Status and perspectives of the direct neutrino mass measurements

Lutz Bornschein
KIT – Forschungszentrum Karlsruhe/IK

bmb+f - Förderschwerpunkt
Astro-Teilchenphysik
Großgeräte der physikalischen Grundlagenforschung

Status and perspectives of the direct neutrino mass measurements

Outline:

- motivation: m(ν) in astroparticle physics
- status of direct m(ν) measurements
- the KATRIN experiment
  goal, set-up and status
- e.g. the test experiment pre-spectrometer
- conclusion and outlook

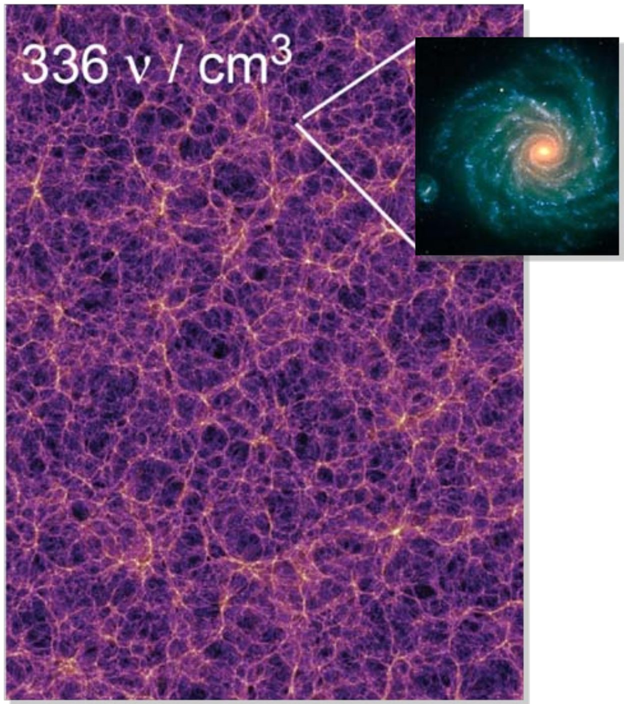
bmb+f - Förderschwerpunkt
Astro-Teilchenphysik
Großgeräte der physikalischen Grundlagenforschung

Neutrinos in astroparticle physics

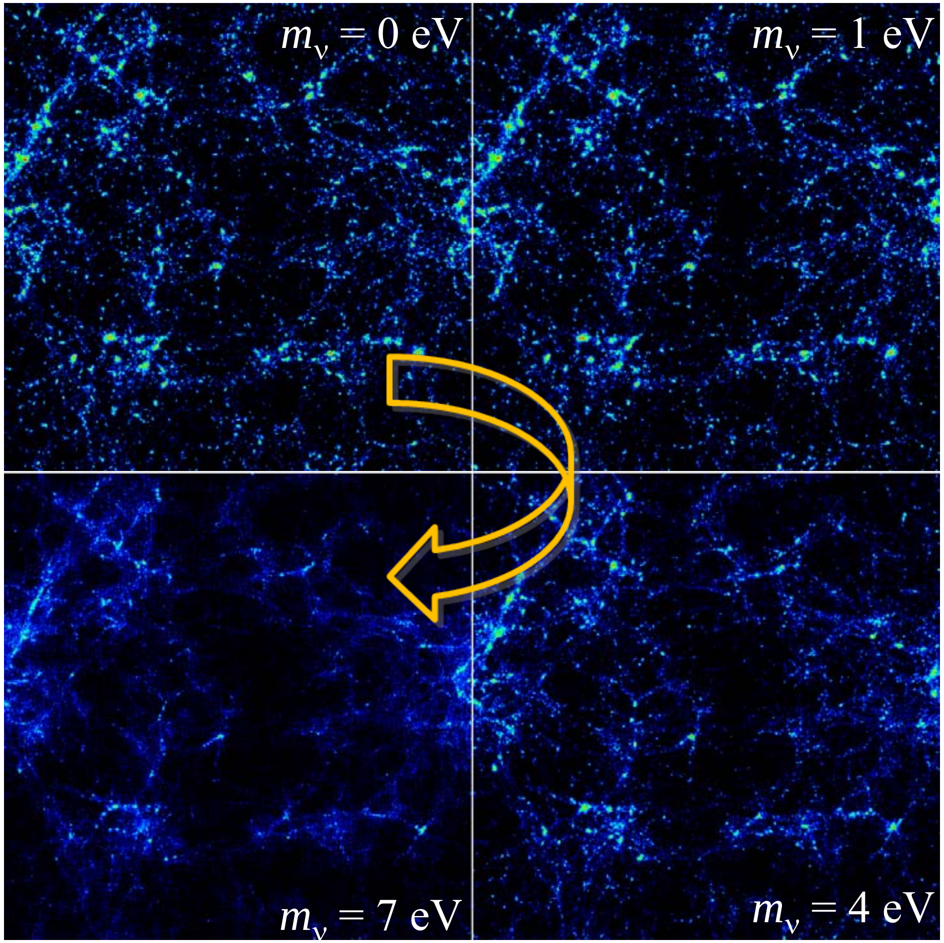
cosmic architects: role of relic ν´s as hot dark matter?

large scale structures: free streaming of ν´s on Gpc scales

cosmology



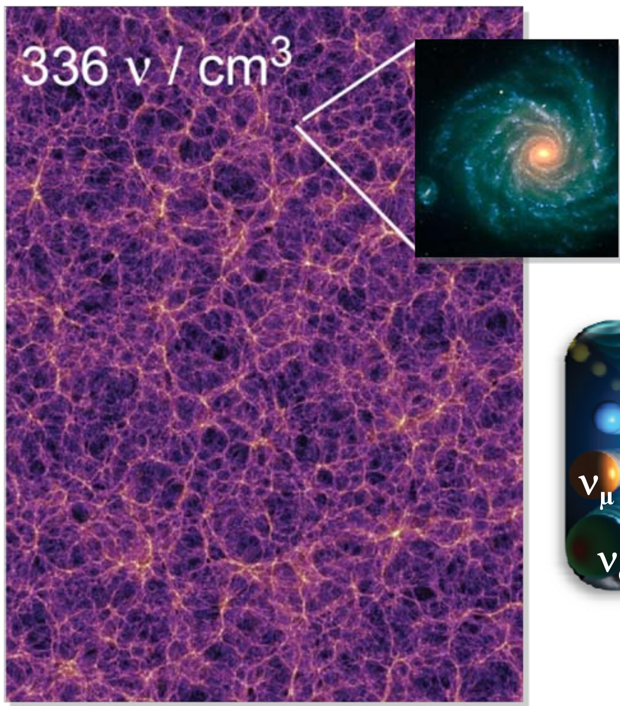
structure of the universe
(Millenium Simulation)



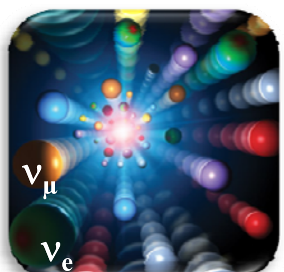
Neutrinos in astroparticle physics

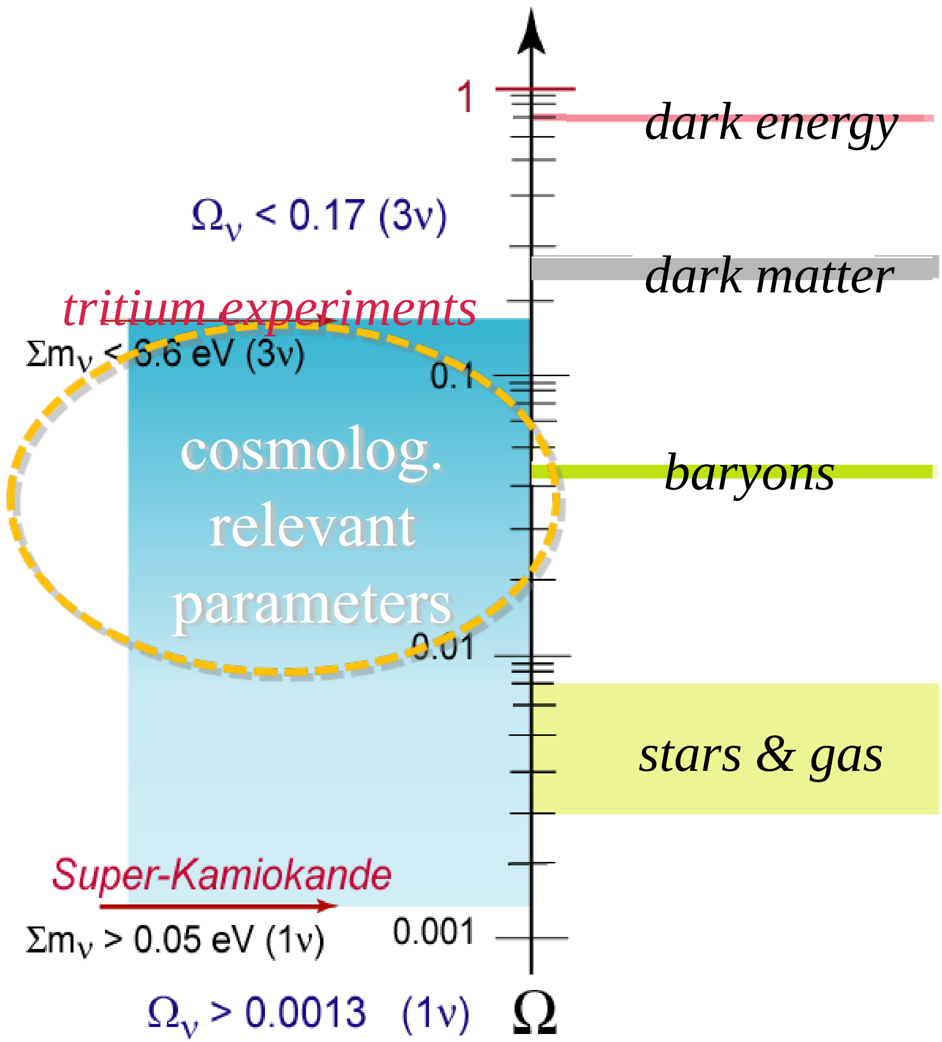
cosmic architects: role of relic ν´s as hot dark matter?

$$\Omega_\nu h^2 = \Sigma m_\nu / 92 \text{ eV}$$



structure of the universe
(Millenium Simulation)



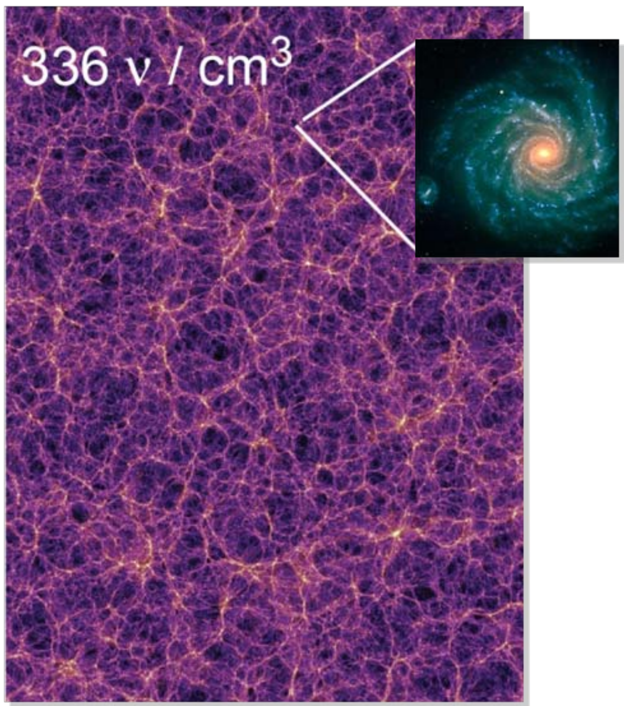


Neutrinos in astroparticle physics

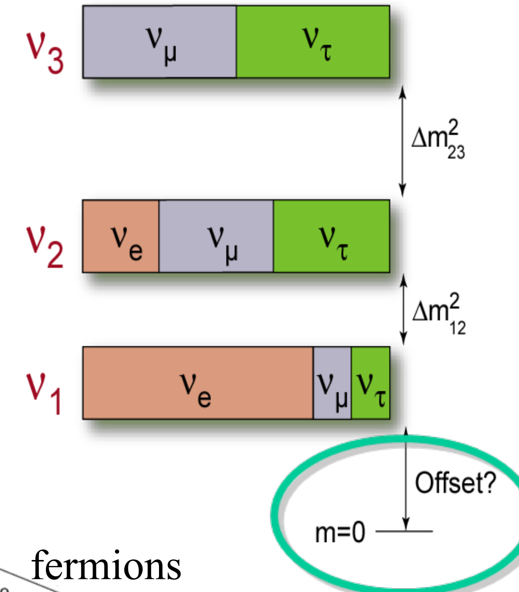
cosmic architects: role of ν´s as hot dark matter?

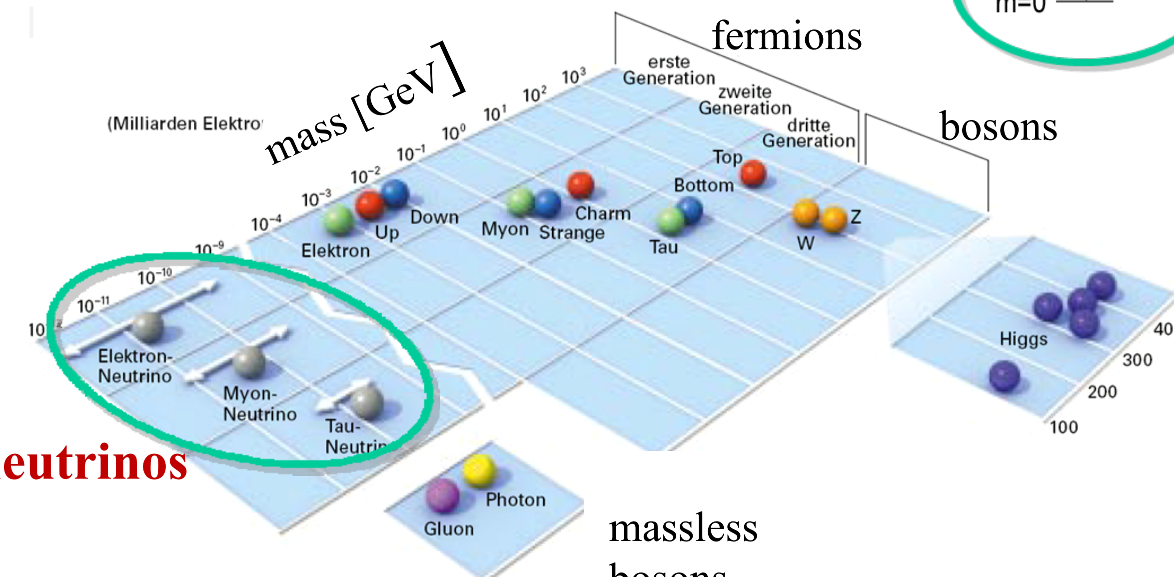
microscopic keys: origin of the ν-mass?

cosmology ⇔ **particle physics**



structure of the universe
(Millenium Simulation)





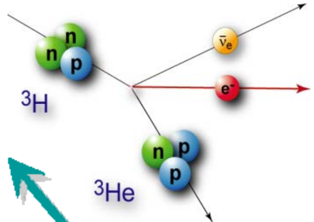
neutrinos

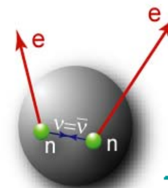
massless bosons

Neutrino mass: status and perspectives

Karlsruhe Institute of Technology

kinematics of ß-decay
absolute ν_e-mass: m_ν





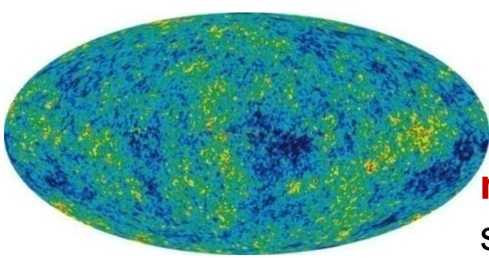
search for 0νßß
eff. Majorana mass $m_{ßß}$

model-independent
status: m_ν < 2.3 eV
potential: m_ν = 200 meV
KATRIN (MARE-II)

model-dependent (CP-phases)
status: $m_{ßß}$ < 0.35 eV, evidence?
potential: $m_{ßß}$ = 20-50 meV
GERDA, EXO, CUORE

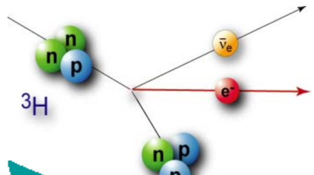
neutrino masses
experimental techniques:
status & potential

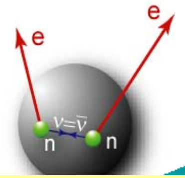
cosmology
sum Σm_i, HDM Ω_ν



model-dependent (multi-parameter fits)
status: Σm_i < 1 eV [Hannestad et al., arXiv:0803.1585v2]
potential: Σm_i = 20-50 meV
Planck, LSST, weak lensing

kinematics of ß-decay
absolute ν_e-mass: m_ν





search for 0νßß
eff. Majorana mass $m_{ßß}$

direct mass measurements:

single β decay
- no further assumptions needed
- use $E^2 = p^2c^2 + m^2c^4 \Rightarrow$
  $m^2(\nu)$ is observable
- Sensitive to incoherent sum

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

0νββ decay:

Very sensitive, but
- needs Majorana type ν's
- helicity flip: $m(\nu) \neq 0$,
  or other type of new physics
- sensitive to coherent sum:

$$m_{\beta\beta}(\nu) = |\Sigma\, |U_{ei}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$$

$\Rightarrow$ partial cancelation possible
- uncertainty of nuclear matrix elements

Evidence for $m_{\beta\beta}(\nu) \approx 0.4$ eV ?

Planck, LSST, weak lensing

ß-decay: Fermi´s theory & ν-mass

a model-independent measurement of $m(\nu_e)$
based on kinematics & energy conservation

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$

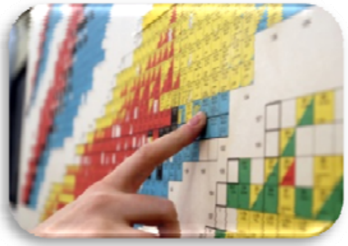
incoherent sum

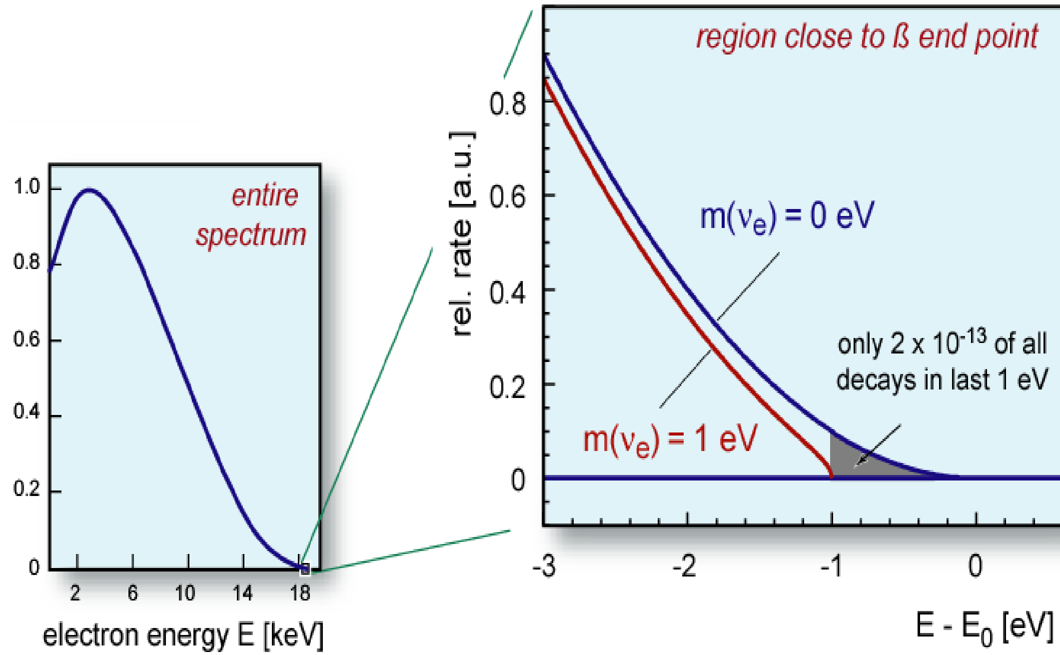
$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

which isotope?

