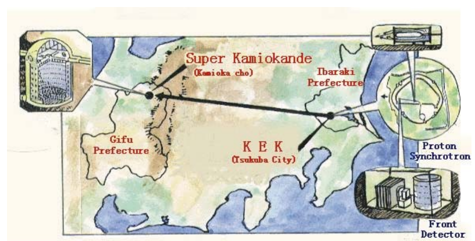
Positive results from ν oscillation experiments

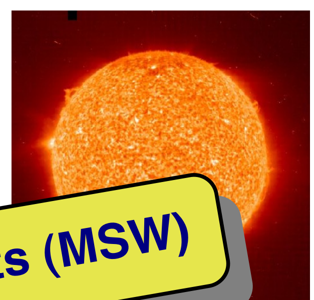
atmospheric neutrinos
(Kamiokande, Super-Kamiokande, ...)



accelerator neutrinos
(K2K, T2K, MINOS, OPERA, MiniBoone)

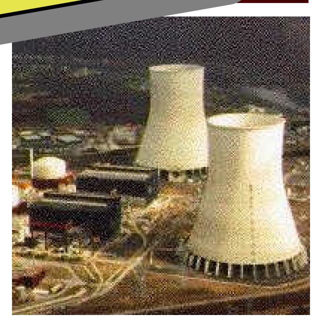


solar neutrinos
(Homestake, Gallex, Sage, Super-Kamiokande, SNO, Borexino)



Matter effects (MSW)

reactor neutrinos
(KamLAND, CHOOZ, Daya Bay, DoubleCHOOZ, RENO, ...)



⇒ non-trivial ν-mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

with:

$0.34 < \sin^2(\theta_{23}) < 0.64$ maximal!

$0.26 < \sin^2(\theta_{12}) < 0.36$ large !

$\sin^2(\theta_{13}) = 0.089 \pm 0.010 \pm 0.005$

$7.0 \cdot 10^{-5}\,\text{eV}^2 < \Delta m_{12}^2 < 8.2 \cdot 10^{-5}\,\text{eV}^2$

$2.1 \cdot 10^{-3}\,\text{eV}^2 < |\Delta m_{13}^2| < 2.7 \cdot 10^{-3}\,\text{eV}^2$

⇒ $m(\nu_j) \neq 0$, but unknown !

Three complementary ways to the absolute neutrino mass scale

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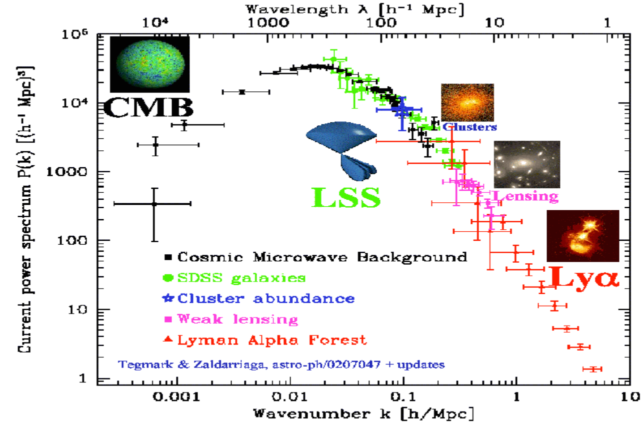
1) Cosmology

very sensitive, but model dependent

compares power at different scales

current sensitivity: $\Sigma m(\nu_i) \approx 0.5$ eV

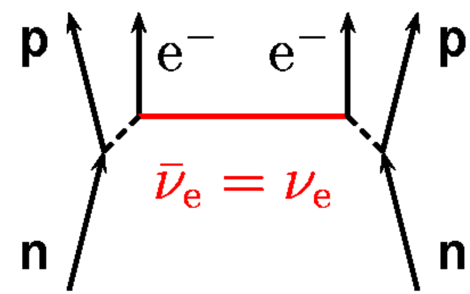


2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

Evidence for $m_{ee}(\nu) \approx 0.3$ eV (Klapdor-Kleingrothaus et al.)?

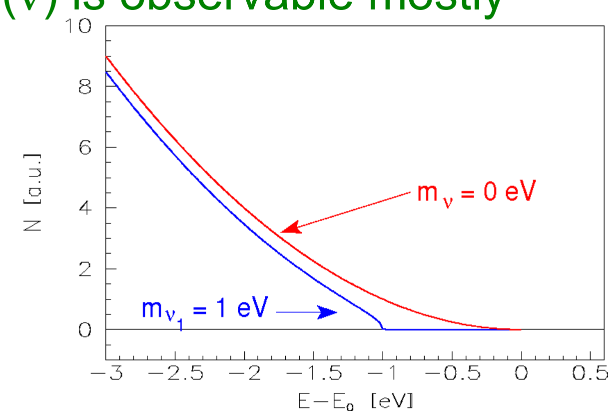
First upper limit by EXO-200, GERDA is running



3) Direct neutrino mass determination:

No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly

- **Time-of-flight measurements** (ν from supernova)
  SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV
- **Kinematics of weak decays**
  measure charged decay prod., E-, p-conservation
  β-decay searchs for $m(\nu_e)$ - tritium β spectrometers
  - ^{187}Re bolometers



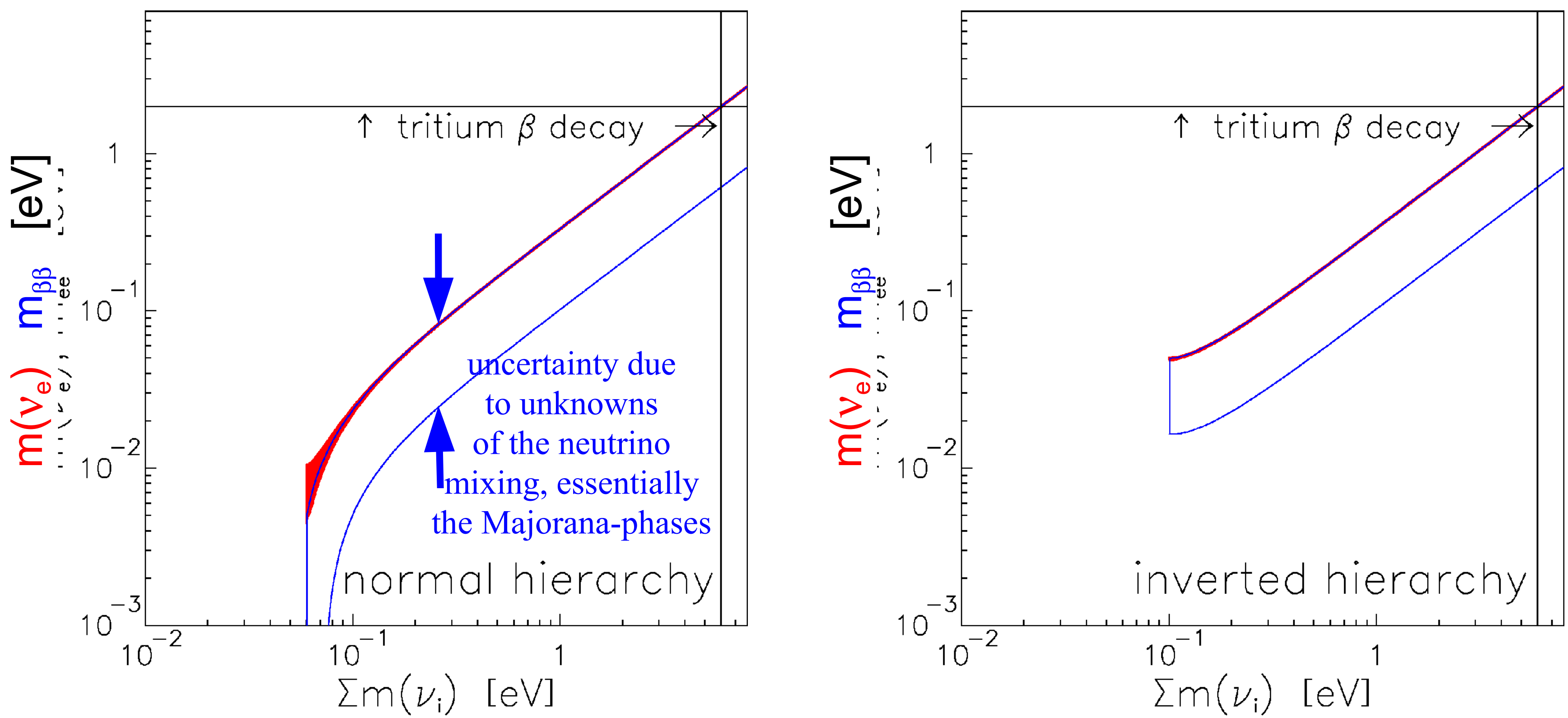
Comparison of the different approaches to the neutrino mass

Direct kinematic measurement: $m^2(\nu_e) = \Sigma |U_{ei}^2| \, m^2(\nu_i)$ (incoherent)

Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = | \Sigma |U_{ei}^2| \, e^{i\alpha(i)} m(\nu_i)|$ (coherent)

if no other particle is exchanged (e.g. R-violating SUSY)

problems with uncertainty of nuclear matrix elements



⇒ absolute scale/cosmological relevant neutrino mass in the lab by single β decay

Neutrino mass from supernovae (time-of-flight)

Only one SN detected in ν`s: SN1987a

Simple dependence for sharp ν emission in time:

$$\Delta t = \frac{L}{c} - \frac{L}{\beta_\nu} = L - \frac{L}{1 - \frac{m_\nu^2}{2E_\nu^2}}$$

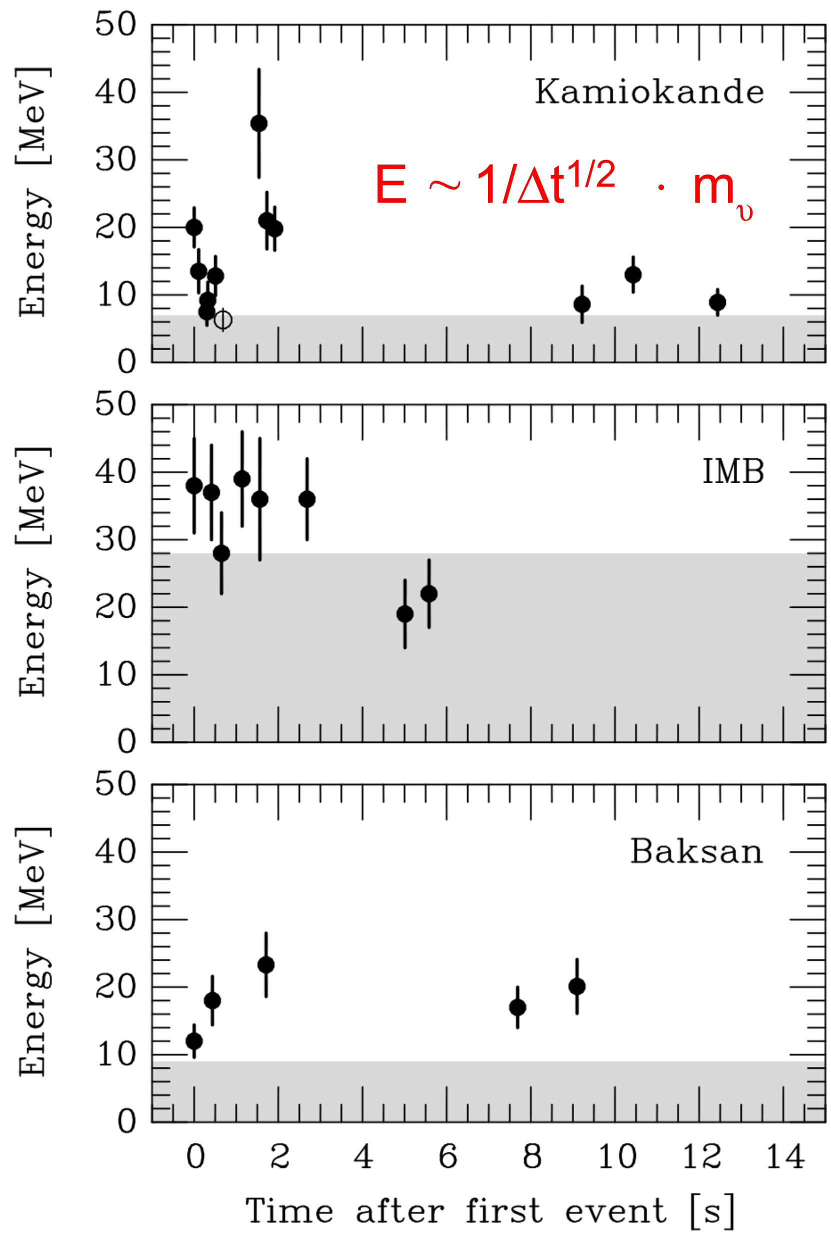
$$\approx L - L \cdot \left(1 + \frac{m_\nu^2}{2E_\nu^2}\right) = -L \cdot \frac{m_\nu^2}{2E_\nu^2}$$

with:

$$m^2 = E^2 - p^2 = E^2(1-\beta^2)$$

$$= E^2(1+\beta)(1-\beta) \approx 2E^2(1-\beta)$$

$$\Rightarrow \beta = 1 - \frac{m^2}{2E^2}$$



G. Raffelt, Ann. Rev. Nucl. Part. Sci. 49 (1999) 163

Neutrino mass from supernovae (time-of-flight)

Only one SN detected in ν`s: SN1987a

No energy versus time dependence visible

→ only upper limit on neutrino mass

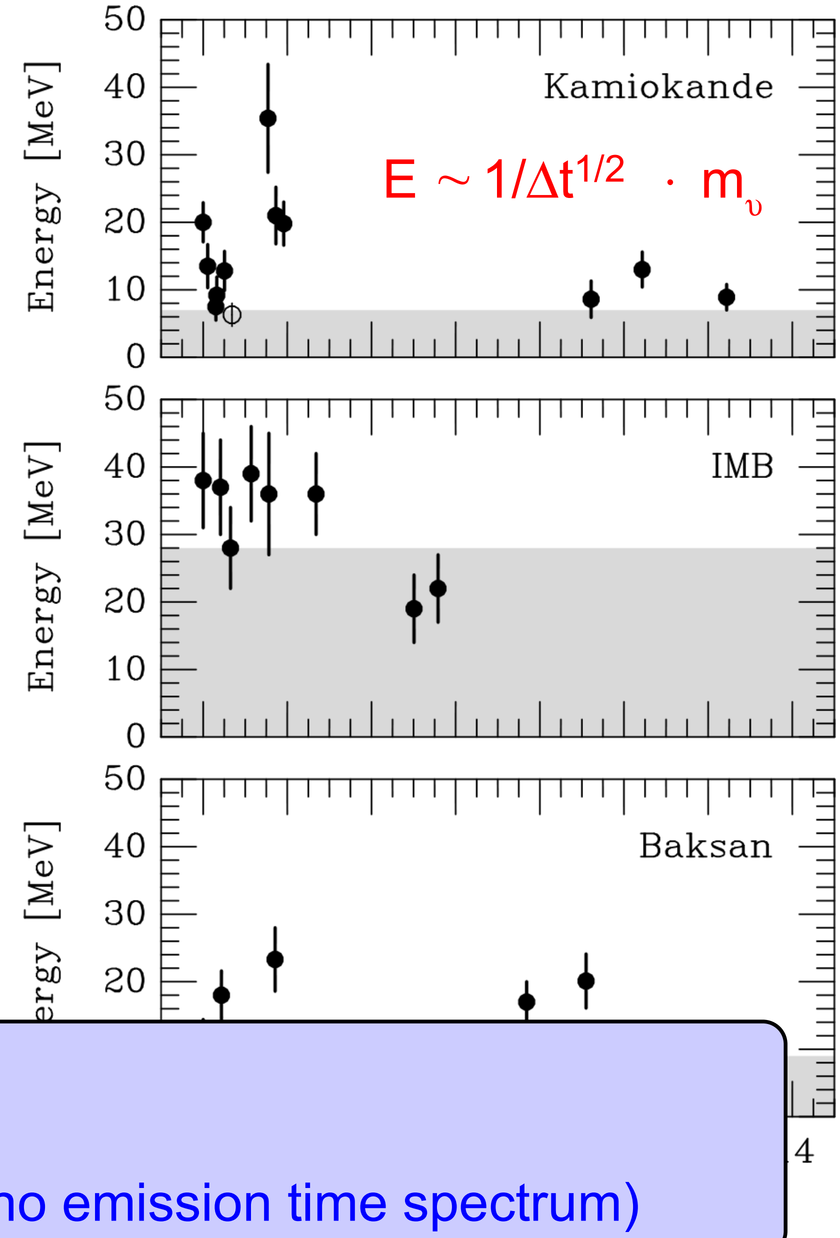
Results depends on underlying SN model, e.g.:

$m(\nu_e) < 5.7$ eV

T.J. Loredo et al., PRD65 (2002) 063002

$m(\nu_e) < 5.8$ eV

G. Pagliarolia, F. Rossi-Torresa and F. Vissani, Astropart. Phys. 33 (2010) 287



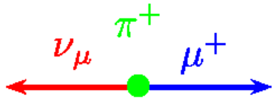
G. Raffelt, Ann. Rev. Nucl. Part. Sci. 49 (1999) 163

BUT
- galactic SN only about every 40 years
- not sensitive below 1eV (uncertainty of neutrino emission time spectrum)

Determination of „$m(\nu_\mu)$“ what does $m(\nu_\mu)$ mean ?

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$ (Two body decay)

Decay at rest:



$$|\vec{p}_\nu| = |\vec{p}_\mu|$$

$$m_\pi = E_\nu + E_\mu$$

$$\rightarrow \mathrm{m}_\nu^2 = \mathrm{m}_\pi^2 + \mathrm{m}_\mu^2 - 2 \cdot \mathrm{m}_\pi \cdot \sqrt{\mathrm{m}_\mu^2 + \mathrm{p}_\mu^2}$$

3 different Experiments:

Values from PDG2000

Pionic atoms: $\mathrm{m}_\pi = 139.570180(350)$ MeV

Myonium: $\mathrm{m}_\mu = 105.658357(5)$ MeV

Magnetic spektrometer (PSI): $\mathrm{p}_\mu = 29.791998(110)$ MeV

$\rightarrow \mathrm{m}(\nu_\mu) < 170\mathrm{keV/c^2}$ (95% c.l.) (K. Assamagan *et al.*, Phys. Rev. D53 (1996) 6065)

PDG2000: $\mathrm{m}(\nu_\mu) < 190\mathrm{keV/c^2}$ (95% c.l.)

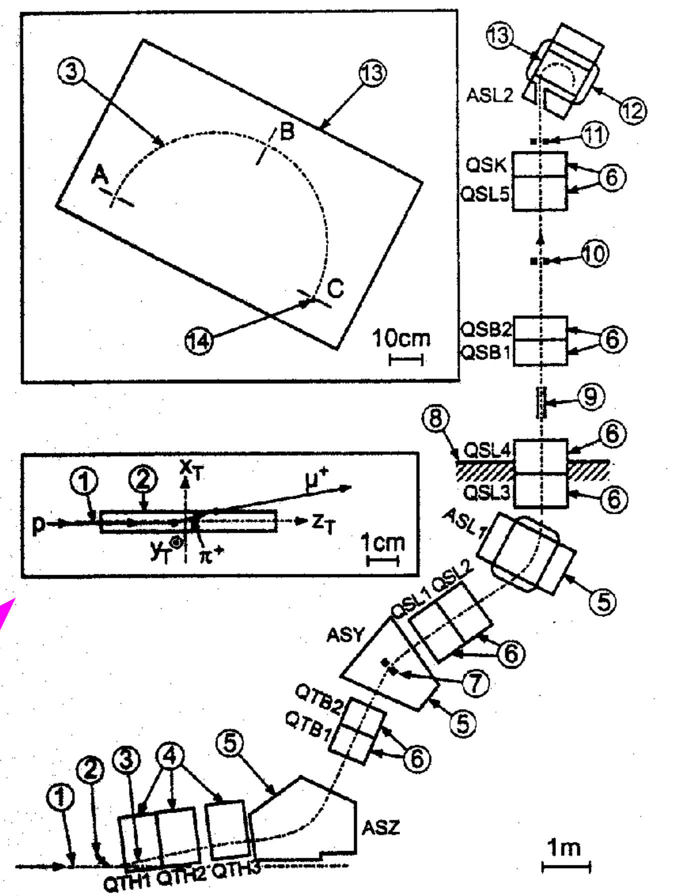
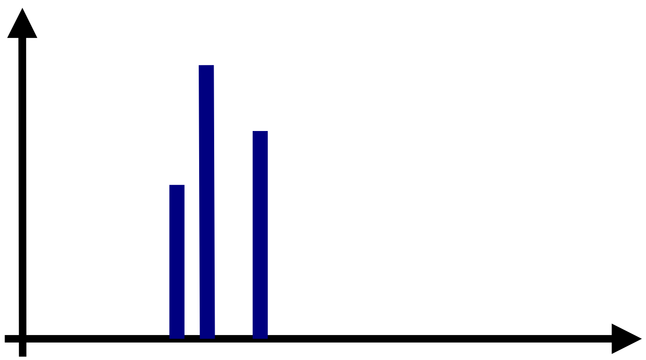


FIG. 1. Experimental setup. (1) Central trajectory of 590 MeV proton beam; (2) graphite target; (3) central trajectory of muon beam; (4) half-quadrupole magnets; (5) dipole magnets; (6) quadrupole magnets; (7) collimator defining the beam momentum acceptance; (8) concrete shielding of proton channel; (9) crossed-field particle separator; (10) lead collimator; (11) remotely movable collimator system (normally open); (12) magnetic spectrometer; (13) pole of spectrometer; (14) muon detectors (silicon microstrip and single surface-barrier detectors); A,B,C: copper collimators.

