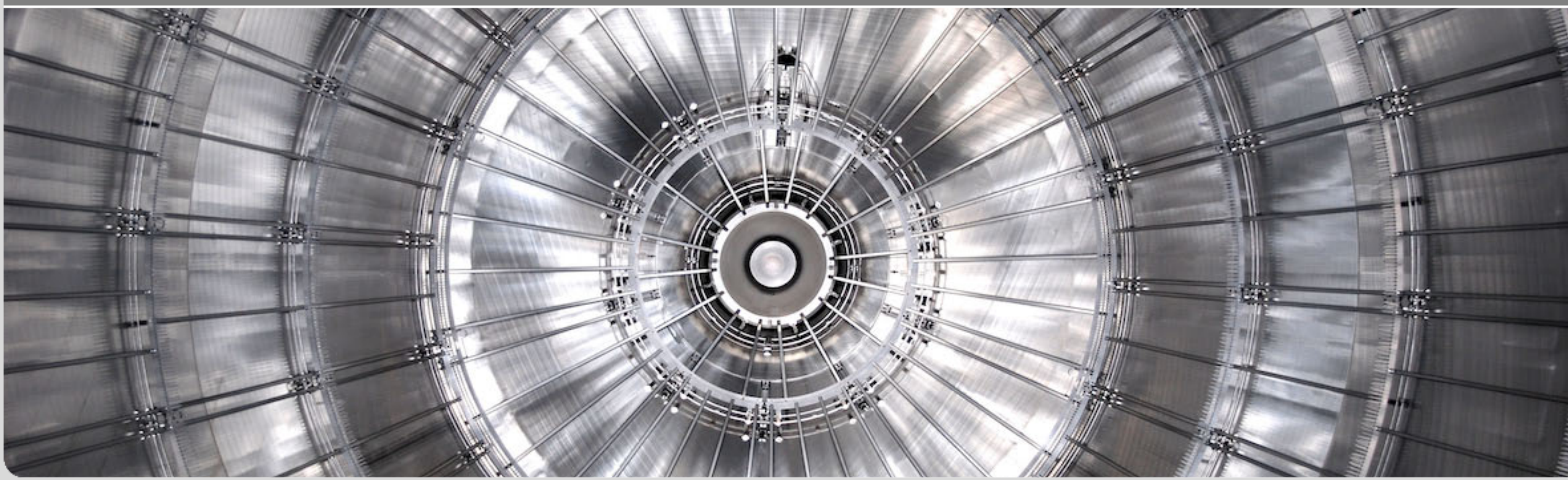
Status of the KATRIN Experiment and commissioning of the spectrometer and detector section

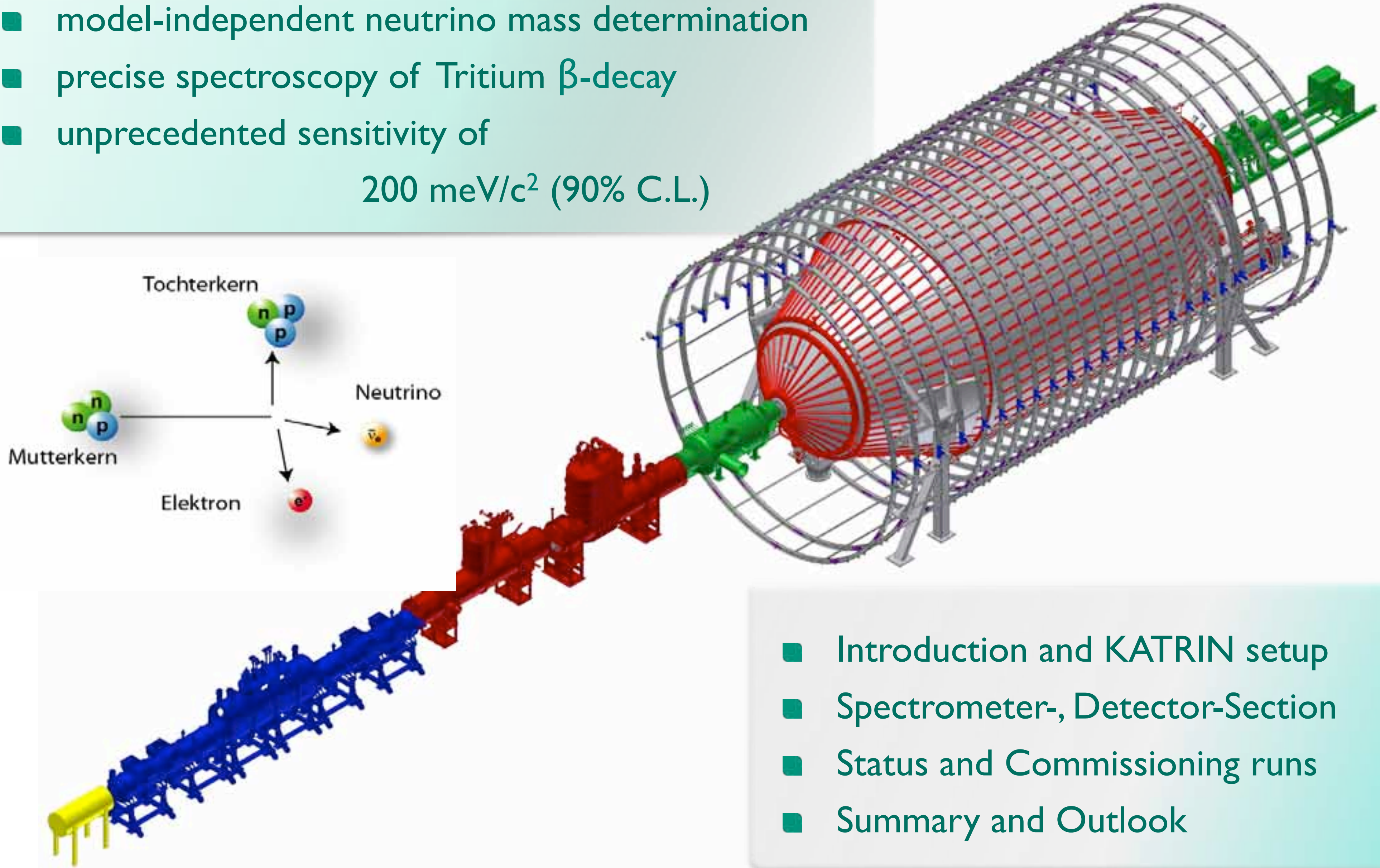
Thomas Thümmler for the KATRIN collaboration
DESY-Physikseminar, June 2013, Hamburg & Zeuthen

KIT Center Elementary Particle and Astroparticle Physics (KCETA)
Institute for Nuclear Physics (IKP)



Goal of KATRIN

- model-independent neutrino mass determination
- precise spectroscopy of Tritium β-decay
- unprecedented sensitivity of
  200 meV/c^2 (90% C.L.)



- Introduction and KATRIN setup
- Spectrometer-, Detector-Section
- Status and Commissioning runs
- Summary and Outlook

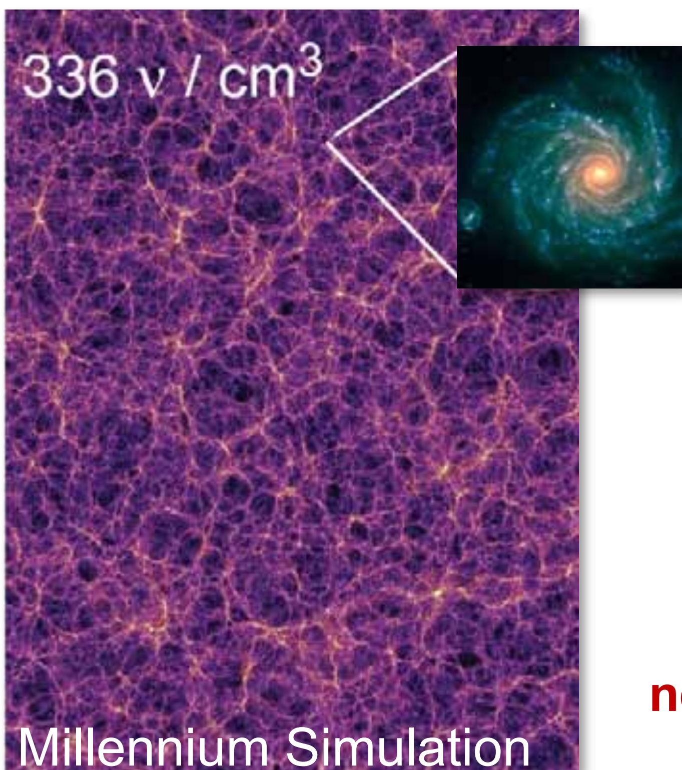
Motivation: Neutrinos in Astroparticle Physics

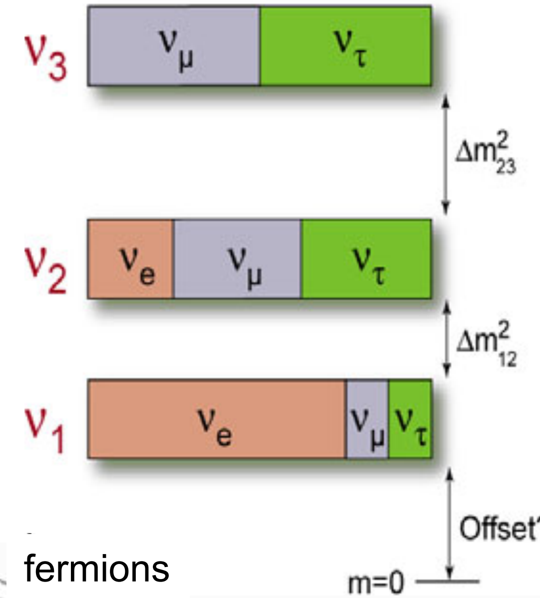
Karlsruhe Institute of Technology

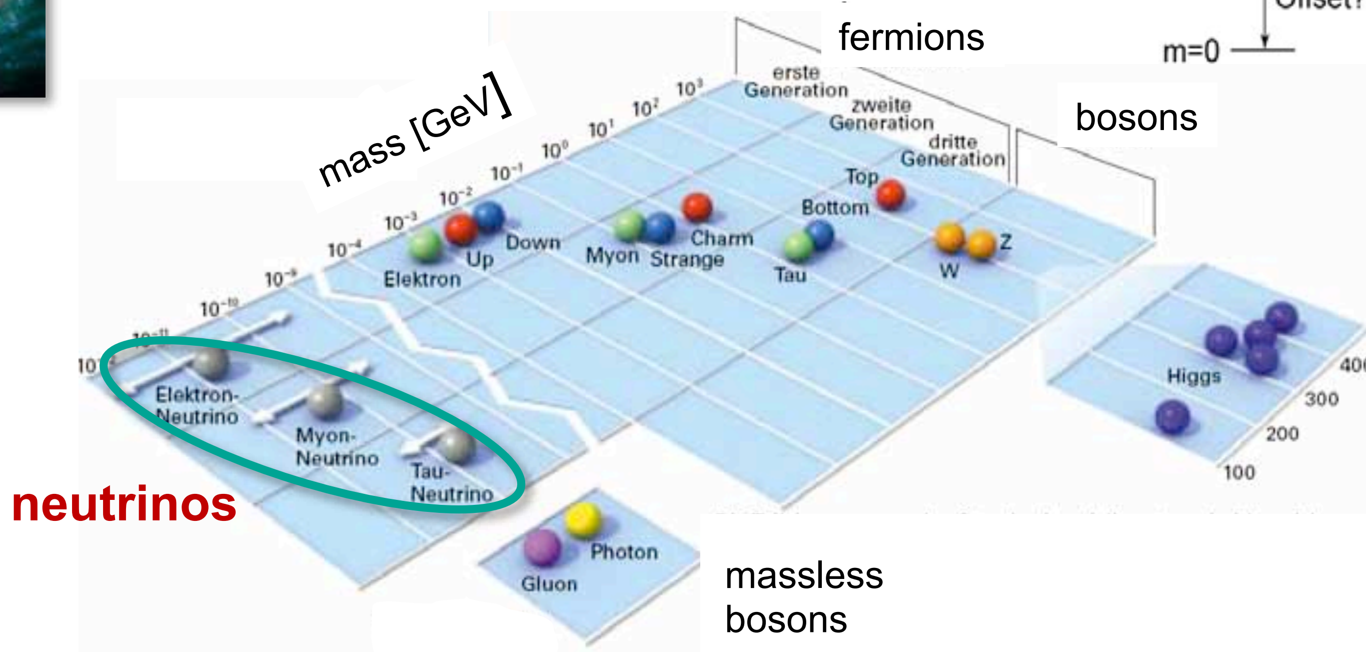
cosmology: role of ν´s as hot (warm?) dark matter?

particle physics: origin and hierarchy of the ν-mass?

cosmology ⇔ **particle physics**







Neutrino Mass: Status and Perspectives

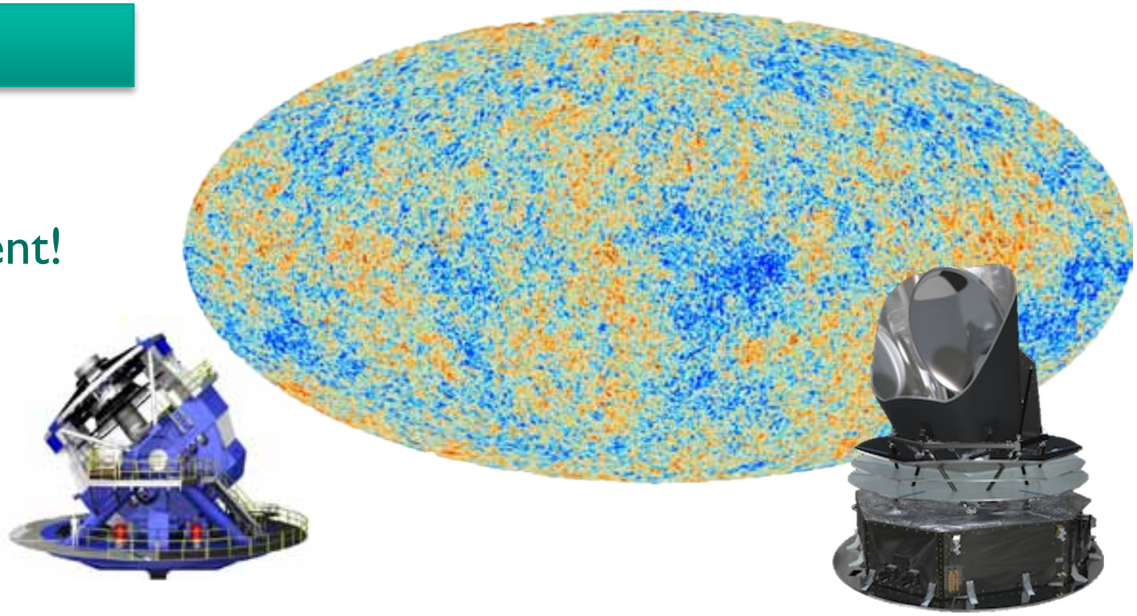
Experiments on Neutrino Oscillations:

- Clear evidence for neutrino flavour oscillations:
  - Atmospheric neutrinos: $(\Delta m_{32})^2 \cong 2.4 \times 10^{-3}\ \mathrm{eV}^2/c^4$
  - Solar neutrinos: $(\Delta m_{21})^2 \cong 7.6 \times 10^{-5}\ \mathrm{eV}^2/c^4$

➔ Well established fact: $m_\nu \neq 0$

Input from Cosmology:

- measures Σm_i and HDM Ω_ν
- very sensitive, but model dependent!
- Planck: $\Sigma m_i < 0.98$ eV
  (Planck 2013 results. XVI. Cosm. param.)
- potential: $\Sigma m_i = 20\text{-}50$ meV
  (Planck, LSST, weak lensing)



Neutrino Mass: Status and Perspectives

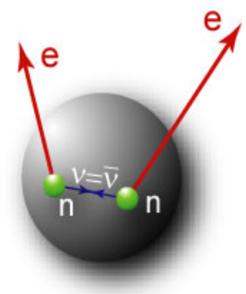
neutrino masses
in lab. experiments

Neutrino Mass: Status and Perspectives

Karlsruhe Institute of Technology

neutrino masses
in lab. experiments

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



model-dependent (CP-phases)

effective Majorana mass:

$$m_{\beta\beta} = \left| \sum_{\mathrm{i}} U_{\mathrm{ei}}^2 \cdot m_{\nu_{\mathrm{i}}} \right|$$

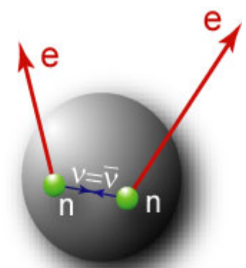
- probe ν as Majorana particle: $\nu = \overline{\nu}$?
- status: $m_{ßß}$ < 0.35 eV, evidence?
- potential: $m_{ßß}$ = 20-50 meV
- GERDA, EXO, SNO+, MAJORANA, Cuore, KamLAND-Zen, ...

Neutrino Mass: Status and Perspectives

neutrino masses
in lab. experiments

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

kinematics of ß-decay
absolute ν_e-mass: m_ν



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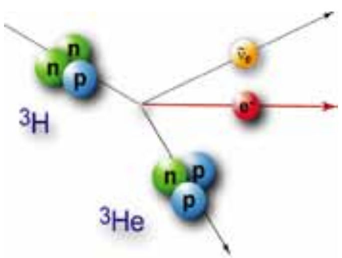


model-independent

squared neutrino mass:

$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

- direct, from kinematics
- status: m_ν < 2.3 eV
- potential: m_ν = 200 meV
- KATRIN, MARE, Project 8, ECHO

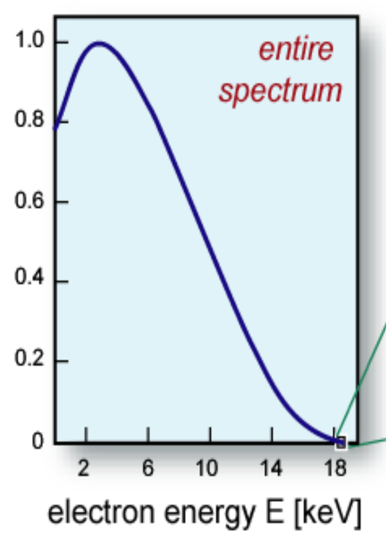
ß-decay – Fermi theory & ν-mass

ß-decay kinematics close to endpoint E_0: model independent measurement of $m(\nu_e)$, based solely on **kinematic parameters & energy conservation**

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

observable $m^2(\nu_e)$:
effective electron-ν-mass

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



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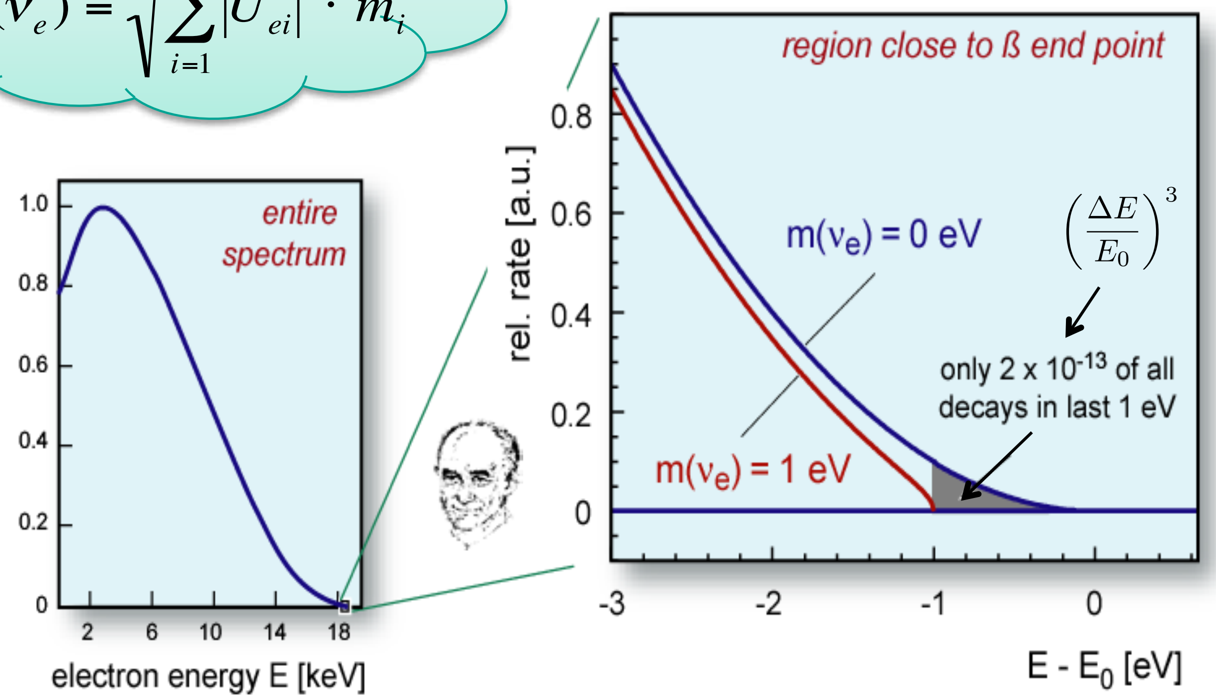

- small modifications by final states, radiative & recoil corrections

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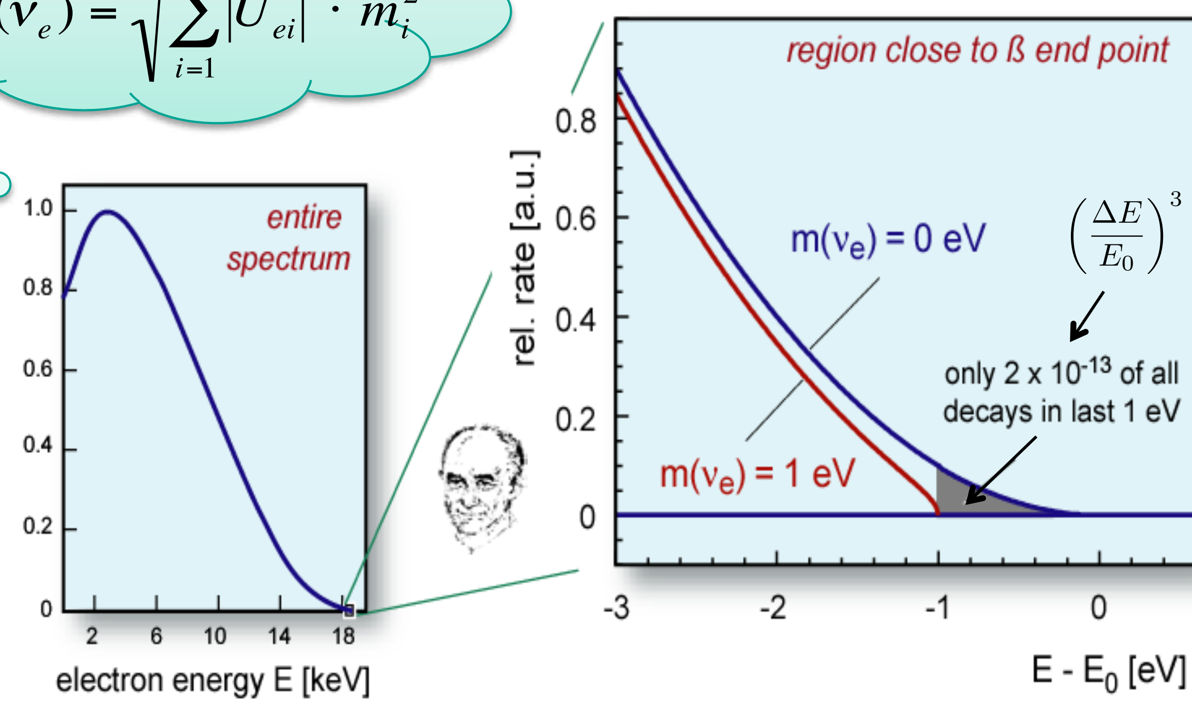
key requirements:

