Monitoring a very low current and wide beam at KATRIN

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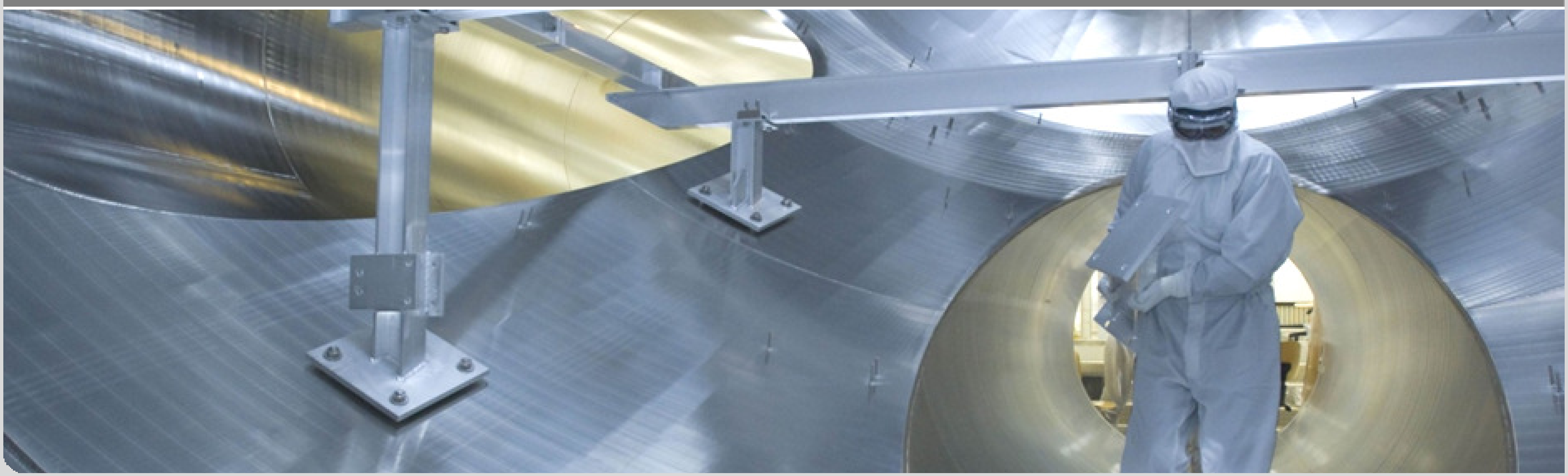


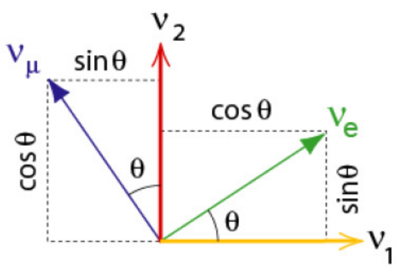
Topics

- Massive Neutrinos
- The KATRIN experiment
- Beam monitoring at KATRIN
  - The Focal Plane Detector
  - The Forward Beam Monitor Detector
  - The Rear Section BIXS Monitor
- Improved beam monitoring
  - time-of-flight mode
  - sterile neutrinos

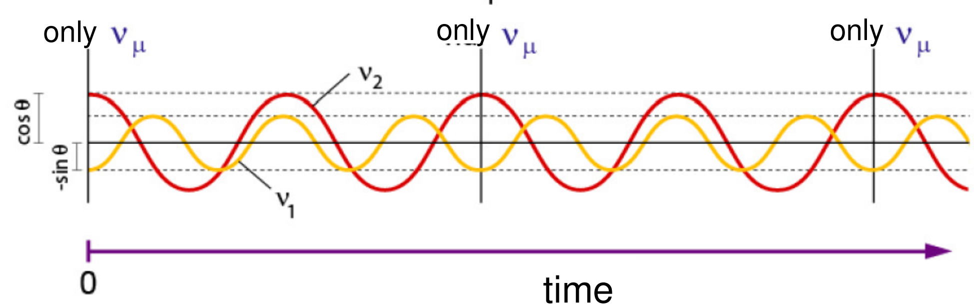
Massive Neutrinos

- The „solar neutrino problem“ (missing electron neutrinos) was solved by experiments (e.g. SNO, SuperKAMIOKANDE)
- electron **+** muon type neutrinos = expected **electron** neutrino flux

NEUTRINO OSCILLATION
neutrino flavor/weak eigenstates ≠ mass eigenstates
at least 2 mass eigenstates with m≠0
massive neutrinos

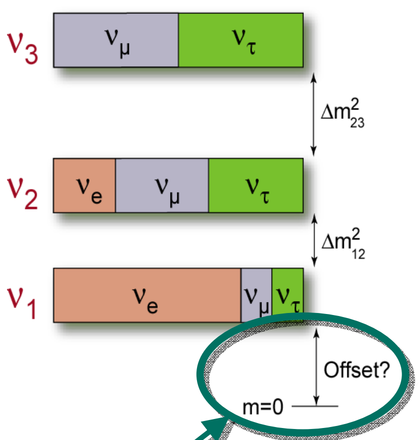


$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$



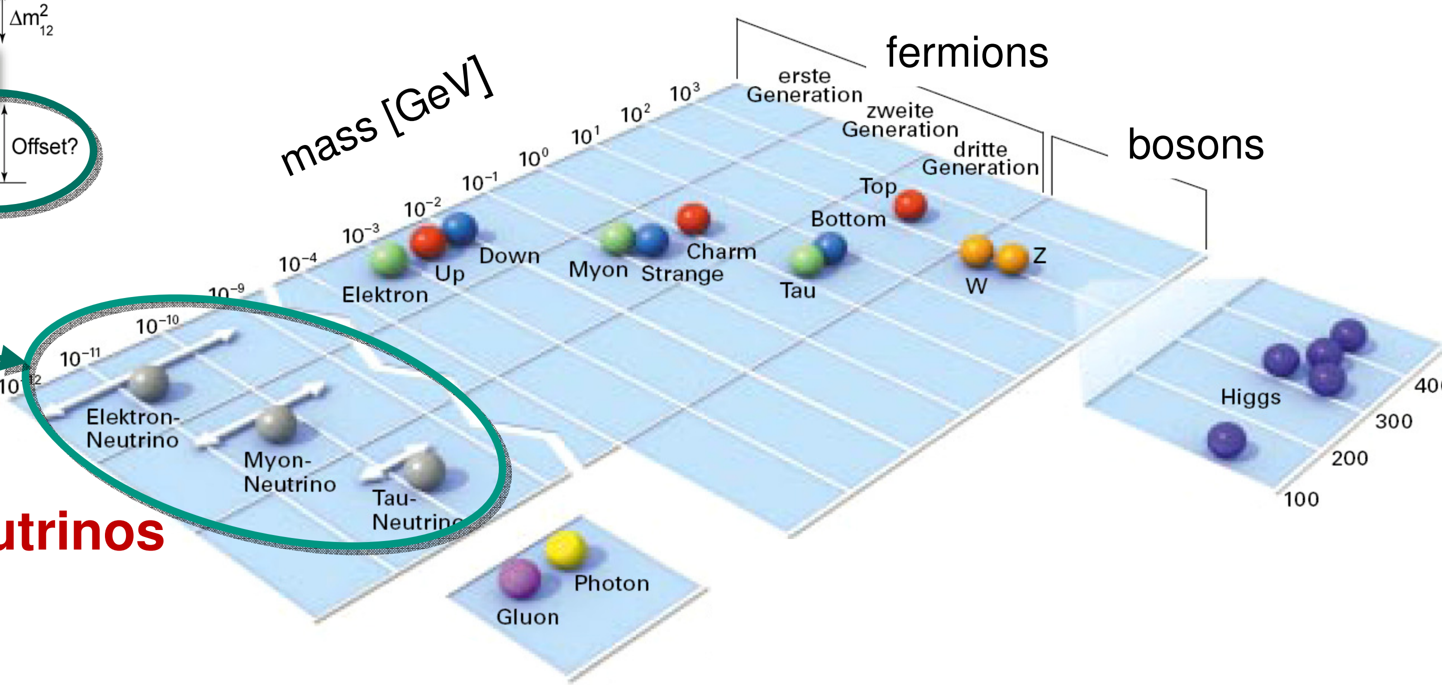
Massive neutrinos – particle physics

- Neutrinos are massless in the standardmodel of particle physics!



- Mixing angles and differences between the mass eigenstates are being measured by neutrino oscillation experiments (reactor, solar and atmospheric neutrinos)

