23rd International Magnet Measurement Workshop: IMMW #23

Sunday 6 October 2024 - Friday 11 October 2024

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Book of Abstracts

Contents

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MAGNETIC MEASUREMENTS AT THE ADVANCED PHOTON SOURCE

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The Advanced Photon Source (APS) has successfully completed a major upgrade, transitioning its storage ring from a 7.0-GeV double-bend lattice to a 6.0-GeV multi-bend achromat (MBA) design. The efforts involved the fabrication, measurement, installation, and commissioning of:

- 1,380 storage ring magnets
- 46 new hybrid permanent magnet undulators (HPMUs)
- 26 existing HPMUs (refurbished)
- 13 phase shifters
- 8 superconducting undulators (SCUs)

Meeting demanding field requirements within a tight schedule posed a significant challenge. However, rigorous testing ensured all magnets and undulators met specifications before installation in the new storage ring. This presentation will detail the APS magnetic measurement facilities, the tuning and measurement procedures, along with the achieved results.

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IMMW23 Welcome - Introductory Remarks

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SENIS Advanced Sensors and Instruments for Magnetic Field and Electric Current Measurement

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SENIS develops advanced sensors and measurement instruments essential for the precise characterization of magnetic fields in accelerator magnets and insertion devices. This abstract presents the latest innovations and applications of SENIS's vertical and horizontal Hall sensors, 3D Hall sensors, low-noise teslameters, cryogenic low-noise magnetic field transducers, 3D magnetic field mappers and 3D camera, as well as Hall-based current sensors used in the detectors for monitoring boards at CERN. These devices, notable for their high resolution, accuracy, and compact design, are crucial tools for the fiducialization and alignment of magnets as well as for monitoring, ensuring high precision and reliability in various scientific and industrial applications.

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Magnetic field measurement of the center bend magnet for Korea-4GSR

Authors: Yoon Geol Choi[1]; Dong Eon Kim[1]; Ga Ram Han[1]; Young Gyu Jung[1]; Beom Jun Kim[1]; Woul Woo Lee[1]; Min Jae Kim[1]; Seong Hun Jung[1]

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The Multipurpose Synchrotron Radiation Accelerator (4GSR), supported by the Pohang Accelerator Laboratory (PAL), has brightness 100 times higher and extremely low beam emittance (<100 pm·rad) compared to third-generation synchrotron radiation accelerator. To achieve these specifications, 4GSR storage ring is designed with 28 cells based on the Hybrid 7-Bend Achromat lattice concept, utilizing longitudinal gradient bends (LGBMs) and reverse bends (RBs) in each cell to suppress emittance. The circumference of the storage ring is 800 meters, and each cell features a 2T center bend magnet (CB) located at its center for harder X-ray source. This paper describes the design, specifications and magnetic field measurement system of the CB prototype used in the storage ring. The field mapping system is designed using a 3-axis Hall probe sensor (I3C-03C10L-B02T0K5J) from SENIS, which minimizes planar effects. The driving system for the X, Y, and Z axes consists of linear motors and stepper motors, achieving an accuracy of less than 5 µm. This system is capable of measuring a three-dimensional space of 400 mm x 200 mm x 3200 mm.

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Pulsed magnetic field measurement of the Nonlinear kicker for Korea-4GSR

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The multipurpose synchrotron radiation accelerator (4GSR), supported by Pohang accelerator laboratory (PAL), aims to achieve an ultralow emittance of less than 100 pm·rad, which requires a significantly reduced dynamic aperture size. The existing local bump injection scheme, which uses four kicker magnets to inject the beam, is unsuitable for 4GSR because it demands a large dynamic aperture. To solve this problem, PAL is researching the implementation of an injection method utilizing a single nonlinear kicker (NLK), with a prototype NLK made of G10 material. The magnetic field measurement system integrates the voltage across a single long coil to measure the magnetic field. It has an accuracy of less than 10 µm on each axis and can measure a space of 470 mm x 50 mm x 750 mm. The pulsed power supply is constructed with solid-state switches, capable of supplying a maximum pulse current of 10 kA for 7 µs.

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SUNDAE2 Magnetic Measurement Test Stand at European XFEL

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The SUNDAE2 magnetic field test facility aims to perform in-vacuum magnetic field measurements of superconducting undulators (SCUs) at the European XFEL. This work provides an update on the progress of SUNDAE2, which employs Hall probe, moving wire, and pulsed wire techniques for precise magnetic field characterization.

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Upgrade and performance of test equipment at Danfysik

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The Danfysik precision Hall probe measurement bench has previously been used for field mapping of the demanding MAXLab IV combined function dipoles [1]. This measurement bench has recently been upgraded for position accuracies of better than 10 µm for strait on-the-fly measurements over lengths of up to 5m and has been prepared for efficient measurements along curved trajectories. Work is now in progress to upgrade if for precision mapping of long closed H-type of magnets such as the Diamond booster dipoles [2] with a length of up to 1.3 meter. Our design is partially inspired by the field mapper made at ALBA [3] with a probe suspended on a high tension wire supported by a C-type of carriage structure placed on a long support bench. Our concept is based on a dual master/slave carriage system used to suspend a 3m long carbon rod with a Hall probe placed in the middle.