(ν– mass)^2

Fermi´s theory





ß-decay: Fermi´s theory & ν-mass

Source requirements:

- low endpoint energy, high β decay rate, …

⇒ ^{187}Re: E_0 = 2.47 keV ; $T_{1/2}$ = 43.2 Gy ; unique 1st forbidden

⇒ ^{3}H: E_0 = 18.57 keV ; $T_{1/2}$ = 12.3 y ; superallowed

Detection requirements:

- very high energy resolution &
- very high luminosity &
- very low background

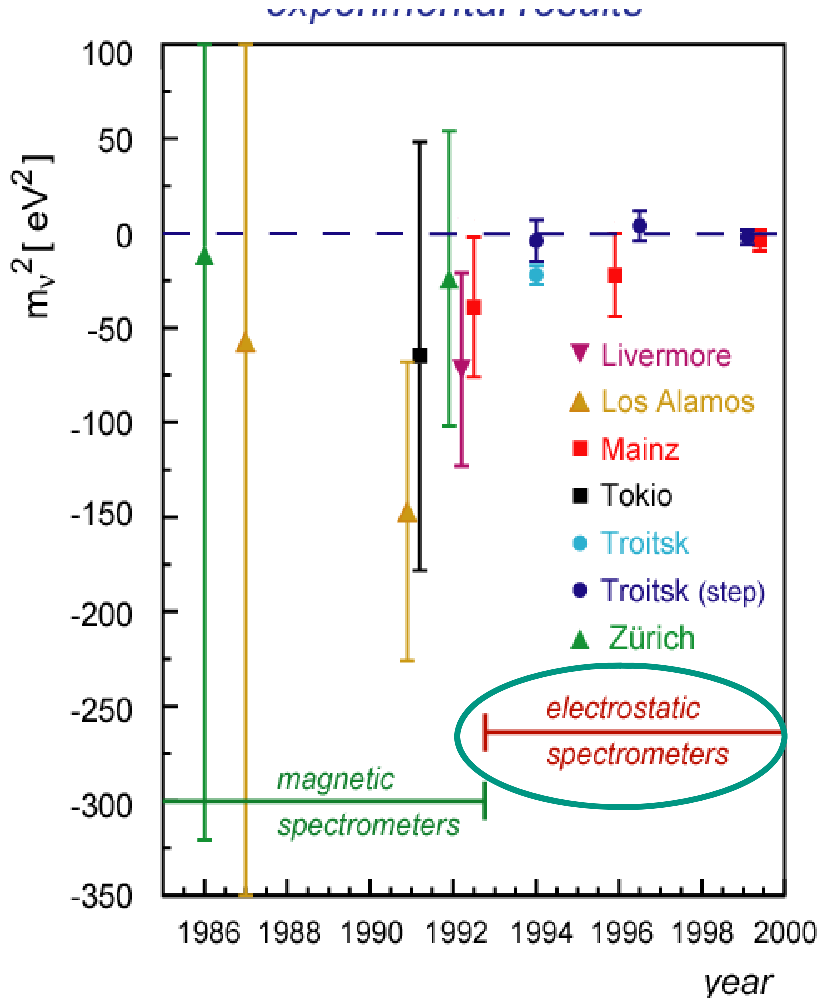
⇒ MAC-E-Filter or bolometer for ^{187}Re

Details about Re-experiments see next talk
M. Galeazzi : „Status and perspectives of MARE“

history of tritium ß-decay experiments

	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*	< 2.3 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV

experimental results for m_ν^2



MAC-E filter – principle

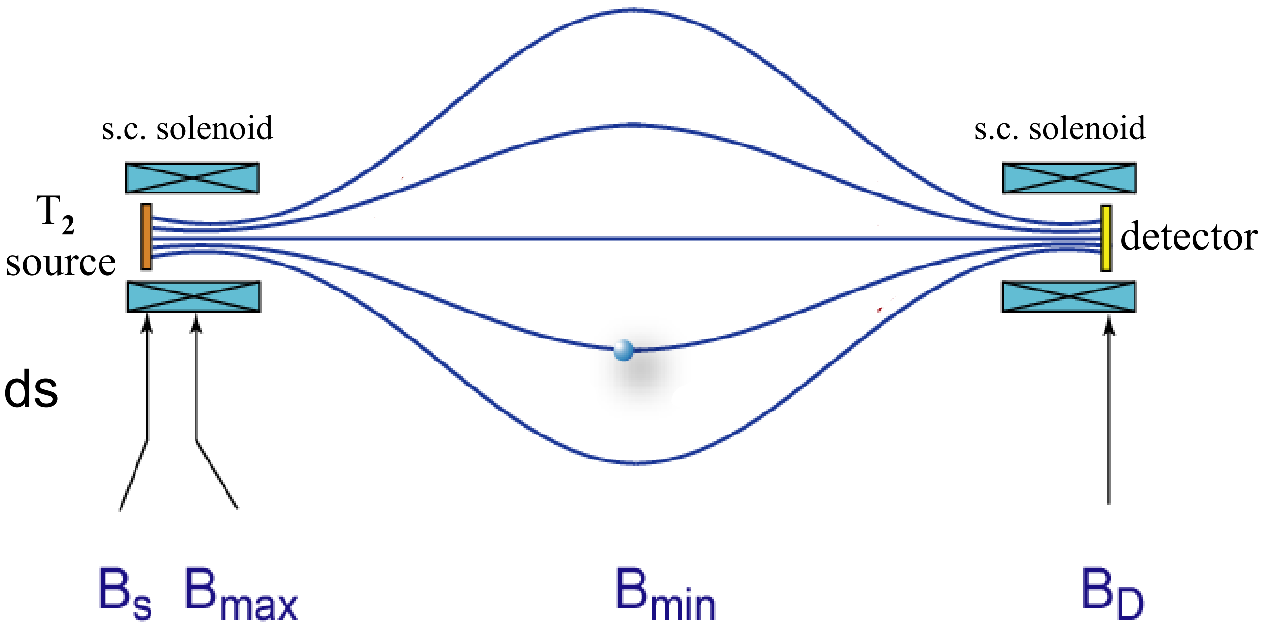
MAC – Magnetic Adiabatic Guiding

adiabatic guiding
of electrons along
magnetic field lines

inhomogenous B-field:
superconducting solenoids
B_{max} = 3 – 6 T
B_{min} < 1 mT
solid angle $d\Omega \sim 2\pi$

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

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



adiabatic transformation $E_{\perp} \rightarrow E_{||}$

MAC-E filter – principle

E Filter – Electro-static filter

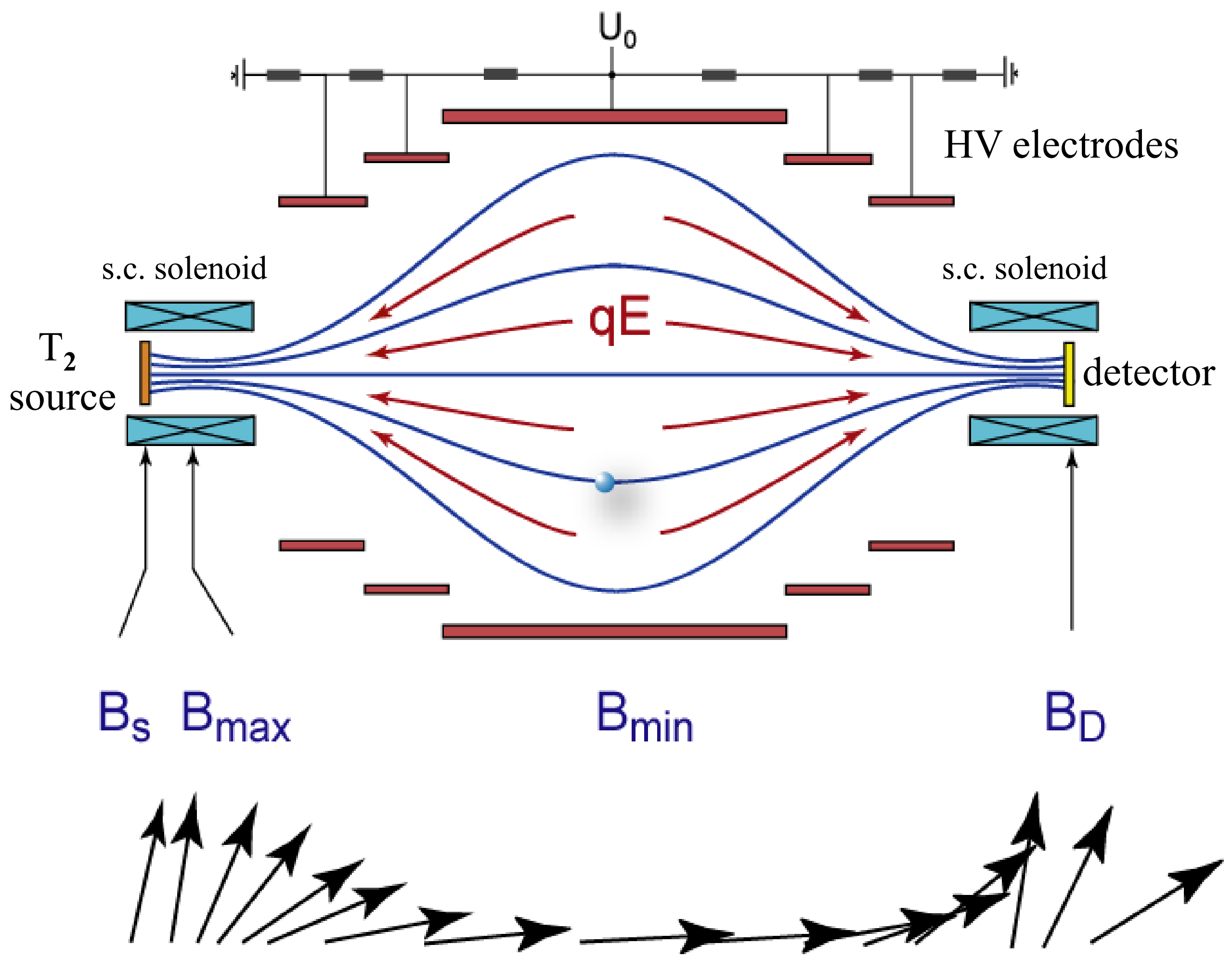
energy analysis by an electrostatic retarding field

variable E-field:
inner electrodes
U_0 = 18.5 – 18.7 kV

integral transmission
for E > U_0
high pass filter

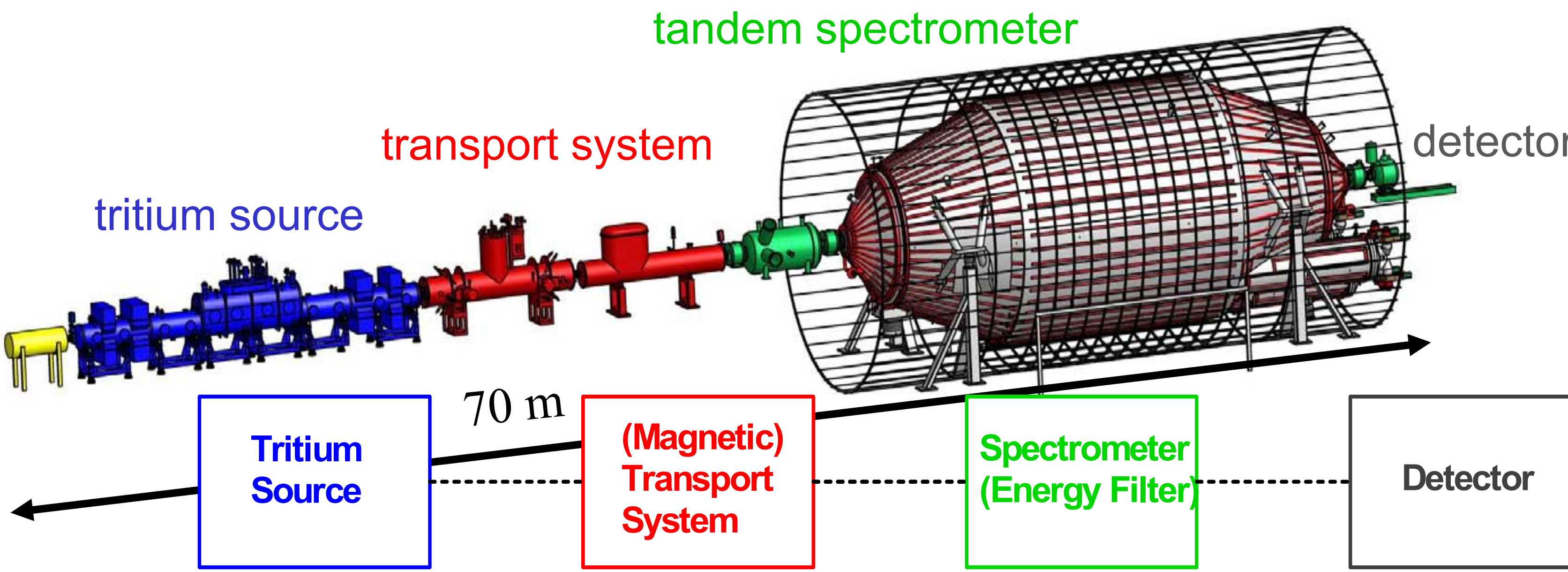
E Feld || B-Feld

conversion → retarding



adiabatic transformation $E_\perp \rightarrow E_{||}$

KATRIN – set up



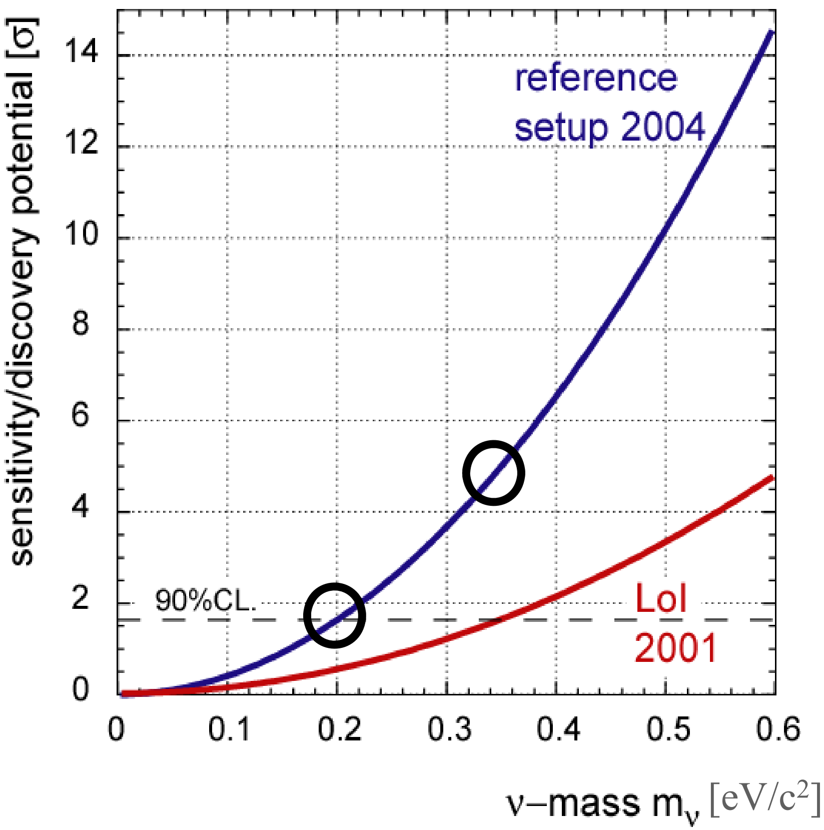
Tritium Source
1) Very high source strength
2) Very good understanding of systematic effects

(Magnetic) Transport System
1) No disturbance of kinetic energy of beta decay electrons (adiabatic transport)
2) No loss of electrons
3) Elimination of residual tritium molecules

Spectrometer (Energy Filter)
1) Very high energy resolution
2) Very low background

Detector
1) Very low background
2) Segmented

Goals of KATRIN



after 3 „full beam“ years data taking:

discovery potential
$m(\nu) = 0.35\ eV/c^2\ (5\sigma)$

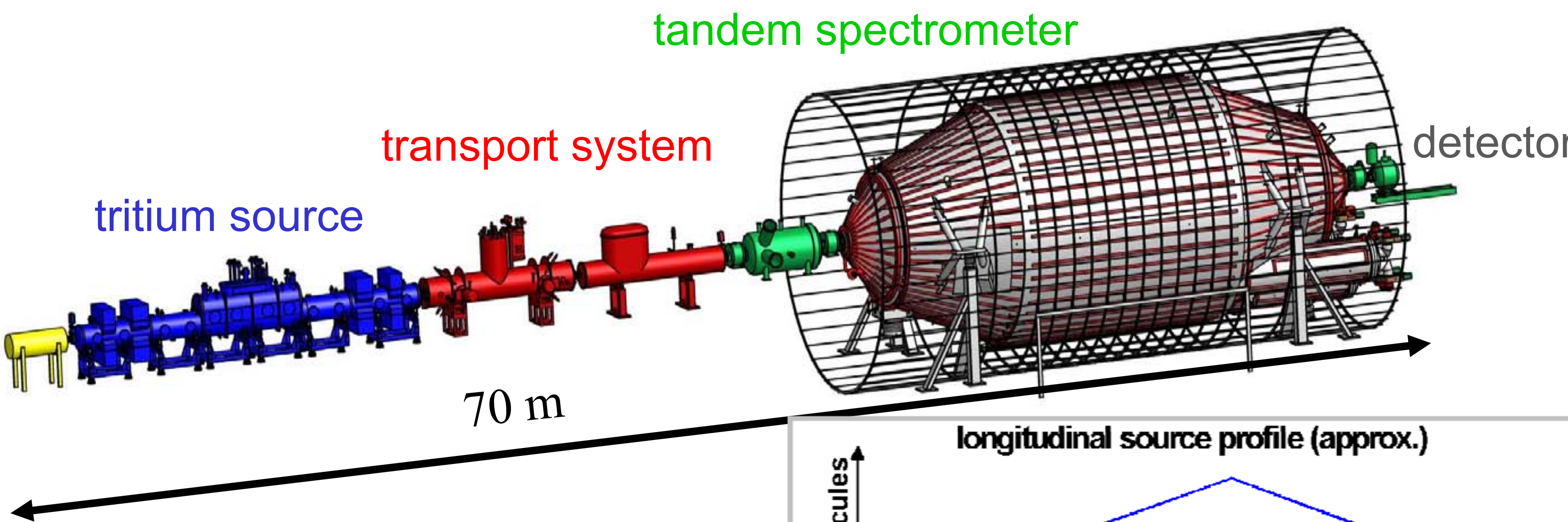
sensitivity (90% CL)
$m(\nu) < 0.2\ eV/c^2$

with $\sigma_{tot}{}^2 = \sigma_{stat}{}^2 + \sigma_{systot}{}^2 \approx 0.025\ eV^2/c^4$
and $\sigma_{stat} = \sigma_{systot}$

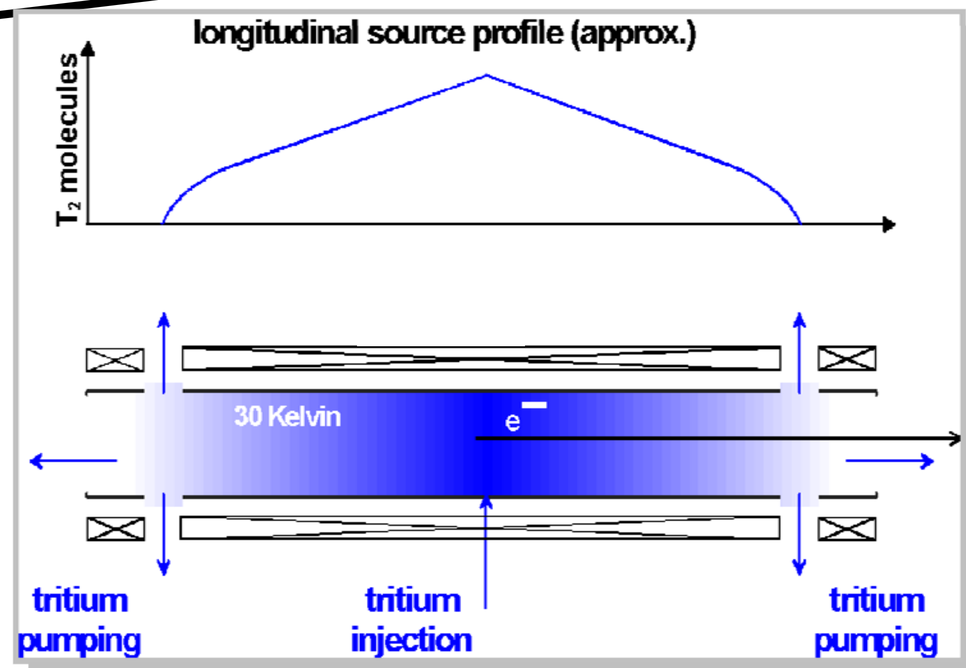
requires better sensitivity on $m_\nu{}^2$ by a factor of 100

⇒ precise knowledge of systematic effects necessary

The tritium source

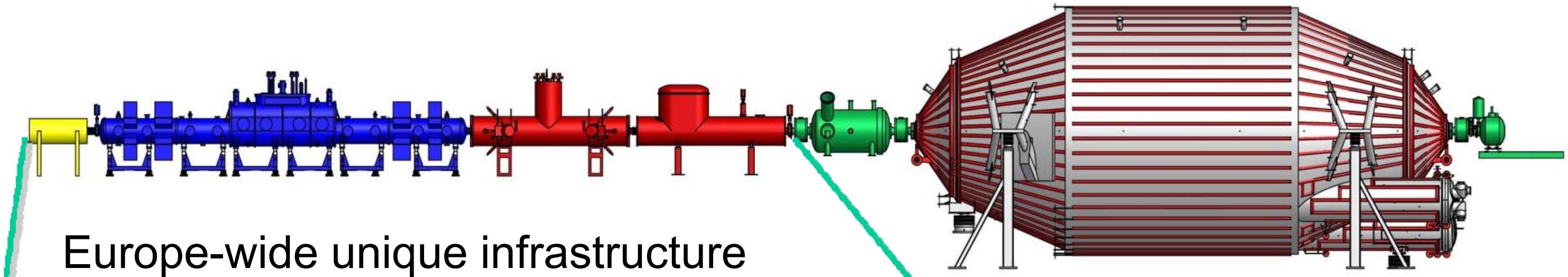


priciple of a
“Windowless Gaseous
Tritium Source” (WGTS)

