HIGH-PRECISION THREE-AXIS TESLAMETER FOR SUPERCONDUCTING MAGNET ALIGNMENT OF A GYROTRON AT THE SWISS PLASMA CENTER*

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Abstract

This paper presents a novel high-precision three-axis Teslameter and its application for magnetic field alignment of a superconducting magnet prior to gyrotron installation, at the Swiss Plasma Center. The instrument integrates an advanced 3-axis Hall sensor with an ultra-compact sensitive volume of 0.10×0.01×0.10 mm³, enabling true point-like vector field measurements. We describe the sensor architecture, Teslameter performance, and calibration procedures, including precise orthogonality characterization. The Teslameter achieves DC accuracy better than 100 ppm and 1 µT resolution. The system was employed to verify and optimize magnetic field alignment for high-power gyrotrons, vacuum electronic devices generating sub-terahertz radiation via the cyclotron maser instability. Efficient operation of these devices requires that the magnetic field axis remain confined within a cylinder of 0.15 mm diameter over a 600 mm length to maintain correct electron–field interaction. Using the Teslameter, the magnetic field was mapped with high accuracy, enabling fine realignment of the superconducting magnet and ensuring the electron beam coincides with the electric field maximum of the transverse electric (TE) mode. This methodology guarantees optimal gyrotron performance, contributing to reliable and efficient operation of Electron Cyclotron Resonance Heating and Current Drive systems in magnetic confinement fusion research.

INTRODUCTION

High-power gyrotrons are critical components in Electron Cyclotron Resonance Heating (ECRH) and Current Drive systems used in magnetic confinement fusion research. Their efficient operation depends on precise alignment of the magnetic field with respect to the electron beam. Even minor deviations can significantly affect device performance and stability. To meet stringent alignment requirements, advanced measurement instrumentation is necessary. This work presents a high-precision three-axis Teslameter developed to perform accurate vector magnetic field measurements and enable fine alignment of superconducting magnets used in gyrotron systems.

*Swiss Plasma Center (SPC): https://www.epfl.ch/research/domains/swiss-plasma-center/

HIGH-PRECISION 3-AXIS TESLAMETER

The 3MH6-E Teslameter (see Fig. 1) combines a highly compact three-axis Hall sensor with advanced analog and digital electronics within a modular measurement platform. The instrument offers four selectable magnetic field ranges: ±100 mT, ±500 mT, ±2 T, and ±20 T. It achieves a DC accuracy better than 100 ppm, while reaching a resolution below 1 ppm in the ±2 T range. The 3MH6-E system features full interchangeability of its Hall probes. Each probe can be connected to any compatible electronics unit without compromising performance, maintaining an overall DC accuracy better than 100 ppm (0.01%). This flexibility is enabled by independent calibration of both the probe and the electronic unit.

Figure 1: 3-axis Teslameter 3MH6-E, reproduced from SENIS website [1].

The signal processing architecture includes low-noise amplification, 24-bit analog-to-digital conversion, and digital correction algorithms addressing linearity, thermal drift, and orthogonality deviations. Integrated temperature sensors continuously monitor both the probe and the electronics, allowing real-time thermal compensation. With sampling rates of up to 7.5 kSPS, the device is also suitable for time-varying magnetic field measurements.

The 3MH6-E is widely adopted in reference laboratories where traceable and absolute magnetic field measurements are required. Typical applications include characterization of magnetic field distributions in undulators, insertion devices, and superconducting magnets. For instance, within the HITRIplus project coordinated by CERN, the system is used for precise vector field measurements at localized points with minimal spatial disturbance [2]. It is also applied at the Swiss Plasma Center (SPC) for gyrotron magnet alignment as described in this paper.

In applications such as undulator field mapping, the 3MH6-E demonstrates superior spatial resolution compared to fluxgate and NMR-based systems. The compact field sensitive volume (FSV) of its 3-axis Hall probe allows accurate detection of fine magnetic field variations. Combined with DC accuracy and angular misalignment below 0.1°, the system delivers high-performance measurements suitable for demanding metrological applications.

At the core of SENIS Teslameter probes lies a CMOS-integrated three-axis Hall sensor. This device integrates vertical Hall elements, which detect magnetic field components parallel to the chip surface, and horizontal Hall elements, which measure the perpendicular component. This configuration enables simultaneous acquisition of Bx, By, and Bz, as well as the total magnetic field vector at a nearly single spatial location.

The concept of the vertical Hall element was originally introduced by Popovic [3-5]. Advances in CMOS technology have since enabled the development of high-performance vertical Hall elements [6]. The latest version [7] exhibits performance comparable to high-quality horizontal Hall devices, with a noise-equivalent magnetic field spectral density (NEMFsd) of 120 nT·V/√Hz/Vb.

This level of performance enables a magnetic field resolution of 1 μT in the three-axis configuration, representing a significant improvement over earlier vertical Hall sensors, which typically achieved resolutions around 20 μT at 1 kHz [8].

The SENIS three-axis Hall sensor achieves a magnetic field resolution of 1 μT and features an exceptionally small FSV of 0.10 × 0.01 × 0.10 mm³, see Fig. 2, enabling precise measurements even in regions with strong field gradients.

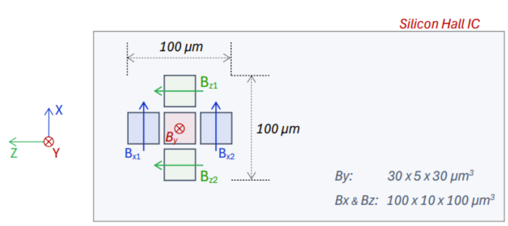

Figure 2: The layout of the 3-axis Hall sensor combining horizontal and vertical Hall elements.