Efficient on-the-fly precision field mapping of electromagnets requires temperature compensated high stability and high accuracy analog Hall probes such as previously demonstrated [1]. For measurements of multipole magnets like quadrupoles a gradient Hall probe with two probes placed in a known distance on a line perpendicular to the probe scan direction is efficient in minimizing the effect of probe position errors on the gradient measurement. We are currently making an upgraded probe with four Hall elements to allow accurate mapping of local field gradients in higher order multipoles like sextupole and octupole magnets.

An efficient and robust software has been developed for the control of the Hall bench which allow easy selection of measurement probes, power supplies and other equipment. This allows fully automate field measurements including power supply control with a high degree of standardization. A similar concept is use for our stretched wire measurement bench.

Test result will be shown to illustrate the performance of both our Hall probe field mapper and stretched wire measurement systems.

[1] F. Bødker et al., IPAC 2013, p. 36.
[2] J. Campmany et al., Phys. Proc. 75, 2015, p. 1222.
[3] I.P.S. Martin et al., IPAC 2021, p. 286.

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Measurement and simulation of demagnetization in a prototype Halbach array quadrupole

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We present the design, construction, measurement and troubleshooting of a prototype hybrid Halbach quadrupole magnet. This magnet was significantly under-strength due to local demagnetization in the permanent magnet material. We discuss how this effect was uncovered, measured and reconstructed in simulations, as a guide to any reader considering similar magnets in future.

Full Abstract in attachment.

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Comparison of Magnetic Field Maps by Direct Measurement and Reconstruction Using Boundary Element Methods

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Boundary Element Methods (BEM) can be applied to determine the value of the magnetic field at any point within a domain if the magnetic field components are measured on the surface of the domain. For large magnetic volumes, BEM provides an attractive alternative to fine three-dimensional Hall probe scans as the fields can be evaluated inside the volume with an arbitrary position and with a reduced measurement time. BEM have been applied to the field data measured on the boundary of three-dimensional Hall probe scans for two example magnets, which have been measured at Daresbury Laboratory. The fields reconstructed using BEM are compared to the fields directly measured during the Hall probe scans. The reconstructed fields can be calculated to within 1 mT of the directly measured fields.

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Development of Rotating Coil Measurement System for Superconducting multiplets in HIAF-HFRS

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HIAF (High Intensity heavy-ion Accelerator Facility) is the next-generation high-intensity heavy-ion accelerator built by the Institute of Modern Physics, Chinese Academy of Sciences. HFRS (High

Energy FRagment Separator) is a part of the HIAF, it is the segmentsthe radioactive beamline used for ion fragmentation analysis. The design requires a magnetic stiffness of 25 Tm. It is composed of 11 superconducting dipole magnets and 39 sets of superconducting combined multipole lenses. According to the Ion-optical design of HFRS at HIAF, the design of superconducting combined multipole lenses adopts a variety of magnetic field combination methods. It has the characteristic of a large aperture (φ330 mm), high field quality and a high integration field uniformity (plus or minus eight parts per million) and so on. In order to meet the requirements testing of HFRS multi-pole combined magnets, a measurement scheme of temperature hole and moving coil is proposed in this paper. Meanwhile, corresponding combined function harmonic coils are designed for different types of combined magnets. The test system was built and the magnetic field performance of the multipole composite magnet prototype was tested. In this paper, the test system and test results are introduced and analyzed in detail. The magnetic field measurement results reach the magnetic field measurement index and verify the performance index of the magnet.

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Three-dimensional magnetic field mapping system for large spectrometer magnets utilizing on-fly technology

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The Institute of Modern Physics of the Chinese Academy of Sciences is currently building the Cooler-Storage-Ring External-target Experiment (CEE) magnet. The magnet's measurement needs to be conducted online, as depicted in the figure 1. The magnet has a center magnetic field of 0.5T, and the measurement area inside the magnet must cover a volume of 2.0 m × 1.6 m × 1.6 m. Furthermore, it is necessary to measure the edge field and the three-dimensional magnetic field in all the areas to be examined, which presents a significant challenge to the measuring system. Firstly, a large moving area is required. Secondly, a high-precision three-dimensional Hall sensor is needed. The proposed magnetic measurement system utilizes a robotic arm and an aluminum alloy measurement module as the transmission device. The robotic arm is responsible for moving the measurement module to any point in the XOY plane of the coordinate system, with the magnet's center as the origin. Meanwhile, the measurement module continuously drives the Hall sensor to move in the z-direction without pausing. The localization of the sensor in the XOY plane is solely dependent on the robotic arm, while the localization in the z-direction is dependent on the measurement module. The sensor's location in the XOY plane is entirely determined by the robotic arm, whilst its positioning in the z-direction is determined by the measurement module. The alignment of the Hall sensor's location and the magnetic field value depends on the Z-direction motor controller of the measurement module. This controller sends out TTL pulses at regular intervals, which act as trigger signals for capturing the position and magnetic field data. The Kuka KR210 is recommended for use as the robotic arm in the magnetic measuring system. After calibration, the robotic arm can achieve an absolute accuracy of 0.2mm@1000mm. The measurement module is self-customized, with the Z-direction motor utilizing a Beckhoff servo motor known for its repeatability precision of over 0.005mm. The Hall sensors are F3A models from SENIS, and to enhance efficiency, a set of 5 F3A sensors are custom-made as a Hall array. To enhance efficiency, we have developed 5 F3A Hall arrays with a maximum measuring magnetic field of 0.6T and an accuracy of 0.1%. Currently, the system is undergoing debugging.