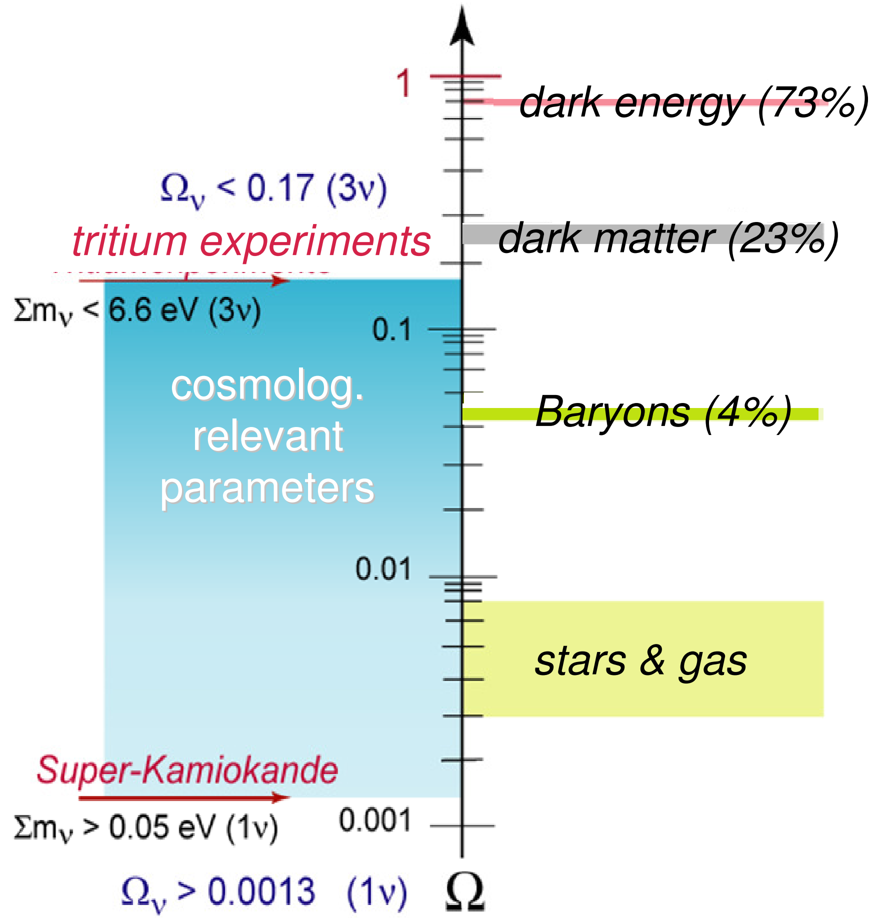
Absolute scale:
KATRIN



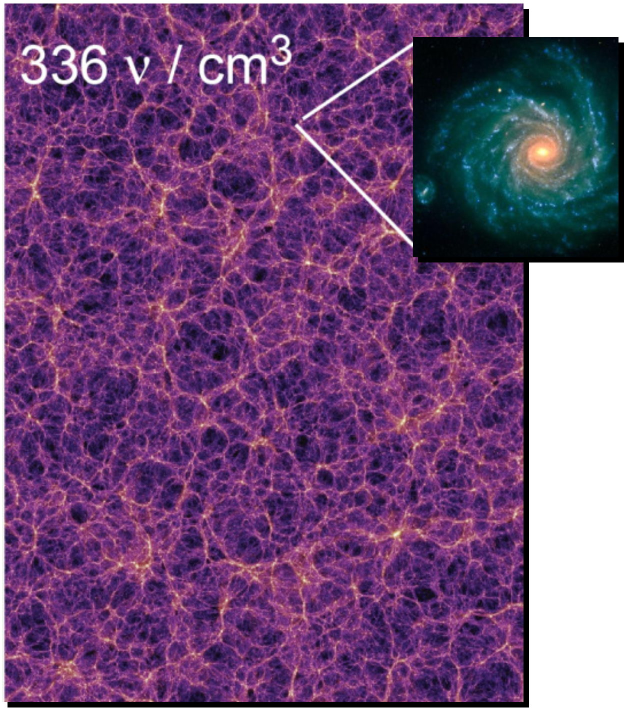
neutrinos

Massive neutrinos - cosmology

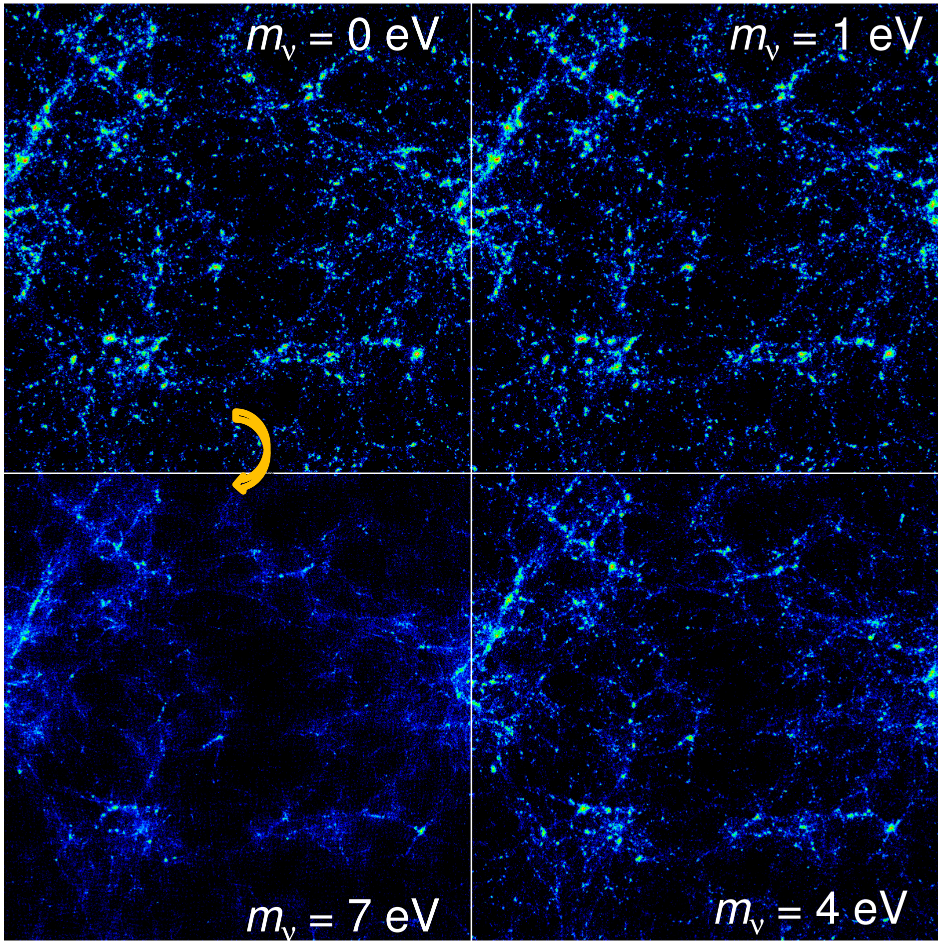
- Neutrinos are the 2nd most abundant *known* particle in the universe
- Relic neutrinos contribute to Hot Dark Matter (HDM) ?
- Sterile keV neutrinos contribute to Warm Dark Matter (WDM) ?



Massive neutrinos – Large scale structures



Large scale structure
of the universe
(Millenium Simulation)



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  - time-of-flight mode
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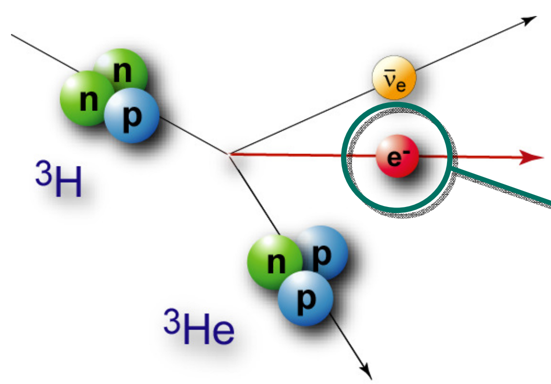
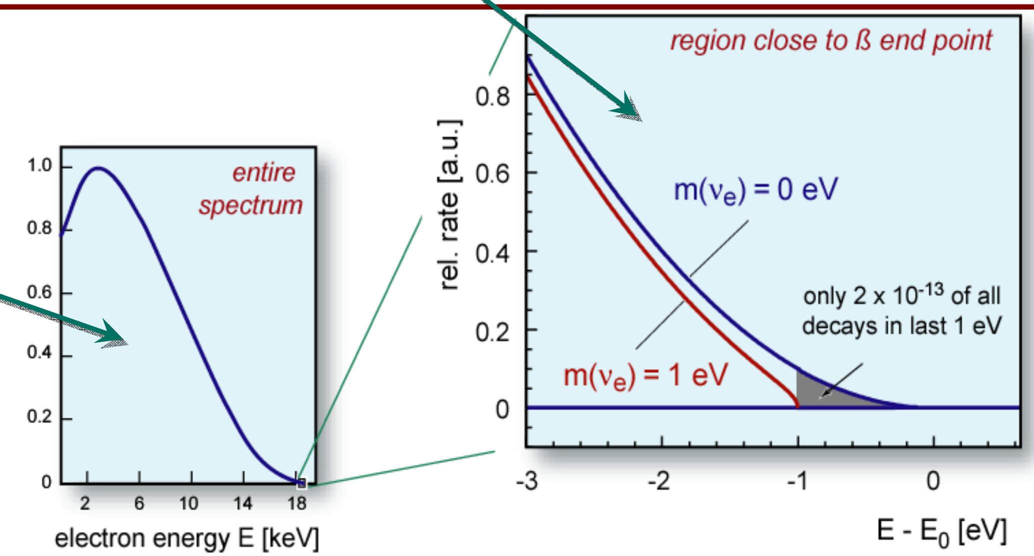
KATRIN

- Model independent neutrino mass from tritium β-decay kinematics
- Sensitivity on m_ν: 0.2 eV (current limit: 2.2 eV)
- Only assumption: relativistic energy-momentum relation
- Neutrino beam *monitored* by electron beam

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



^{3}H: E_0 = 18.6 keV
$T_{1/2}$ = 12.3 y



KATRIN - MAC-E-Filter principle

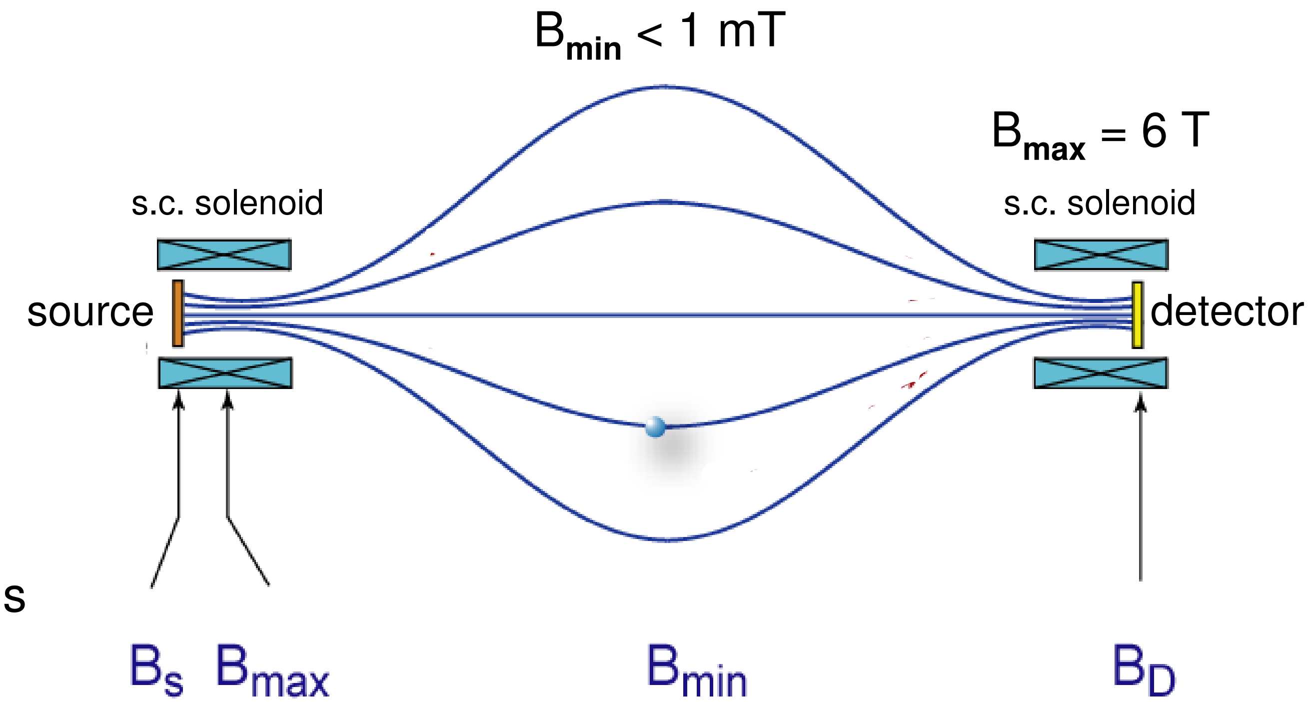
MAC – Magnetic Adiabatic Guiding

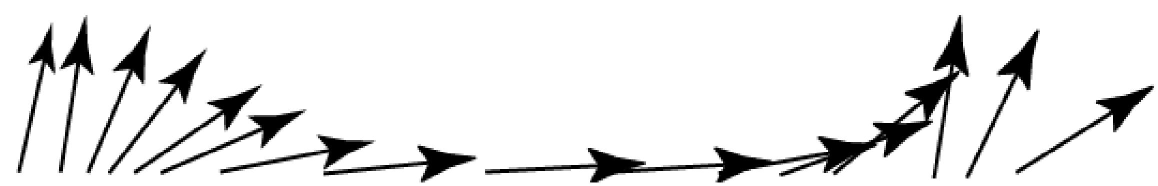
adiabatic guiding of electrons along magnetic field lines

