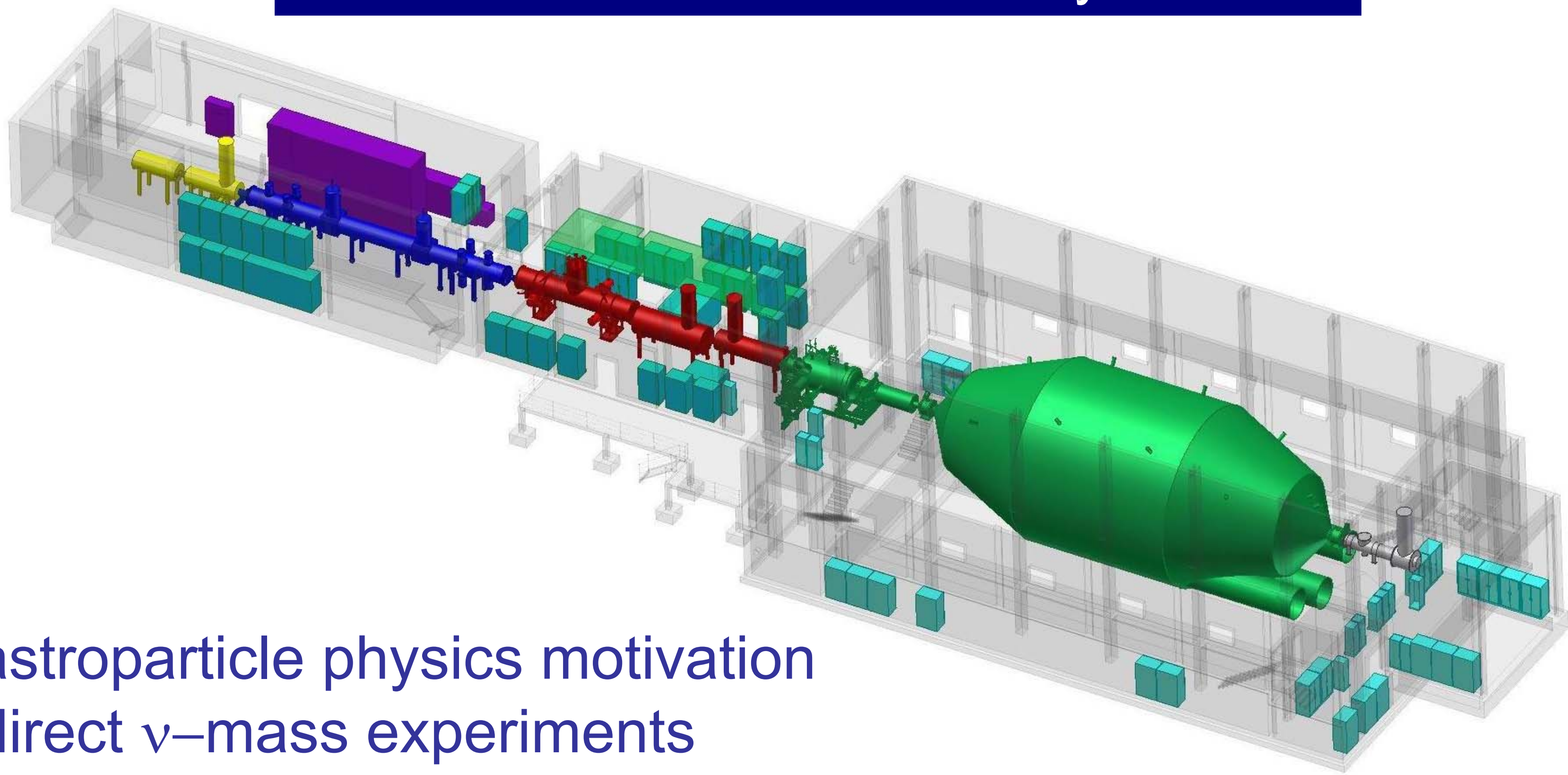
The KATRIN experiment

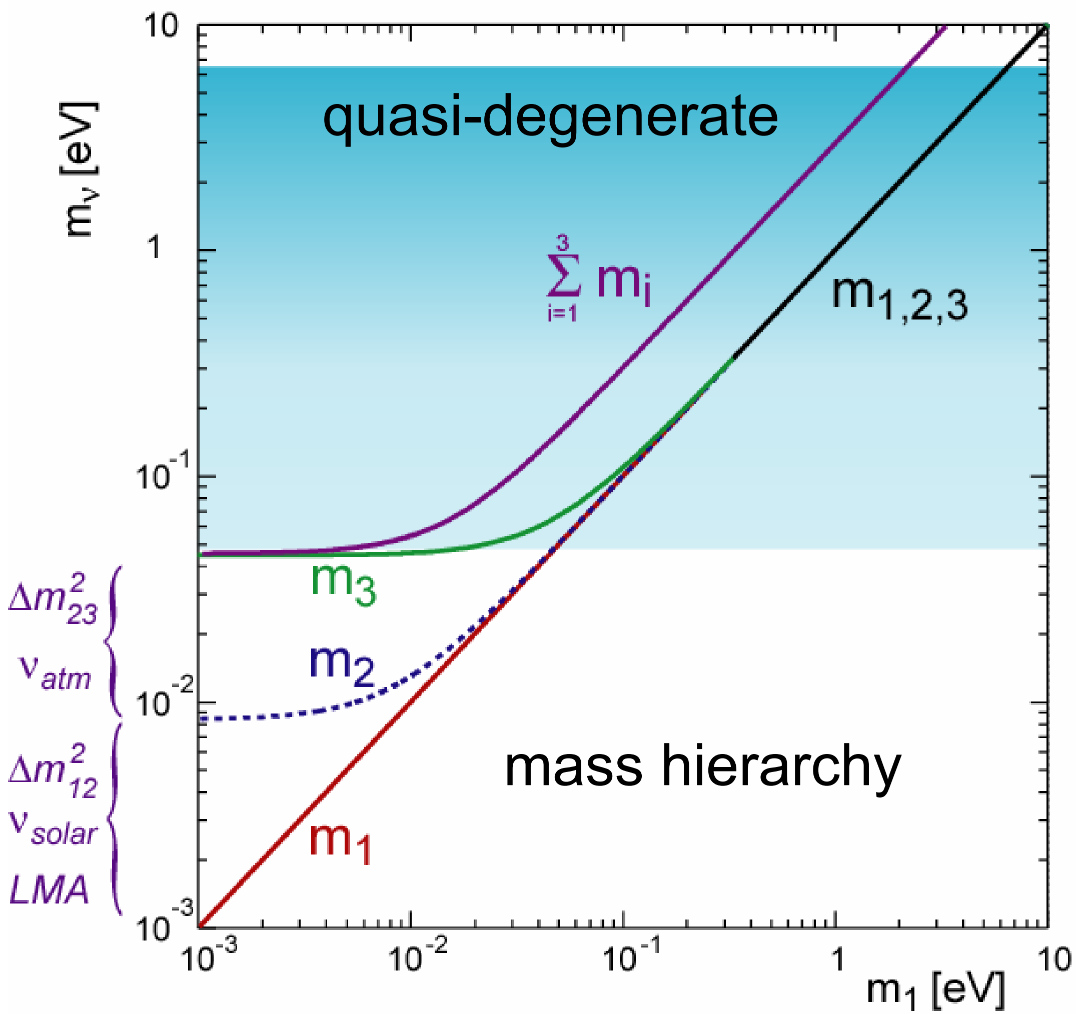
direct ν–mass measurement
with sub-eV sensitivity

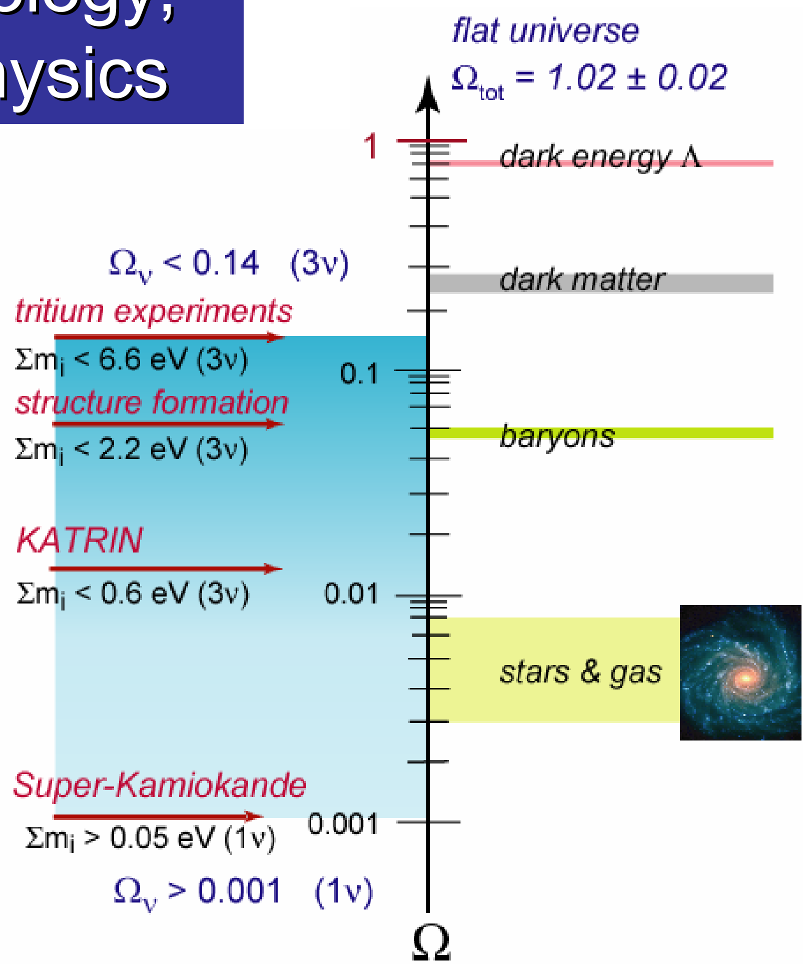


- astroparticle physics motivation
- direct ν–mass experiments
- KATRIN components: source & spectrometers
- sensitivity & outlook

neutrino masses in cosmology, astrophysics & particle physics

neutrino mass and hot dark matter





$$\Omega_\nu h^2 = \Sigma m_\nu / 93.5 \text{ eV}$$

three roads to neutrino masses

ß-decay: absolute ν-mass

model independent, kinematics

status : m_ν < 2.3 eV

potential : m_ν < 200 meV

EU&US: KATRIN

$0\nu ßß$-decay: eff. Majorana mass

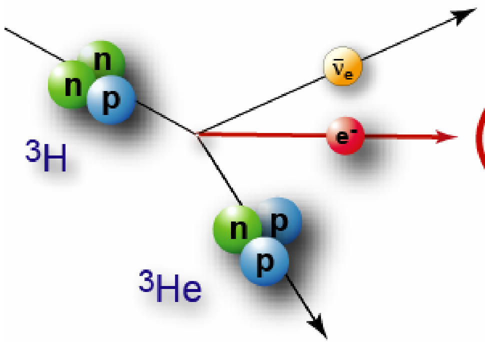
ν-nature (CP), peak at E_0

status : m_ν < 0.35 eV

potential : m_ν < 30 meV

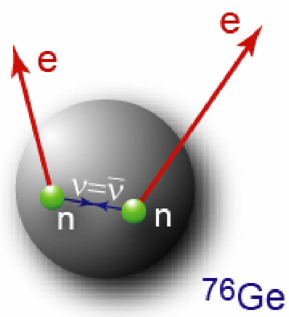
US: Majorana,EXO, EU: Cuore,Gerda

$m_ß$ *laboratory* m_{ee}



neutrino mass measurements

status 2004 & potential 2014



Σm_i

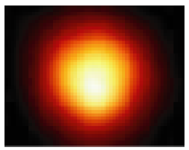
cosmology: ν hot dark matter Ω_ν

model dependent, analysis of LSS data

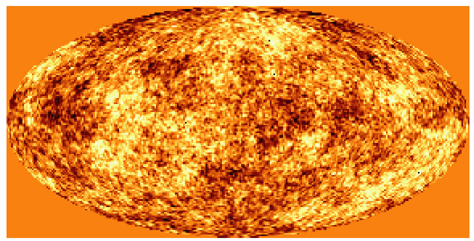
status : m_ν < 0.7 eV

potential : m_ν < 70 meV

US: WMAP, SDSS, LSST, EU: Planck



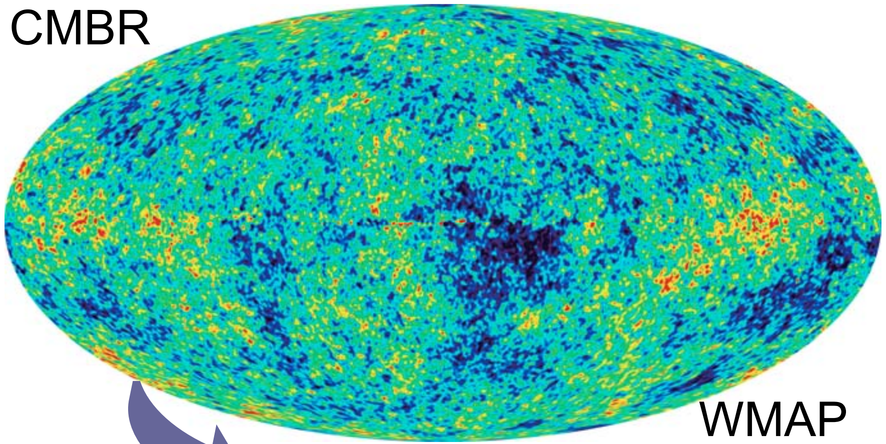
SN20xx



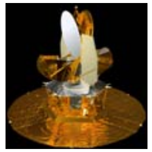
CMBR

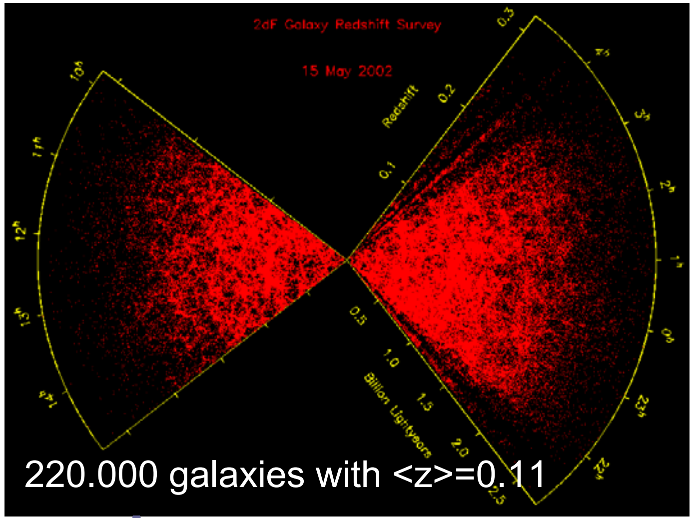
cosmological studies

CMBR

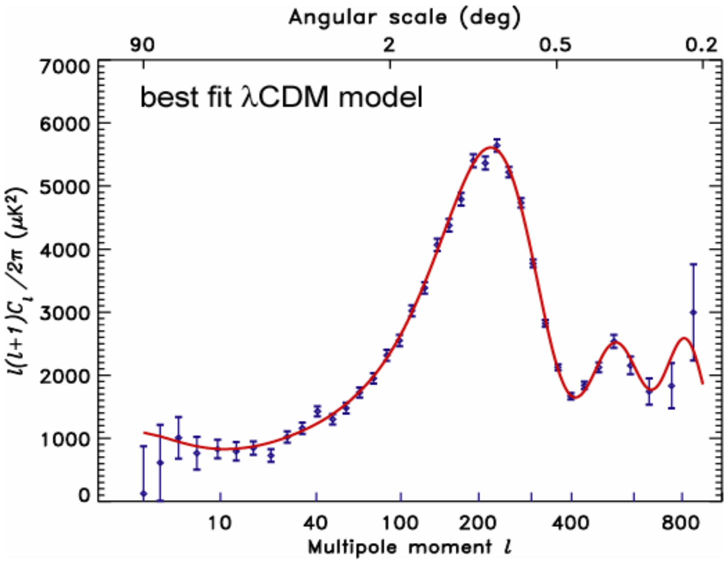


WMAP





Powerspectrum of CMBR



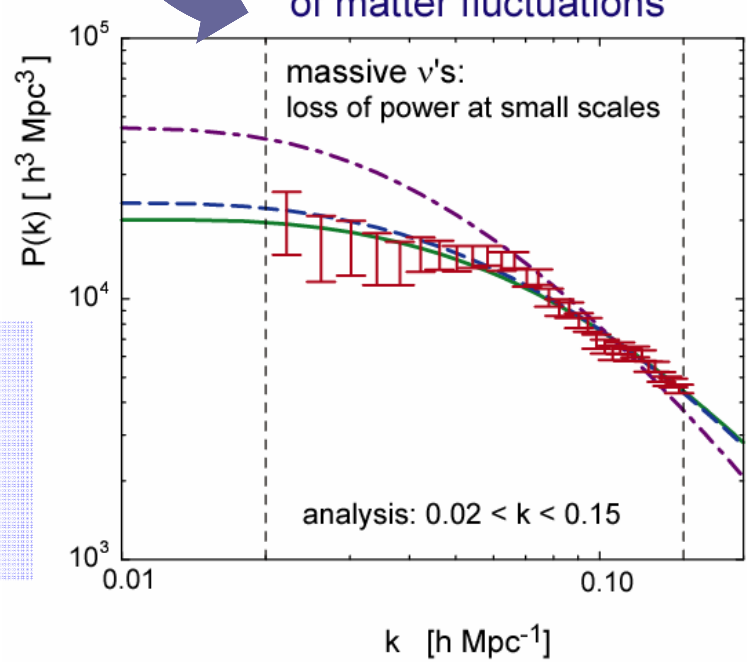
+ Ly α data

combined result

$m_\nu < 0.24$ eV

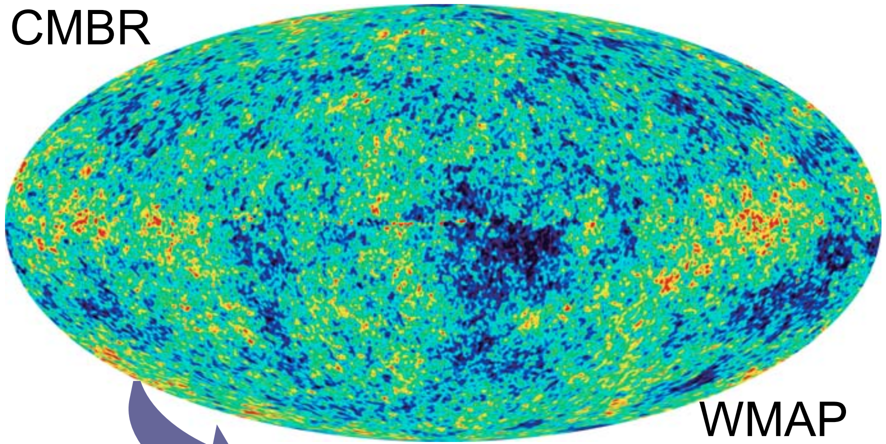
(95%CL.)