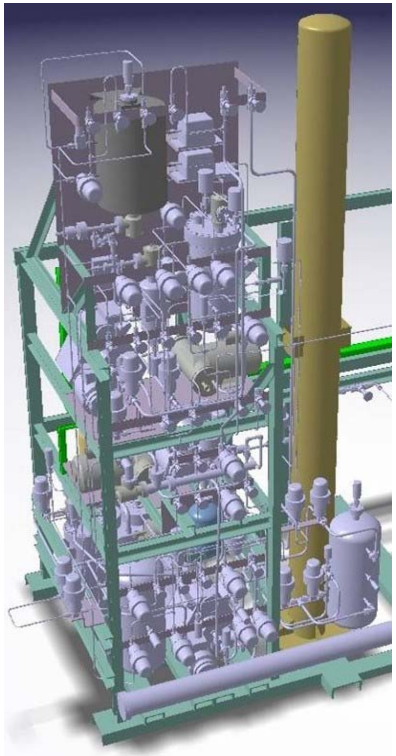


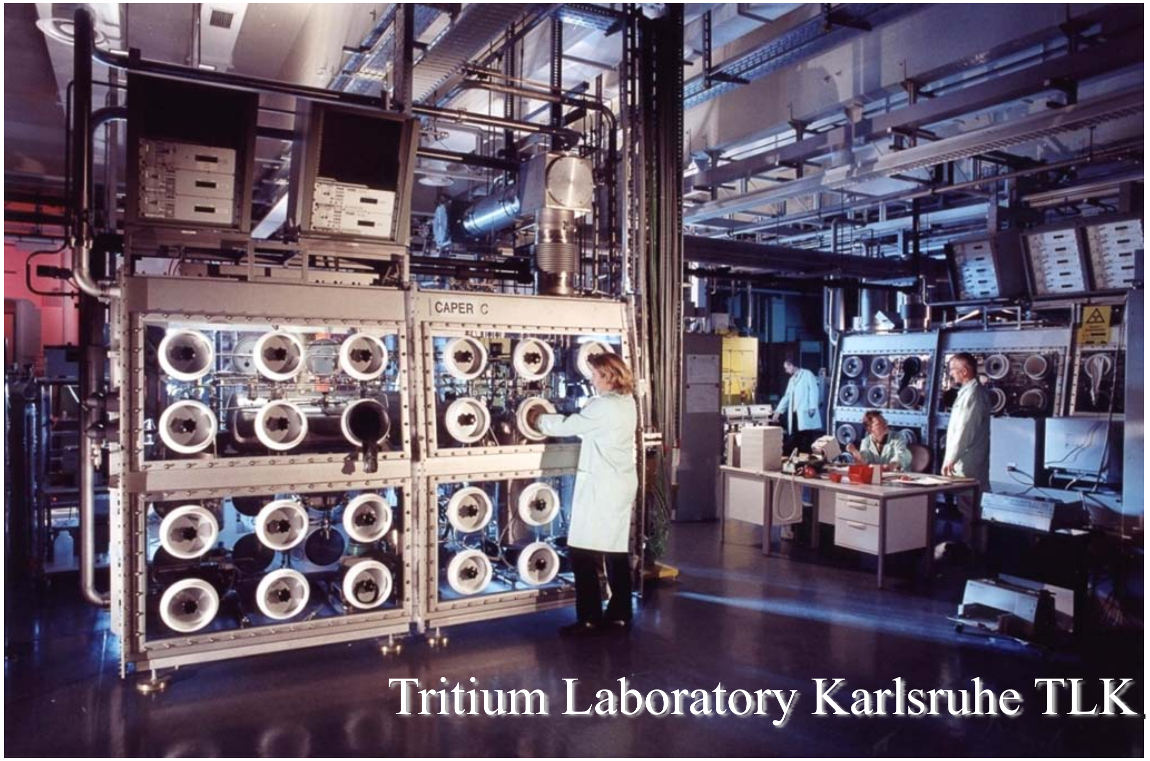
tritium loops required!

Tritium technology - TLK



Europe-wide unique infrastructure





KATRIN source parameter

source strength: $N(T_2) = A_S * \rho d * \varepsilon_T$

A_S = source area
ρd = column density
ε_T = tritium purity

optimized source design parameters:

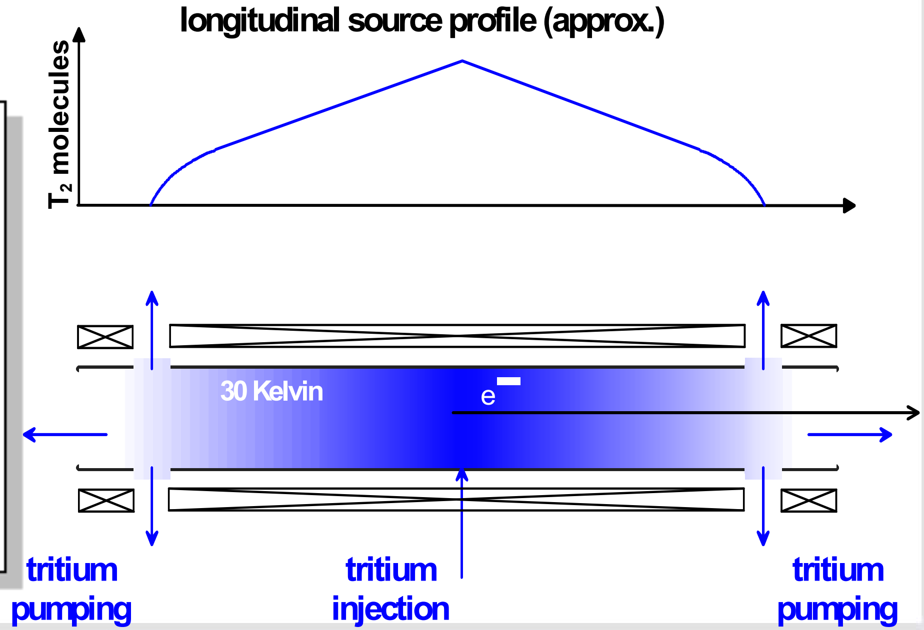
- $\rho d = 5*10^{17}$ cm^{-2} (= 86% of maximum count rate of unscattered electrons)
- $A_S = 53$ cm^2, B = 3.6 T, $\varepsilon_T = 95\%$

$\Rightarrow$ KATRIN needs closed tritium loop with stabilized gas injection rate of 1.8 mbar l/s = $1.5*10^{16}$ Bq/d

source stability requirements:

column density ρd
has to be stabilized on 0.1% i.e.:

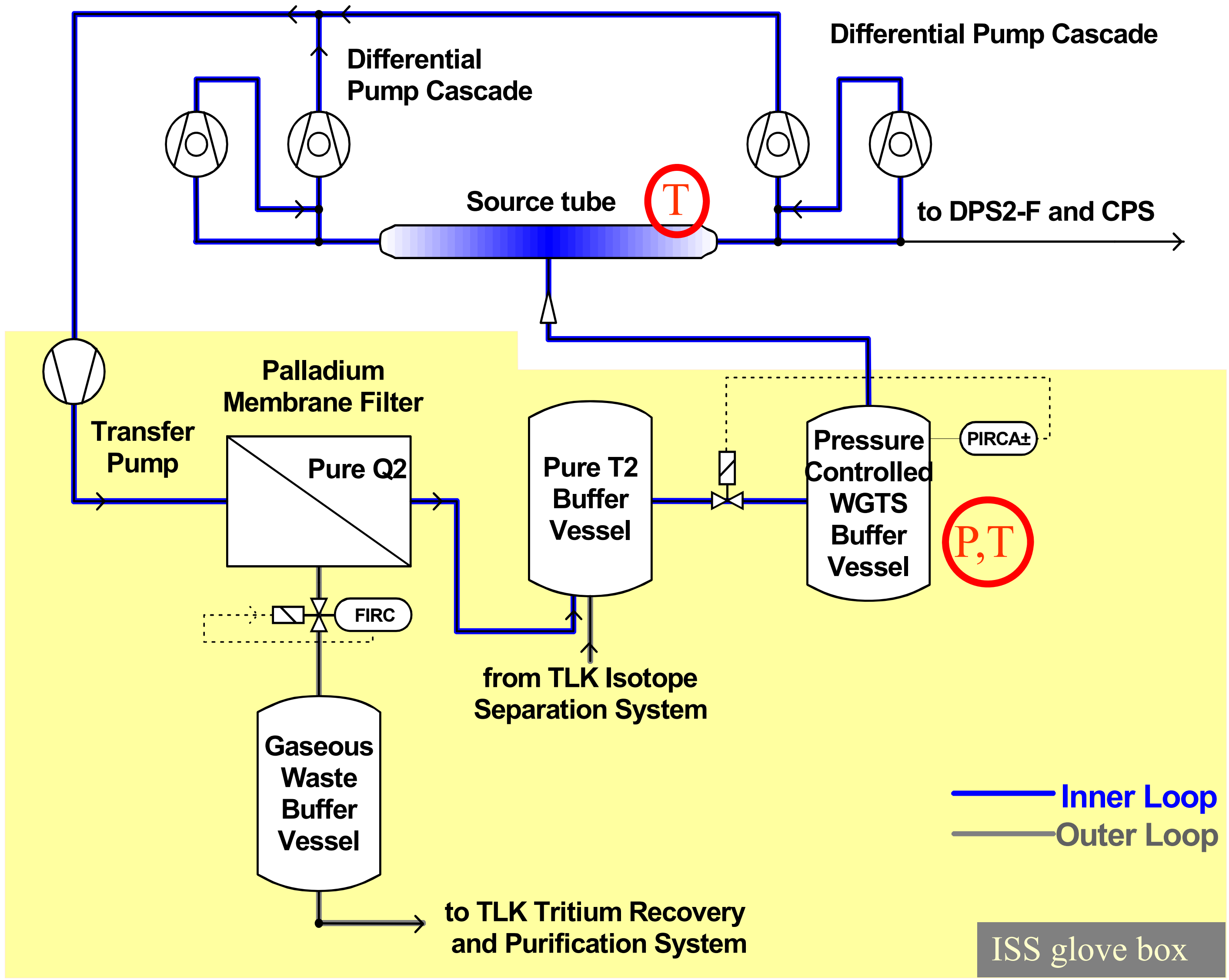
$\Delta\varepsilon_T/\varepsilon_T$	< 0.001	purity
$\Delta T/T$	< 0.001	temperature
$\Delta q/q$	< 0.001	injection rate



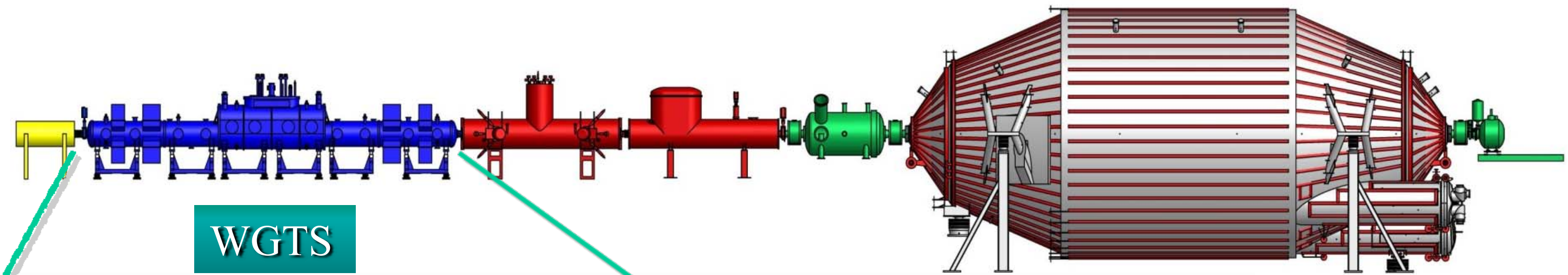
WGTS & closed tritium loops

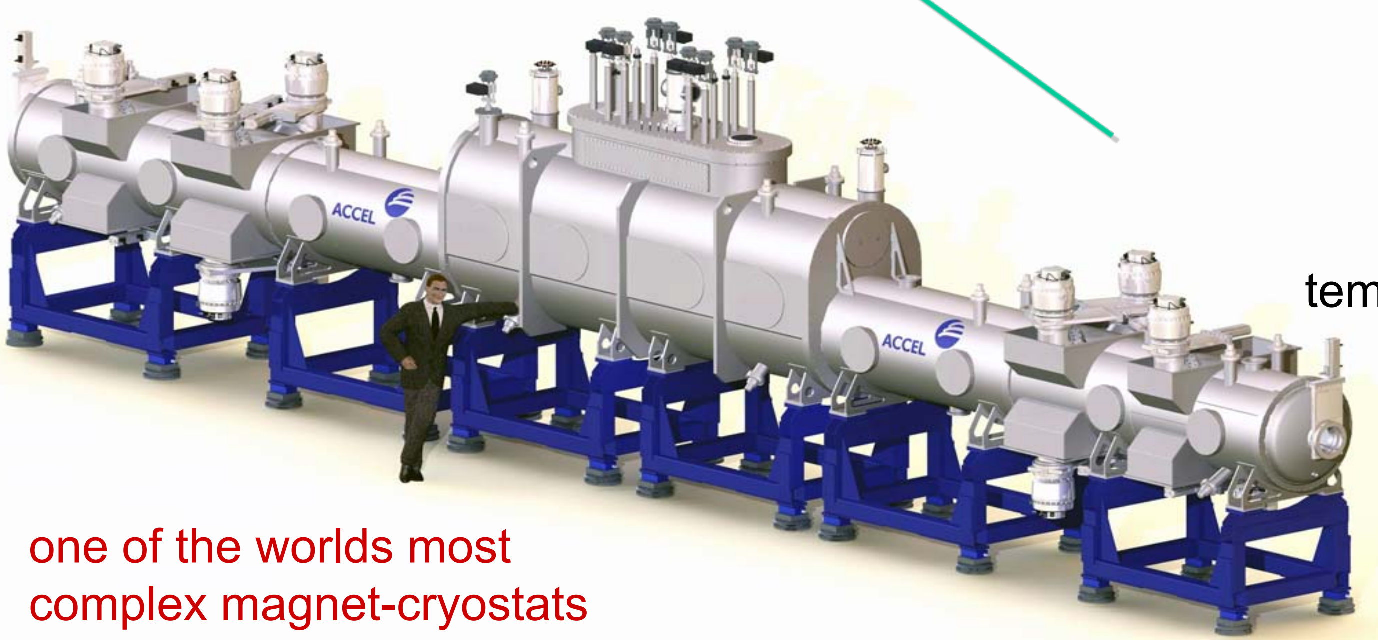
Inner Loop:
stabil (±0.1%)
tritium injection

Outer Loop:
high (>95%)
and
stabil (±0.1%)
tritium purity



Windowless Gaseous Tritium Source





16 m long complex magnet-cryostat:

-12 cryogenic circuits

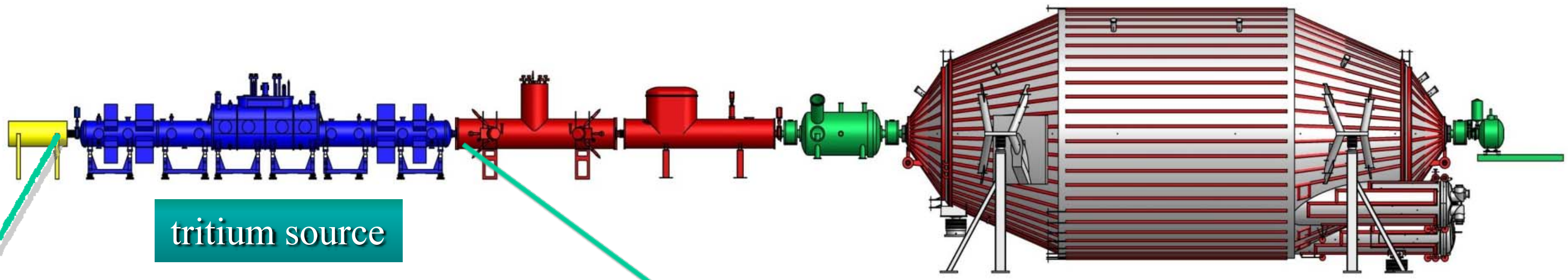
- 6 cryogenic fluids

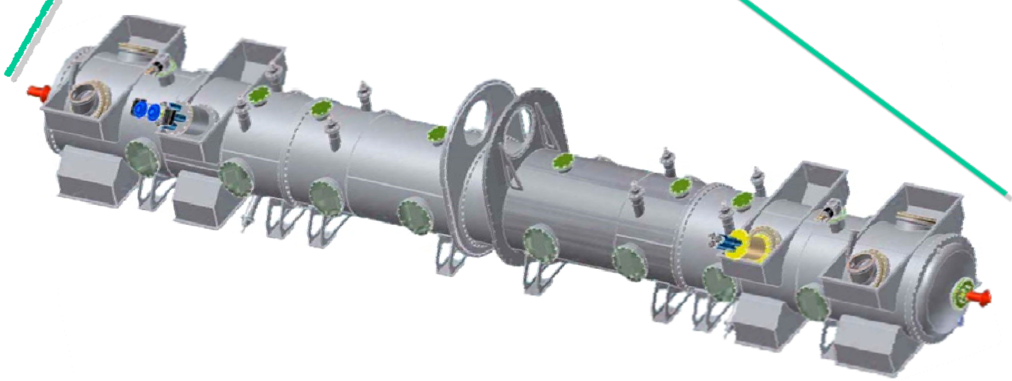
- instrumentation:

~500 sensors for temperature (4 – 600 K), LHe level, gasflow, B-field, pressure, …

one of the worlds most complex magnet-cryostats

Tritium source: WGTS demonstrator





WGTS demonstrator (12m)

currently being assebled
delivery early 2010

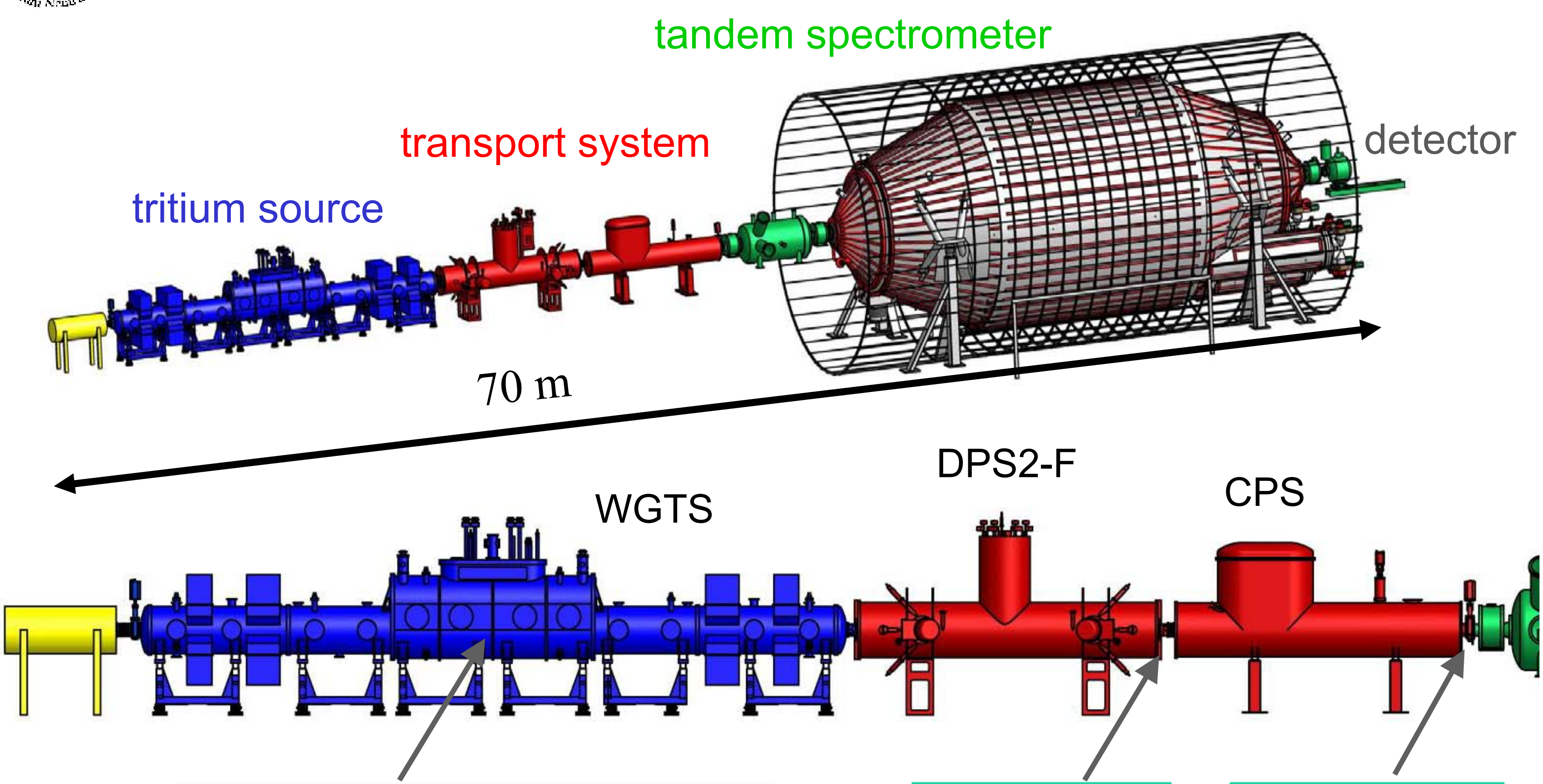
WGTS	design value	precision
luminosity	1.7 × 10^{11} Bq	
injection rate	5 × 10^{19} mol/s	± 0.1 %
column density ρd	5 × 10^{17} mol/cm^2	± 0.1 %
tritium purity	> 95%	
magnetic field	3.6 T	± 2%

key technological challenge:
precise cooling of beam tube

⇨ temperature stabilsation of beam tube of 10^{-3}

2-phase-Neon @ 30K

reduction of tritium flux by 10^{14}



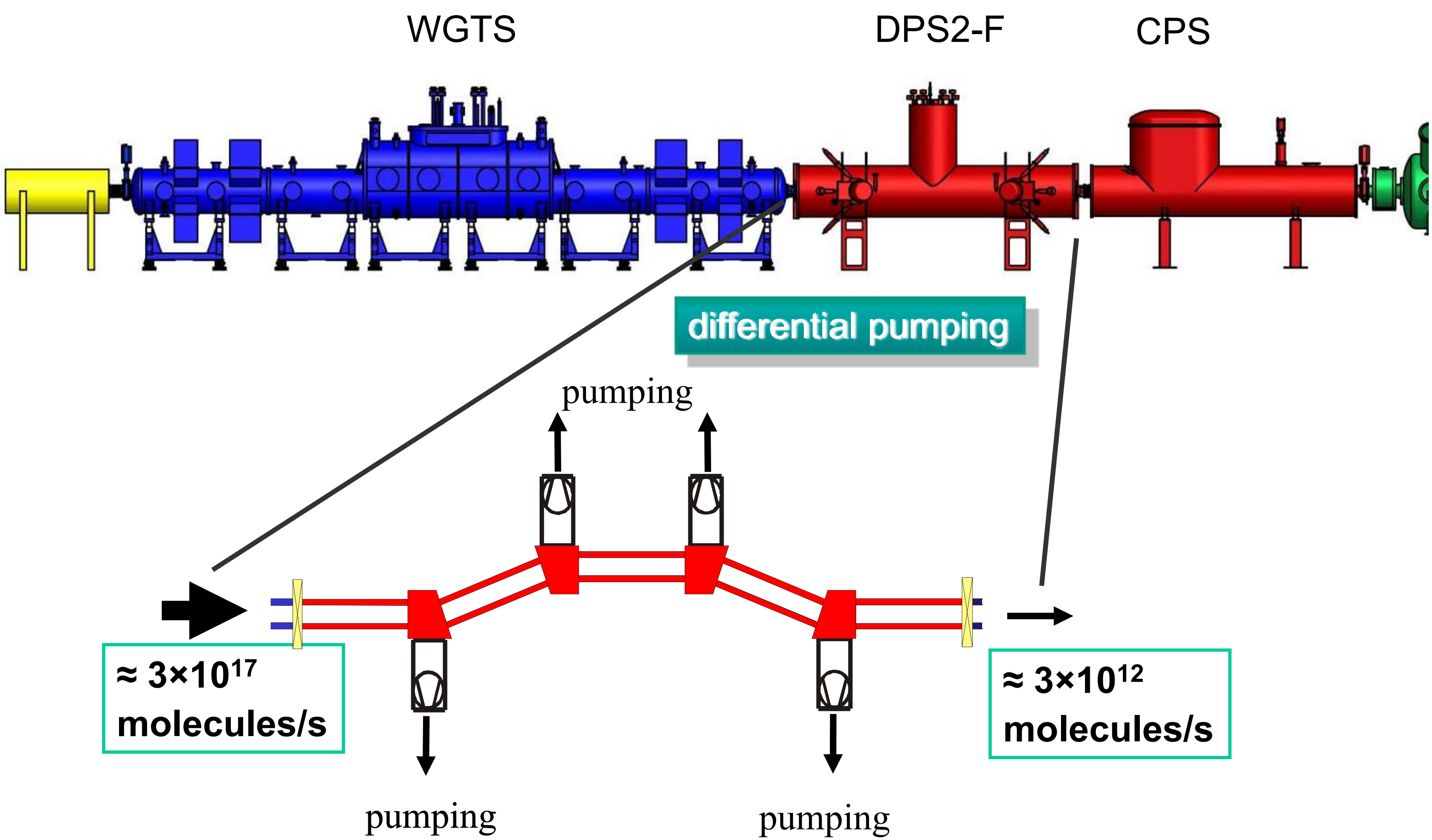
T_2-injection rate 1.8 mbar l/s (STP)
= $1.7 \cdot 10^{11}$ Bq/s = 40 g/d

≈ 10^{-7} mbar l/s

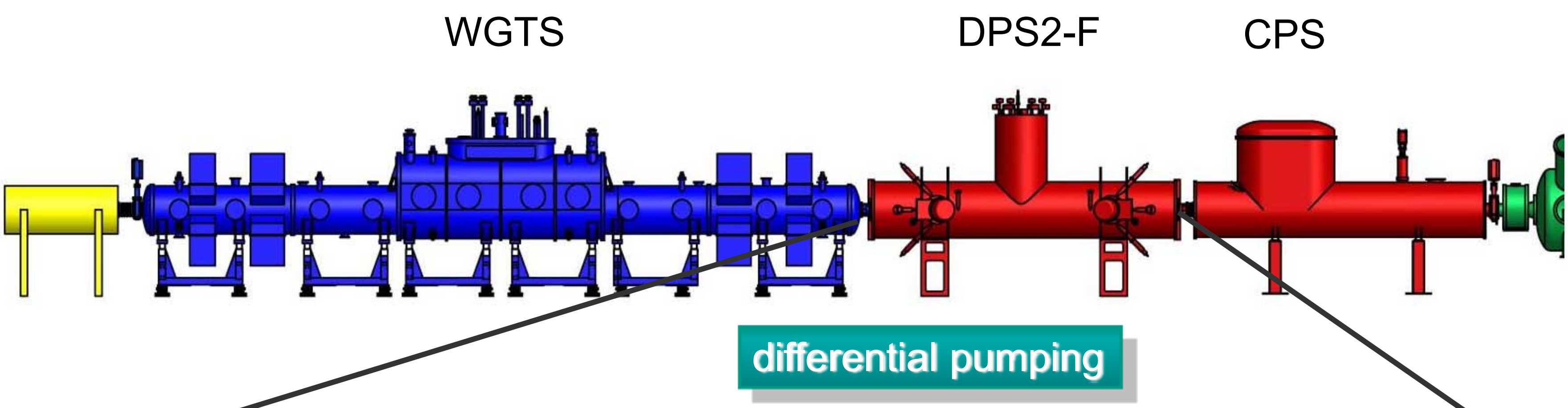
< 10^{-14} mbar l/s

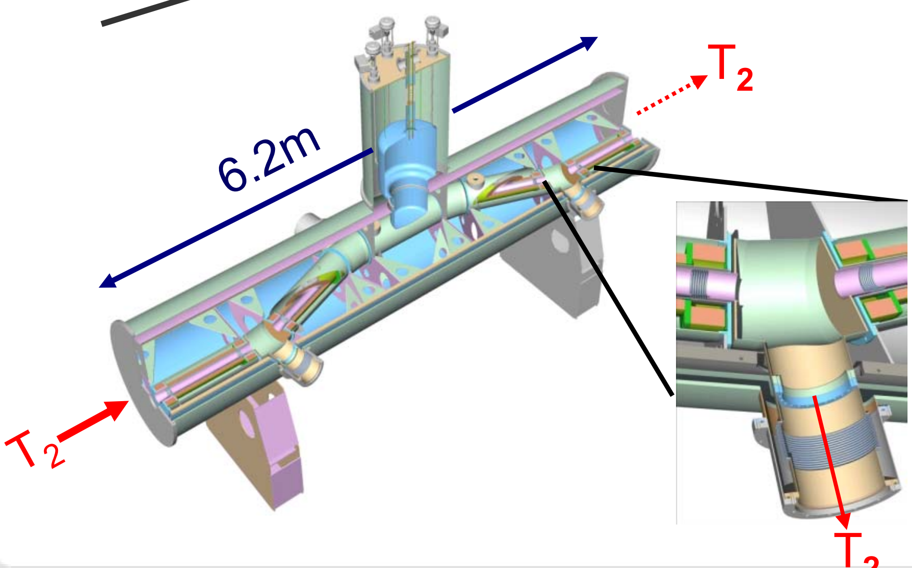
➡ tritium reduction factor > 10^{14}

DPS2-F: T_2-flux reduction by 10^5



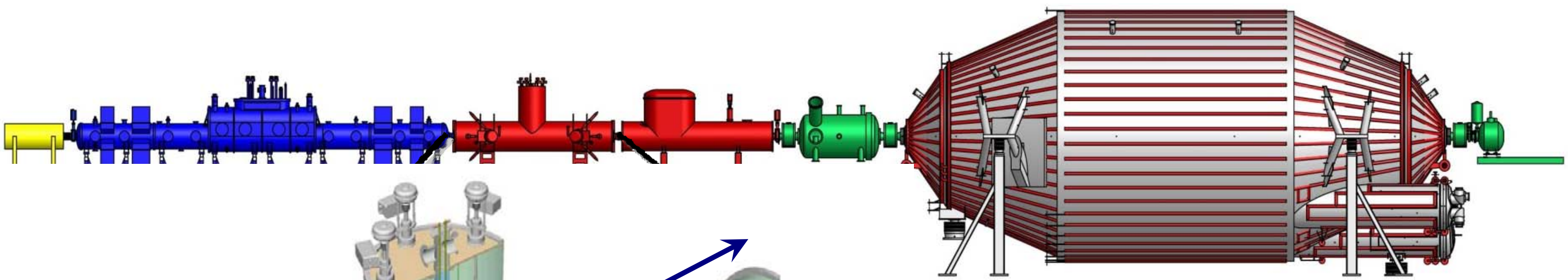
DPS2-F: T_2-flux reduction by 10^5

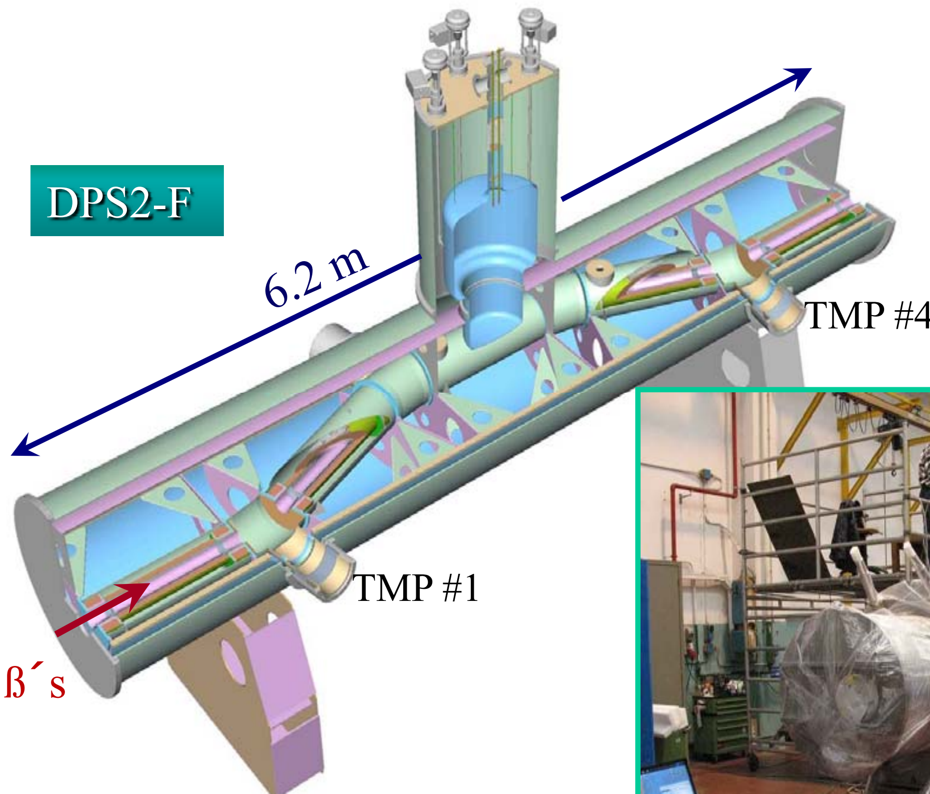


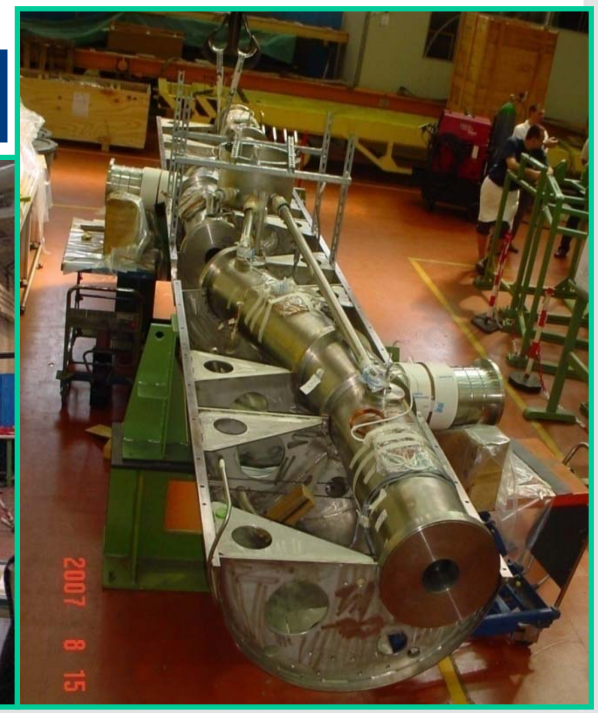


- differential pumping of T_2 (TMPs)
- magnetic guiding of electrons (5.6T)
- identification and removal of positive ions (FT-ICR & dipoles)

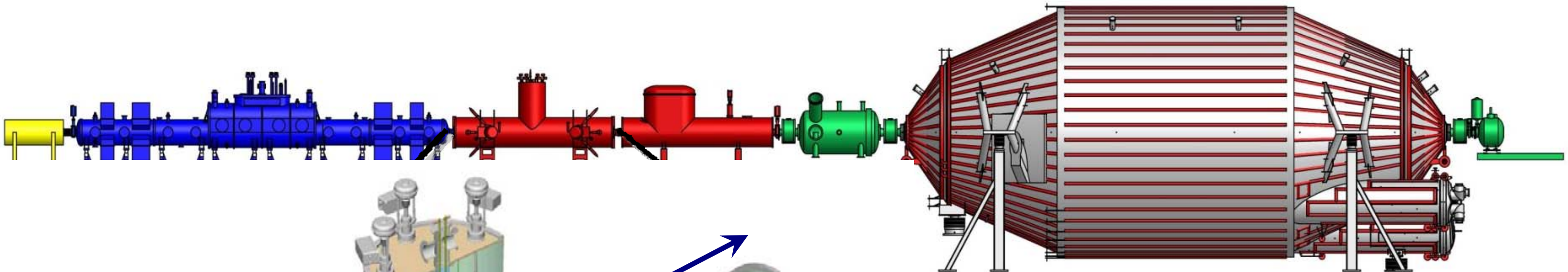
arrival of DPS2-F



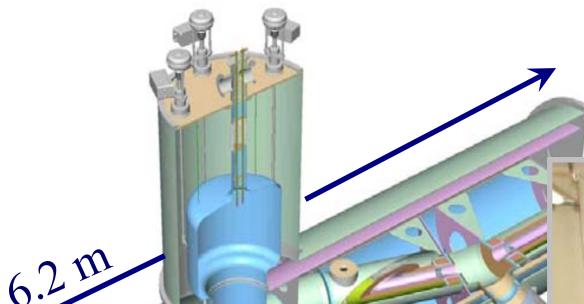




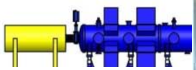
arrival of DPS2-F

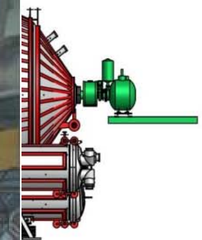


DPS2-F



arrival of DPS2-F



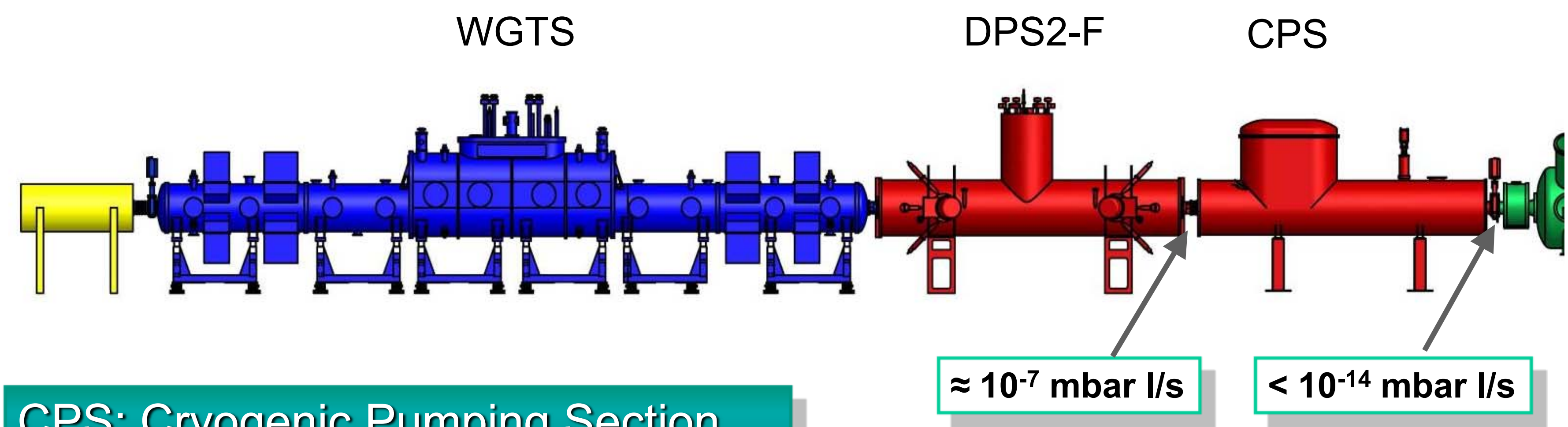


DPS2-F

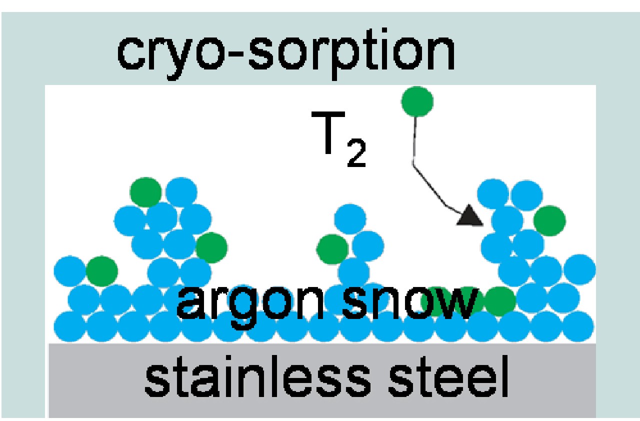
status:

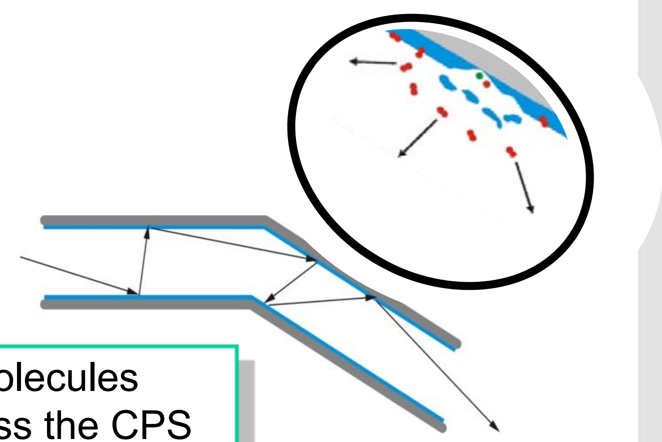
- Acceptance tests in 2009
- extended test program 2010 (gas reduction factor, identification and removal of charged particles with FT-ICR and dipoles …)