inhomogenous B-field: superconducting solenoids solid angle dΩ ~ 2π

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

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





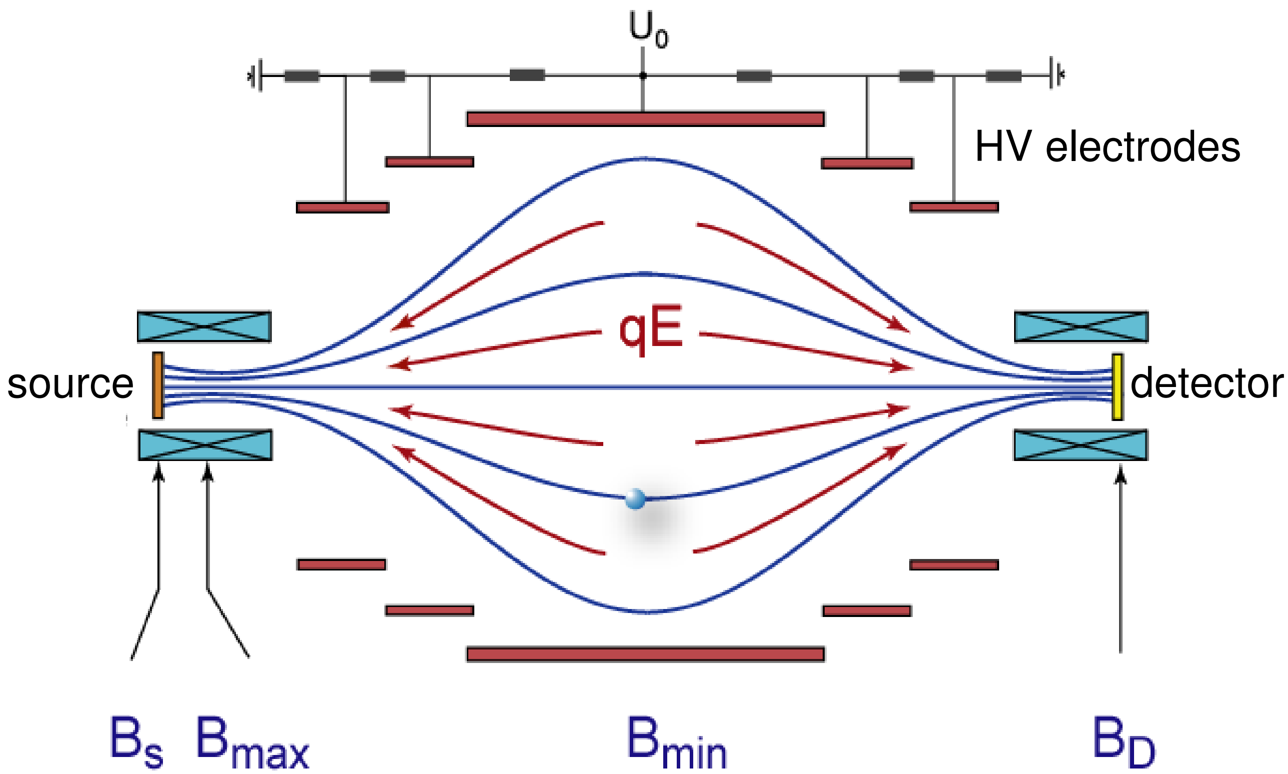
KATRIN - MAC-E-Filter principle

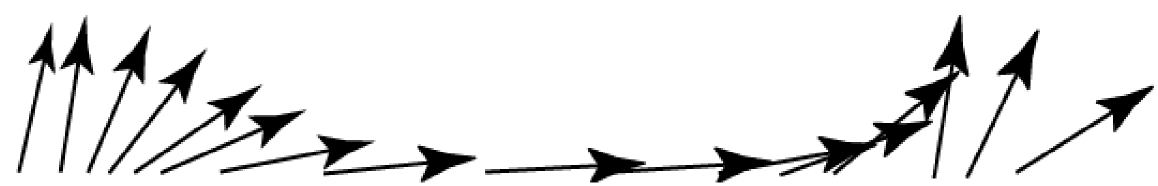
E Filter – Electro-static filter

energy analysis by an electrostatic retarding field

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

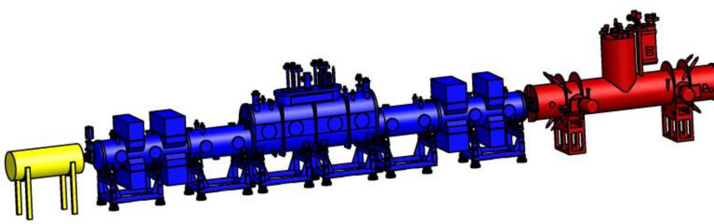
integral transmission for $E > U_0$
high pass filter

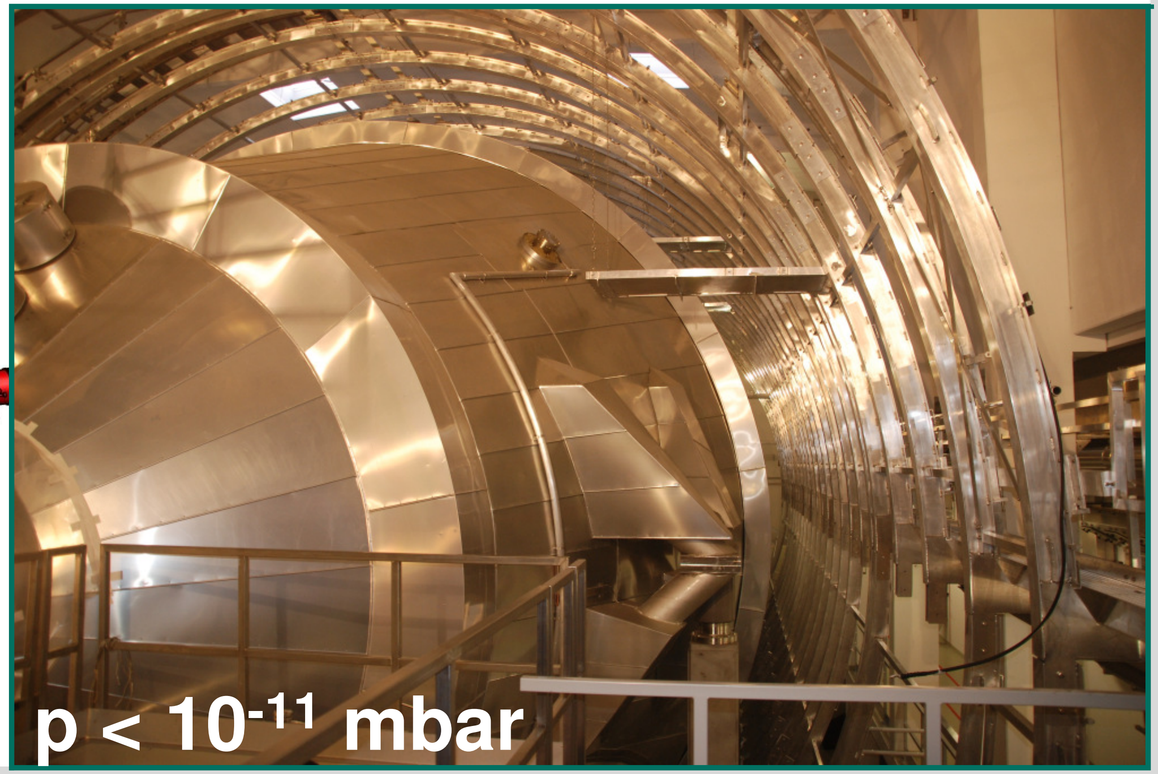




KATRIN – main components

- High-luminosity windowless gaseous tritium source (1.7 × 10^{11} e^-/s)
- High-performance pumping section (T_2 reduction factor: > 10^{14})
- Two electrostatic retarding spectrometers (MAC-E-filters)
- Main detector (148 pixels)