- low endpoint β source
- high count rate
- high energy resolution
- extremely low background



- small modifications by final states, radiative & recoil corrections

The MAC-E filter

Magnetic Adiabatic Collimation with Electrostatic Filter A. Picard et al., NIM B 63 (1992)

Design Facts:

$B_{max} = 6$ T

$B_{min} = 0.3$ mT

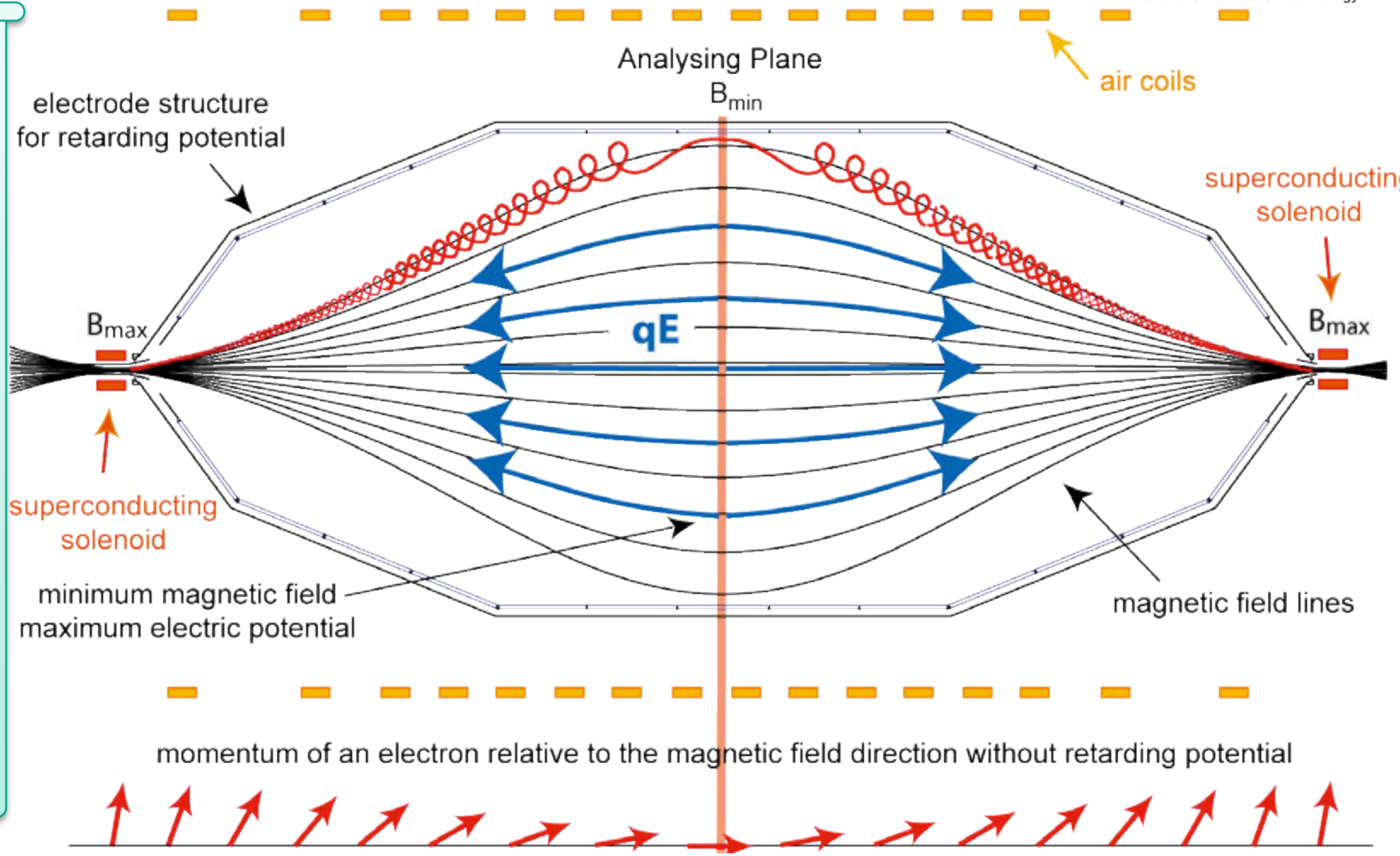
$B_{min} / B_{max} = 5 \cdot 10^{-5}$

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

$U_0 = 18.6$ kV

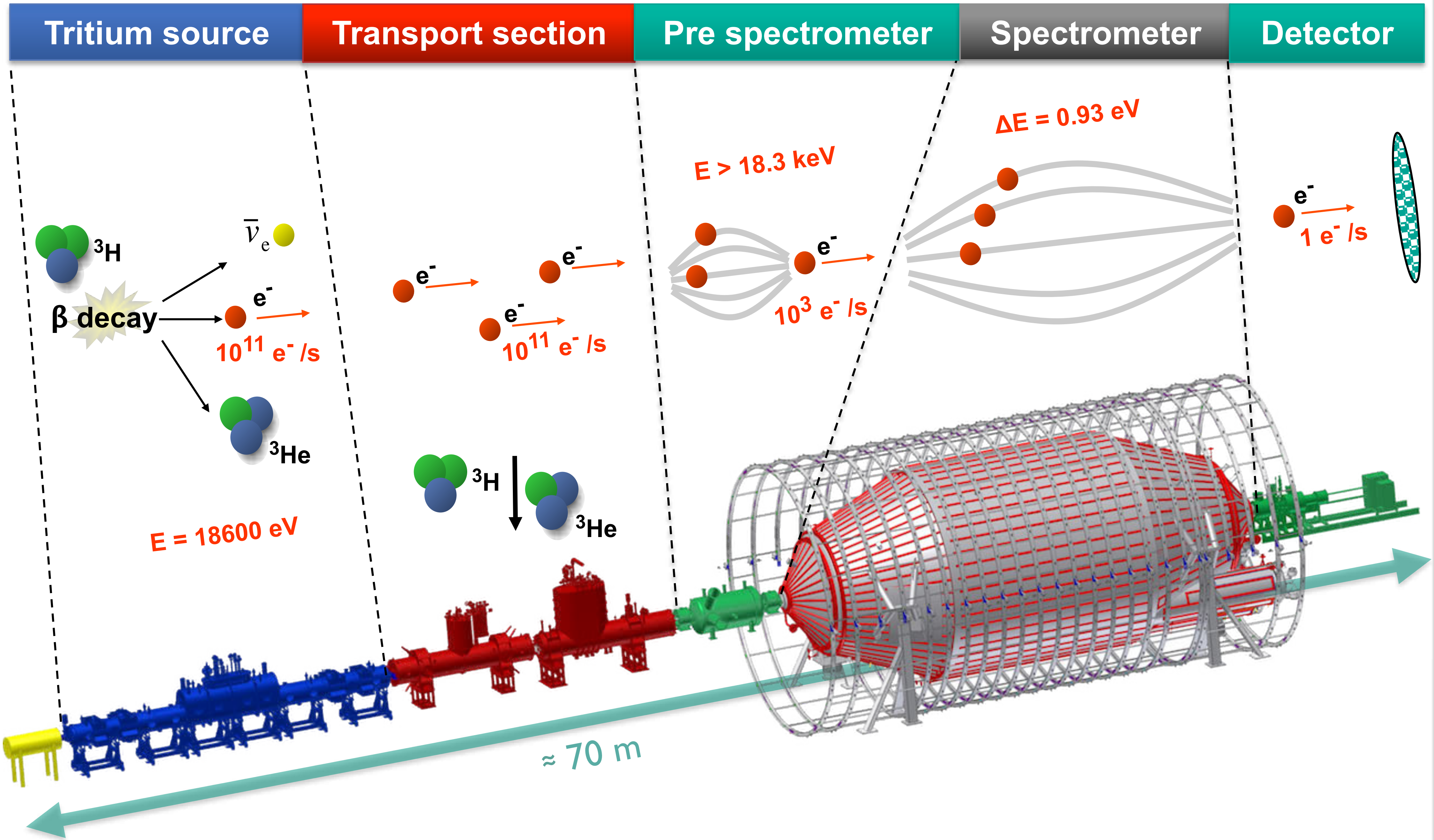
$E = 18.6$ keV

$E = E_{\perp} + E_{\parallel}$

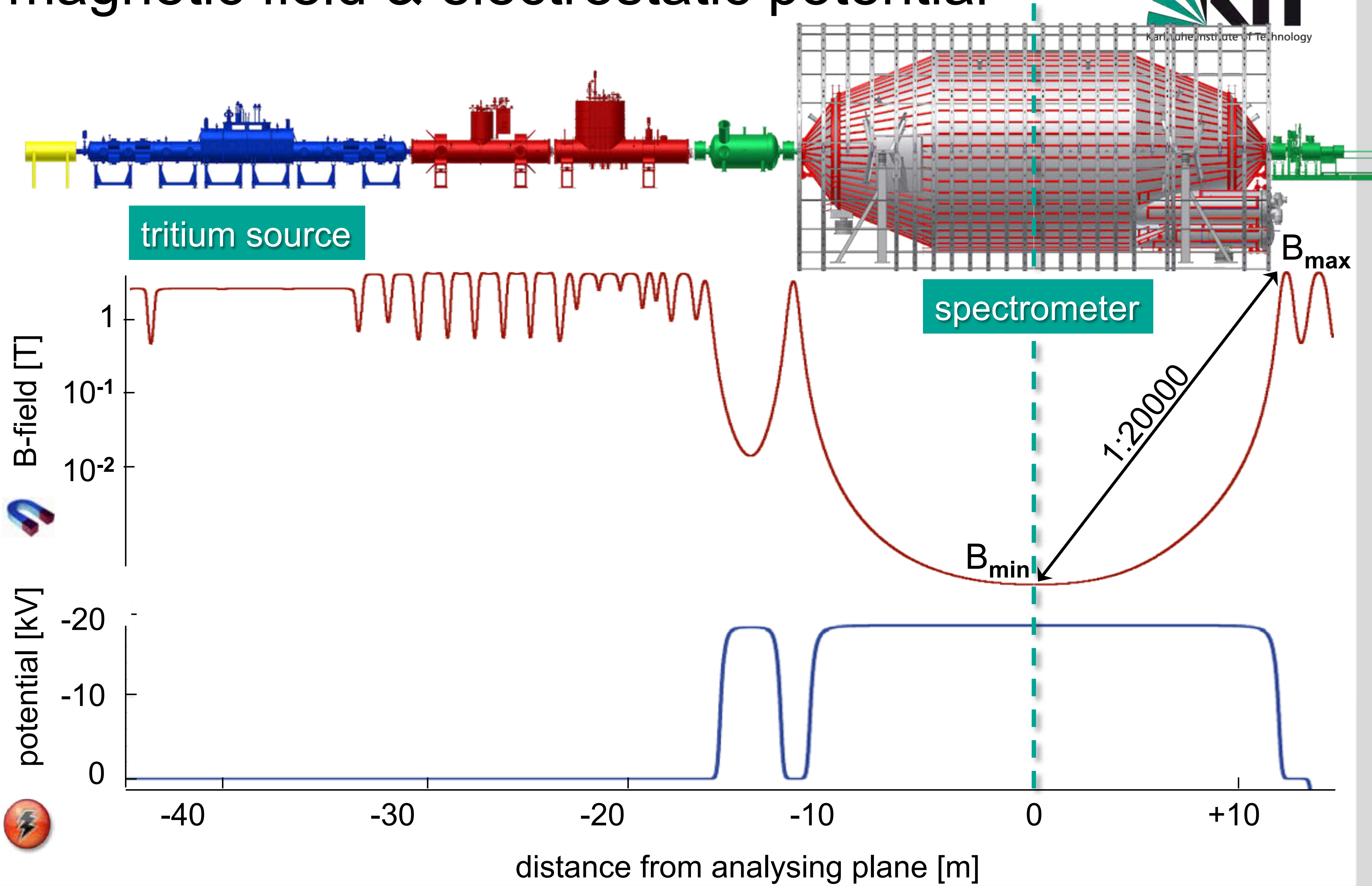


- **collimation:** adiabatic transport: $E_{\perp} \rightarrow E_{\parallel}$ due to $\mu = const.$
- **energy analysis:** only electrons with $E_{\parallel} > eU_0$ (retarding potential) can pass analysing plane → **high-pass filter** with a sharp transmission function, no tails!
- **energy resolution:** $\Delta E = E \cdot B_{min} / B_{max} = 0.93$ eV

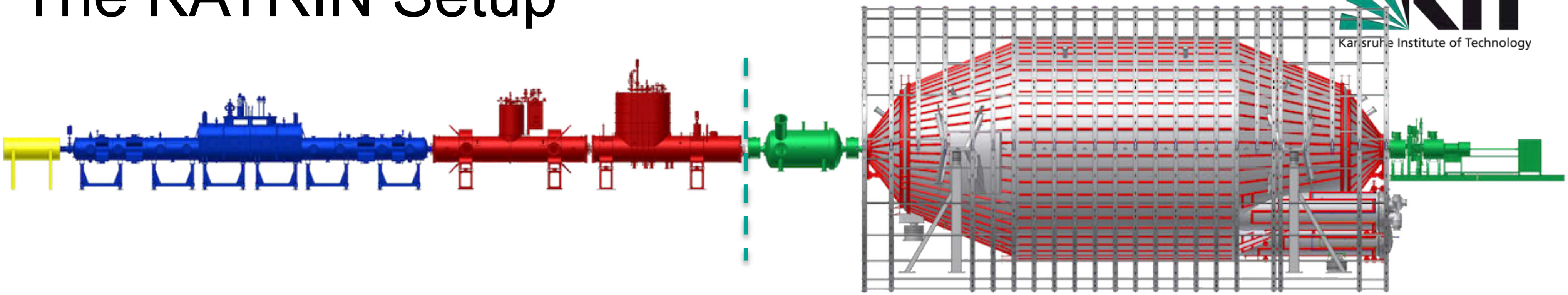
The KATRIN Setup - Overview



magnetic field & electrostatic potential



The KATRIN Setup



tritium-bearing components

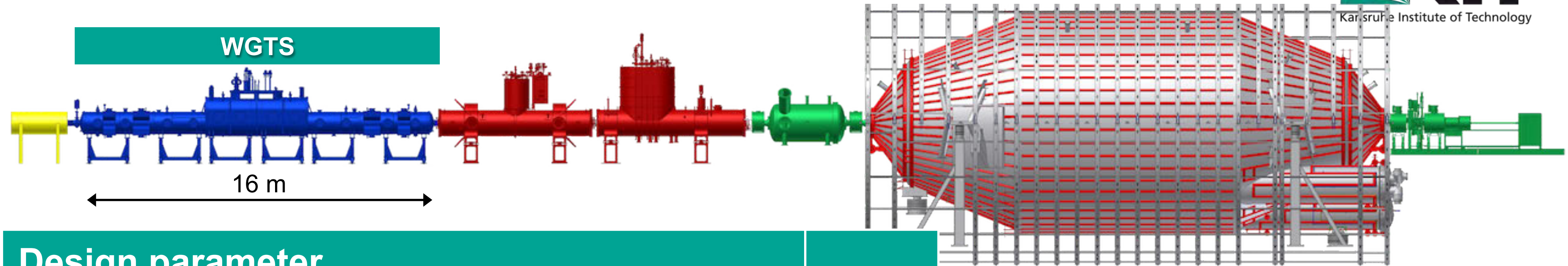
electrostatic spectrometers & detector

10^{11} electrons/s tritium source

$<10^{-2}$ cps total background

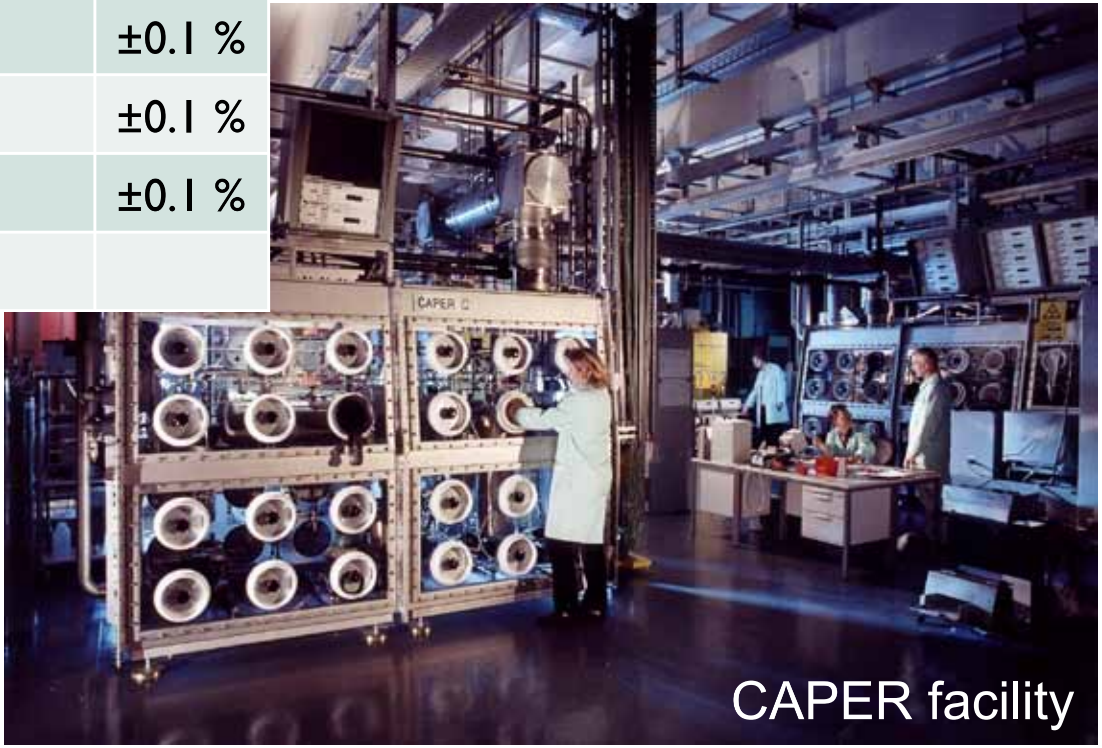
- 10^{-3} stability of tritium source column density ρd
- retention factor for molecular tritium R = 10^{14}
- effective removal of ions
- fully adiabatic (meV scale) transport of electrons over > 50 m
- avoid particle storage in Penning-like traps
- avoid contermination by Rn in the volume

Windowless Gaseous Tritium Source WGTS



Design parameter		
luminosity	1.7×10^{11} Bq	
injection rate	5×10^{19} T_2/s ≈ 40 g/day ≈ 10 kg/y	
Tritium purity	> 95%	±0.1 %
temperature	T = 27 K ± 30 mK	±0.1 %
pressure	$p_{inj} \approx 10^{-3}$ mbar	±0.1 %
magnetic guiding	B = 3.6 T	

Tritium Laboratory Karlsruhe
- a unique research facility in Europe



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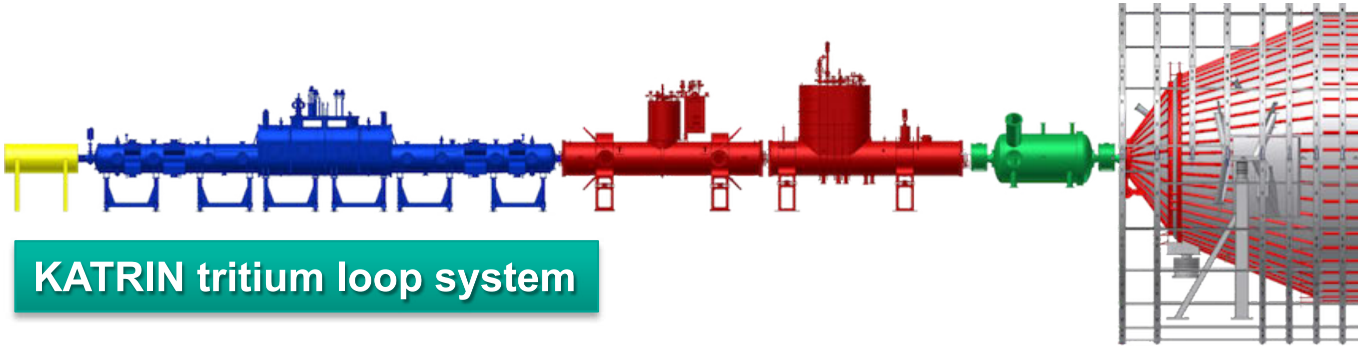
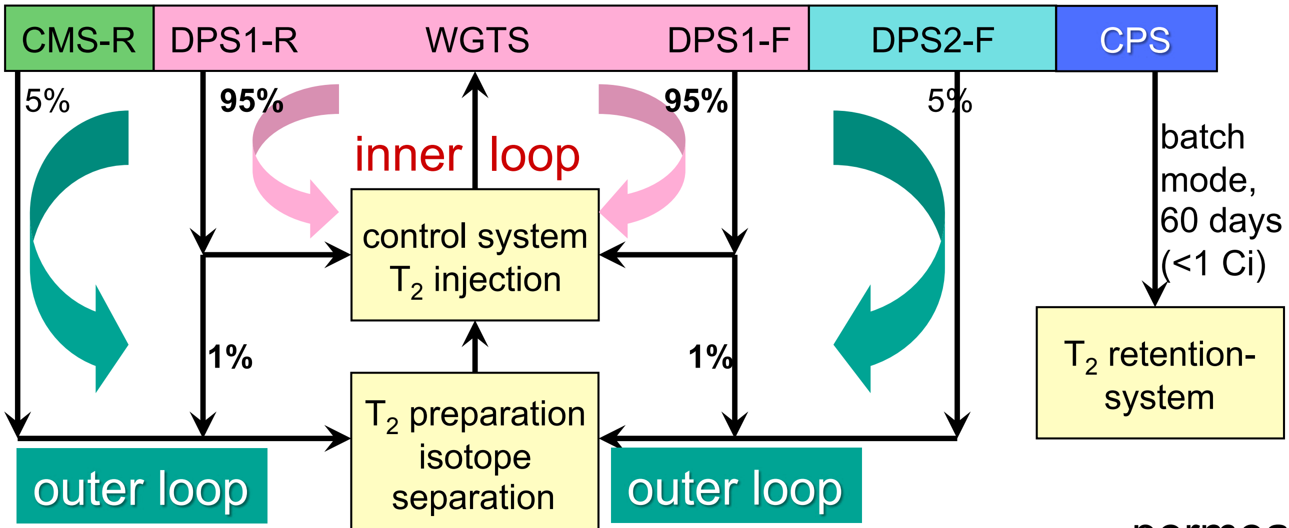
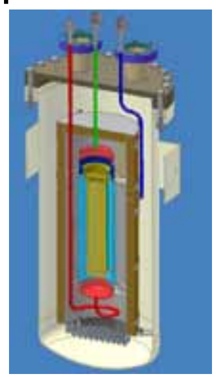
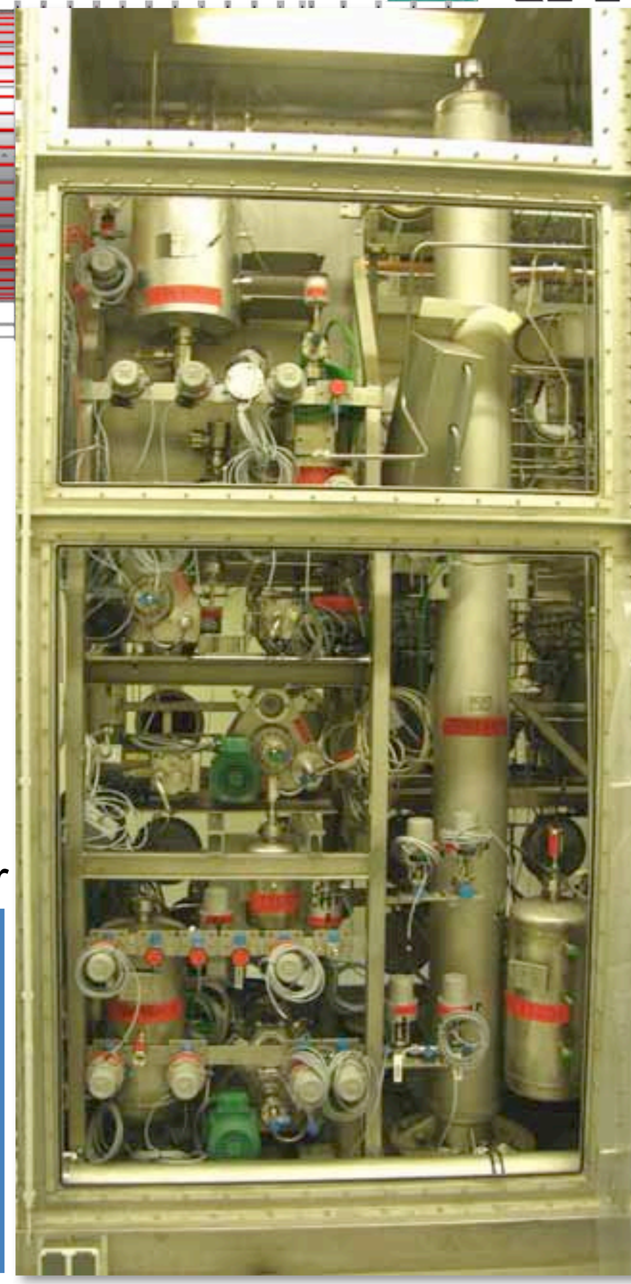