2dF powerspectrum of matter fluctuations

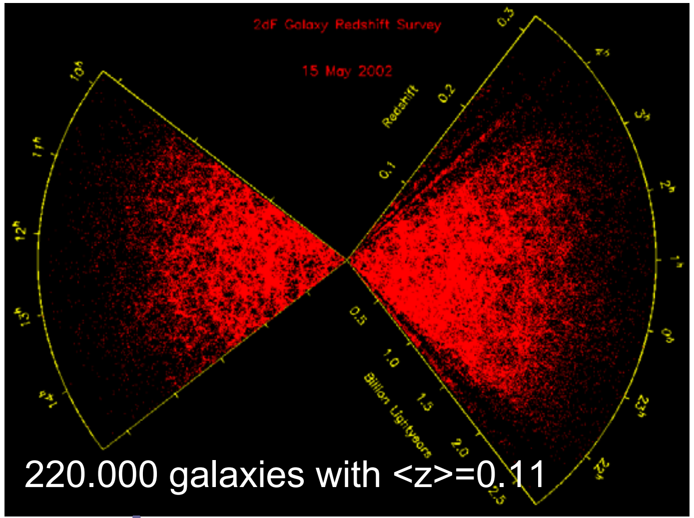


cosmological studies

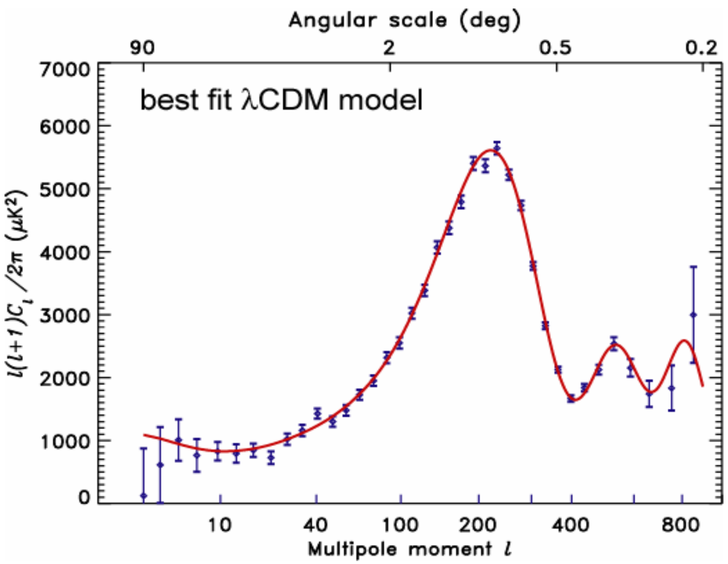
CMBR



WMAP



Powerspectrum of CMBR



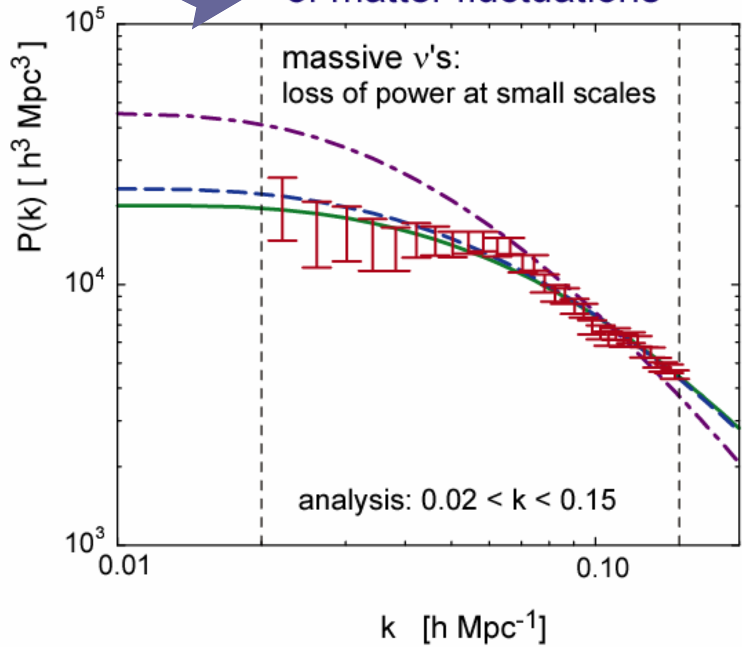
+ XLF data

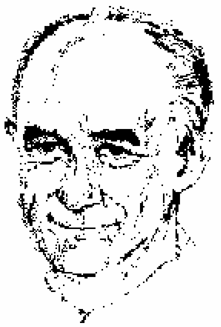
combined result

$m_\nu = 0.24$ eV

(central value)

2dF powerspectrum
of matter fluctuations





ß-decay and neutrino mass

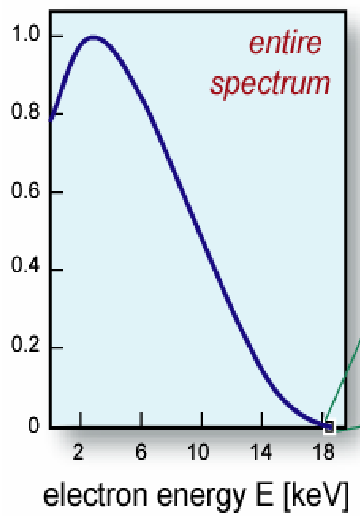
model independent neutrino mass from ß-decay kinematics

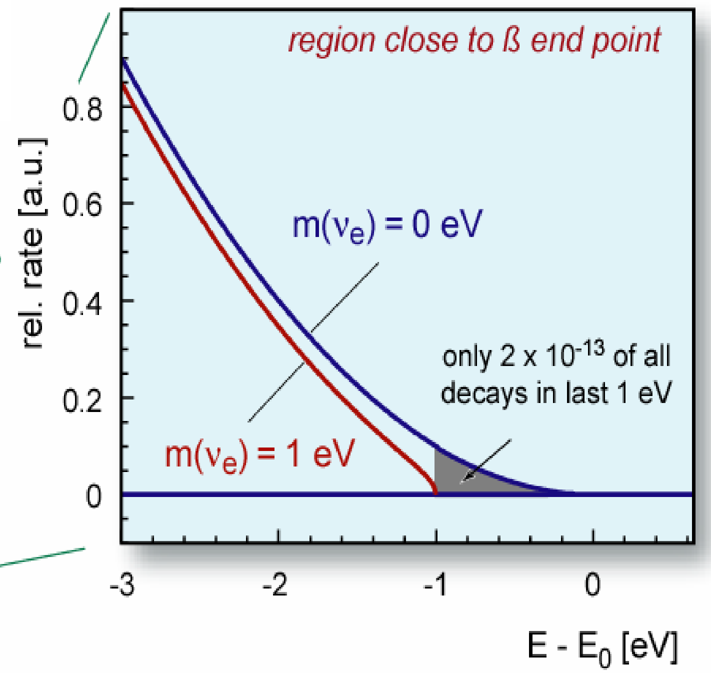
$$\frac{d\Gamma_i}{dE} = C\, p\, (E + m_e)\, (E_0 - E) \sqrt{(E_0 - E)^2 - m_i^2}\, F(E)\, \theta(E_0 - E - m_i)$$

$$C = G_F^2 \frac{m_e^5}{2\pi^3} \cos^2\theta_C\, |M|^2$$

experimental observable is m_ν^2

E_0 = 18.6 keV
$T_{1/2}$ = 12.3 y





ß-source requirements :

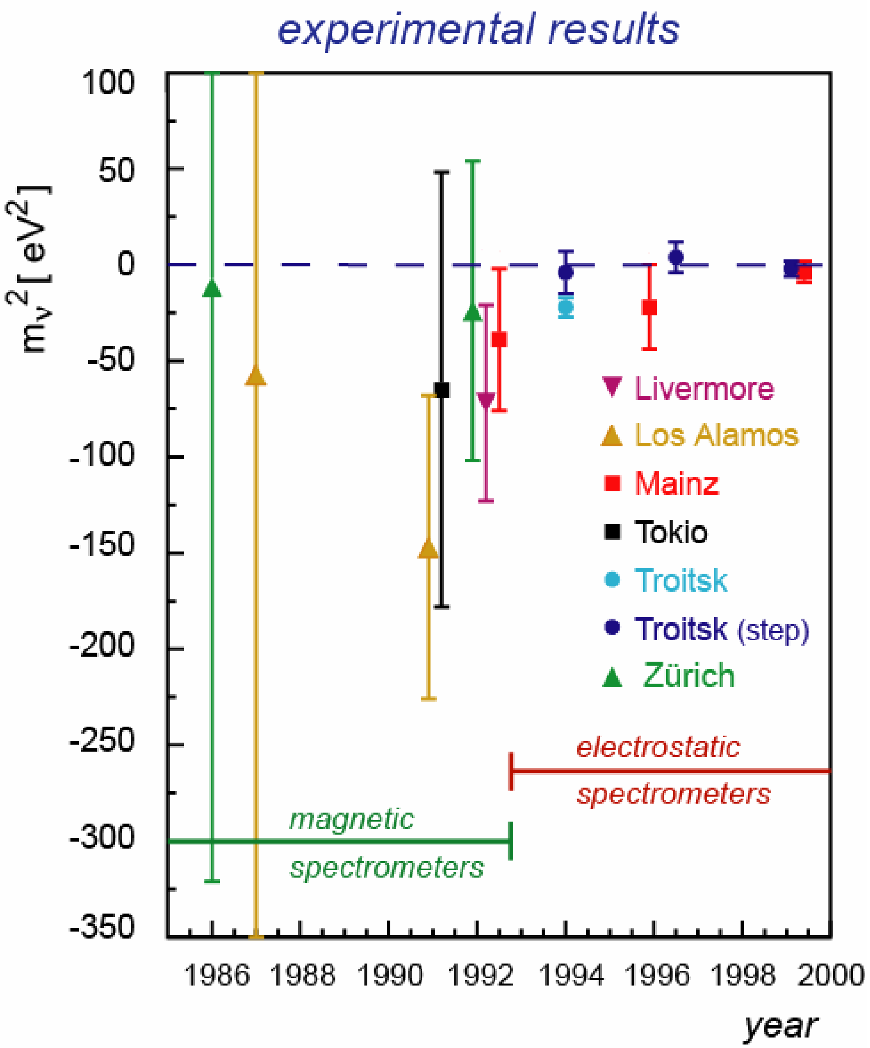
- high ß-decay rate (short $t_{1/2}$)
- low ß-endpoint energy E_0
- superallowed ß-transition
- few inelastic scatters of ß's

ß-detection requirements :

- high resolution ($\Delta E <$ few eV)
- large solid angle ($\Delta\Omega \sim 2\pi$)
- low background

history of tritium ß-decay results

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.05 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV



electrostatic filter with magnetic adibatic collimation

E-technique

energy analysis by electro static retarding field (electrodes)

variable E-field:

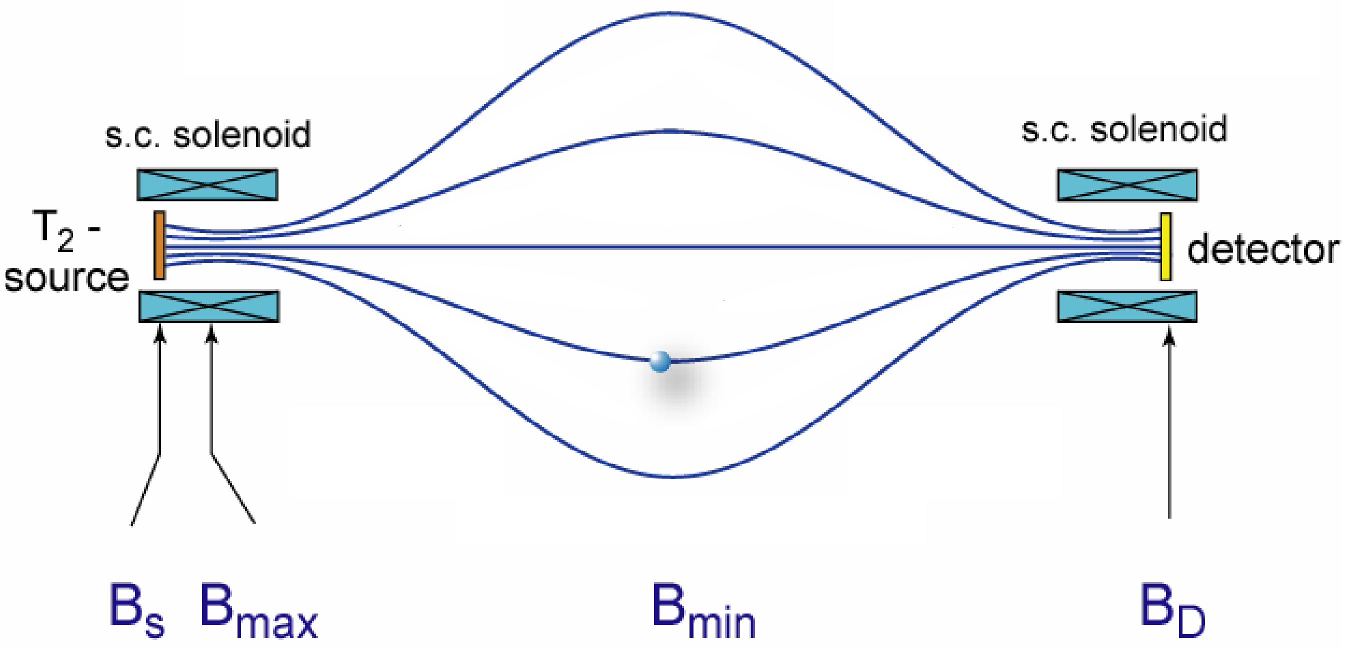
$U_0 < 30$ kV

integral particle transmission $E>U_0$

high pass filter !

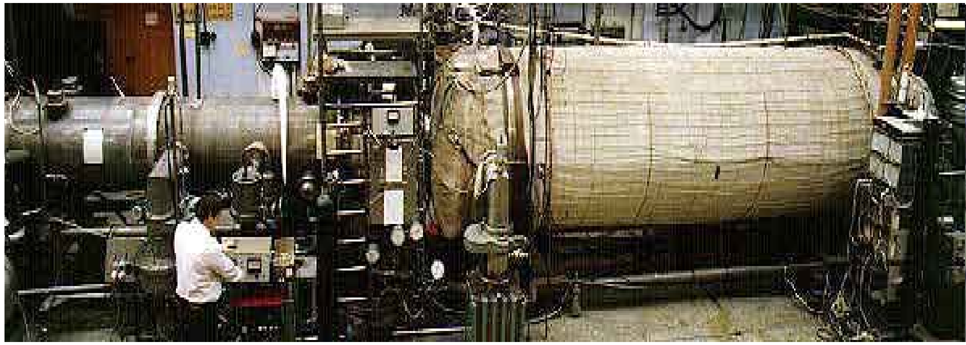
$$\vec{F} = (\vec{\mu} \cdot \vec{\nabla})\,\vec{B} + q\,\vec{E}$$

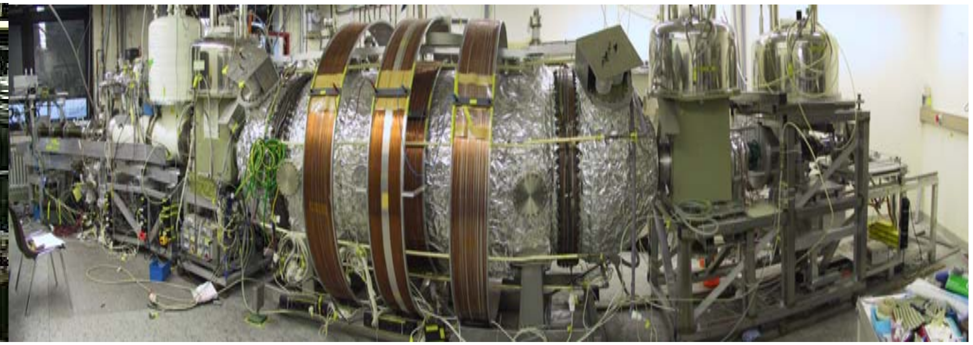
$$\mu = E_{\perp} / B = const$$



Status of previous tritium experiments

Mainz & Troitsk have reached their intrinsic limit of sensitivity





Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

$$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0 \text{ eV}^2$$

$$m_\nu \leq \quad 2.2 \text{ eV} \quad (95\% \text{ CL.})$$

Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

$$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2$$

$$m_\nu \leq \quad 2.2 \text{ eV} \quad (95\% \text{ CL.})$$

both experiments now used for systematic investigations

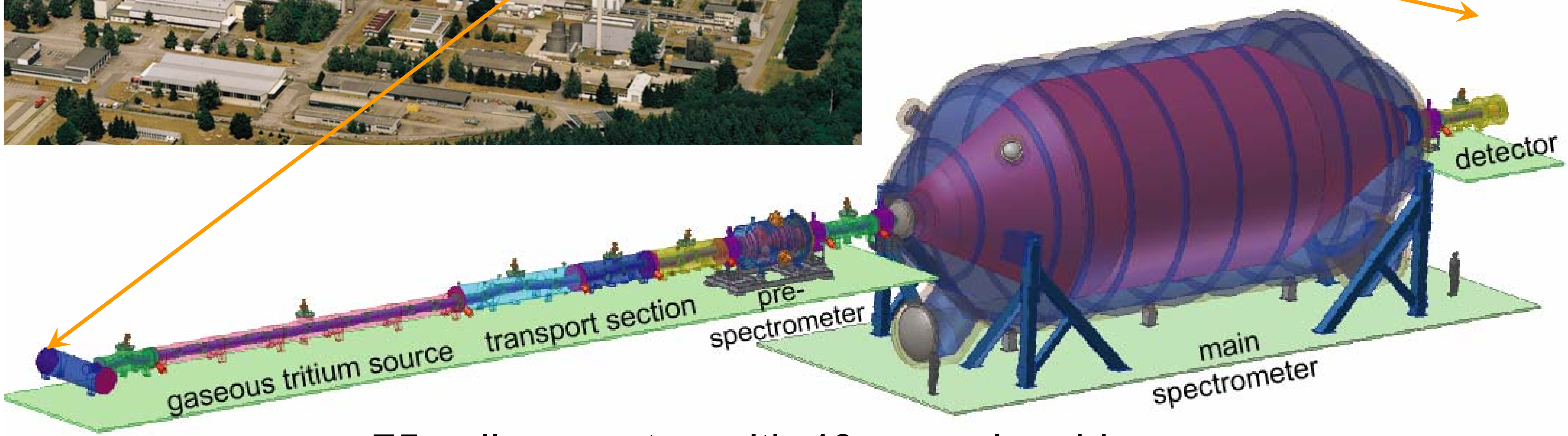
KATRIN experiment

Karlsruhe **Tri**tium **N**eutrino Experiment

at Forschungszentrum Karlsruhe

unique facility for closed T_2 cycle:

Tritium Laboratory Karlsruhe



~ 75 m linear setup with 40 s.c. solenoids

designing a next-generation experiment

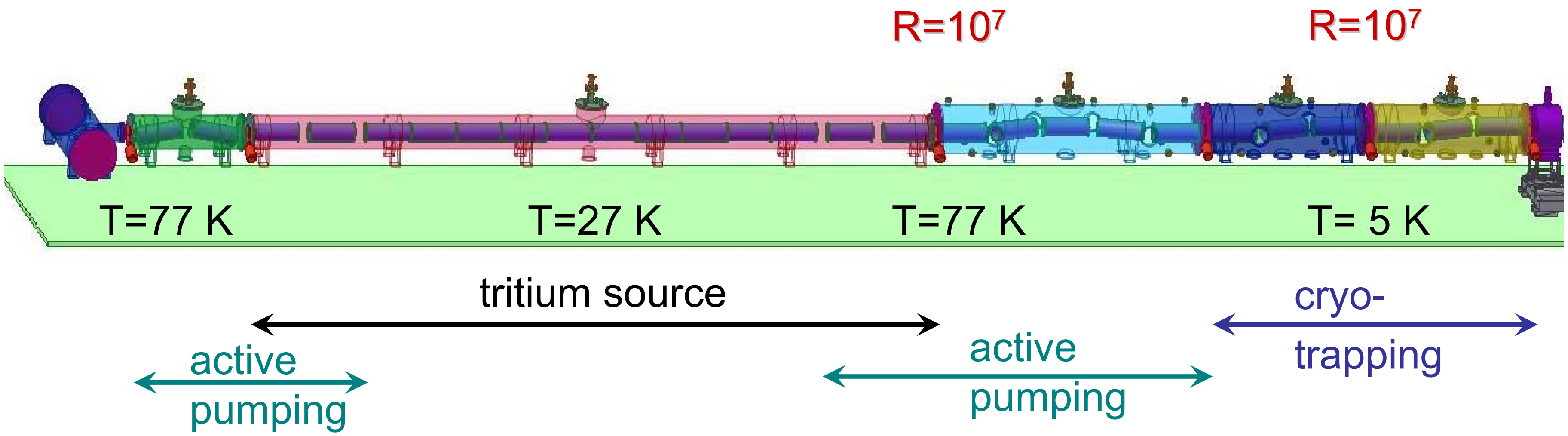
experimental observable in ß-decay is m_ν^2

aim : improve m_ν by one order of magnitude (2 eV $\rightarrow$ 0.2 eV)

requires : improve m_ν^2 by two orders of magnitude (4 eV^2 $\rightarrow$ 0.04 eV^2)

problem : count rate close to ß-end point drops very fast ($\sim\delta E^3$)

tritium bearing components - overview

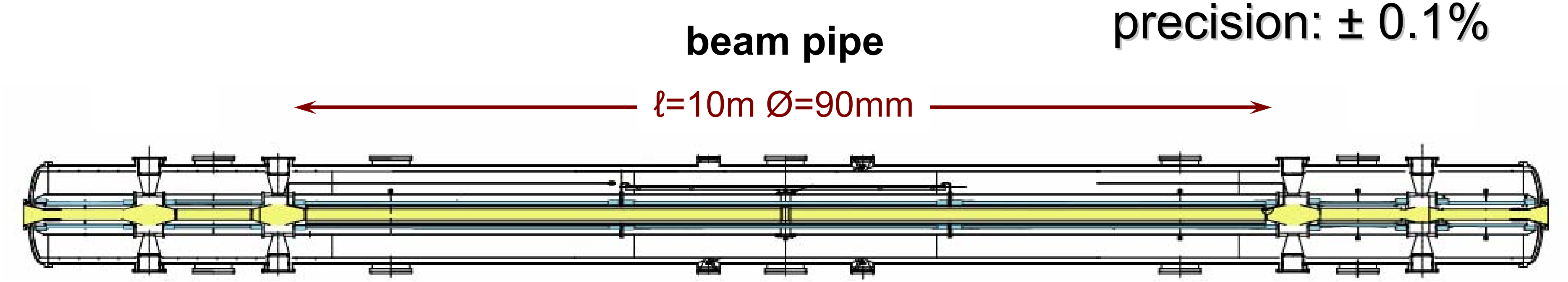


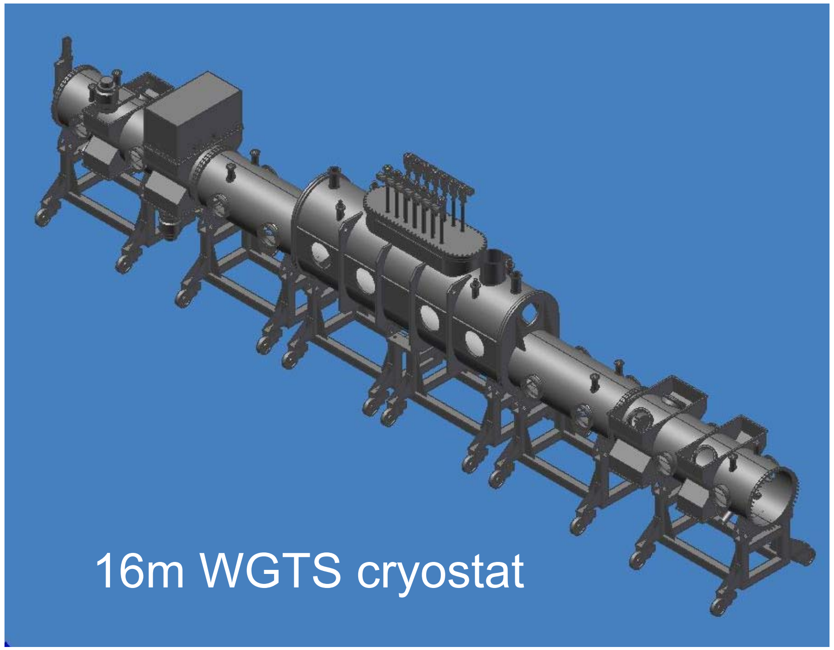
windowless tritium source- design

molecular gaseous ß-decay source, maximum luminosity (10^{11} ß/s)