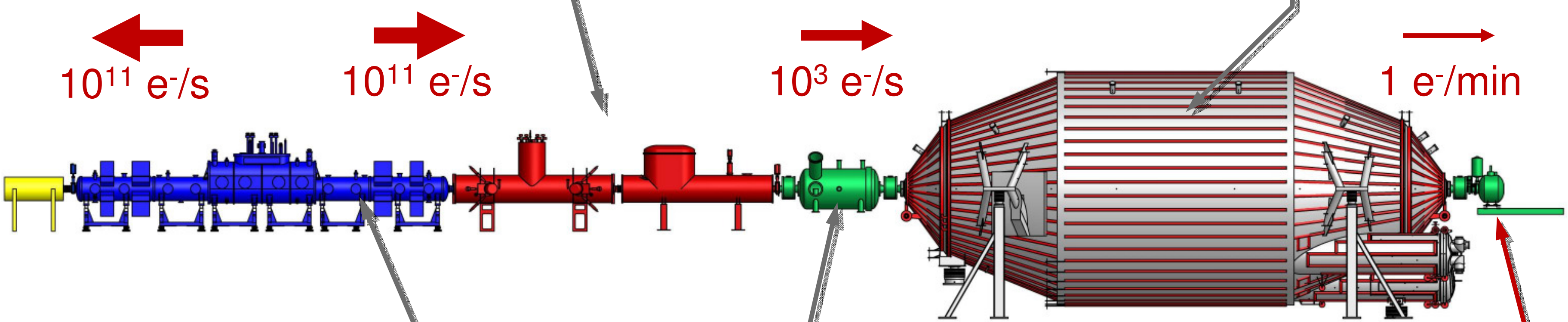




KATRIN – beamline

Transport Section
Tritium Retention
Turbopumps + Cryotraps

Main Spectrometer
U = -18.3 … -18.6 kV
ΔE=0.93 eV

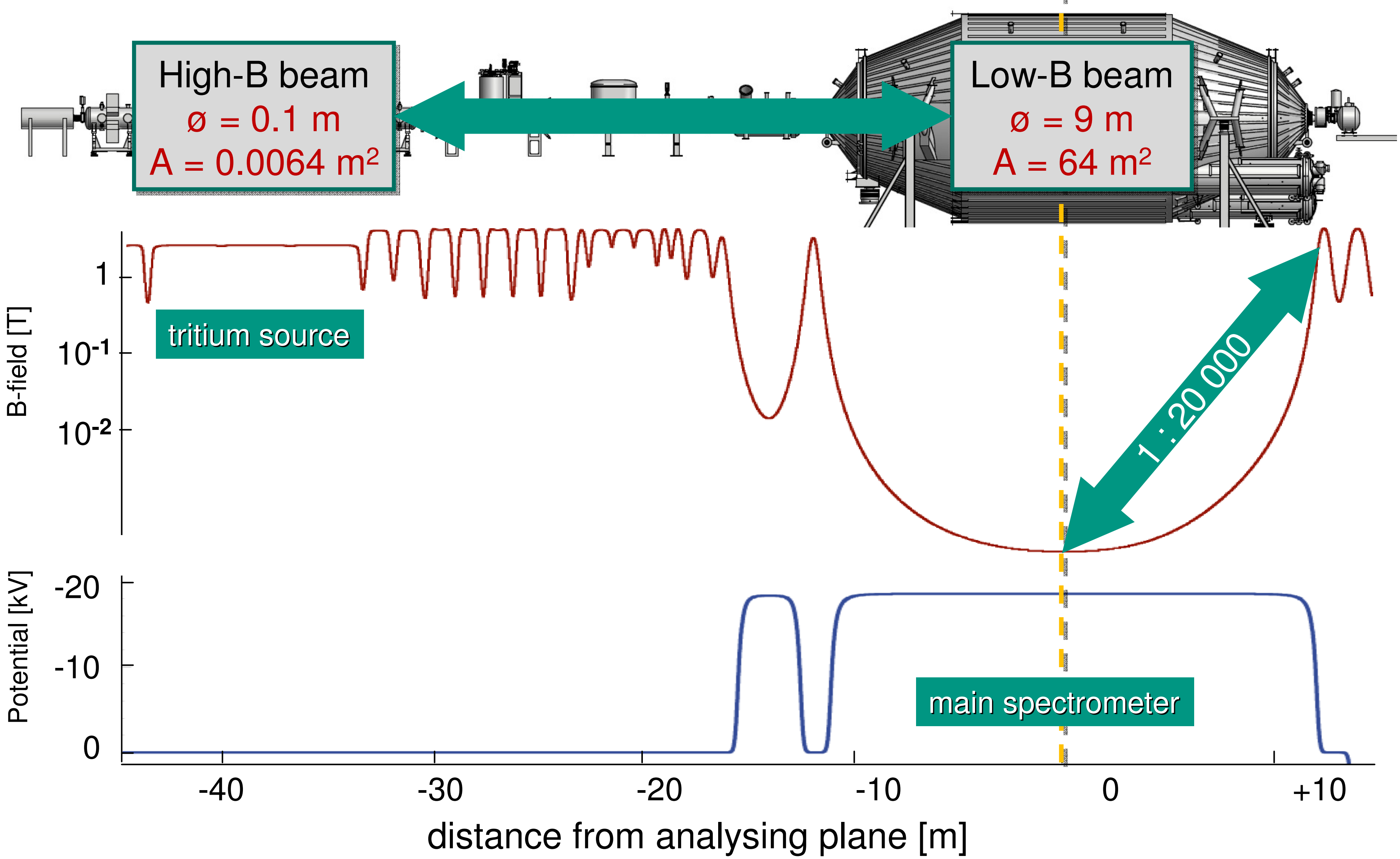


Windowless gaseous
Tritium Source (WGTS)
R=1.7 x 10^{11} Bq

Pre-Spectrometer
U = -18.3 kV

Focal Plane Detector (FPD)

KATRIN - beamline



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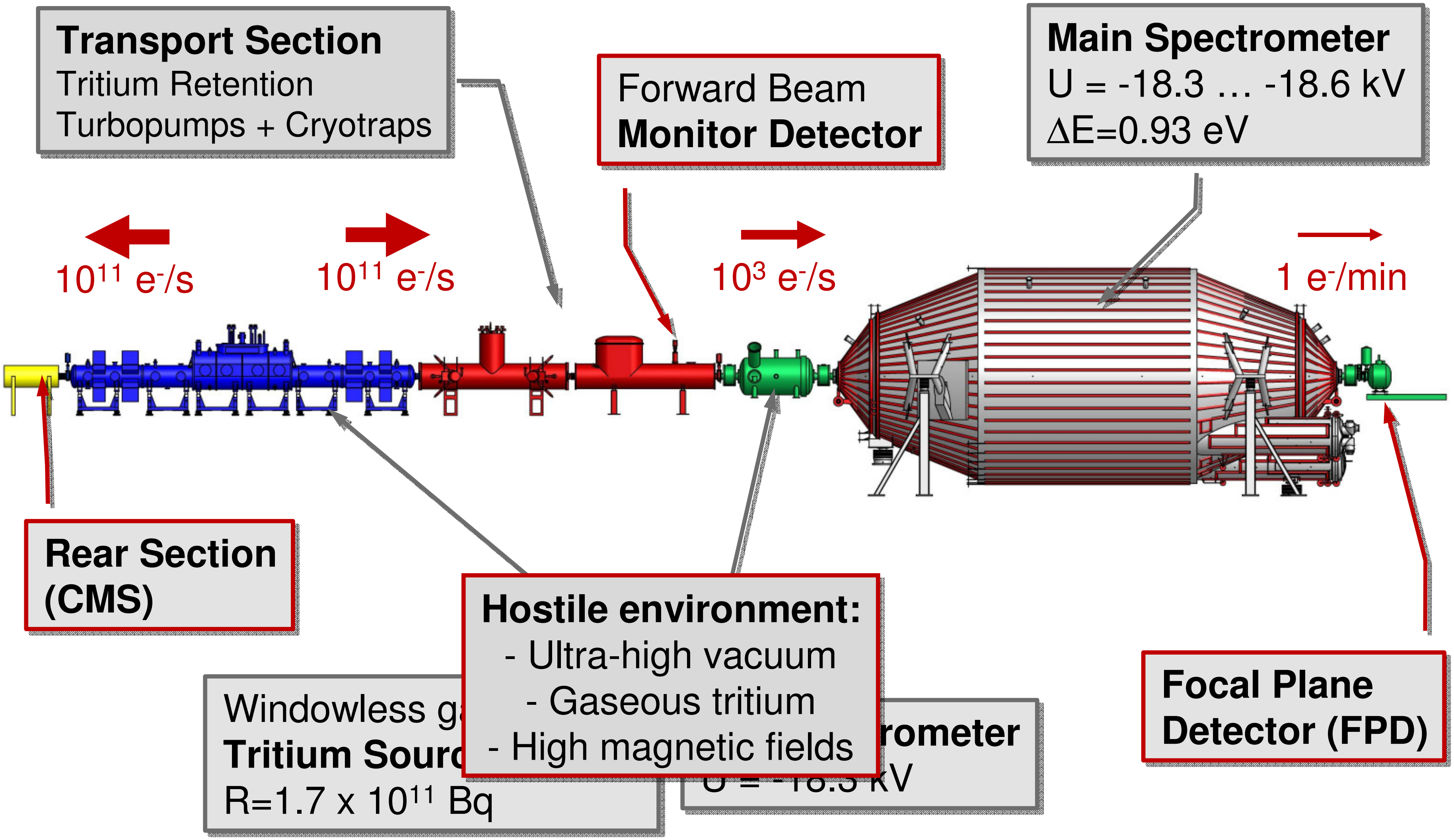
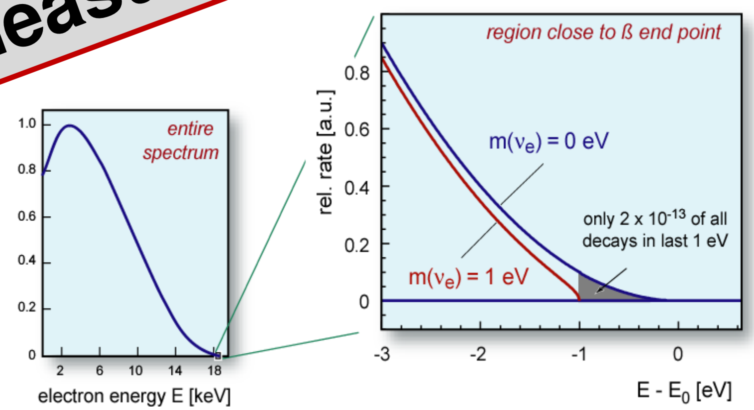
  - **The Rear Section BIXS Monitor**
- **Improved beam monitoring**
  - **time-of-flight mode**
  - **sterile neutrinos**