KATRIN tritium loop system



permeator



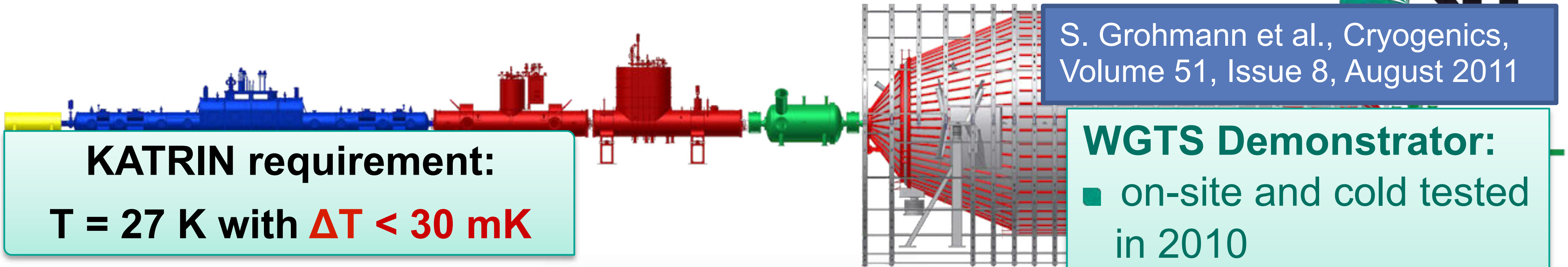


Up and running extremely stable!

- **designed for a stability at 10^{-3} level**
- **achieved: 2×10^{-4} over 4 months**

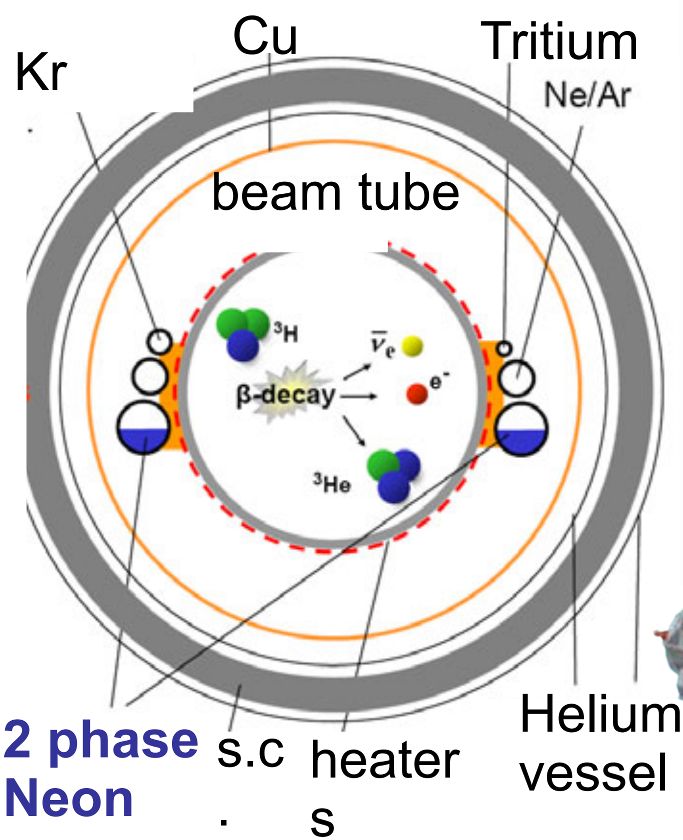
Windowless Gaseous Tritium Source WGTS

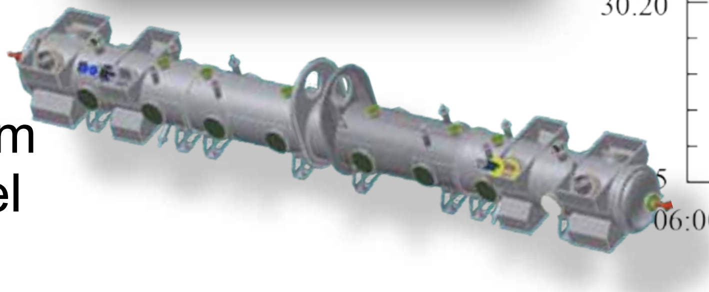
S. Grohmann et al., Cryogenics, Volume 51, Issue 8, August 2011

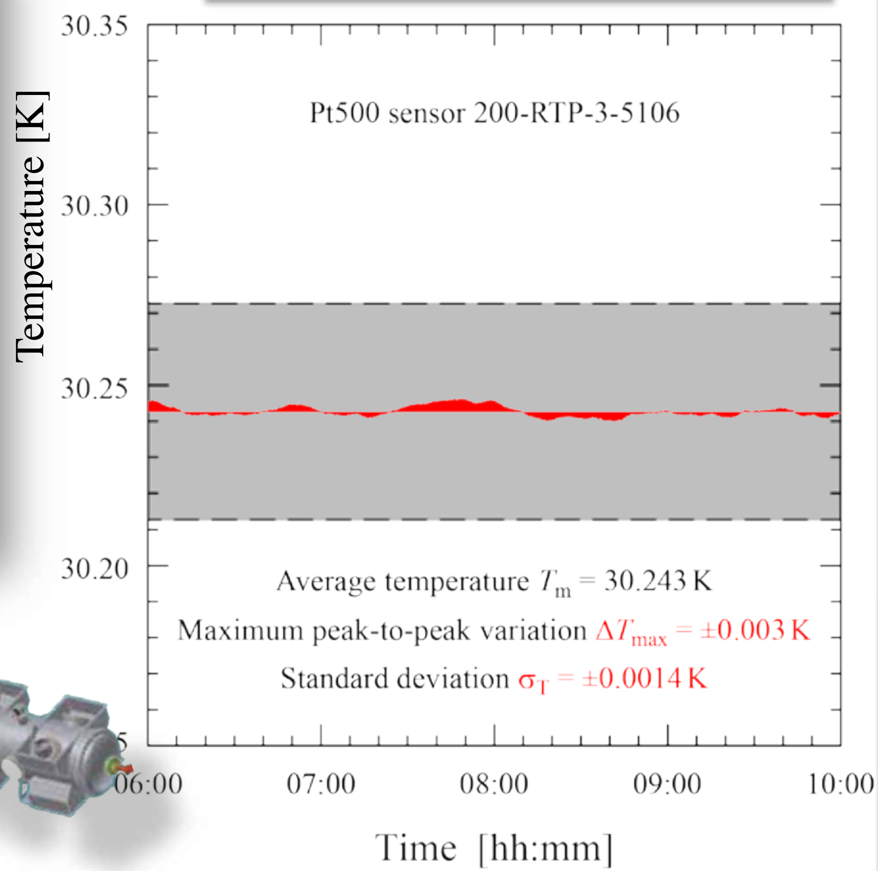


KATRIN requirement:
T = 27 K with ΔT < 30 mK

WGTS Demonstrator:
- on-site and cold tested in 2010
- $\Delta T_{max} = \pm 3$ mK



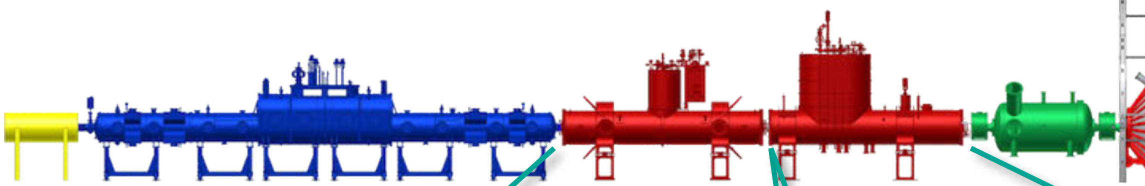


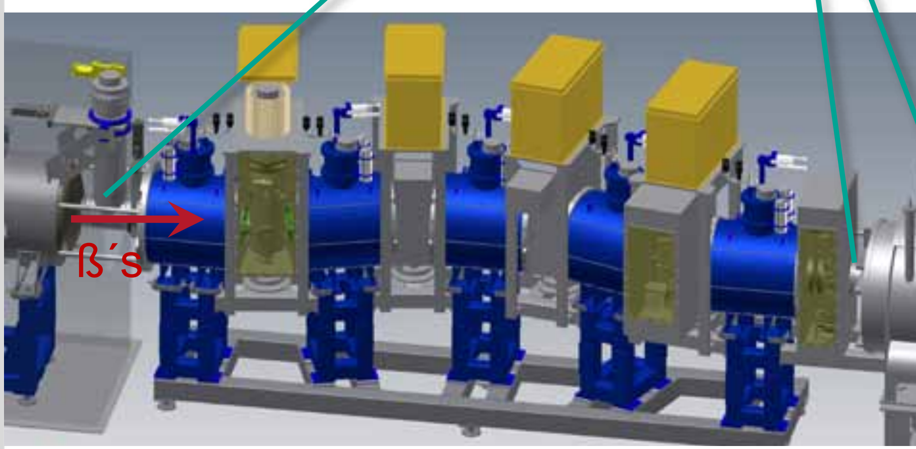


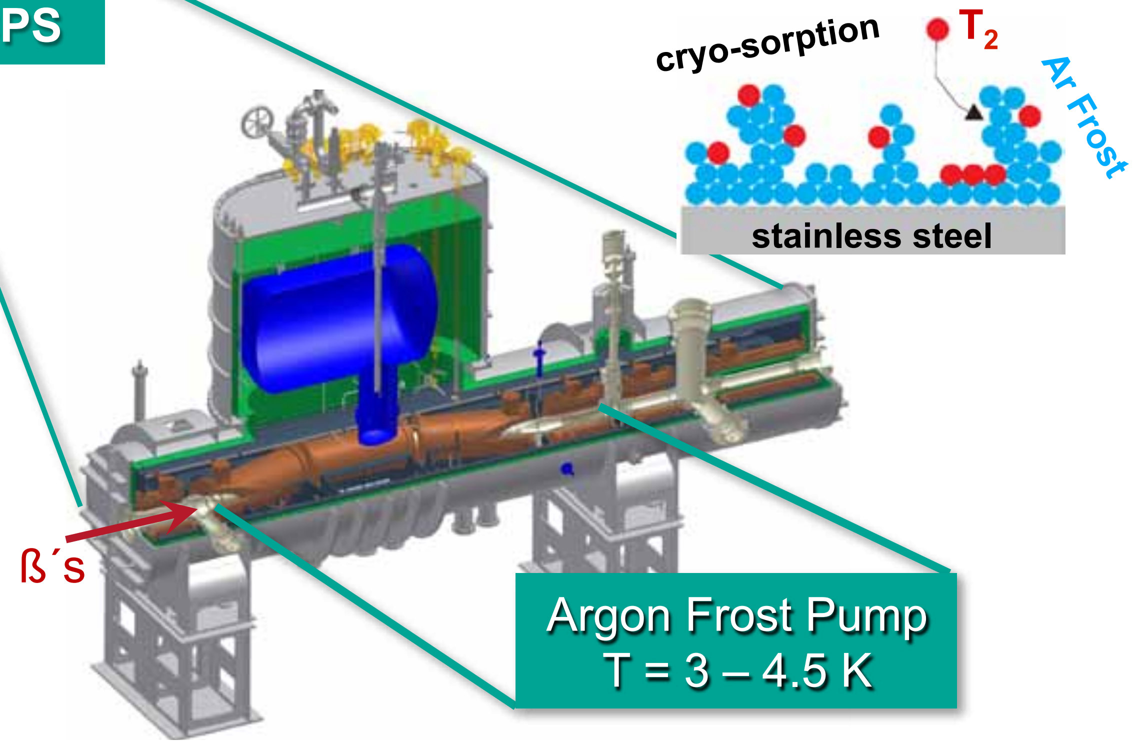
Transport and Pumping Sections

O. Kazachenko et al., NIM A 587 (2008) 136

F. Eichelhardt et al, Fusion Science and Technology 54 (2008) 615



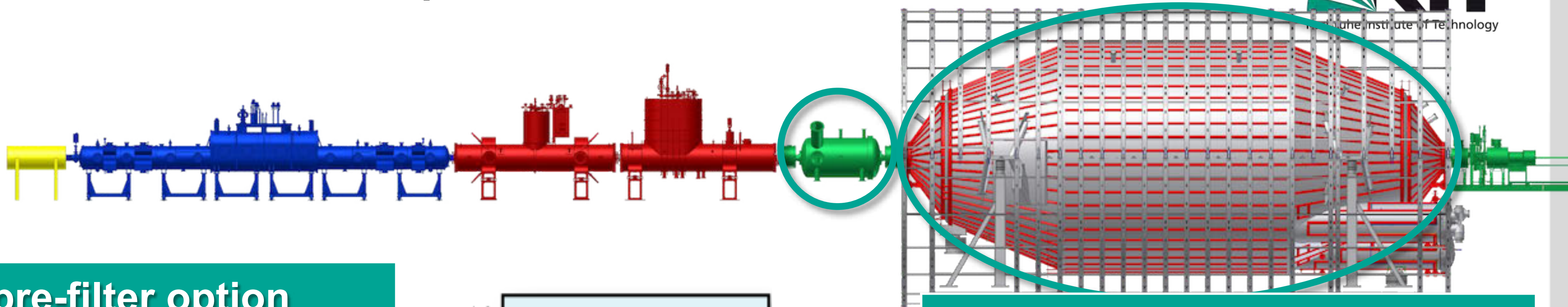




- active pumping, 4 TMPs
- Tritium retention 10^5
- magnetic field: 5.6 T
- under construction, to be installed 2014

- pumping by cryo-sorption
- Tritium retention $>10^7$
- magnetic field: 5.6 T
- delivery Spring 2014

Electrostatic Spectrometers



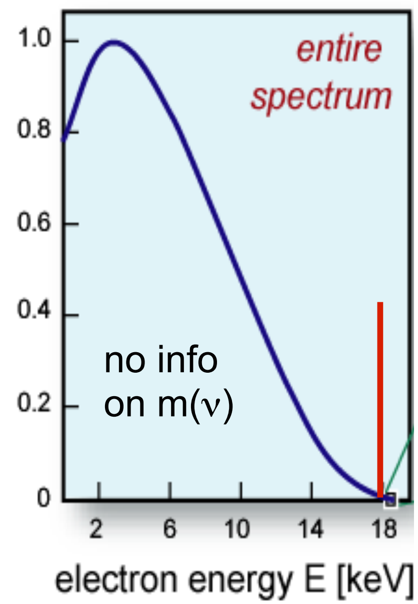
pre-filter option

fixed retarding potential

U_0 = - 18.3 kV

ΔE ~ 100 eV

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

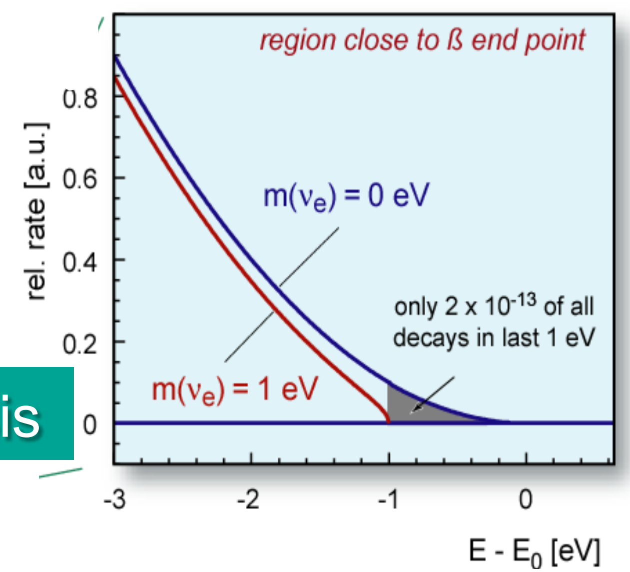


precision filter - scanning

variable retarding potential

U_0 = - 18.4 … -18.6 kV

ΔE ~ 0.93 eV (100% transmission)

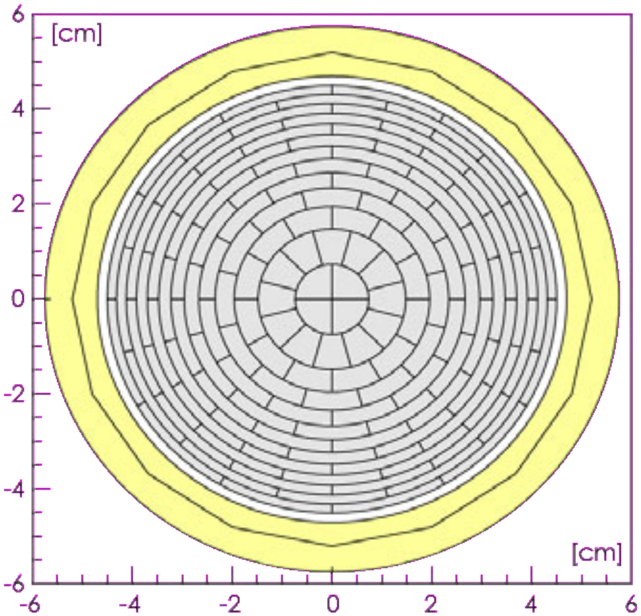


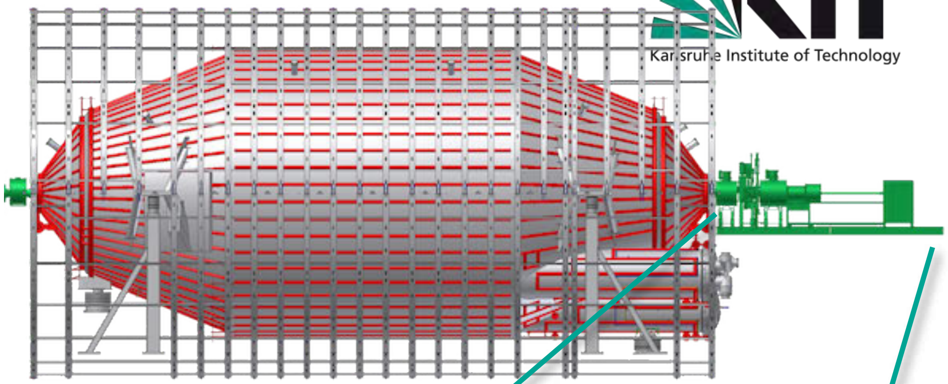
tandem design: pre-filter & energy analysis

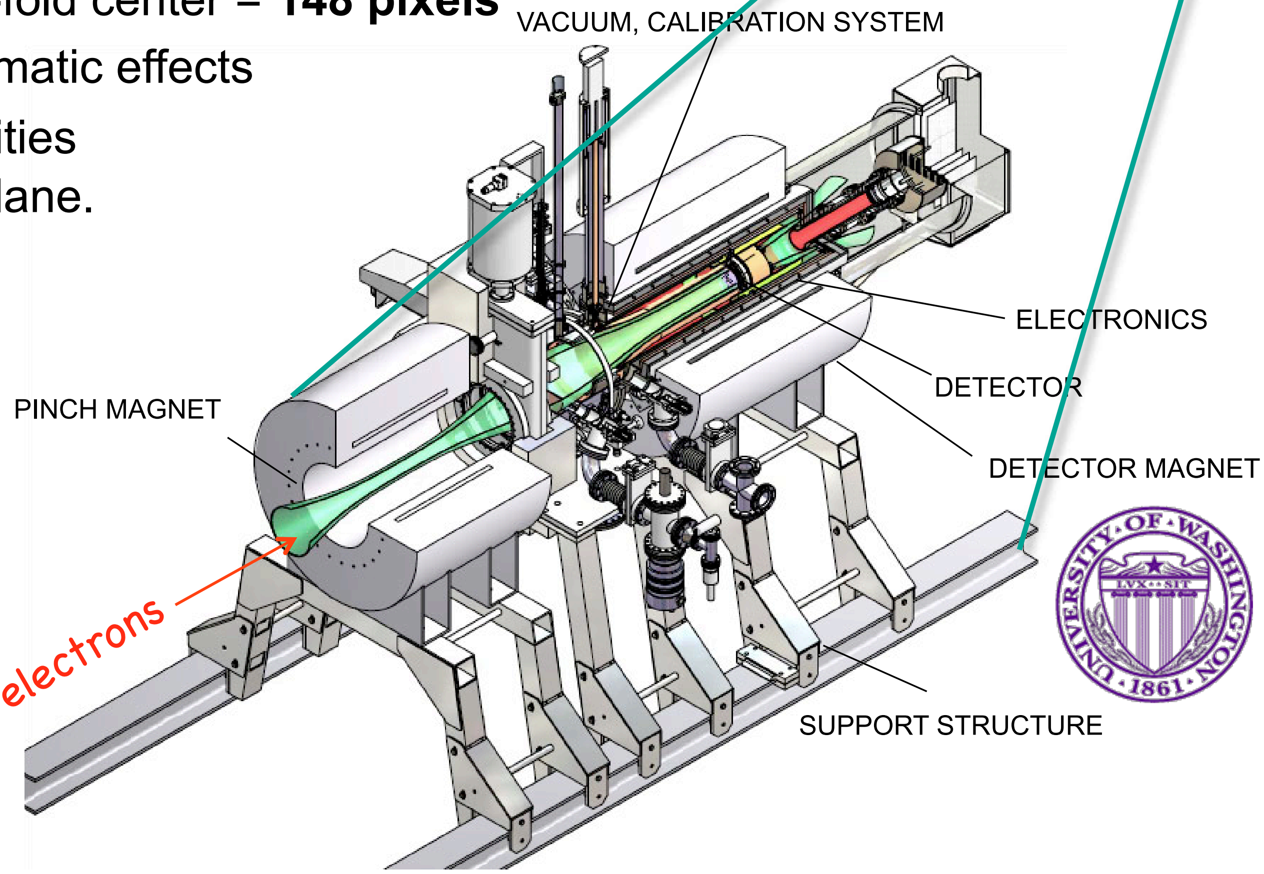
10^{11} electrons/s ⇨ 10^{-2} electrons/s

KATRIN Main Detector

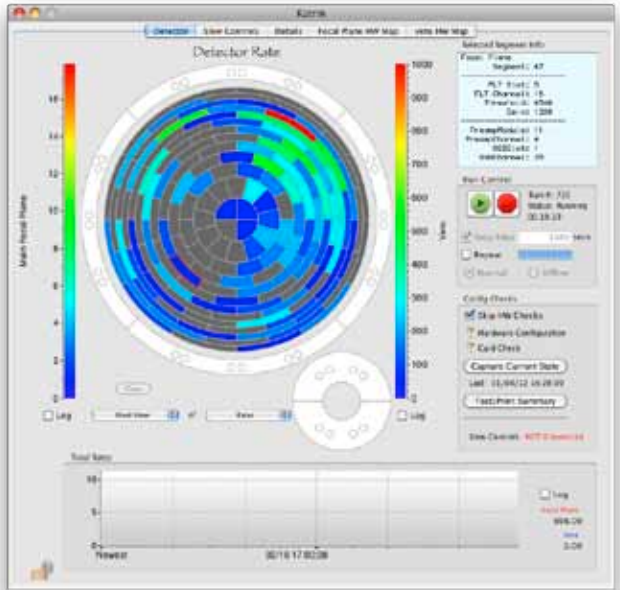
- Si-PIN diode
- detection of transmitted β's (mHz to kHz)
- **low background for T_2 endpoint investigation**
- high energy resolution:
  ΔE = 1.48(1) keV (FWHM) at 18.6 keV
- 12 rings with 30° segmentation + 4-fold center = **148 pixels**
  - minimize bg, investigate systematic effects
  - compensate field inhomogeneities of spectrometer's analyzing plane.