- integral design criterium: column density $\rho d = 5 \times 10^{17}$ molecules / cm^2

precision: ± 0.1%

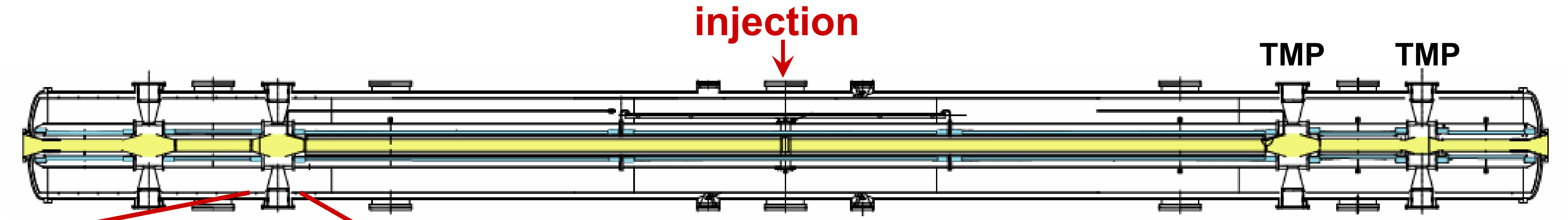


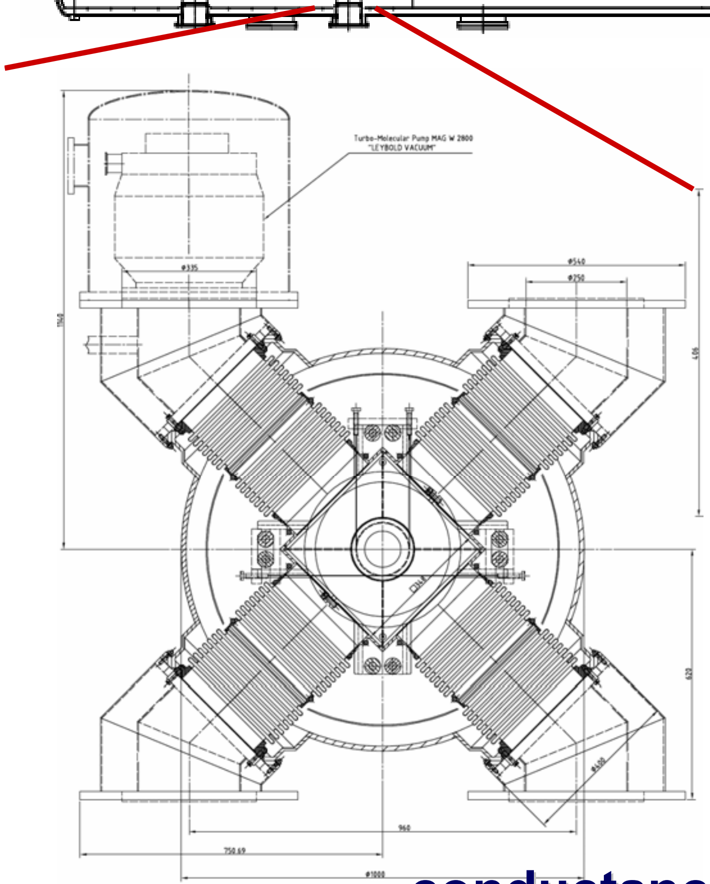


single design criteria:

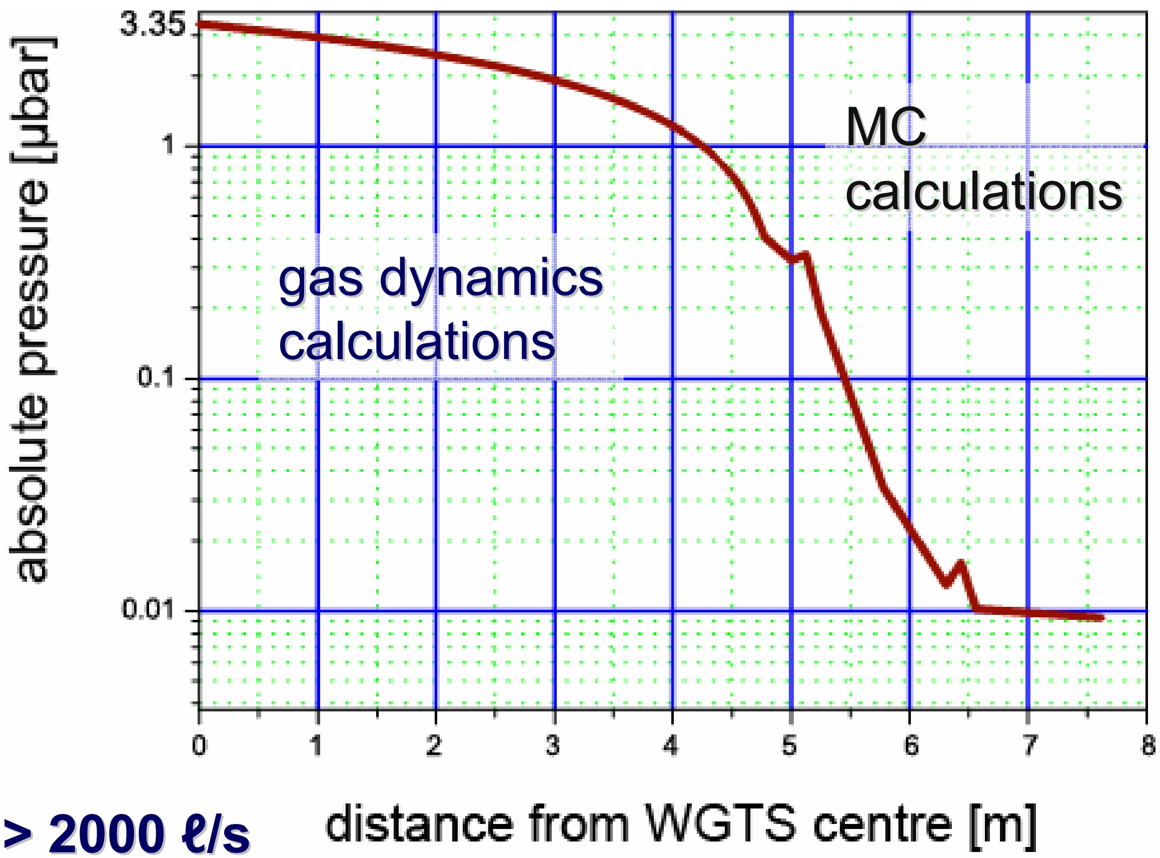
- magnetic field B = 3.6 T (±2%)
- tritium injection 5×10^{19} mol/s = 4.7 Ci/s = 1.7 x 10^{11} Bq/s = 40 g tritium / day
- temperature T = 27-30K $\Delta T \leq 30$ mK
- pumping speed 12.000 ℓ / s

WGTS – tritium pressure

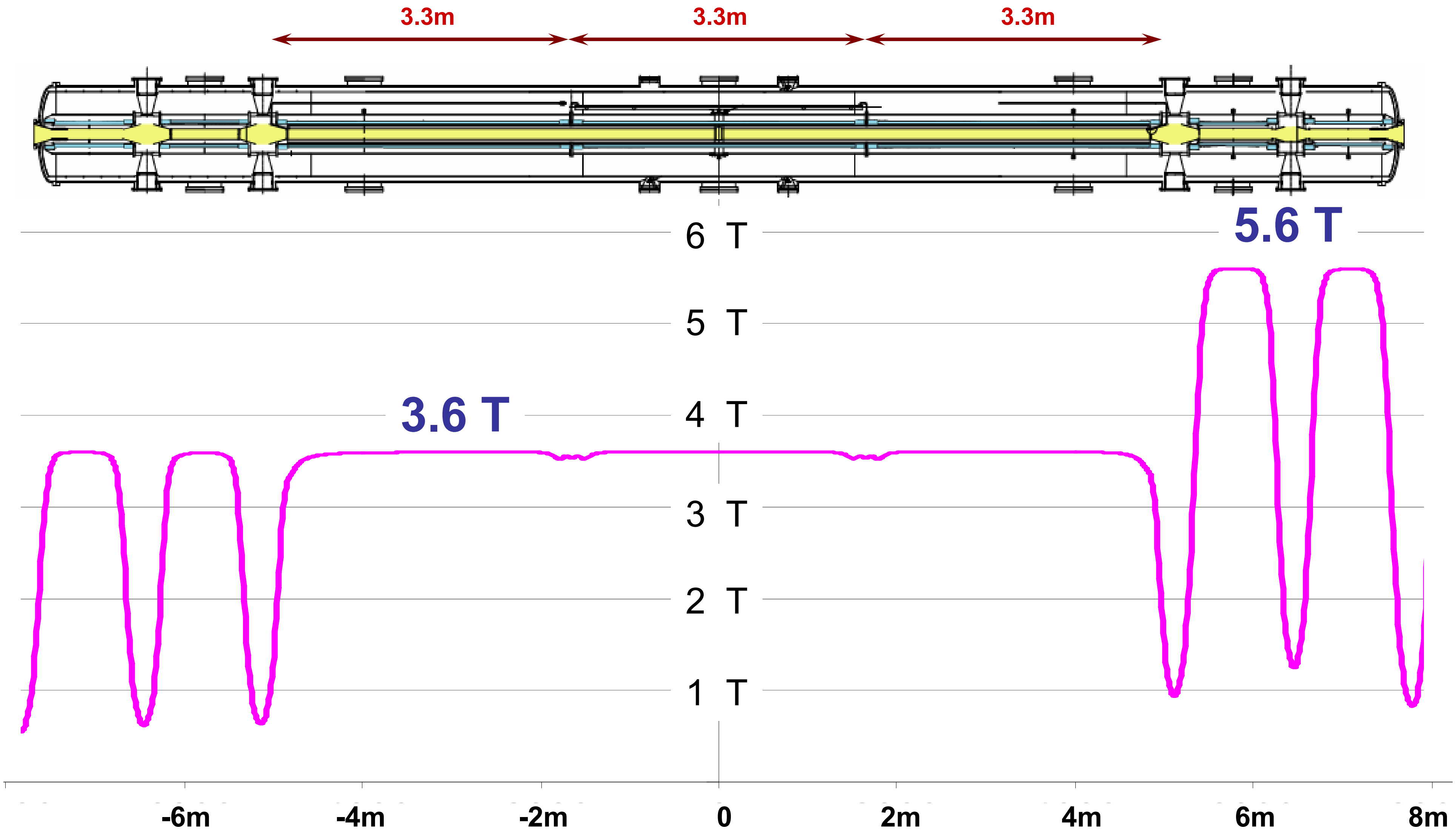




conductance > 2000 ℓ/s



WGTS – magnetic field

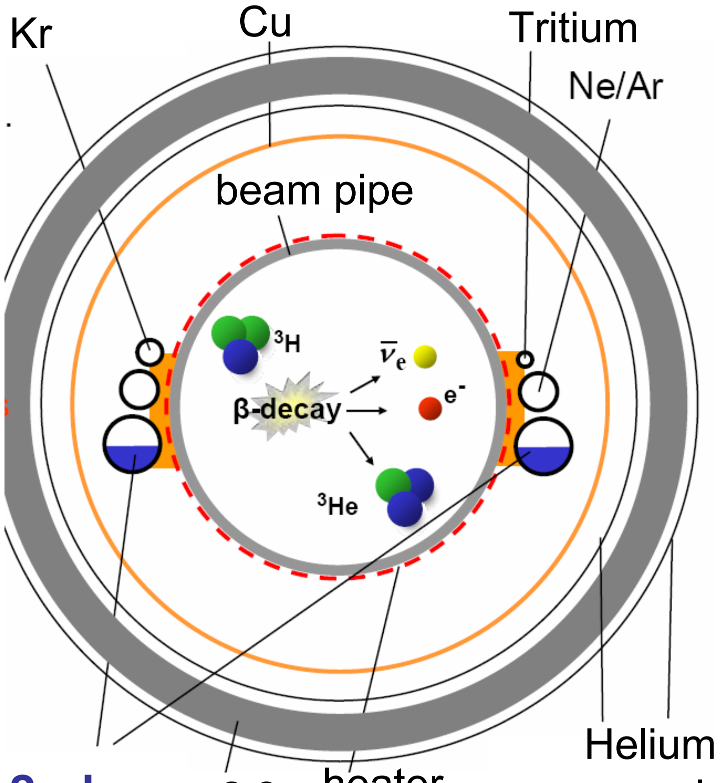


WGTS – cooling concept

ΔT ≤ ± 30 mK !

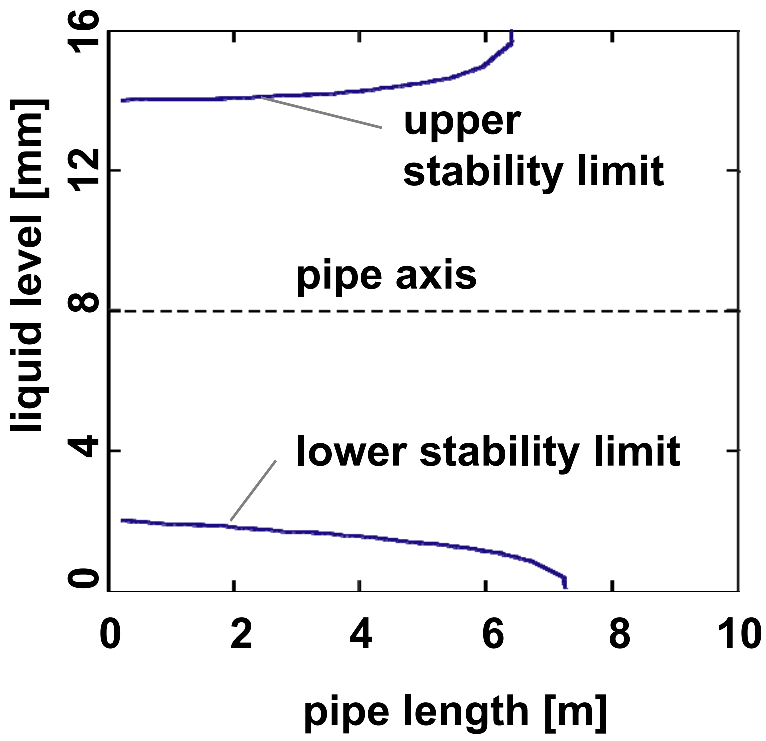
operating temperature: 27–28 K

- **spatial** (homogeneity): ± **0.1%**
- **time** (stability/hour): ± **0.1%**



conceptual design:

2-phase Neon (boiling liquid)



2 separate cooling pipes Ø=16mm

(2 wall barrier concept for T_2)

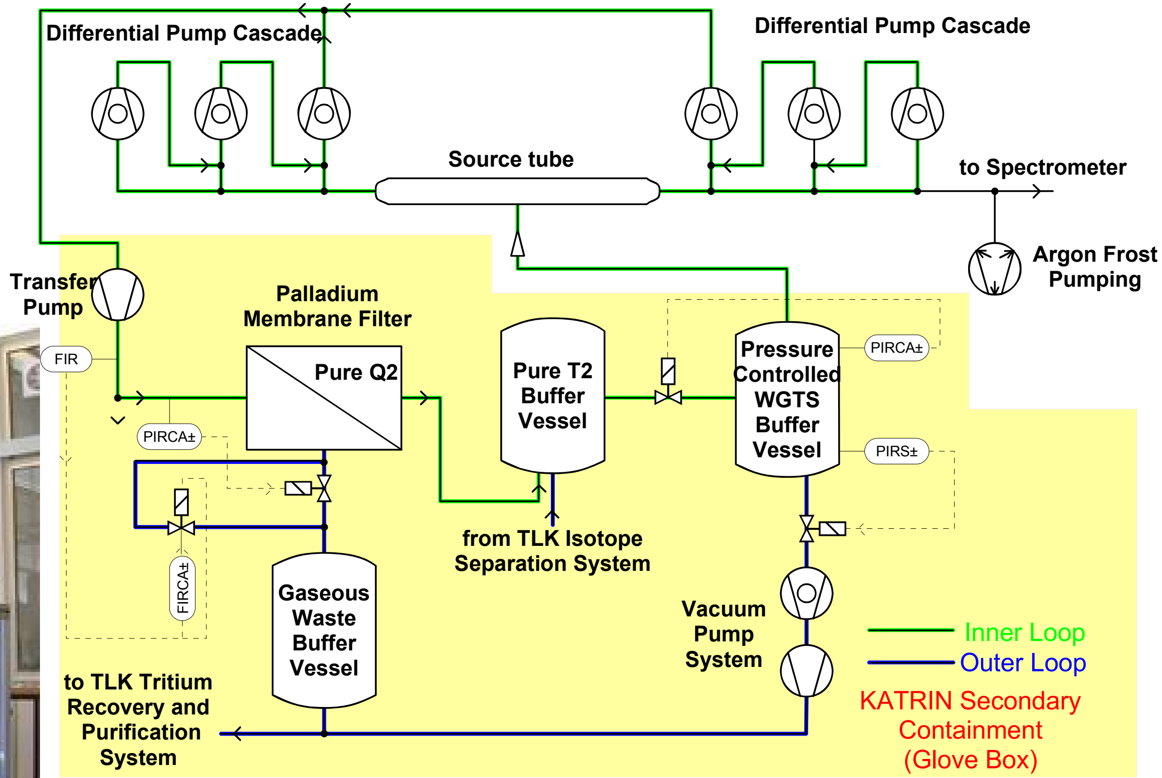
closed tritium cycle

test experiment TILO design tritium cycle at TLK

experimental aims: test of

- molecular-kinetetic models
- measurement- & controlsystem

measurements since June 2005



inner Loop – stable WGTS parameters

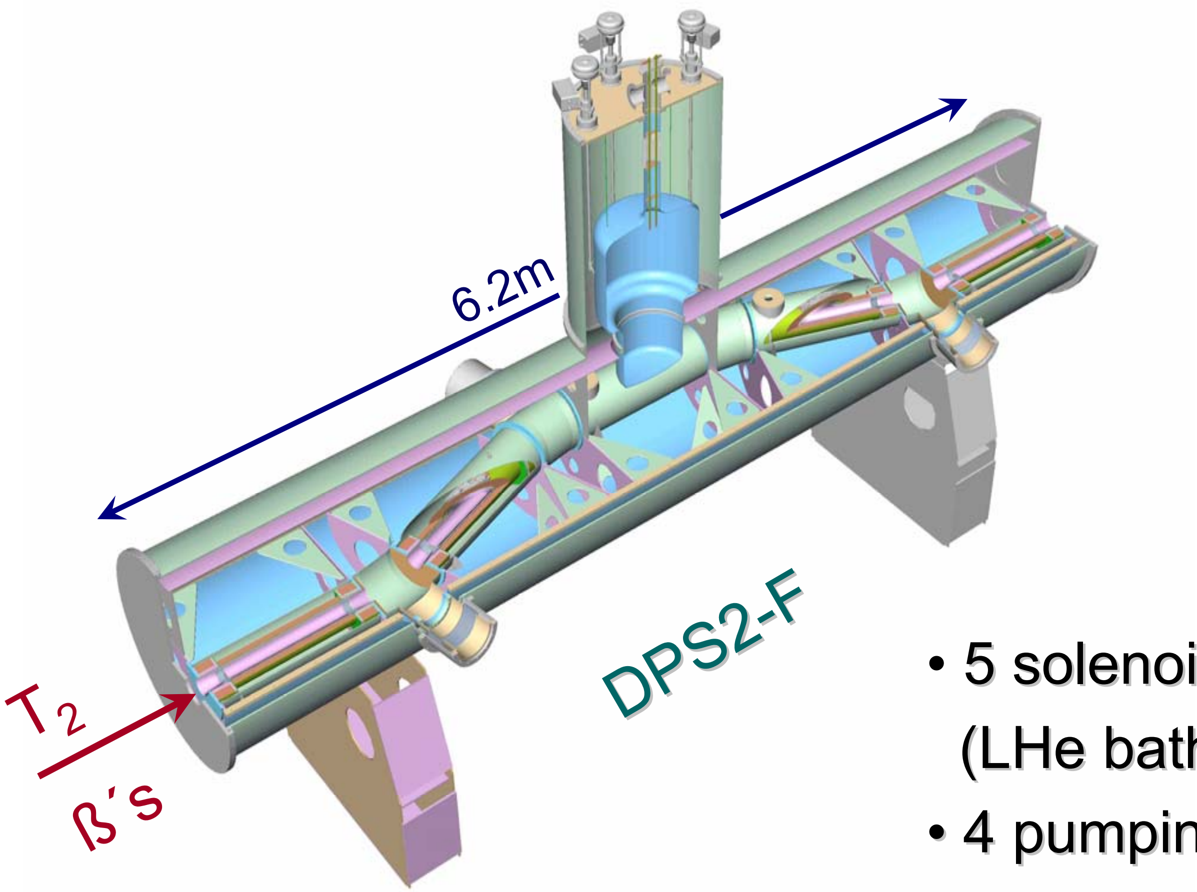
outer Loop – high tritium purity

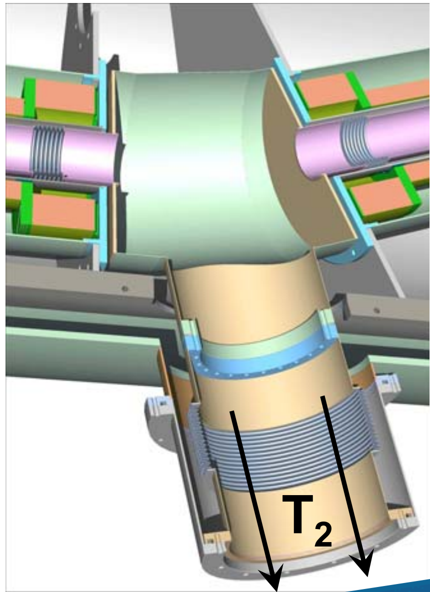
differential pumping section

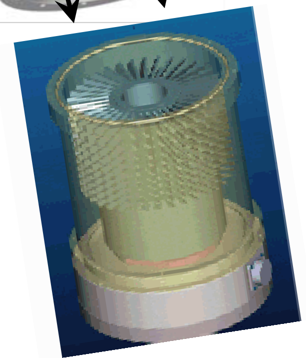
task: active pumping of T_2 molecules

↳ flux reduction by factor 2×10^8

method: serial TMP pumpports (2000 ℓ/s)







