Magnetic field measurement and optimization at the KATRIN main spectrometer

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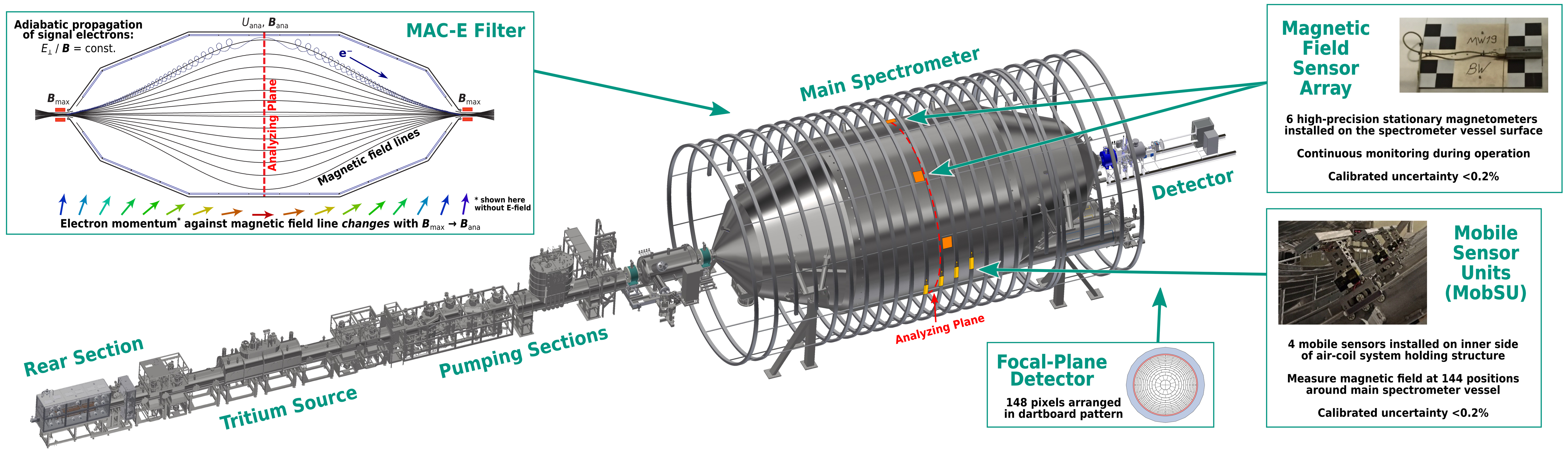
The KATRIN experiment

The *KArlsruhe TRItium Neutrino* (KATRIN) experiment aims to determine the mass of the electron anti-neutrino with a sensitivity of $0.2\,\mathrm{eV}/c^2$ at 90 % confidence level.

Overview:

- Windowless Gaseous Tritium Source (WGTS) with 10^{11} decays/second
- β decay of tritium: $^3\mathrm{H} \to {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$ (half-life $t_{1/2} = 12.3$ years; endpoint energy $E_0 \approx 18.6\,\mathrm{keV}$)
- Decay e^- are adiabatically guided to Main Spectrometer by magnetic fields
- Analysis of the kinetic energy of e^- in a MAC-E Filter (Main Spectrometer)
- Measurement of integral β spectrum with 148-pixel Focal-Plane Detector
- Integral spectrum combines differential β spectrum and response function
- Response function depends on spectrometer magnetic fields and other parameters