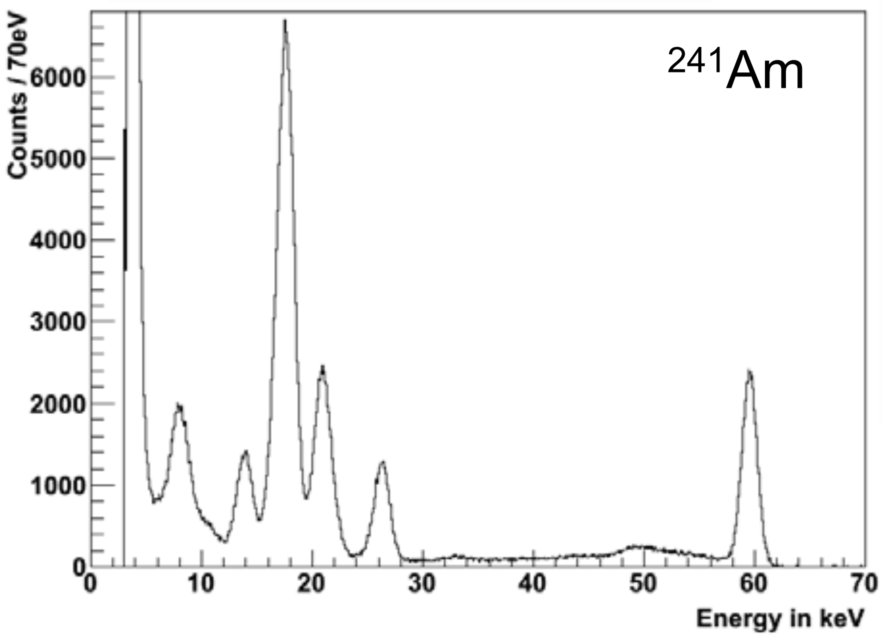


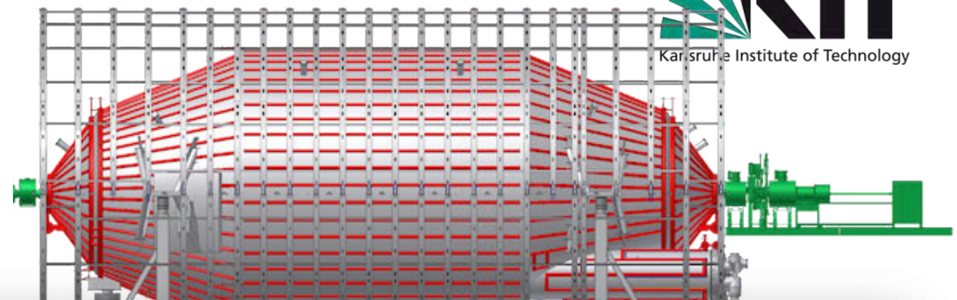




KATRIN Main Detector



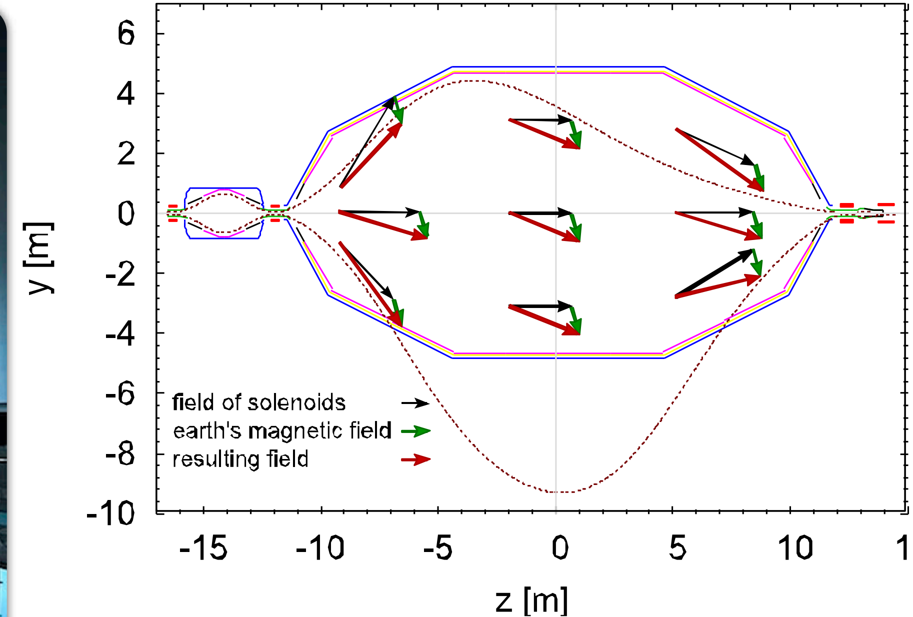




- detector commissioning completed
- first light from spectrometer – May 2013

Air Coil System

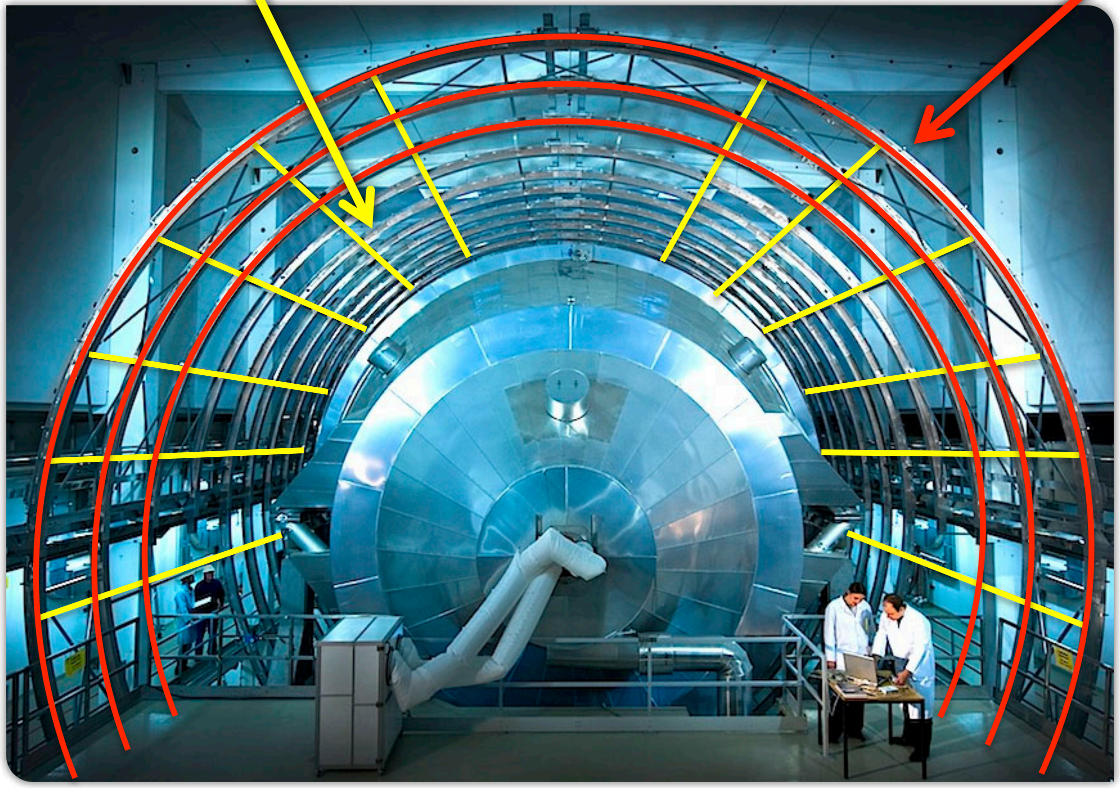
- Earth magnetic field compensation & low field correction

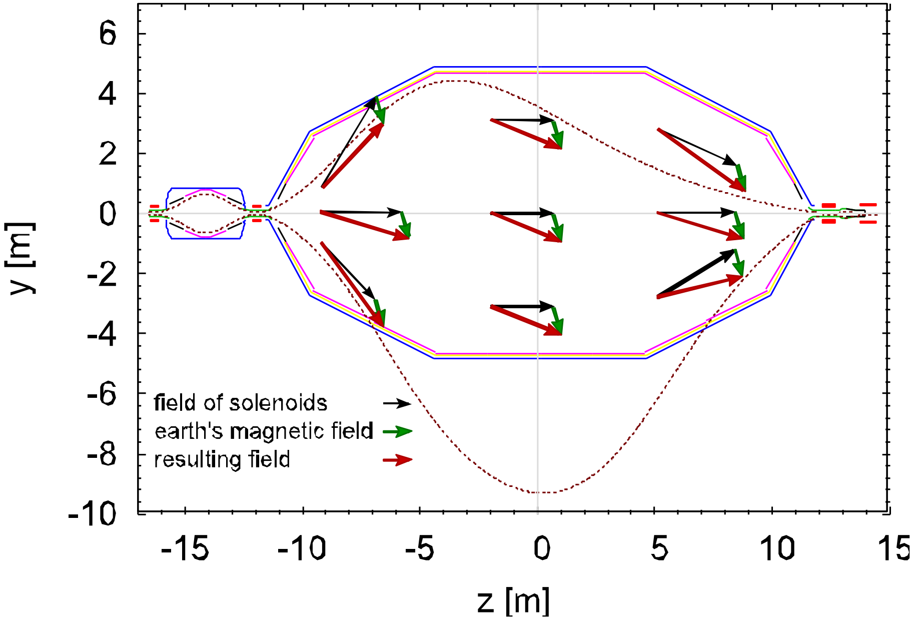


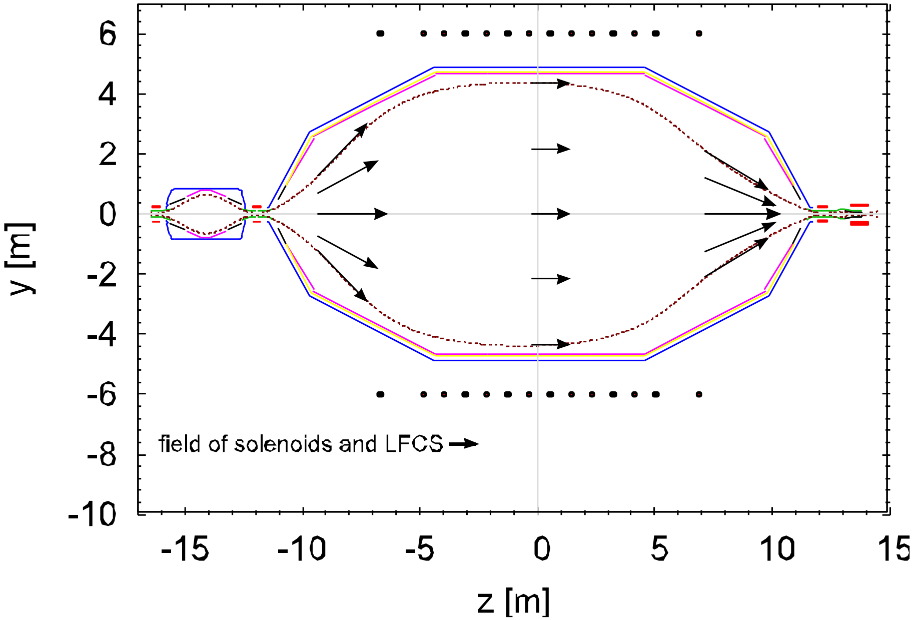
- earth magnetic/environmental fields distort magn. flux tube in low field region (0.3 mT)
- needs to be compensated!
- low field correction:
  - optimize flux tube
  - fine tune transmission and resolution.

Air Coil System

- Earth magnetic field compensation & low field correction







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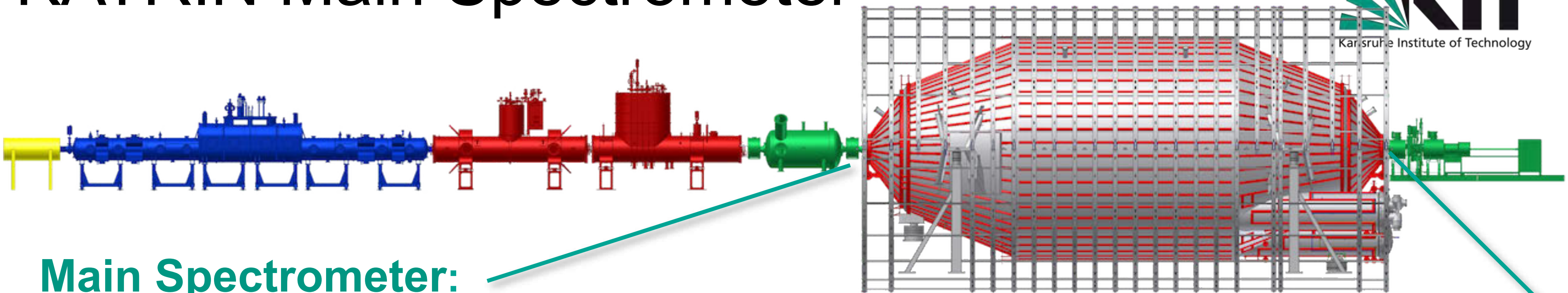
KATRIN Main Spectrometer



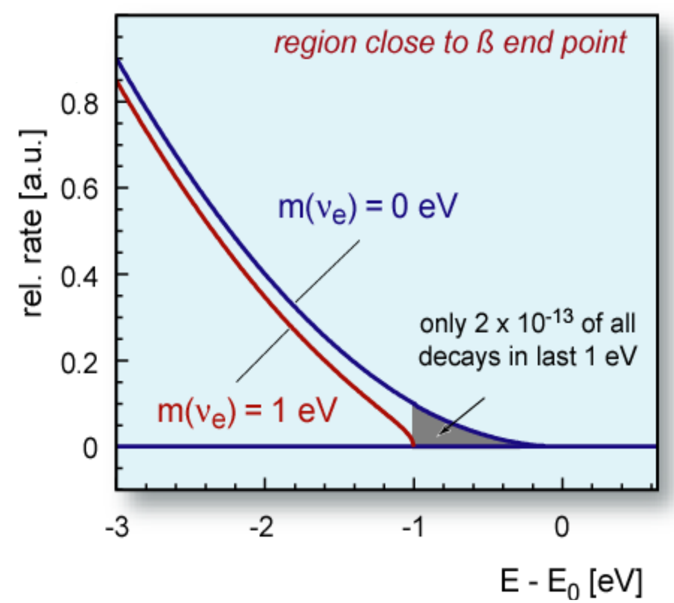
Main Spectrometer:

- MAC-E Filter principle → precise energy analysis
- Vacuum vessel on retarding potential
- high resolution: **ΔE = 0.93 eV**

$$\Delta E / E_0 = B_{min} / B_{max} = 1/20000$$

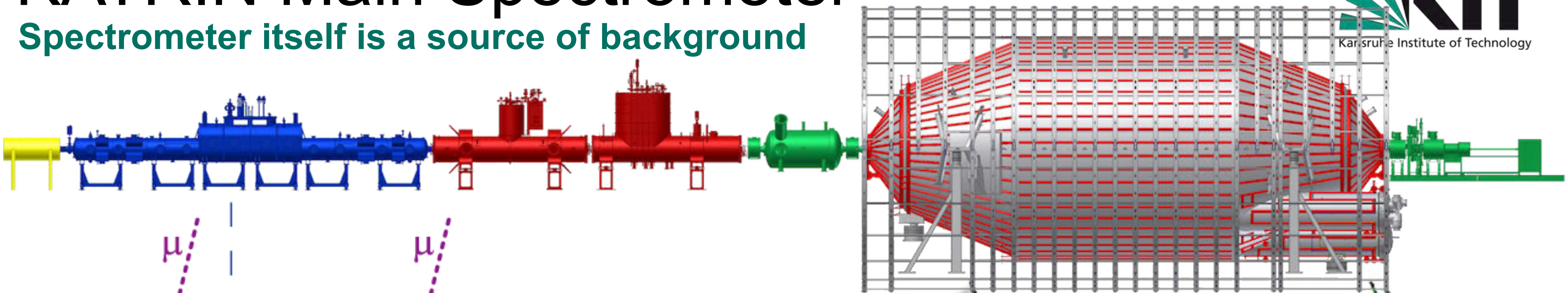
- ∅ 10 m, length 23 m
  - volume: 1240 m³
  - inner surface: 690 m²
- **Reduce background rate:**
  - **ultra high vacuum (UHV): $p < 10^{-11}$ mbar**
  - **induced by cosmic ray muons:**
    → background increase
    → counter measure: wire electrode

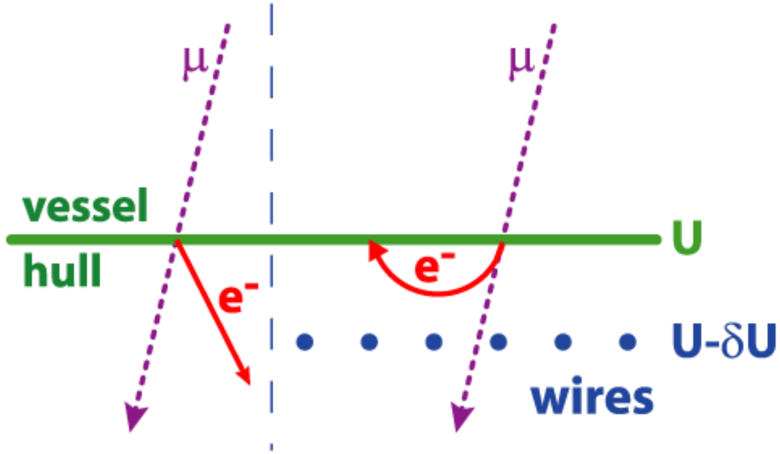
Precision Energy Filter:
variable retardation
U_0 = -18.4 … -18.6 kV
ΔE ~ 0.93 eV