CPS: T_2-flux reduction by 10^7



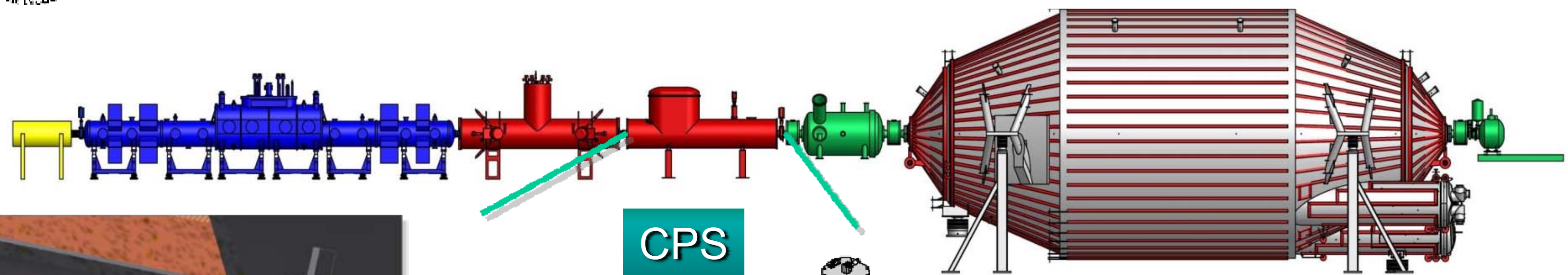
CPS: Cryogenic Pumping Section
principle: cryosorption (< 4.5 K)

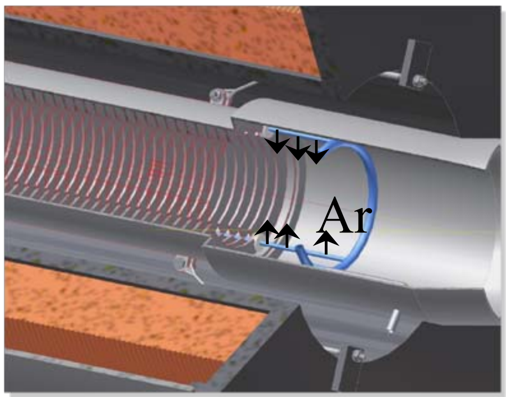


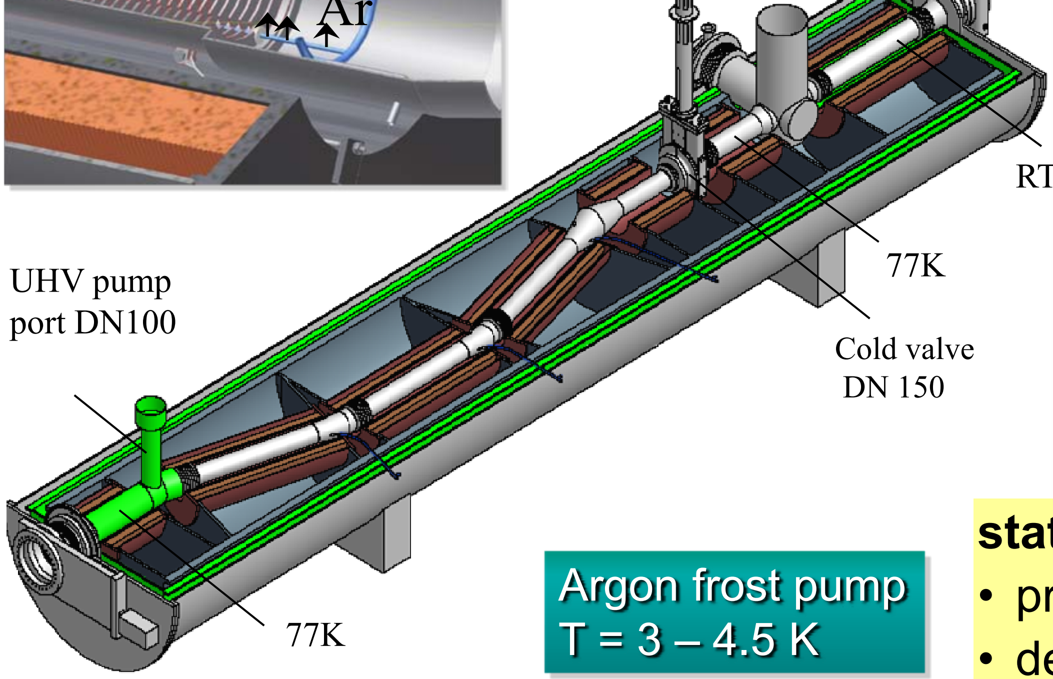


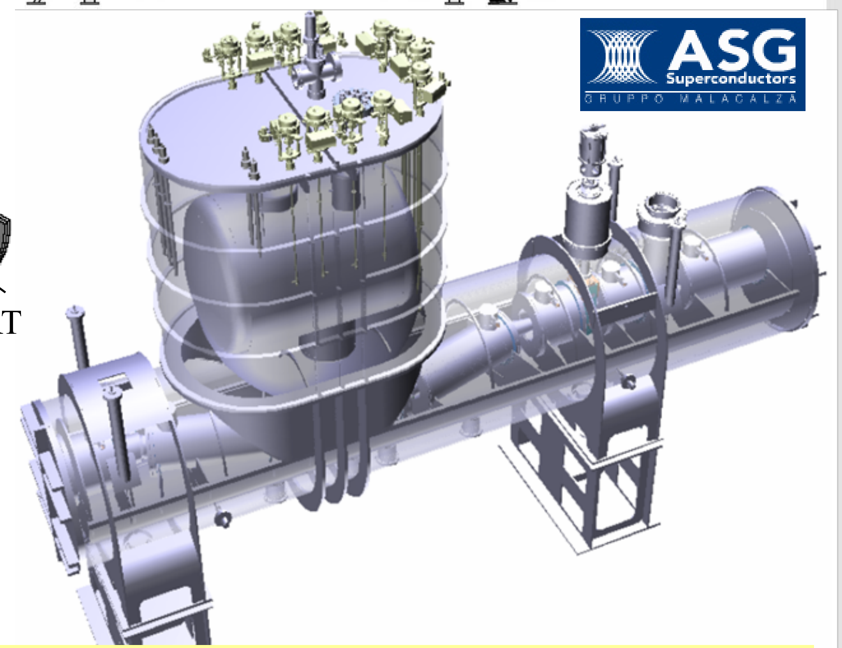
tritium molecules might pass the CPS due to migration

CPS: status of assembly





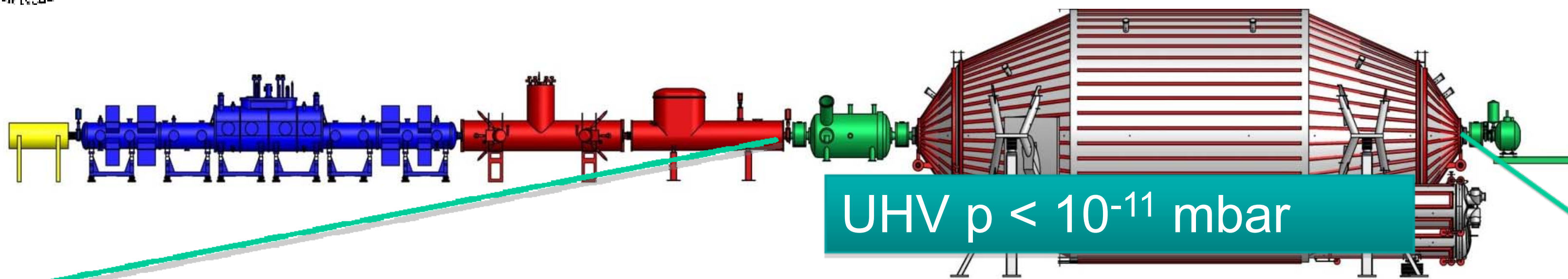




Argon frost pump
T = 3 – 4.5 K

status:
- presently being manufactured at ASG
- delivery to FZK in fall 2010
- commissioning 2011

electrostatic Spectrometers



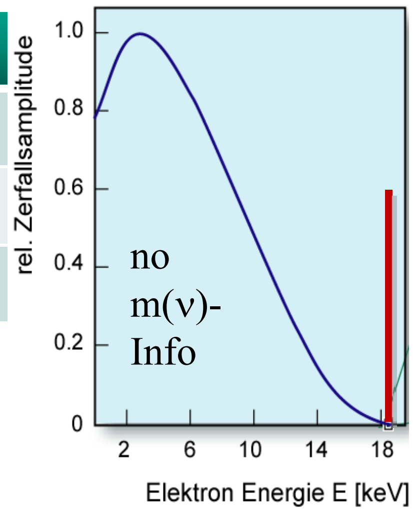
preselection

fixed retard. potential

U_0 = - 18.3 kV

ΔE ~ 100 eV

- filter out all ß-decay electrons without m(ν)-Info
- reduce background from ionising collisions

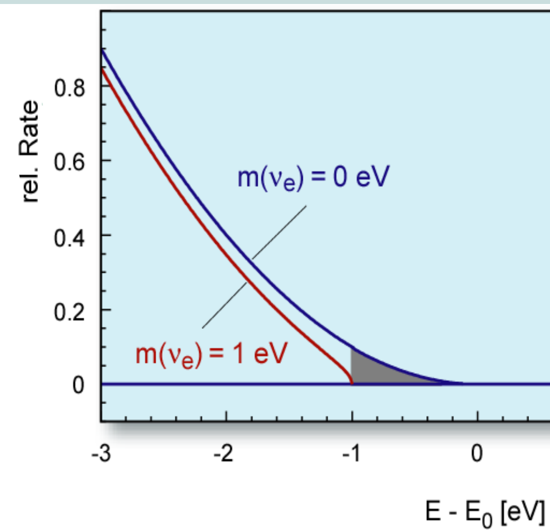


precision filter - Scanning

variable retard. potential

U_0 = - 18.4 … -18.6 kV

ΔE ~ 0.93 eV (100% transmission)

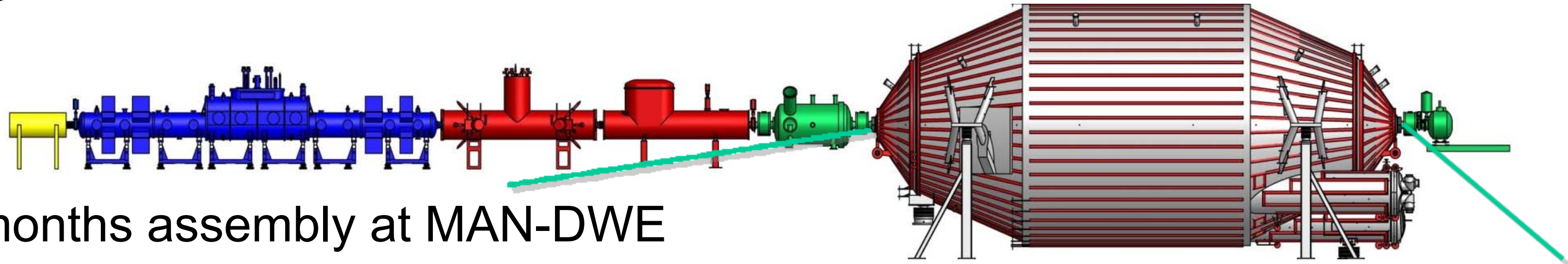


tandem design: pre-filter & energy analysis

10^{11} electrons/s ⇨ 10^{3} electrons/s

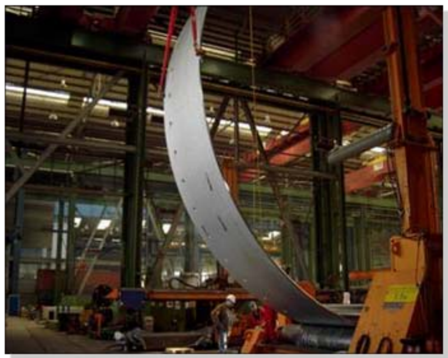
Spectrometer vessel – assembly

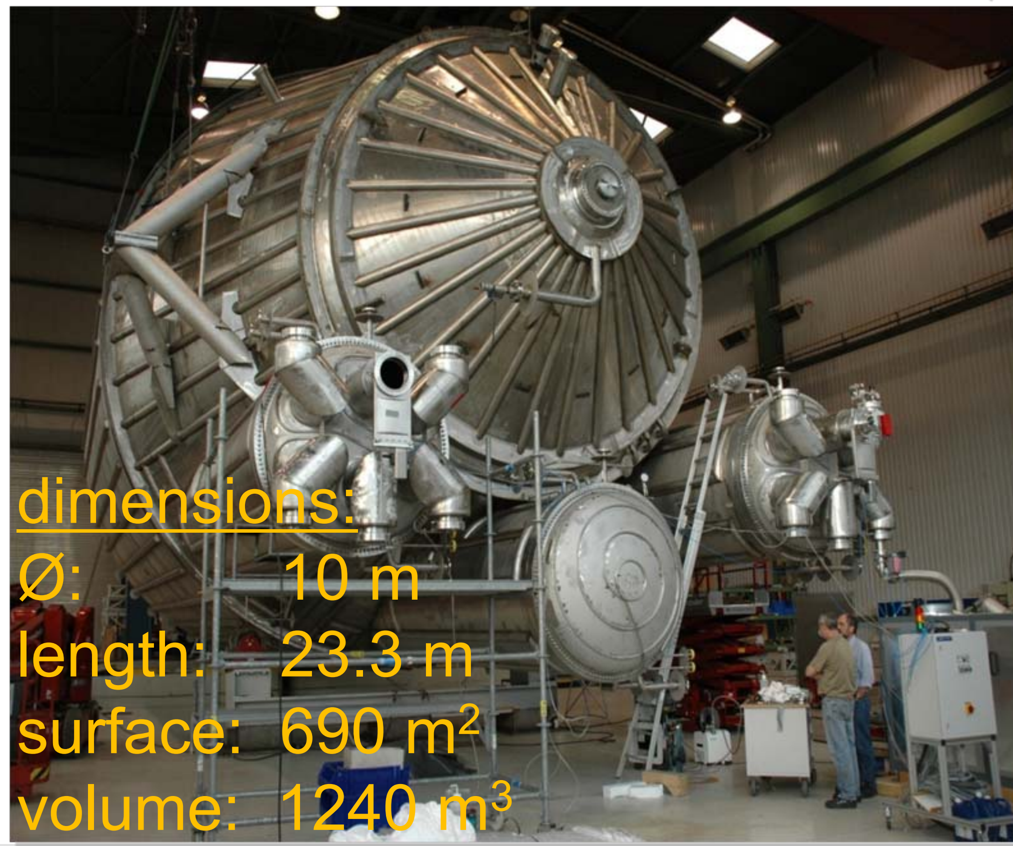
Karlsruhe Institute of Technology



18 months assembly at MAN-DWE

MAN DWE GmbH





dimensions:

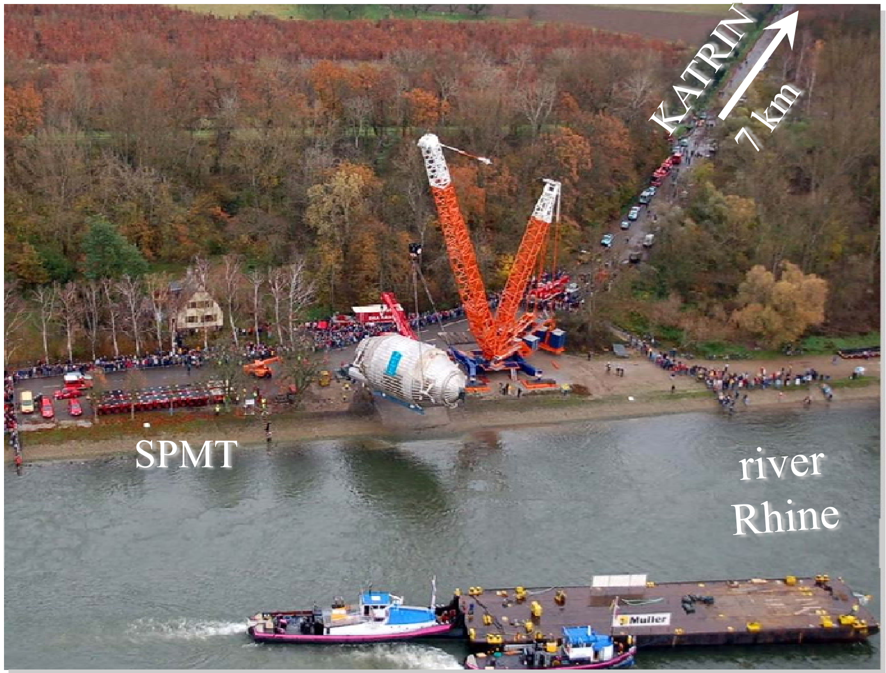
Ø:	10 m
length:	23.3 m
surface:	690 m^2
volume:	1240 m^3

main spectrometer: transport

the final 7km: passing Leopoldshafen

November 25, 2006: after an 8800 km sea-going voayge the main Spectrometer was manoeuvred by an SPMT over 7km to the final destination at the KATRIN experimental halls…
(30.000 visitors)