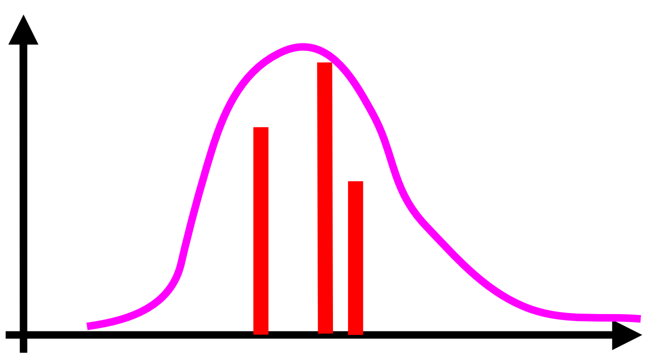
Different neutrino mass states ν_i

⇒ Measure different muon momenta p_μ with probability $|U_{\mu i}{}^2|$



$$m_\nu{}^2 = m_\mu{}^2 + m_\pi{}^2 - 2m_\pi\,(m_\mu{}^2 + p_\mu{}^2)^{1/2}$$

⇒ 3 different neutrino masses $m^2(\nu_i)$ with probability $|U_{\mu i}{}^2|$



if different mass states can experimentally not be resolved:
⇒ $m^2(\nu_\mu) := \Sigma_i \cdot |U_{\mu i}{}^2| \cdot m^2(\nu_i)$

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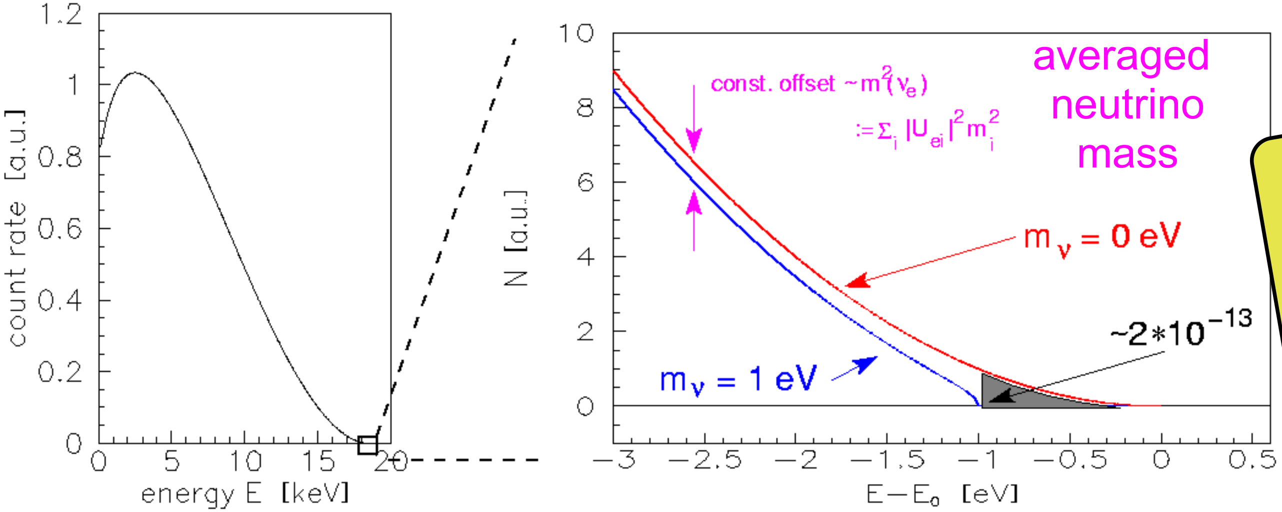
Direct determination of $m(\nu_e)$ from β decay

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

β electron energy spectrum:

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

(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)

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

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

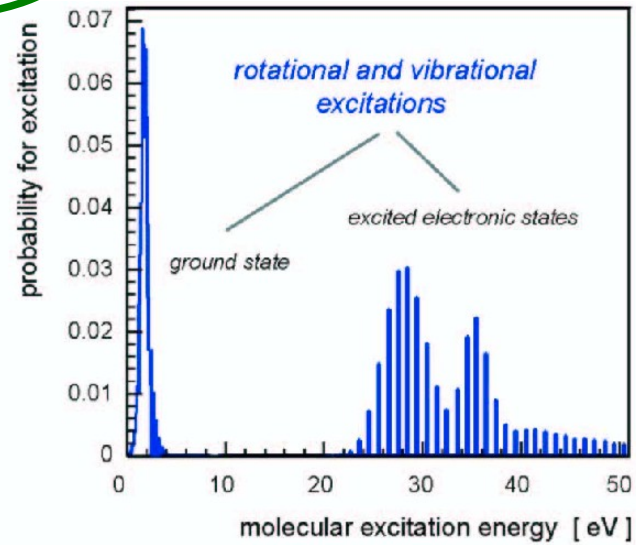
$$W_j = |\langle \Psi_0 | \Psi_{f,j} \rangle|^2$$

⇒ **look at endpoint region only**

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 of T_2 β-decay:
(A. Saenz et al. Phys. Rev. Lett. 84 (2000) 242,
N. Doss et al., Phys. Rev. C73 (2006) 025502)



⇒ **electronic final states are very important**

Including neutrino mixing

$$\frac{d^2N}{dt\,dE} = A \cdot F(E,Z+1) \cdot p \cdot (E+m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \left(\sum_i |U_{ci}|^2 \sqrt{{\varepsilon_j}^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i)) \right)$$

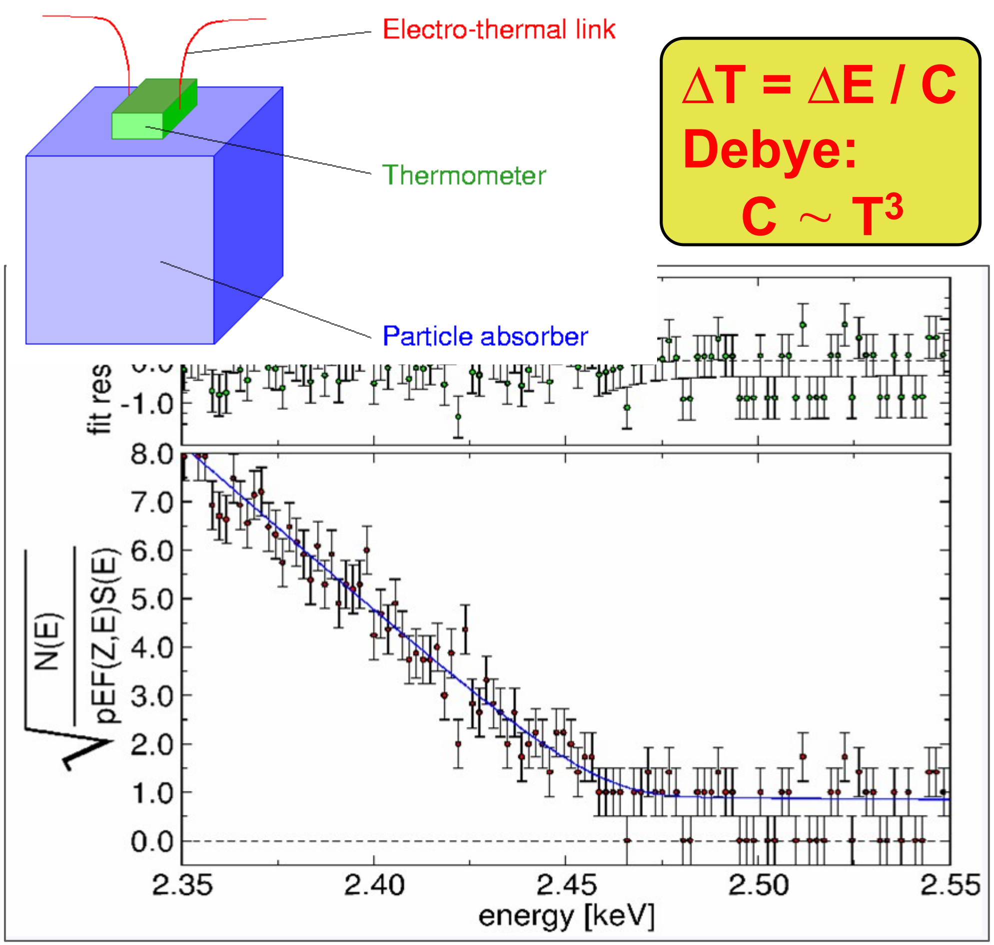
⇒ "Electron neutrino mass"

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

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

Cryogenic bolometers with ^{187}Re
MIBETA (Milano/Como)

$\Delta T = \Delta E / C$
Debye:
$C \sim T^3$



Measures all energy except that of the neutrino

detectors: 10 ($AgReO_4$)

rate each: 0.13 1/s

energy res.: ΔE = 28 eV

pile-up frac.: $1.7\ 10^{-4}$

$M_\nu^2 = -141 \pm 211_{stat} \pm 90_{sys}\ eV^2$

$M_\nu < 15.6$ eV (90% c.l.)

(M. Sisti et al., NIMA520 (2004) 125)

MANU (Genova)

- Re metalic crystal (1.5 mg)
- BEFS observed (F.Gatti et al., Nature 397 (1999) 137)
- sensitivity: $m(\nu) < 26$ eV (F.Gatti, Nucl. Phys. B91 (2001) 293)

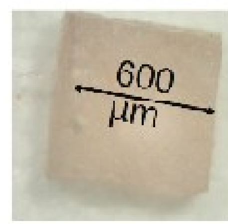
MARE neutrino mass project: ^{187}Re beta decay with cryogenic bolometers

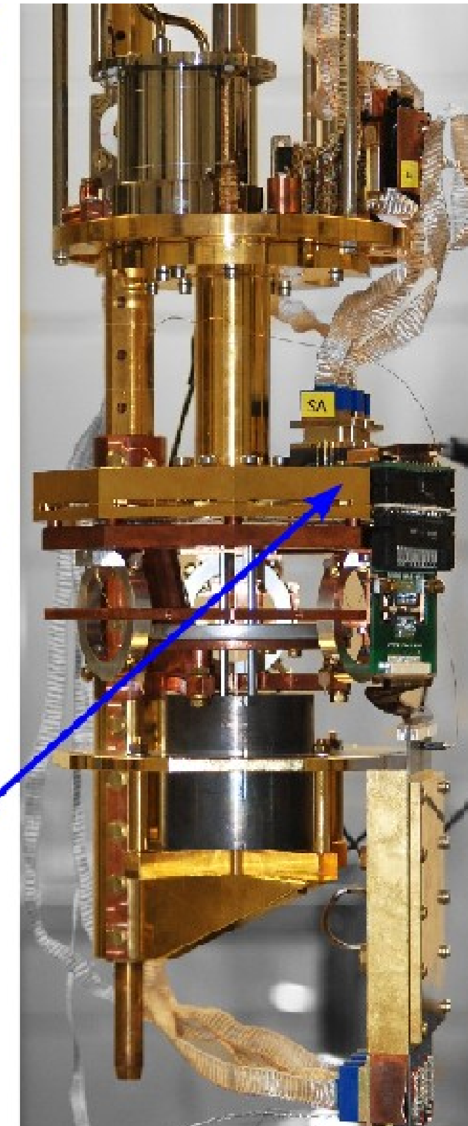
Advantages of cryogenic bolometers:
- measures all released energy except that of the neutrino
- no final atomic/molecular states
- no energy losses
- no back-scattering

Challenges of cryogenic bolometers:
- measures the full spectrum (pile-up)
- need large arrays to get statistics
- understanding spectrum
- still energy losses or trapping possible

MARE-1 @ Milano-Bicocca

- 6x6 array of Si-implanted thermistors (NASA/GSFC)
- 0.5 mg $AgReO_4$ crystals
- $\Delta E \approx 30$ eV, $\tau_R \approx 250$ µs
- experimental setup for up to 8 arrays completed
- starting with 72 pixels in 2011
- up to 10^{10} events in 4 years → ~ 4 eV sensitivity





MARE-1 @ Genova

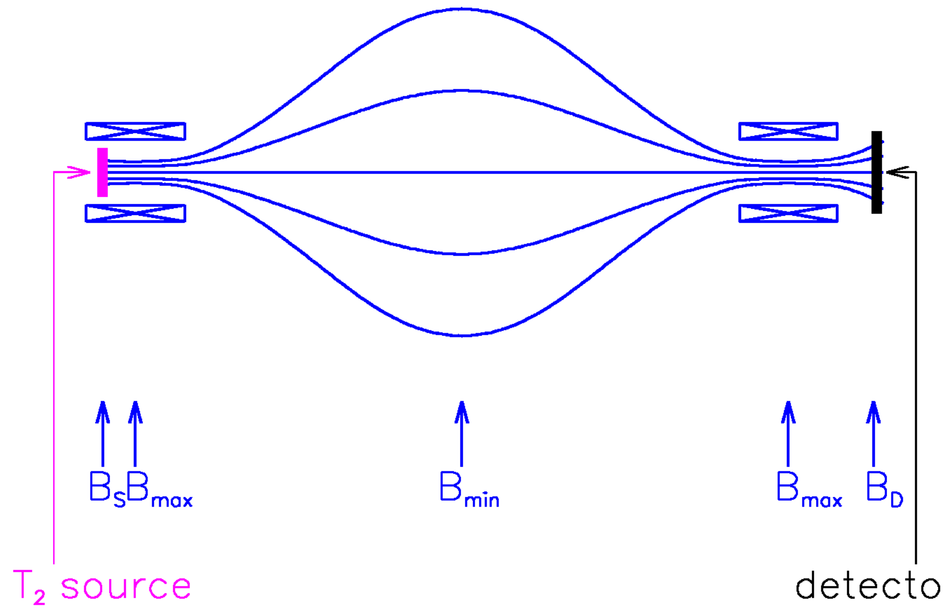
- R&D effort for Re single crystals on transition edge sensors (TES) → improve rise time to ~ µs and energy resolution to few eV
- large arrays (≈10^3 pixels) for 10^4-10^5 detector experiment
- high bandwidth, multiplexed SQUID readout
- also used with ^{163}Ho loaded absorbers

Angelo Nucciotti, Meudon 2011

Principle of the MAC-E-Filter

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

- Two supercond. solenoids compose magnetic guiding field
- Electron source (T_2) in left solenoid



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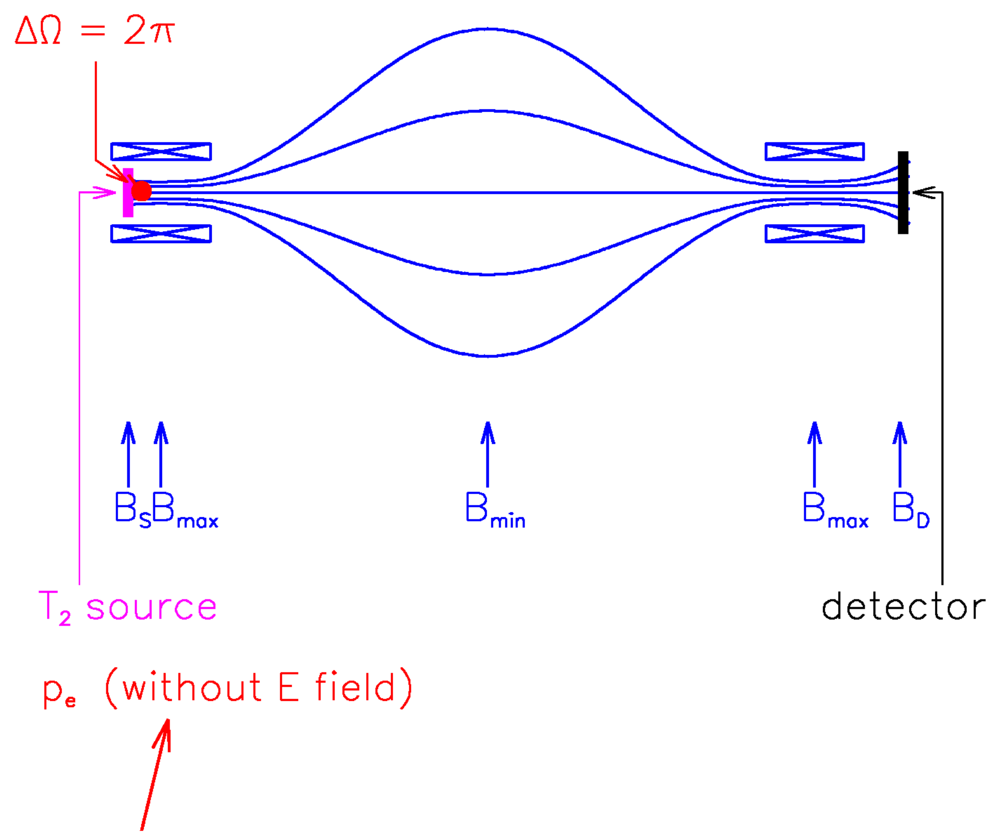
- Two supercond. solenoids compose magnetic guiding field
- Electron source (T_2) in left solenoid
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_{cycl}/B = \text{const.}$
  $\Rightarrow$ parallel e^- beam



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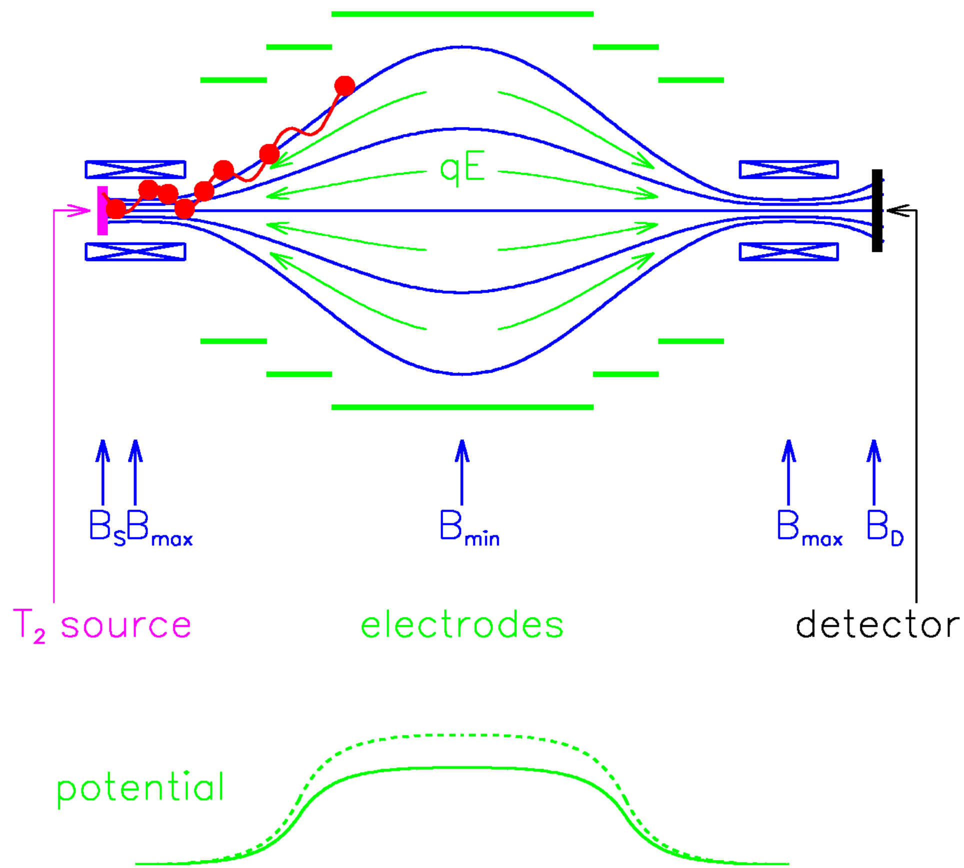
- Two supercond. solenoids compose magnetic guiding field
- Electron source (T_2) in left solenoid
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_{cycl}/B = const.$
  $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field

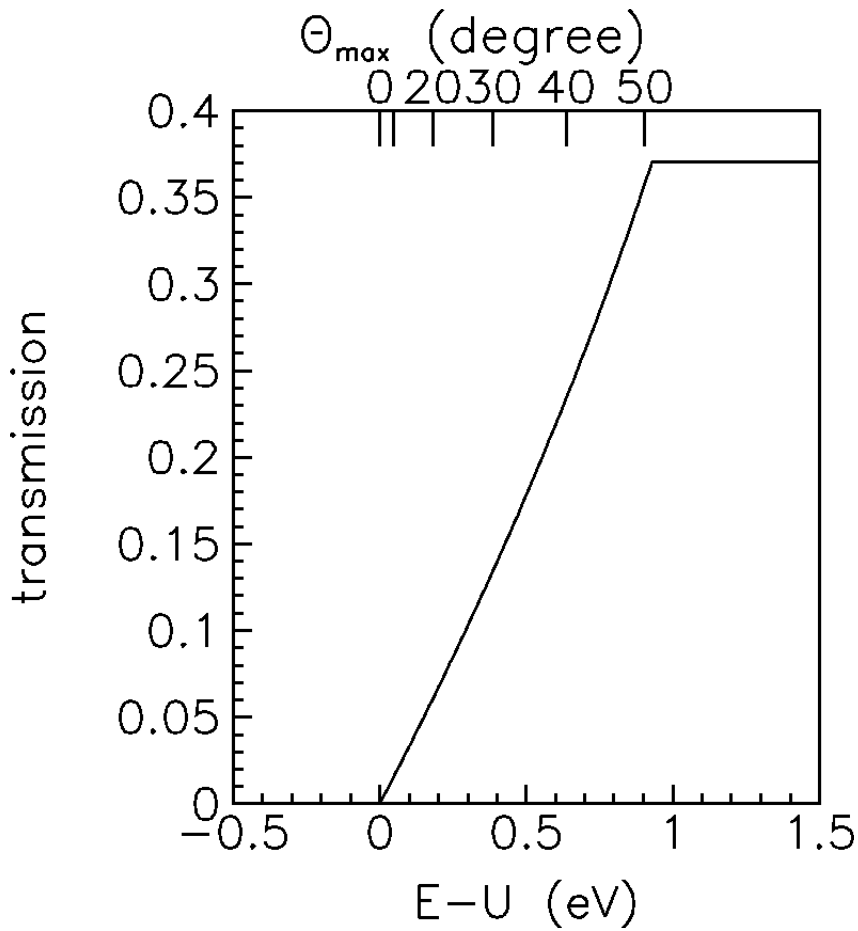


$\Delta E = E B_{min}/B_{max} = E A_{s,eff}/A_{analyse} \approx 4.8$ eV (Mainz) $= 0.93$ eV (KATRIN)

Principle of the MAC-E-Filter

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

⇒ sharp integrating transmission function without tails:



$\Delta E = E\, B_{min}/B_{max} = E\, A_{s,eff}/A_{analyse}$ ≈ 4.8 eV (Mainz) = 0.93 eV (KATRIN)

The Mainz Neutrino Mass Experiment
Phase 2: 1997-2001

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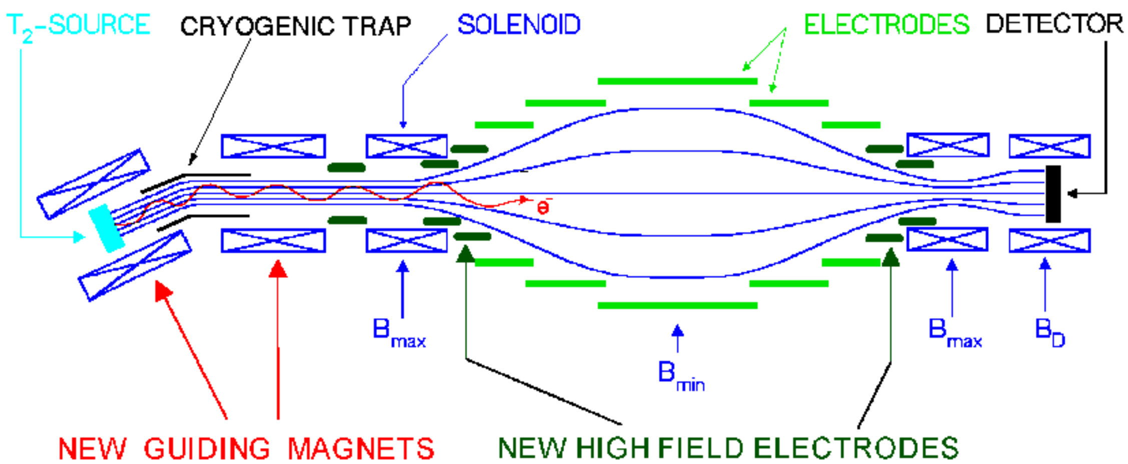
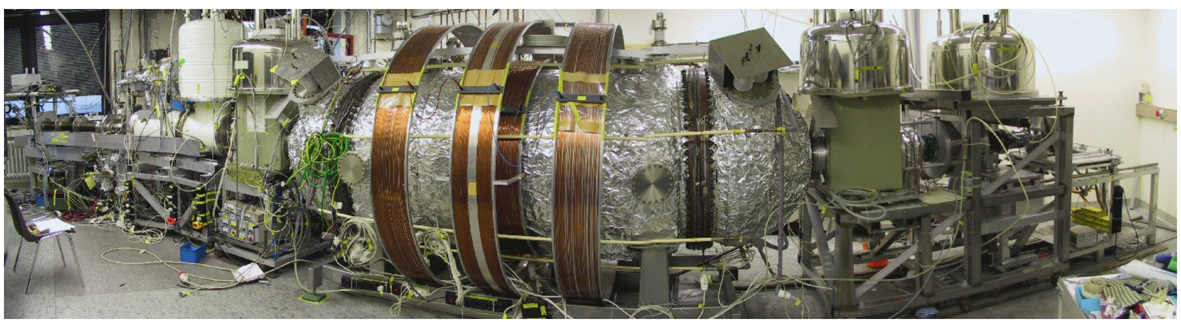
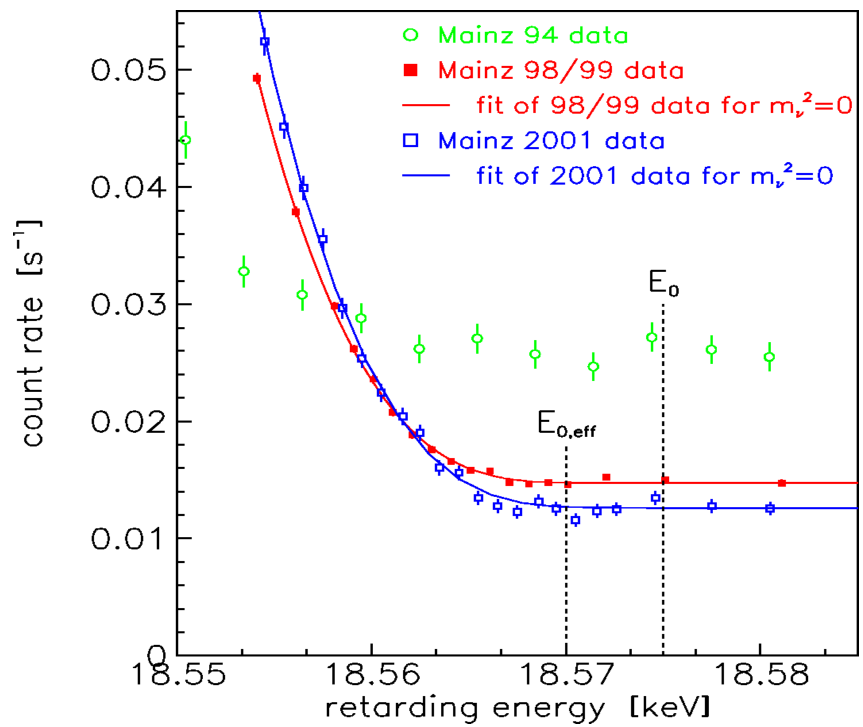
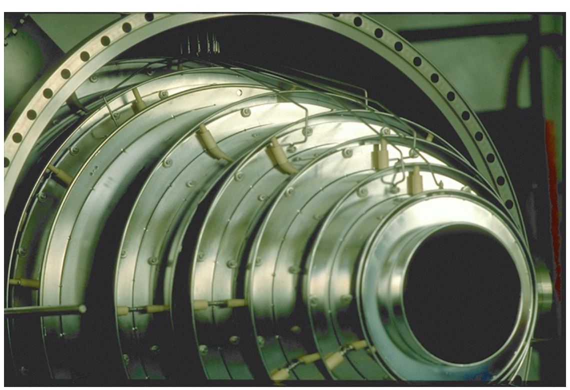