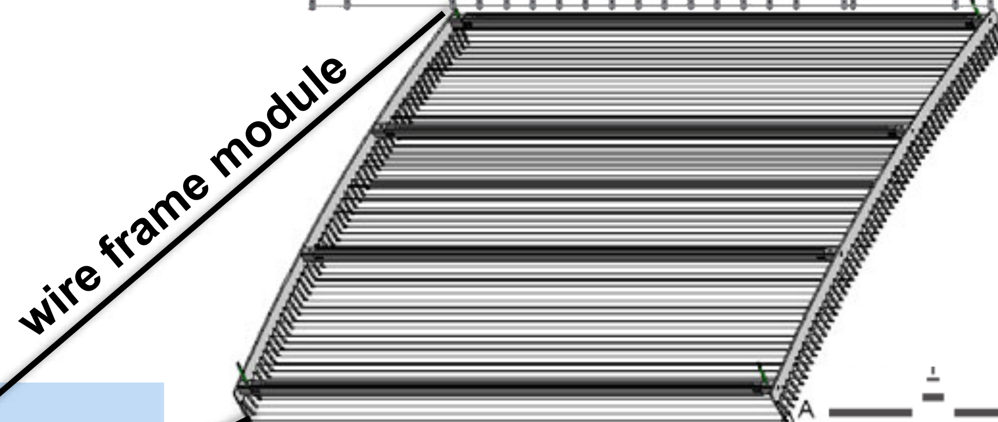


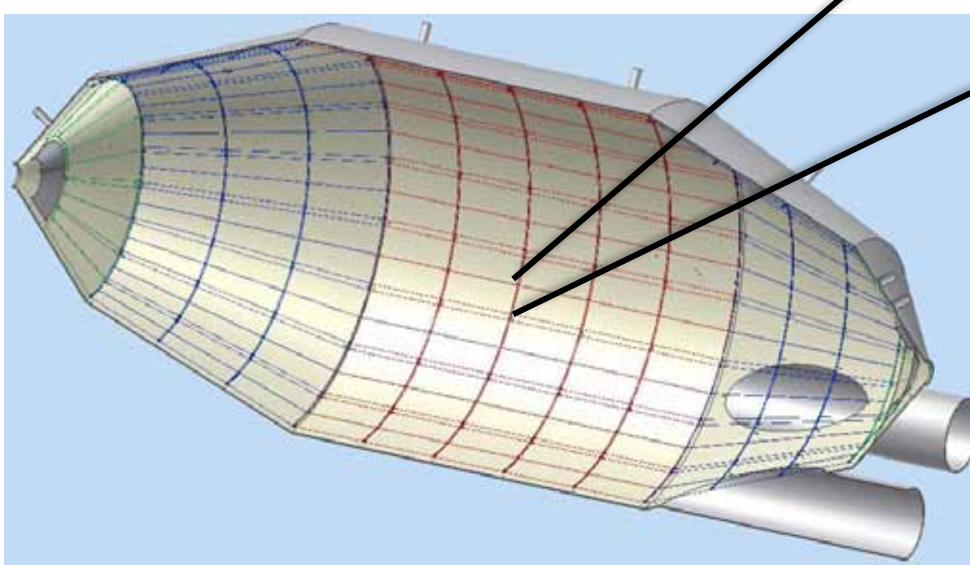
KATRIN Main Spectrometer

Spectrometer itself is a source of background







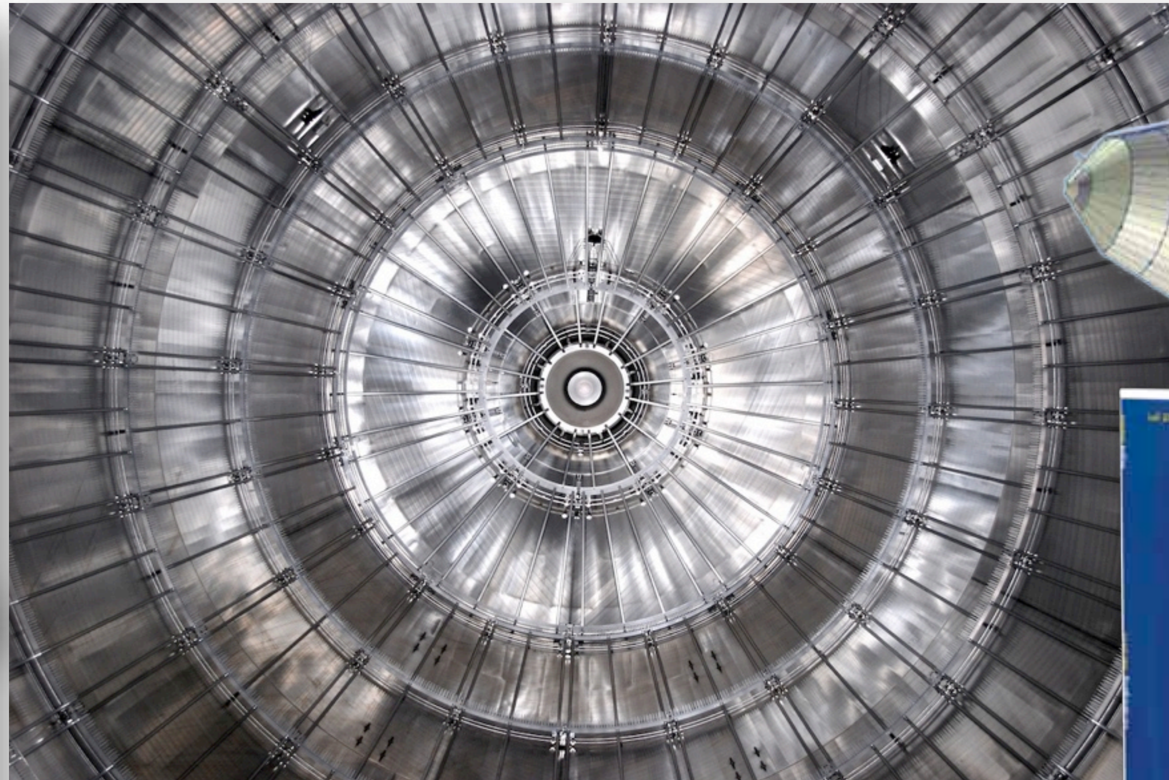


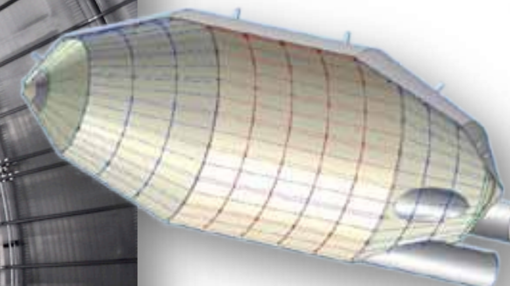
Wire defines electrostatic filter:

- 240 modules, 23000 wires
- precision requirement 0.2 mm
- compatible to UHV

K. Valerius et al., Particle and Nuclear Physics, Volume 64, Issue 2, April 2010

Wire Electrode Installation - completed

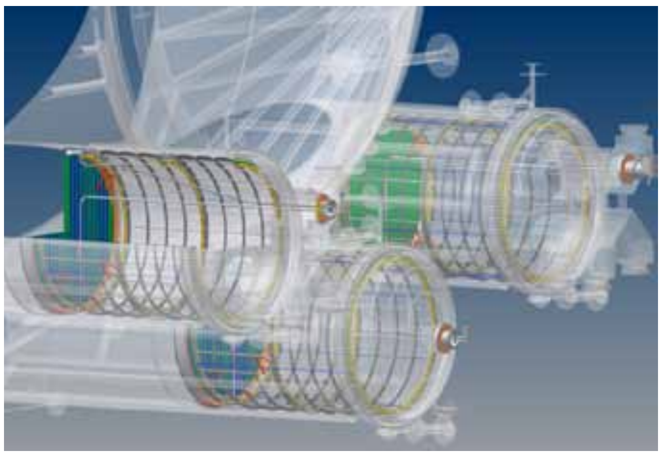


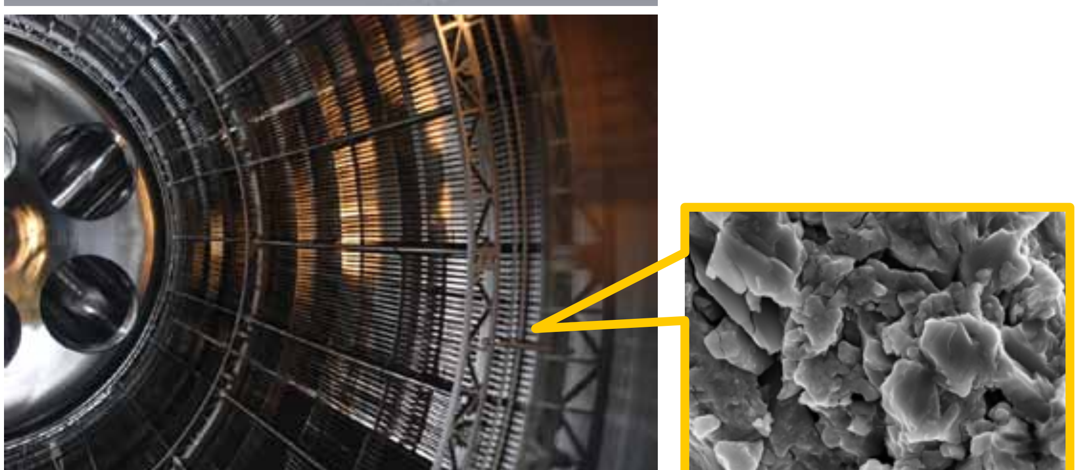


- wire installation until Jan. 2012 (7 Years)
- entry electrodes mid 2012
- baffle and getter pump and
  complete vacuum system until Nov. 2012
- next: baking / vacuum conditioning

Radon as Background Source

- ^{219}Rn emanation from St707 NEG getter strips (3 · 1 km) in pump ports





Radon as Background Source

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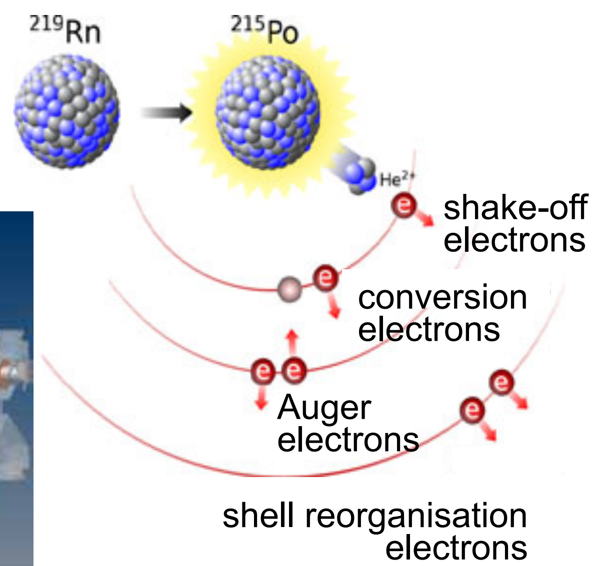

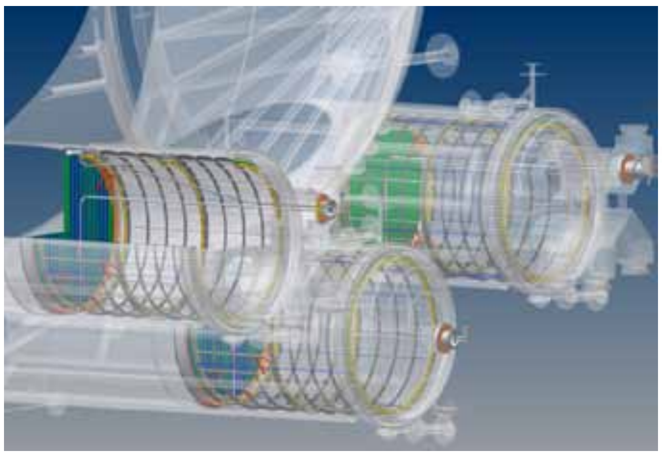

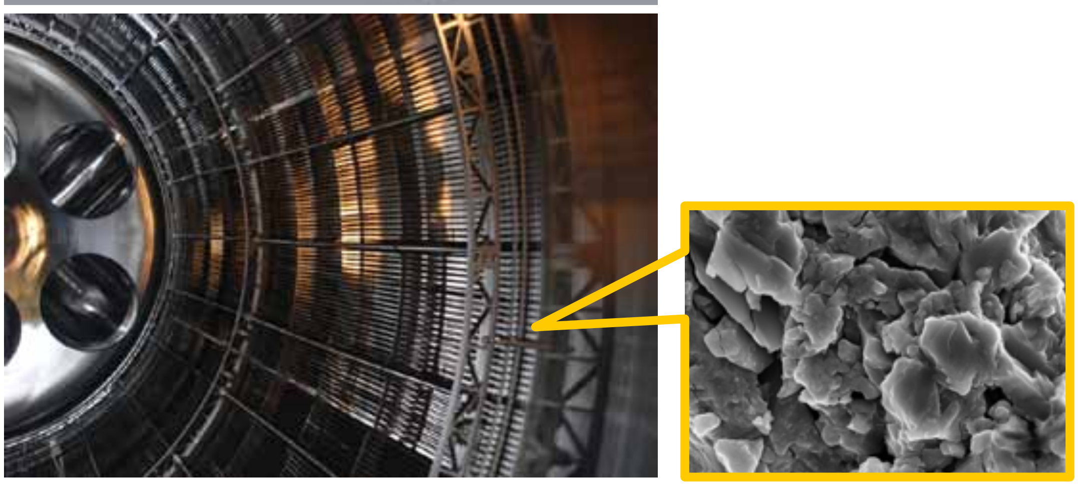

Radon as Background Source

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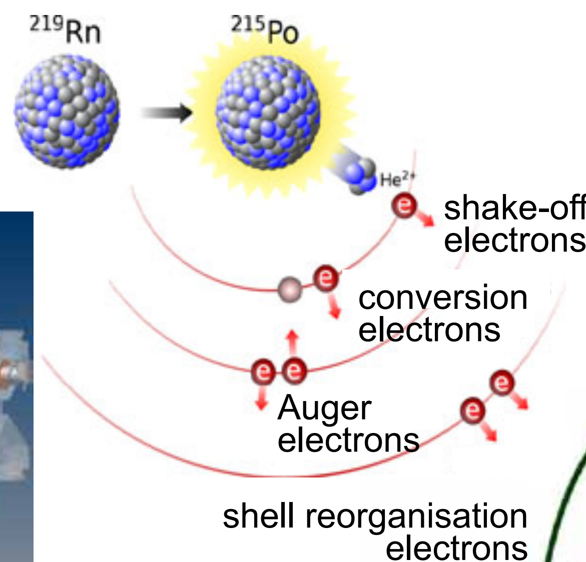
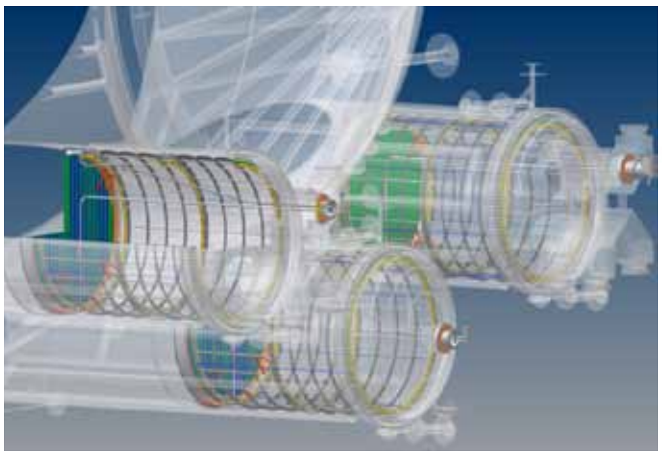
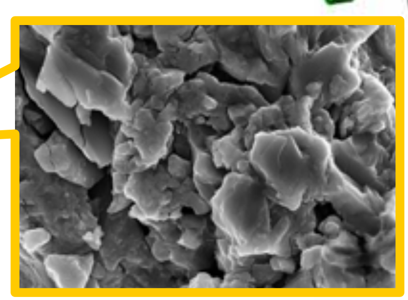
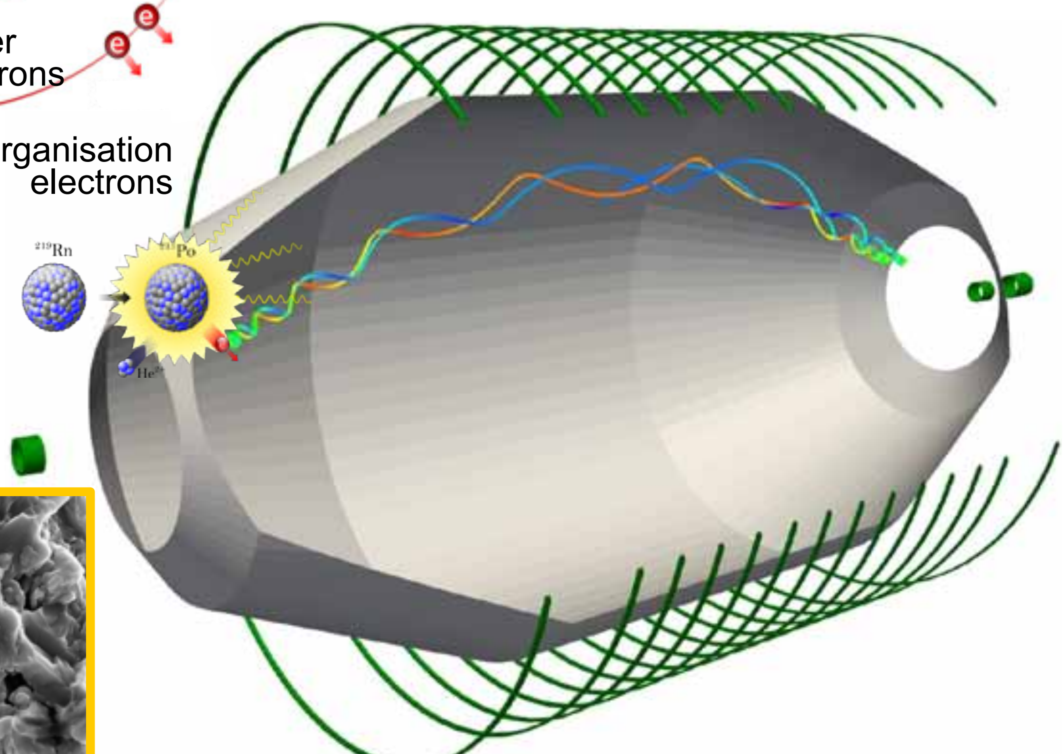


F.M. Fränkle et al.,
Astropart. Phys. **35** (2011) 128

S. Mertens et al.,
Astropart. Phys. **41** (2013) 52

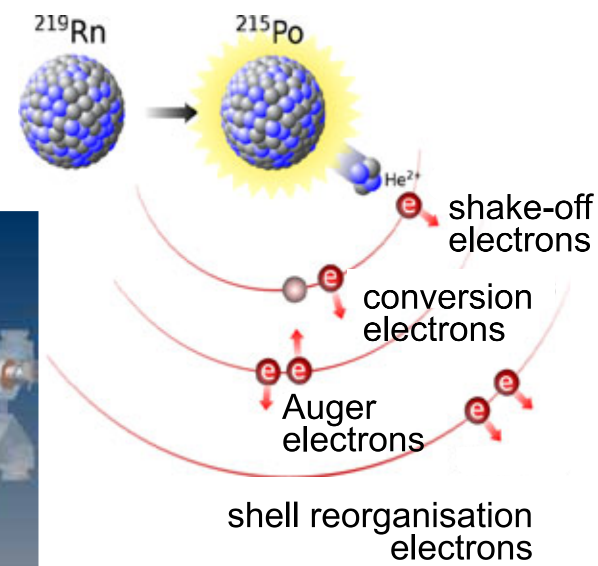


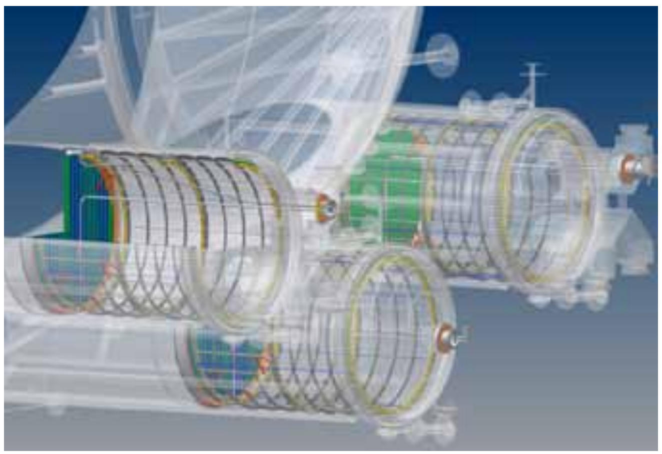


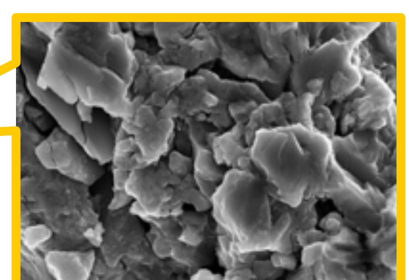


Radon as Background Source

- passive background reduction: **LN2-cooled baffles** to cryocondense ^{219}Rn

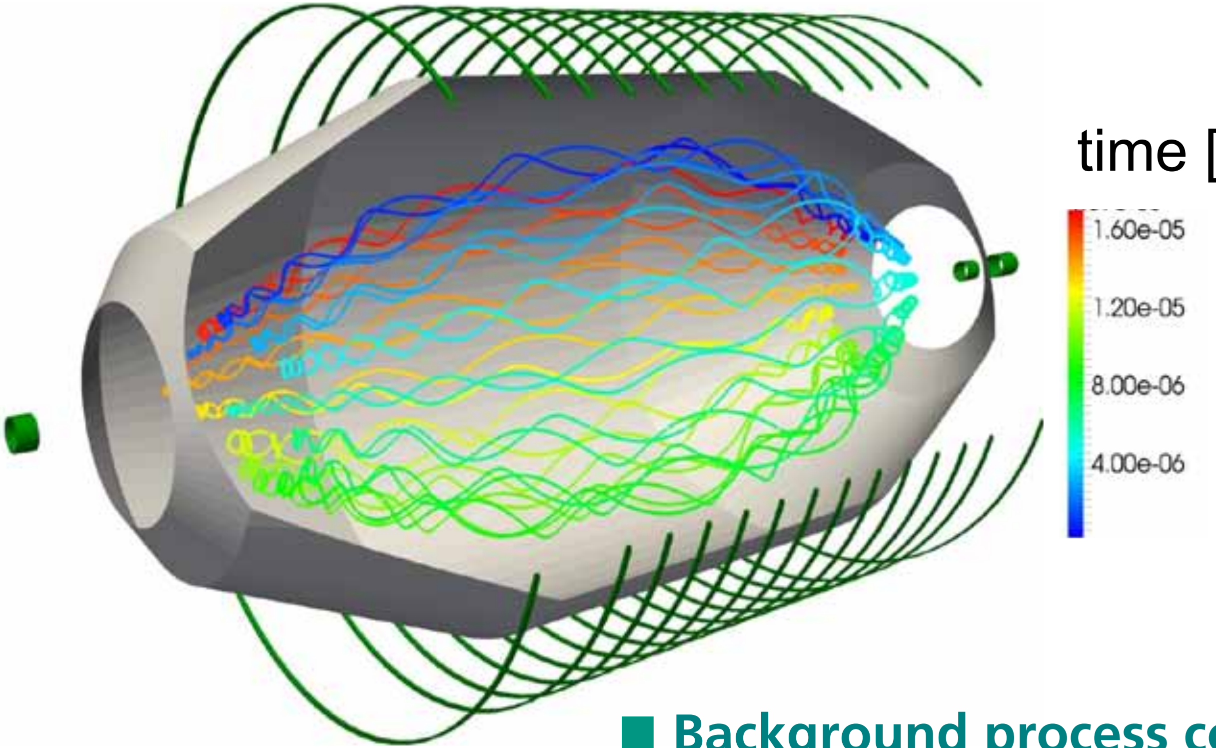






Background Reduction

- $^{219,220}Rn$ emanation from bulk material of vessel
- **need active background suppression**

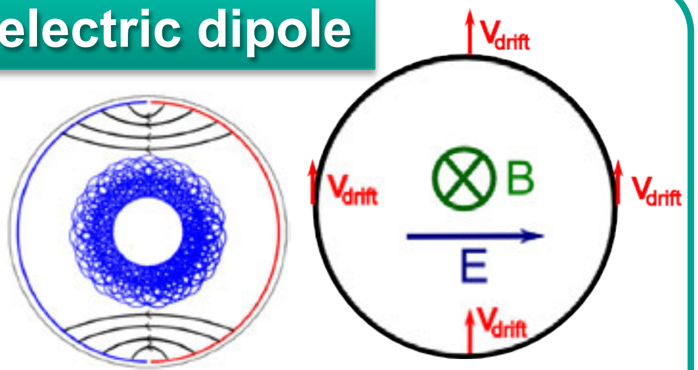


- **stored multi-keV electrons:**
  rapid cyclotron motion
  intermediate axial oscillation
  slow magnetron drift