arrival at Leimersheim ferry & reloading onto SPMT with heavy-duty crane



BBC NEWS

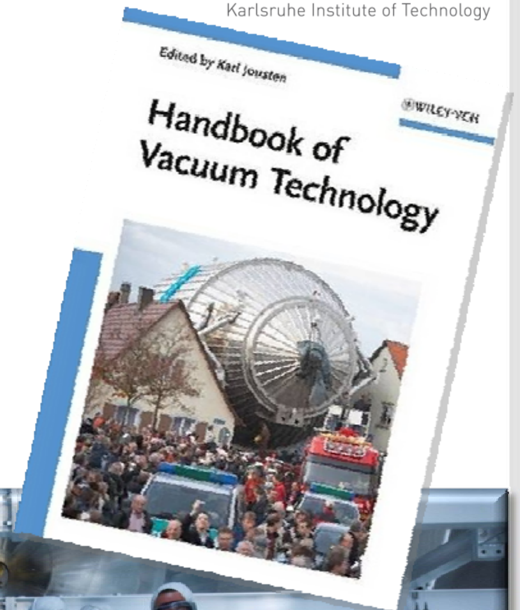
In pictures: photos of the year 2006

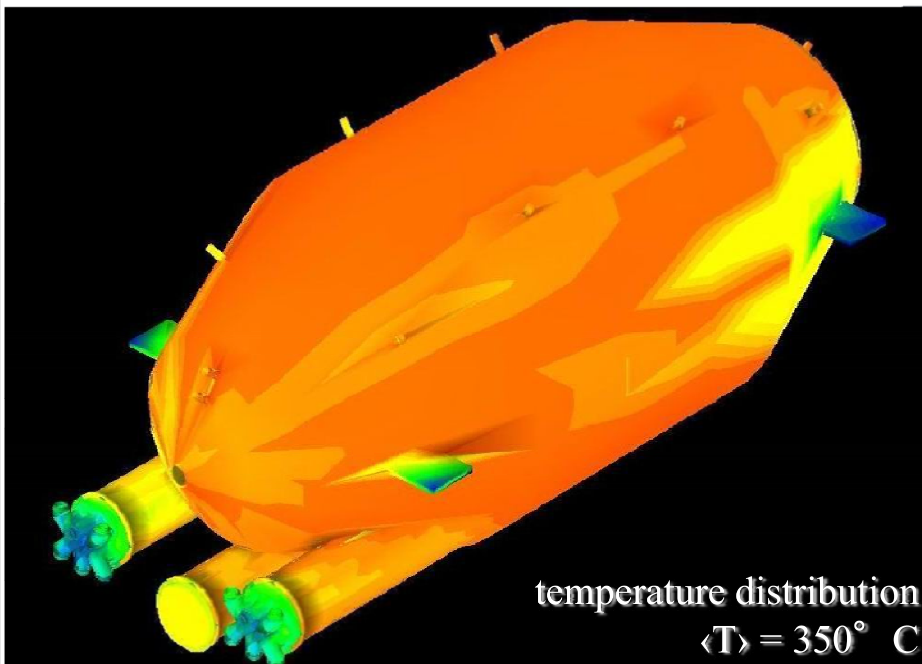
baking and first vacuum test

July 2007: first UHV test of the vessel
after baking with 6 TMPs

outgassing rate [T = 20° C]
1.18×10^{-12} mbar ℓ / cm^2 s
p = 10^{-10} mbar

⇨ H_2O ↓ H_2





temperature distribution
‹T› = 350° C

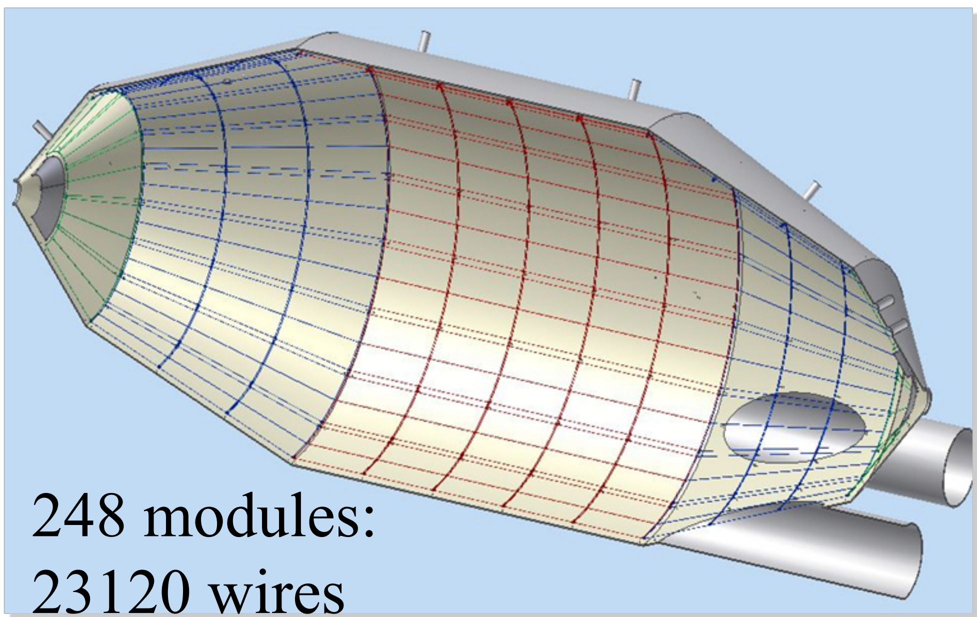
KIT board of directors

inner electrode system

spectrometer inner surface: covered by a ´massless´ inner wire-based electrode

#1: fine forming electric field

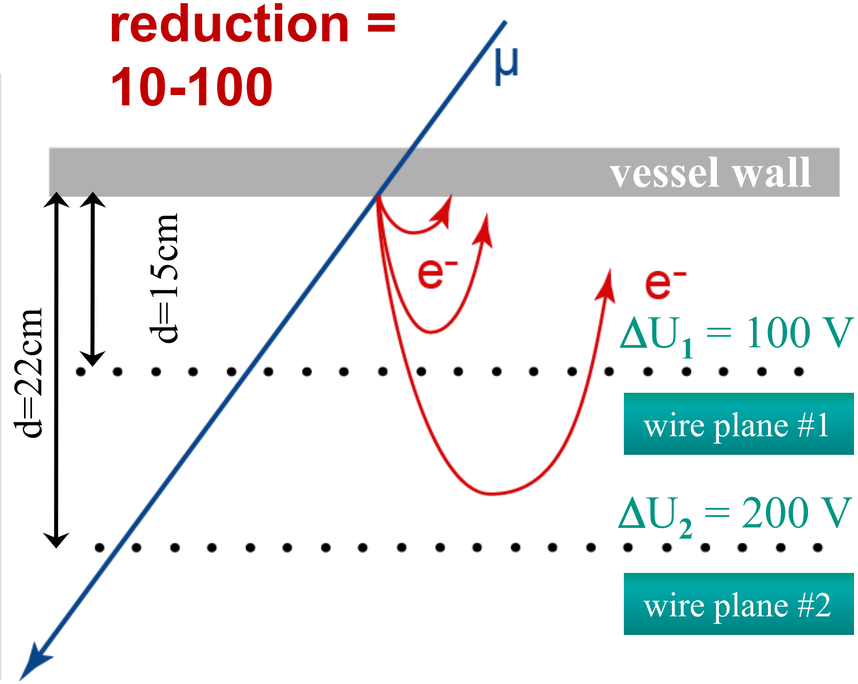
- precision-HV-supplies measurements with 1ppm
- dipole mode to empty stored electrons in Penning traps



#2: background suppression

- inelastic reactions of cosmic muons
  ↳ low-energy secondary electrons from 690 m² large inner surface

reduction = 10-100



inner electrodes: single module

positioning precision of wires ± 200 μm, wire sag < 200 μm

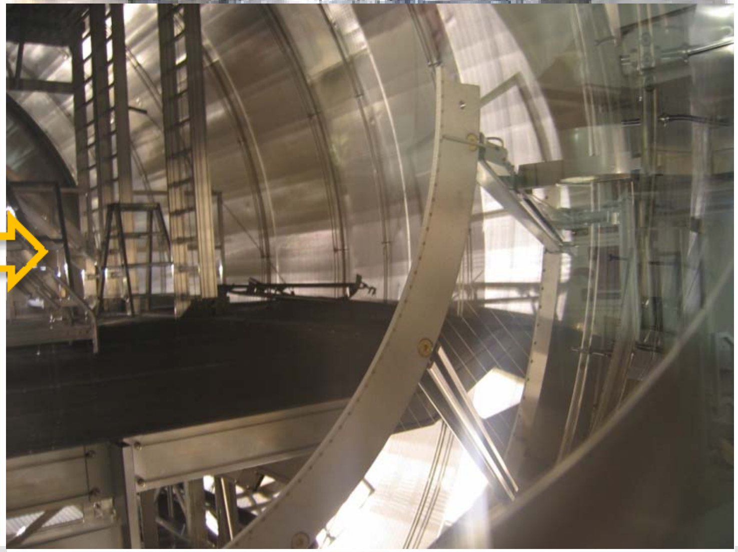
- wire frame in 3 geometries
- UHV compatibility
- low wire radioactivity
- 24.000 wires (intense QA!)

mounting system for inner electrodes

- access to main spectrometer via 85 m^2 clean room at rear end
- specially cleaned & electropolished mounting system with large-area platform for precision mounting of inner electrodes

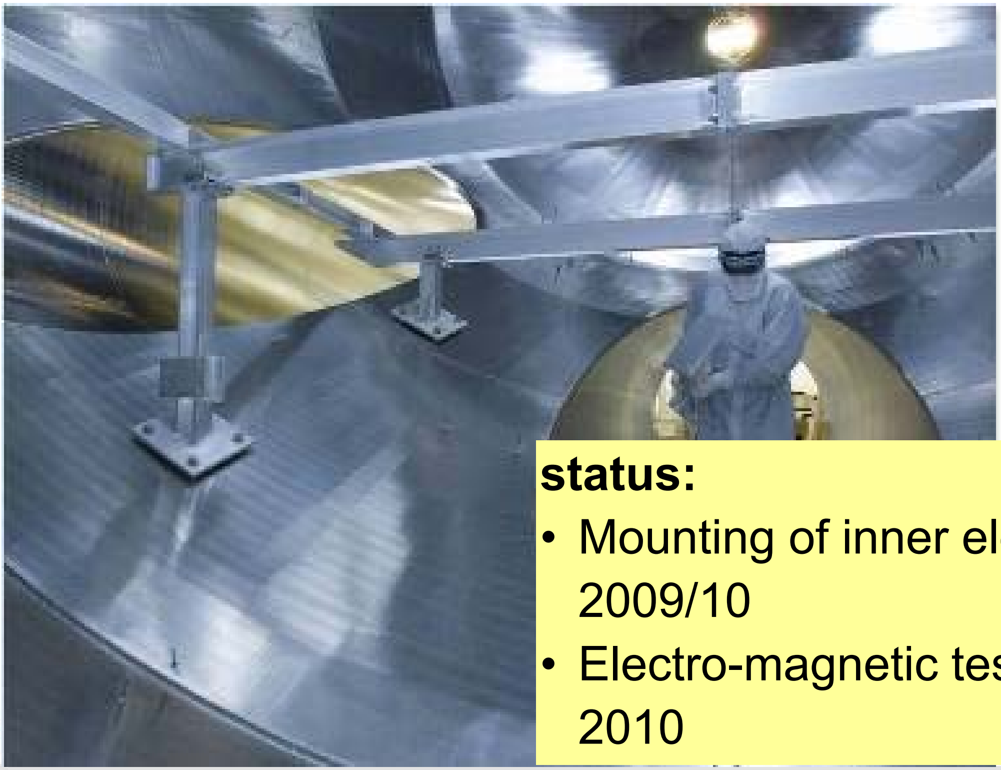
mounting system for inner electrodes

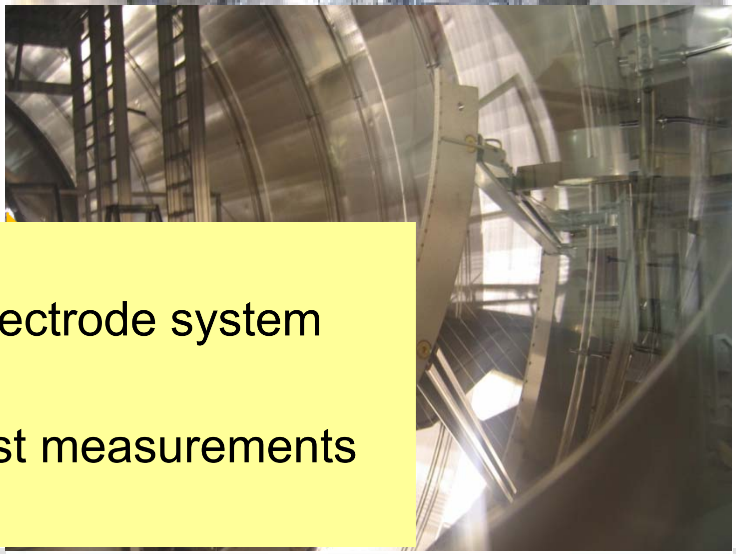
- access to main spectrometer via 85 m^2 clean room at rear end
- specially cleaned & electropolished mounting system with large-area platform for precision mounting of inner electrodes



mounting system for inner electrodes

- access to main spectrometer via 85 m² clean room at rear end
- specially cleaned & electropolished mounting system with large-area platform for precision mounting of inner electrodes

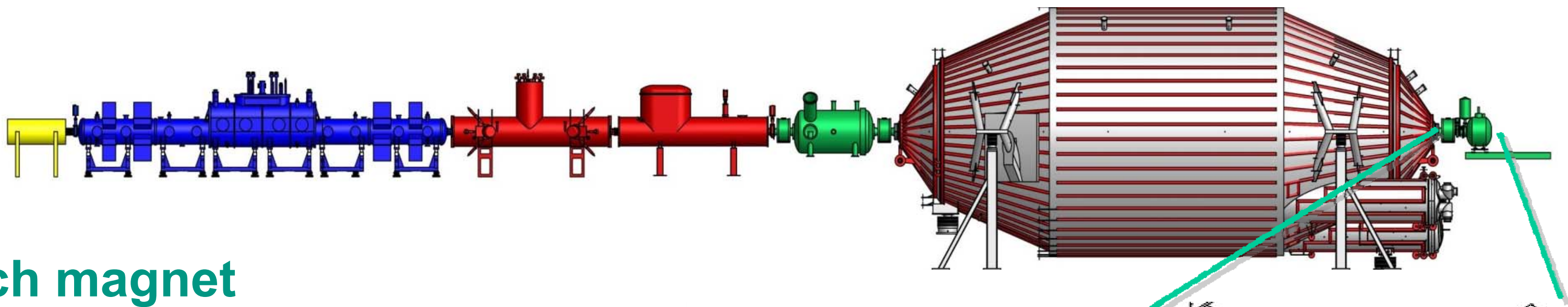




status:

- Mounting of inner electrode system 2009/10
- Electro-magnetic test measurements 2010

detector system



pinch magnet

provide maximum field B_{max} = 6 T (bore 340mm)

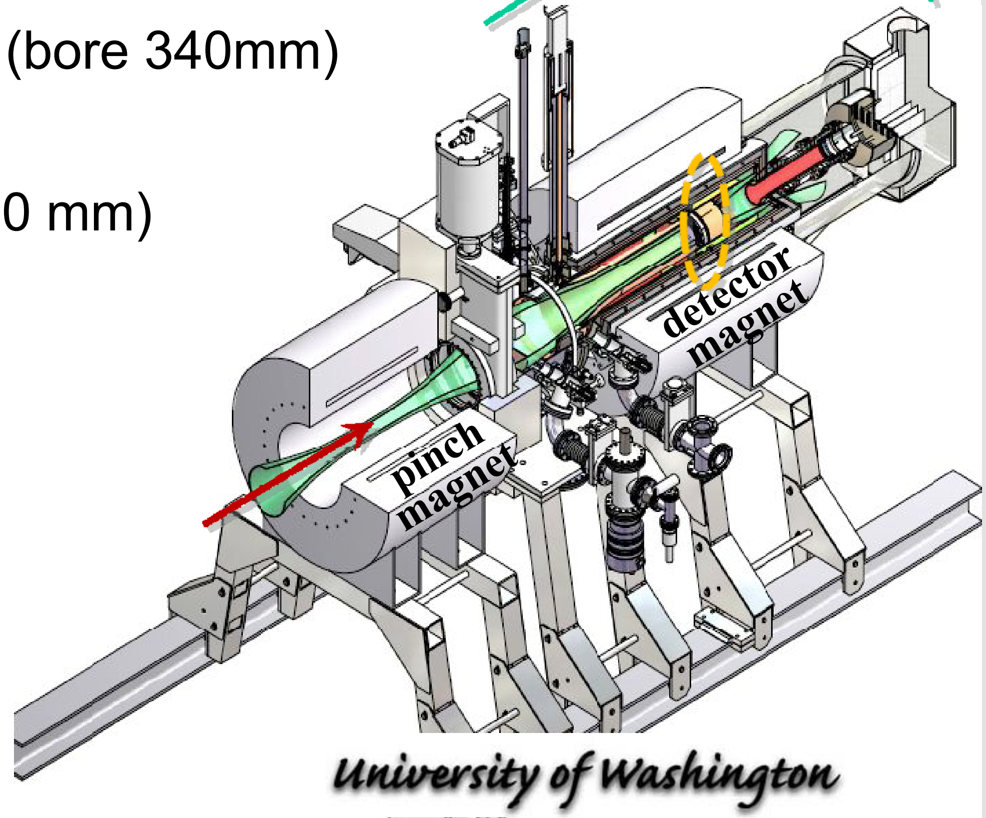
detector magnet

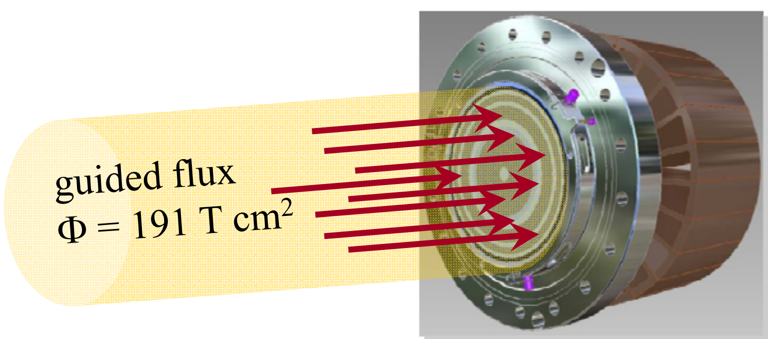
strong field B_{det} = 3 – 6 T (bore 440 mm)

focal plane detector

segmented Si-PIN diode array

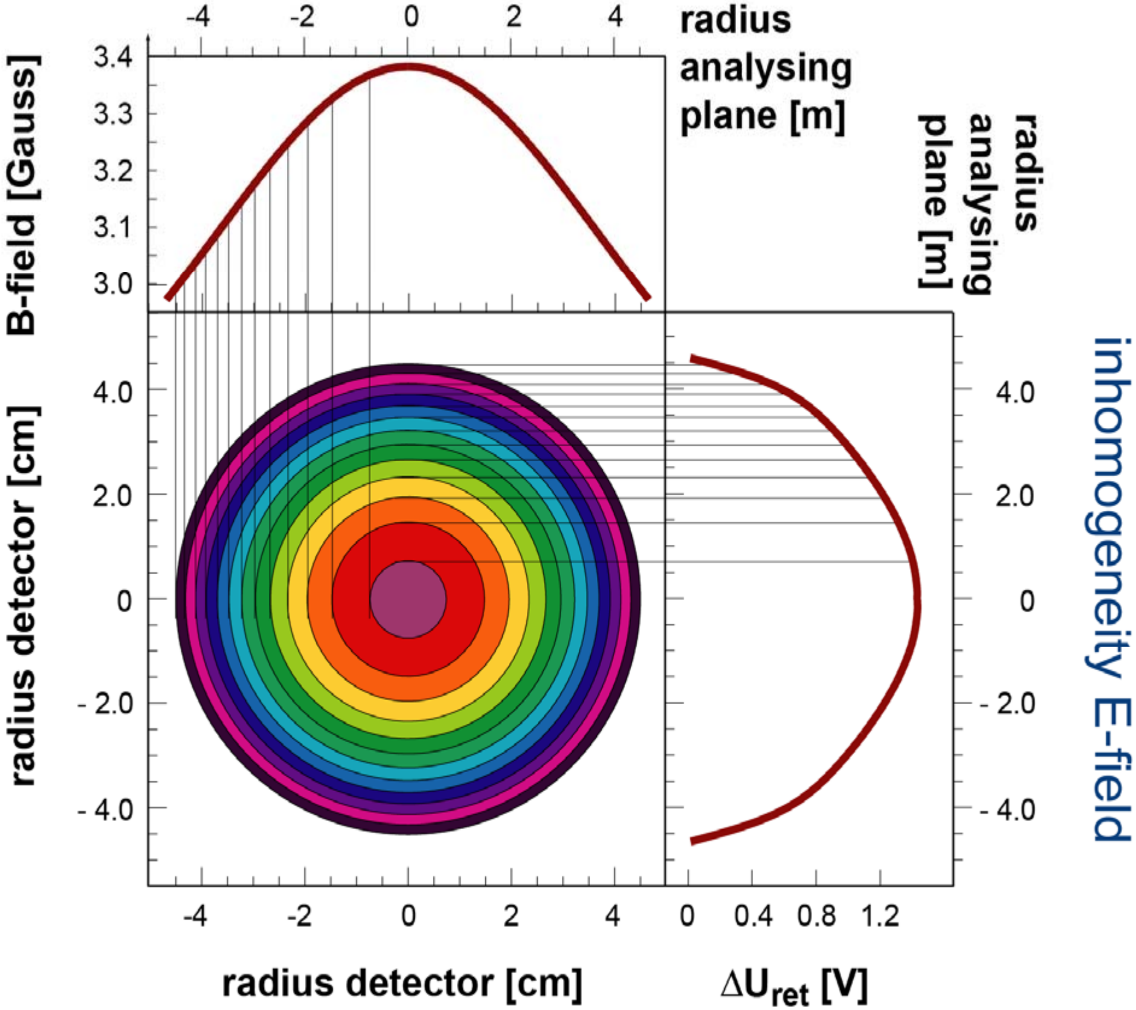
read-out electronics





compensation of field inhomogeneities

inhomogeneity B-field



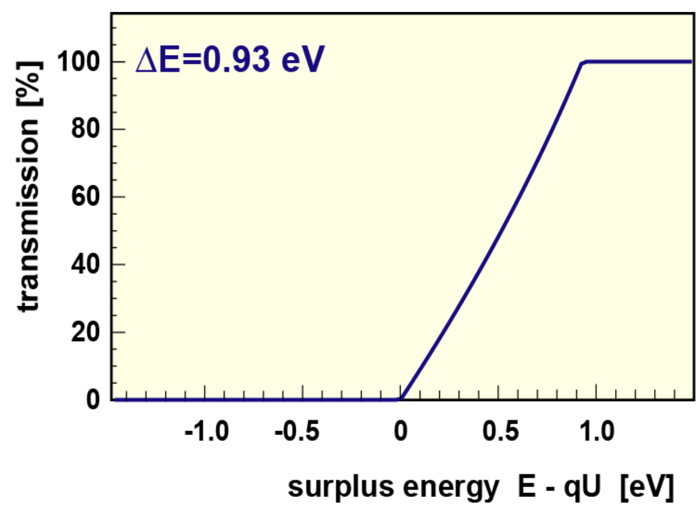
B (detector) ≈ 3 T

B (analys. plane) ≈ 3 × 10^{-4} T

to first order

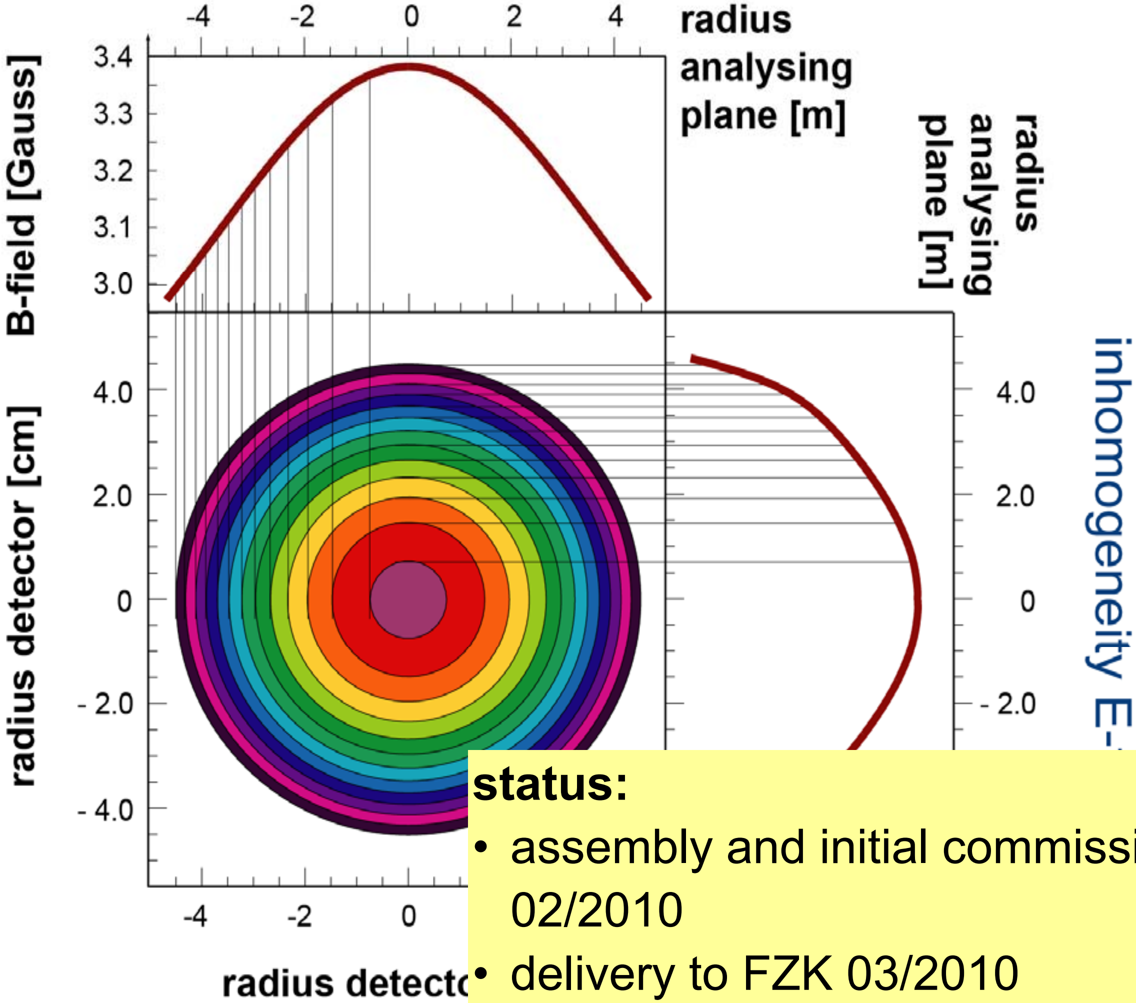
$$\frac{r\,(\text{analys. plane})}{r\,(\text{detector})} = \frac{100}{1}$$

