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## The development of the KATRIN magnet system

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**Abstract.** The Karlsruhe Tritium Neutrino Experiment KATRIN aims to measure the mass of the electron neutrino with unprecedented accuracy. For this experiment a special magnet system with about 30 LHe bath cooled superconducting magnets grouped in 10 different sections needs to be developed. The magnetic fields required for the electron transport and spectrometer resolution have a level between 3 and 6 T and must be constant in time over months. Further requirements for field homogeneity and tritium compatibility lead to a unique magnet system. A challenging task of this system is to keep the 10 m beam tube of the source magnet at a constant temperature of 30 K with extremely high temperature stability in time and length. This paper presents the general setup and the magnet system data, shows the main requirements, and gives a status about the ongoing work. Furthermore, the cooling concept of the beam tube is discussed.

### 1. Introduction

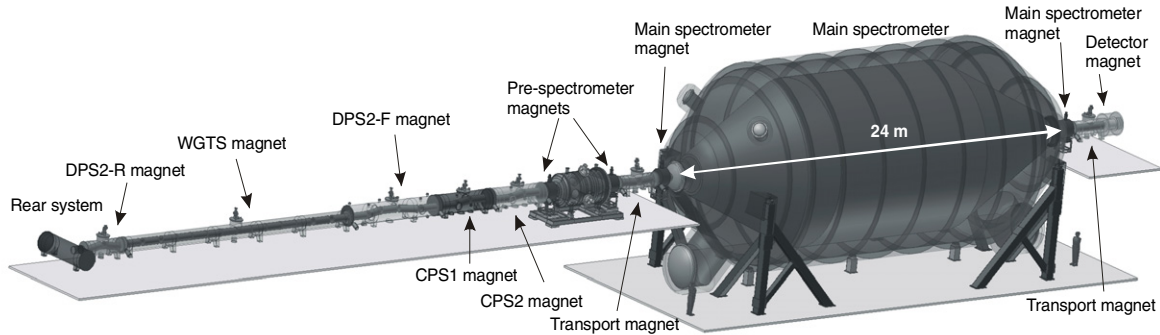
An essential task of particle physics over the next years will be the determination of the absolute mass scale of neutrinos. A key contribution to this issue is expected from the KATRIN experiment [1],[2]. An international collaboration aims to improve the sensitivity of electron neutrino mass measurement from its current value of 2.3 eV/c<sup>2</sup> [3] by one order of magnitude to 0.2 eV/c<sup>2</sup> (3  $\sigma$ ) corresponding to a 5  $\sigma$  discovery potential of 0.35 eV/c<sup>2</sup>.

This measurement is based on the so-called MAC-E filter technique [4],[5], where  $\beta$ -electrons are adiabatically guided and transferred into an almost parallel beam by a magnetic gradient field and where a retarding potential at the centre plane of the main spectrometer works as an integral energy filter. The electrons are obtained by beta decay of molecular tritium, and the energy of the electrons near the endpoint contains information about the mass of the electron neutrino.

To produce and guide the electrons from the source to the detector, a magnet system consisting of about 30 LHe bath cooled superconducting magnets grouped in several sections needs to be developed. The main magnet sections are (see figure 1):

- Windowless gaseous tritium source magnet (WGTS) where the electrons are produced via  $\beta$ -decay of tritium.
- Several differential pumping section magnets (DPS) together with turbomolecular pumps to provide a total tritium reduction factor of about 10<sup>7</sup> and to adiabatically guide the electrons.

**Figure 1.** Scheme of the experimental set-up of the KATRIN experiment (Total length of appr. 70 m).



- Two cryo-pumping section magnets (CPS) to safely trap the remaining tritium flow after the active pumping and to adiabatically guide the electrons.
- Two pre- and main spectrometer magnets (PSM, MSM) to generate a stray magnetic field guiding the  $\beta$ -electrons through the spectrometers.
- Two transport magnet groups: one to connect the pre- and the main spectrometer, and one to connect the main spectrometer with the detector.
- Detector magnet to house the detector that counts the transmitted electrons and discriminates against background.

A major requirement is that the flux tube of  $191 \text{ Tcm}^2$  must be free of any material obstructions including a minimum distance to the wall depending on the magnetic field to the wall. A persistent mode switch must be provided for each magnet, with a decay time of better than 0.01% in 3 months for most of the magnets. In general, the attractive forces of the magnets must be sustained internally by the magnet and externally by the magnet support structure.