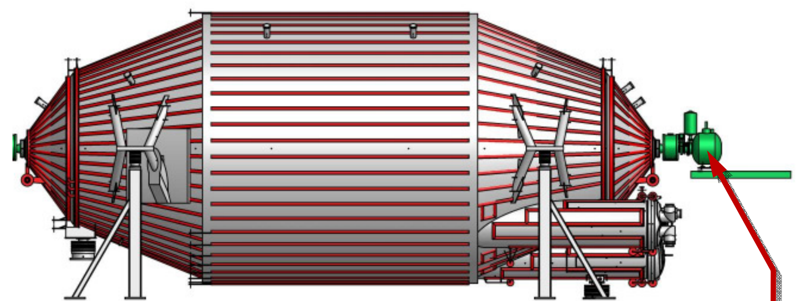
KATRIN – beam monitoring



Main spectrometer and focal plane detector

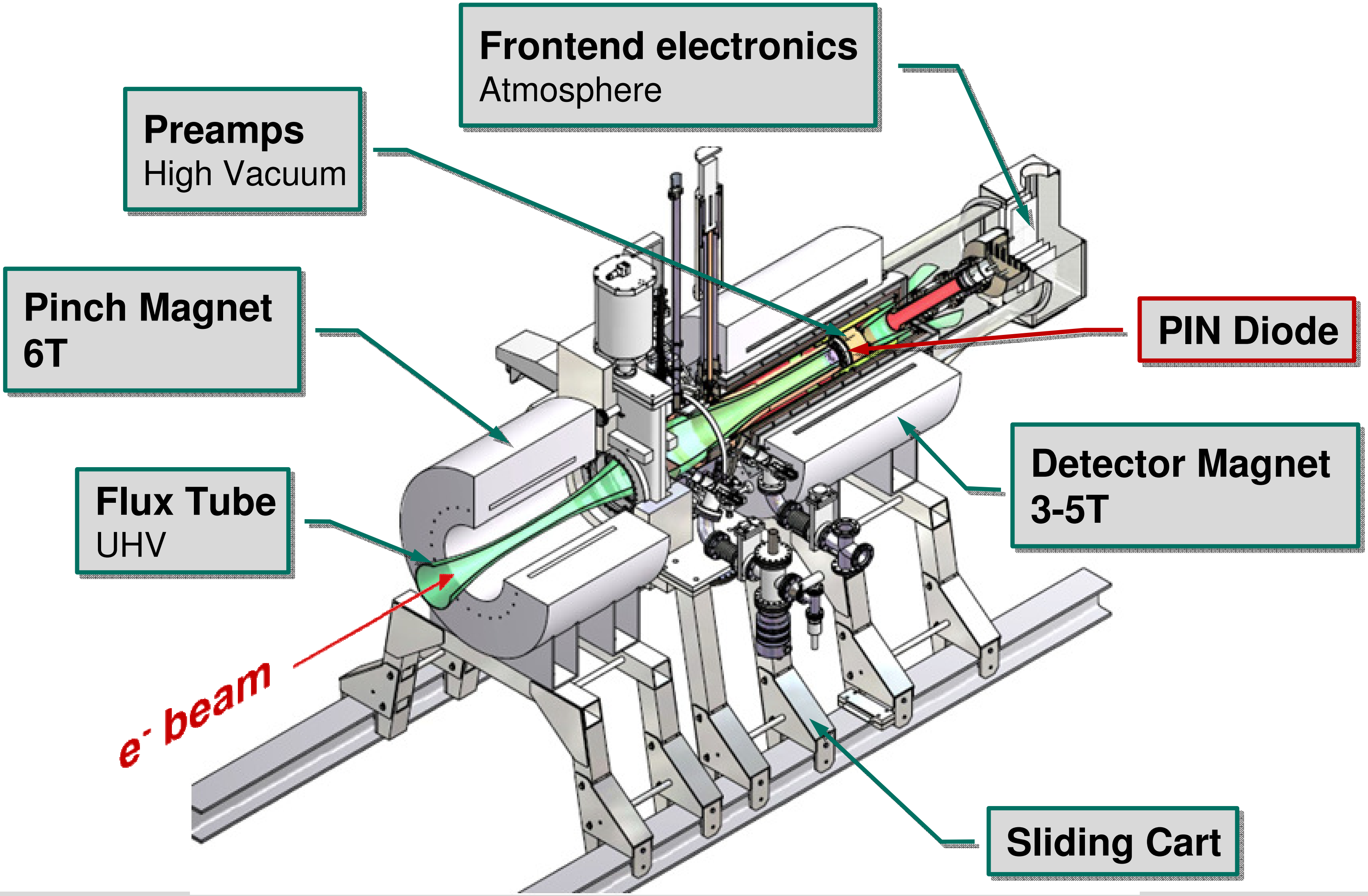
Measure beta spectrum close to endpoint!





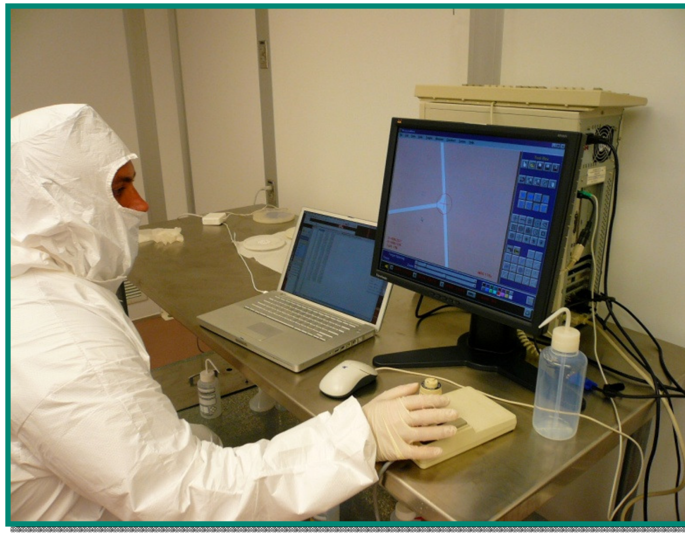
Focal Plane Detector (FPD)
sub-fA current
single electron detection

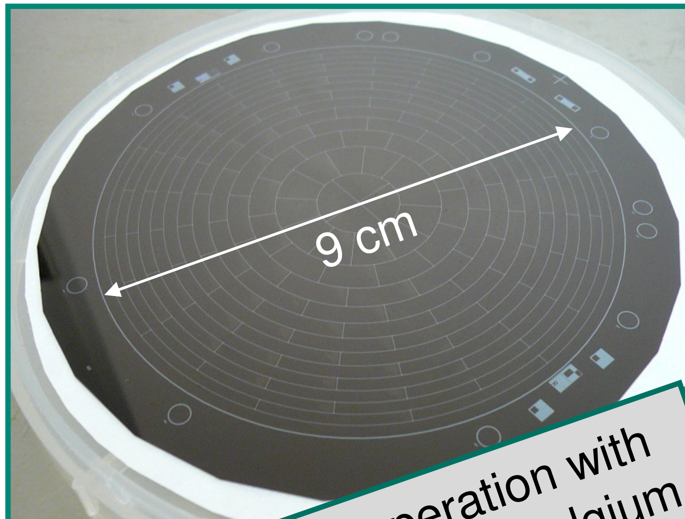
Focal Plane Detector System



Focal Plane Detector (FPD)

- **measures / counts highest energy electrons** (Hz rates)
- but also used for calibration / monitoring at reduced spectrometer potential (kHz rates)
- custom designed monolithic PIN diode
- active and passive veto
- 148 pixels (same area)
- energy resolution: 1.4keV (to increase S/N)
- dead layer: < 200nm (model dependent!)
- e^- and x-ray calibration system
- DAQ trace mode (< 350Hz)
- energy mode (350Hz < R < 120kHz)
- energy histogram mode (> 120kHz)

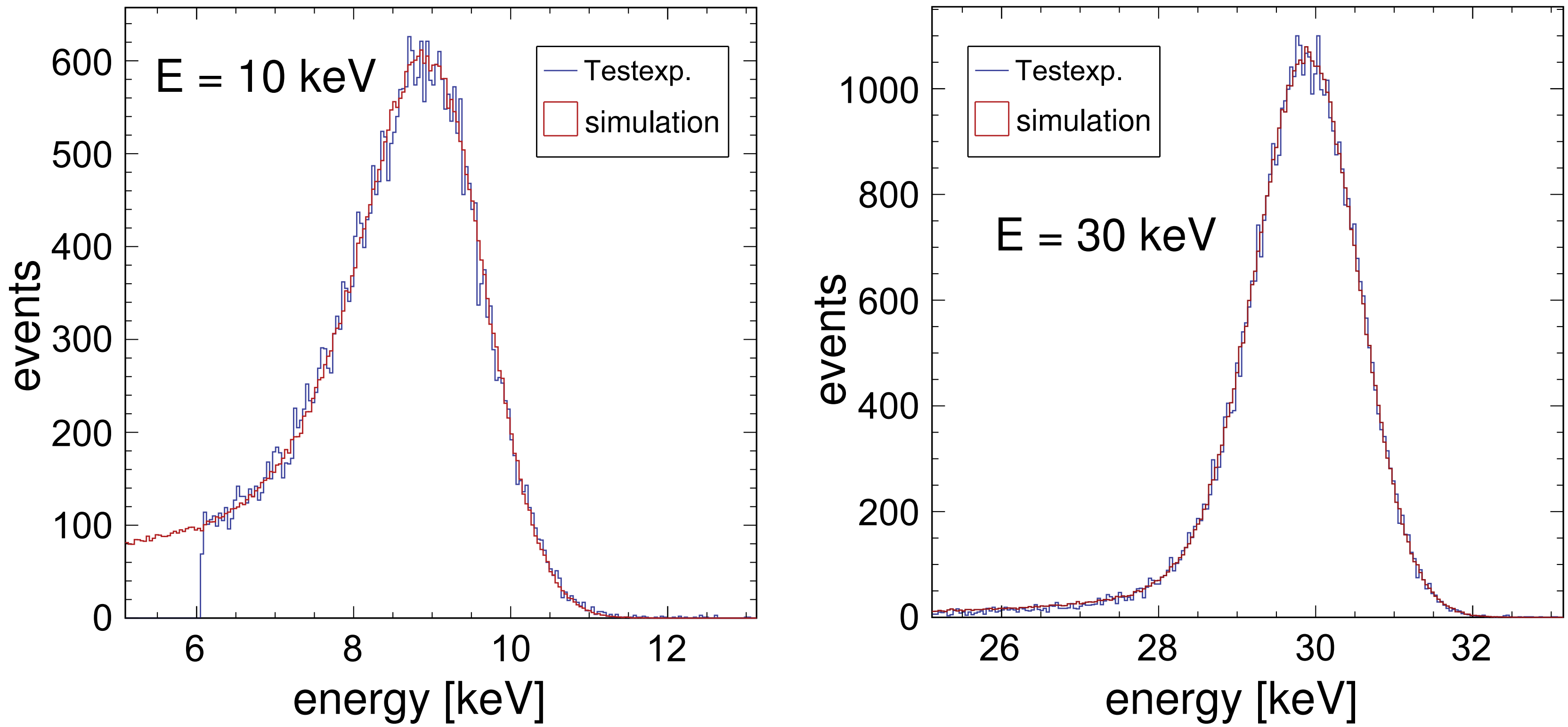




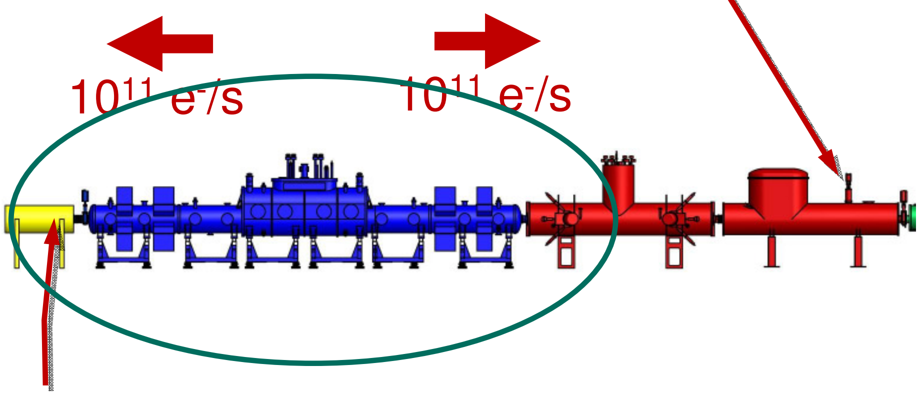
Cooperation with Canberra, Belgium

Focal Plane Detector (FPD) – Data vs. Sim

- Data from test setup of the actual FPD wafer
- Mono-energetic electron beams
- Simulation includes dead layer and backscattering effects