without inhomogeneities



compensation of field inhomogeneities

inhomogeneity B-field



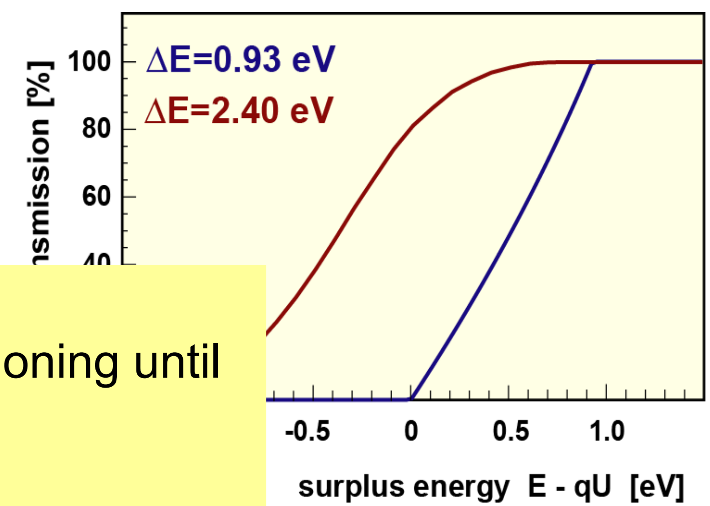
B (detector) ≈ 3 T

B (analys. plane) ≈ 3×10^{-4} T

to first order

$$\frac{r\ \text{(analys. plane)}}{r\ \text{(detector)}} = \frac{100}{1}$$

with inhomogeneities



status:

- assembly and initial commissioning until 02/2010
- delivery to FZK 03/2010

a lot of tricky things to do …

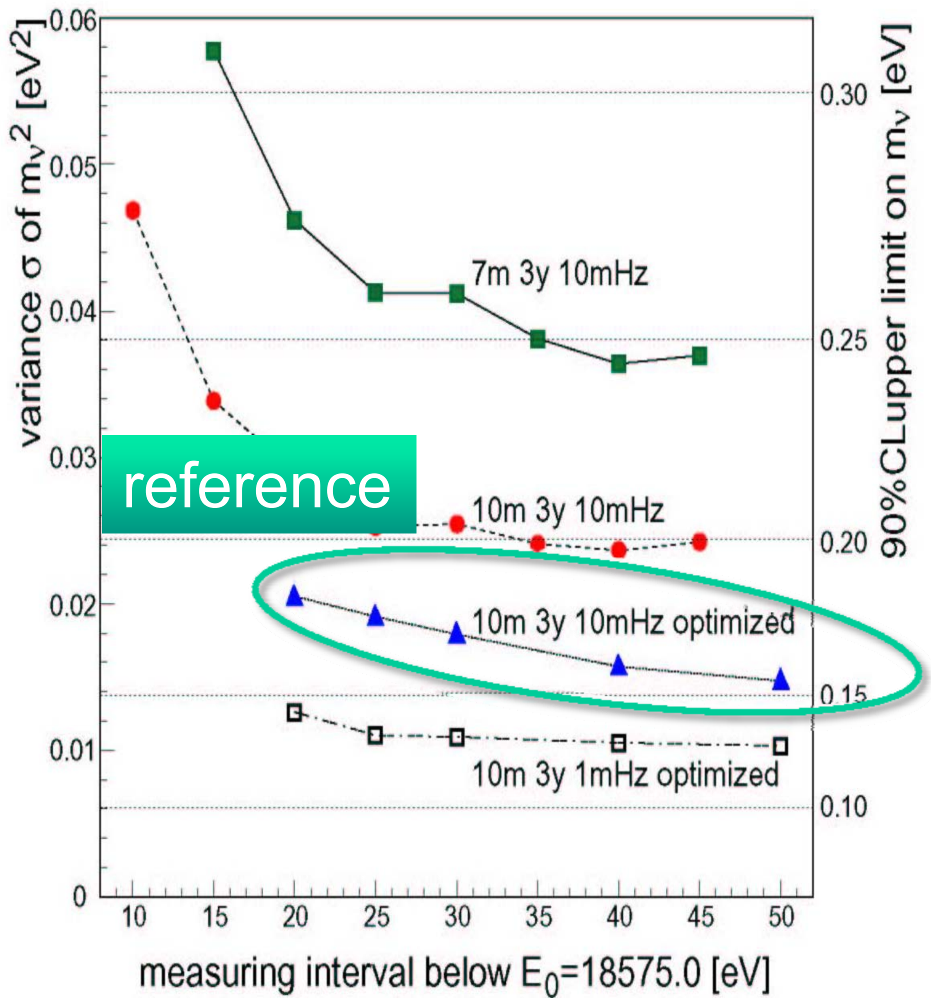
- **developments, test experiments, simulations, …**
  - develop, set up and test of „small“ components (HV-divider, e-guns, ion sources, monitor detektor, air coils, …)
  - test experiments as proof of priciple for KATRIN-components (pre-spectrometer, Test of Inner LOop, TRitium Argon frost Pump, …)
  - test experiments to investigate systematic effects (pre-spectrometer, Laser-Raman measurements, FT-ICR, Kr-sources, …)
  - modelling und simulation (electro-magnetic design, gas dynamical model of the WGTS, …)

predominantly tasks of graduated students

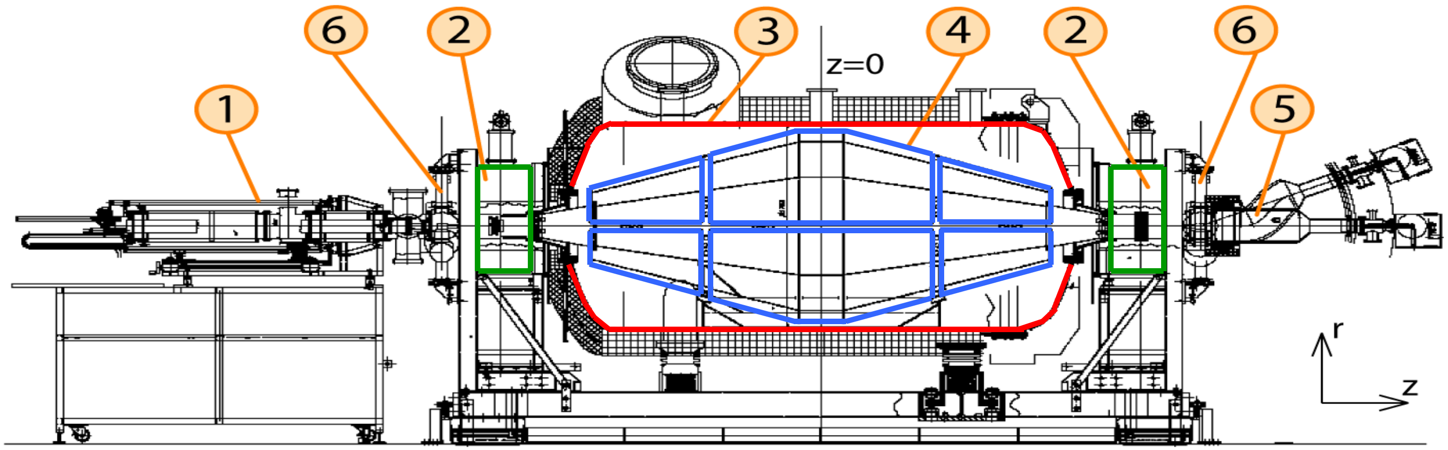
a lot of tricky things to do …

- **developments, test experime**
  - develop, set up and test of „small‘
    (HV-divider, e-guns, ion sources,
  - test experiments as proof of pricip
    (pre-spectrometer, Test of Inner L
  - test experiments to investigate sys
    (pre-spectrometer, Laser-Raman
  - modelling und simulation
    (electro-magnetic design, gas dyn

predominantly tasks c



Pre-spectrometer test set-up

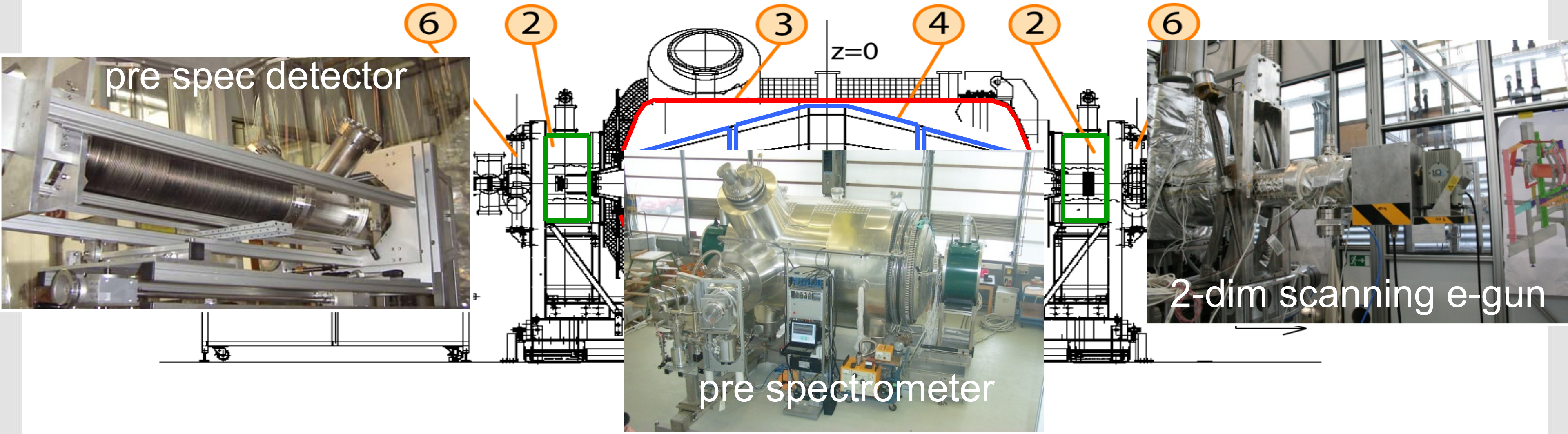


1 detector **2** magnets (4.5 T)
3 vessel **4** electrode system
5 electron gun **6** valve

prototype for main spectrometer:

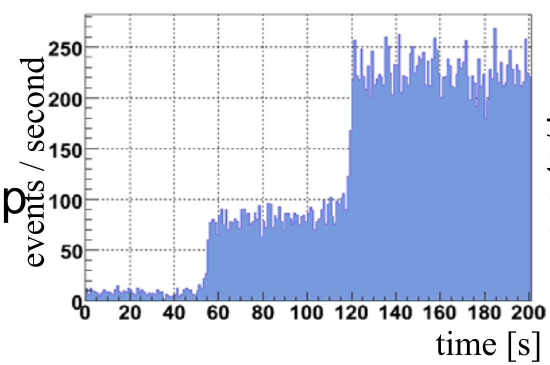
- vacuum concept successfully tested (p = 10^{-11}mbar, routinely)
- active HV stabilization tested
- test of new electromagnetic design
- background suppression
- optimization of electrode system

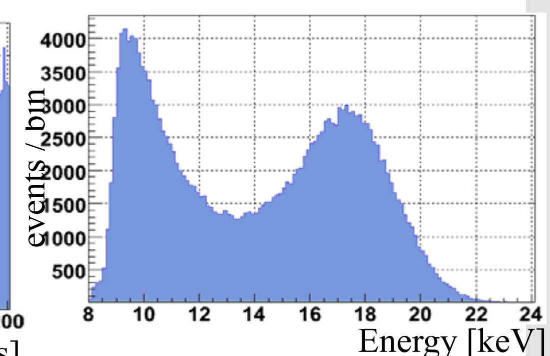
Pre-spectrometer bg studies



Background at high B-fields (B_{max} > 2T)

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

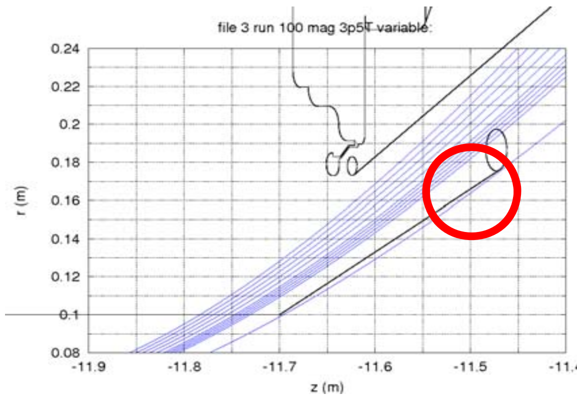


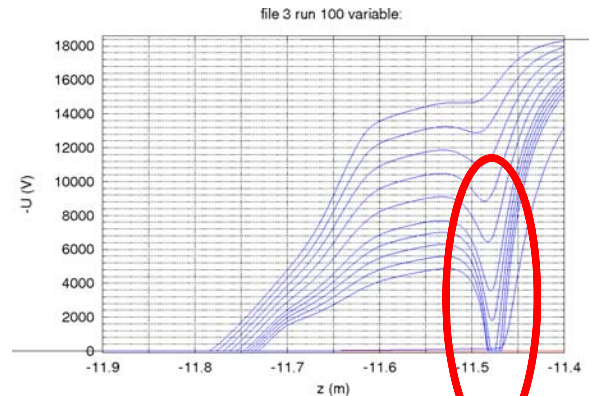


background caused by trapped particles

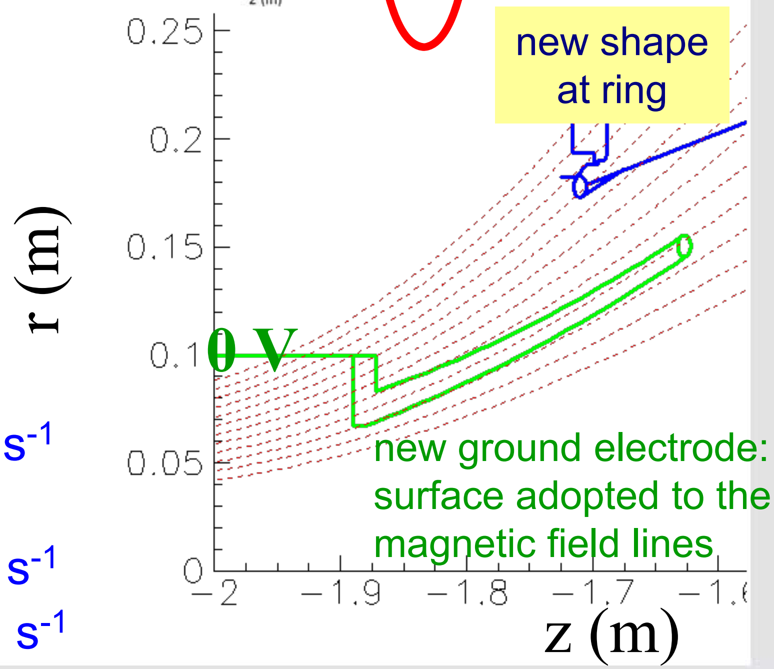
Pre-spectrometer bg studies

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

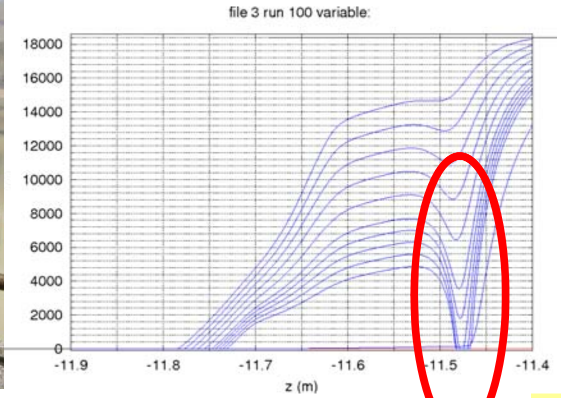


Result: Background reduction by 10^4:

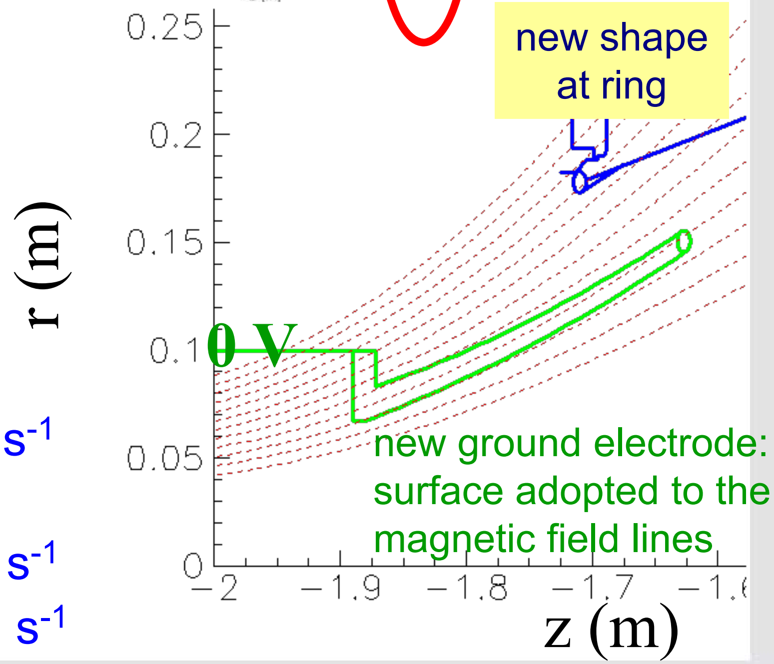
- with small Penning traps: bg 1000 s^{-1}
- optimally shaped electrodes with residual shallow Penning trap bg 1s^{-1}
- no residual Penning trap bg 0.1 s^{-1}

Pre-spectrometer bg studies

Problem ... ear 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:

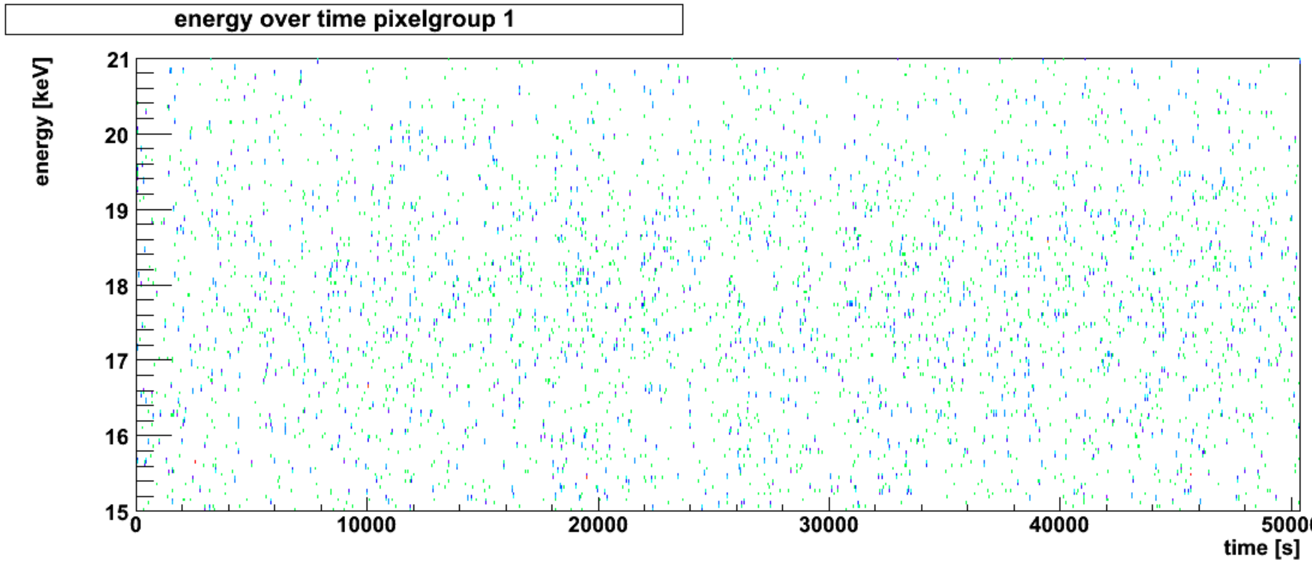
- with small Penning traps: bg 1000 s^{-1}
- optimally shaped electrodes with residual shallow Penning trap bg 1s^{-1}
- no residual Penning trap bg 0.1 s^{-1}