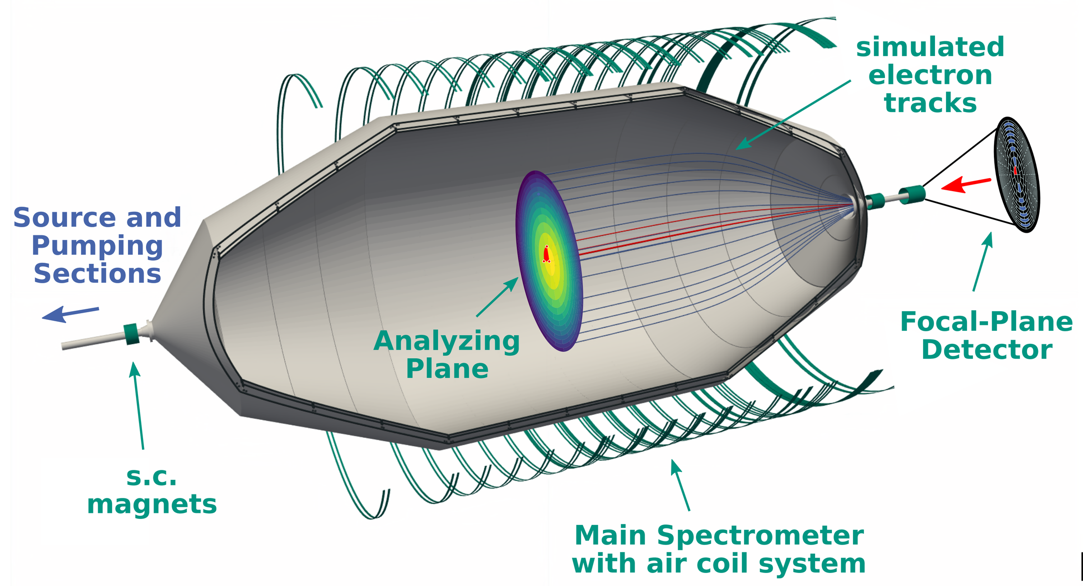
- **Analyzing magnetic field B_{ana} of the MAC-E Filter is an important systematic parameter**



Simulations

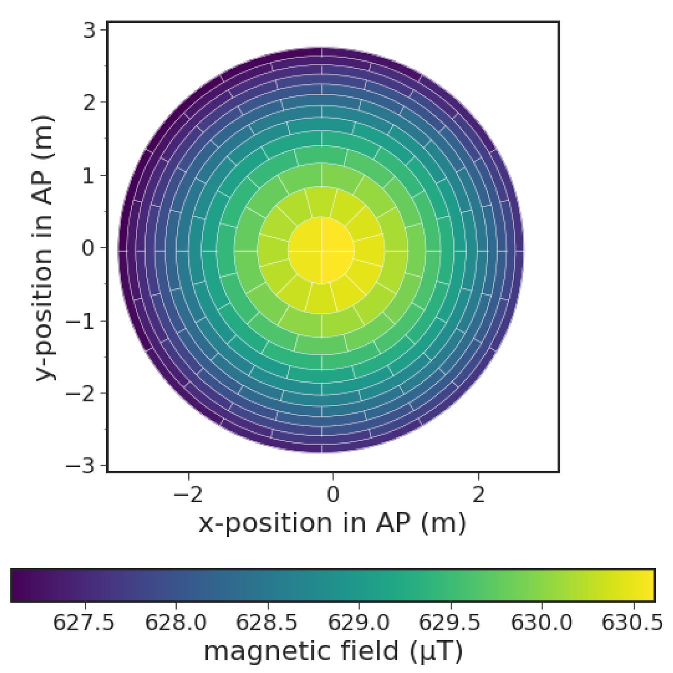
The magnetic fields in the Analyzing Plane (AP) are calculated from simulations with KASSIOPEIA.

- AP is located at center of the Main Spectrometer
- Each detector pixel maps to a specific area in AP
- Determine pixel positions in the AP by field line tracking
- Calculate magnetic field at the center of each pixel
- Calculate inhomogeneity by sampling effective pixel areas
- "As-built" geometry models the actual experimental setup



Results:

- AP radius at nominal setting: 2.79 m
- Magnetic field: $B_{ana} = (628.8 \pm 1.0)\,\mu\mathrm{T}$
- Radial inhomogeneity: $< 3.5\,\mu\mathrm{T}$
- Per-pixel inhomogeneity: $< 0.2\,\mu\mathrm{T}$