- 5 solenoids with B=5.6T (LHe bath cooling)
- 4 pumping ports (T=77K)

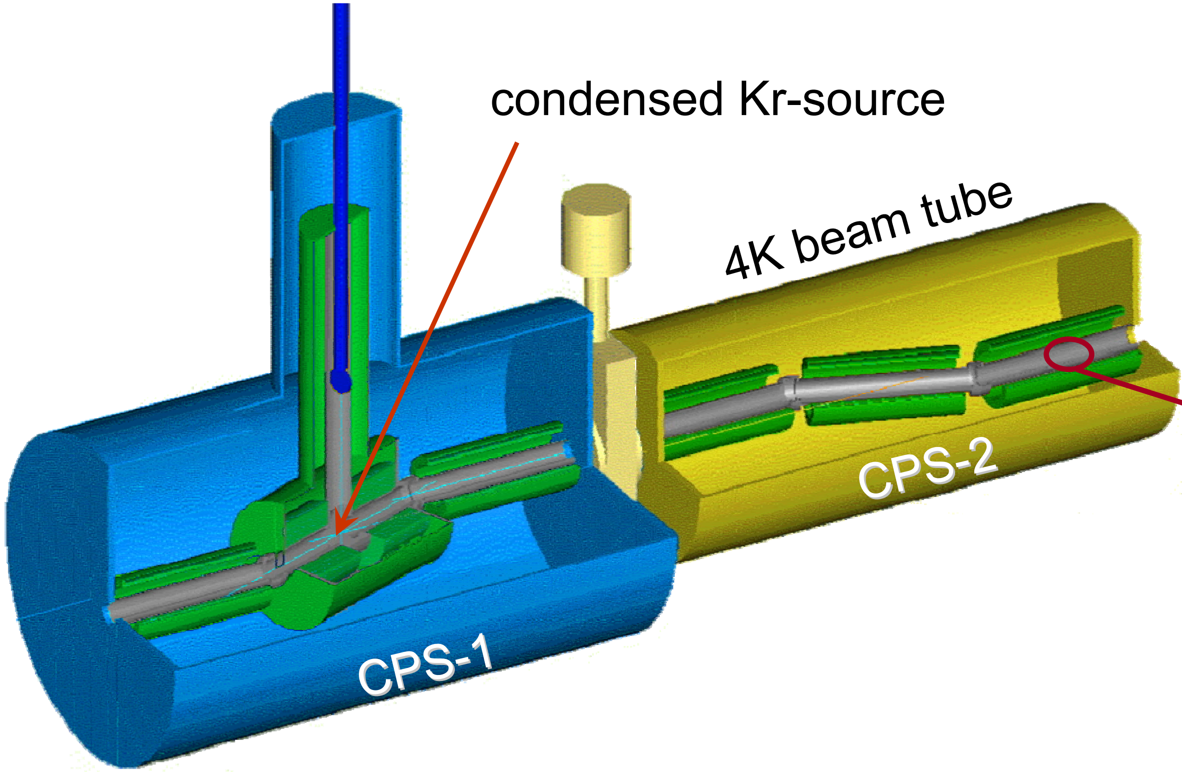
cryogenic pumping section

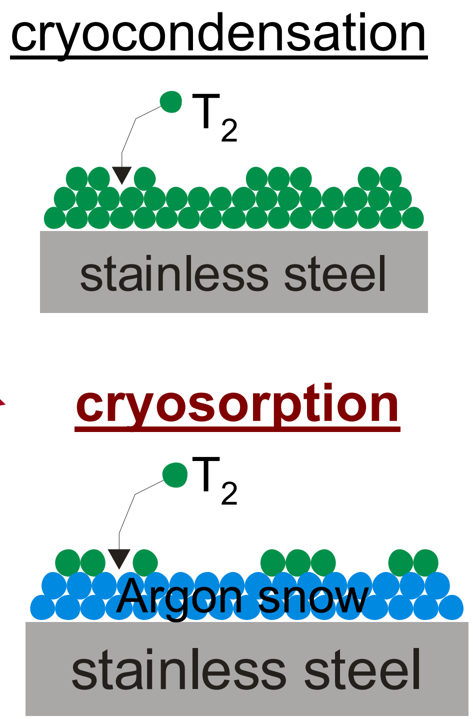
objective: retention of remaining tritium flux

tritium partial pressure spectrometer $p < 10^{-20}$ mbar

method: cryo-sorption on condensing Ar-frost

rate: <1 Ci T_2 in 60 days (regeneration with warm He-gas)





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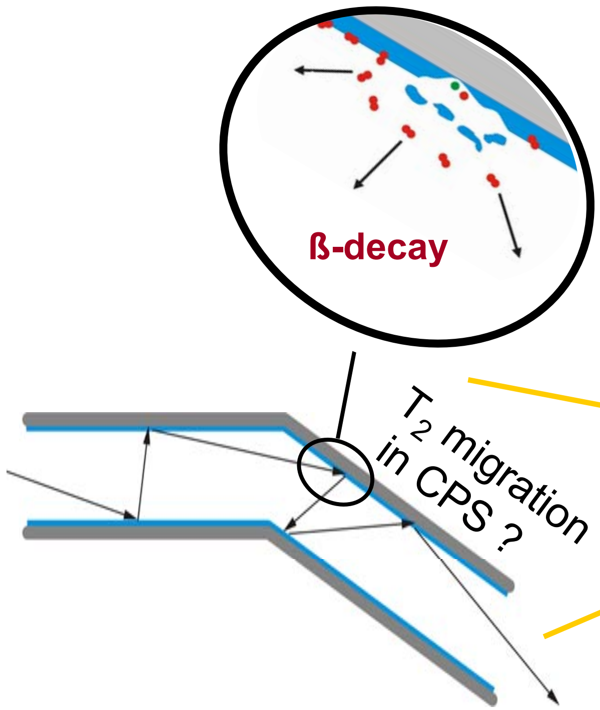
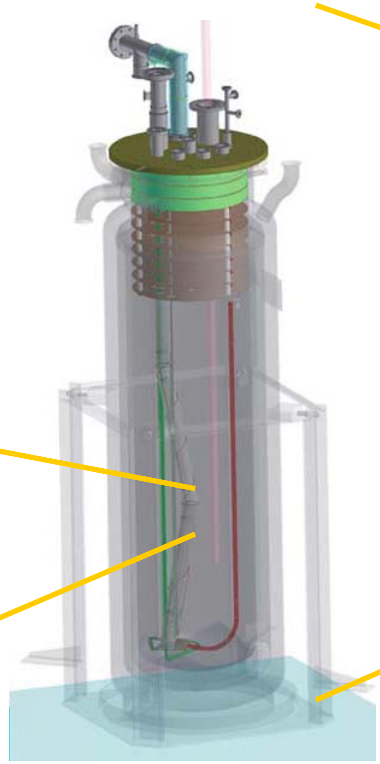
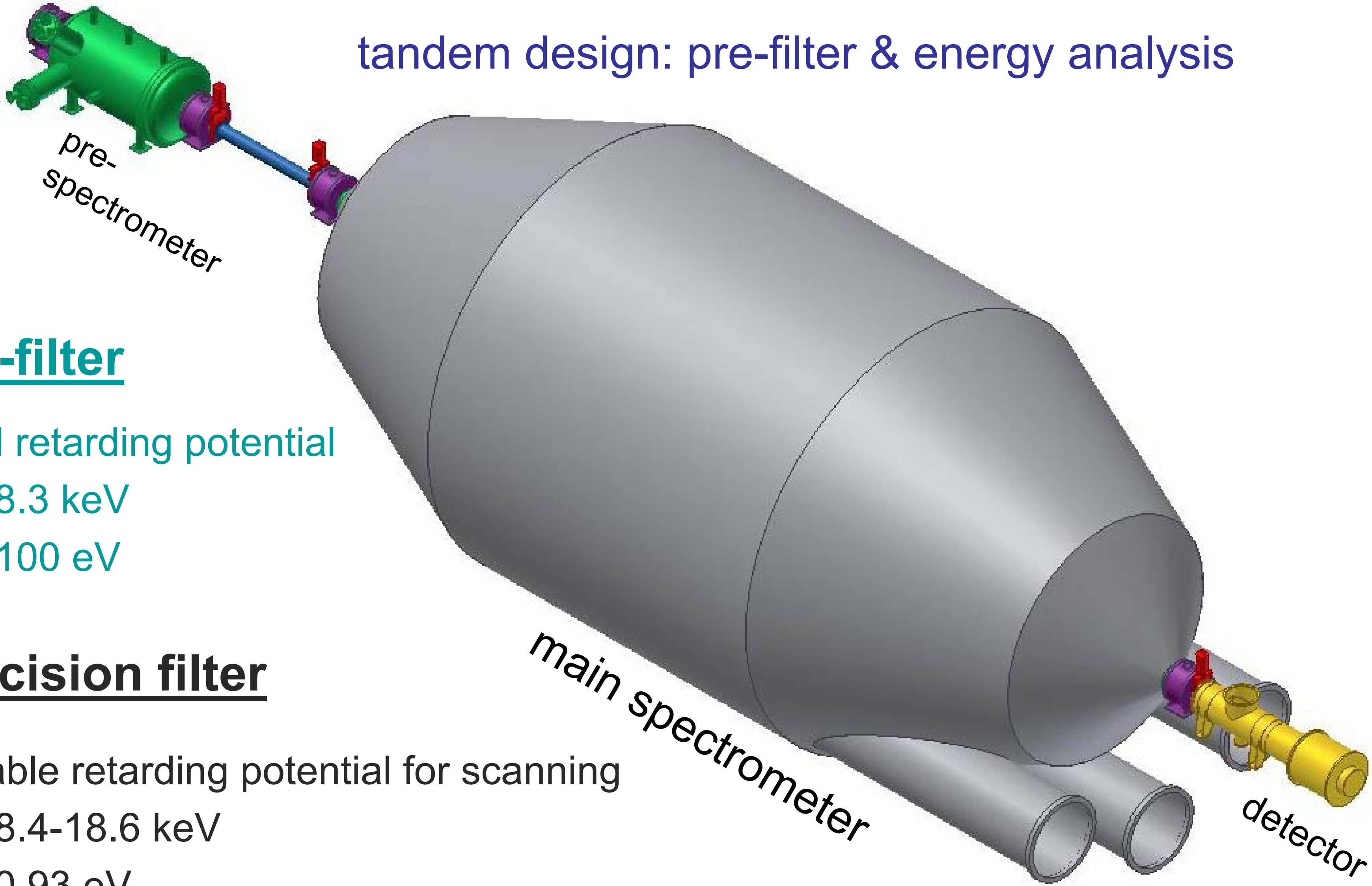




TRAP - Tritium Argon Frost Pump

electrostatic spectrometers

tandem design: pre-filter & energy analysis



pre-filter

fixed retarding potential

U=18.3 keV

ΔE~100 eV

precision filter

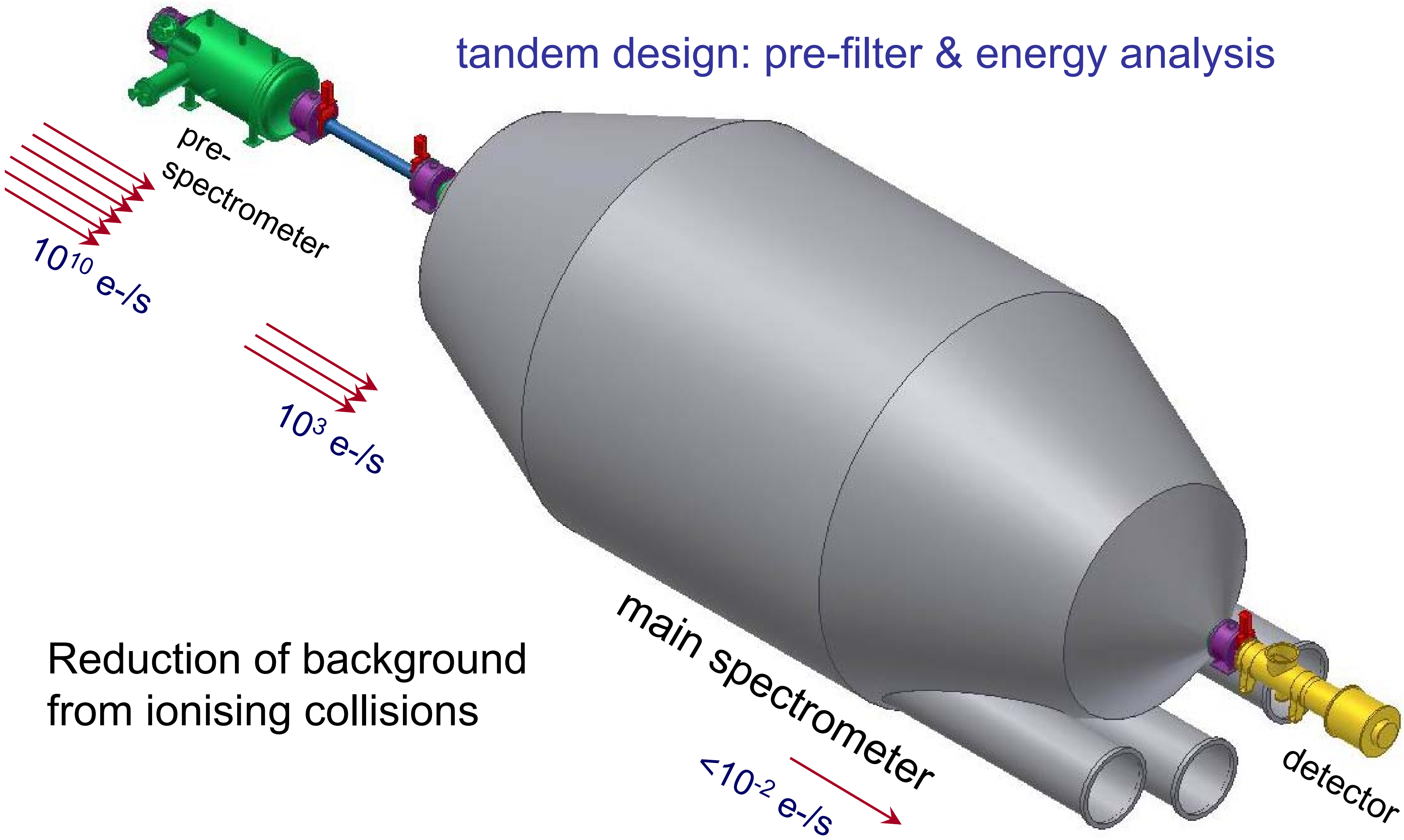
variable retarding potential for scanning

U=18.4-18.6 keV

ΔE=0.93 eV

electrostatic spectrometers

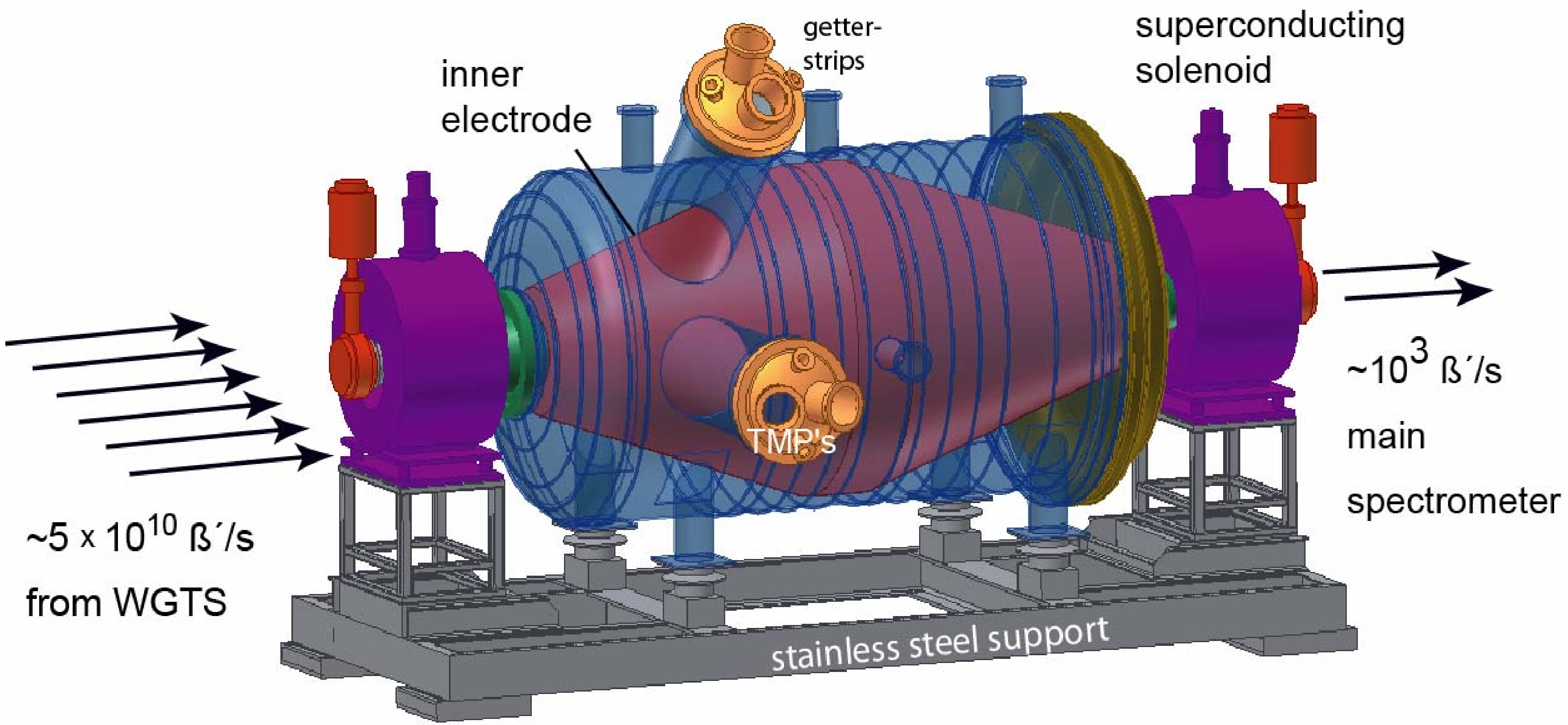
tandem design: pre-filter & energy analysis



Reduction of background
from ionising collisions

pre-spectrometer

Task: pre-filter for low-energy ß-decay electrons (E < 18.4 keV)