## 2. WGTS

The WGTS houses the WGTS tube magnet, a first forward differential pumping magnet (DPS1-F) and a first rear differential pumping magnet (DPS1-R). The WGTS ends with two DN250 gate valves at room temperature. The WGTS scheme and the main parameters are given in figure 2. In addition, deflector coils are mounted onto the outer magnets of DPS1-R and DPS1-F to generate an additional dipole field in x and y direction to investigate alignment and source characteristics. Besides a standard operation mode with tritium at 30 K beam tube temperature, there is an e-gun and a krypton mode with 120 K for calibration purposes, and a bake out mode with temperatures of up to 550 K, to reduce the amount of tritium at the beam tube surface.

One of the major technical challenges of the WGTS is to keep the temperature stability and homogeneity of the beam tube at  $\pm 0.1\%$  at standard operation mode. This is necessary to keep the precision of the neutrino mass measurement within acceptable limits. A suitable cooling scheme is

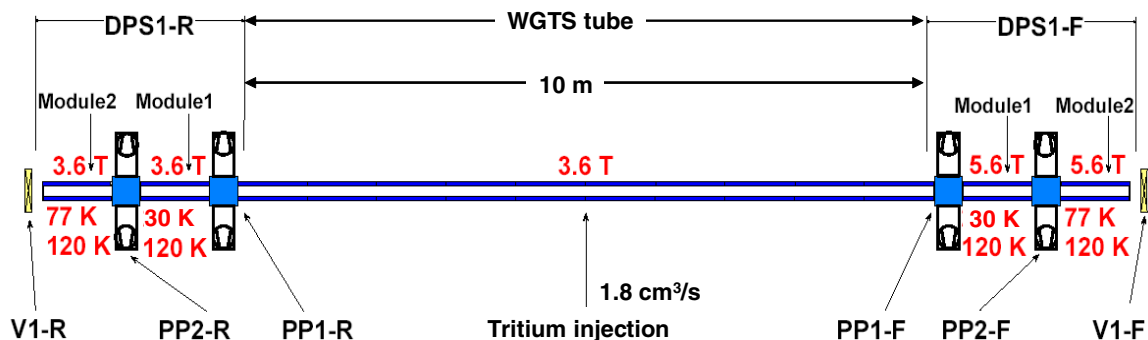
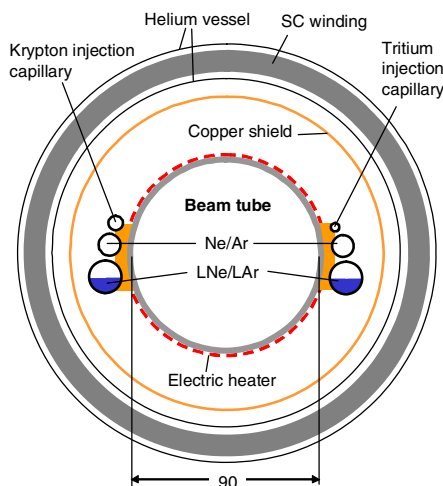


Figure 2: Scheme of WGTS set-up and main parameters



**Figure 3:** Scheme of the WGTS beam tube cooling concept

shown in figure 3. The temperature of the inner tube is stabilized by direct contact with a two phase cooling tube, in which Ne is boiling at 30 K/2.3 bar and Ar at 120 K/12 bar. Precise gas thermometers are chosen to measure the beam tube temperature at standard operation because they have the required accuracy and can withstand 550 K.

### 3. DPS2 magnets

The DPS2 magnets are attached to the DPS1 magnets via a DN250 room temperature valve. The forward part DPS2-F is made of five magnets tilted by  $\pm 20$  degrees to have a natural barrier for neutral particles ( $T_2$  molecules) while still guiding the charged particles along the magnetic field lines. In addition, the flux tube should never have field strengths below 0.5 T between two magnets to ensure an adiabatic

particle transport. This results in a small distance between two neighbouring magnet modules. On the other hand, a pump port needs enough space to achieve an adequate pumping speed. Both requirements can be fulfilled by introducing correction coils at both ends of the solenoids.

The rear part DPS2-R is made out of two magnets and will have 2 pump ports to protect the rear control and monitoring system from too high partial tritium pressures.