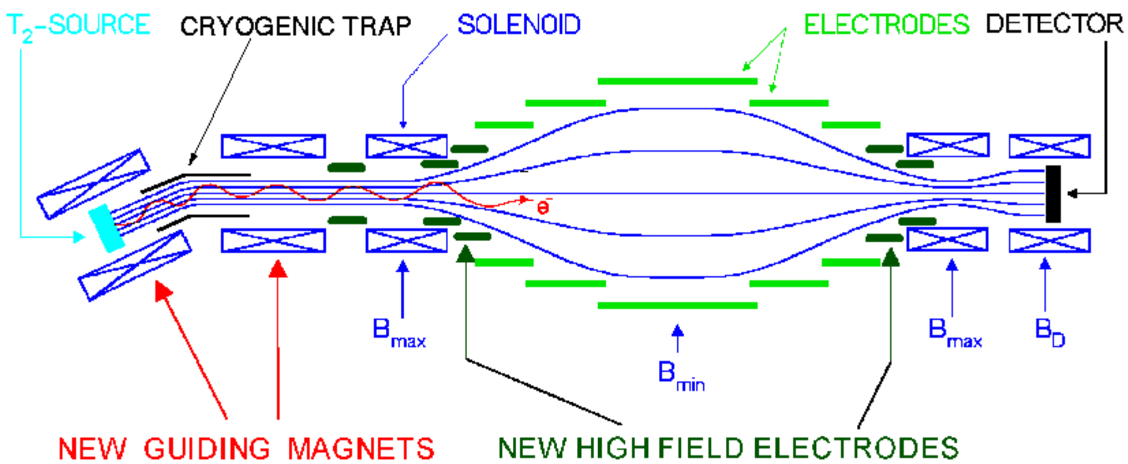


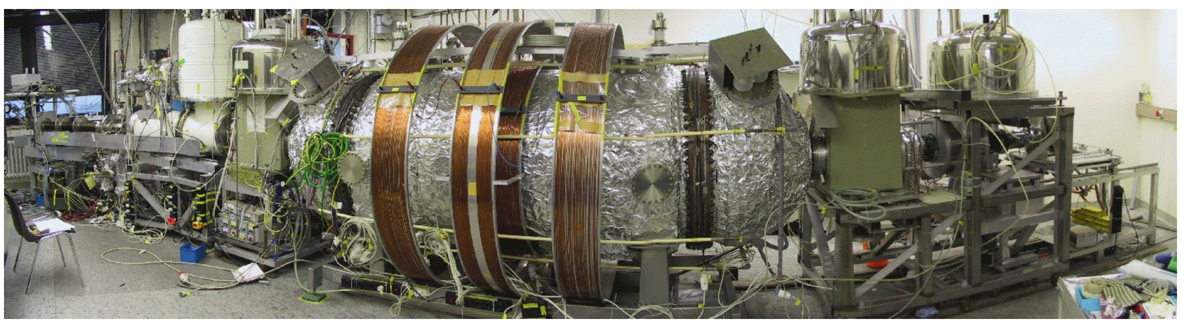
After all critical systematics measured by own experiment (atomic physics, surface and solid state physics:
inelastic scattering, self-charging, neighbour excitation):

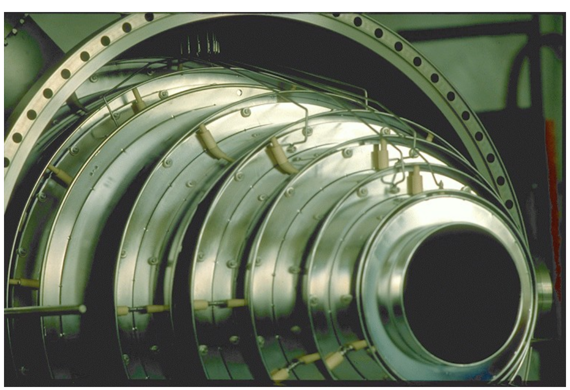
$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1\ \mathrm{eV}^2 \quad \Rightarrow m(\nu) < 2.3\ \mathrm{eV}$ (95% C.L.)

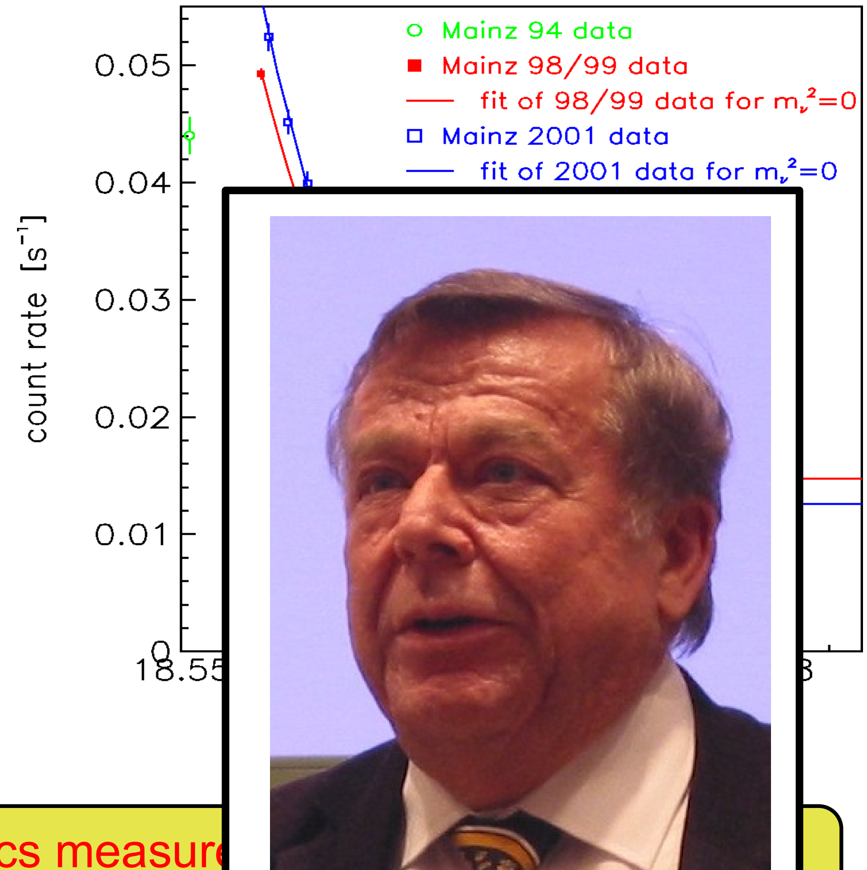
C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

The Mainz Neutrino Mass Experiment Phase 2: 1997-2001









Dr. Jochen Bonn

* 7.4.44

+ 27.8.12

After all critical systematics measure
(atomic physics, surface and solid s
inelastic scattering, self-chargin

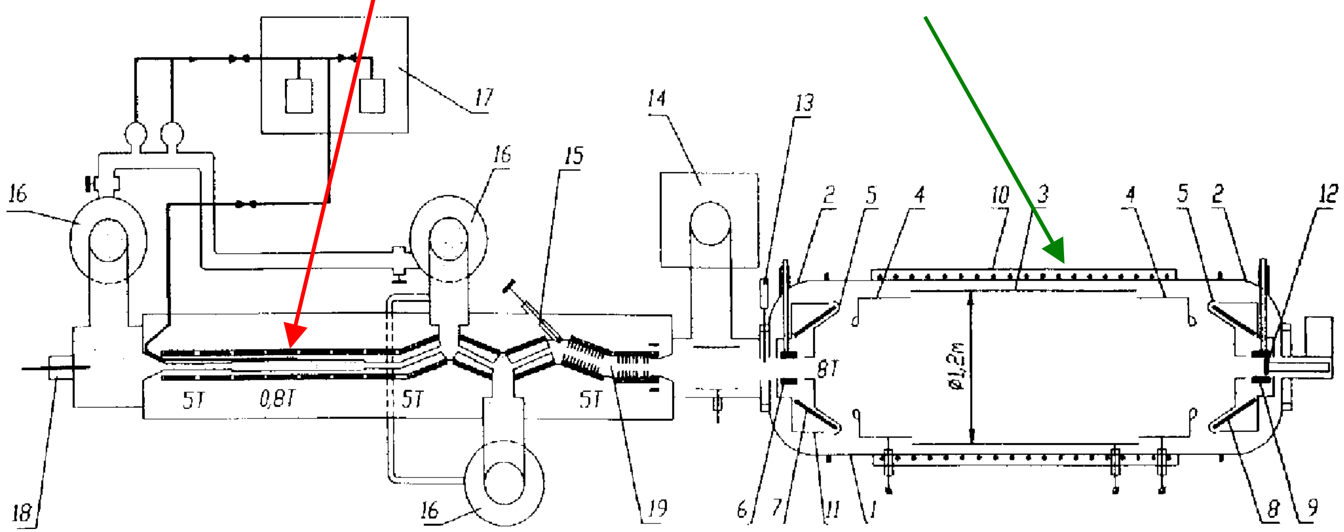
$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1\ eV^2 \quad \Rightarrow$ …)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

The Troitsk Neutrino Mass Experiment

windowless gaseous T_2 source, similar to LANL

MAC-E-Filter, similar to Mainz



Vladimir Mikhailovich Lobashev 1934-2011

Luminosity: L = 0.6cm²
($L = \Delta\Omega/2\pi * A_{source}$)

Energy resolution: $\Delta E = 3.5$eV
3 electrode system in 1.5m diameter UHV vessel ($p<10^{-9}$ mbar)

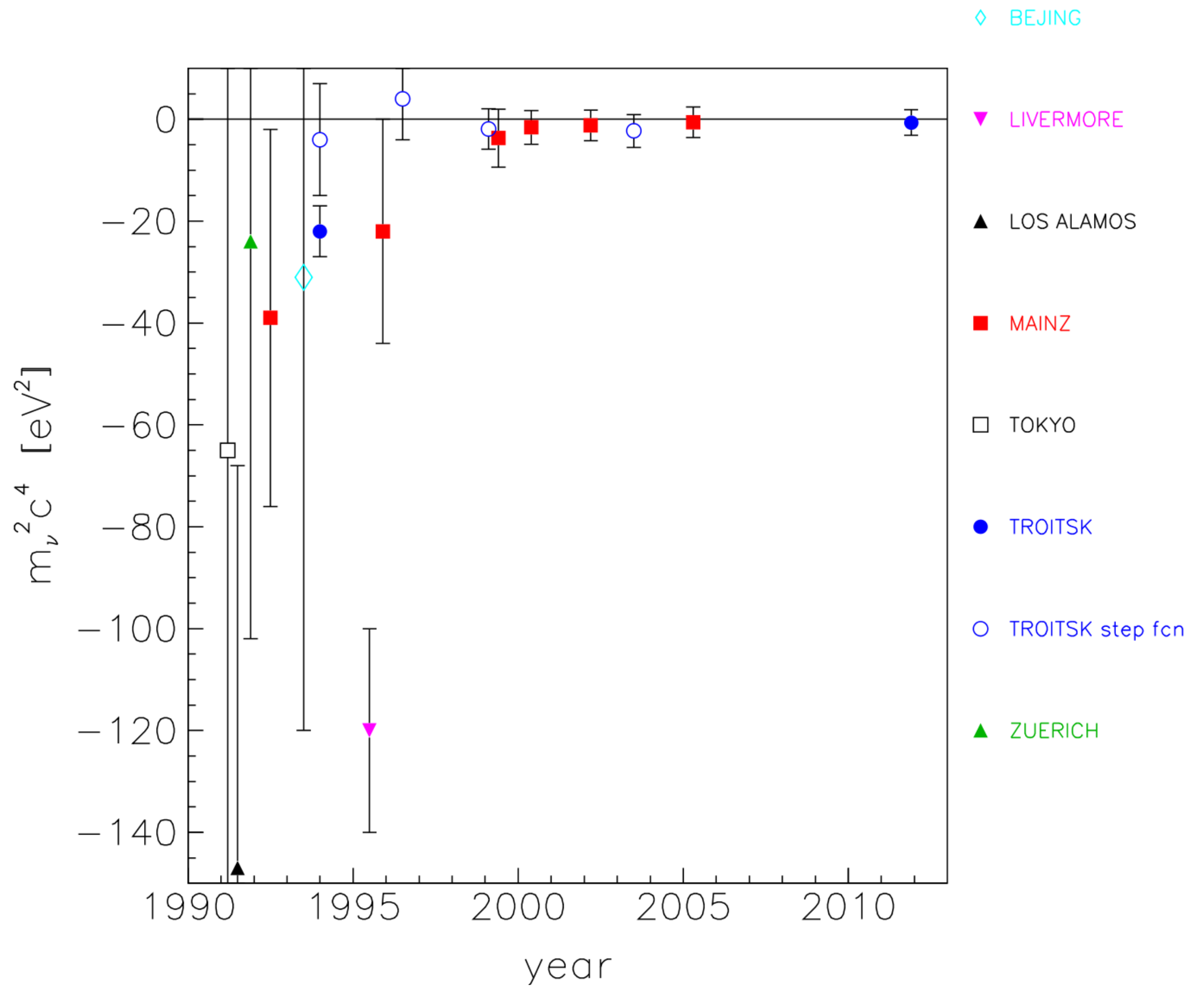
Re-analysis of Troitsk data

(better source thickness, better run selection)

Aseev et al, Phys. Rev. D 84, 112003 (2011)

m_β < 2.05 eV, 95% CL

m(ν_e) from tritium β decay



2 tritium exp. with MAC-E-Filter (Mainz,Troitsk):
⇒ former problem of negative $m^2(\nu)$ solved
Rhenium experiments not competitive yet

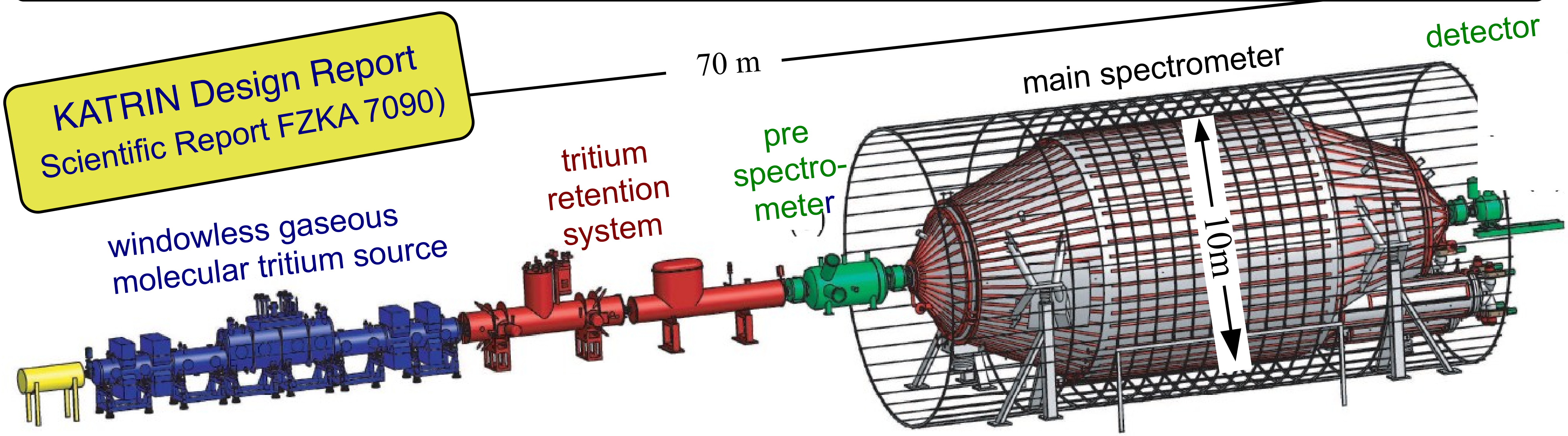
The KATRIN experiment at KIT

Aim: $m(\nu_e)$ sensitivity of 200 meV (currently 2 eV)

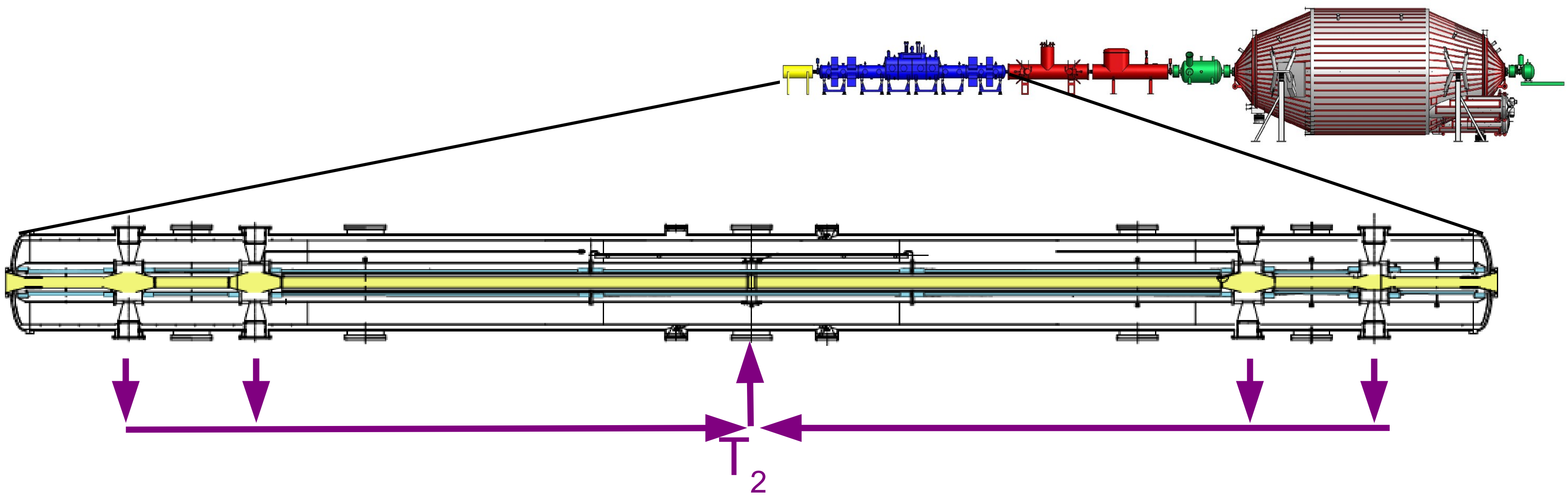
- very high energy resolution
  ($\Delta E \leq$ 1eV, i.e. σ = 0.3 eV) $\Rightarrow$ source $\neq$ spectrometer concept
- strong, opaque source $\Rightarrow$ $dN/dt \sim A_{source}$
- magnetic flux conservation (Liouville) $\Rightarrow$ scaling law:

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

KATRIN Design Report
Scientific Report FZKA 7090)



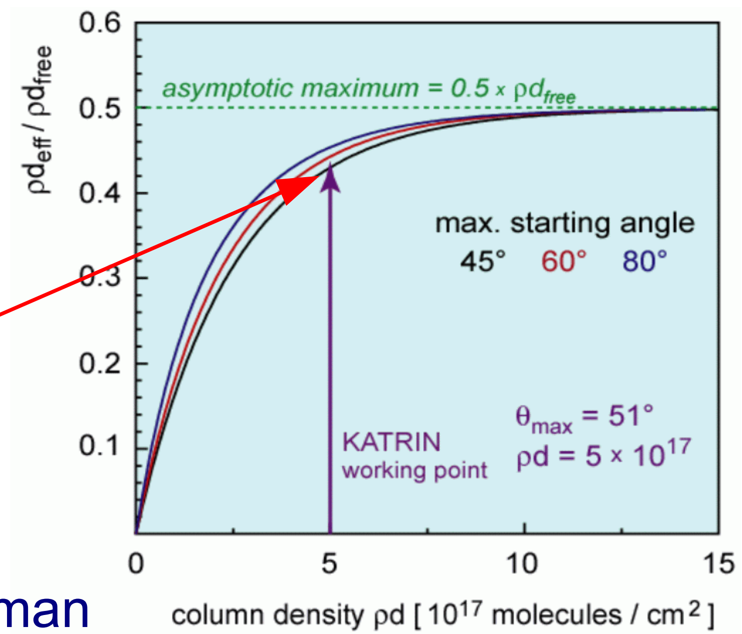
Molecular Windowless Gaseous Tritium Source WGTS



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

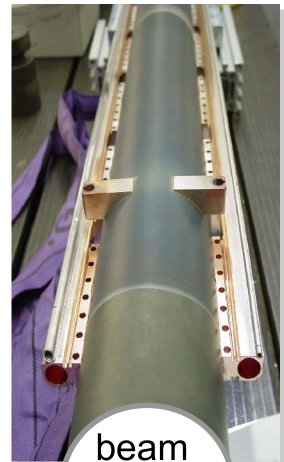


check column density by e-gun, T_2 purity by laser Raman

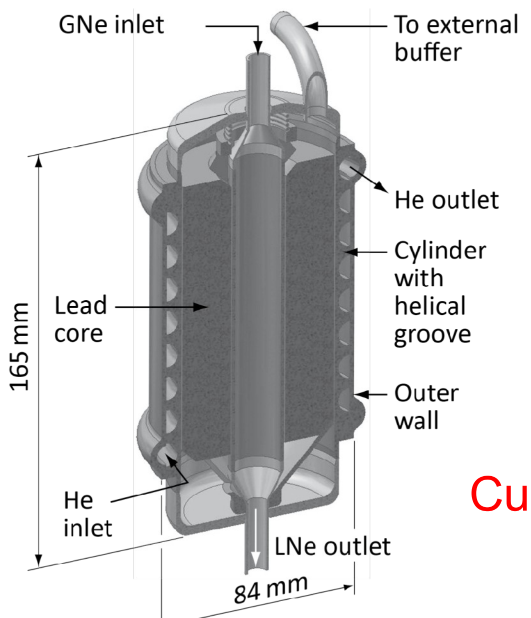
Very successful cool-down and stability tests of the WGTS demonstrator

per mill stability request:
$dN/dt \sim n = p\,V / R\,T$
ideal gas law

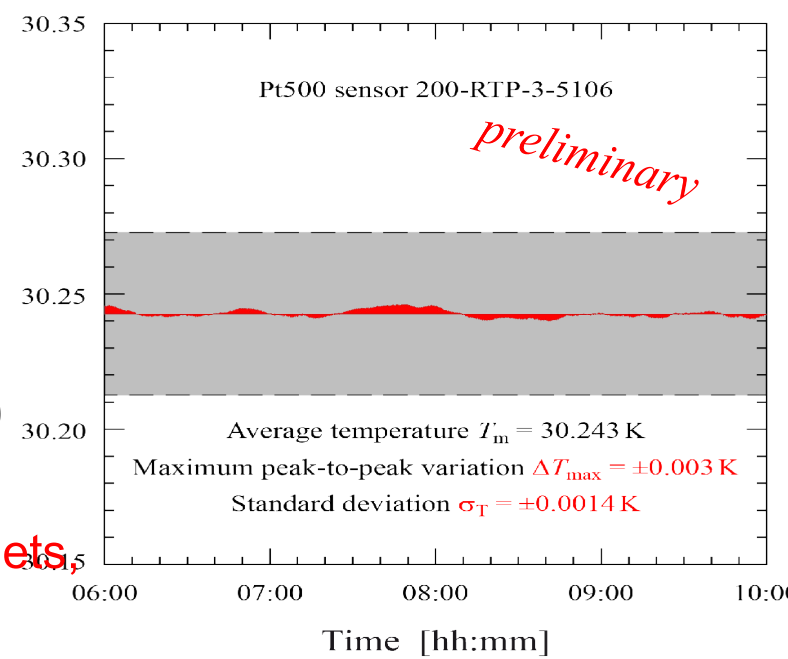

arrival of WGTS demonstrator at KIT: April 2010


beam tube Ø=90mm


cooling concept of WGTS: pressurized 2-phase Ne



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



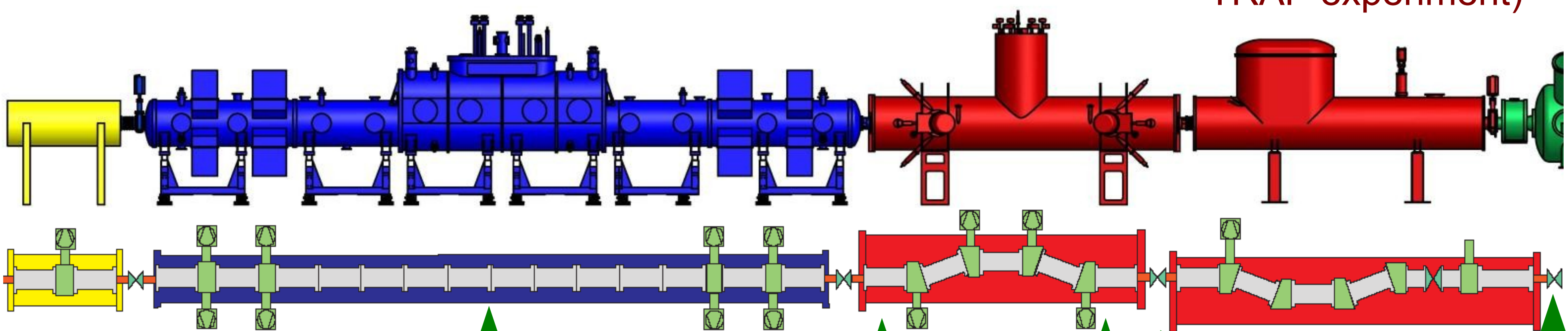
Currently: tests of sc magnets, constructing of WGTS out of demonstrator