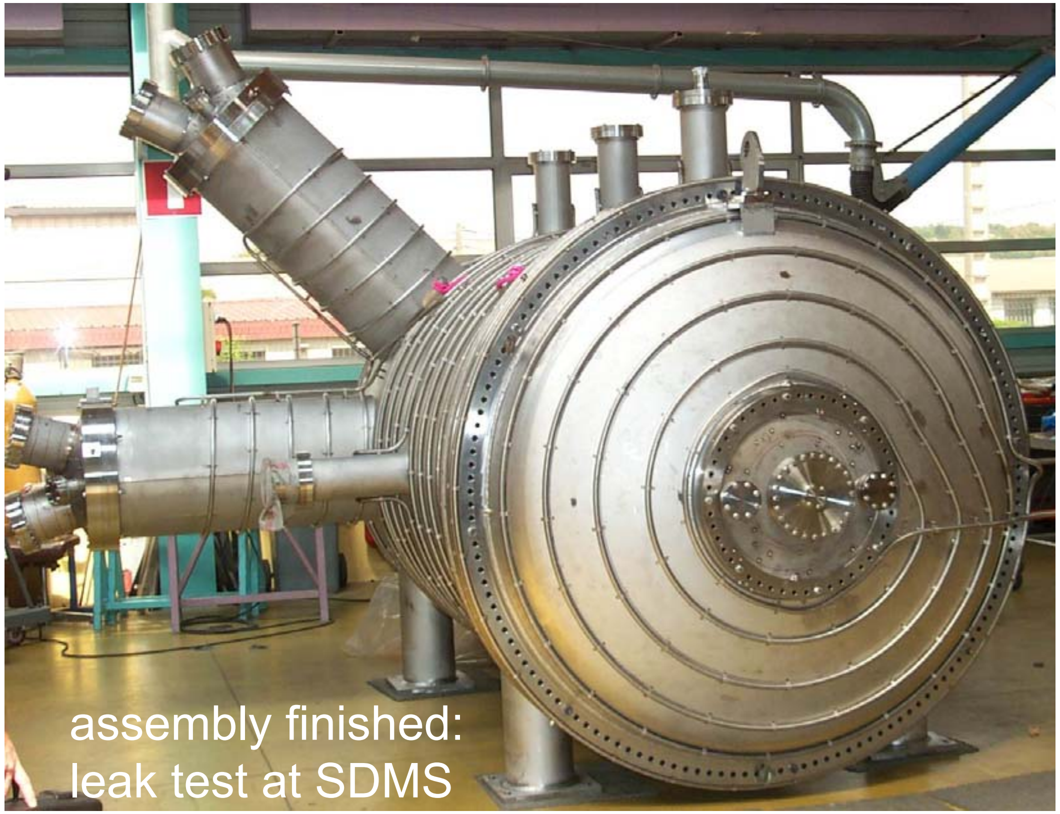


length : 3.42 m (flange-flange)

diameter : 1.70 m, stainless steel 1.4429

pre-spectrometer

assembly works at French manufacturer SDMS



assembly finished:
leak test at SDMS

electropolished inner surface

pre-spectrometer

assembly works at Karlsruhe

heating / cooling system, s.c. magnets, vacuum instrumentation,

dry air compartment & HV safety interlock

pre-spectrometer: vacuum tests

UHV concept: TMP`s & NEG-getters

1. outgassing rate @ -20°C

specified: 1×10^{-12} mbar l / cm^2 s

measured: 7×10^{-14} mbar l / cm^2 s

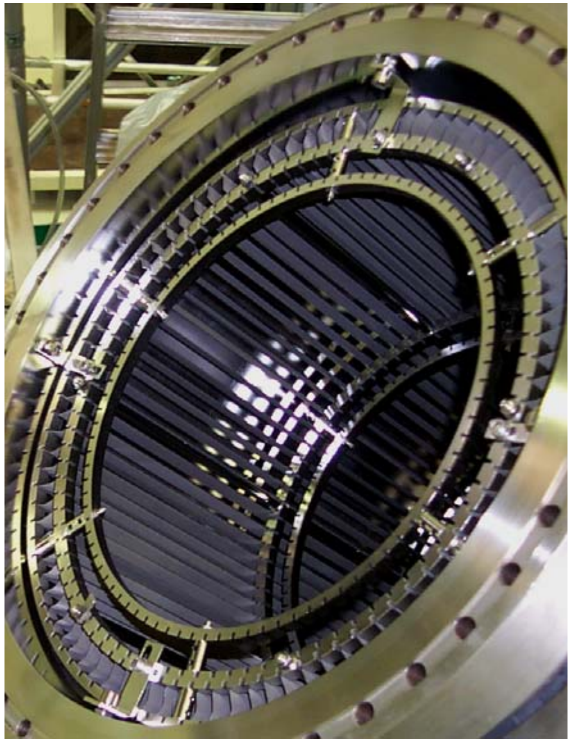
gas charge: ~50% vessel, ~50% TMP&QMS

2. final pressure

specified: $p < 10^{-11}$ mbar @ -20°C

measured: $p < 10^{-11}$ mbar @ RT

important radioactivity tests of
NEG getters @MPIK → low level getters



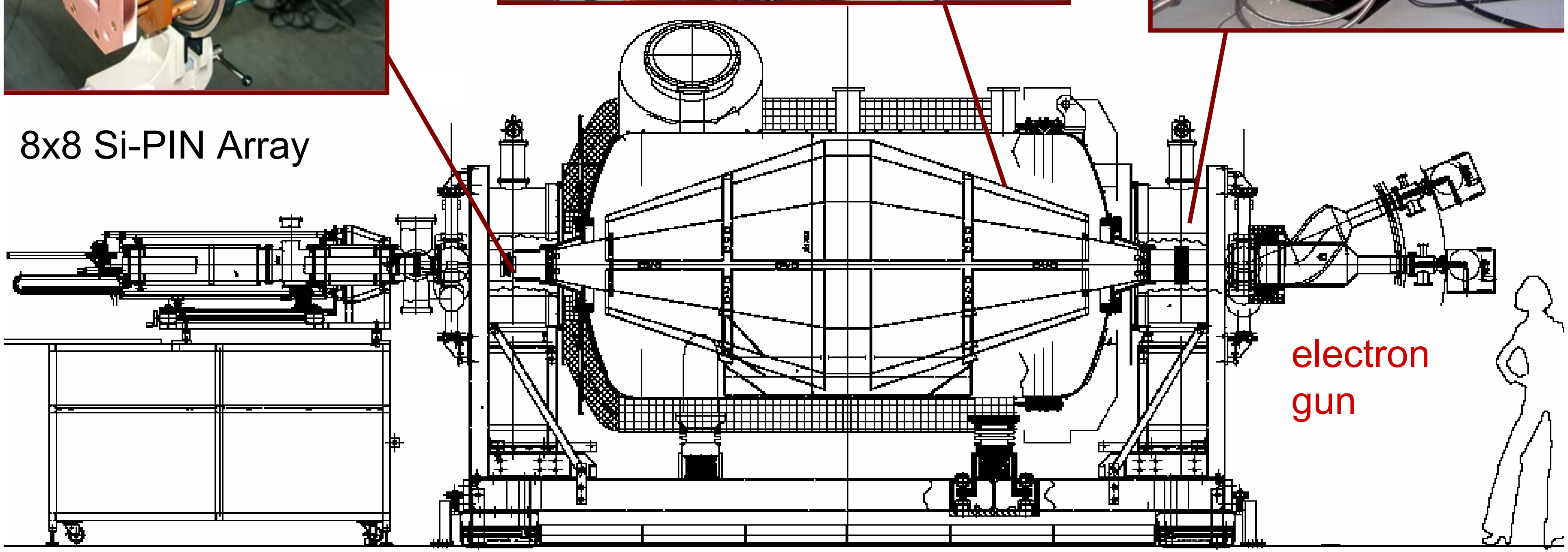
pre-spectrometer: elmagn. tests

task: verification of electromagn. concept

wire electrode

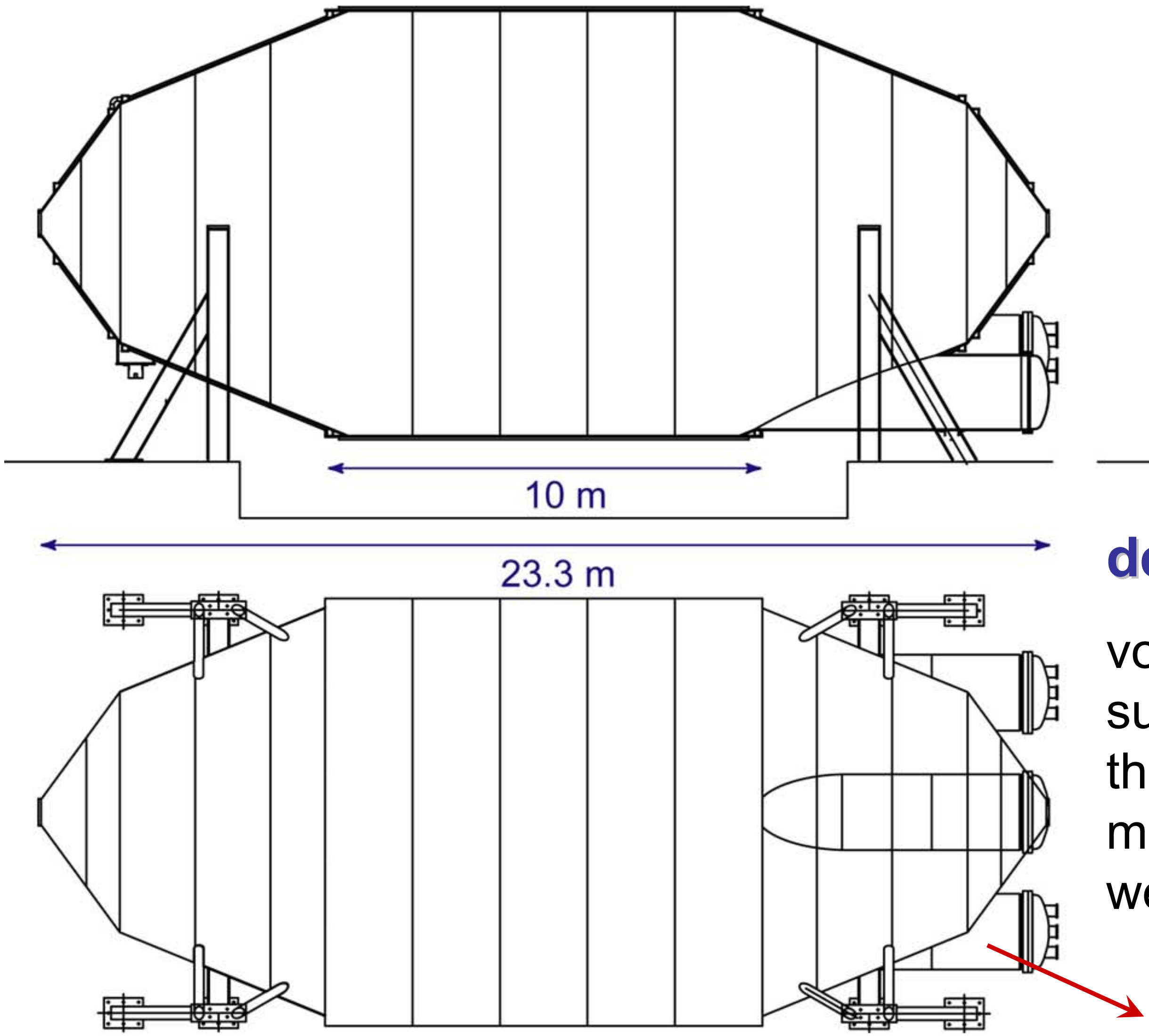
s.c.-magnets

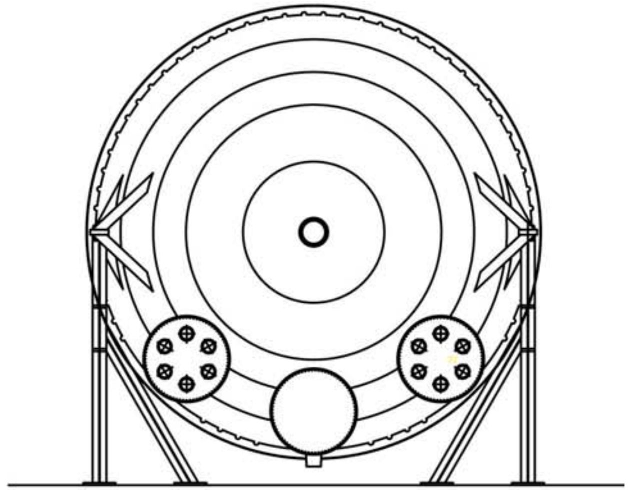
8x8 Si-PIN Array



electron gun

main spectrometer – design





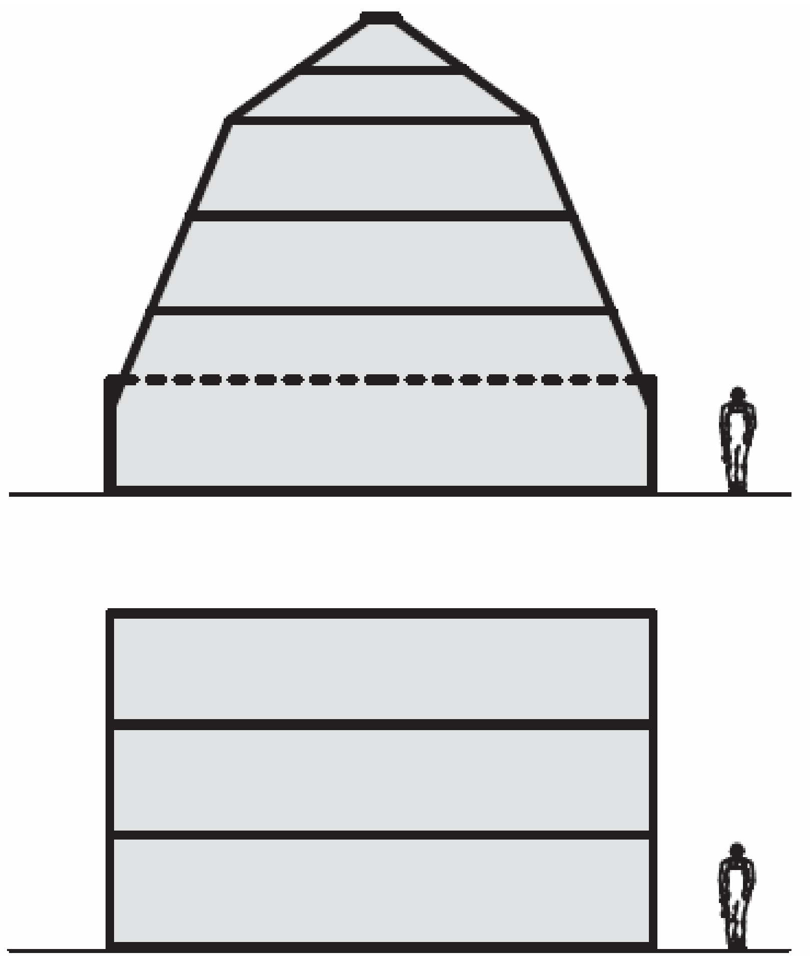
design parameters:

volume:	1258 m^3
surface:	605 m^2
thickness:	32 mm
material	1.4429
weight:	192 t

pumping port
for getters

main spectrometer – manufacture

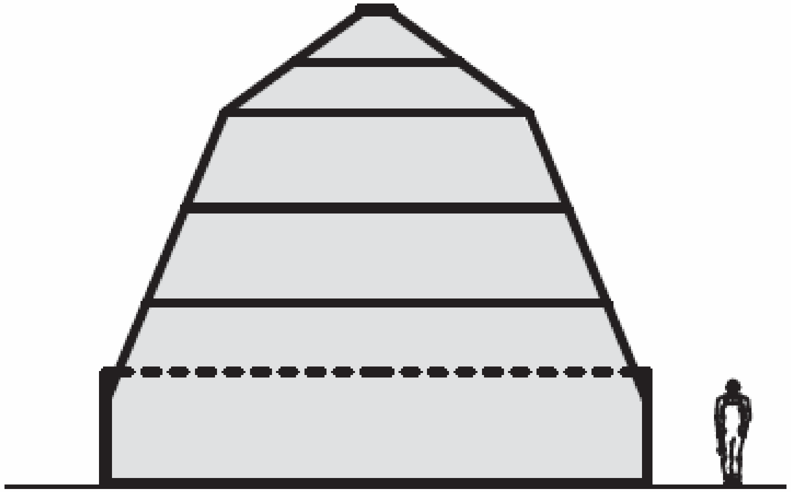
2 conical end pieces



1 cylindrical centre piece

main spectrometer – manufacture

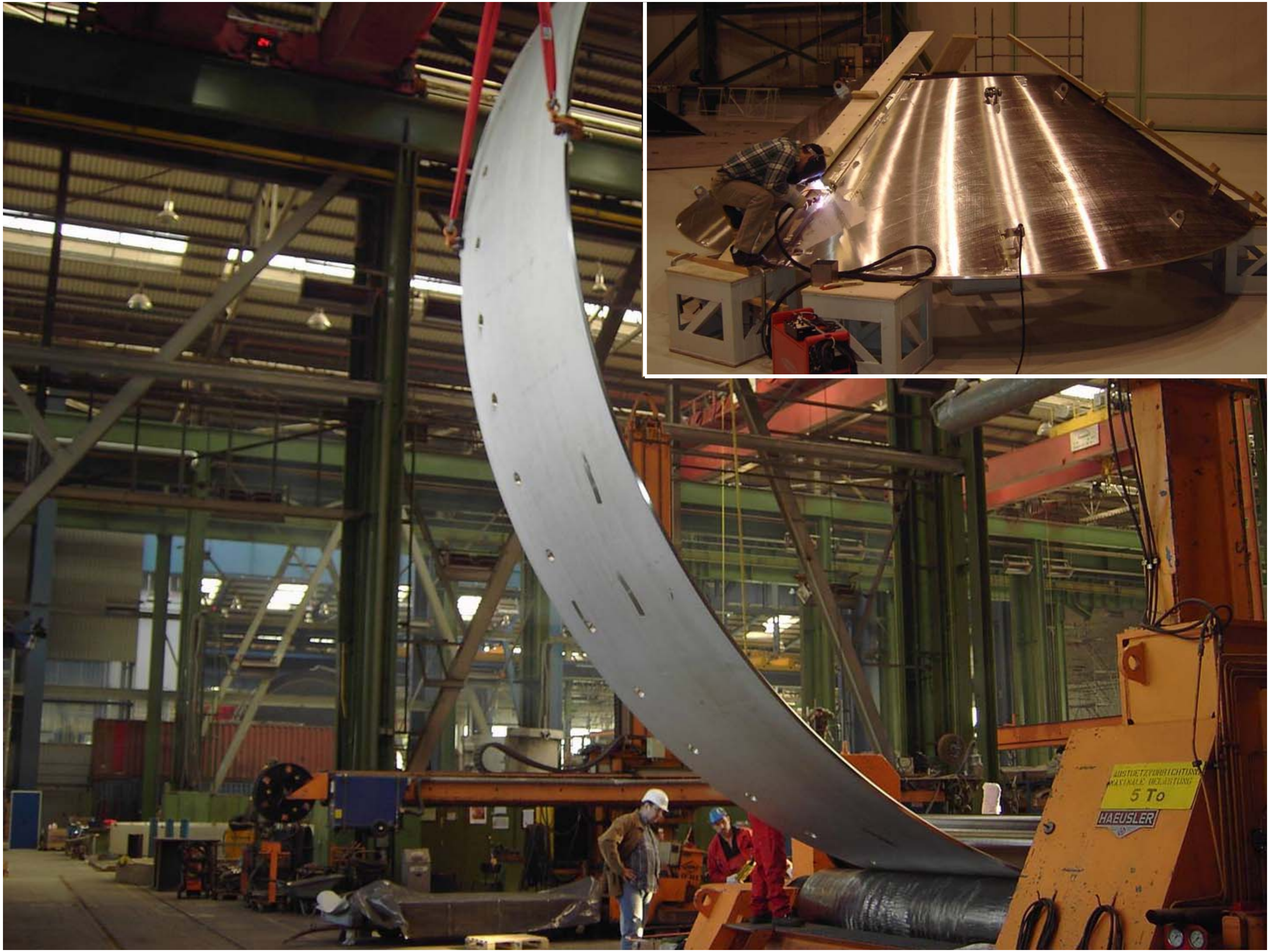
2 conical end pieces



1 cylindrical centre piece

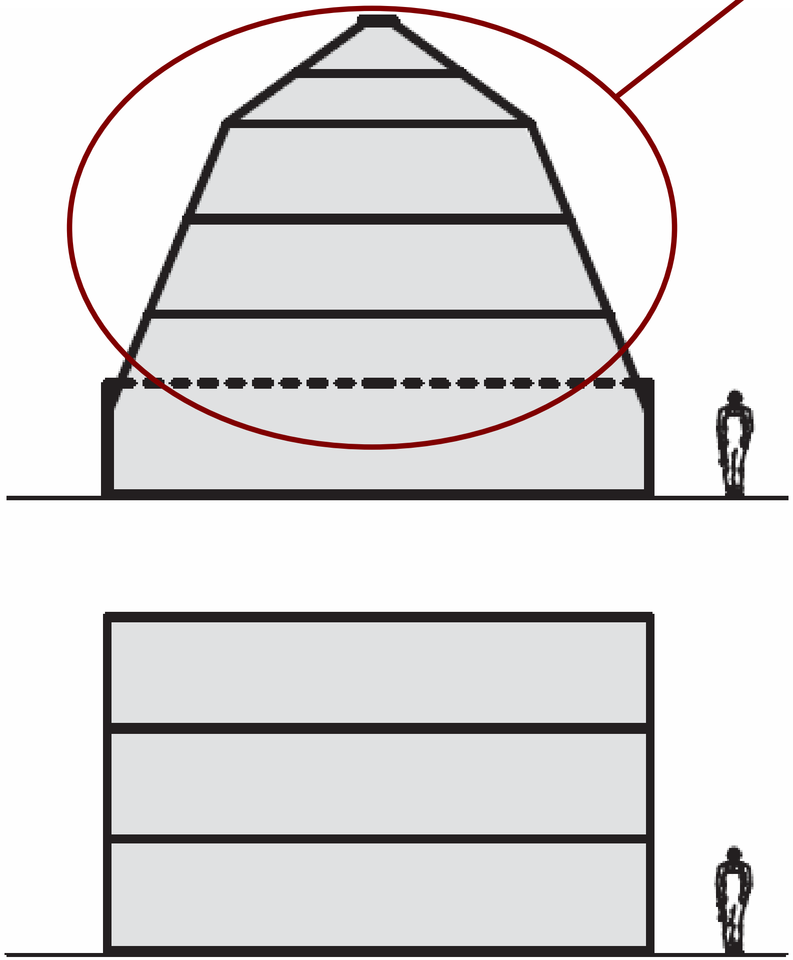
plasma cutting under water

stainless steel plates


5 To
HAEUSLER

main spectrometer – manufacture

2 conical end pieces

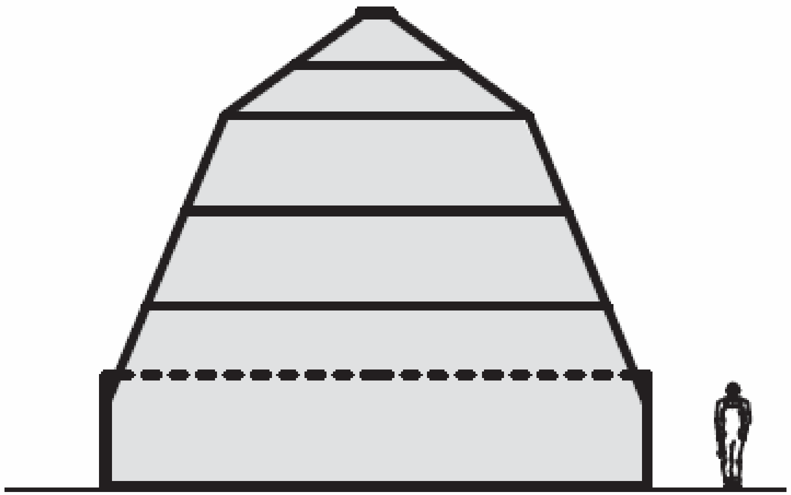


1 cylindrical centre piece

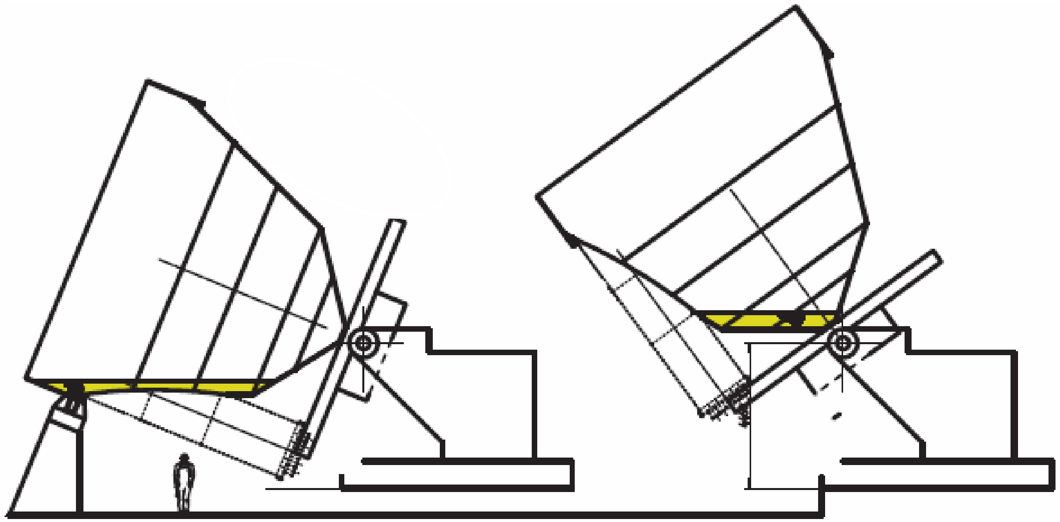
Deggendorf, January 31 2006

main spectrometer – manufacture

2 conical end pieces

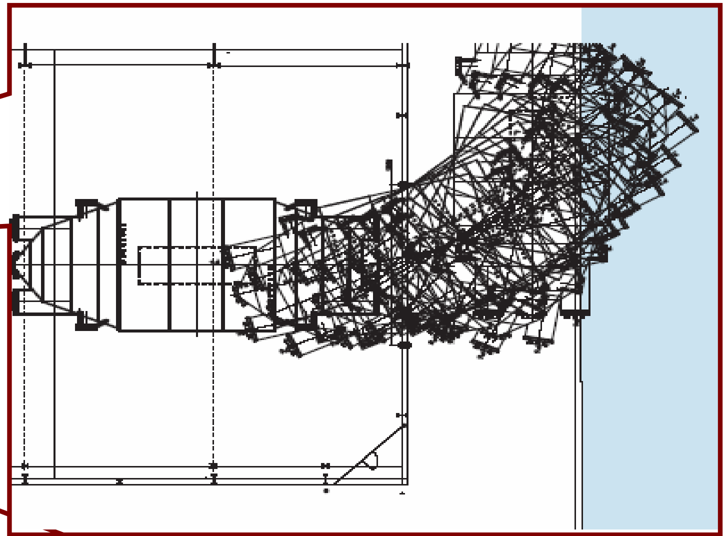


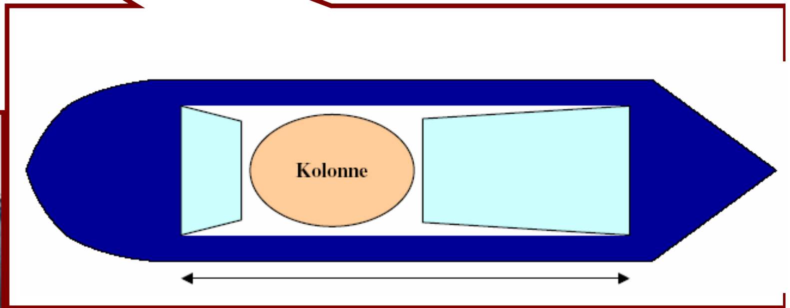
1 cylindrical centre piece



electro-polishing

main spectrometer – transport logistics





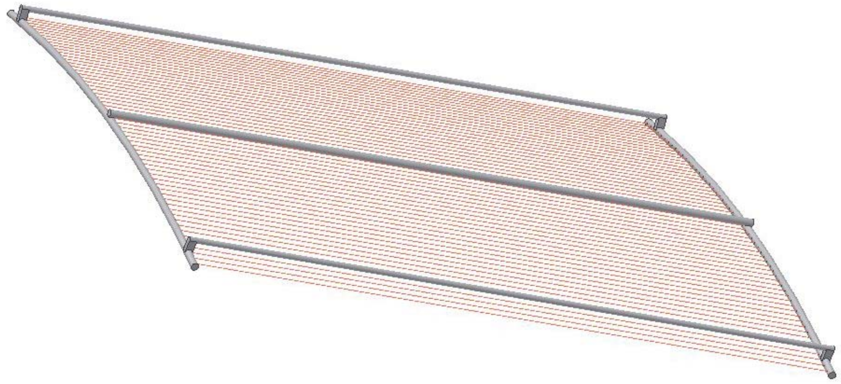
Delivery to FZK:
September, 21 2006

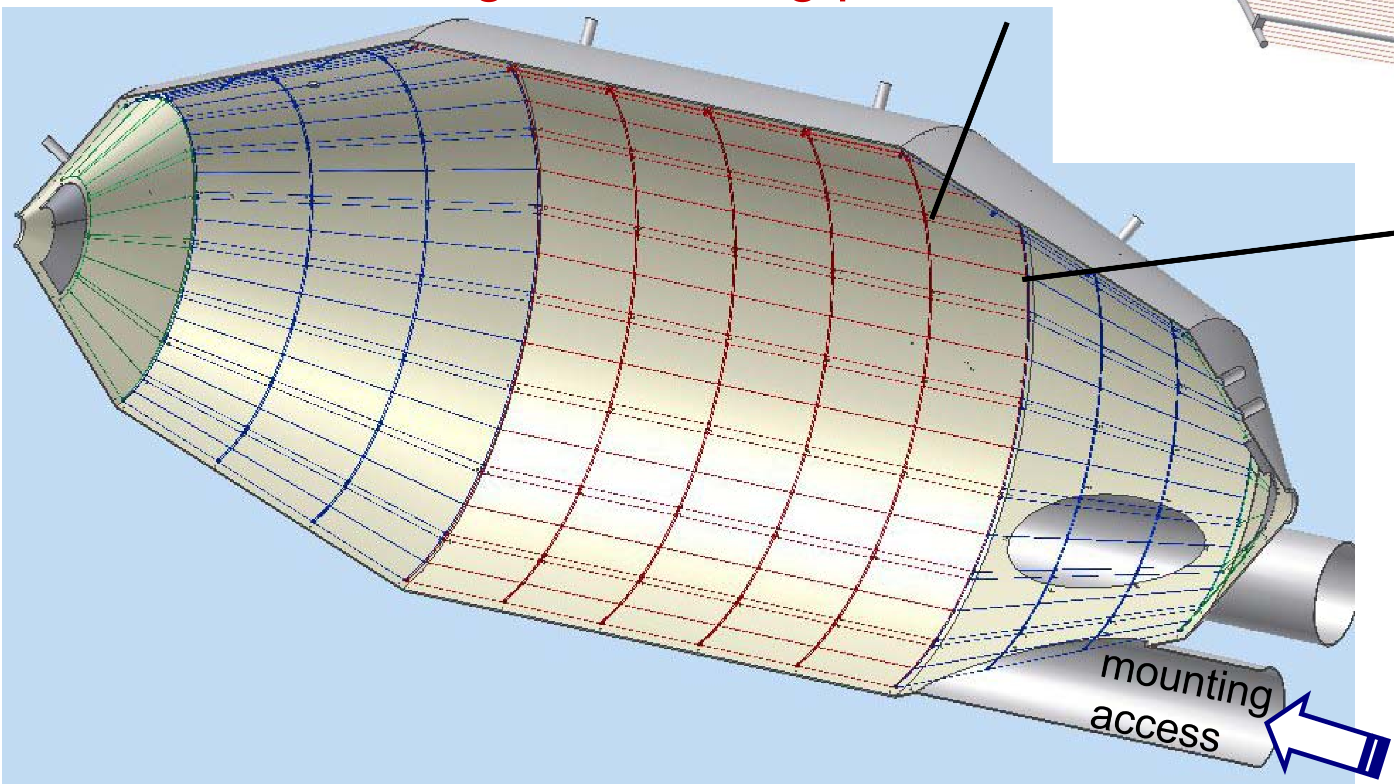
main spectrometer – inner electrode

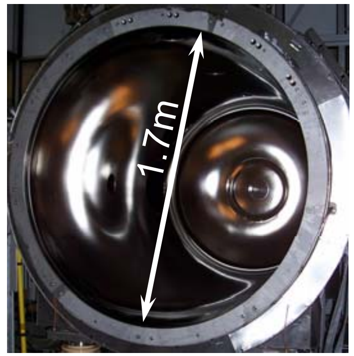
tasks of inner wire-based electrode system:

- background reduction
  - screening of low-energy electrons
  - removal of trapped particles
- fine forming of retarding potential

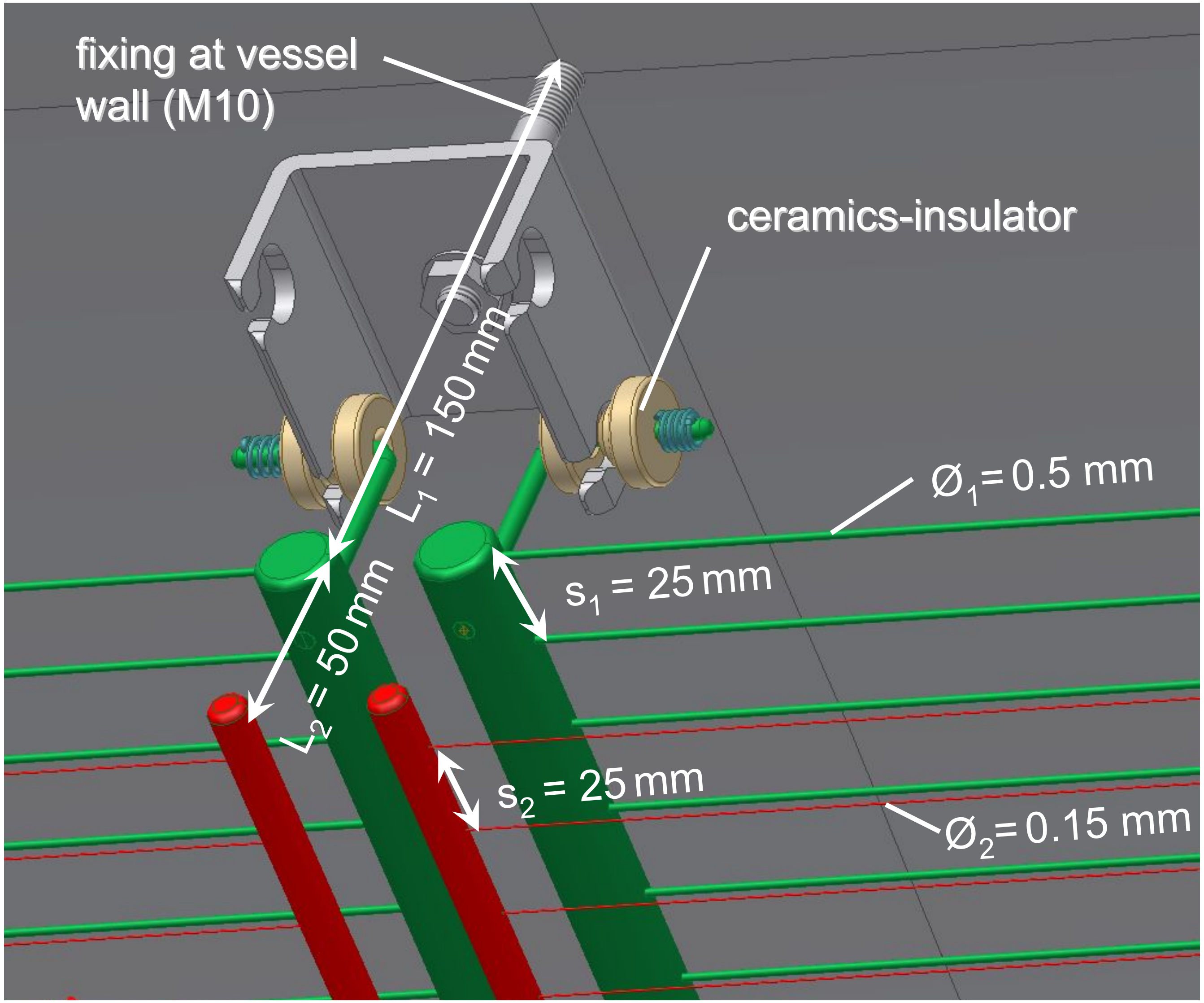
U Münster







inner wire-based electrode system



two-layer system

1. wire plane

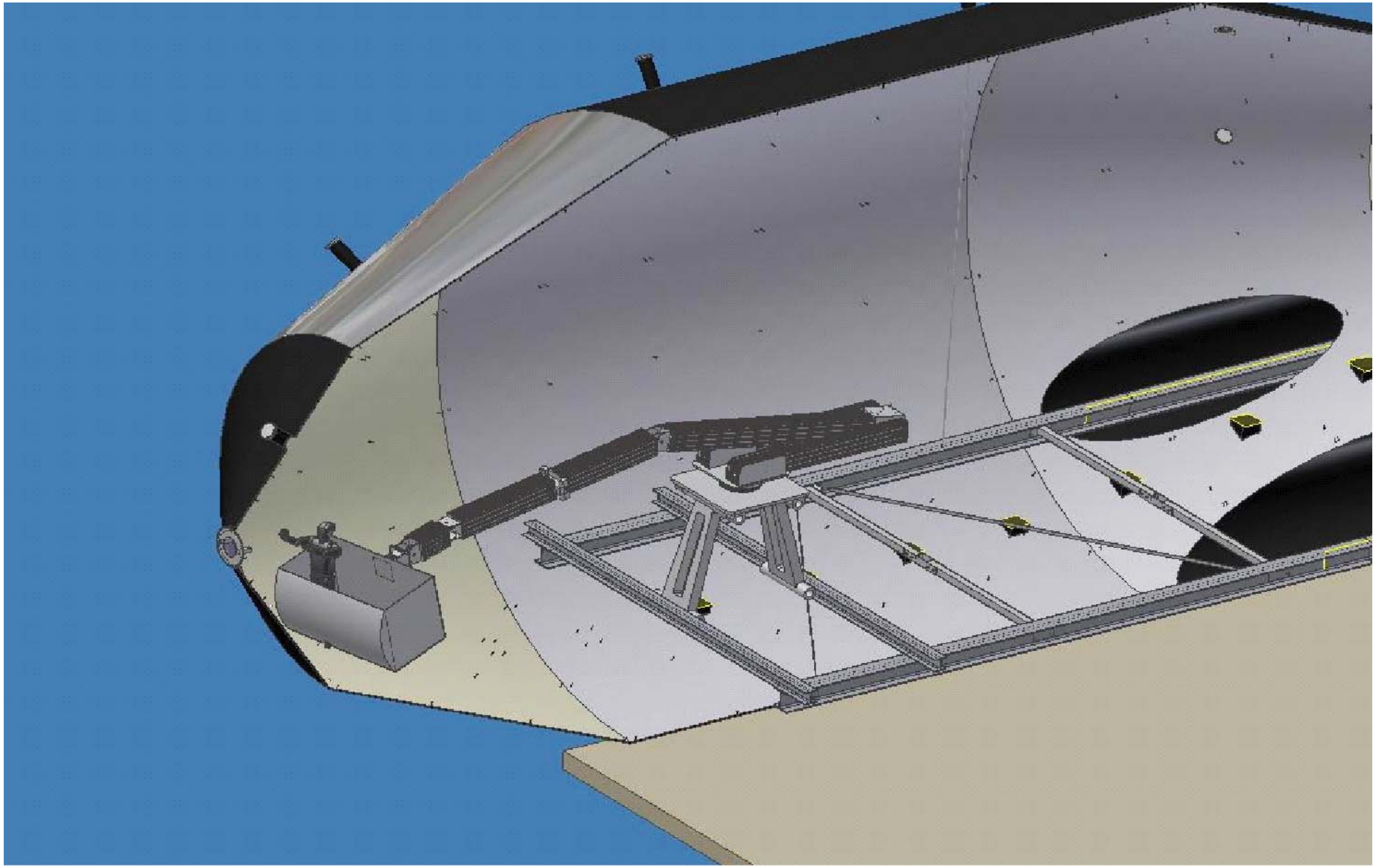
parallel / equidistant
to spectrometer wall
const. wire spacing
const. $U_1 = U_{sp} + \Delta U_1$

2. wire plane

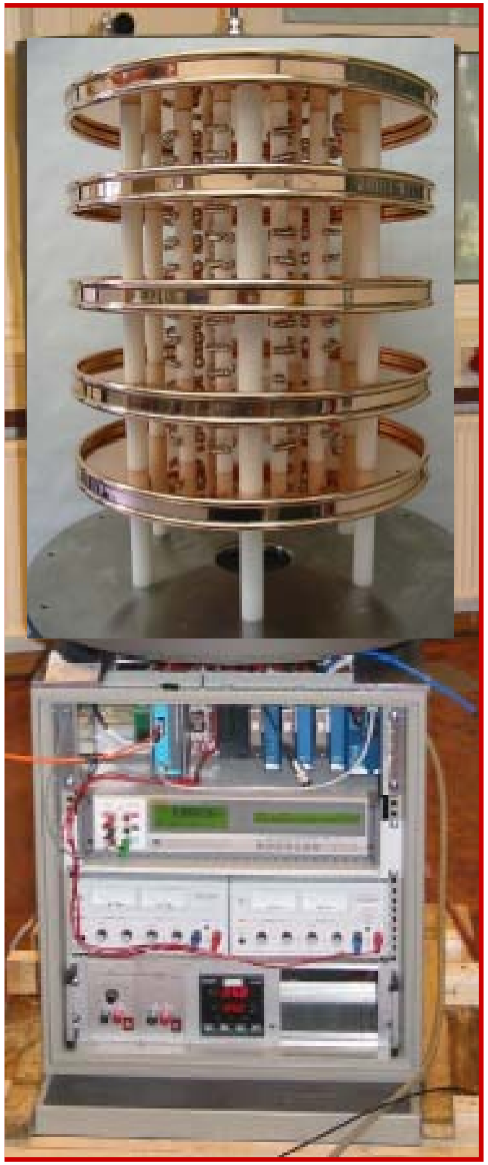
non-equidistant
var. wire spacing
var. $U_2 = U_{sp} + \Delta U_2$
wire sag: sub-mm!

mounting system for electrode system

conceptual design for a UHV compatible mounting system in main spectrometer inner volume

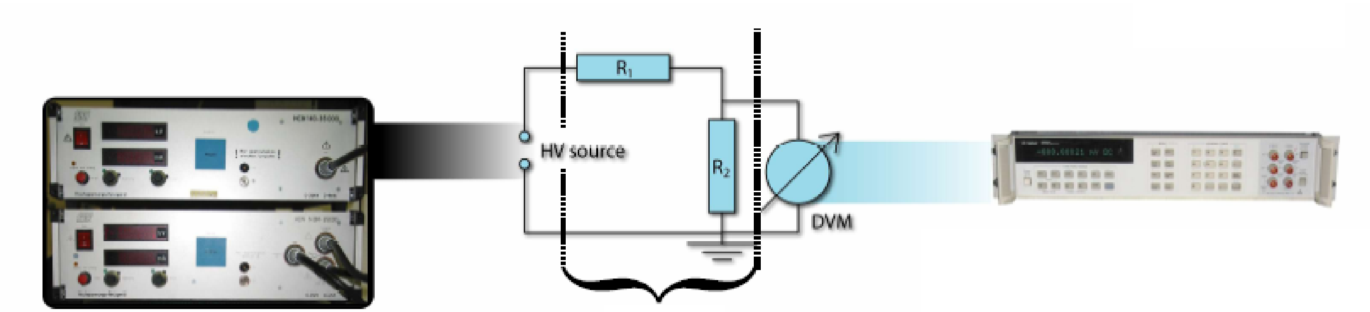


precision HV supply



measurements require HV-stabilisation/monitoring/ calibration on ppm level (wideband: DC up to MHz)

0 - 35 kV | voltage divider 1:1972 | 0 - 10 V



precision-HV power supply

< ± 5 ppm stability

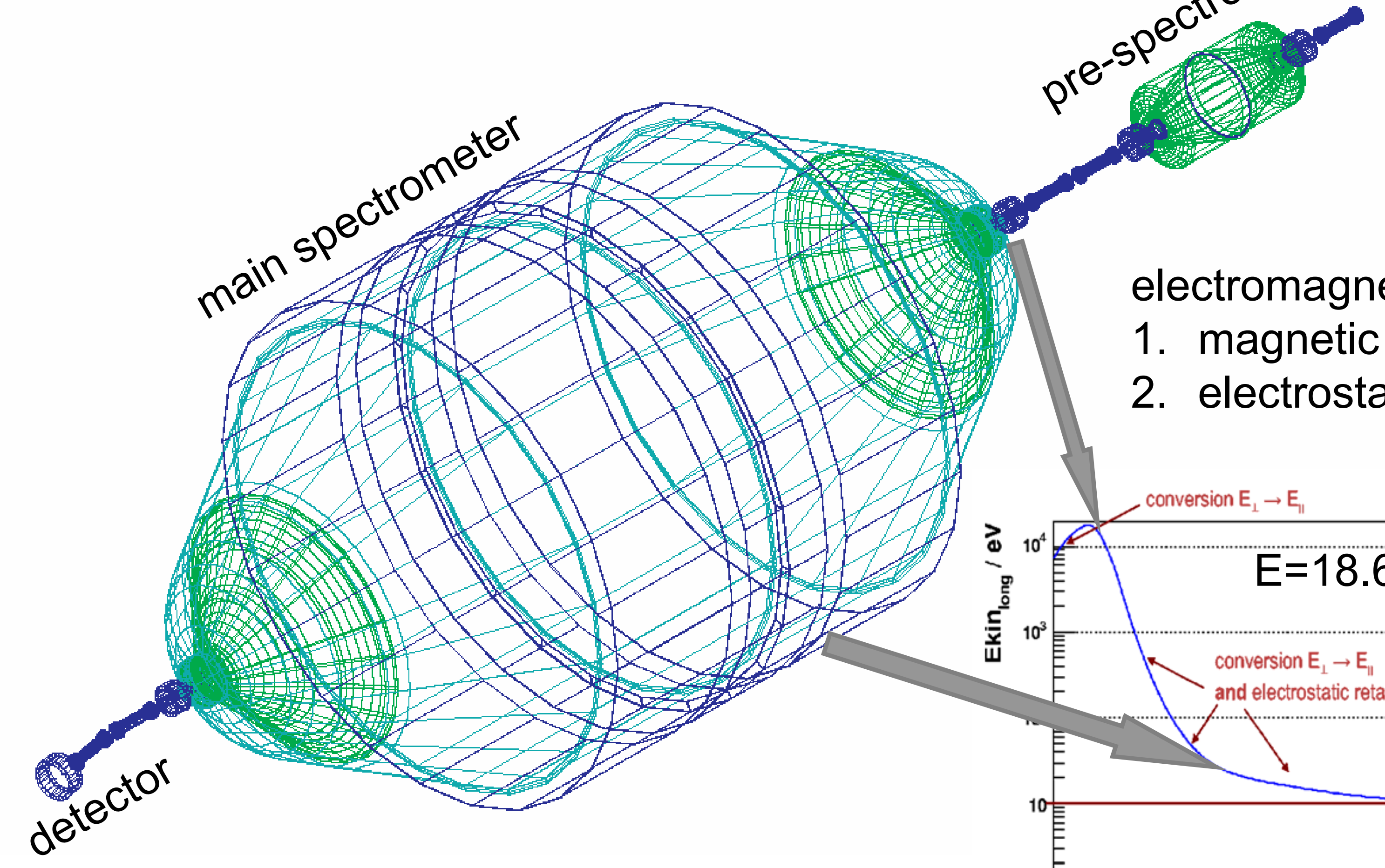
precision-digital-Voltmeter

0.5ppm/h (4ppm/1y)

test at PTB: sub-ppm level reached!!

