Electromagnetic Design of the Spectrometer Section of the KATRIN Experiment

Susanne Mertens for the KATRIN Collaboration
Overview

- Why do we have electric and magnetic fields at the KATRIN experiment?
- What are the challenges of the Electromagnetic Design?
- How is it realized?
Why do we have electric and magnetic fields at the KATRIN experiment?

\[ ^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e \]
Role of the electric potential: high energy electron filter
Role of the magnetic field: guiding system
Interplay of electric potential and magnetic field
Interplay of electric potential and magnetic field

- Electron kinetic energy:
  \[ E_{\text{kinetic}} = E_{\text{longitudinal}} + E_{\text{cyclotron}} \]

- Electron transmitted if:
  \[ E_{\text{longitudinal}} > 0 \text{ keV} \]

- Adiabatic motion of electron from high to low magnetic field:
  \[ E_{\text{cyclotron}} \rightarrow E_{\text{longitudinal}} \]
  \[ E_{\text{kinetic}} \approx E_{\text{longitudinal}} > 0 \text{ keV} \]

MAC-E-Filter-Principle:
Magnetic Adiabatic Collimation and Electric filter
Overview

- Why do we have electric and magnetic fields at the KATRIN Experiment?
  - High energy electron filter (electric potential)
  - Guiding and energy transformation (magnetic field)
- What are the challenges of the Electromagnetic Design?
- How is it realized?
1st Goal:
Realize the MAC-E-Filter principle in the optimal way

- Homogeneous electric potential in analyzing plane
- Homogeneous magnetic field in analyzing plane
- Slowly increasing electric potential relative to decrease of magnetic field
- Slowly decreasing magnetic field to assure adiabaticity
2nd Goal: Reduce Background

\[ \frac{N_e}{s} = 10^{11} \]

Probability: \(10^{-7}\)

\[ \frac{N_e}{s} = 10^{-2} \]

1 Electron/min

region close to \(\beta\) end point

only \(2 \times 10^{-13}\) of all decays in last 1 eV

\[ m(v_e) = 0 \text{ eV} \]

\[ m(v_e) = 1 \text{ eV} \]
Background Sources

1. Electrons being emitted from the inner surface of the wall
2. Stored Electrons in penning traps
Reduce background with the Electromagnetic Design

Desired background level:

\[10^{-2} \text{ electrons/s} = 10 \text{ mHz}\]

- \(10^5 \text{ electrons/s from the wall}\) → Magnetic shielding \((10^5)\)
- \(\rightarrow \text{Wire electrodes (10}^2\)\) (Talk by Kathrin Valerius)

- \(10^2 - 10^{15} \text{ electrons/s from penning traps}\) → Specially designed electrodes
Reduce background with the Electromagnetic Design

Desired background level: 
$10^{-2}$ electrons/s 
$= 10$ mHz

$10^5$ electrons/s from the wall  
→ Magnetic shielding ($10^5$)  
→ Wire electrodes ($10^2$) (Talk by Kathrin Valerius)

$10^2 - 10^{15}$ electrons/s from penning traps  
→ Specially designed electrodes
Reduce background with the Electromagnetic Design

Desired background level:
$10^{-2}$ electrons/s
$= 10$ mHz

$10^5$ electrons/s from the wall
→ Magnetic shielding ($10^5$)
→ Wire electrodes ($10^2$) (Talk by Kathrin Valerius)

$10^2 - 10^{15}$ electrons/s from penning traps
→ Specially designed electrodes
Overview

- Why do we have electric and magnetic fields at the KATRIN Experiment?
  - High energy electron filter (electric potential)
  - Guiding and energy transformation (magnetic field)
- What are the challenges of the Electromagnetic Design?
  - Realize MAC-E-Filter in optimal way
  - Reduce Background
- How is this realized?
1st Example: Aircoil System
Technical realization