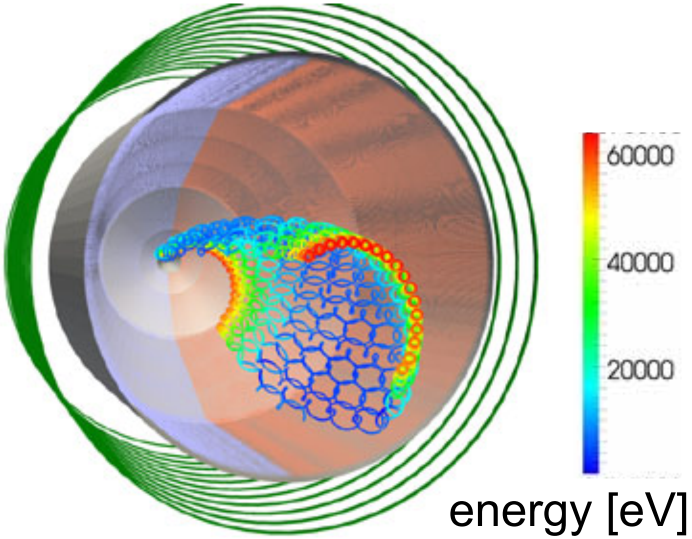
- **Background process continues:**
  - ionization of residual gas → secondary electrons
  - primary electron energies: 100 eV < E < 500 keV
  - up to 5000 secondary electrons per stored primary
  - significant background increase for hours

Background Reduction Methods

electric dipole



- 1 kV between dipole halves, vessel Ø 10m → E=100 V/m
- ExB drifts: electrons hit wall (works for E < 2 keV)



Background Reduction Methods

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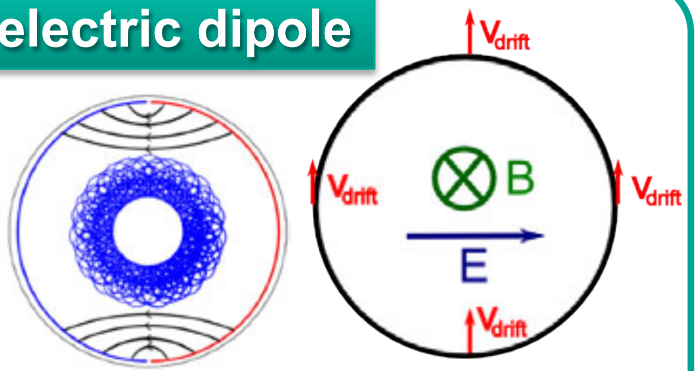

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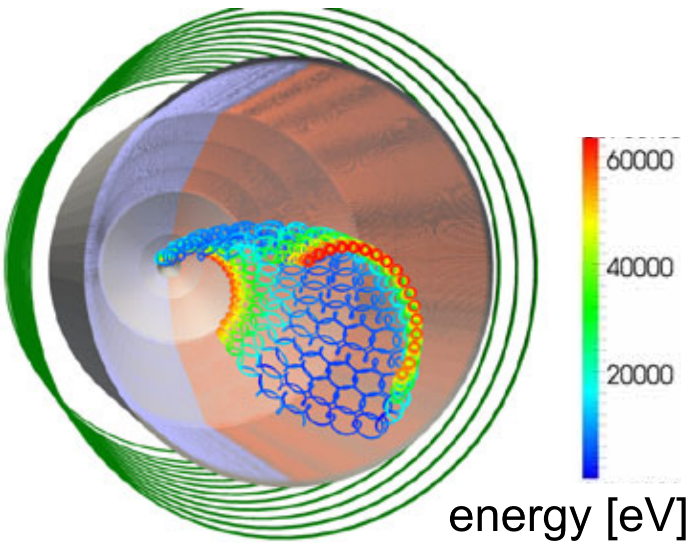
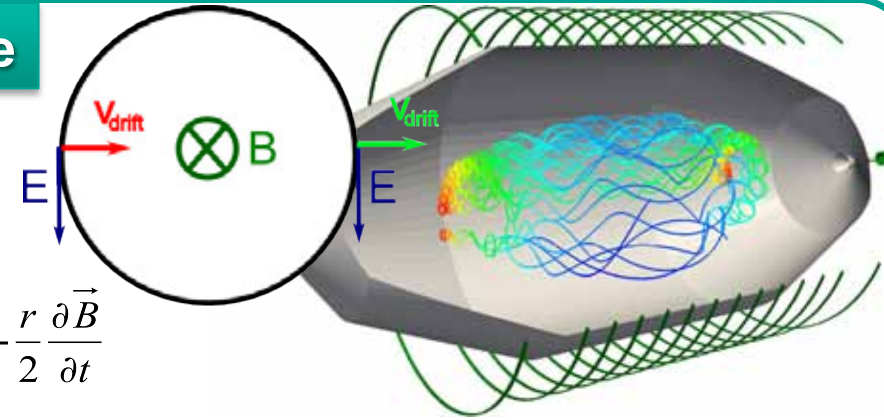


magnetic pulse

- Maxwell law of induction:



$$rot\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{E} = -\frac{r}{2}\frac{\partial \vec{B}}{\partial t}$$

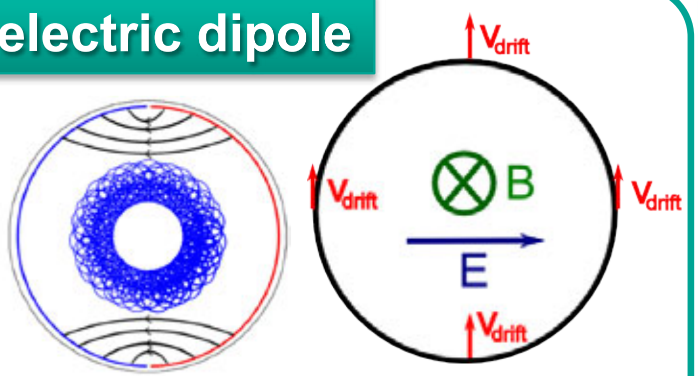
- Reduction of field strength
  → increased cyclotron radius
  → electrons hits the wall
  (works for all energies, but reversible)

$\frac{\partial \vec{B}}{\partial t} < 0$ **drift into flux tube**

$\frac{\partial \vec{B}}{\partial t} > 0$ **drift out of flux tube**

Background Reduction Methods

electric dipole



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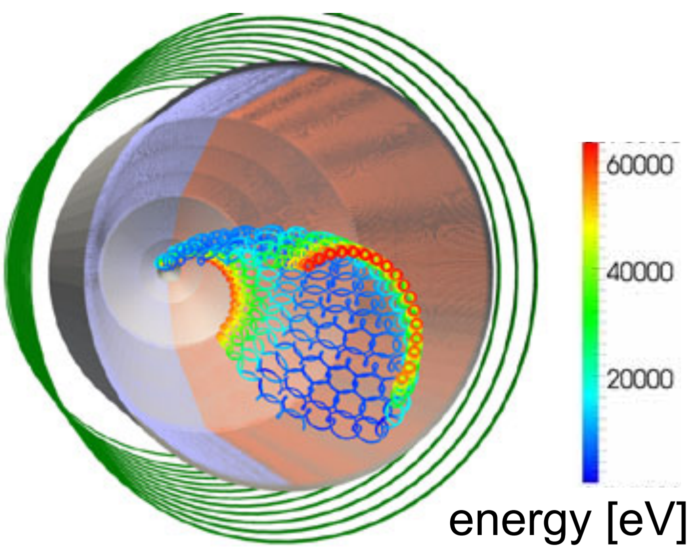

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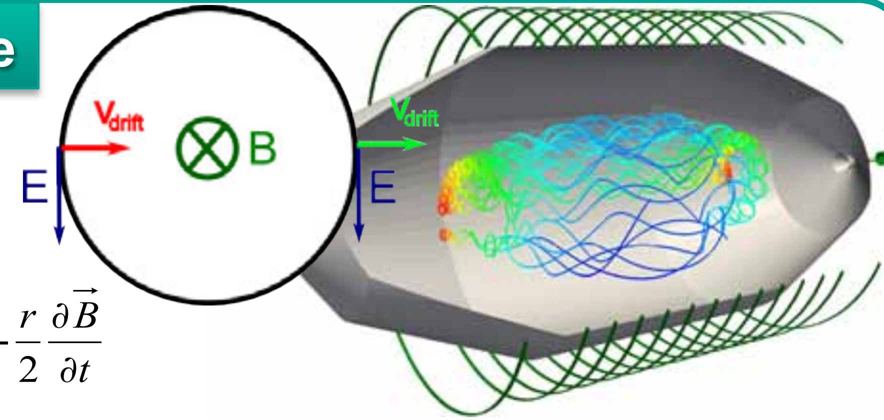

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$\frac{\partial \vec{B}}{\partial t} > 0$ **drift out of flux tube**

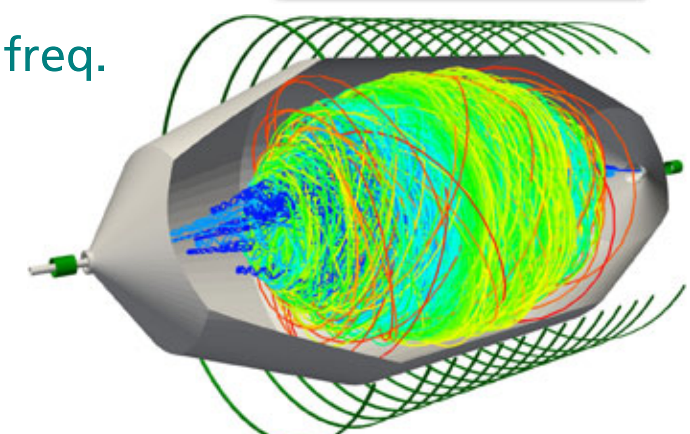
electron cyclotron resonance

S. Mertens et al., arXiv:1205.3729

- Stochastic heating:
  RF puls matched to cycl. freq.

$$\omega_{RF} = \omega_{cycl} \qquad \omega = \frac{eB}{m\gamma}$$

→ inc. cyclotron radius
→ electron hits the wall
(works for all energies)

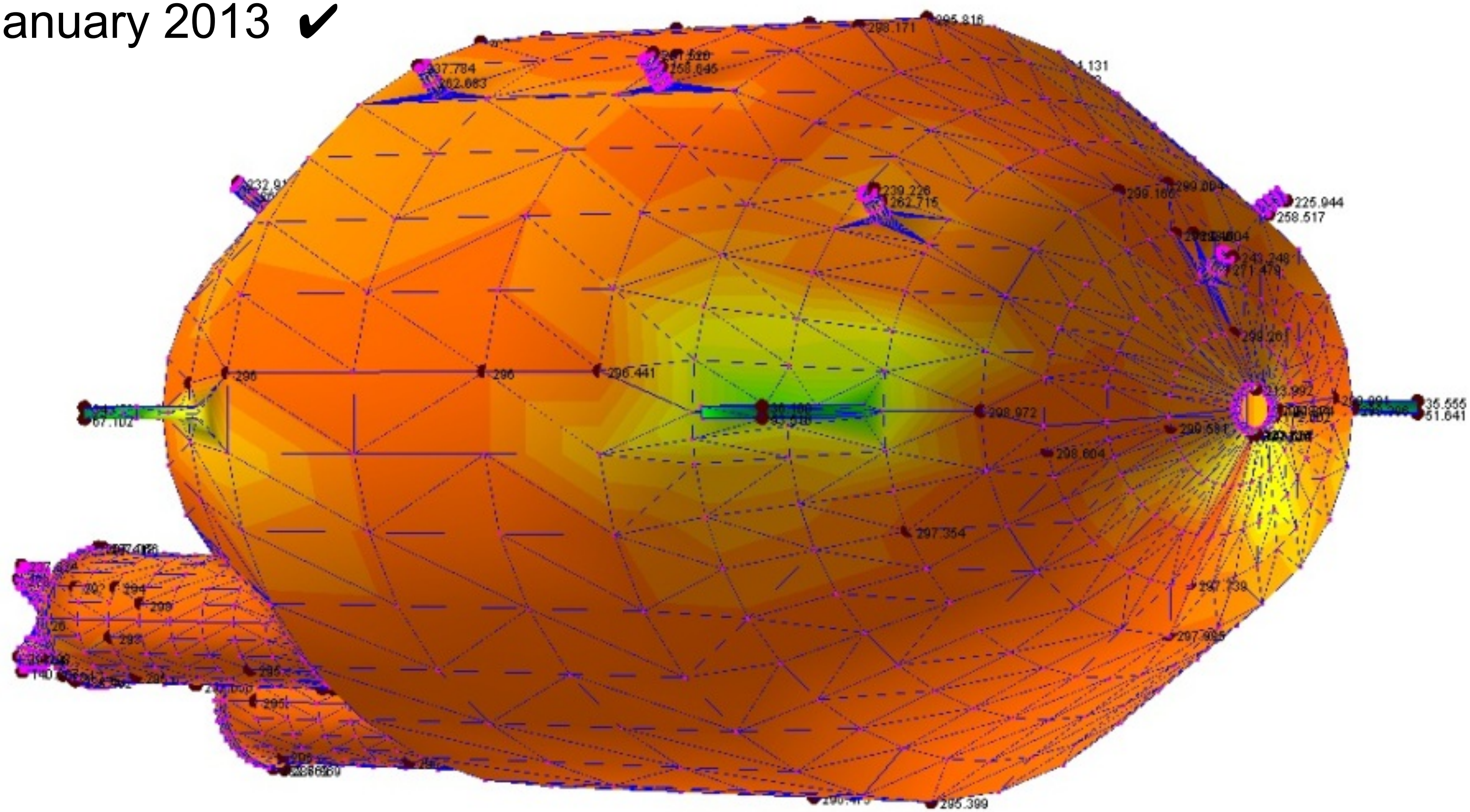


Spectrometer Commissioning

Karlsruhe Institute of Technology

Vacuum conditioning for the commissioning measurements

- aim: UHV in huge spectrometer: $p \approx 10^{-11}$ mbar
- to do: spectrometer bake-out at T = 300 °C
- achieved in January 2013 ✔

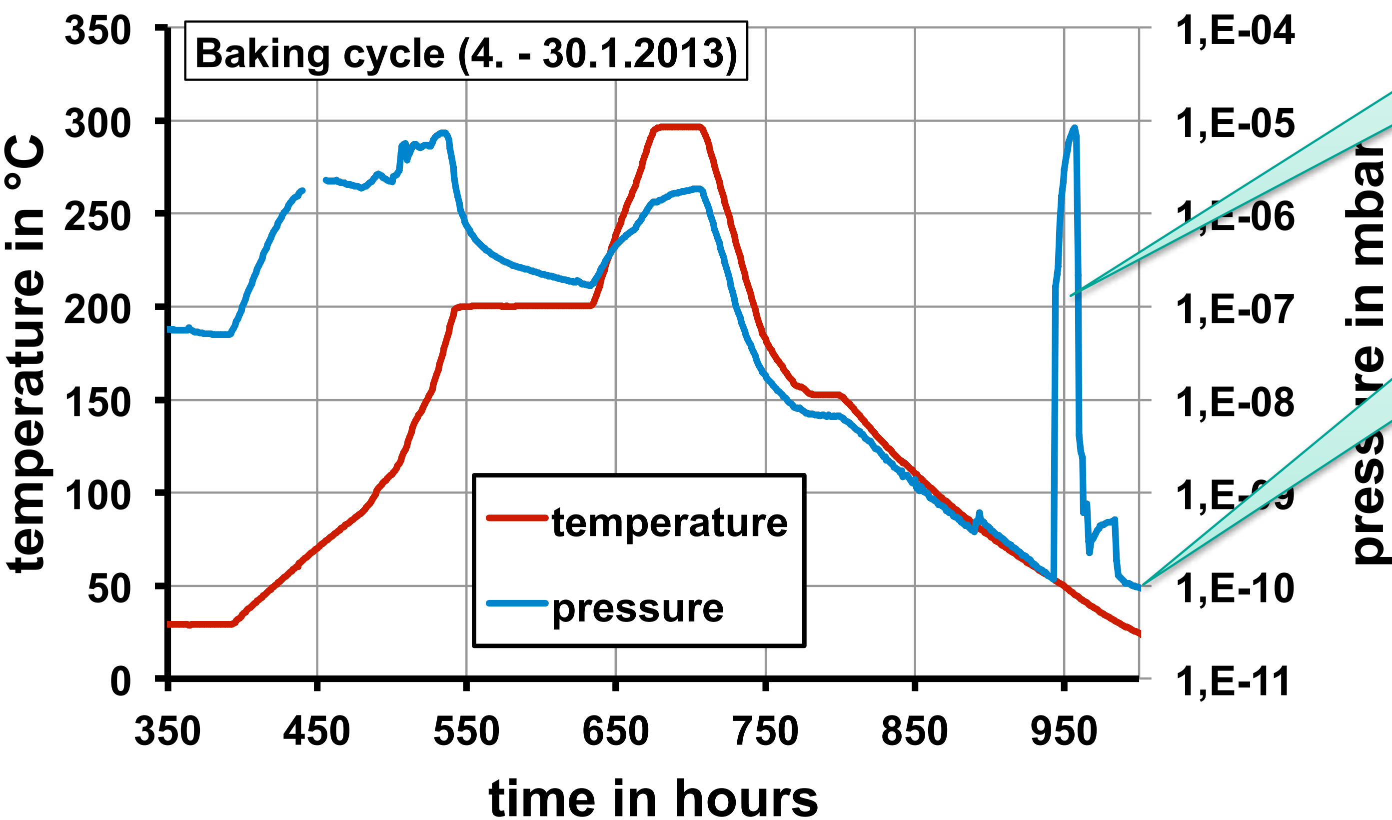


Spectrometer Commissioning Status

Karlsruhe Institute of Technology

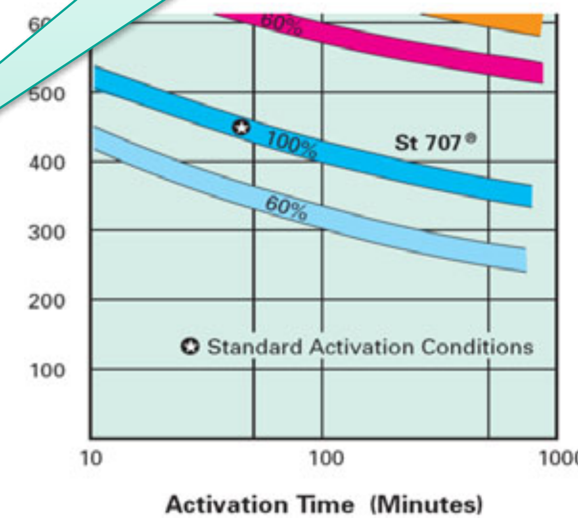
Spectrometer bake-out: procedure

- slow heating: expansion of vessel and electrode by 10 cm
- temperature breakpoints: 200°C – water vapor removal
  300°C – activation of getter material



leak developed

pressure back at 10^{-11} mbar level



Spectrometer Commissioning Status

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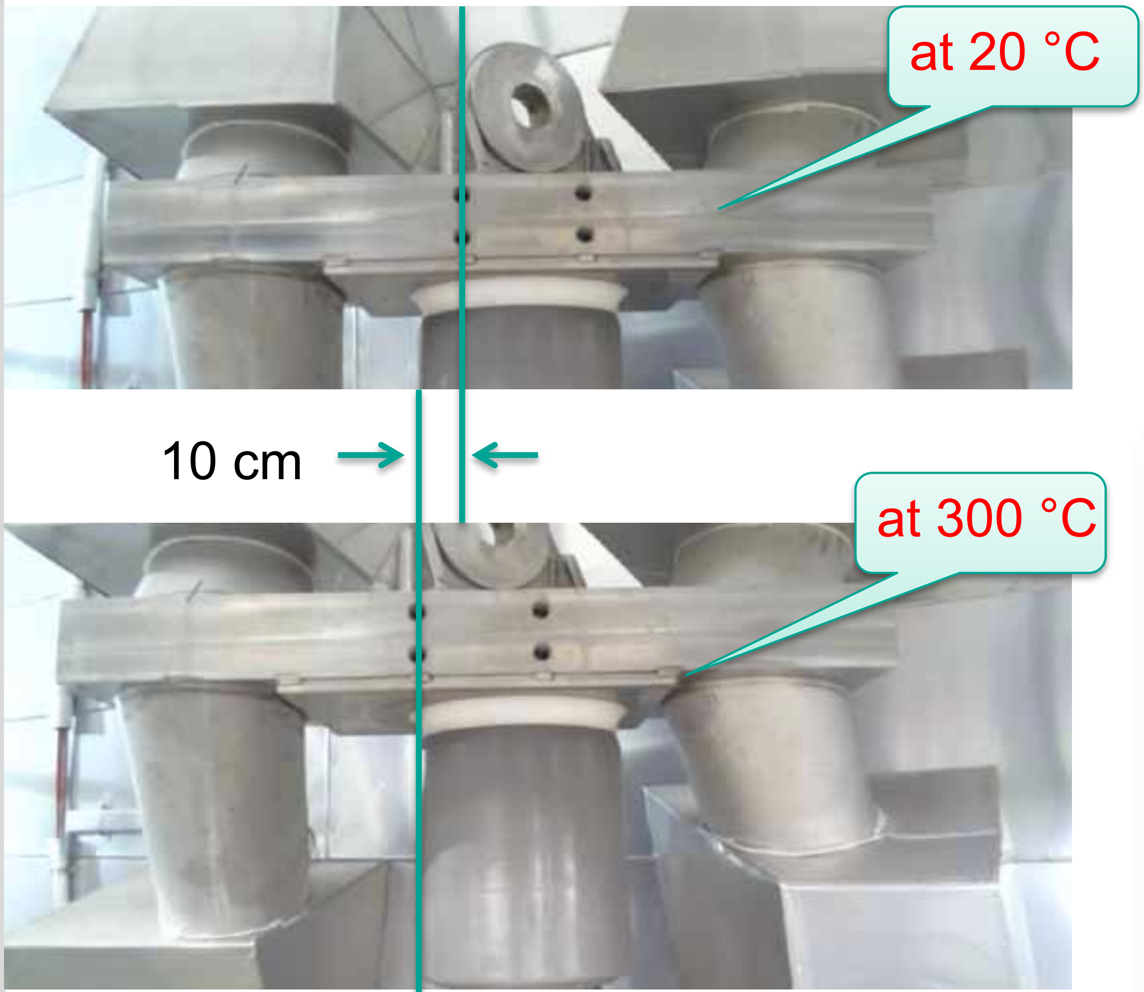
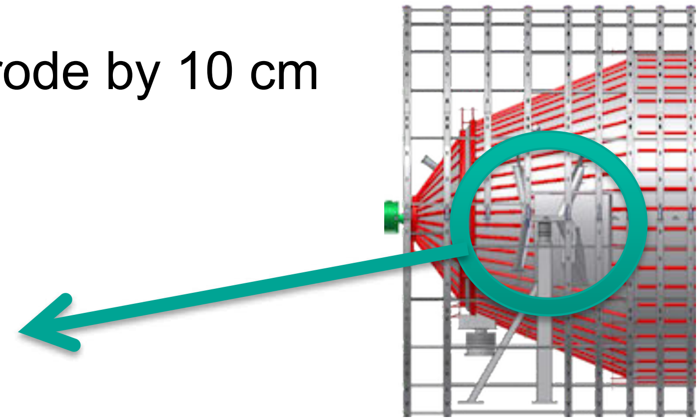
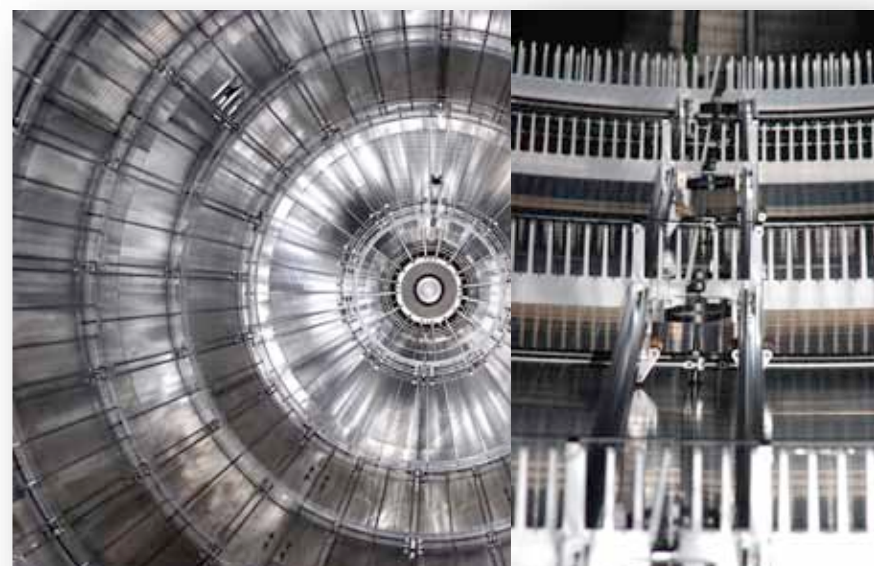




Remember what's inside!