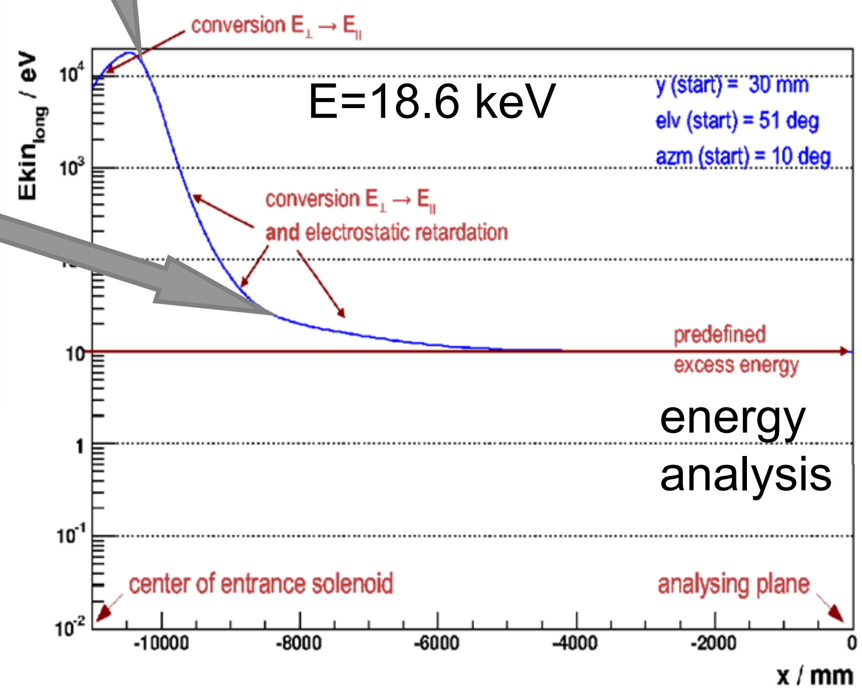
↳ ppm-voltage divider ☑

electromagnetic design



electromagnetic transmission :

1. magnetic conversion
2. electrostatic retardation



transported magnetic flux 191 T cm^2

air coil system

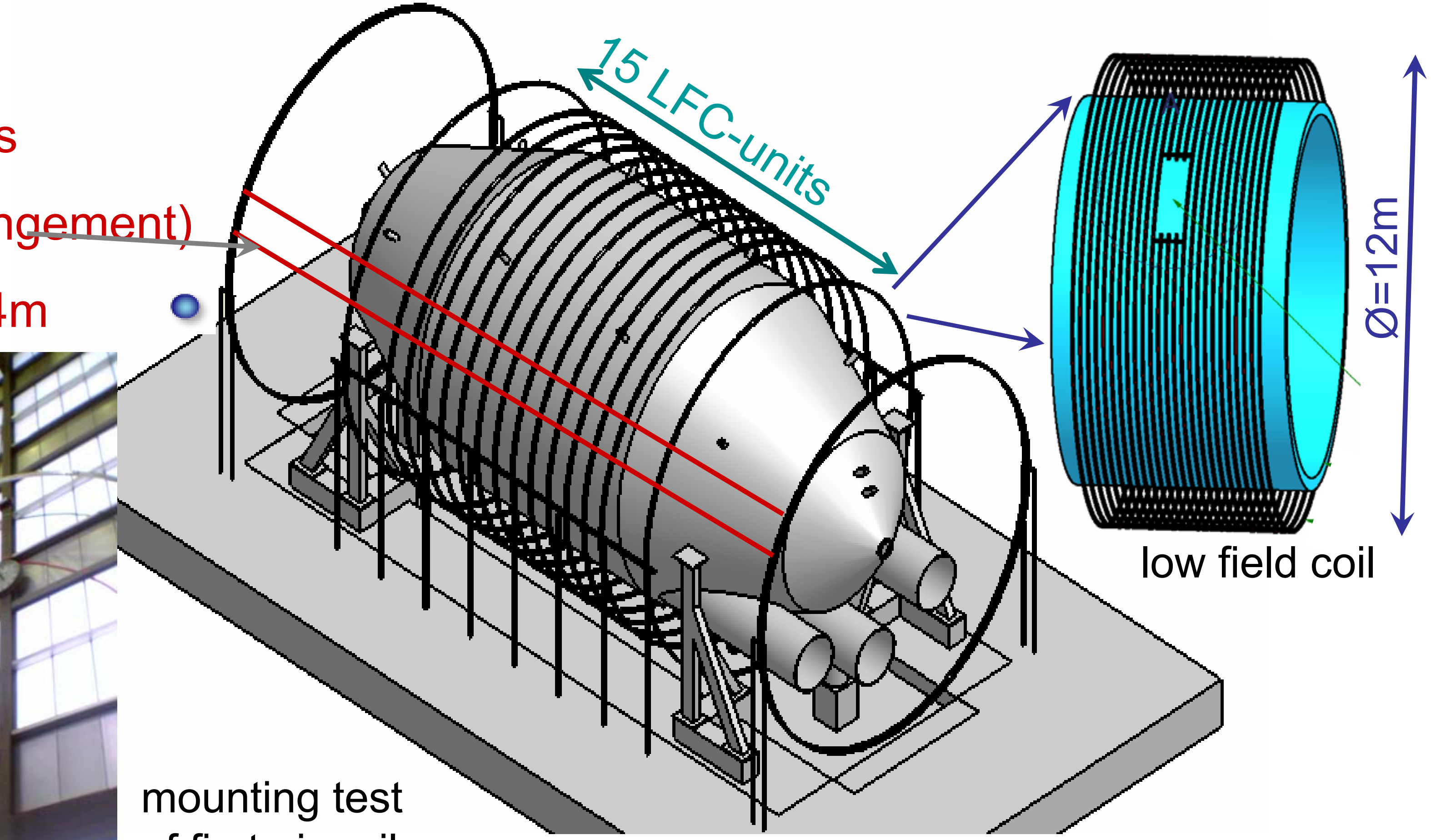
elctromagnetic layout based on additional air coil system:

- compensation earth magnetic field (EMC) *axially*
- homogeneity B-field analysing plane (LFC) radially

EMC units

(cos-arrangement)

length=24m

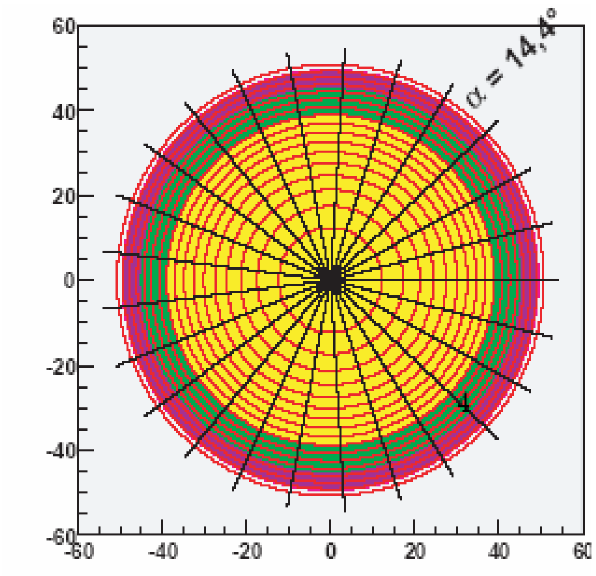


mounting test
of first air coil

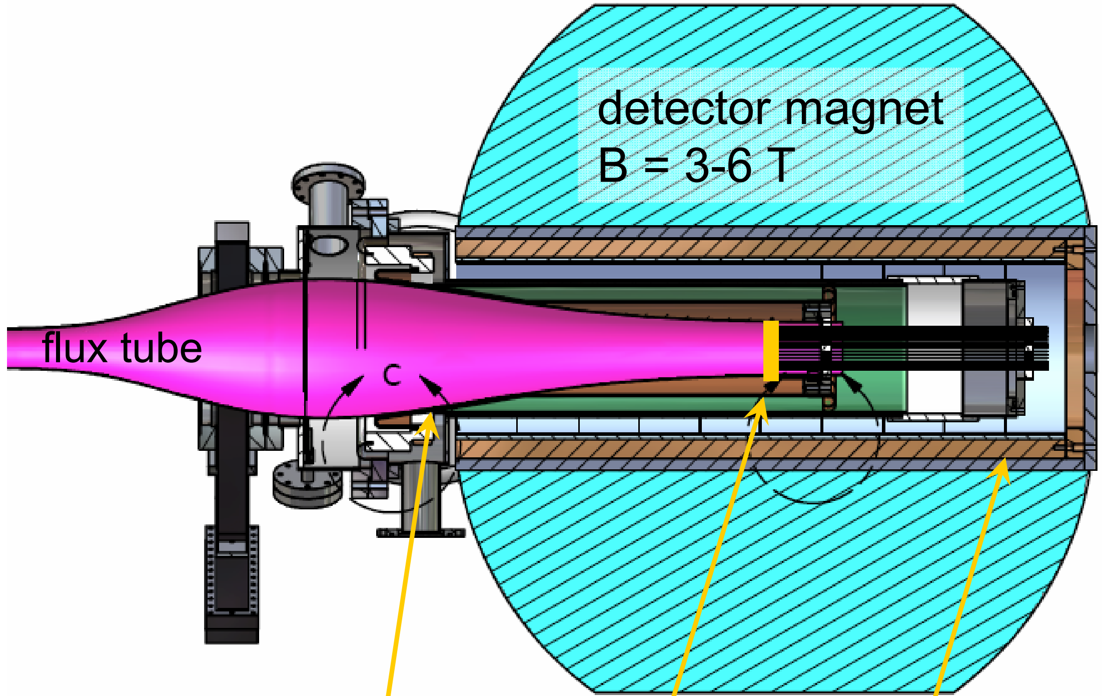
focal plane detector

task: detection of transmitted ß-decay electrons
with high energy resolution (ΔE =1 keV)
record radial profile of flux tube

aim: background minimisation, systematic effects



design: radially segmented
Si-PIN diode array
~400 pixels with A=100 cm²



KATRIN design optimisation

improvement of experimental sensitivity (2001-04)

statistics

- enlargement of WGTS diameter (×2)
- enlargement of main spectrometer dimensions (Ø = 7 m → 10 m, L = 20 m → 23 m) for ΔE=0.93 eV
- improved tritium infrastructure (T_2 purity 70% → 95%)

back-ground

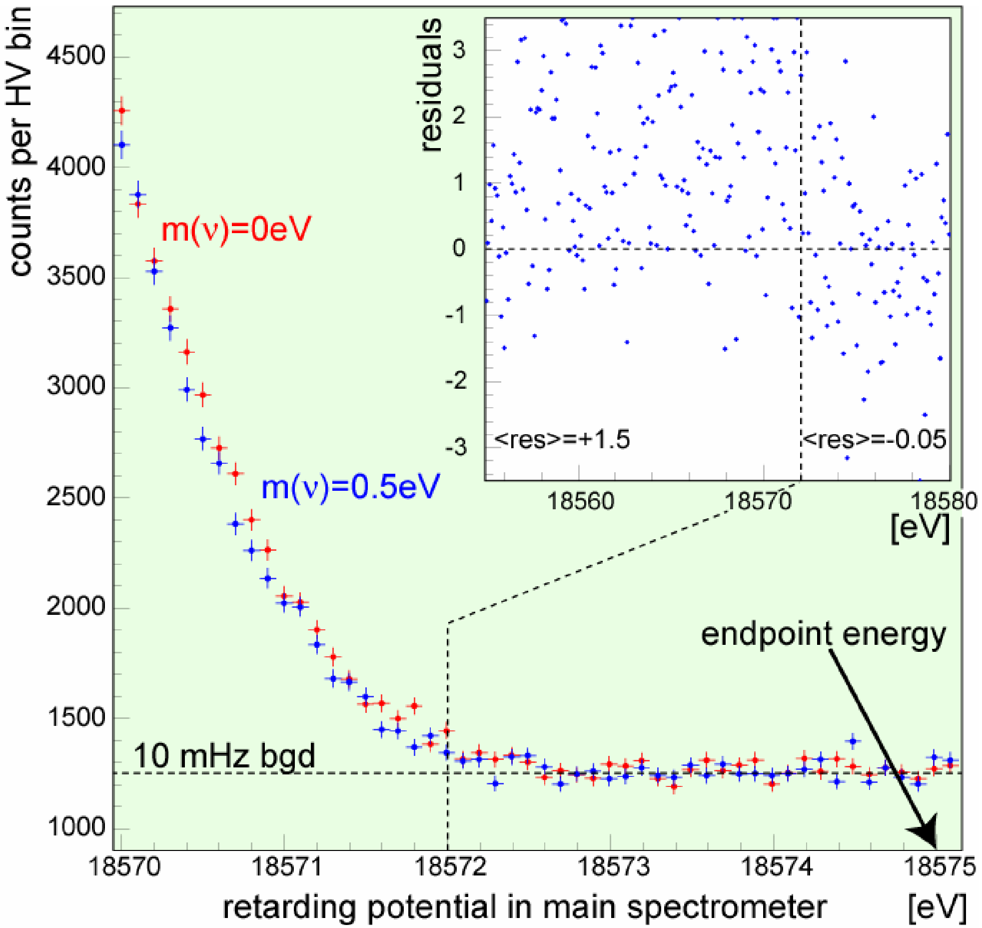
- inner wire electrode system (pre- & main spectrometer)
- active trap clearing (dipole fields, FT-ICR)
- extreme UHV with $p < 10^{-11}$ mbar

system. errors

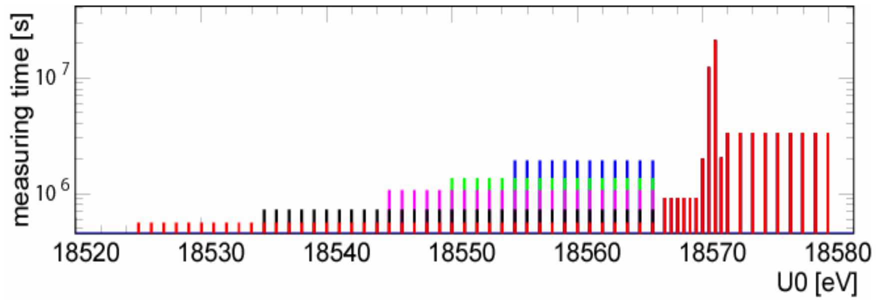
- monitor spectrometer (reference for HV)
- system for measuring inelast. ß-scatterings in WGTS
- stabilisation of WGTS-parameters to 0.1% ($T, p_{inj}, \ldots$)
- optimisation & enlargement of tritium pumping section

simulated spectra at endpoint

MC spectra for 1 full measuring year KATRIN



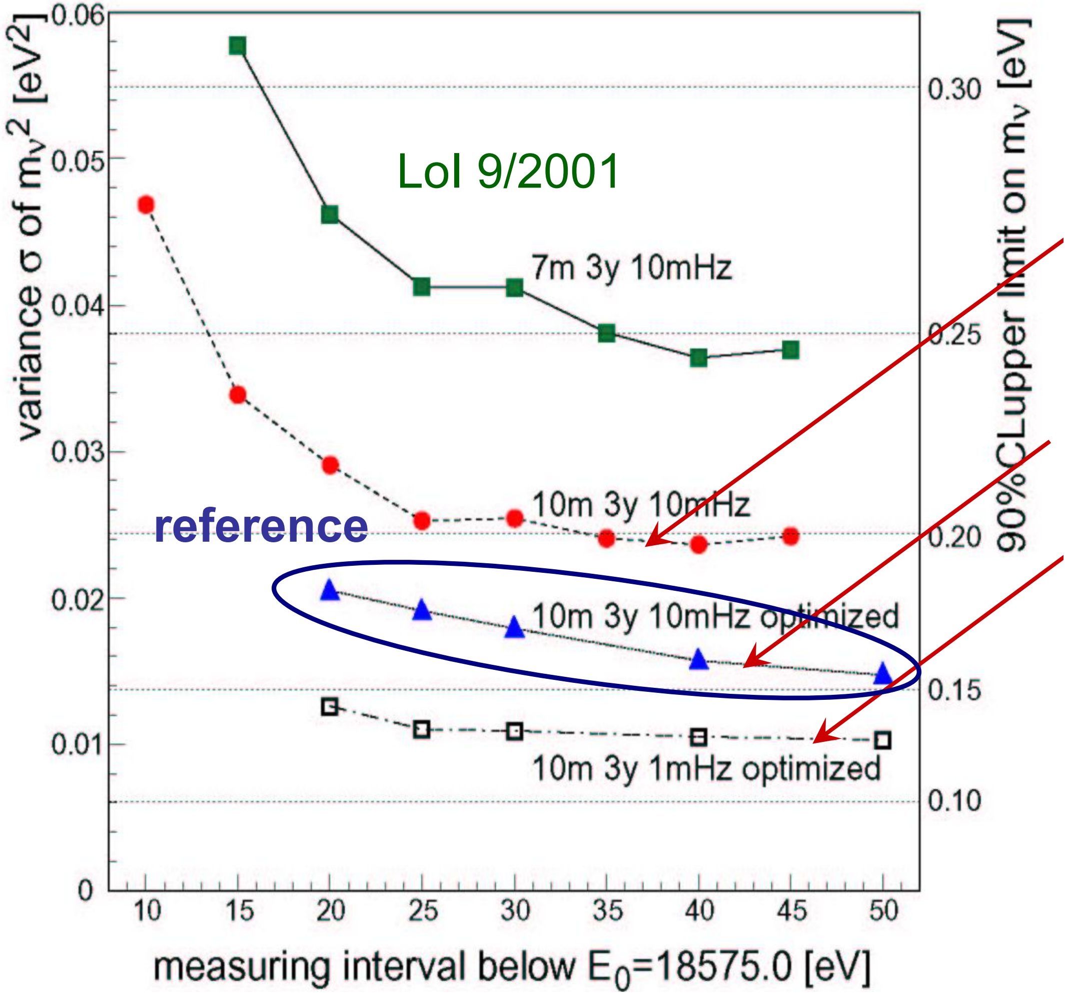
source column density:	$\rho d = 5 * 10^{17}\ cm^{-2}$
magnetic field strengths:	B_S, B_{pinch}, B_A = 3.6, 6, $3*10^{-4}$ T
energy resolution:	$\Delta E/E$ = 1/20000 = 0.93/18600
effective analysing area:	$A_{A,eff} = \pi*(450cm)^2$
imaged source area (deduced):	$A_S = \pi*(4.11cm)^2$
Tritium purity:	$\varepsilon_{Tritium}$ = 0.95
detector efficiency:	$\varepsilon_{Detector}$ = 0.9
β endpoint energy:	E_0 = 18575.0 eV
background rate per U_0:	Γ = 10 mHz (1mHz)



scanning procedure: time per U_0

KATRIN statistical errors

design optimisation 2002-2004: improved sensitivity



- 2× stronger gaseous source (Ø=75mm → Ø=90mm) required Ø=10m spectrometer)
- optimised measuring point distribution (~5 eV below E_0)
- active background reduction by inner electrode system, low background detector (needs further detailed tests)

background – sources & suppression

total background rate at Mainz/Troitsk: ~10 mHz, aim for same rate at KATRIN

- detector: aim for bg-rate in few mHz range, environmental γ's / X-rays & cosmics, , larger area: better energy resolution & better shielding, thinner detector, material selection
  develop background model on GEANT4.4 simulations

- spectrometer: aim for bg-rate in few mHz range

T_2

a) low energy shake off electrons from tritium ß-decays
   1mHz bg-rate from ~10^{-20} mbar tritium partial pressure (cryotrapping section)

b) ß-decay electrons in keV-range that get trapped (-> ionising collisions)
   stringent XHV conditions <10^{-11} mbar & active removal of trapped particles

CR

c) cosmic ray induced δ-electrons (muons, elmag. showers, hadronic component)
   can create ions, -> tertiary reactions: electrons & H^- ions,
   stringent XHV conditions <10^{-11} mbar & active removal of trapped particles

ß's

d) trapped ß-electrons (from 'normal' tritium decays in WGTS)
   stringent XHV conditions <10^{-11} mbar & active removal of trapped particles

- sources:
  a) ß-electrons from tritium decays in areas with different source potential
  b) ß-electrons from T^- ions (higher end-point)   careful electromag. design

Systematic uncertainties

$$\Delta m_\nu^2 = -2\,\sigma_{syst}^2$$

general relation for KATRIN statistics

1. inelastic scatterings of ß´s inside WGTS (major uncertainty in KATRIN)

   - requires dedicated e-gun measurements, unfolding techniques for response fct.