Transport and differential & cryo pumping sections

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping
with Argon snow
at LHe temperatures
(successfully tested with the TRAP experiment)



T_2-injection 1.8 mbar l/s (STP)
= $1.7 \cdot 10^{11}$ Bq/s = 40 g/d

FT-ICR Penning traps to measure ions from WGTS

$\approx 10^{-7}$ mbar l/s

< 2.5 10^{-14} mbar l/s

$\Rightarrow$ adiabatic electron guiding & T_2 reduction factor of $\sim 10^{14}$

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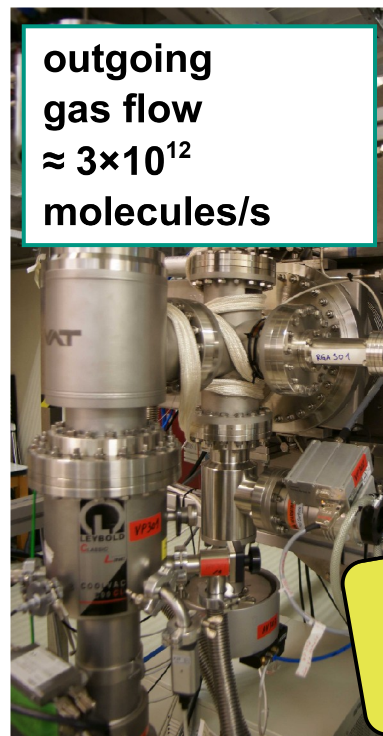
Commissioning of DPS2-F

Ion test source:
S. Lukic et al.,
Rev. Scient. Instr.
82 (2011) 013303

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



outgoing gas flow ≈ 3×10^{12} molecules/s

First gas flow reduction measurements with Ar

gas inlet ≈ 3×10^{17} molecules/s

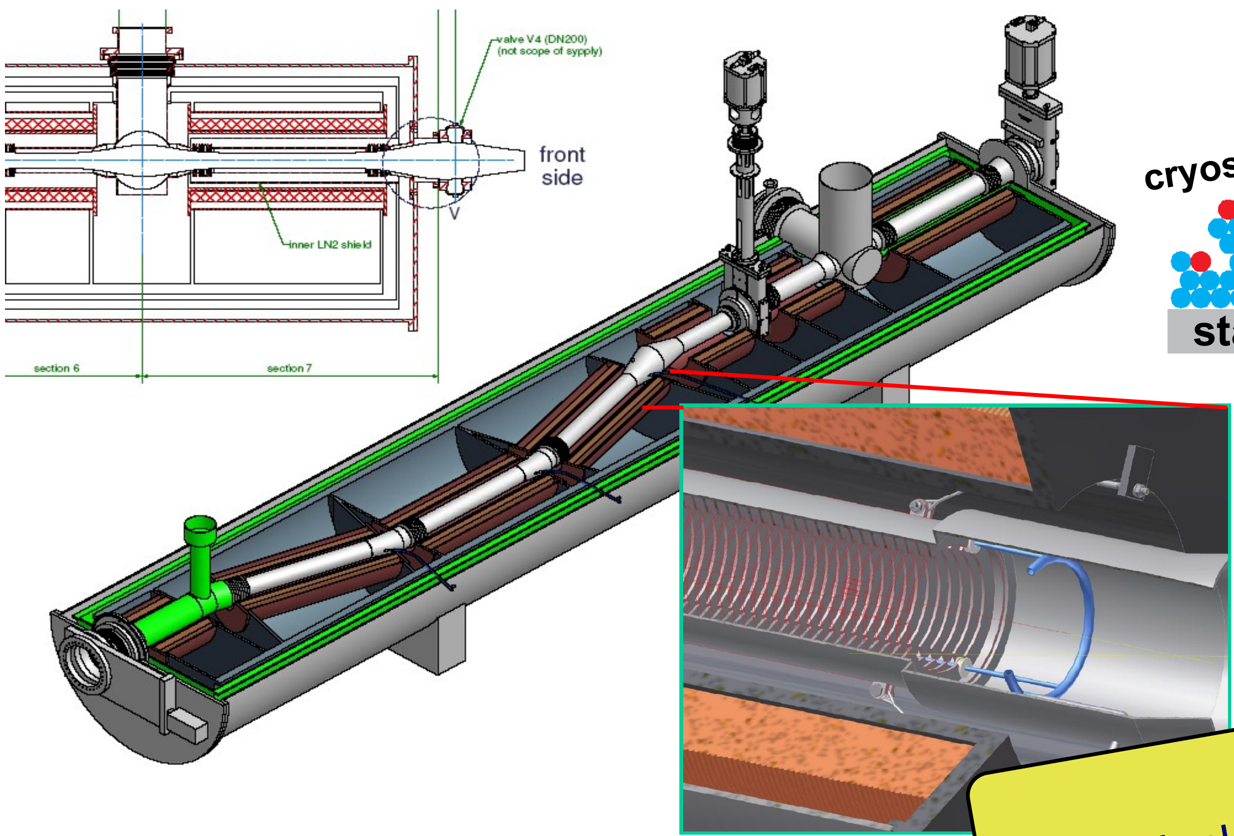
S. Lukic et al.,
Vacuum 86 (2012) 1126

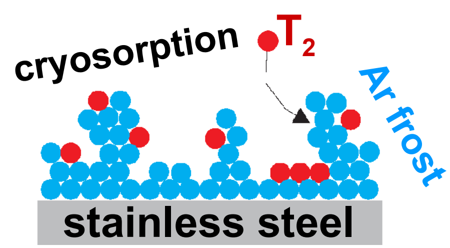
Currently:
Problem of a broken diode of the safety system of a superconducting coil

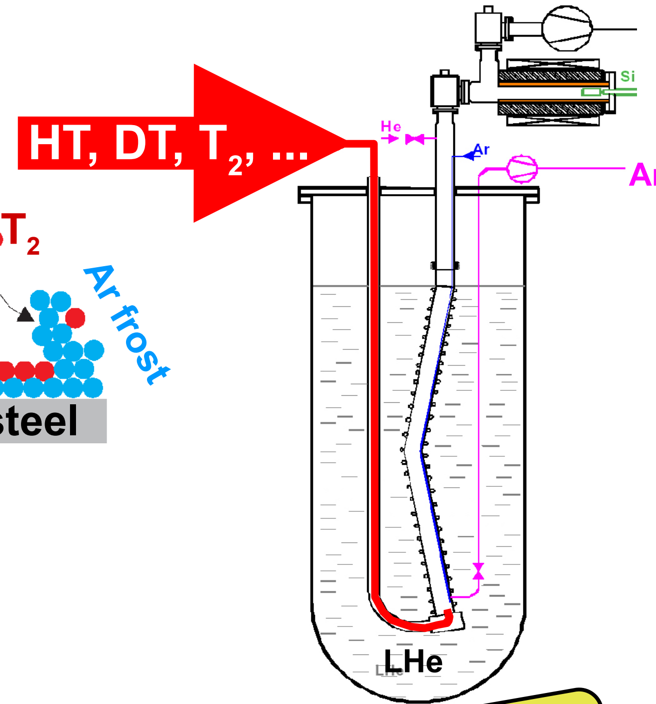
Cryogenic pumping section and test of principle

TRAP: TRitium Argon frost Pump

CPS: cryogenic pumping section



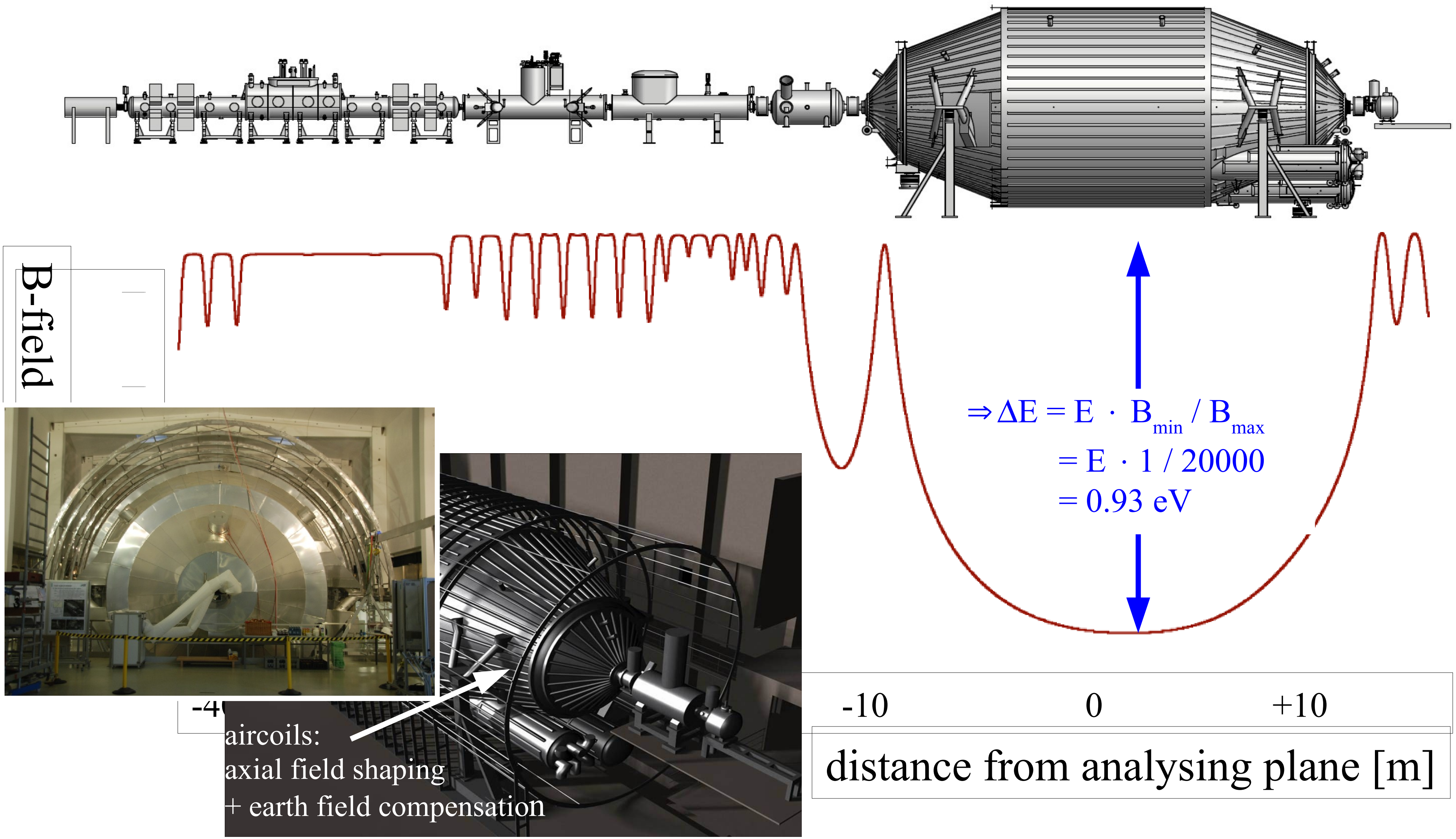




- cryosorption of T_2 by Ar frost
- magnetic guiding field B = 5.6 T
- specification finished
- estimated delivery 2010

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

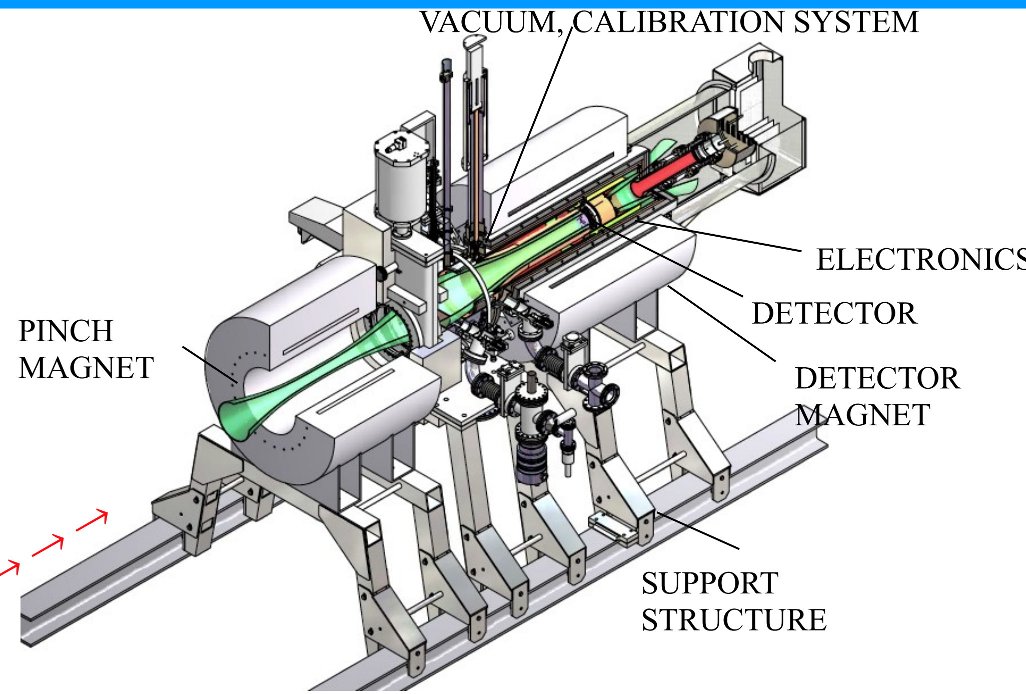
Electromagnetic design: magnetic fields



The detector

Requirements

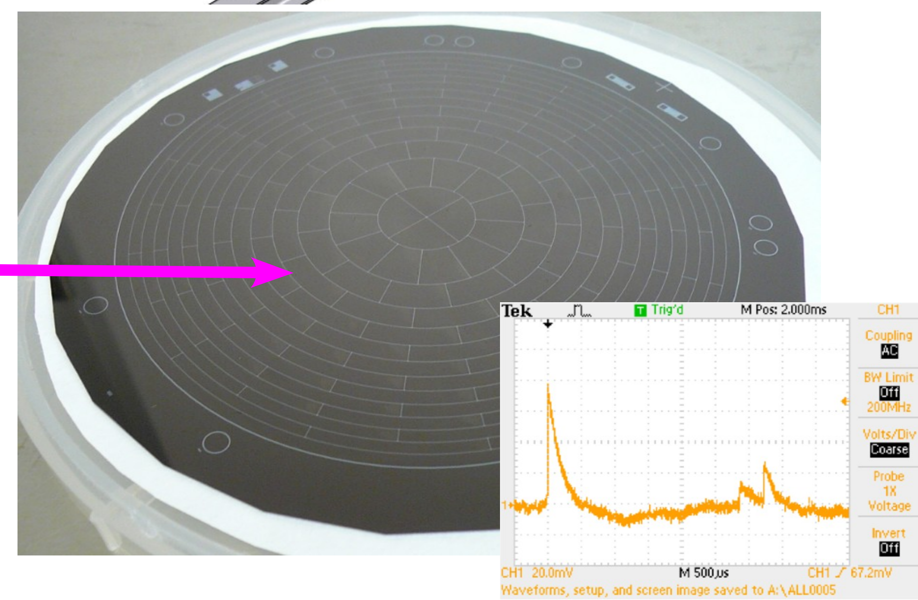
- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz) (passive and active shielding)
- good energy resolution (< 1 keV)



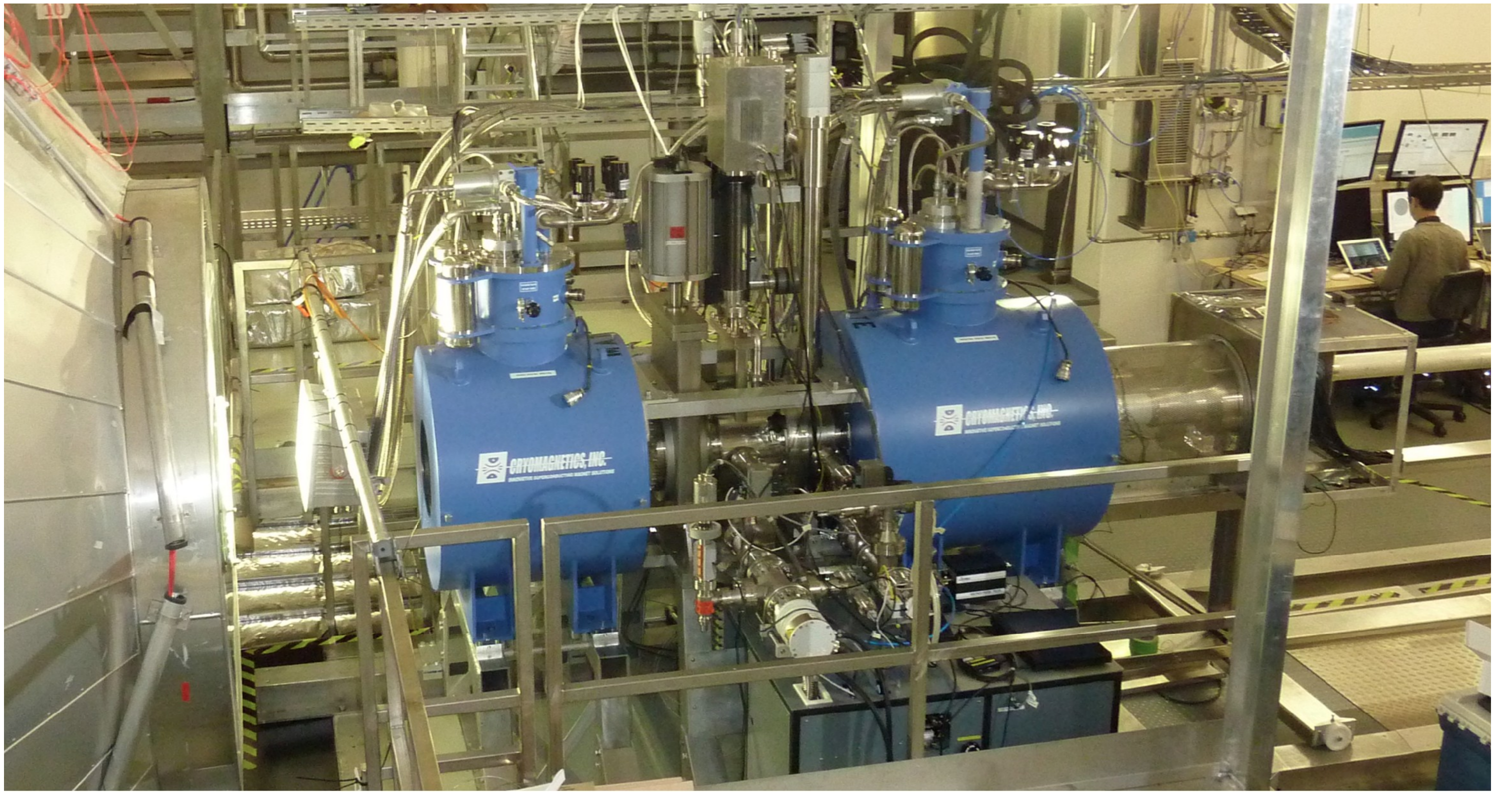
Properties

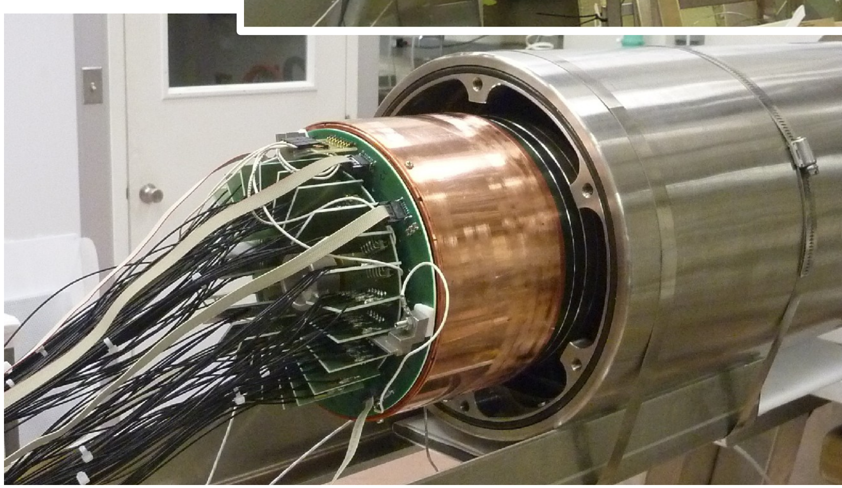
- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV) (to lower background in signal region)
- segmented wafer (148 pixels)
  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities

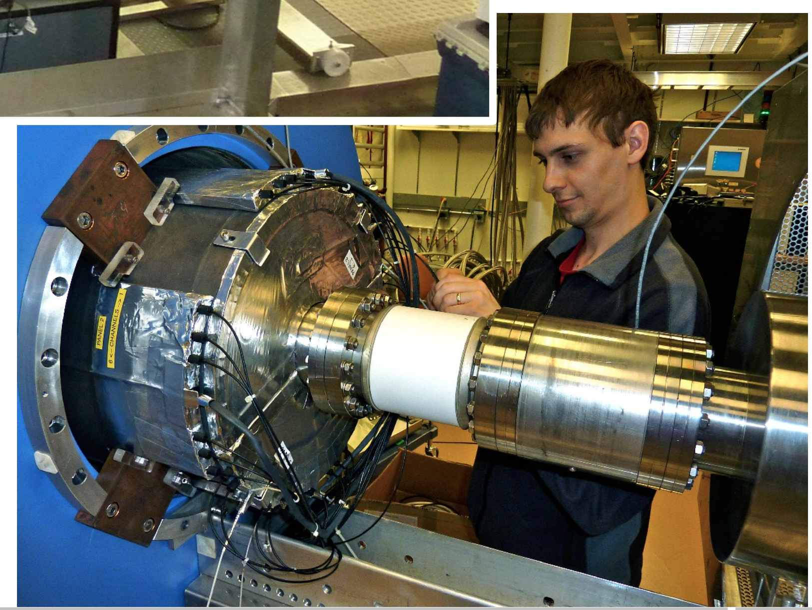
electrons → → →



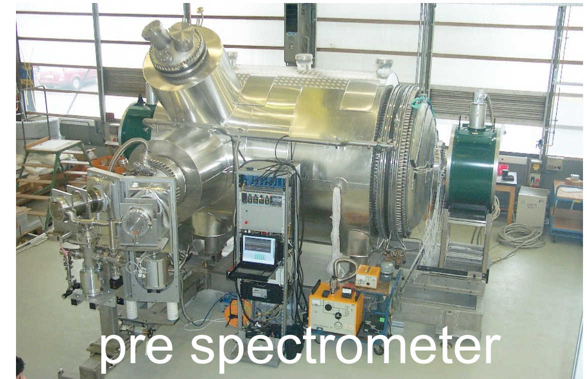
KATRIN detector is being commissioned at KIT