Spectrometer Commissioning Status

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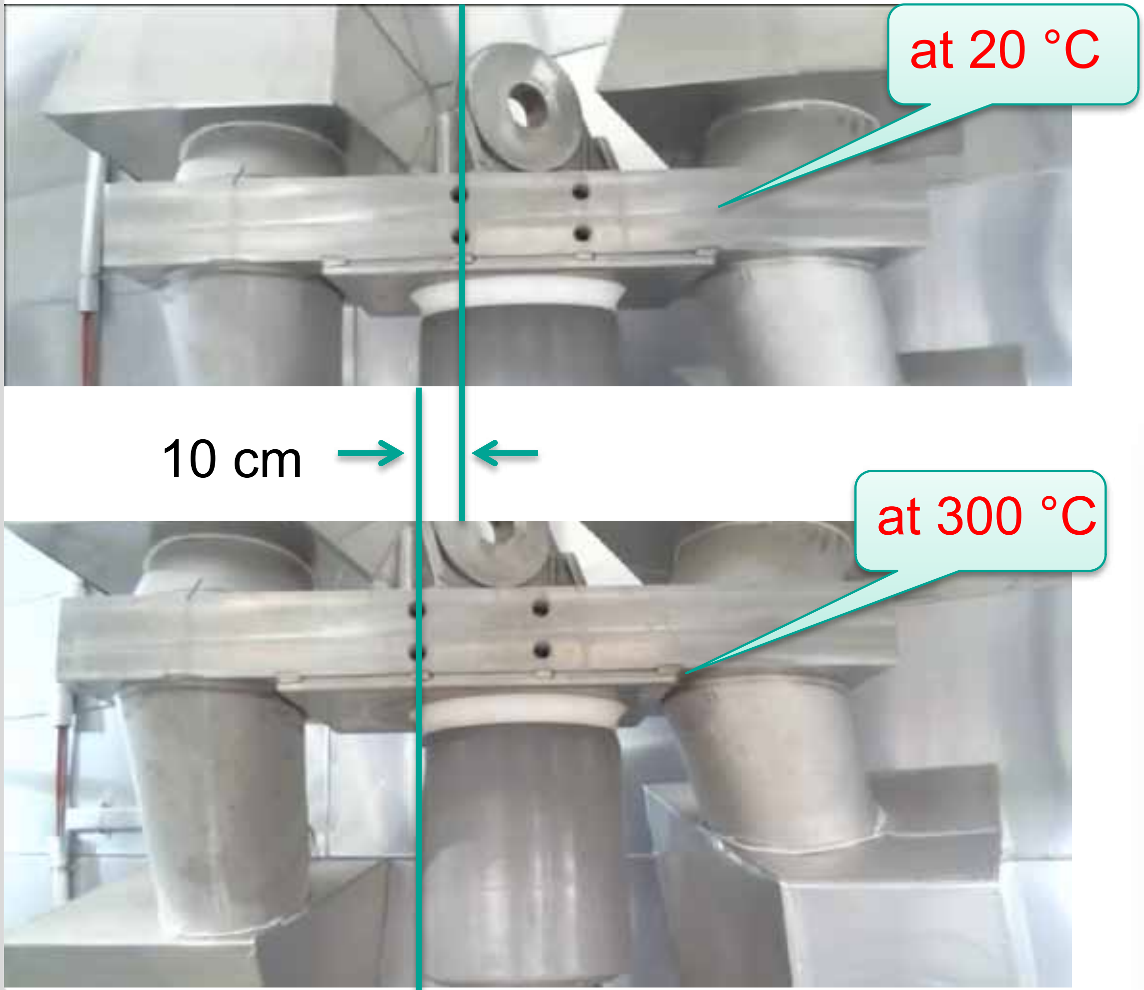

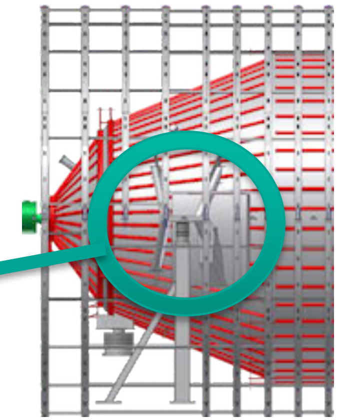

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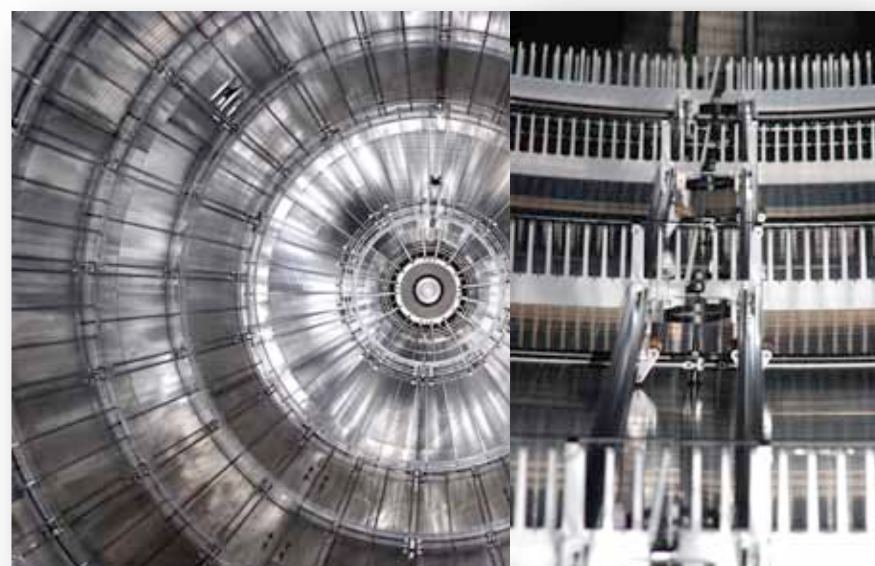
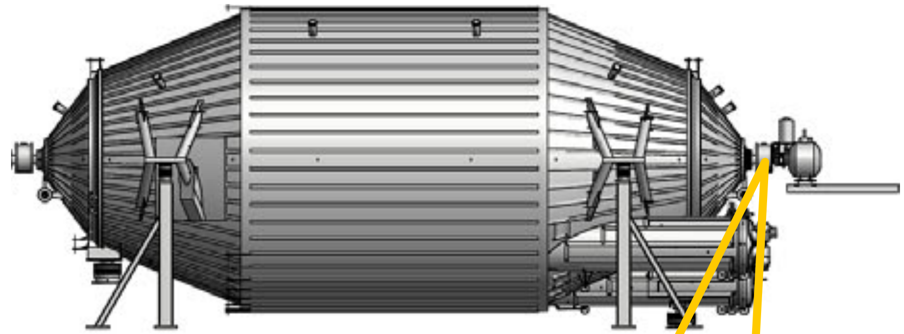
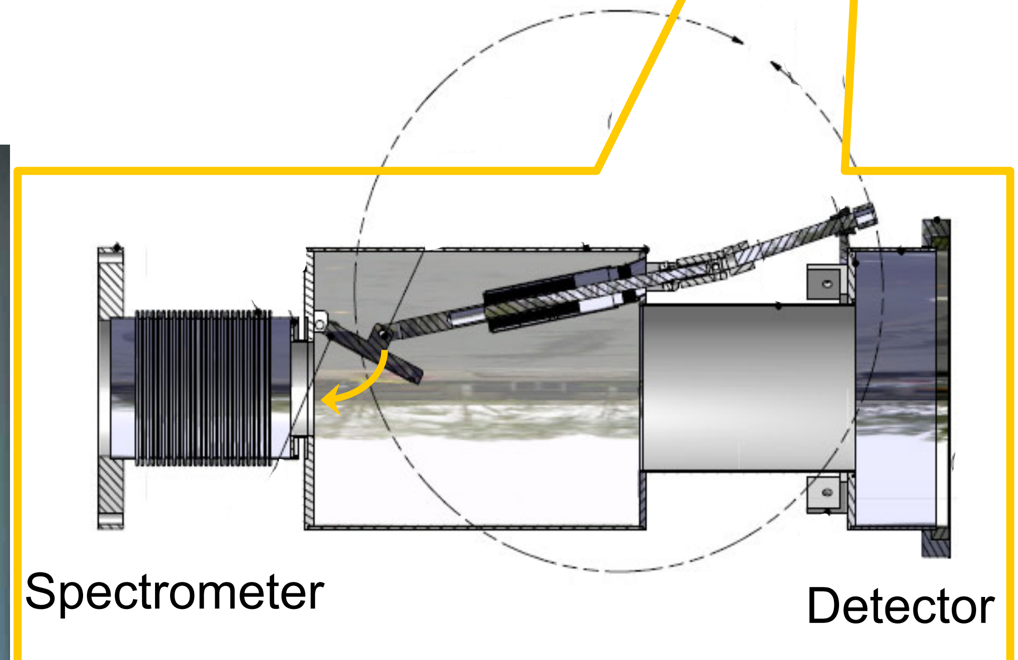


Spectrometer – Detector Integration

Karlsruhe Institute of Technology

- detector integration requires valve inside magnet bore: *beam-line valve*
- deformation of O-Ring during baking disabled the valve's basic function
- challenge to attach detector without venting / getter contamination

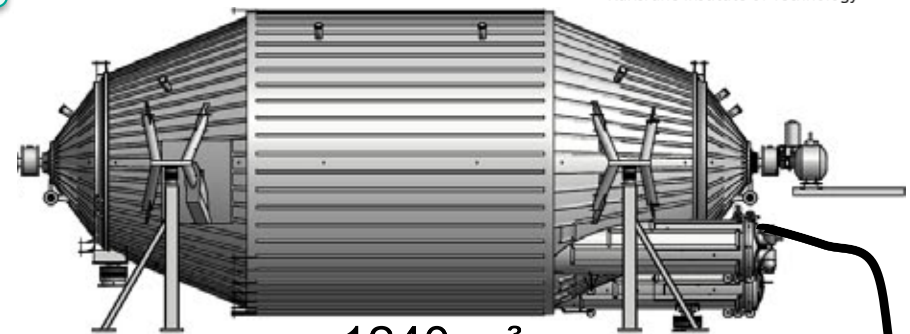




Spectrometer – Detector Integration

Karlsruhe Institute of Technology

- replacing the O-Ring requires work under Ar gas atmosphere
- NEG pump requires Ar of quality N9.0 to prevent contamination



1240 m³

Ar 9.0

AIR LIQUIDE

144 bottles of Argon gas N6.0

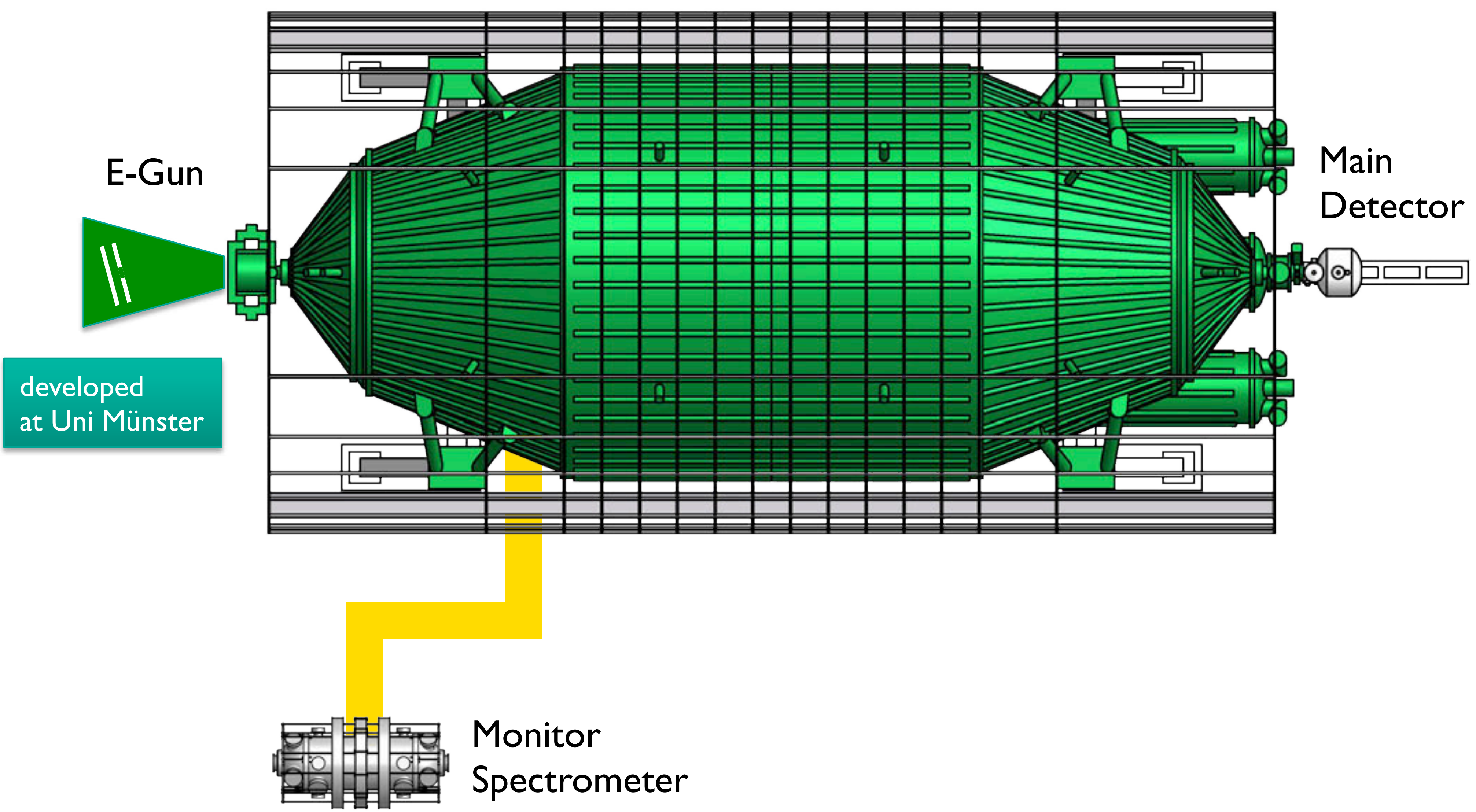
Ar 6.0

XENON 1t gas purification technology

☑ O-Ring exchanged under Ar over pressure
☑ beal-line valve leak tight
☑ detector section attached

SDS Commissioning

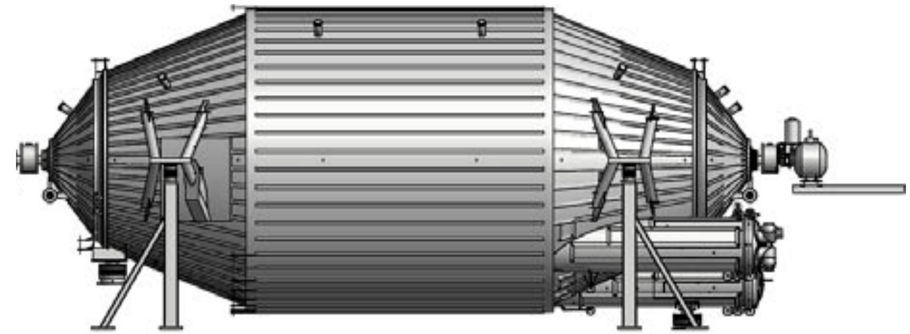
- Commissioning of the Spectrometer and Detector Sections (= all non Tritium parts of KATRIN)



SDS Commissioning

Present Status:

- pressure p = 7 x 10^{-11} mbar
- identical to situation before venting
- all subsystems operational:
    - Vacuum and High Voltage
    - S.C. Magnets, Air Coils
    - Detector and DAQ
    - Monitoring and Database
    - Online-Analysis
- first light seen on May 31, 2013



FirstLight

M1 - First Light

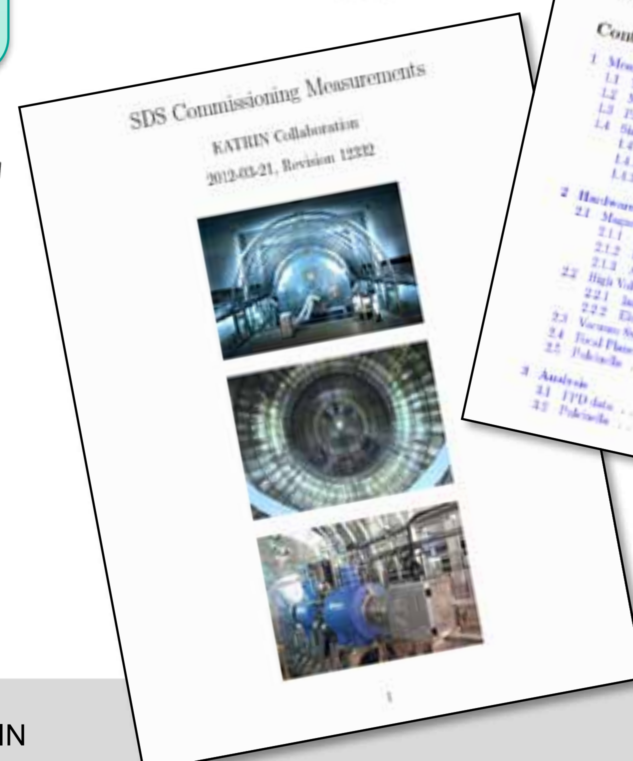
May 16, 2013

Contents

1 Measurement Objective

2 Hardware Requirements

3 Analysis



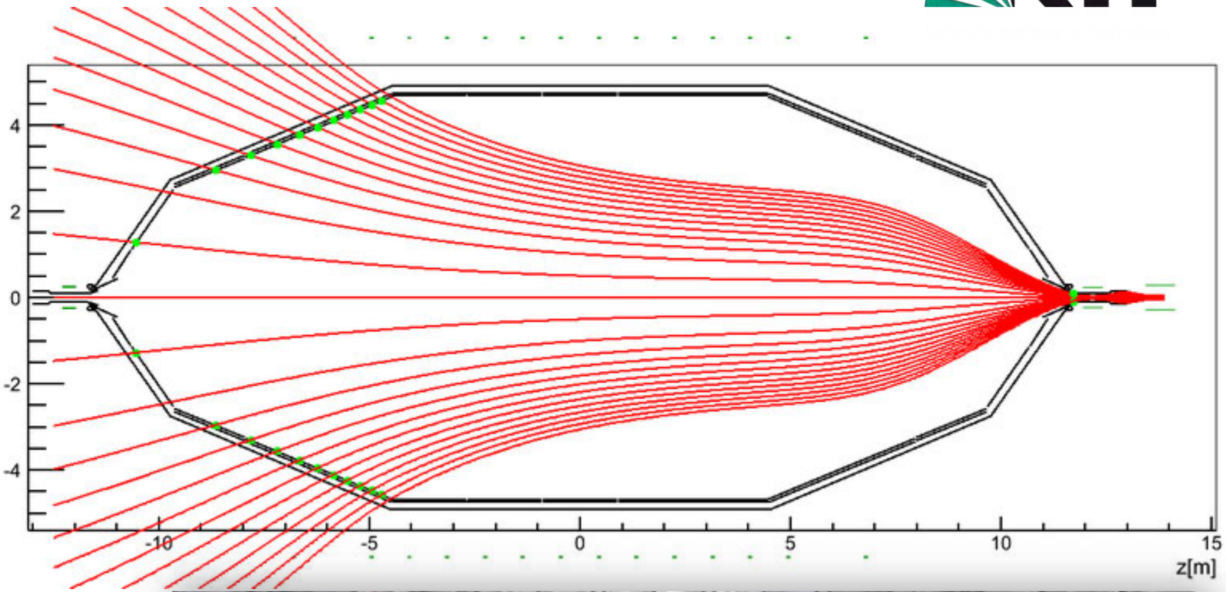
SDS Commissioning Measurements

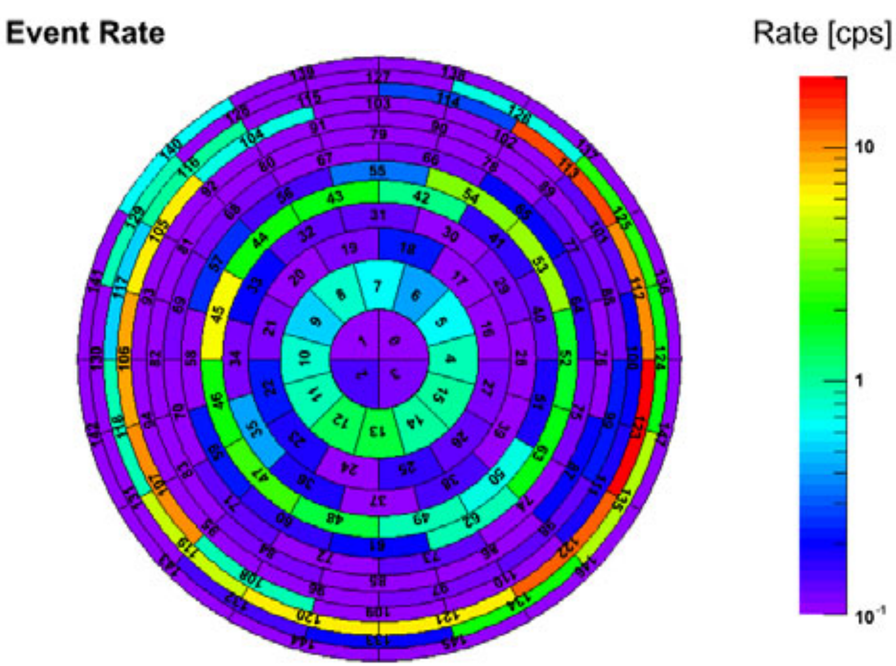
KATRIN Collaboration

2012-03-21, Revision 12332

SDS Commissioning & First Light

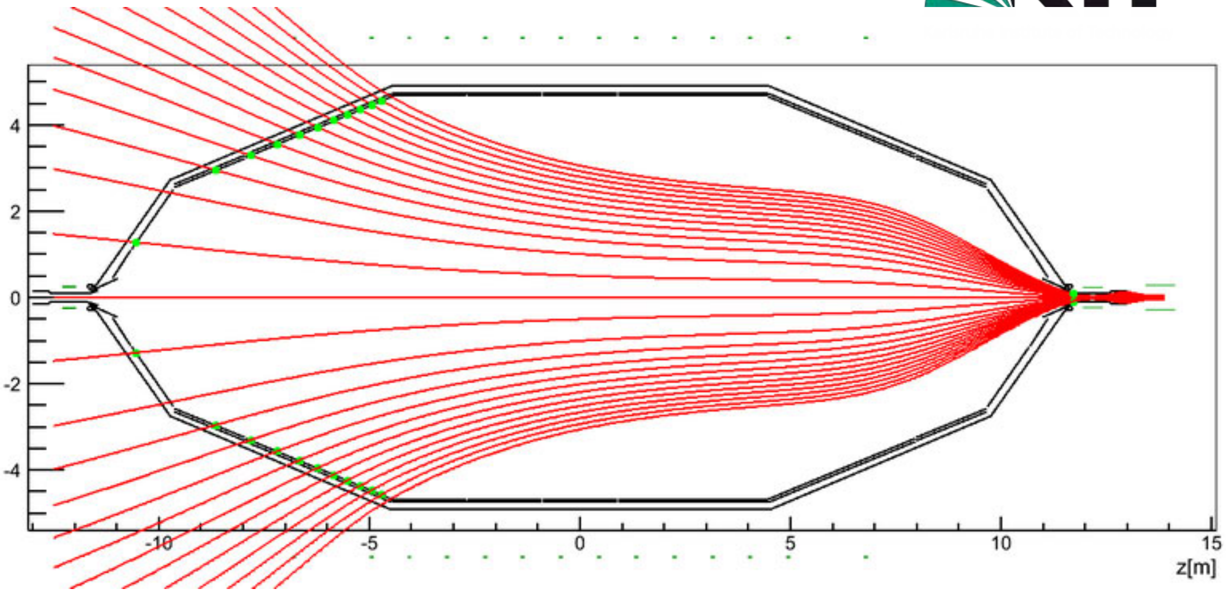
- asym. magn. field
- map electrode structure onto detector