Forward Beam Monitor Detector
nA current
small, movable detector
measure beam profile and source intensity



Rear Section BIXS
nA current
monitors full beam
measure source intensity

Monitor source / beam stability

Source stability

- We need a stable tritium source to avoid systematic errors on m_ν^2!
  - To combine measurements at different retarding voltages (Intensity N)
  - To account for scattering of the electrons in the source (column density)

$N(T_2) = A_S$ …

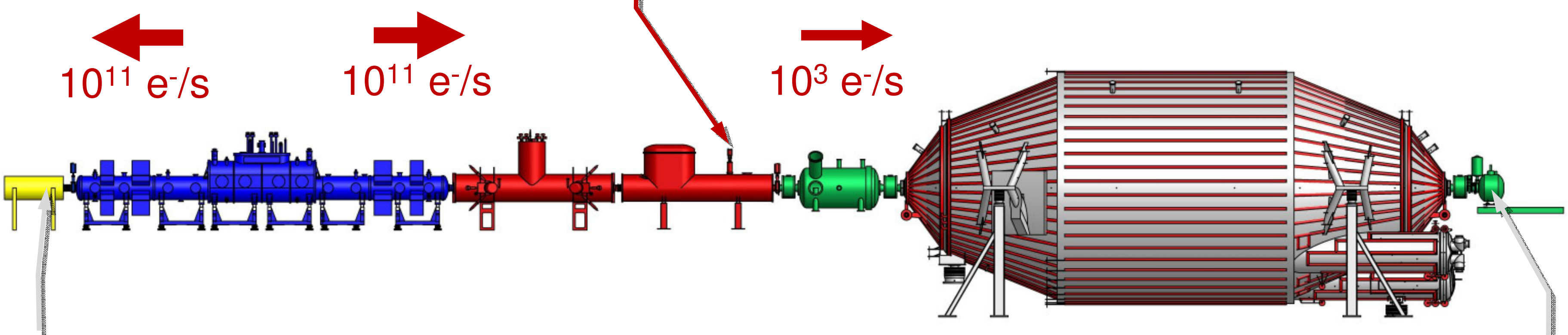
triti… ty ε_T

… density ρd

We need 0.1% precision

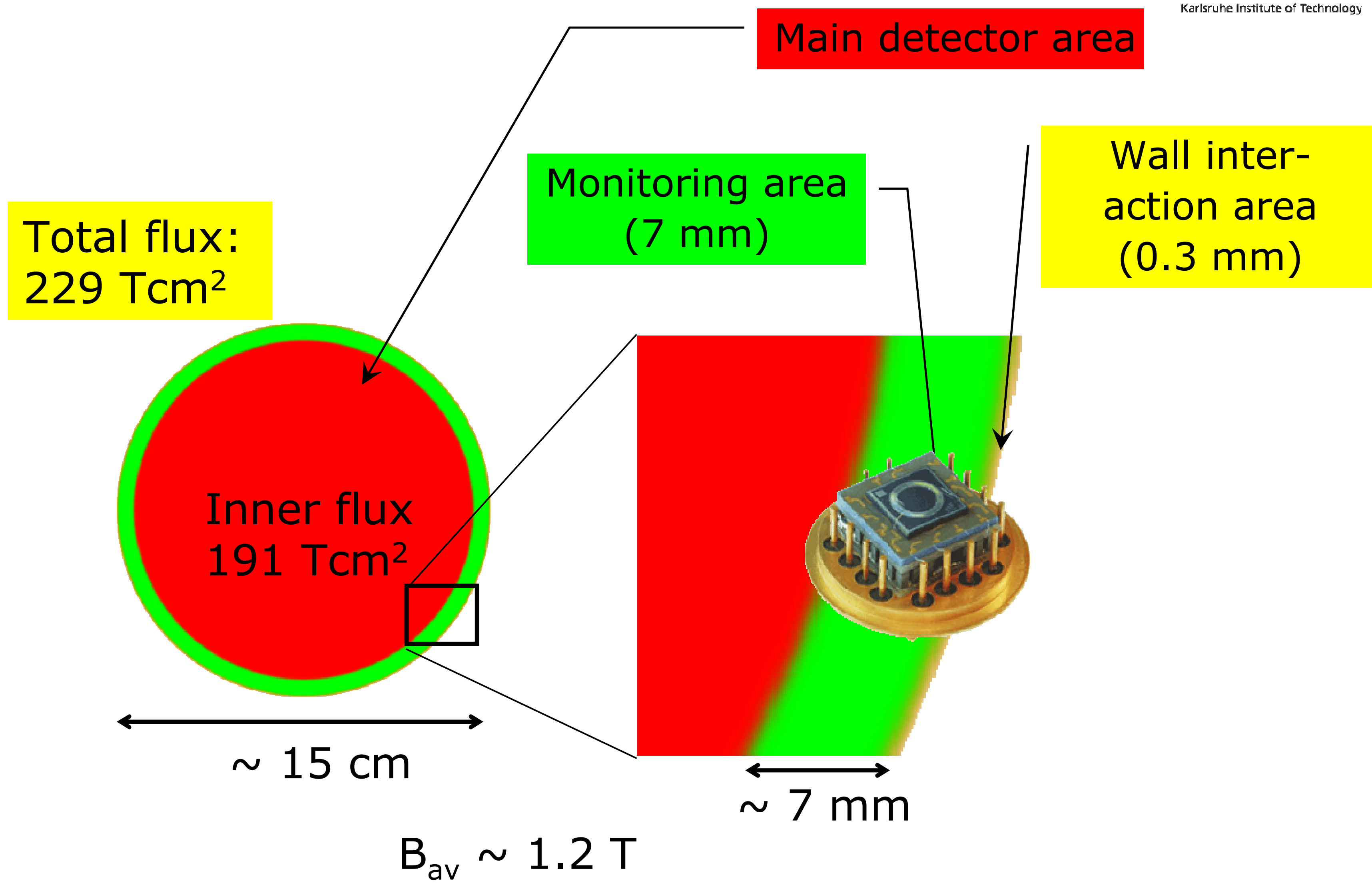
- Geometry (A) is fixed
- Tritium purity is *continuously* monitored by Laser-Raman-Spectroscopy
- Column density is measured by rear e-gun (*every 2 hours*)
- Source intensity is *continuously* measured by
  - Forward beam monitor measures beam profile, spectroscopy and **partial** beam intensity (sampling time < 10 s)
  - Rear Section BIXS (**full** beam intensity, samplig time 100 s)

Forward Beam Monitor Detector
nA current
small, movable detector
measure beam profile and
source intensity

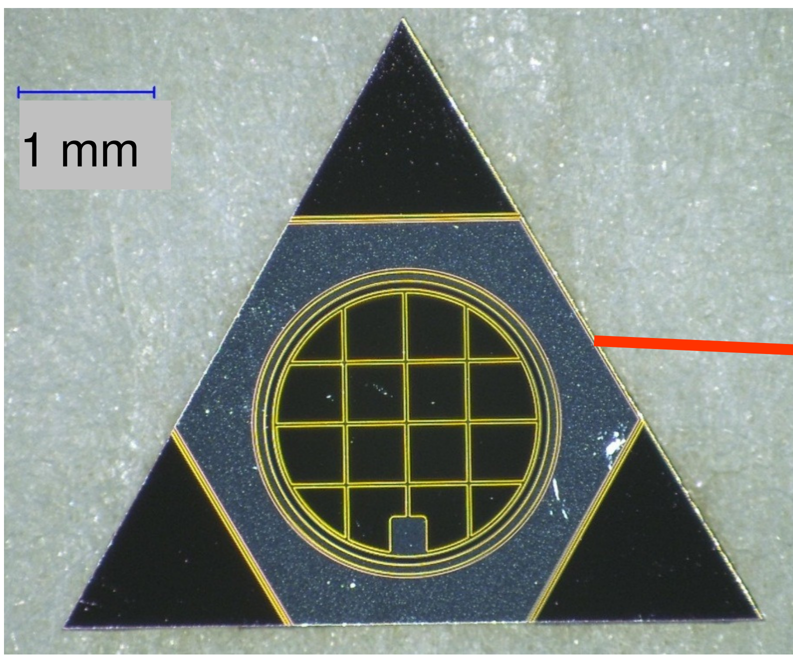


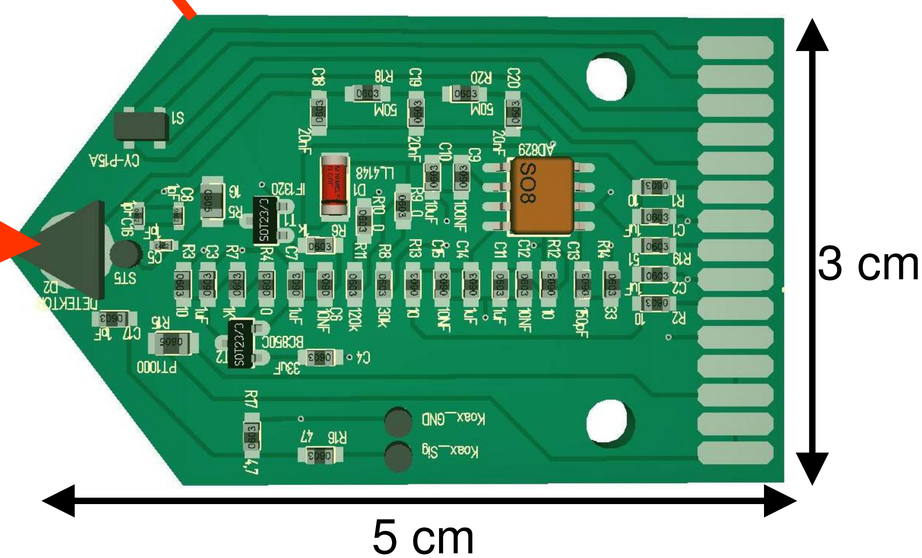
Rear Section BIXS
nA current
monitors full beam
measure source intensity