Magnetic field in AP (simulation)

Measurements

Magnetic field *inside* Analyzing Plane cannot be measured directly, rely on KASSIOPEIA simulations

- Compare simulation to measurement of stationary Magnetic Field Sensor Array outside Analyzing Plane to estimate accuracy of simulation inside Analyzing Plane
- Maximal deviation to measurement yields uncertainty on simulation: conservatively estimated to $6\,\mu\mathrm{T}$
- Deviation can be explained by magnetic field $\vec{B}_R$ due to magnetized material near Main Spectrometer

MobSU data enables empirical model for $\vec{B}_R$:

- Using Ampère's law

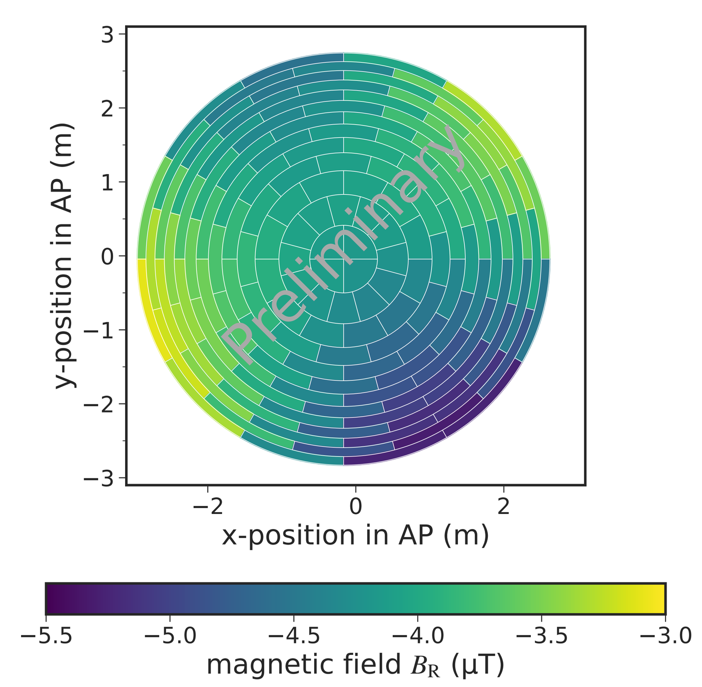
$$\vec{\nabla} \times \vec{B}_R = \mu_0 \cdot \left(\vec{j} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right) \equiv 0,$$

we can introduce a magnetic scalar potential

$$\vec{\nabla} \cdot V(\vec{x}) = \vec{B}_R(\vec{x}) \ \wedge \ \vec{\nabla} \cdot \vec{B}_R(\vec{x}) = 0$$

and solve $\vec{\nabla}^2 \cdot V(\vec{x}) = 0$ with MobSU data as boundary conditions to determine $\vec{B}_R(\vec{x})$ in AP [arXiv:1209.5184]

- Adding empirical model for $\vec{B}_R$ to simulation can improve accuracy of magnetic field model with respect to measurements to better than $3\,\mu\mathrm{T}$



Empirical model for $\vec{B}_R$ in analyzing plane

Summary & Outlook

The analyzing magnetic field B_{ana} is an important systematic parameter for KATRIN.

- Simulations of magnetic field B_{ana} with the KASSIOPEIA software [NJP.19.053012]
- B_{ana} is affected by external magnetic fields
- Empirical model based on MobSU data enables optimization of magnetic field model
- Magnetic field uncertainties (B_{ana} uncertainty: $6\,\mu\mathrm{T}$) cause systematic uncertainty on $m^2_{\bar\nu}$ of $0.05\,\mathrm{eV}^2$ [PhysRevLett.123.221802].
- MobSU optimization and measurements with calibration sources will significantly reduce the uncertainty for future science runs.

More KATRIN neutrino mass data is currently being taken, leading to further improvements in statistical and systematic uncertainty

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