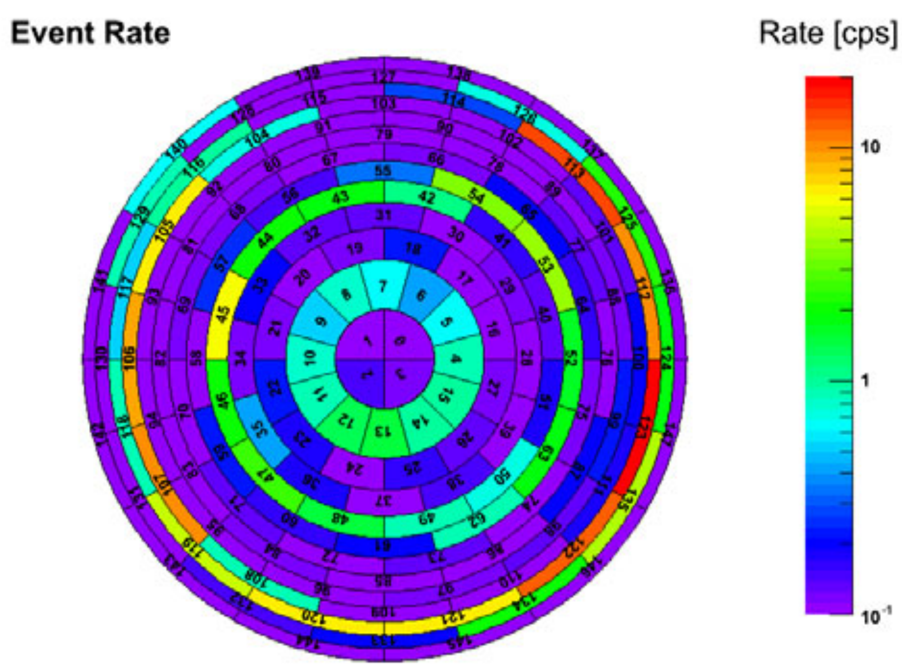


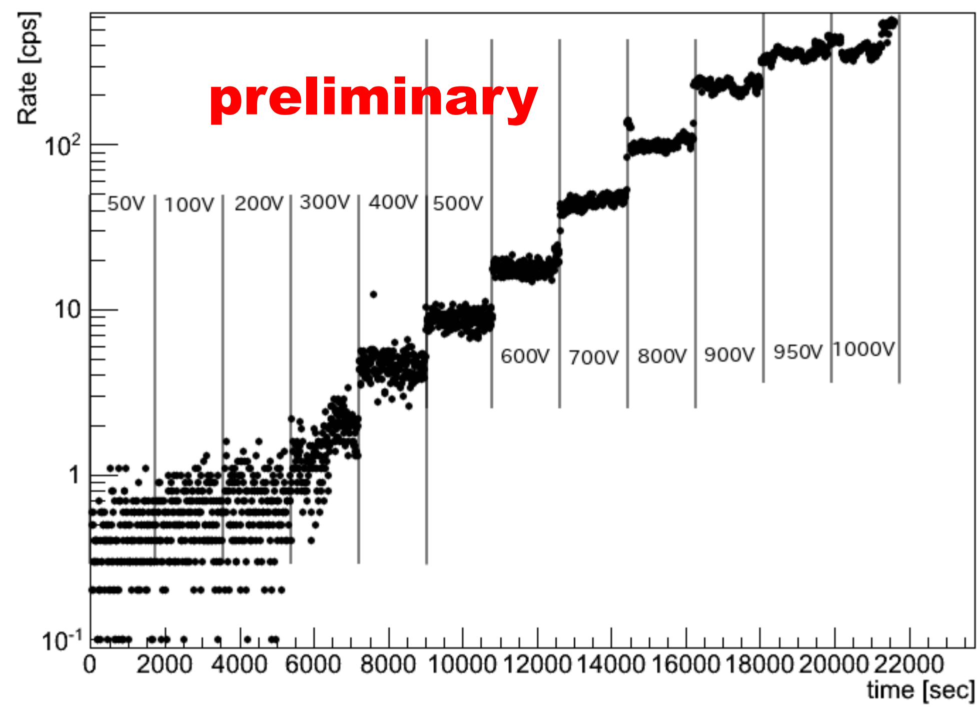


SDS Commissioning & First Light

- asym. magn. field
- map electrode structure onto detector
- rate related to electrode potential

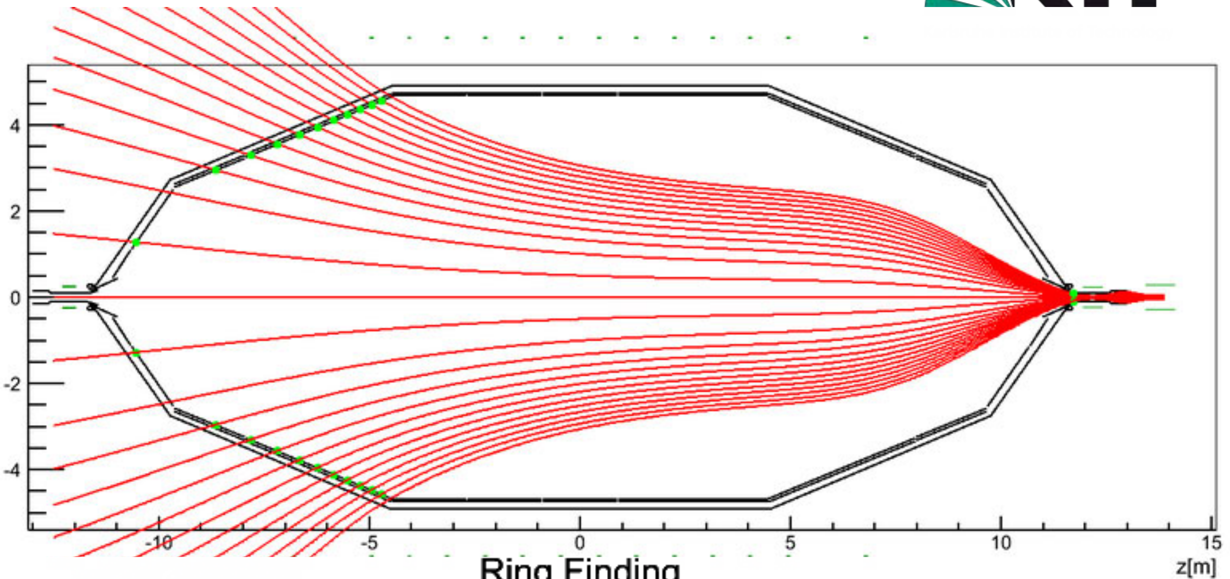




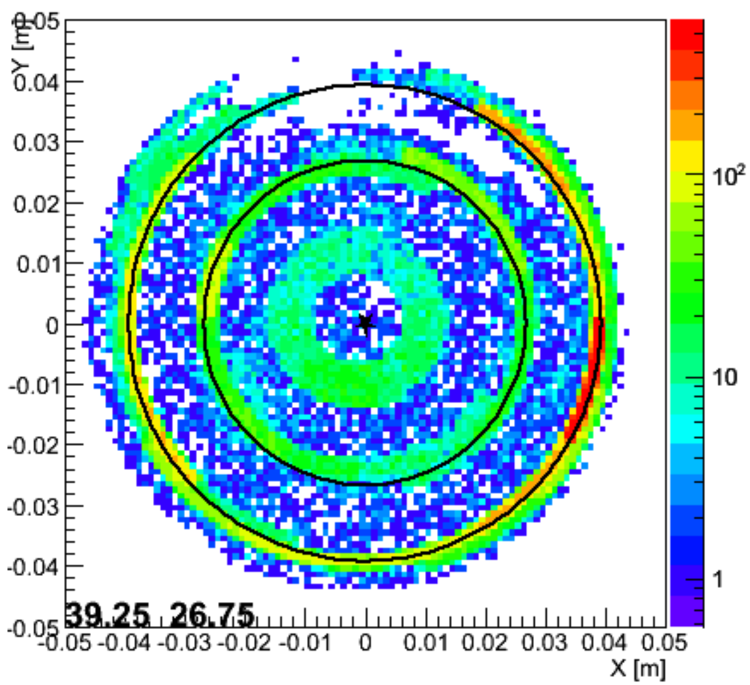


SDS Commissioning & First Light

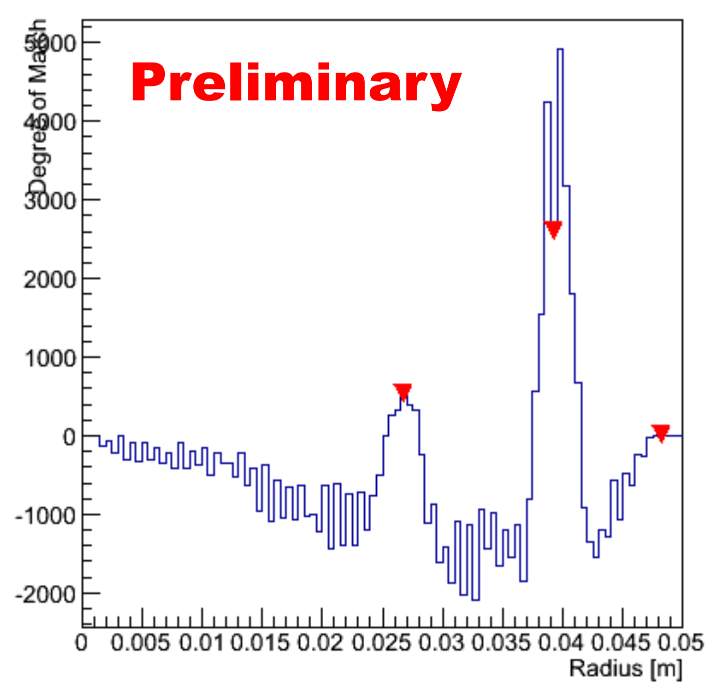
- asym. magn. field
- map electrode structure onto detector
- rate related to electrode potential
- rings identified



Ring Finding

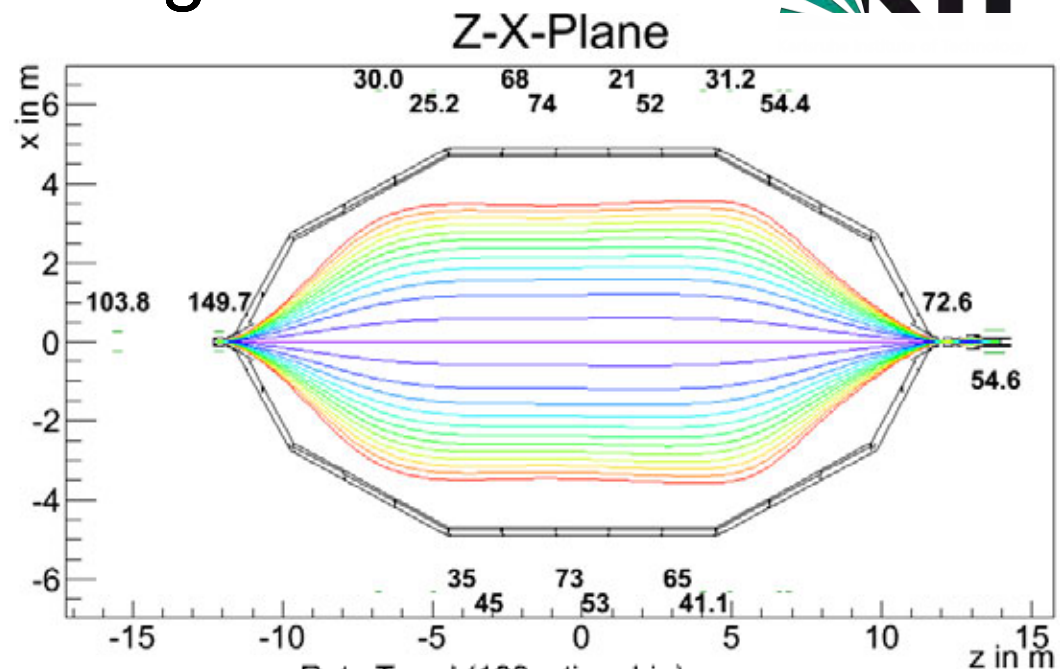


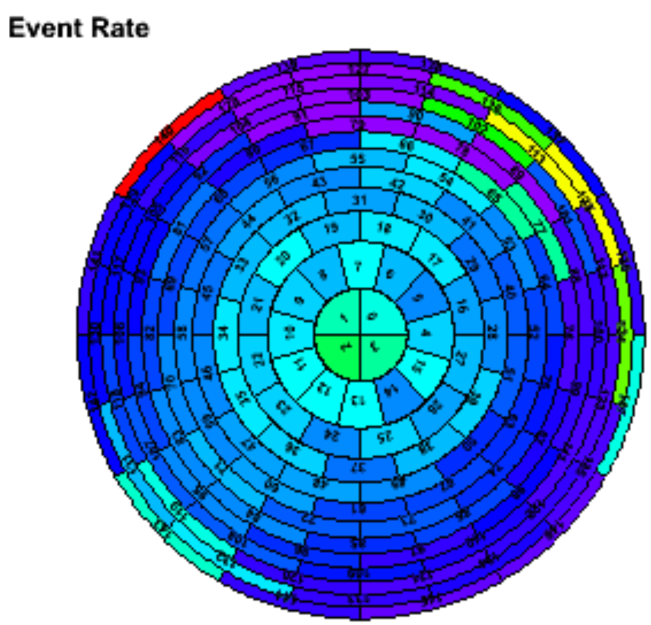
Ring Finding

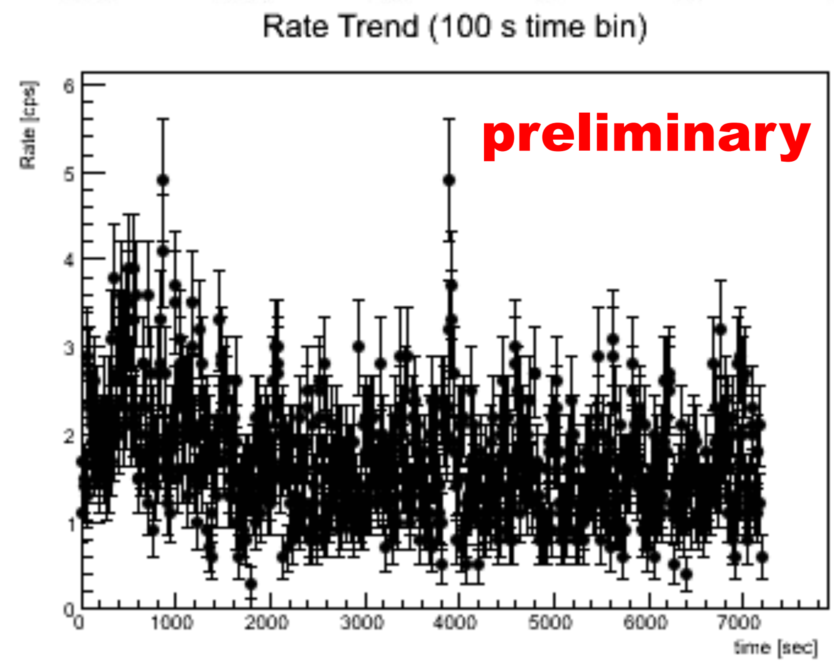


SDS Commissioning & First Light

- sym. magn. field
- MAC-E filter conditions
- rate dropped to 1.6 cps at retarding pot. U = -600 V
- preliminary and to be improved!







SDS Commissioning & Next Steps

- Setup, DAQ, Database and Analysis working fine
  - there is room for improvements
- Background rate is low, but not low enough for KATRIN
  - 1.6 cps at 146 pixels makes 10^{-2} cps per pixel
  - Tritium runs requires 10^{-2} cps for all pixels
  - no evidence for Penning-like traps found
- angular selective electron gun to be commissioned next
  - check transmission properties of MAC-E filter
- commission high-voltage operation up to 35 kV
  - check background and transmission under KATRIN conditions
- commission LN2 baffle system
  - investigate Rn-related background
  - investigate background reduction methods
- **qualify main spectrometer for Tritium operation in 2015**

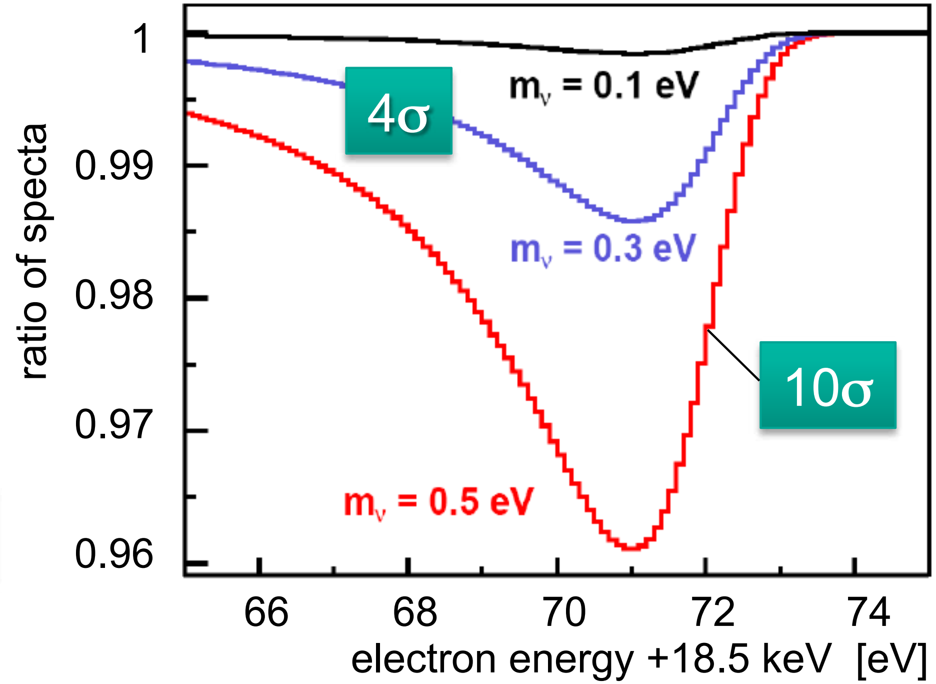
KATRIN Sensitivity

Karlsruhe Institute of Technology

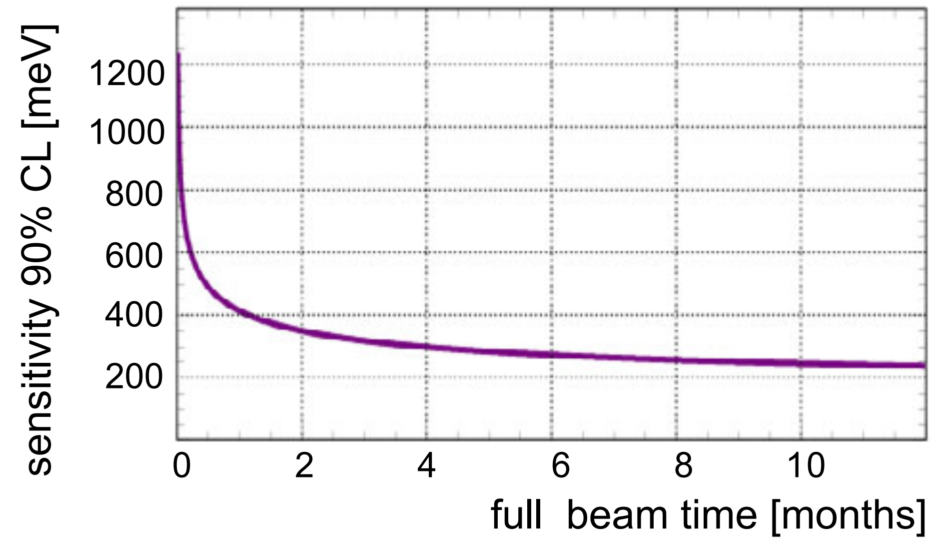
- **reference ν-mass sensitivity**
  for 3 ´full beam´ years (5y cal. time):
  - statistical & systematic errors contribute equally:
    statistics σ_{stat} = 0.018 eV²
    systematics σ_{syst} < 0.017 eV²

sensitivity m(ν) = 200 meV (90% CL)

350 meV (5σ)



- **plans for a later KATRIN phase II:**
  - differential ß-energy spectrum:
    cryo-bolometer array with ΔE ~ 1eV?
    synchrotron emission (GHz-range)?
  - precision external value end point E_0
  - atomic tritium source?



Summary & Outlook

- motivation for neutrino mass meas. from particle and astroparticle physics
- β decay offers a model-independent method to determine m_ν
- KATRIN is designed to reach a sensitivity of 200 meV on m_ν

- KATRIN continuing construction and started commissioning:
- Source under construction, to be delivered in early 2015
- Transport sections under construction, to be delivered Spring 2014
- Main Spectrometer and Detector commissioning just started
  - First Light on May 31st
  - Continuing with HV and Baffle operation until September.
  - Upgrade program in Fall 2013