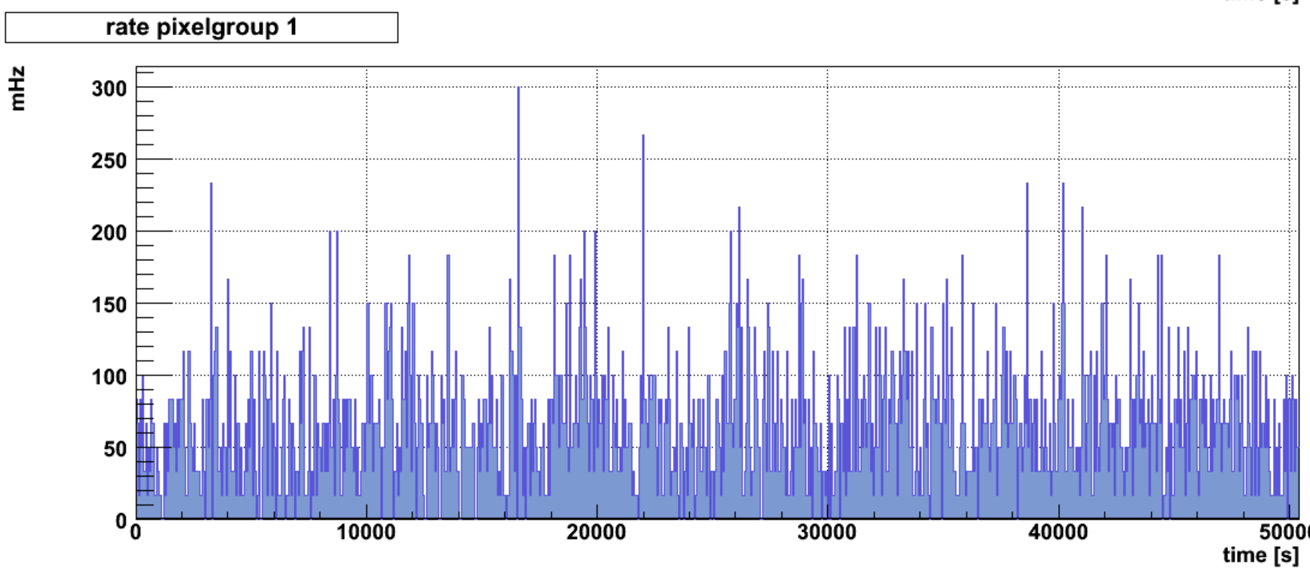
Pre-spectrometer bg studies

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

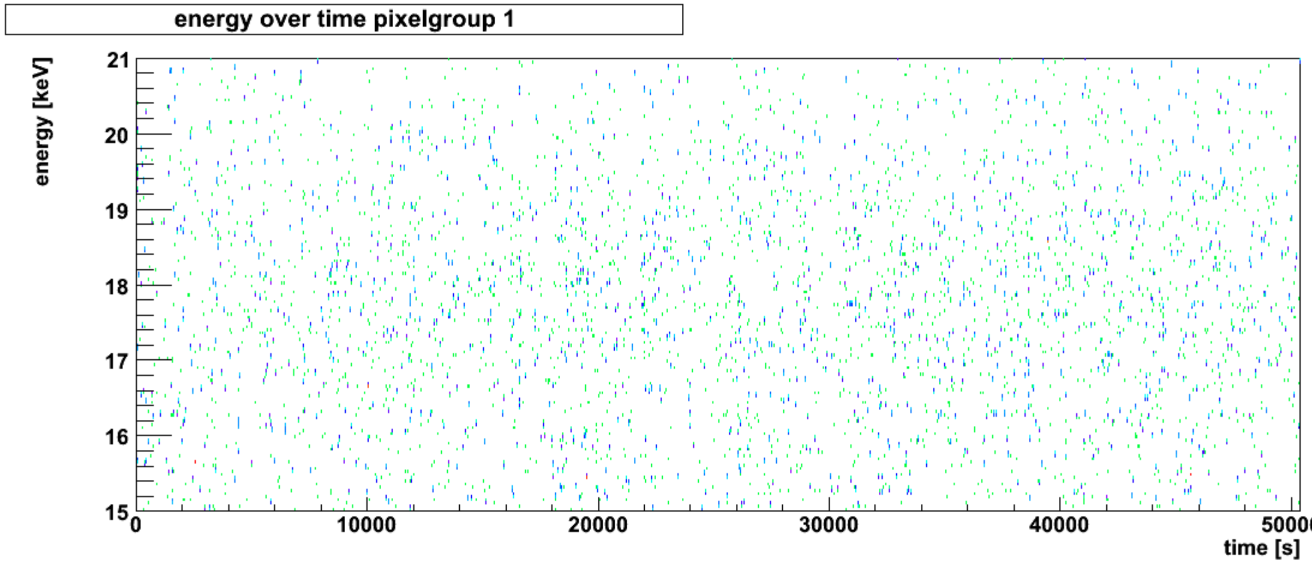
magnetic field
4.5 T (max. field)

measured time: 14 h
no increase of rate!





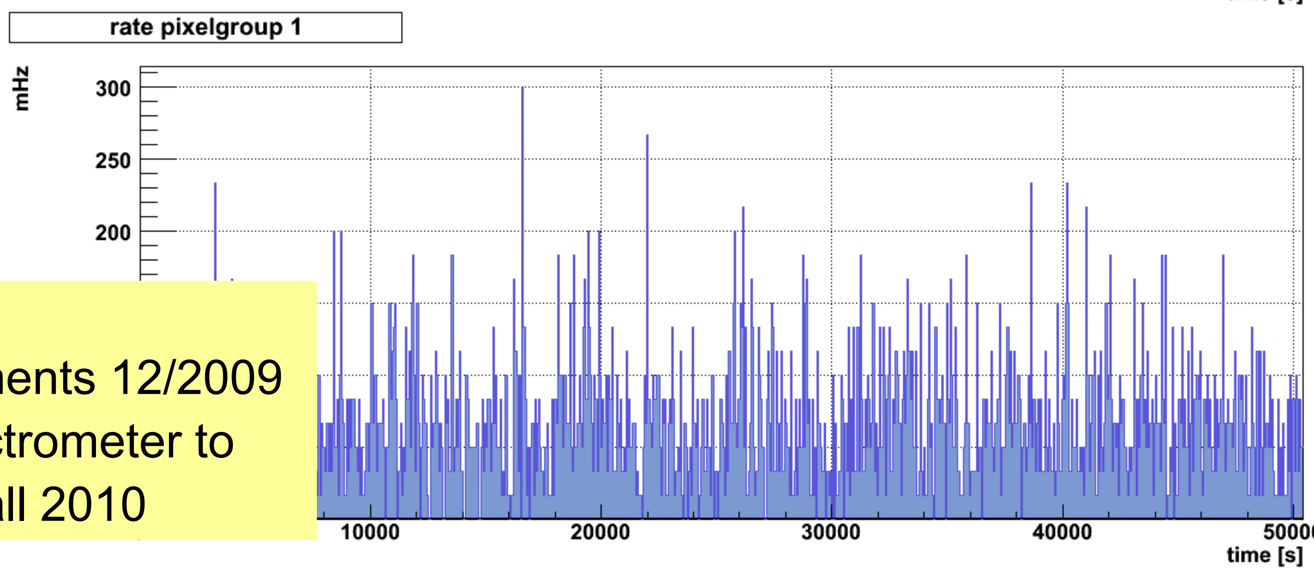
Pre-spectrometer bg studies



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

magnetic field
4.5 T (max. field)

measured time: 14 h
no increase of rate!



status:

- end of test measurements 12/2009
- relocation of pre-spectrometer to main spectrometer hall 2010

summary & outlook

- direct measurements are the only model independent way to determain the neutrino mass
- currently best upper limit for neutrino mass: $m(\nu) < 2.3$ eV (tritium decay experiments Mainz, Troitsk)
- near goal for Re-187 experiments: sensitivity of Mainz and Troitsk
- Ultimate tritium decay experiment KATRIN will measure $m(\nu)$ with a sensitivity of 0.2 eV
  - Tritium source: construction 2011/12
  - Tritium retention:
    DPS: has arrived; 2009: acceptance tests; 2009/10 test program
    CPS: TDR finished, delivery to FZK 10/2010
  - Main Spectrometer: electrode installation & start of EM test program 2010
  - Detector: assembly & initial commissioning, delivery to FZK 03/2010
  - Assembly of components & system integration 2011/12
  - Start of T_2 measurements: **2012 ⇒ 2018**

summary & outlook

- direct measurements are the only model independent way to determain the neutrino mass
- currently best upper limit for neutrino mass: $m(\nu) < 2.3$ eV (tritium decay experiments Mainz, Troitsk)
- near goal for Re-187 experiments: sensitivity of Mainz and Troitsk
- Ultimate tritium decay experiment KATRIN will measure $m(\nu)$ with a sensit

  - Tr
  - Tr
    DI
    CI
  - Ma 2010
  - Detector: assembly & initial commissioning, delivery to FZK 03/2010
  - Assembly of components & system integration 2011/12
  - Start of T_2 measurements: **2012 ⇒ 2018**

If we are lucky we might find the neutrino mass in 2015 ?

KATRIN collaboration

Universität Karlsruhe (TH)
Forschungsuniversität • gegründet 1825

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Westfälische Wilhelms-Universität Münster

University of Washington

UCL

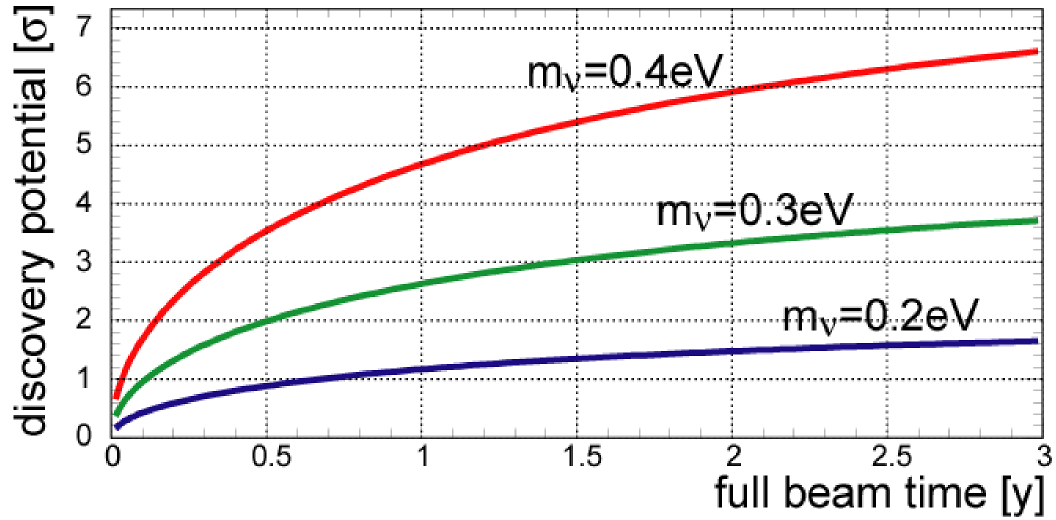
Hochschule Fulda
University of Applied Sciences

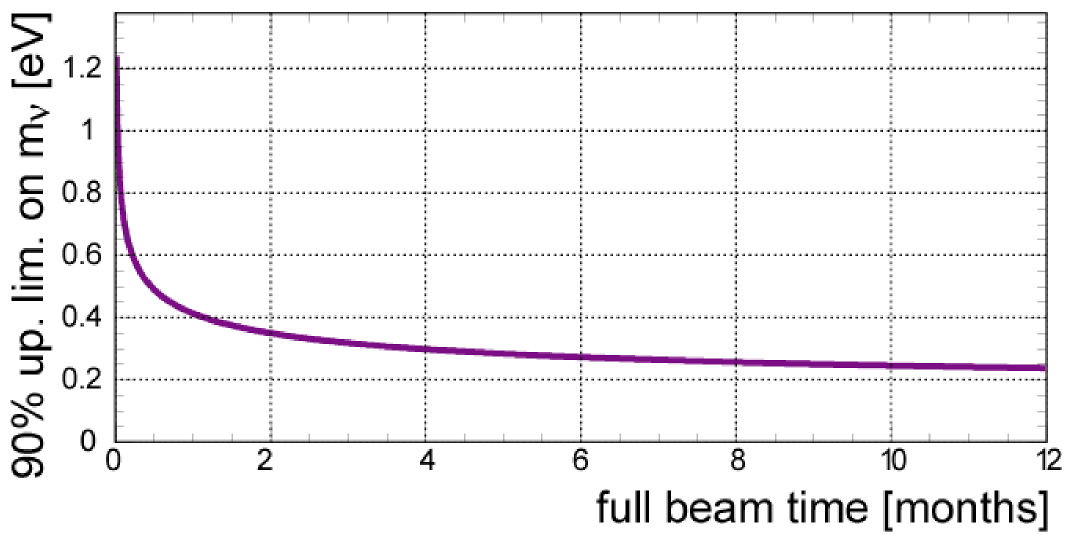
Swansea University
Prifysgol Abertawe

Johannes Gutenberg Universität Mainz

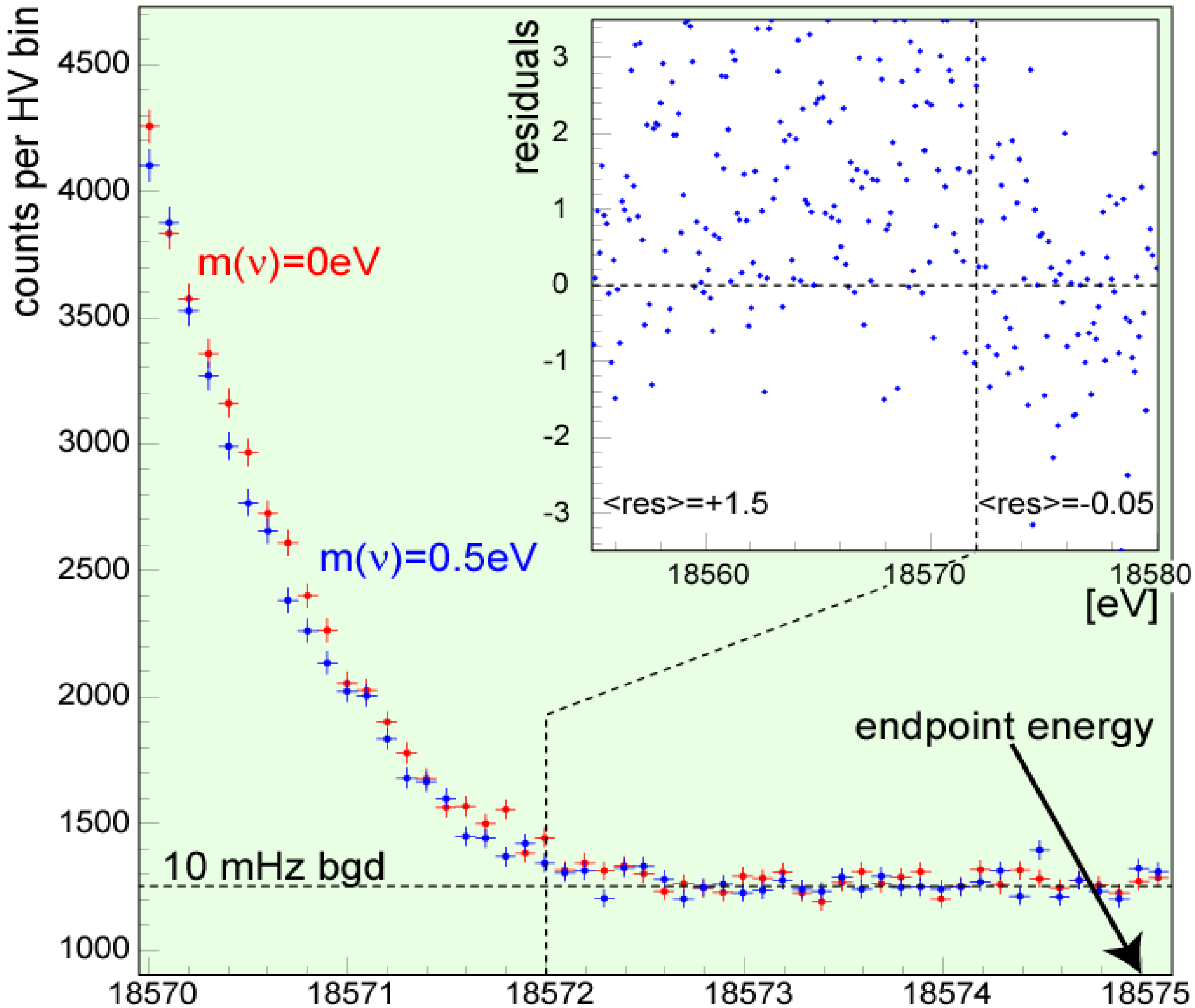
The University of North Carolina at Chapel Hill

discovery potential



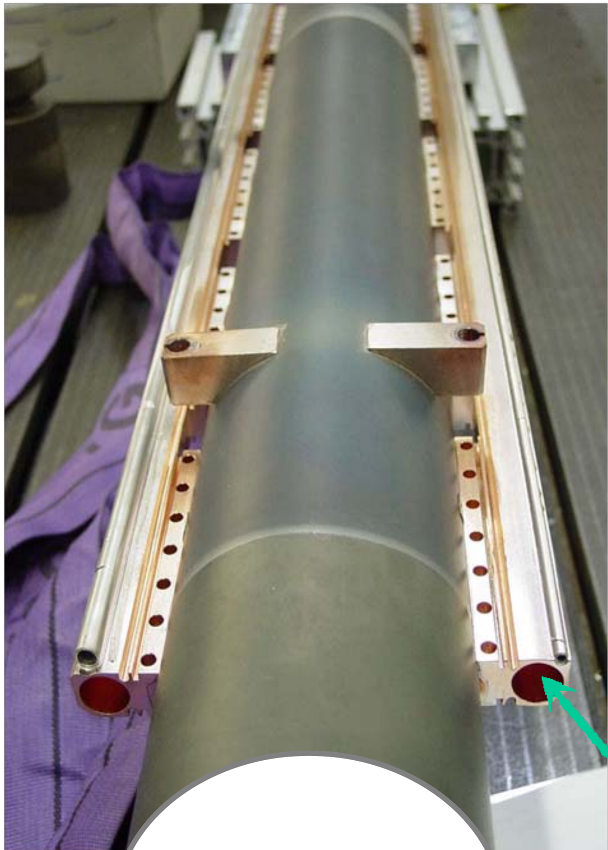


energy spectra



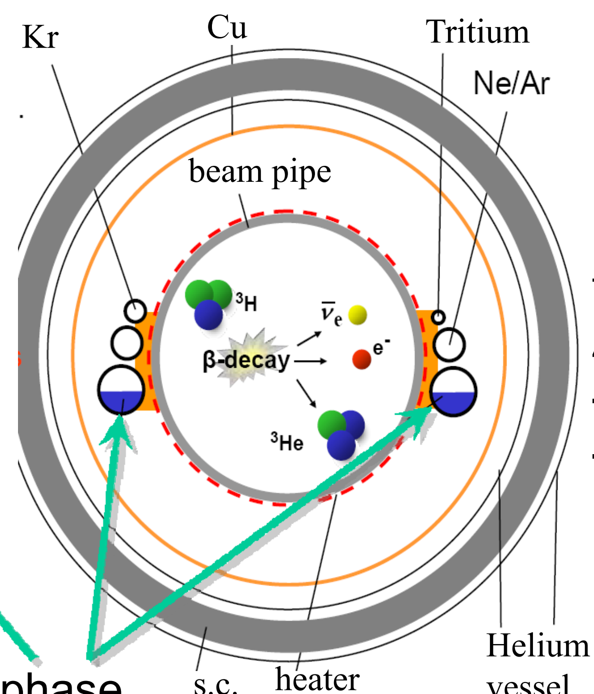
beam tube cooling for T= 30 K

Karlsruhe Institute of Technology



beam tube
Ø=90mm

principle:
2 separate cooling tubes (Ø=16mm) with
boiling LNe at p = 1 bar (thermosiphon)



temperature:
$\Delta T < \pm 30$mK
- spacial homogeniety
- stability/time

2-phase
Neon