CALIBRATION

The calibration of the Teslameter is performed in the SENIS's ISO 17025 accredited lab and ensures high accuracy and traceability to NMR standards. Key parameters (sensitivity, offset, linearity, orthogonality) are determined and stored in each probe's EEPROM. The expanded measurement uncertainty is 0.01% of full scale.

The calibration includes the measurement of the probe sensitivity 3*3 matrix and, subsequently, its amendment to obtain the correct diagonal matrix. Thereby SENIS patented techniques [9, 10] are used. A stable magnetic field from permanent magnets, combined with precise 90° rotations and a rigid fixture, ensures accurate alignment and minimizes the final probe angular errors to below 0.1°. This method is applied to all SENIS three-axis Hall probes, enabling reliable high-accuracy measurements.

APPLICATION TO GYROTRON MAGNET ALIGNMENT

Figure 3: Two high-power gyrotrons used for plasma heating at the Swiss Plasma Center (SPC).

In Fig. 3 is shown two dual-frequency gyrotrons used at the Swiss Plasma Center. One of the key advantages of using a gyrotron as an electromagnetic source is its relatively high electronic efficiency, which can reach up to 50%. This requires a very precise alignment between the electron beam, guided by the magnetic field lines generated by a superconducting magnet, and the mechanical axis of the vacuum tube. Two locations require particularly high magnetic field alignment precision. The first is at the cathode position, where the electrons are emitted. The magnetic field amplitude and its angle with respect to the electric field determine the initial electron drift, resulting in the desired pitch factor. The second is at the interaction cavity position, where the electron wave interaction takes place. Here, the magnetic field amplitude sets the required electron cyclotron resonance frequency, while the uniformity of the magnetic field profile is essential for optimizing the electron wave interaction. Several numerical and experimental studies have addressed the effect of magnetic field misalignment [11,12]. At SPC, when procuring a superconducting magnet system, we require the magnetic field axis to remain within a cylinder of 0.15 mm radius over the length of the magnet, which is typically 600 mm.

For a laboratory operating gyrotrons, it is extremely important to be able to check the magnetic field alignment, either upon delivery of a new magnet, before gyrotron installation, or as part of routine checks following a quench, for instance. At SPC, the SENIS Teslameter 3MH6-E probe is installed in a custom-made cylindrical probe holder shown in Fig. 4. This probe holder is inserted inside the magnet bore and allows precise positioning of the probe at different longitudinal (vertical) positions and azimuthal angles, either on-axis or slightly off-axis.

Figure 4: Custom-made probe holder for the SENIS 3MH6-E probe.

Reported below is a typical magnetic field misalignment measurement performed after the installation of the magnet and before gyrotron installation. Using the procedure described in [13], we were able to determine the magnetic field misalignment and iteratively correct it until its value fell within the required tolerance.

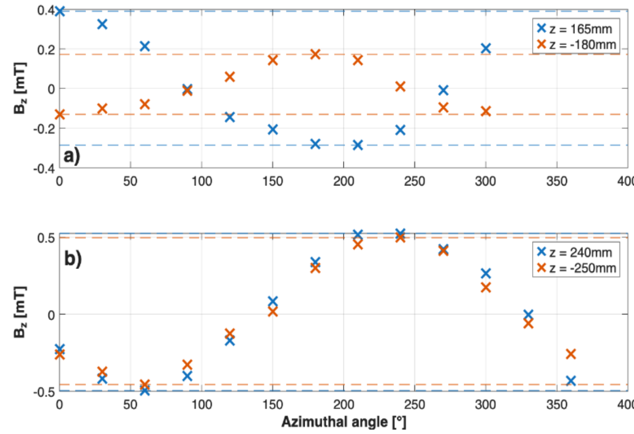

Figure 5: Longitudinal magnetic field measurement B_z, off axis, at four different vertical locations.

The magnetic field misalignment is determined by measuring the longitudinal magnetic field component Bz at a position slightly offset radially (off axis) and over a full rotation around the bore axis. If the magnetic field axis is perfectly aligned, the longitudinal component Bz should not vary during the azimuthal rotation. The maximum difference in the Bz amplitude is thus directly related to the tilt or shift of the magnetic axis.

In Fig. 5.a), the longitudinal magnetic field Bz is plotted for two different positions, respectively above (z = 165 mm) and below (z = -180 mm) the magnet center, where the measurement sensitivity of a shift is minimized. The amplitude of the sinusoidal shape indicates a non-zero tilt, estimated at 0.01°. Similar measurements are shown in Fig. 5.b), for two new longitudinal positions where the effect of a shift is maximized. The amplitude of the measurement oscillation indicated a shift estimated at 0.14mm, below the required value. The measurements at the positions above and below the magnet center are in phase, as expected for a minor tilt.

The measurements presented above are the final verification step, confirming that the alignment was within the required tolerance. This completed the magnet installation procedure and allowed the installation of the gyrotron inside the magnet.

CONCLUSION

A high-precision three-axis Teslameter has been developed and successfully applied to the alignment of a superconducting magnet for gyrotron operation. The combination of a miniaturized Hall sensor, high accuracy, and robust calibration procedures enables precise magnetic field measurements. This methodology ensures optimal gyrotron performance and supports reliable operation of fusion research systems. Future work will focus on further improving measurement automation and integration with alignment control systems.

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