### 4. CPS magnets

The preliminary design concept of the cryo-pumping magnet section consists of two parts (CPS1, CPS2). Each part has 3 magnets grouped in one cryostat. In the first section CPS1, a split coil magnet is introduced to connect a second electron source to the experiment for calibration purposes. Each magnet has a central magnetic field of 5.6 T, a length of 1 m and a beam tube diameter of 75 mm.

The main purpose of the CPS magnet sections is to keep the spectrometer free of tritium. This is important to reduce the background, and for safety reasons. The residual tritium molecules are trapped onto the 4.5 K cold surface of the beam tube, which will be covered by a thin layer of Argon frost or charcoal for enhanced sorption efficiency. After several months of operation the beam tube needs a bake out with temperatures up to 500 K to reduce the amount of tritium. During bake-out an active cooling has to be provided to avoid damage of the magnets. At both ends of each CPS magnet, room temperature DN250 valves will be installed.

### 5. Pre- and main-spectrometer magnets, transport magnets

The pre-spectrometer as well as the main spectrometer requires two magnets (PSM, MSM), one at both ends, to provide a magnetic field of about 250 Gauss in the centre plane of the pre-spectrometer and 3 Gauss in the main spectrometer centre plane, respectively. The pre-spectrometer magnets are cooled by cryocoolers because of an initial two year test phase of the pre-spectrometer without liquid helium supply. To compensate the influence of the earth magnetic field in the centre plane of the main spectrometer, additional dipole copper air coils are necessary. To simplify the cryogenic supply, it is planned to house the main spectrometer magnet and the two neighbouring transport magnets in one cryostat.

In addition, a so-called pinch magnet with 6 T is necessary to reject electrons with starting angles higher than 51 degrees. It is planned to insert the pinch magnet in one of the transport sections.

### 6. Detector magnet

The main purpose of the detector magnet is to guide those electrons onto the detector, which pass the main spectrometer. During standard operation, the detector magnet provides at a central magnetic field of 3 T. When operating in the post acceleration mode, the detector magnet operates at up to 6 T. Post acceleration of the particles of up to 25 keV is considered to reduce the effect of the intrinsic detector background by a factor 5-7. The detector magnet has a warm bore of 40 cm and the solenoid coil has a length of 70 cm, to allow easy access to the detector in case of repairs and maintenance.

## 7. Status and outlook

The KATRIN collaboration was founded in 2001 and the pre-spectrometer magnets were delivered in late 2003. Since then test measurements and improvements are underway. One pre-spectrometer magnet has passed all tests but the other one needs an exchange of the short-circuit switch to obtain a 3 months continuous operation in persistent mode. The DPS2-F magnet is already ordered, and manufacturing started in 2004 at Ansaldo Superconduttori. The first magnet modules are successfully tested, and delivery is expected in mid 2006. The tender action of the WGTS was finished in December 2004, and a detailed technical design is underway at ACCEL. The delivery of the WGTS is expected in 2007. The CPS tender action will start in 2005, and the other magnets will follow in 2006.

It is foreseen to start commissioning of first parts of the experiments in 2007. Final commissioning and first test measurements of parts of the experiment are expected in 2008 and 2009. An operation period of five years, which approximately equals 1000 days of measurement time, is envisaged to reach the final sensitivity for the electron neutrino mass of 0.2 eV with 90% confidence level.

**Table 1:** Summary of main magnet parameters

Magnet section	Nr. of magnets	B (T)	Beam tube Temp (K) <sup>1)</sup>	Beam tube diameter (mm)	Module length (mm)	Winding inner diameter (mm)
DPS2-R	2	3.6	77	90	• 1000	
WGTS tube	3	3.6	30	90	3258	232
DPS1-R	2	3.6	30/77	90	1000	228
DPS1-F	2	5.6	30/77	90	804	238
DPS2-F	5	5.6	77	88 (75)	1001	130
CPS1	3	5.6	4.5	75	• 1000	<sup>2)</sup>
CPS2	3	5.6	4.5	75	• 1000	<sup>2)</sup>
PSM	2	4.5	300	200	320	480
MSM	2	3.5	77	200	320	<sup>2)</sup>
Transport	2x2	5.6	77	75	• 900	<sup>2)</sup>
Detector	1	3-6	300	150	700	600

1) at standard operation mode

2) not yet fixed

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