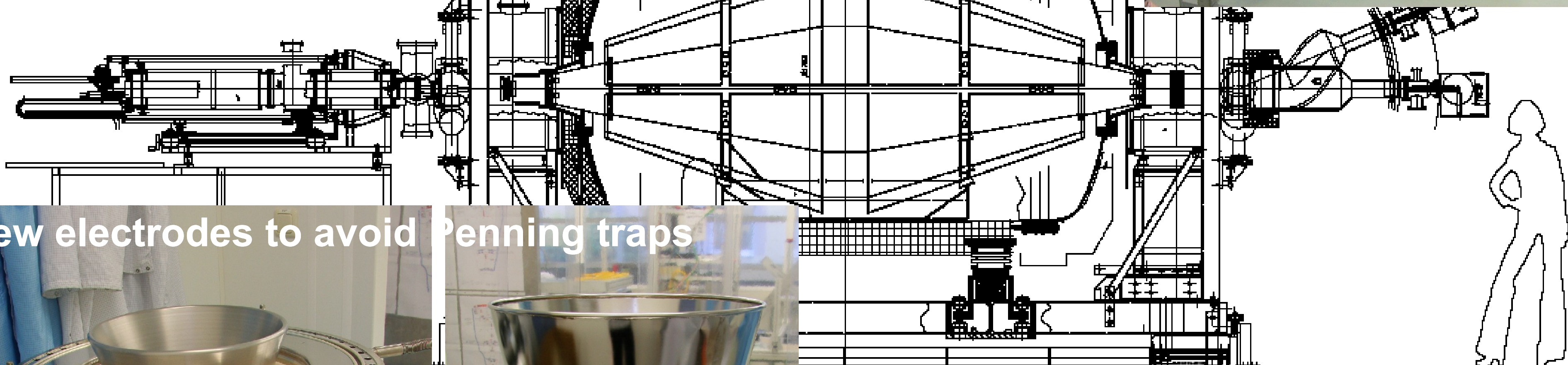


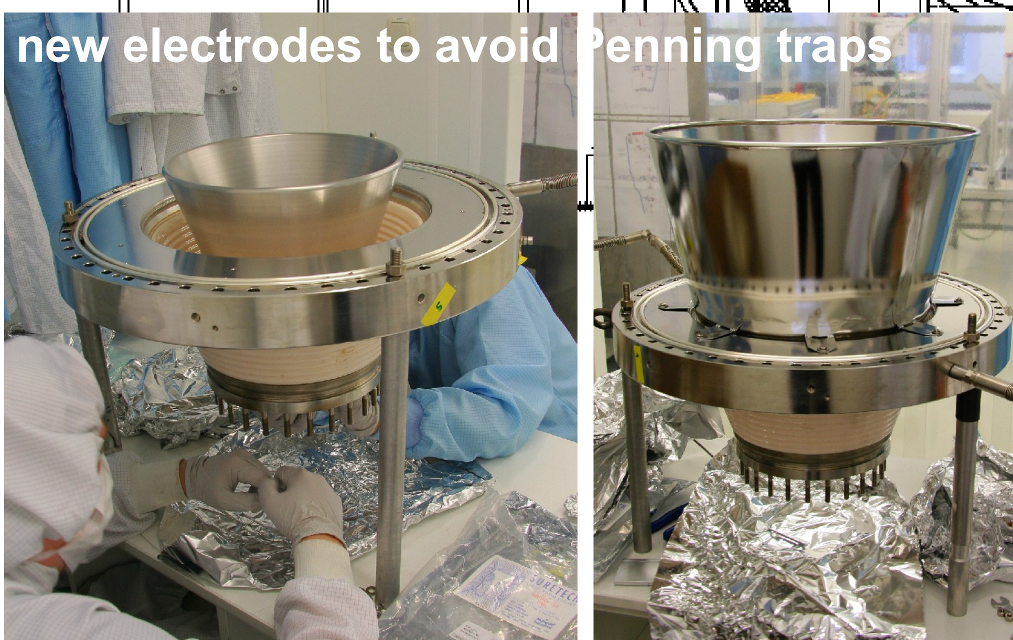




Electromagnetic design tests at the pre spectrometer







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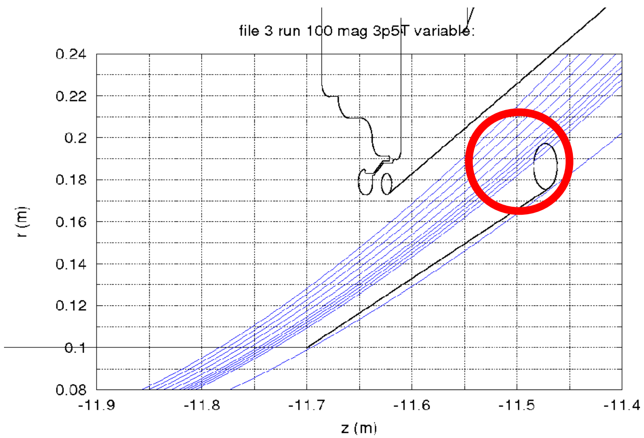
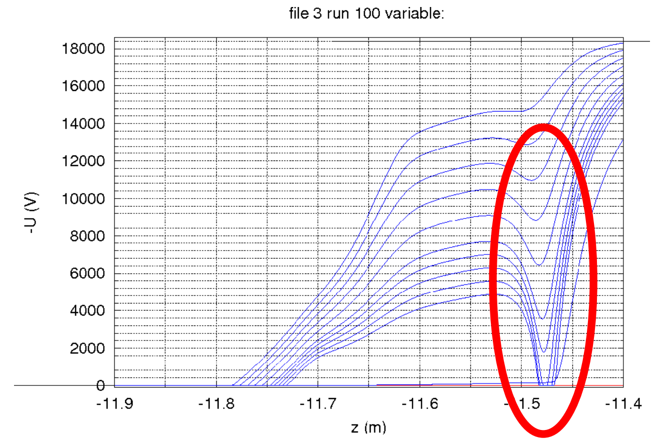
Pre spectrometer background studies I

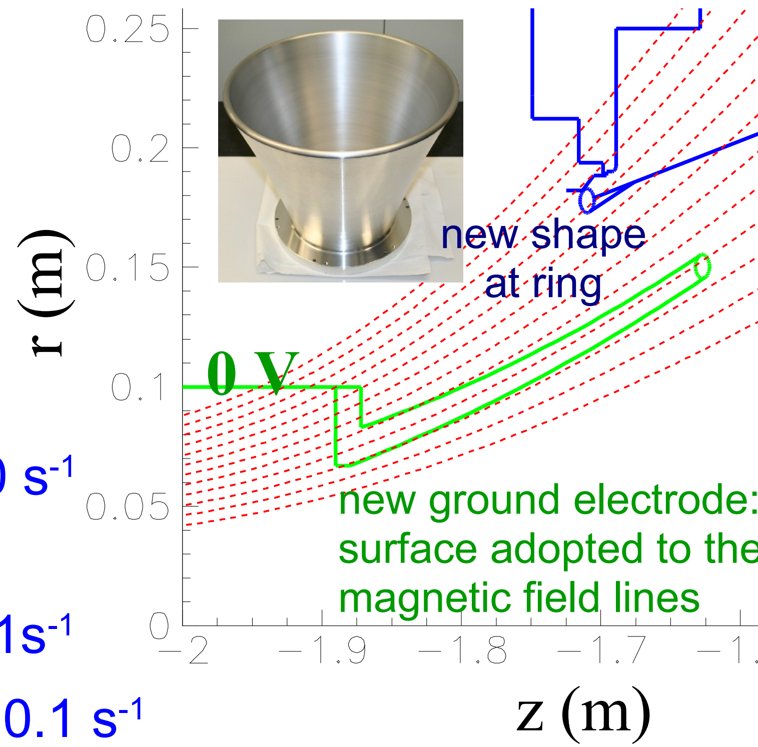
Problem: very small, but deep Penning traps near geometrical corners





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 ≈ 1s^{-1}
- no residual Penning trap bg ≈ 0.1 s^{-1}

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Radon background in the pre spectrometer from the non-evaporable getter (NEG) pumps

Getter strips (SAES ST707) adsorbing residual gas (H_2) are essential to reach 10^{-11} mbar, composition:

70 % Zirconium: contains ^{227}Ac
25 % Vanadium
5 % Iron

$$^{235}\mathrm{U} \rightarrow \ldots \rightarrow {}^{227}\mathrm{Ac} \xrightarrow{\alpha} {}^{223}\mathrm{Fr} \xrightarrow{\beta} {}^{223}\mathrm{Ra} \rightarrow {}^{219}\mathrm{Rn} \xrightarrow{\alpha\ (4s)} {}^{215}\mathrm{Po} \xrightarrow{\alpha\ (2ms)} {}^{211}\mathrm{Pb}$$

^{219}Ra is gaseous → spectrometer → ionizations → **background**

Evidence for Radon background in the pre spectrometer

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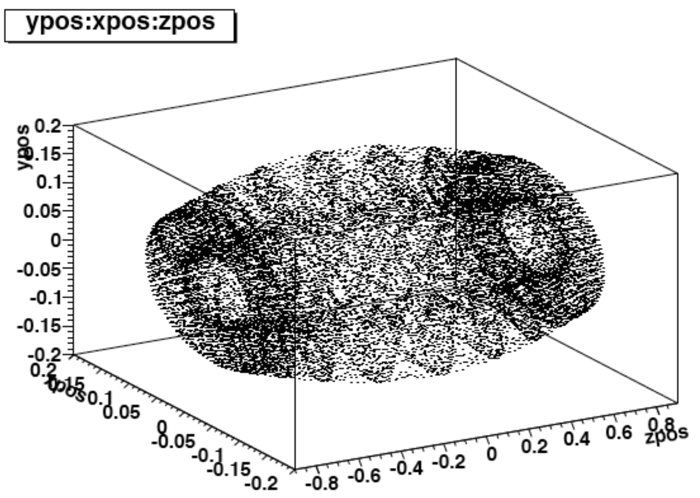
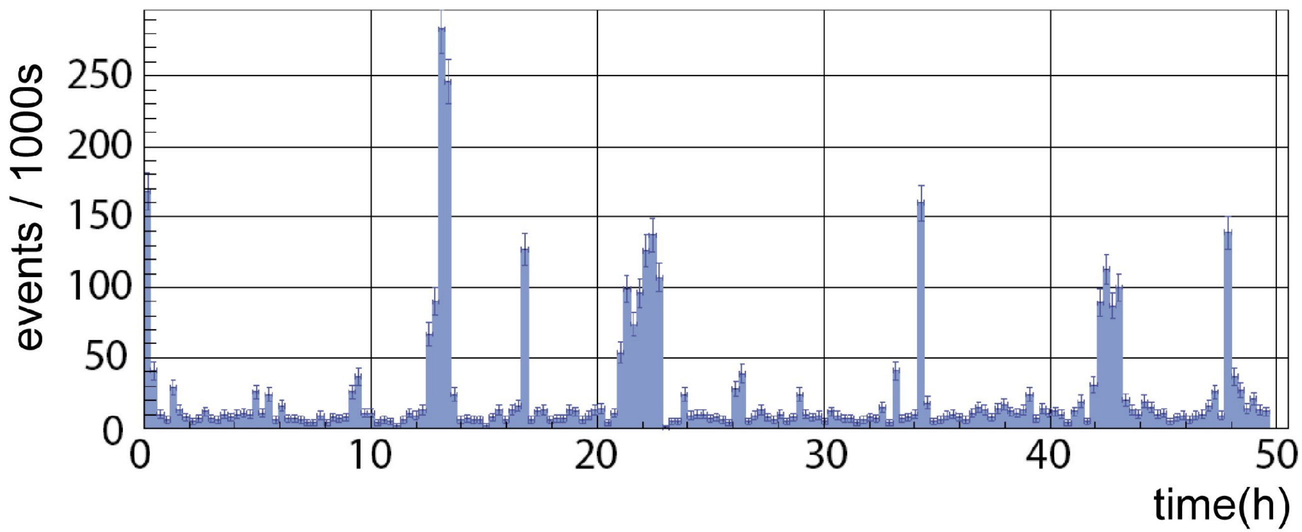
trapped electron trajectory



30 min bursts of background rate

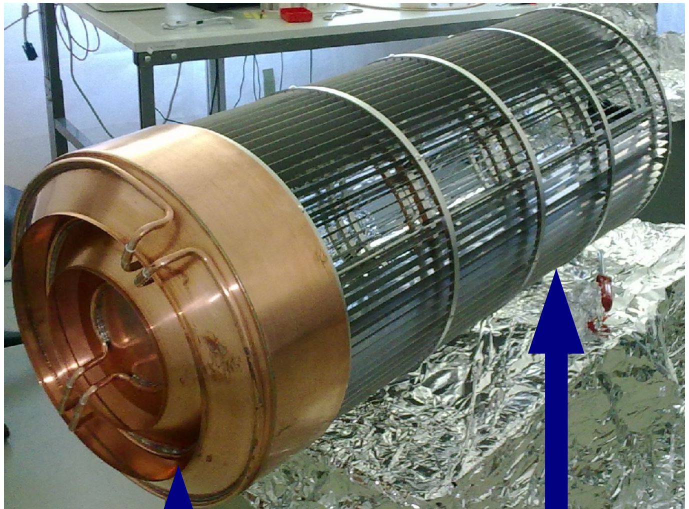


- e^- produced in Rn-decays are stored
- produce secondary e^-
- 30 min intervals with high background (10^{-10} mbar)

F.M. Fränkle et al.
Astropart. Phys. 35 (2011) 128-134

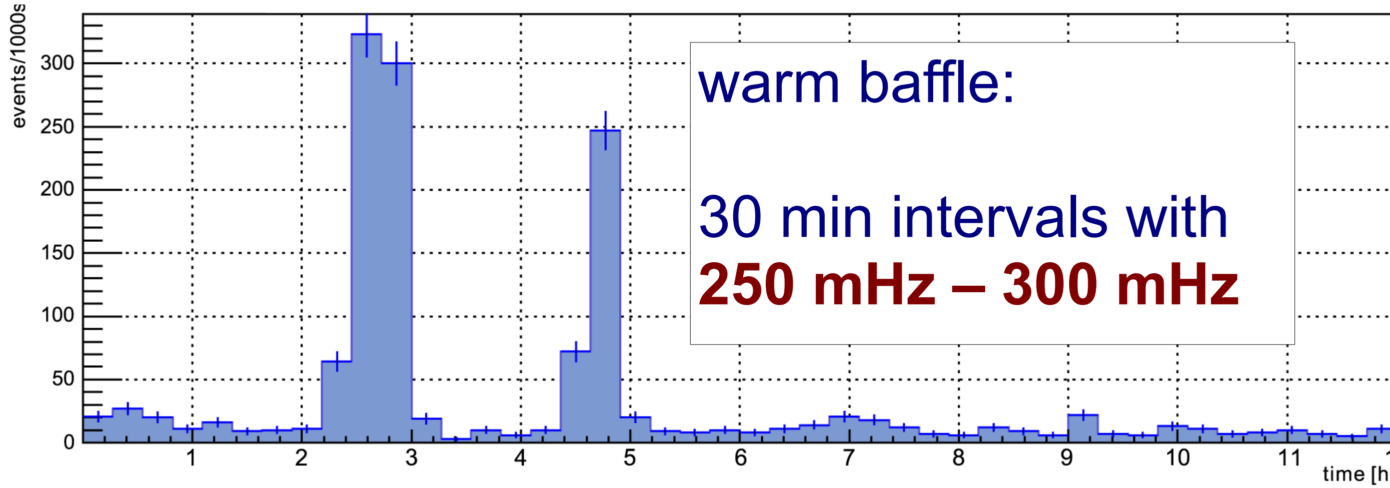
Radon emanation from getter has to be suppressed

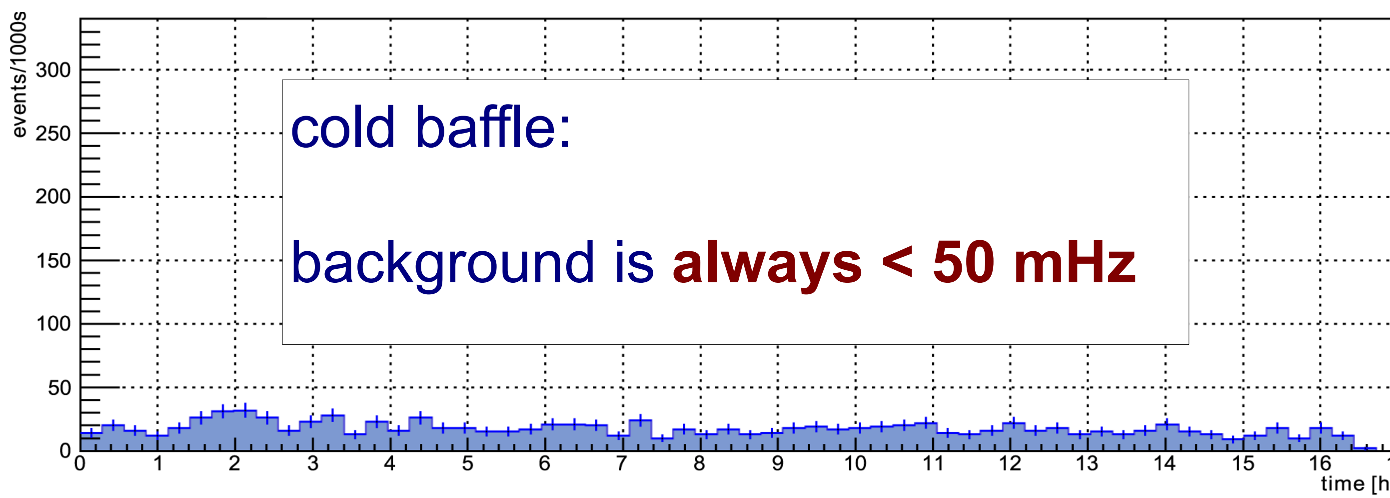
Elimination of Radon background in the pre spectrometer



getter

baffle cooled with LN_2





diploma thesis S. Görhardt/KIT

Westfälische Wilhelms-Universität Münster

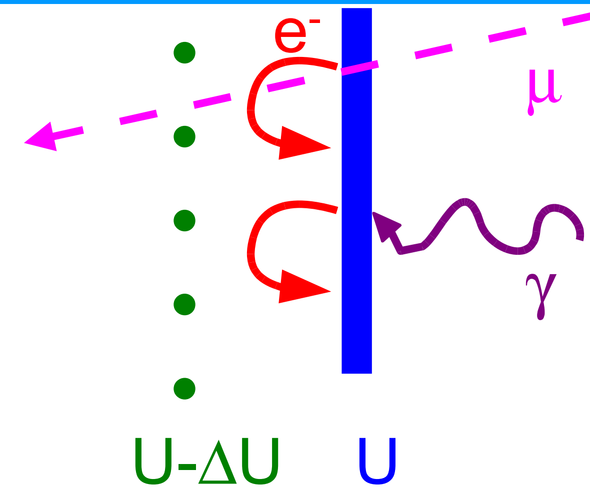
Main Spectrometer – Transport to Karlsruhe Institute of Technology

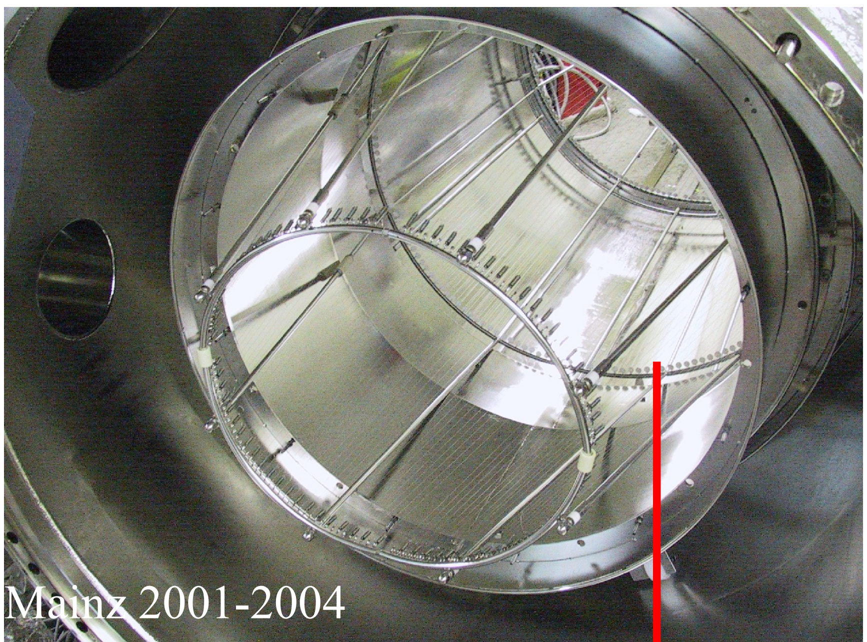
KATRIN has a 100-times larger surface, but requests same bg → something new

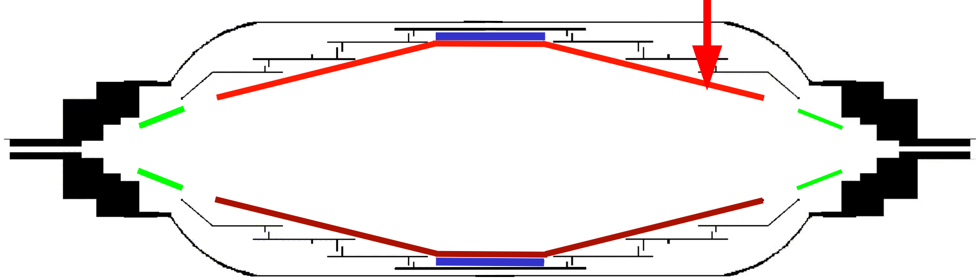
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

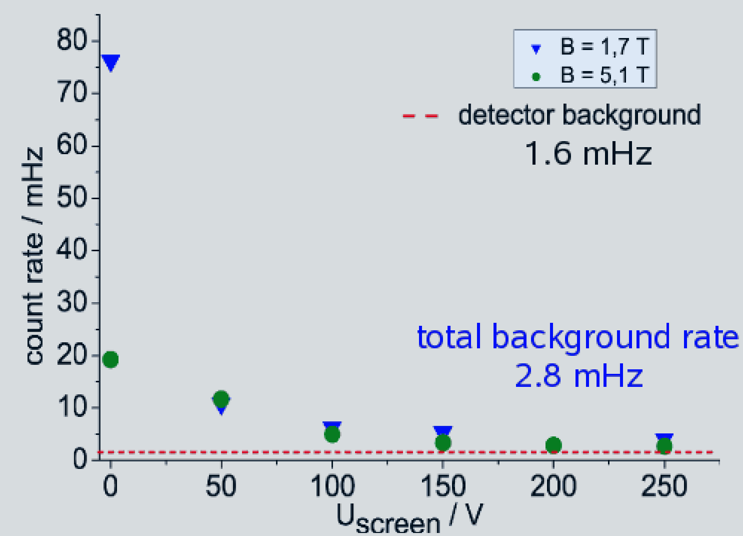
New: wire electrode on slightly more negative potential





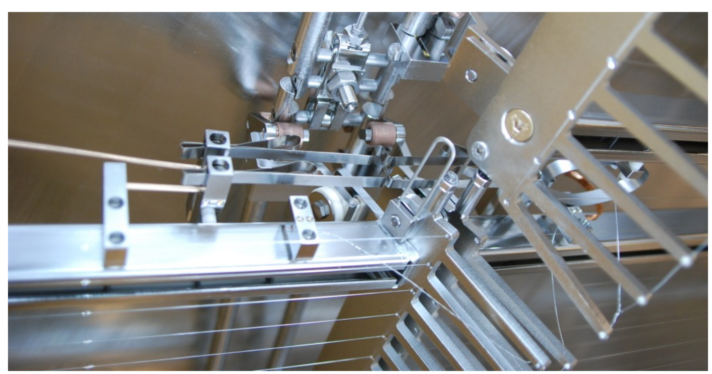


Background suppression successfully tested at the Mainz MAC-E filter:



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

Two-layer wire electrode modules installation inside main spectrometer



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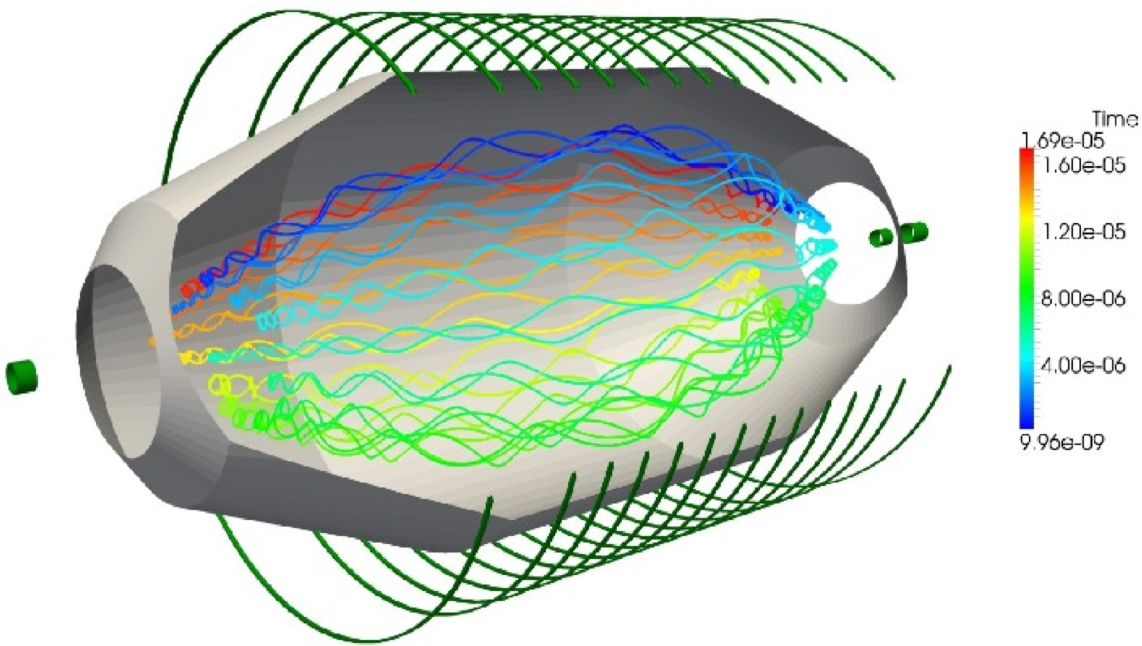
Background from stored electrons: methods to avoid or to eliminate them

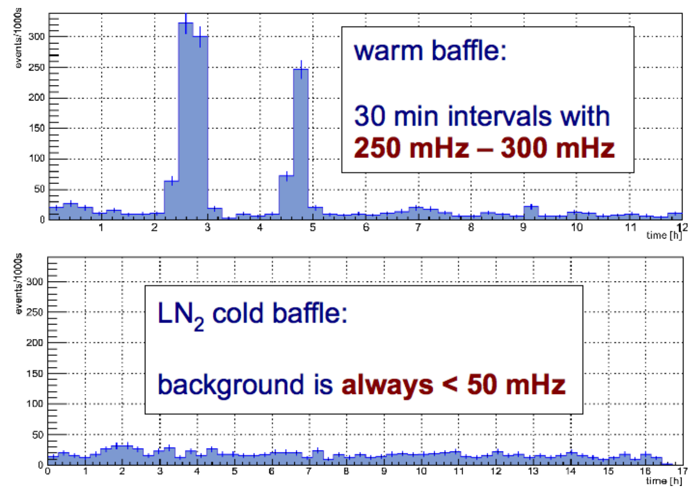
Stored electron by magnetic mirrors

F. Fränkle et al., Astropart. Phys. 35 (2011) 128



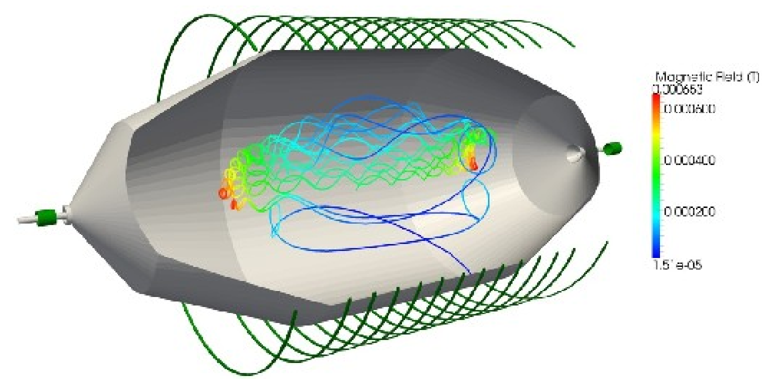
Radon suppression by LN_2 cooled baffle

S. Görhardt, diploma thesis, KIT

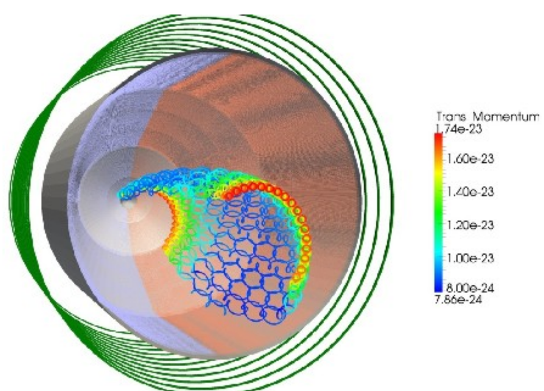


Nulling magnetic field by magn. pulse

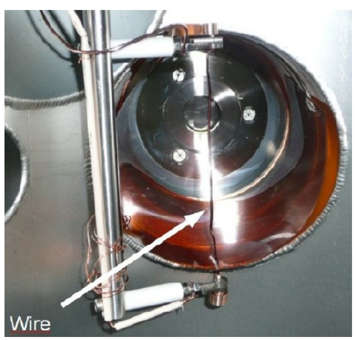
B. Hillen, PhD thesis, Münster



radial E x B drift due to electric dipole pulse



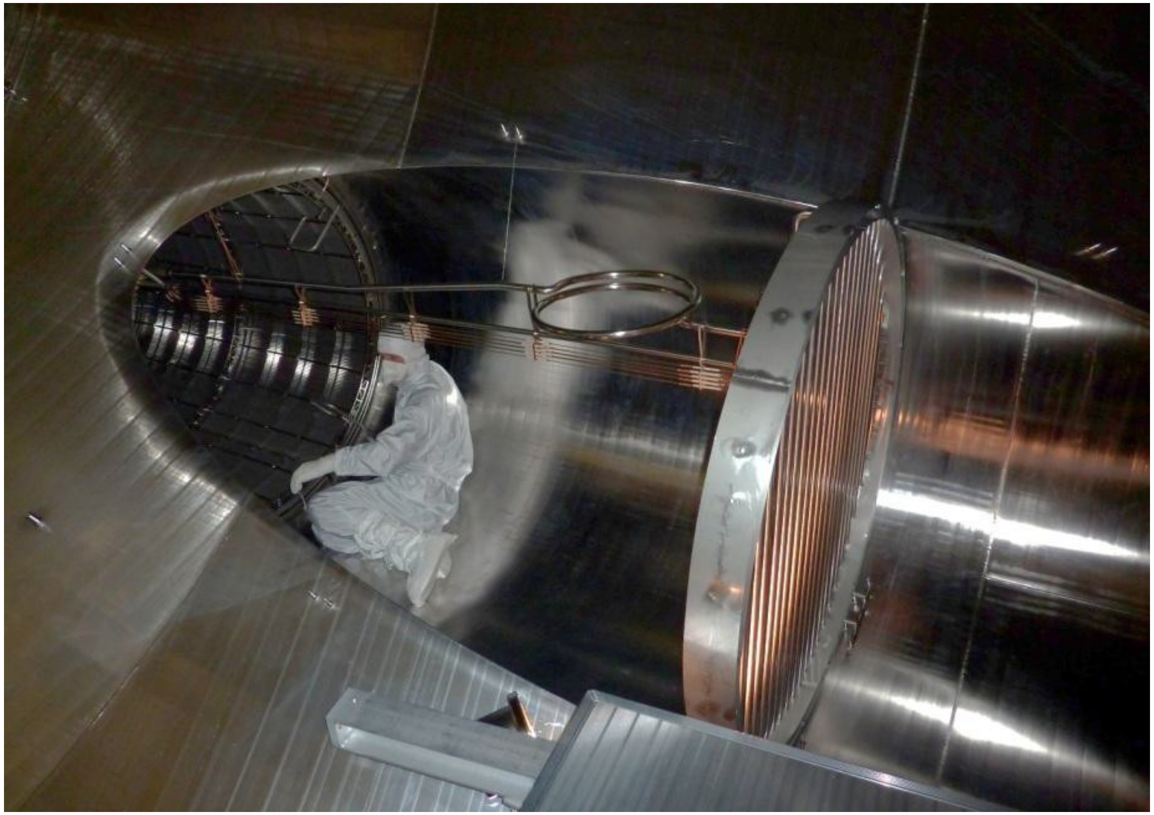
G. Drexlin et al., arXiv:1205.3729

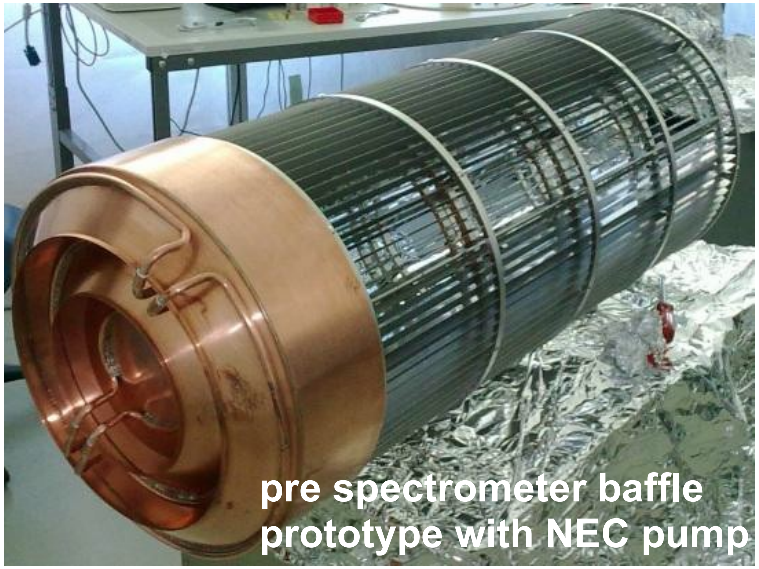


Mechanical eliminating stored particles:

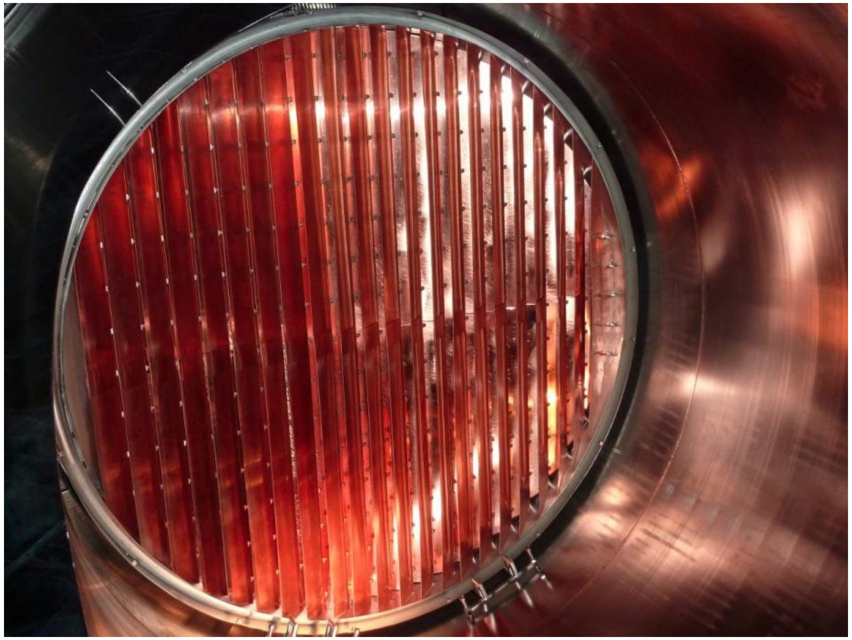
M. Beck et al, Eur. Phys. J. A44 (2010) 499

Radon elimination by LN_2-cooled baffles in the main spectrometer





pre spectrometer baffle prototype with NEC pump



Main spectrometer vessel is closed
Commissioning of main spectrometer with detector and e-gun ist starting in winter 2012

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 $\Delta m_\nu^2 \leq 0.007\ eV^2$ 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**

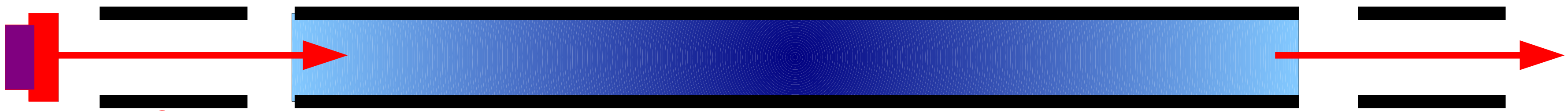
} tritium source

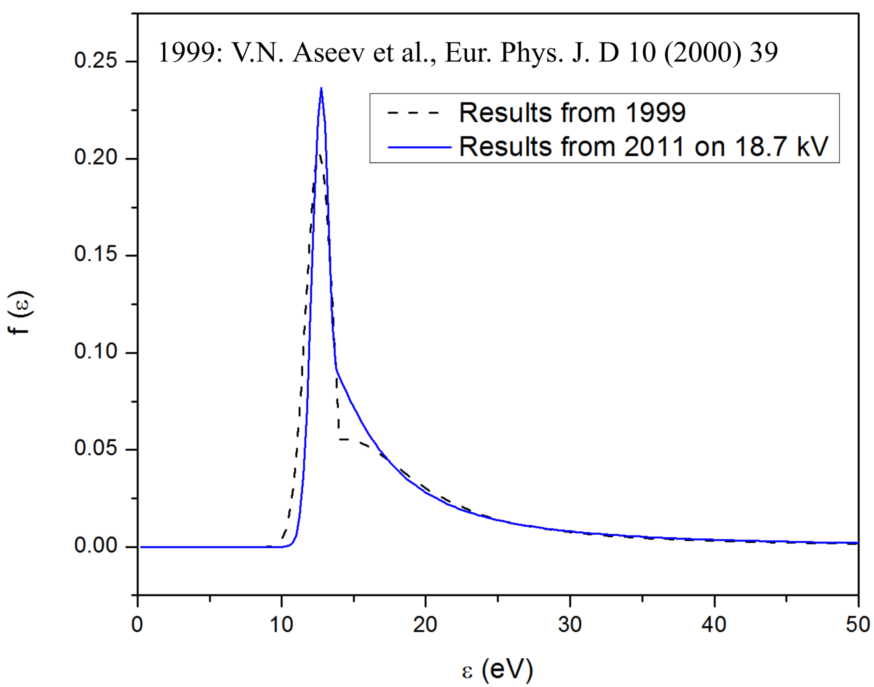
5. transmission function
   - detailed simulations, **angular-selective e-gun measurements**
6. HV stability of retarding potential on ~3ppm level required
   - **precision HV divider (with PTB)**, **monitor spectrometer beamline**

} spectrometer

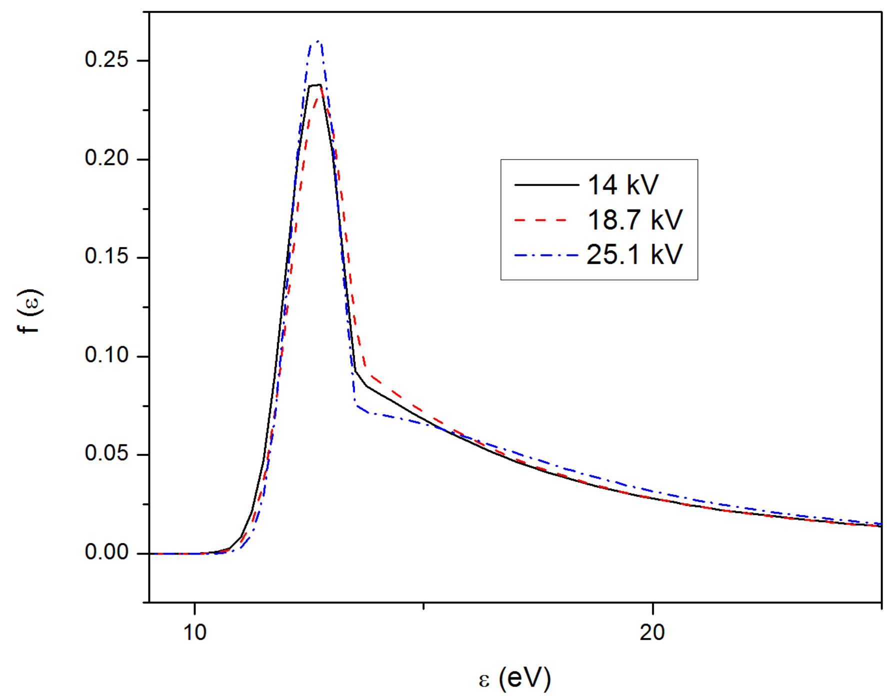
Recently achieved results at Troitsk

Measurement of electron scattering on H_2 at 14, 18, and 25 keV. New data on excitation and ionization spectra obtained with spectrometer resolution of about 1 eV.





Electron energy losses by scattering in H_2



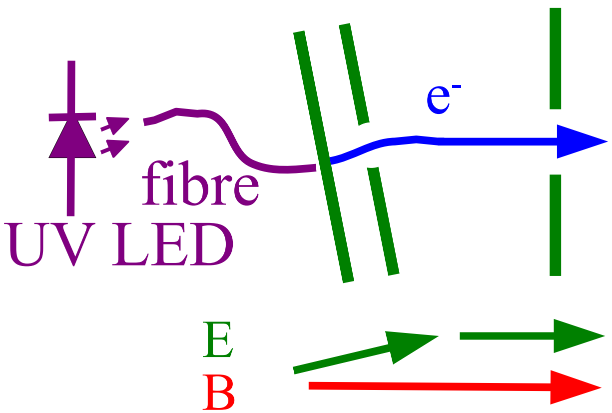
The same, at different energies

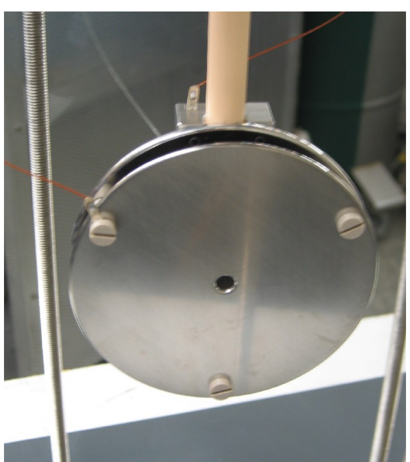
V. Pantuev, Dubna, Dec. 2012

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

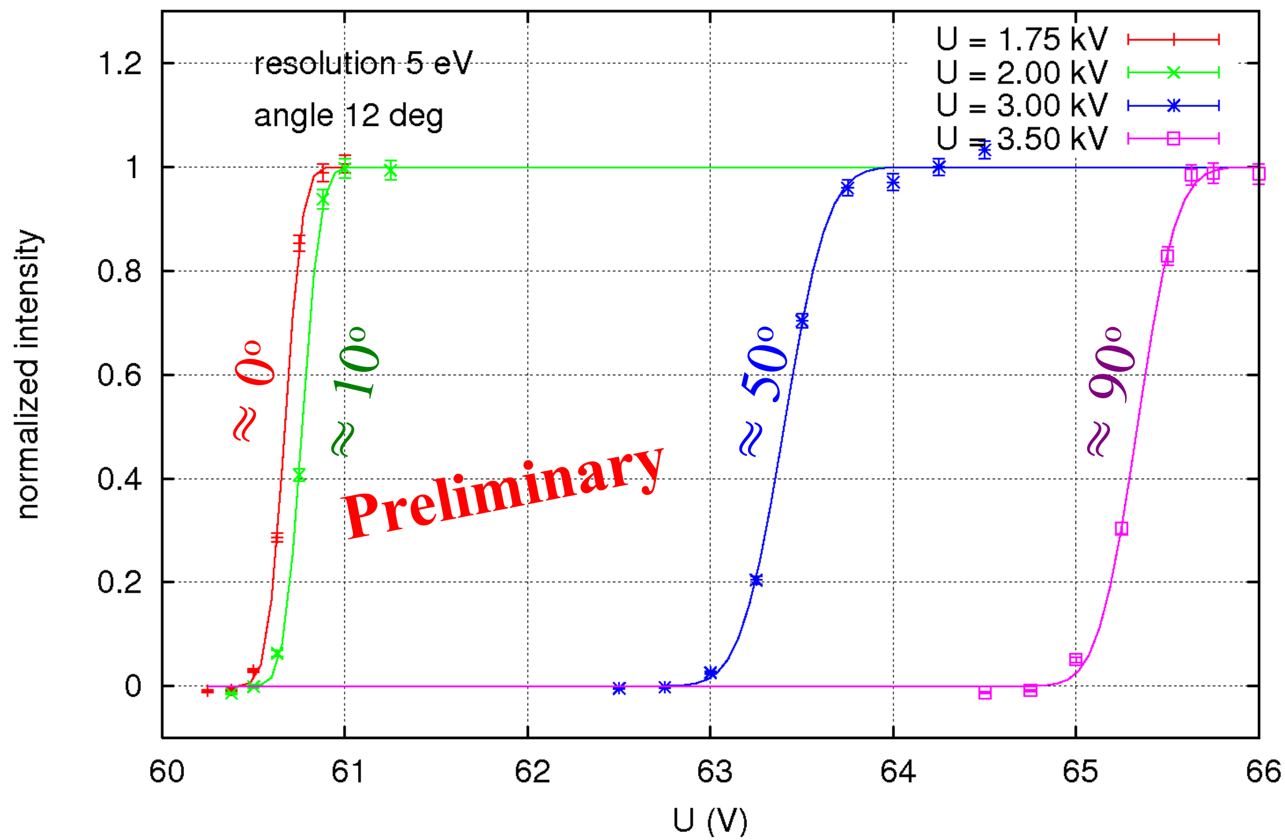
Idea:
fast non-adiabatic acceleration with adjustable non-parallel E and B fields