Focal Plane Detector (FPD)
sub-fA current
single electron detection

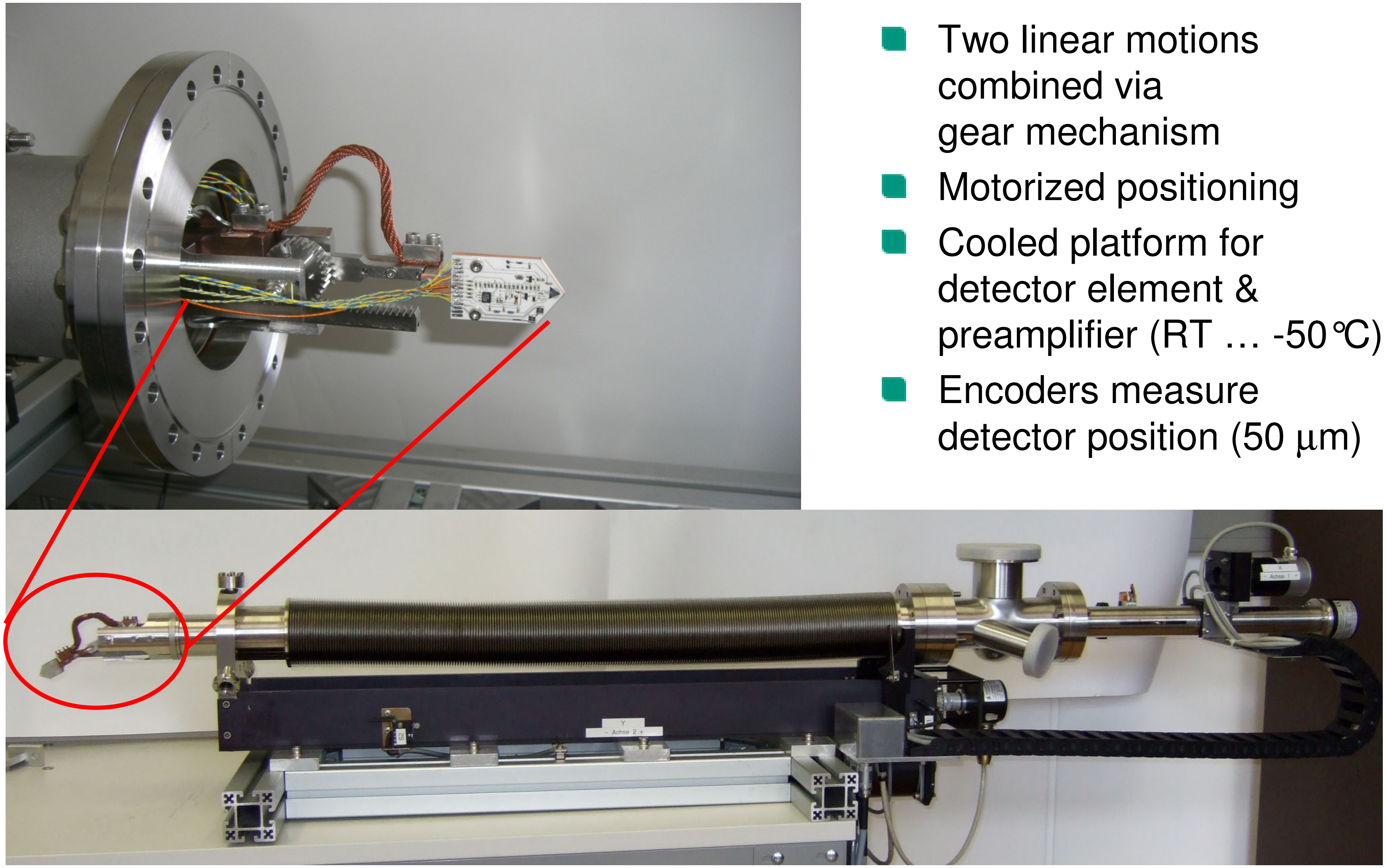

Main detector area
Total flux:
229 Tcm²
Monitoring area
(7 mm)
Wall inter-
action area
(0.3 mm)
Inner flux
191 Tcm²
~ 15 cm
~ 7 mm
B_av ~ 1.2 T

- Movable to scan beam profile
- UHV compatibility
- B-field: 1.2 T
- Can measure current (stability)
- Can measure electron energy
- Small surface for spectroscopy



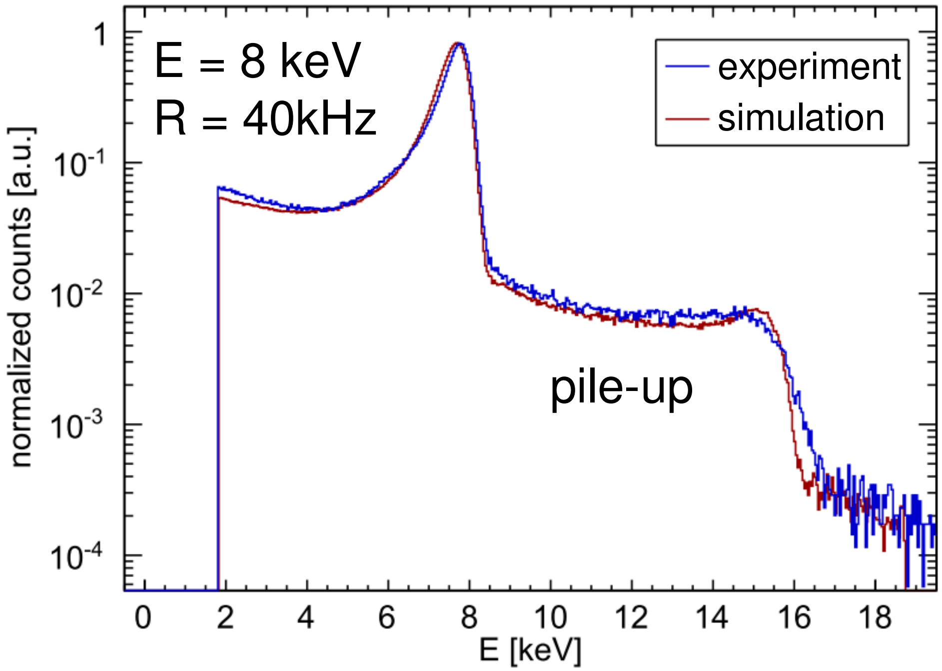


Forward Beam Monitor Detektor

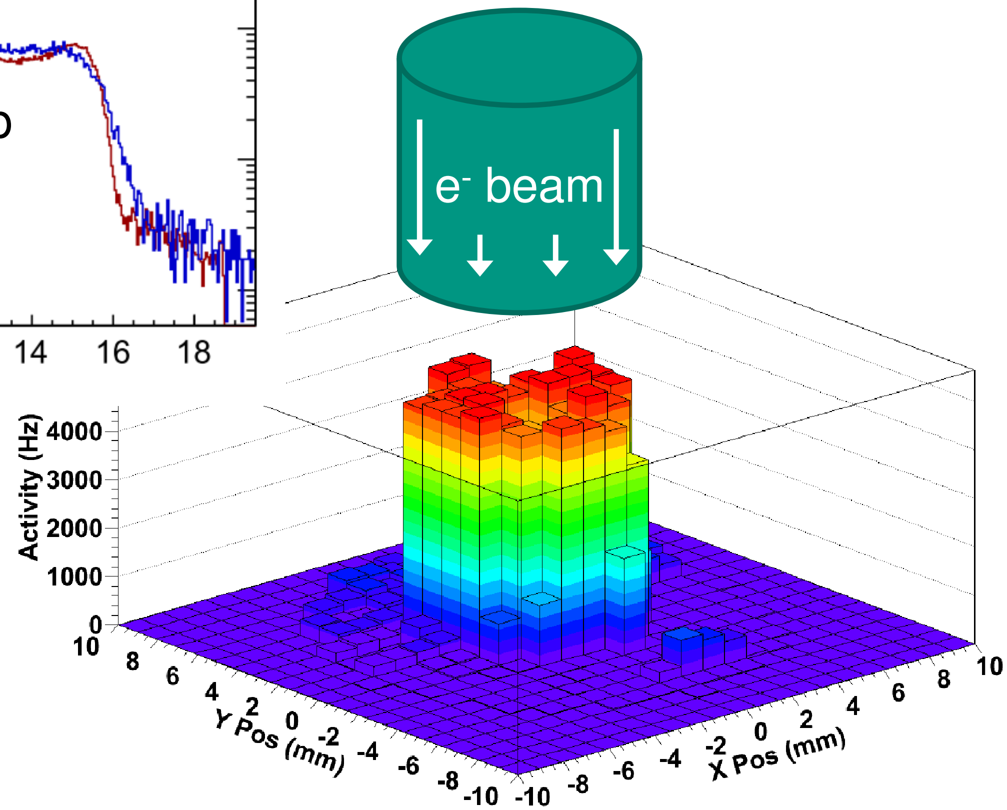


- Two linear motions combined via gear mechanism
- Motorized positioning
- Cooled platform for detector element & preamplifier (RT … -50°C)
- Encoders measure detector position (50 µm)