2. HV stability of retarding potential on ~1ppm level required

   - precision HV divider (PTB), monitor spectrometer beamline

3. fluctuations of WGTS column density (required < 0.1%)

   - e-gun measurements, rear detector, rear plate,
     Laser-Raman spectroscopy, stabilisation of T=27K beam tube, injection pressure

4. WGTS charging due to remaining ions (MC: ϕ<20mV)

   - inject low energy meV electrons from rear side, diagnostic tools available

5. final state distribution

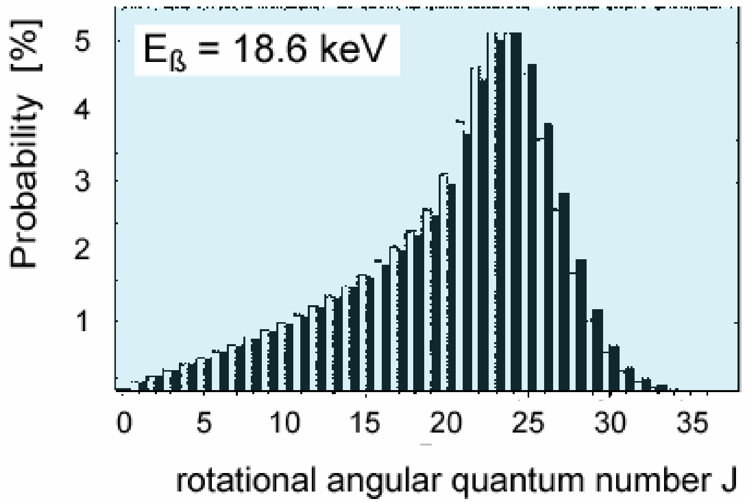
   - very reliable quantum-chem. calculations exist, new calc. by J Tennyson (UCL)

molecular excitations

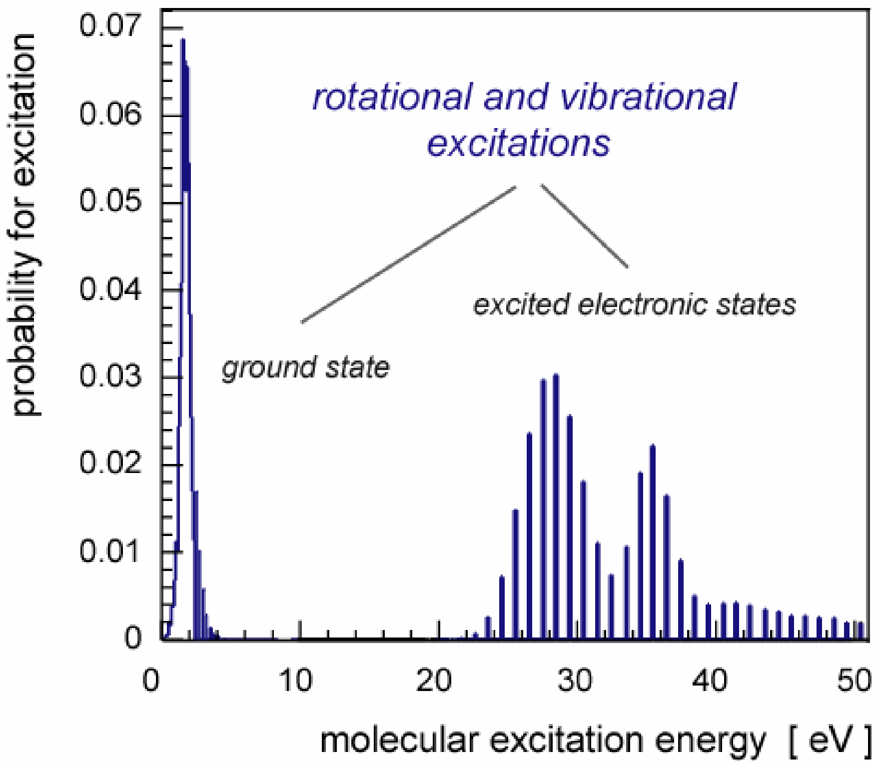
ß-decay of molecular T_2 : recoil energy, electronic & rotational-vibrational excitations

E_R = 1.72 eV @18.6 keV

final state probability	*electronic final state*
14 %	continuum
29 %	excited states
57 %	ground state



improved calculations of molecular final states



absolute accuracy of theory = 0.2 %

integration of spectrum yields 99.93% of total population probability

A. Saenz, S. Jonsell, P. Froelich, Phys. Rev. Lett. 84 (2000) 242

calibration & long-term monitoring

- absolute calibration of energy

K-32 conversion e⁻ line of gaseous ^{83m}Kr

$E = [\,(17\,824.35 \pm 0.75) - (\phi_{spec} - \phi_{spec})\,]$ eV

difference in work functions

based on

E_γ (gamma energy) = (32 151.55 ± 0.75) eV

E_b (bind. energy of K-elec.) = (14 327.09 ± 0.39) eV

& atomic recoil energy corrections

precision for E can be further improved !

$\phi_{spec} - \phi_{spec}$ measurement

- long-term monitoring of retarding energy

use separate monitor source & separate monitor spectrometer

QCMS : *quench condensed* monitor source of ^{83m}Kr

either ^{83}Rb / ^{83}Kr source or repeated condensation of ^{83}Kr

monitor spectrometer :

transfer Mainz spectrometer to KATRIN experimental hall fed by *same HV as spectrometer*

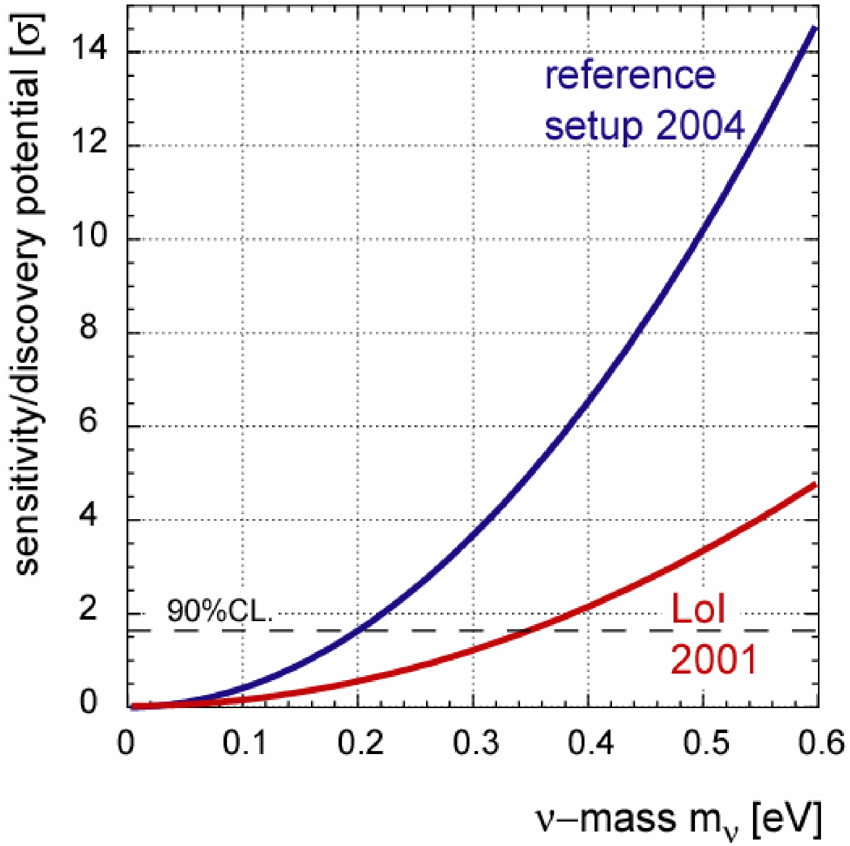
need to accelerate electrons from ^{83m}Kr (~800 V, high prec.)

KATRIN sensitivity

sensitivity optimisation: LoI (2001) → reference design (2004)

- improved statistics: source luminosity, scanning
- reduced systematics: ß-energy losses in source

→ improved sensitivity



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

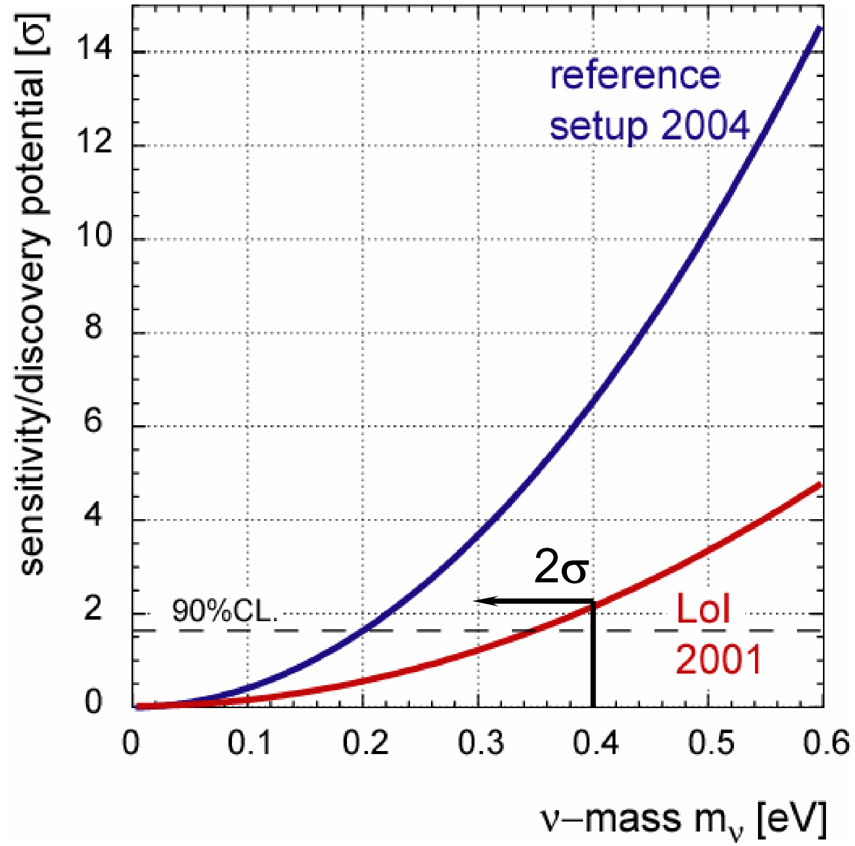
discovery potential
$m(\nu) = 0.35$ eV (5σ)

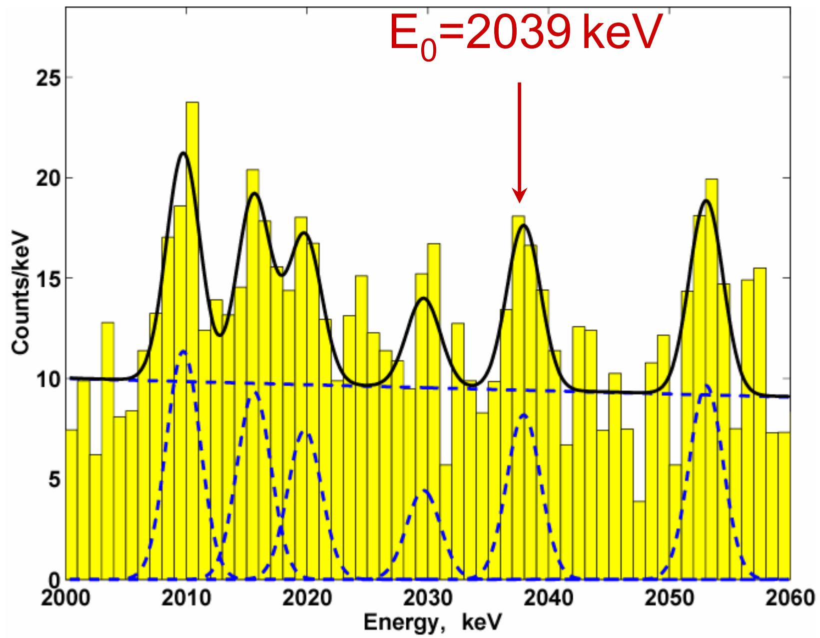
KATRIN sensitivity

sensitivity optimisation: LoI (2001) → reference design (2004)

- improved statistics: source luminosity, scanning
- reduced systematics: ß-energy losses in source

→ improved sensitivity & ßß0ν





claim for m_{ee}=0.44 eV (4.2σ) [0.1-0.9eV]

HV Klapdor et al. Phys.Lett. B586 (2004) 198

KATRIN sensitivity

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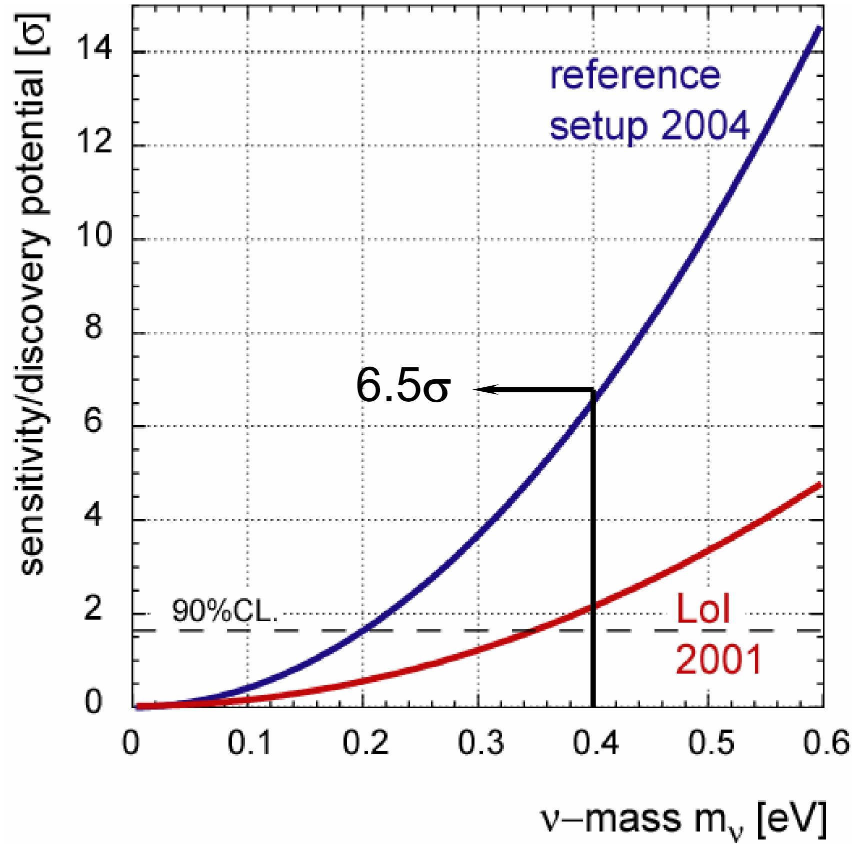

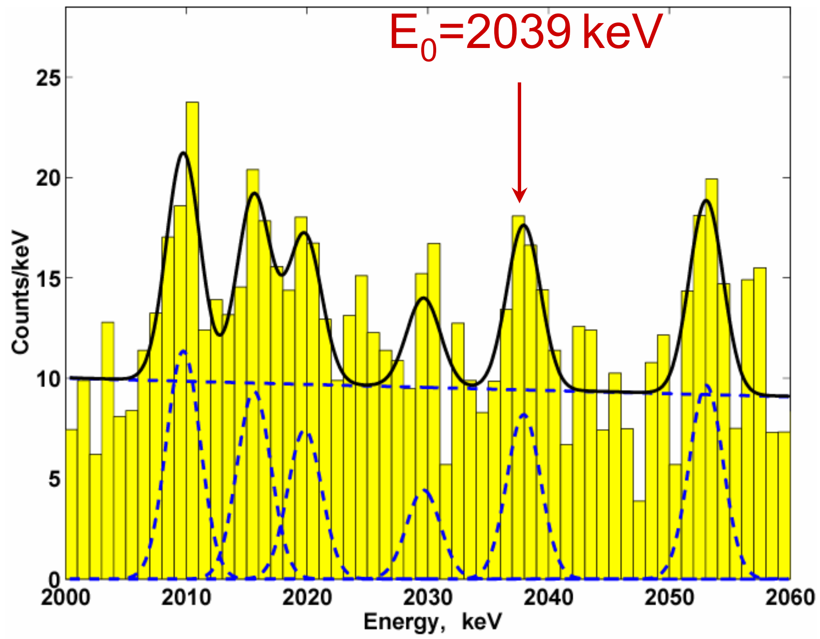

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HV Klapdor et al. Phys.Lett. B586 (2004) 198

KATRIN Collaboration

at present > 105 members
D-USA-UK-RU-CZ-BR
18 institutes

new in 2005: MIT, UCL

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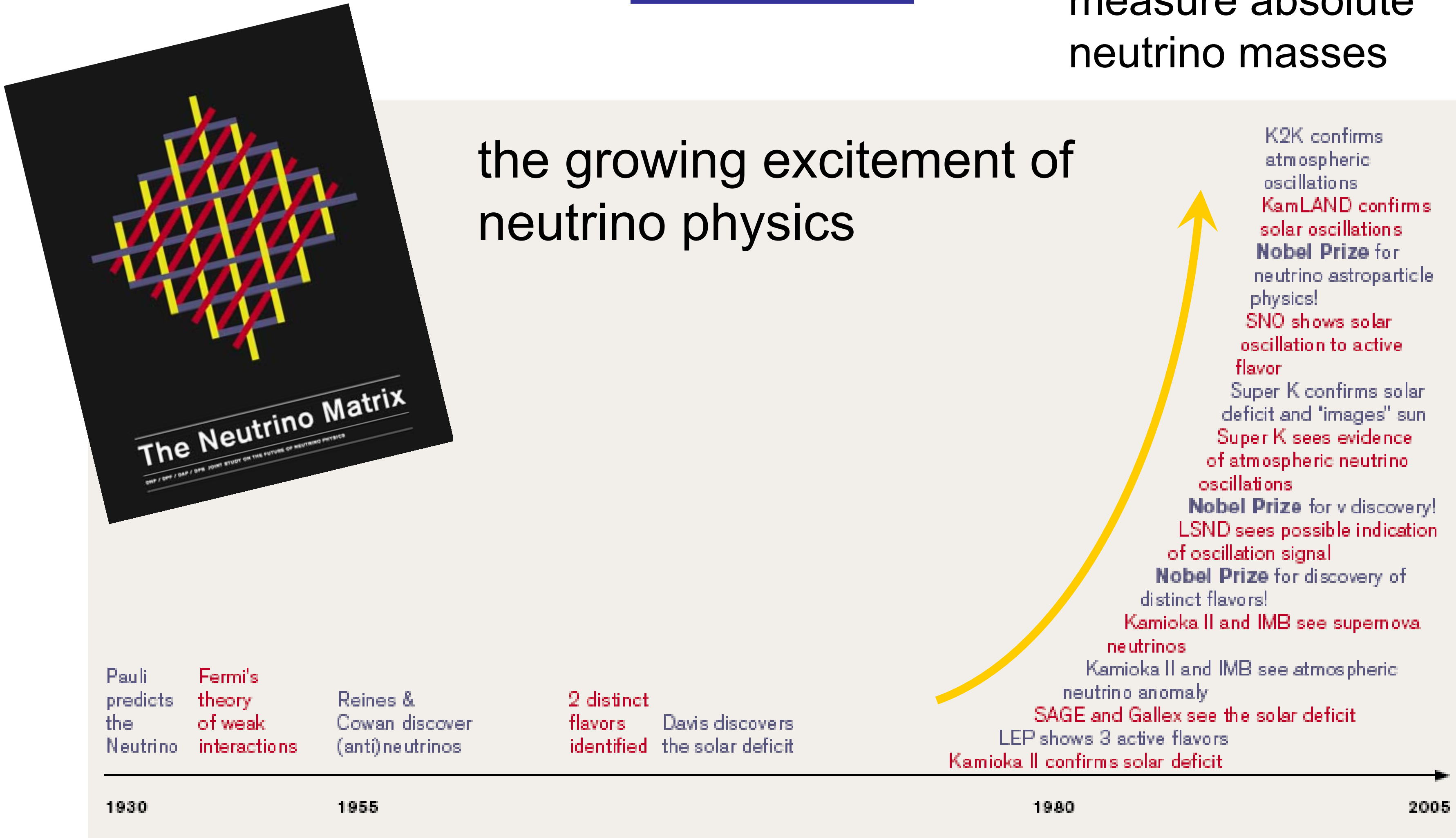
KATRIN time line

2001	first presentation, founding of KATRIN collaboration,
	LoI: *hep-ex/0109033* BMBF funding ‚Astroteilchenphysik‘
since 2002	background studies, R&D works, design optimisation
2003	pre-spectrometer manufacture, order for first large magnet group
2004	evaluation by HGF programme, Design Report 2004,
	orders for main spectrometer, WGTS & He-liquefier,…
2005	vacuum tests pre-spectrometer
2006	electromagn. tests pre-spectrometer, main spectrometer on site
2007	source demonstrator, inner electrode mounting
2008	commissioning of WGTS, tritium loops, em. test of spectrometers
2009	system integration & first tritium runs
	regular data taking for 5-6 years (3fb years)

Summary

measure absolute
neutrino masses



KATRIN only model-independent approach with sub-eV sensitivity