Angle at

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



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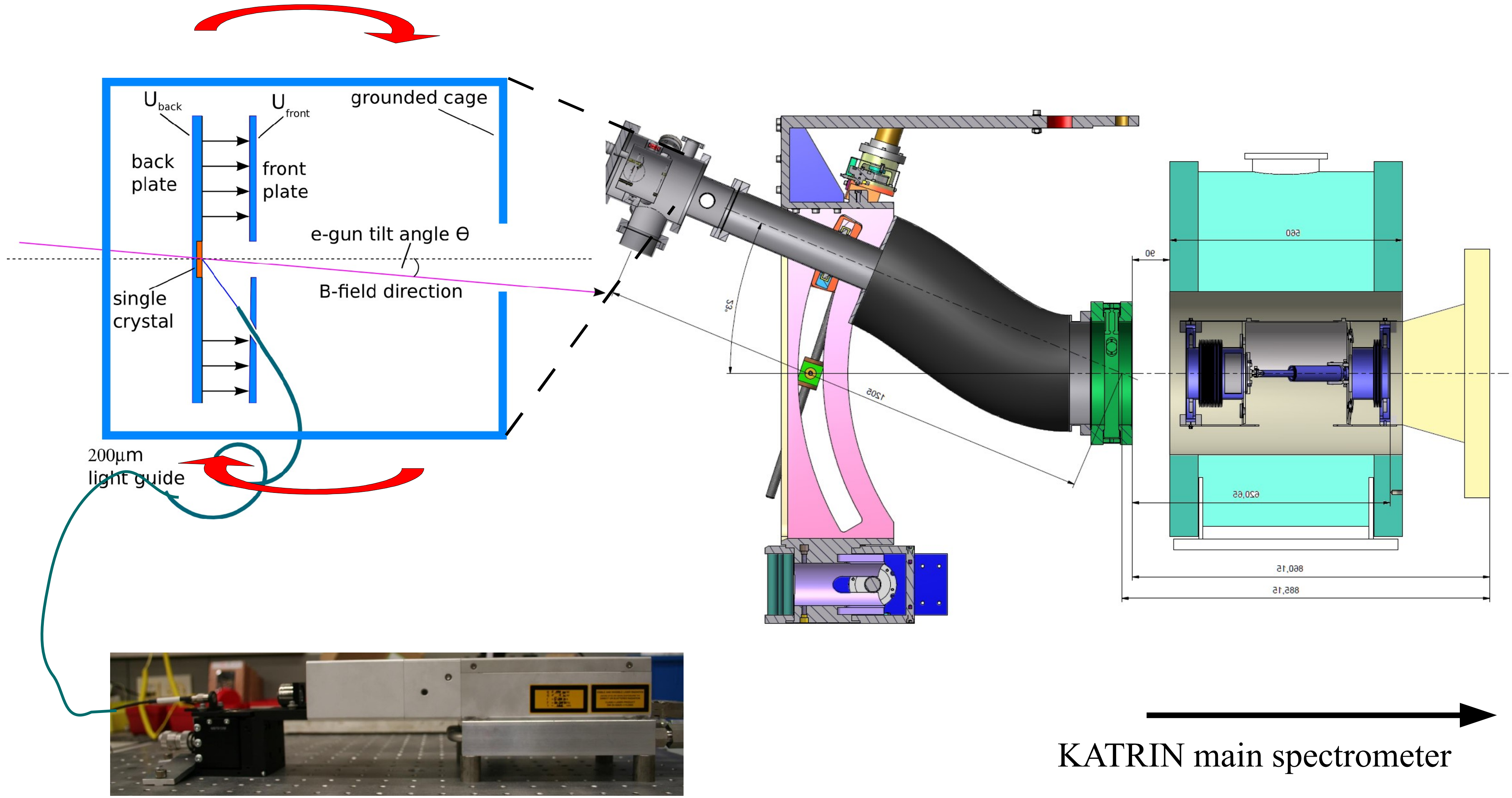
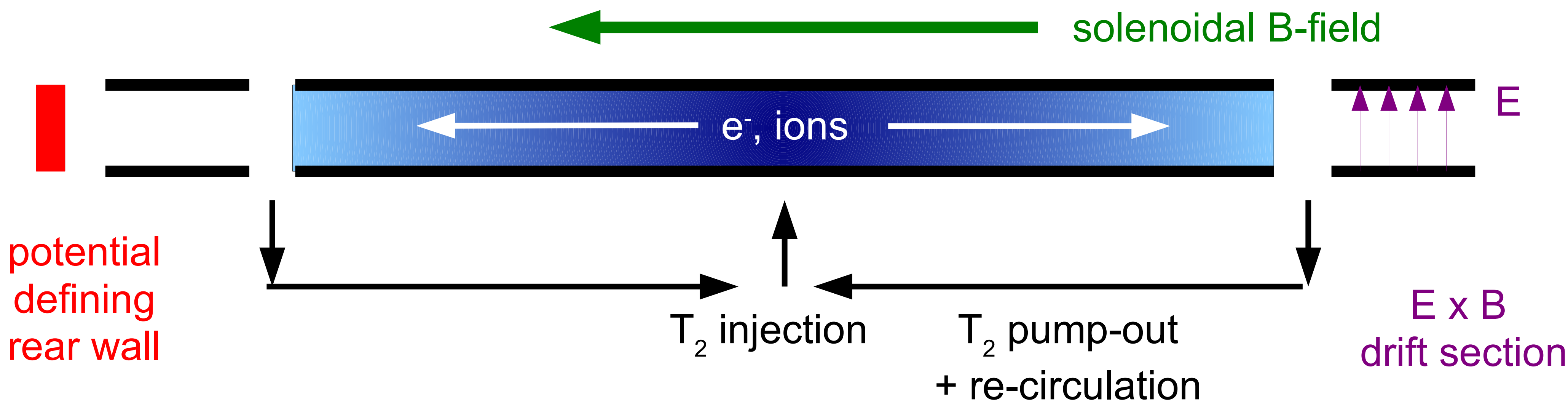
A 2-dim scanning pulsed angular-selective UV laser photoelectoron source



Pulsed frequency-quadrupled high-repetition UV-laser
(266nm, 20ns pulses)

Plasma potential within windowless gaseous tritium source

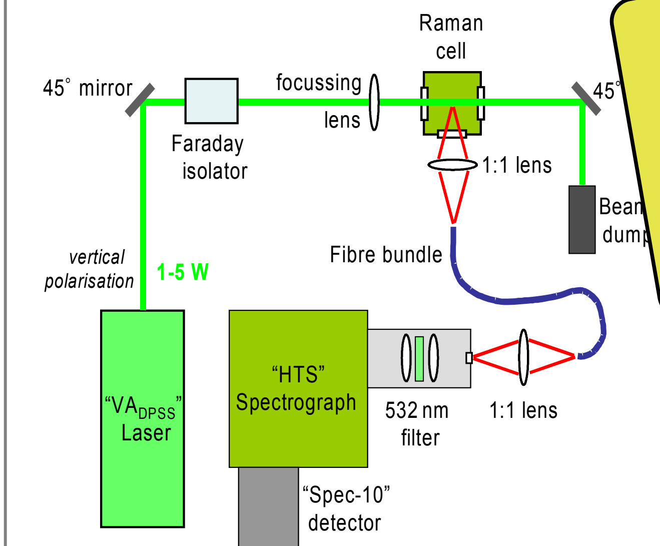


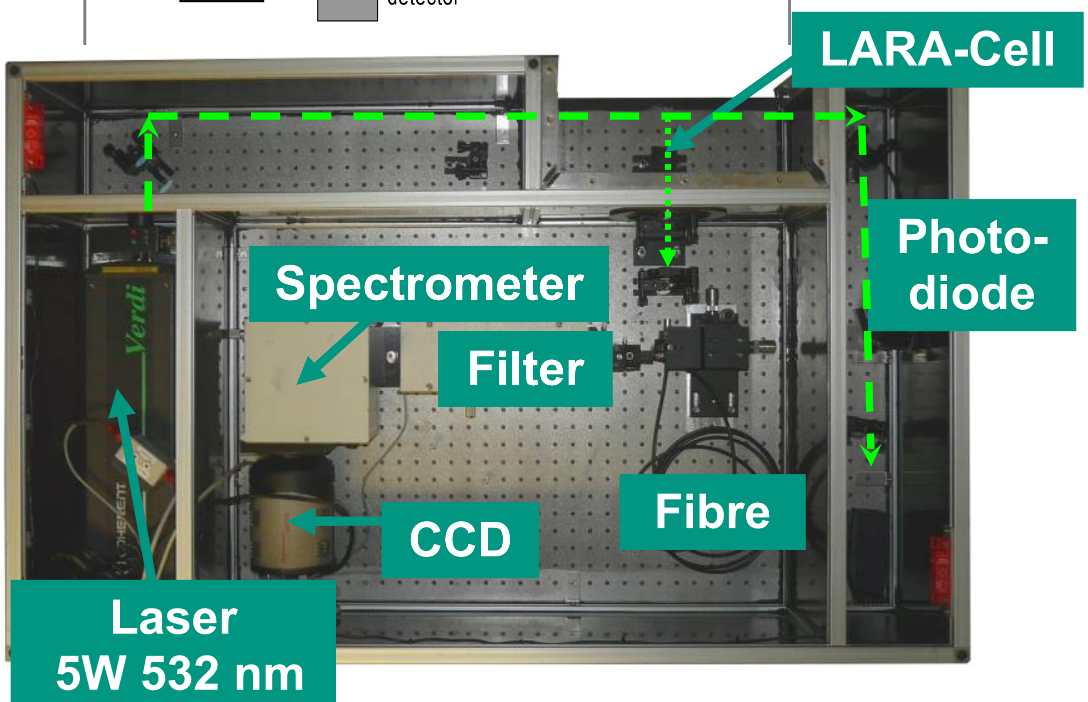
- Plasma is radially confined by the longitudinal B-field (no transverse mobility)
- There is a very good longitinal confinement by magnetic field lines (“short-cut”)
- Plasma is neutralized by low energy electrons (from inelastic scattering)
- Potential in source is defined by “potential defining rear wall”
- Escaping non-neutralized ions are drifted out by transversal E-field

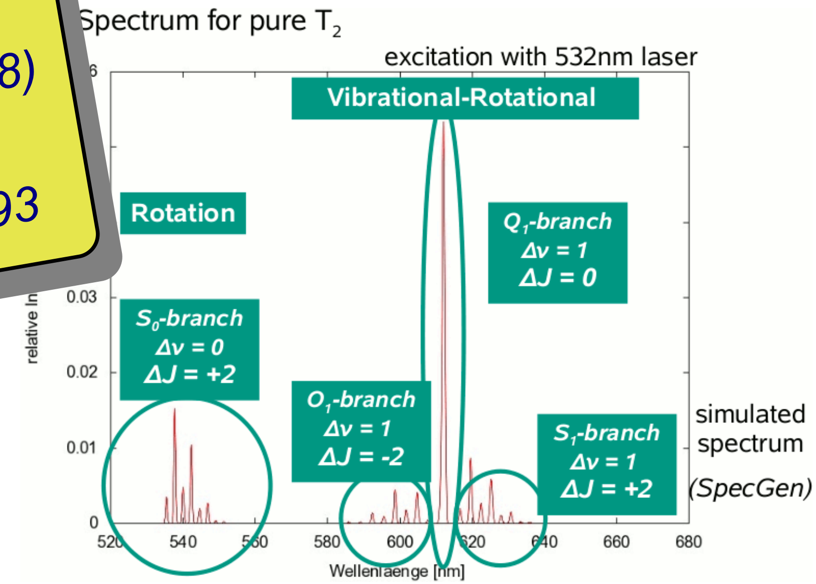
Russian-German cooperation within KATRIN: *A.F. Nastoyashchii, N.A. Titov, I.N. Morozov, F. Glück and E.W. Otten, Fusion Science and Technology, 48 (2005) 743*

Measurement of tritium concentration by laser Raman spectroscopy

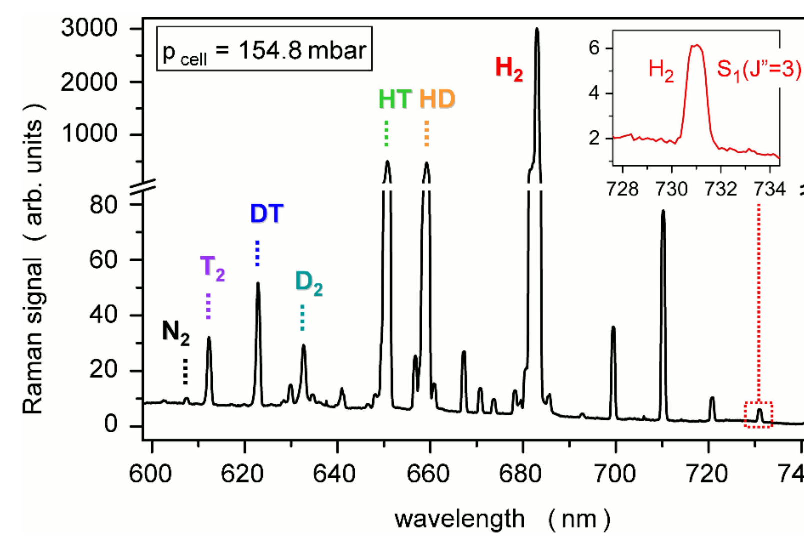
R.J. Lewis et al.,
Las. Phys. Lett.1-10 (2008)
M.Sturm et al,
Las. Phys. 20 (2010) 493







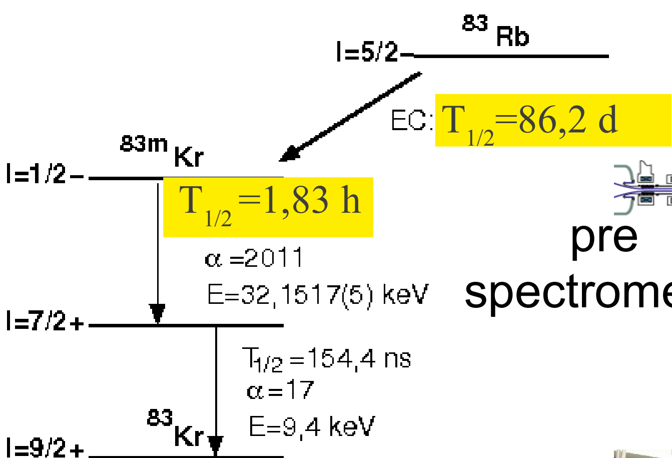
H_2 / HD / T_2 / DT / HT
= 0.820 / 0.083 / 0.003 / 0.005 / 0.085

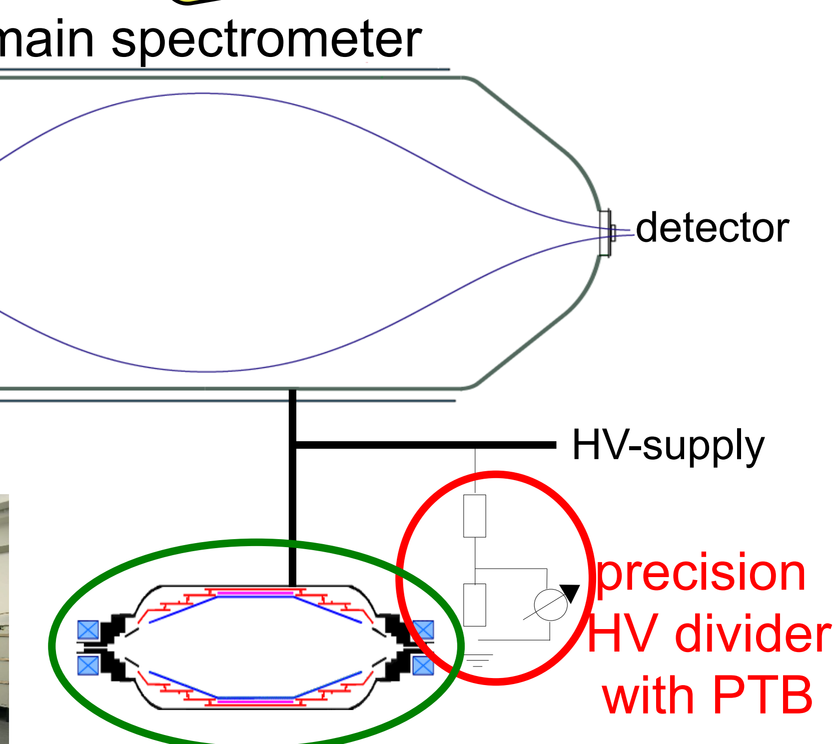


Stability of retarding potential / energy calibration: ppm at 18.6 kV

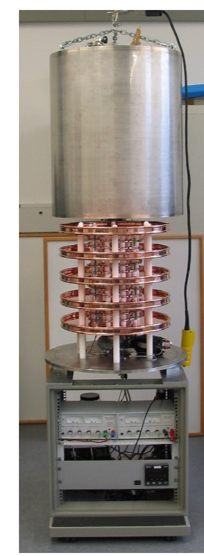
D. Venos et al., Appl. Rad. Iso. 63 (2005) 323
D. Venos et al, Nucl. Instrum. Meth. A 560 (2006) 352
M. Rasulbaev et al., Appl. Rad. Iso. 66 (2008) 1838
Th. Thümmler et al., New J. Phys. 11 (2009) 103007
D. Venos et al., Meas.Tech. 53 (2010) 573
M. Slezák et al., EPJ A48 (2012) 12

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





monitor spectrometer
= modified Mainz spec.:
$\Delta E = 5\,\mathrm{eV} \rightarrow 1\,\mathrm{eV}$



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

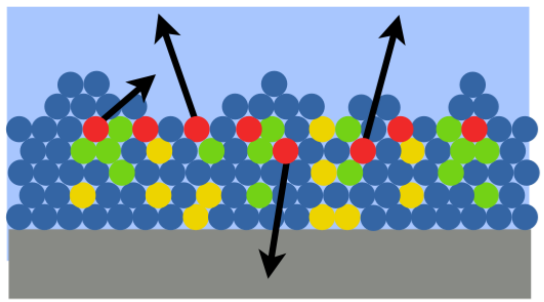
Solid ^{83}Rb/^{83m}Kr source

- original idea: ^{83}Rb vacuum-evaporated on aluminum foil
- compact, high count rate *[Kovalik, J Elec Spec Rel Phen 58 (1992) 49]*
- open radioactive source

^{83}Rb
^{83m}Kr
residual gas
impurity

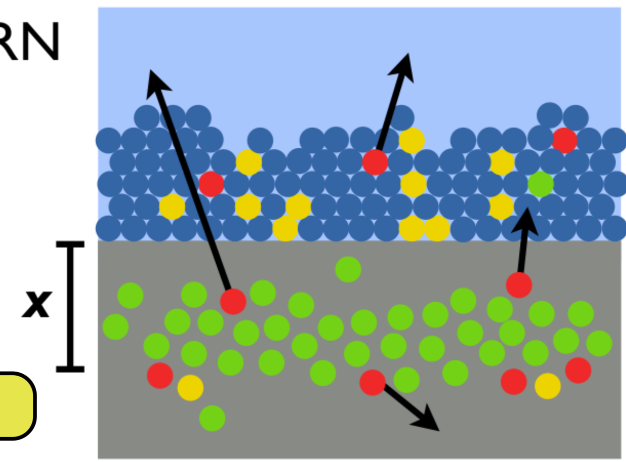
A) pure radiochemistry & vac. evaporation

NPI Řež/Prague
since 2005
backing: C, Al, HOPG



B) implantation of ^{83}Rb ions

ISOLDE/CERN
since 2008
foils: Pt, Au



Idea: A. Kovolik, Inst. Nuclear Problems, JINR, DUBNA

$$\textbf{A)}\quad E_{\text{kin}}^{\text{evap}}(i) = E_\gamma + E_{\text{rec},\,\gamma} - E_{\text{rec},\,\text{e}}(i) - \left(E_{\text{bin}}^{\text{vac}}(\text{gas}, i) - \Delta E_{\text{bin}}^{\text{vac}}(\text{evap}, i)\right) - \left(\phi_{\text{spec}} - \phi_{\text{source}}\right)$$

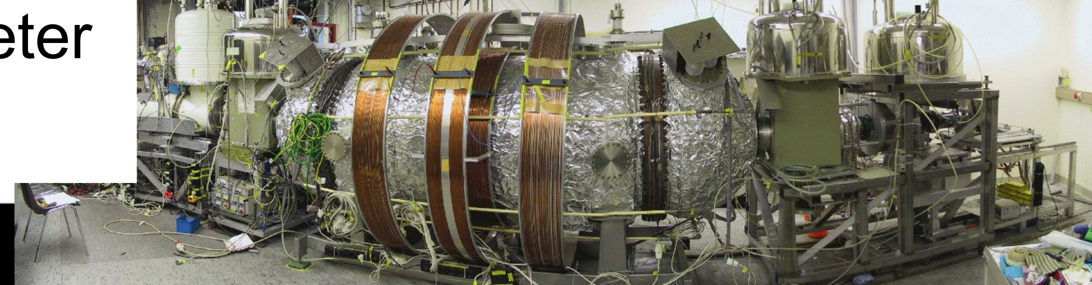
$$\textbf{B)}\quad E_{\text{kin}}^{\text{impl}}(i) = E_\gamma + E_{\text{rec},\,\gamma} - E_{\text{rec},\,\text{e}}(i) - \left(E_{\text{bin}}^{\text{vac}}(\text{gas}, i) - \underbrace{\Delta E_{\text{bin}}^{\text{Fermi}}(\text{impl}, i)\right)}_{\Delta E_{\text{bin}}^{\text{vac}}(\text{impl}, i) + \phi_{\text{source}}} - \phi_{\text{spec}}$$

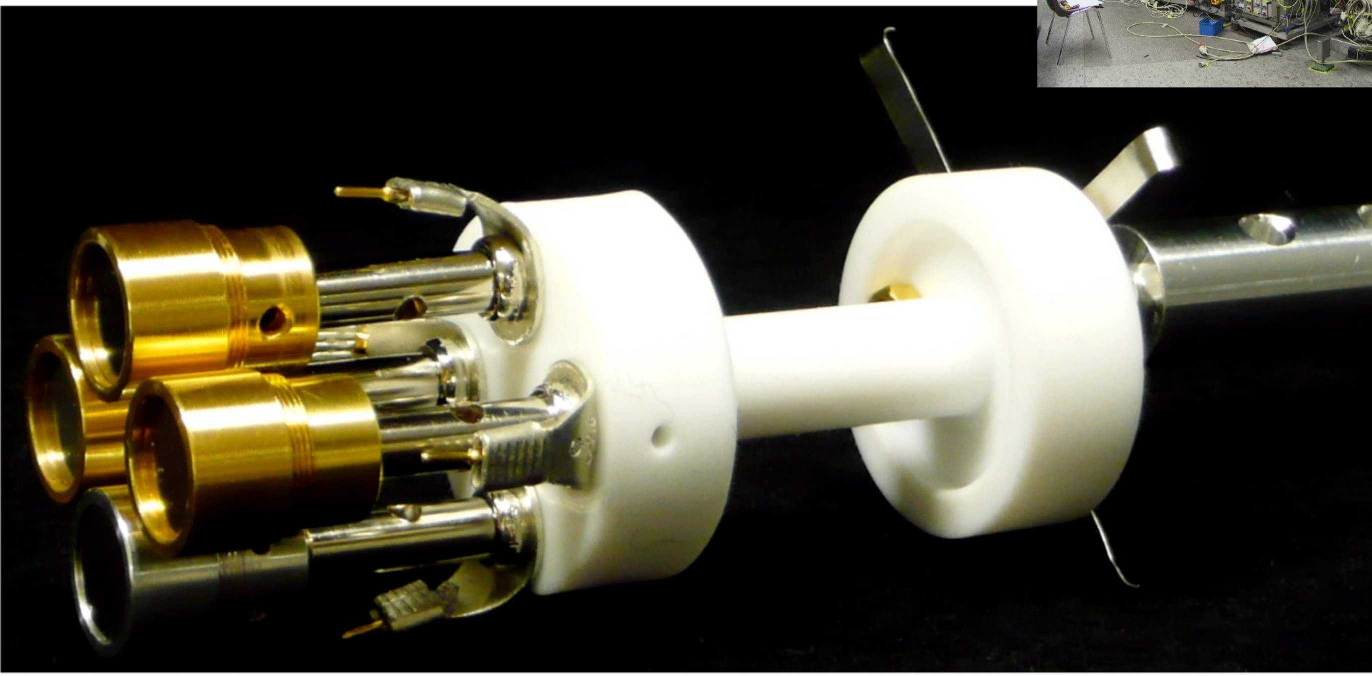
$$\Delta E_{\text{bin}}^{\text{vac}}(\text{impl}, i) = E_{\text{bin}}^{\text{vac}}(\text{gas}, i) - E_{\text{bin}}^{\text{vac}}(\text{impl}, i)$$

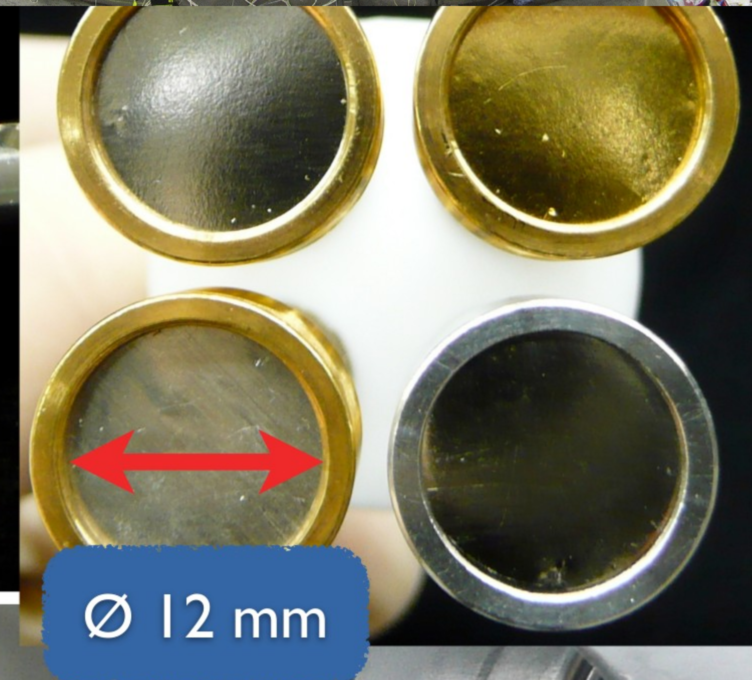
*e^- binding energy is **reduced** when going from free atom to adsorbed/implanted atom*