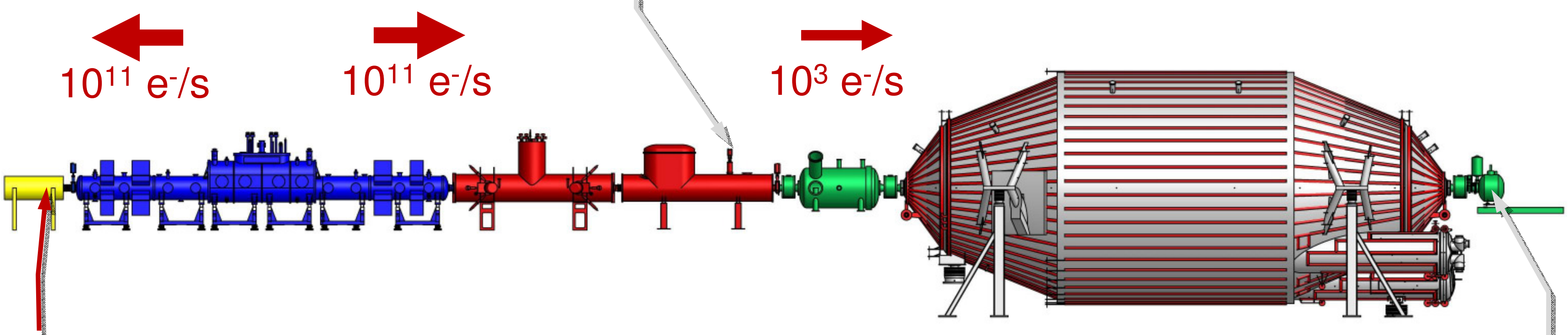
Forward Beam Monitor Detektor



- Energy resolution: typically 1.5 keV (FWHM) @ 15 keV & -30 °C
- Beam profile scanning works



Forward Beam Monitor Detector
nA current
small, movable detector
measure beam profile and source intensity



Rear Section BIXS
nA current
monitors full beam
measure source intensity

Focal Plane Detector (FPD)
sub-fA current
single electron detection

The Rear Section …

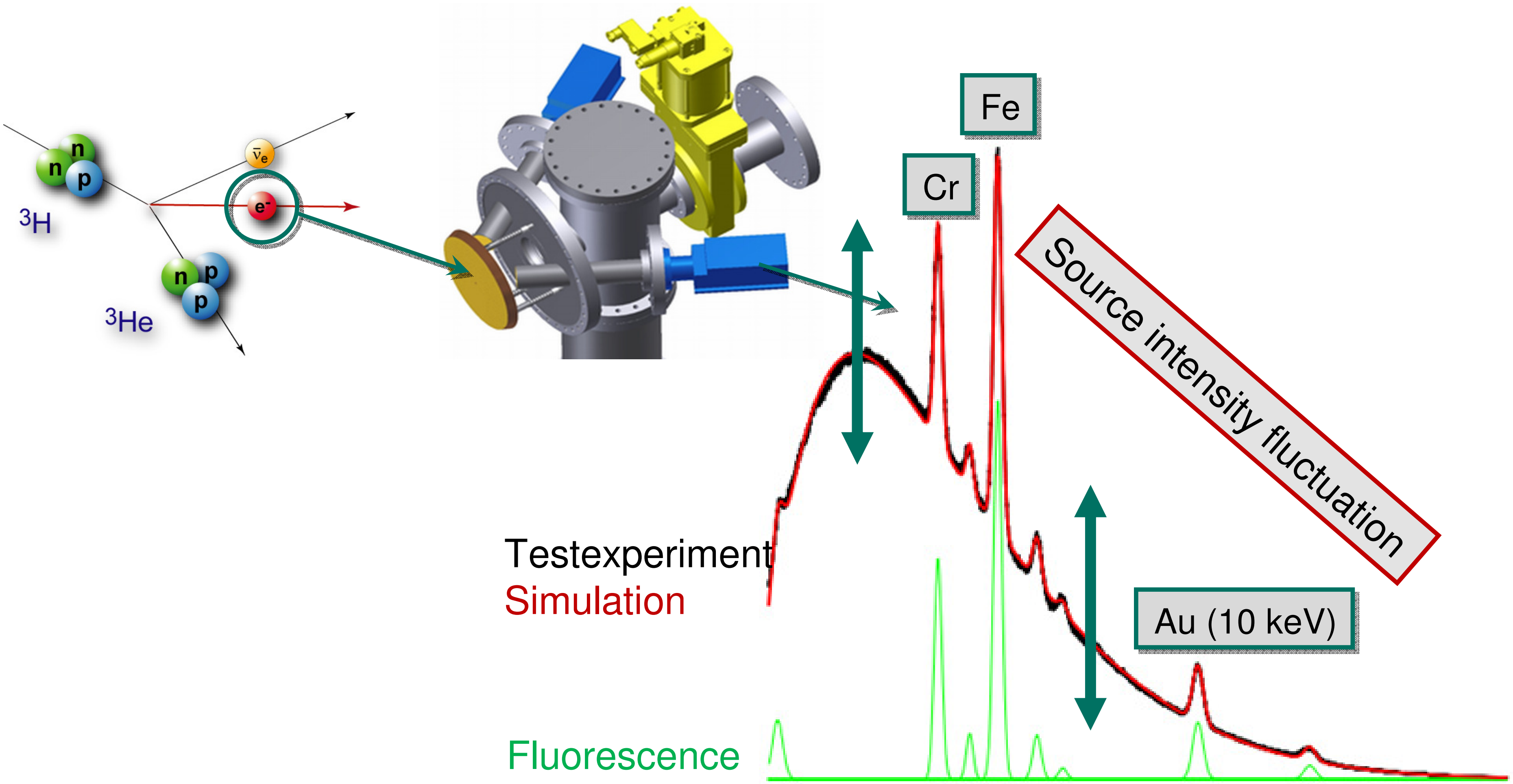
- defines source potential (KATRIN ground potential) (gold coating)
- doubles as a source intensity monitor (beryllium window)
- „absorbs“ half of the total source intensity/beam current
- houses an angular-selective electron gun for calibration measurements (e.g. column density)

Rear Section BIXS

- BIXS – **B**eta **I**nduced **X**-ray **S**pectroscopy

Rear Section BIXS

- BIXS – **B**eta **I**nduced **X**-ray **S**pectroscopy



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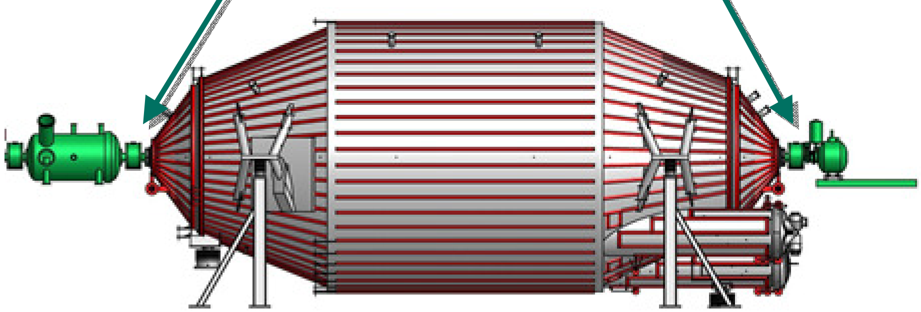
- ➡ **Improved beam monitoring**
  - **time-of-flight mode**
  - **sterile neutrinos**

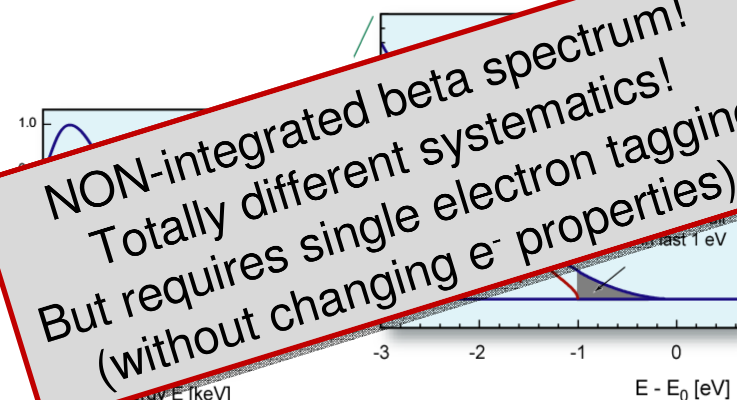
KATRIN Time-Of-Flight (TOF)

- Tag single electrons and measure time difference
- Pathlength depends on angle relative to B-field
- Time difference depends on angle and spectrometer potential
- Correlate TOF distribution with known angular distribution
- Calculate electron energy by

$$E^2=p(\Delta t,\Delta x)^2+m(e^-)^2$$

Time information

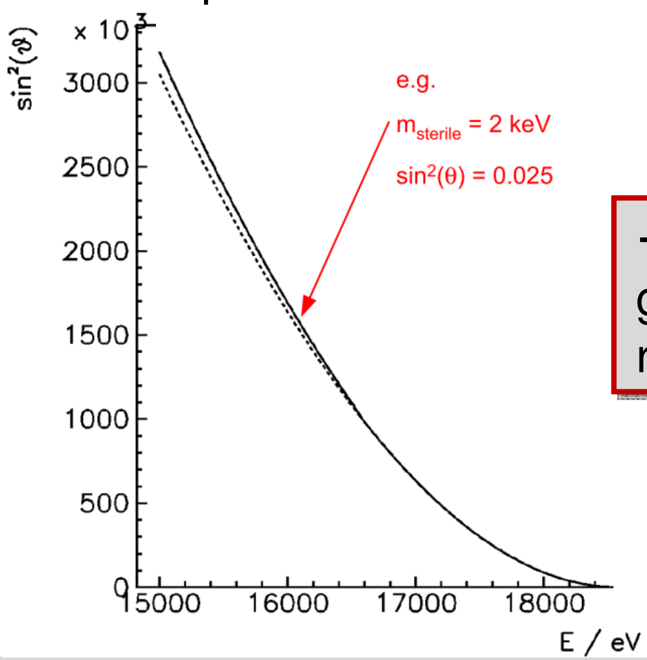




NON-integrated beta spectrum!
Totally different systematics!
But requires single electron tagging
(without changing e^- properties)

Sterile neutrinos at KATRIN

- LEP constrains the number of *standard model* neutrinos to 3
- But Cosmology (BBN) allows for 4 neutrino types
- A keV sterile neutrino …
  - … can explain the observed large scale structures
  - … allows early star formation (Z=80) favored by cosmic ray spectrum
  - … helps in the creation of super-massive black holes



→Need new beam monitor with very good energy resolution at very high rates (10^9 Hz)

Summary

- KATRIN monitors the neutrino beam by measuring a β-electron beam
  - varying diameter of 0.09 to 9 m
  - currents vary from sub-fA to 16 nA
- Upper Beta spectrum *(aA-fA)* is detected by Focal Plane Detector (energy of single electrons)
- Source stability (nA beam) is monitored by Forward Beam Monitor and Rear Section (BIXS)
- The monitoring systems work and are backed up by detailed simulations
- Through precision monitoring, the predicted systematic uncertainties can be reached and KATRIN will measure the neutrino mass with a sensitivity of 200meV
- Improved beam monitoring can largly improve KATRIN sensitivity and allow the search for sterile neutrinos (and further exploit the unique Tritium source)