12.5 m

24 m
Technical realization

Earth’s Magnetic field Compensation System

Earth magnetic field
Technical realization

Earth’s Magnetic field Compensation System

Earth magnetic field

16 rings:
50 Ampere
Technical realization

Earth’s Magnetic field Compensation System

16 rings: 50 Ampere
10 rings: 15 Ampere

Earth magnetic field

Earth’s Magnetic field Compensation System
Technical realization

**Earth's Magnetic field Compensation System**

+ **Low Field Coil System**

Finetune the shape of the magnetic field inside the mainspectrometer

15 rings
Currents individually adjustable
max. 1500 Ampere turns
Without Aircoil system

Countrate reduction

Simulation:

fluxtube, 191 Tcm$^2$
Task of Aircoil System

Without Aircoil system

Increase of background

Simulation:

fluxtube, 191 Tcm$^2$
Without Aircoil system

Incorrect transmission condition

Task of Aircoil System

Simulation:

fluxtube, 191 Tcm²

Without a coil system, the transmission condition is incorrect.
Outcome

With EMCS
(Earth's magnetic field compensation system)

Simulation:

flucture, 191 Tcm$^2$
Outcome

With EMCS + LFCS
(Earth's magnetic field compensation system + Low field coil system)

We expect:
Good transmission properties
Low background
2nd Example: Special shaped ground electrode
Background at prespectrometer

Full magnetic field
Full electric potential

Reason for background: Tiny penning trap at exit/entrance of pre-spectrometer
Penning Trap

Simulation:

Penning Trap

Electric potential along magnetic fieldlines

Magnetic fieldlines
Penning Trap

- How is the penning trap filled?
- How does the penning trap produce background?
How this Penning trap is filled

- Ground potential
- High negative potential
- Positive feedback mechanism

\[ U < 0V \]
How this Penning trap is filled

Ionization

Ground potential

High negative potential

Positive feedback mechanism

Pre-Spectrometer vessel

West magnet (III)

cone electrodes

Anti-Penning electrode

Ground electrode

e-gun

$H_2^+$

$H_2$

$U < 0V$

magnetic field

GND

$H_2^+$

$H_2$
How this Penning trap is filled

- Photoeffect
- Ionization
- Excitation
- High negative potential
- Ground potential
- $H_2^+$
- $H_2$
How this Penning trap is filled

Photoeffect

Ground potential

Ionization

Positive feedback mechanism !!!

Ground potential

High negative potential

Ionization

Exitation
How this Penning trap produces background

- Photoionization
- Ground potential
- High negative potential
- Photoeffect
- Ionization
- Excitation

\[ \text{H}_2^+ \]
Pressure dependence

- Both filling mechanism and background production depend on pressure
- We expect a quadratic dependence on pressure
How to get rid of the background

Full magnetic field
Full electric potential

Solution: Remove penning trap with new specially shaped ground electrode
Technical realization

- Pre-Spectrometer vessel
- west magnet (II)
- cone electrodes
- Anti-Penning electrode
- e-gun
- wire electrodes
- D1
- S1
- S2
- east magnet (I)
- ground electrode
- T

Ground potential

High negative potential
Technical realization

Ground potential

High negative potential
Technical realization

Simulation:

Electric potential along magnetic fieldlines

No penning trap

Before
Result

1 kHz

Factor: 30 000

35 mHz

Old

New

Full magnetic field
Full electric potential

Detector background
Conclusion and Outlook (I)

- By removing all penning traps we reach the desired background level: $O(10 \text{ mHz})$
- Prespectrometer is ready to be implemented in the whole setup
- Low background is expected for the main spectrometer
- Mainspectrometer test measurements will start next year
Precise simulation is necessary to design hardware components

Success at prespectrometer = proof of quality of the simulation programs (Ferenc Glück)

Towards a global simulation (including all KATRIN components, e.g. Source (talk of Wolfang Käfer))
Summary

- Why do we have electric and magnetic fields in the KATRIN experiment?
  - Electric potential used as high energy electron filter
  - Magnetic field used guiding system and to transform energy

- What is the challenge of the electromagnetic design?
  - Realize MAC-E-Filter in optimal way
  - Reduce background

- How is this realized?
  - Aircoil System (good transmission properties, low background)
  - Specially shaped ground electrode (low background)
Thank you for your attention

Thanks to all the pre-spectrometer people:
Florian Fränkle, Florian Habermehl, Ferenc Glück, Michael Zacher, Lutz Bornschein and many others