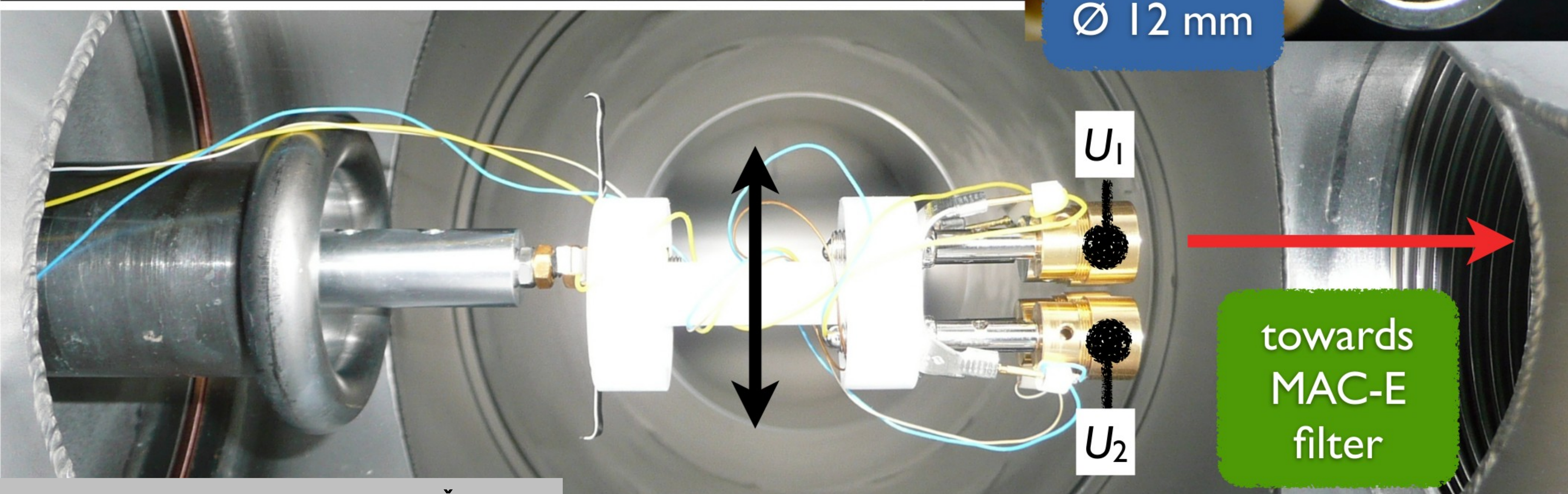
M. Zbořil, PhD thesis, Münster + Řež

Measurements at Mainz spectrometer
source holder for 4 samples





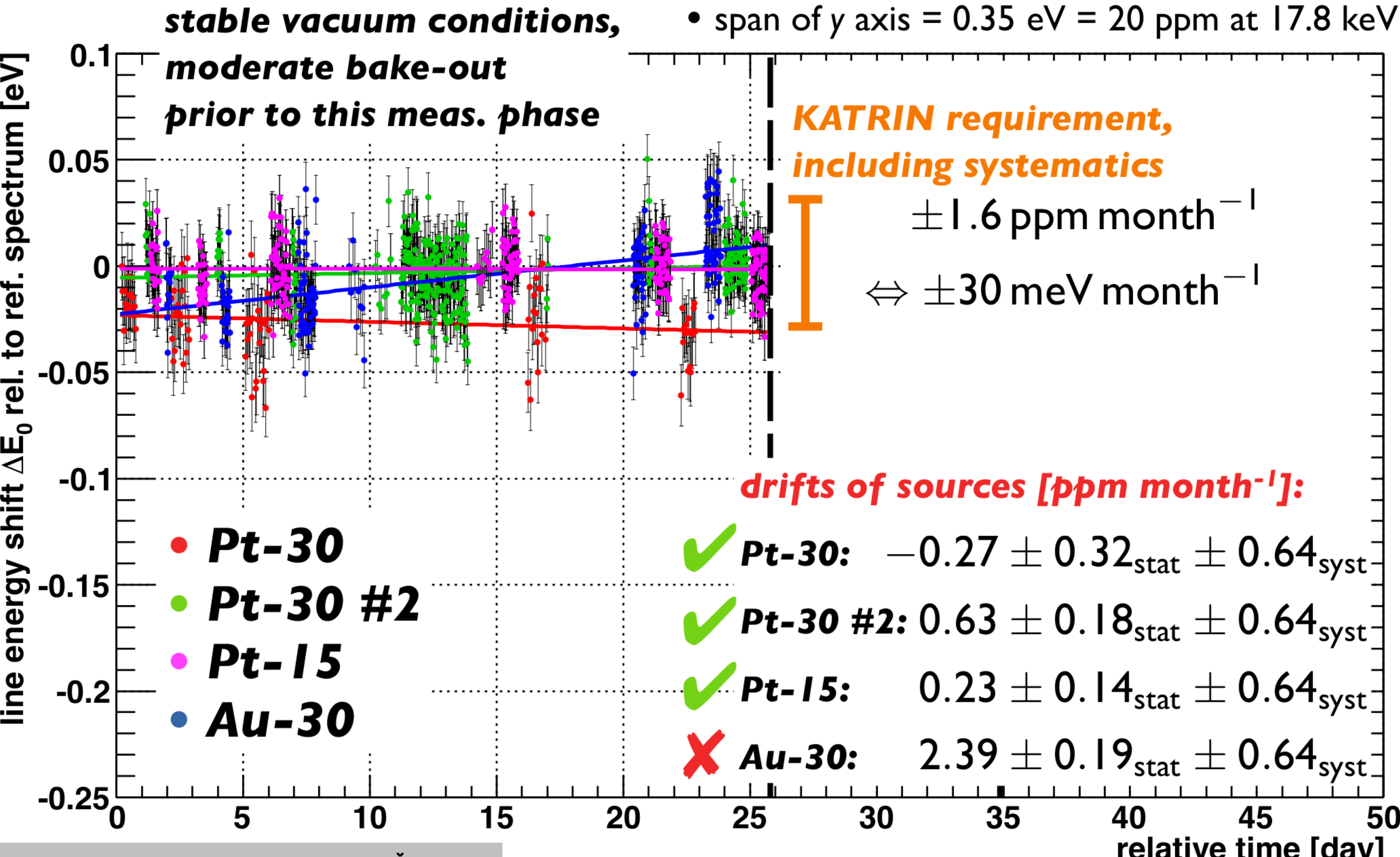




M. Zbořil, PhD thesis, Münster + Řež

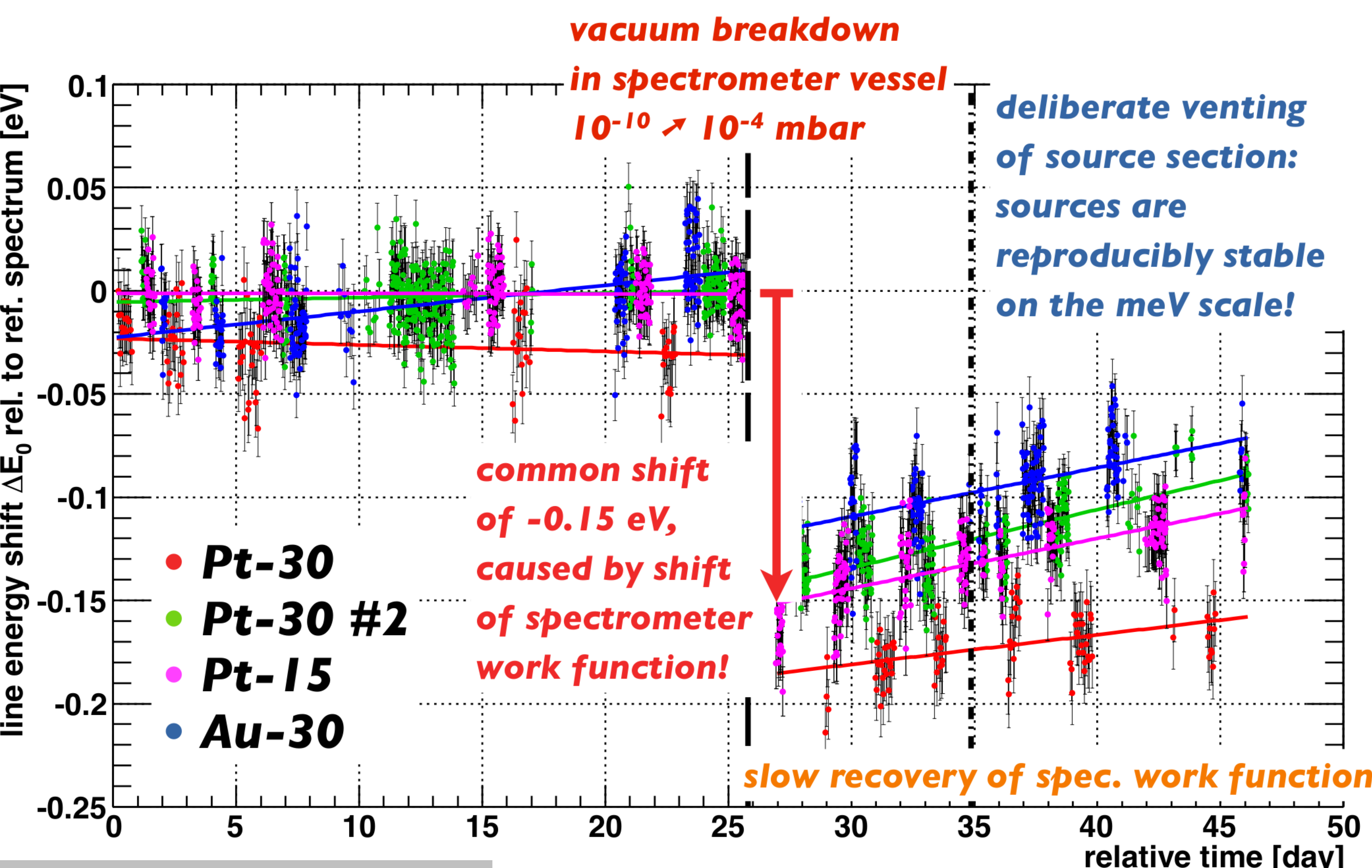
Energy stability of *K-32* line (4 implanted sources)

- cross-correlation method
- span of y axis = 0.35 eV = 20 ppm at 17.8 keV



M. Zbořil, PhD thesis, Münster + Řež

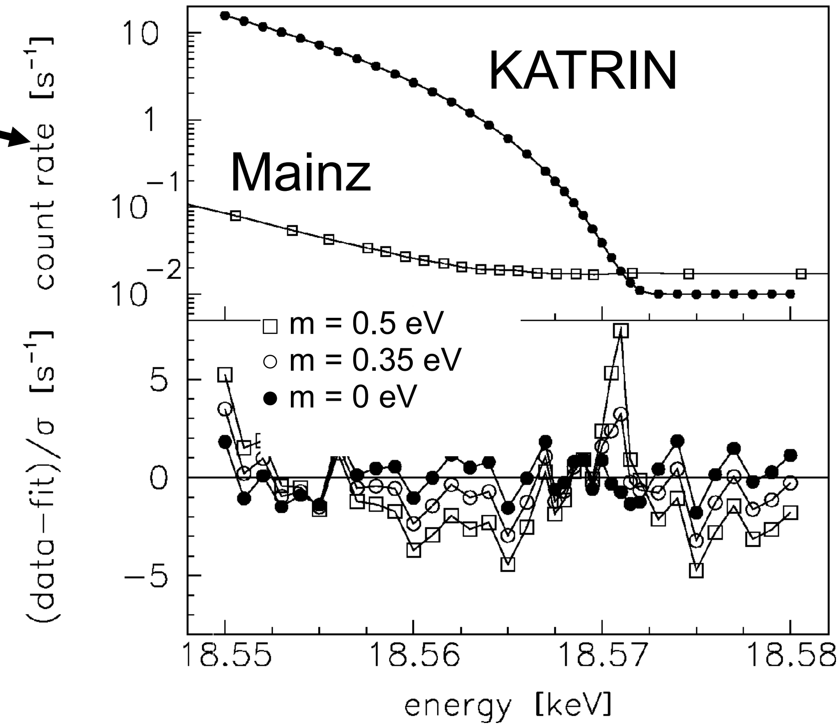
Energy stability of *K-32* line (4 implanted sources)



M. Zbořil, PhD thesis, Münster + Řež

KATRIN´s sensitivity

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



sensitivity:

m_ν < 200 meV (90%CL)

discovery potential:

m_ν = 300 meV (3σ)

m_ν = 350 meV (5σ)

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

Sensitivity is still statistically limited,

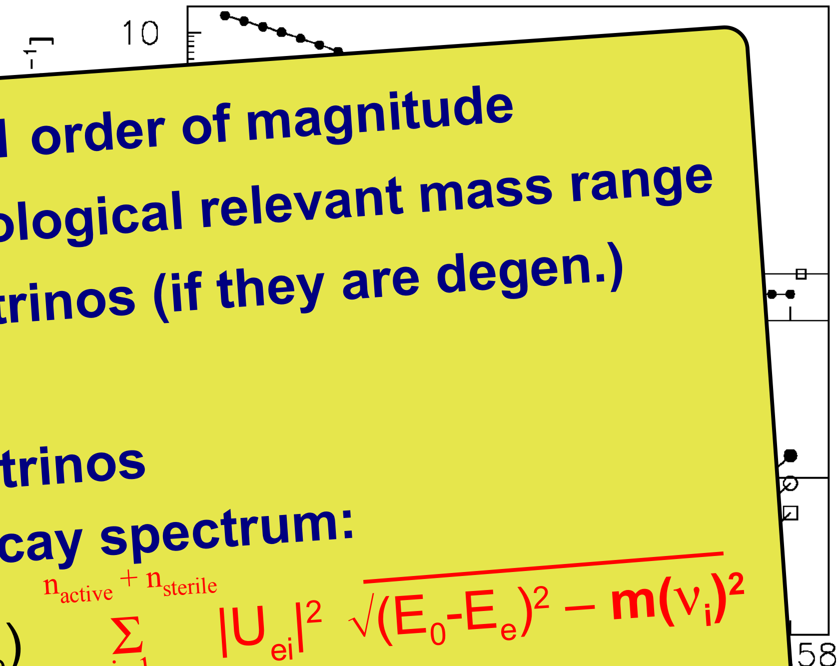
because with more statistics would go closer to the endpoint,
where most systematics nearly vanish

Sensitivity still has to proven, but there might be even some more improvements

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

KATRIN´s sensitivity

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



$\Rightarrow$ **KATRIN will improve the sensitivity by 1 order of magnitude**
will check the whole cosmological relevant mass range
will detect degenerate neutrinos (if they are degen.)

KATRIN can also searching sterile neutrinos
by looking for a kink in the decay spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e) \sum_{i=1}^{n_{active}+n_{sterile}} |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$$

eV scale (reactor anomaly):
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

keV scale (dark matter): under study

Ex...

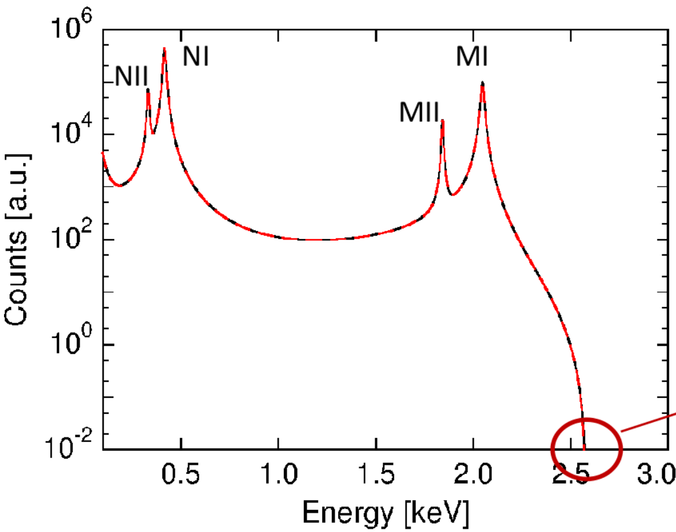
Se...

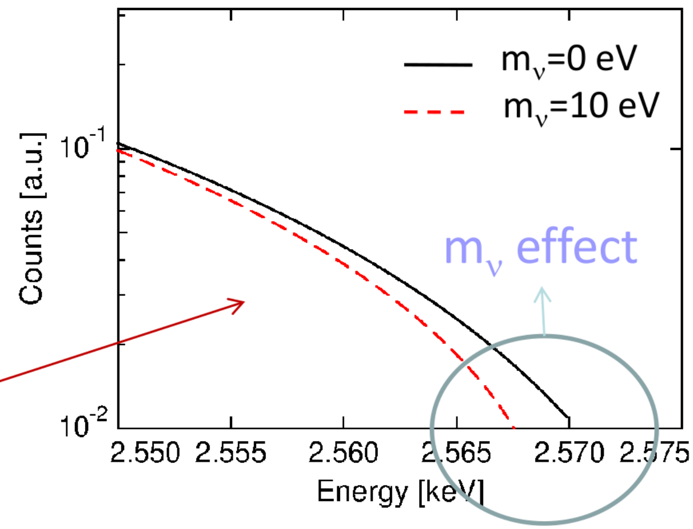
Sensitivity still has to proven, but there might be even some more improvements

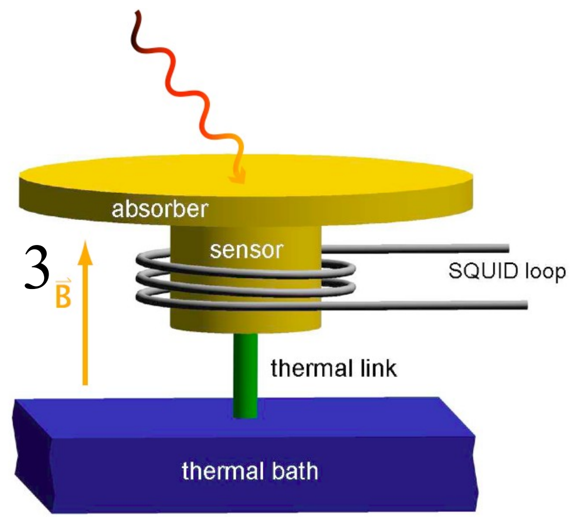
ECHO neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

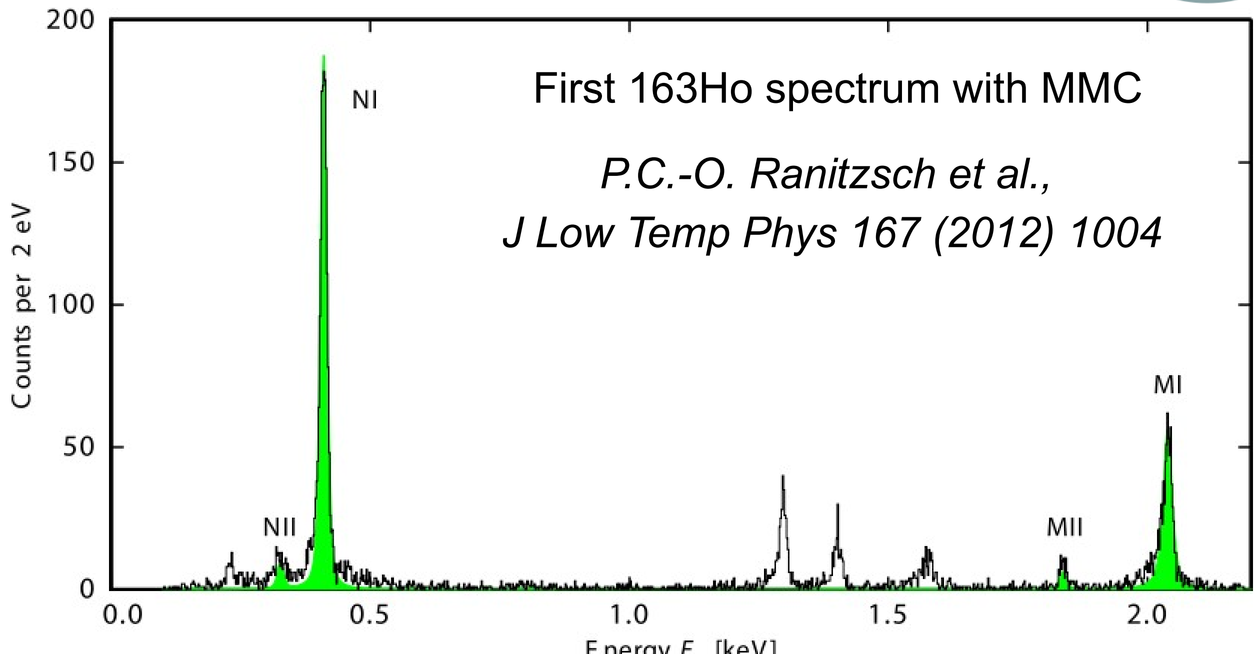
Westfälische Wilhelms-Universität Münster

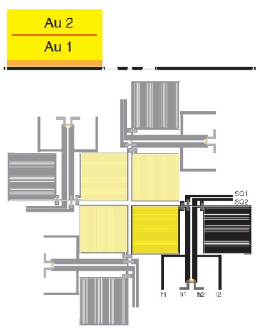
$$^{163}\text{Ho} + e^- \rightarrow {}^{163}\text{Dy}^* + \nu_e \rightarrow {}^{163}\text{Dy} + \gamma/e^- + \nu_e$$

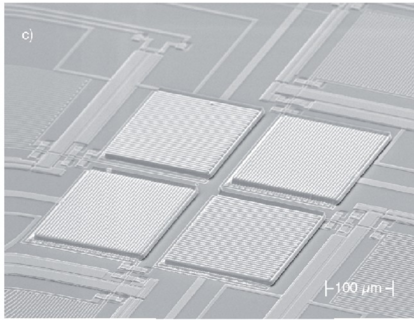








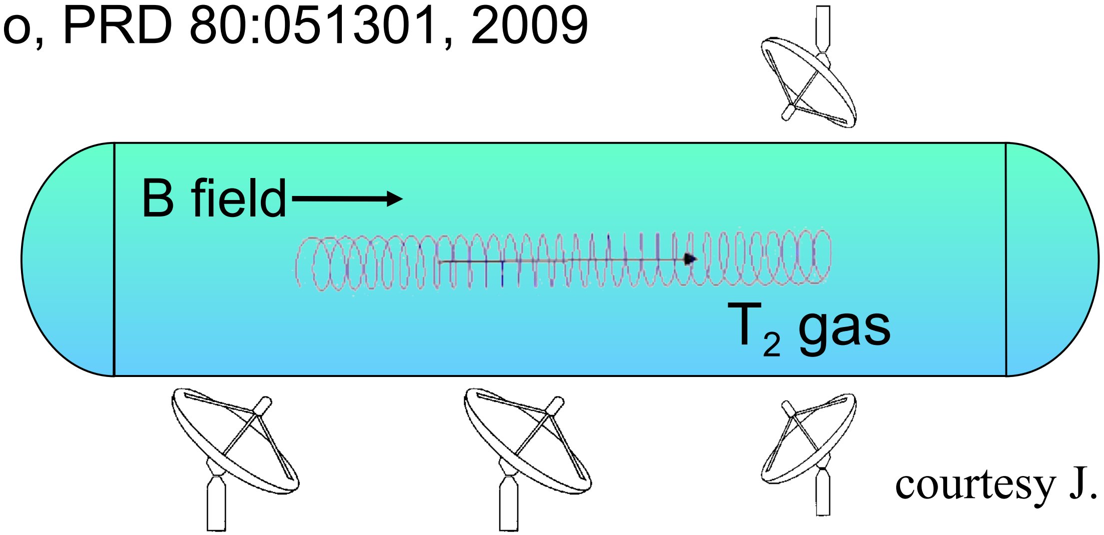




courtesy L. Gastaldo

Project 8: Measure coherent cyclotron radiation of tritium β electrons

B. Monreal and J. Formaggio, PRD 80:051301, 2009



courtesy J. Formaggio

General idea:

- 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

A lot of R&D necessary and has just started
- Is it really possible ?
- What are the systematic uncertainties ?

Summary

3 complementary probes of the neutrino mass:

cosmology: very sensitve, but model-dependent

0νββ: sensitive to Majorana neutrinos (EXO-200, GERDA, ..)
but Majorana phases and nuclear matrix elements
searches for lepton number violation

direct neutrino mass determination (MARE, KATRIN):
no other assumptions, kinematics of β-decay at endpoint

KATRIN: 200 meV sensitivity:

2012-13 commissioning of main spectrometer and detector

2010-14 commissioning of tritium source and tritium elimination lines

from 2015 on regular data taking for 5-6 years (3 years full beam-time)