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Set-up, characterization and mitigation of cross-talk between PM-based and ferrite-enforced appliances for FLASH 2020

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We present the design basics, assembly procedure and the results of the characterization measurements for two magnetic appliances that are part of the current upgrade of the FLASH free electron laser at DESY Hamburg. A permanent magnet-based phase shifter will allow for a tuning of the electron trajectory between two insertion devices to provide constructive interference, while ferrite-enforced corrector coils with variable field direction will not only correct gap-dependent kicks of the undulator but will also be strong enough to serve as steerers in a slow feedback system. We have manufactured ten phase shifters and more than 30 corrector coils which have all been measured with Hall probes and stretched-wire set-ups to measure the achievable phase range and maximum kick, respectively, to correct any multipole contributions and to check for consistency within each series. A particular challenge was the introduction of significant cross-talk between the permanent magnets of the phase shifter and the ferrite core of the coils due to the close proximity of the two devices along the beam line. The ferrite would dampen the fringe field of the phase shifter leading to an unwanted kick to the electron beam. The issue was mitigated by placing a set of ferromagnetic dowels between phase shifter and coil that would compensate for the dampening. Size and position of the dowels were modelled beforehand and verified in stretched-wire measurements.

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Performance study of the vibrating wire technique to determine longitudinal magnetic field profile using measurements to high wire harmonic

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A vibrating wire measurement system, deployed in 2023/24 for locating the magnetic center of quadrupoles at the Canadian Light Source, was used recently to study the magnetic flux density of a test quadrupole magnet. Vibrating wire scans up to the n=200 wire harmonic (˜10 kHz drive frequency) were measured in order to reconstruct the magnetic flux density across the length of the wire. The vibrating wire data agreed with a reference Hall probe scan on the order of 5%, with a flat scaling error caused largely by unsteady gain out of the optical switches used to observe wire vibrations. Software macros were developed to systematically process the many wire harmonics for field reconstruction, with exception handling for real-world noise. The stability of the n=10 wire harmonic was also studied with 340 repeated scans spanning multiple weeks, and limitations in the accuracy of the vibrating wire technique for field mapping are reviewed.

In this work, we briefly recap the theory of the vibrating wire technique for magnetic measurement, citing e.g. Temnykh, Wolf, Arpaia, and we describe a new vibrating wire setup at the Canadian Light Source. We measured the B field off-axis of a test quadrupole with both vibrating wire and Hall probe. We compare the reconstructed B field from n=200 vibrating wire harmonics against the reference Hall probe scan; moreover, we compare the Sine coefficients of a Discrete Sine Transform (DST) of the Hall probe scan against the individual vibrating wire harmonics. We present observed

changes in the measured wire amplitude/phase profiles, distorted from the typical low-harmonic behaviour, beginning in our case at roughly the n=110 harmonic.

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Portable Magnetic Field Mapping Measurement System based on Large-Scale Dipole Magnets

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Hall probe measurement technology is a universally applied technology for the magnetic field mapping measurement of magnets. Traditional Hall probe measurement technology relies on a massive three-dimensional measurement platform, coupled with a three-dimensional adjustable magnet support frame, offering great universality and high positional accuracy in measuring medium and small magnets. However, the traditional point measurement platform faces limitations such as magnet volume, measurement environment, and the range of good field regions in the measurement of large dipole magnets, especially huge superconducting dipole magnets, leading to poor operability, low measurement efficiency, and significant errors in secondary positioning accuracy.

The High-Intensity Heavy-Ion Accelerator Facility (HIAF) is a significant national science and technology infrastructure project constructed by the Institute of Modern Physics, Chinese Academy of Sciences. To achieve high beam intensities, large aperture, high-precision dipole magnets are extensively utilised in HIAF, including the Booster Ring dipole magnets, high-precision Spectrometer Ring dipole magnets, and HIAF Fragment Separator (HFRS) dipole magnets. Consequently, an efficient, high-precision and movable magnetic field measurement system is crucial for magnetic field measurements and project construction.

Based on traditional Hall probe measurements. The new system introduces ultrasonic motors capable of operating under strong magnetic fields (<7T) to design and construct a new magnetic field measurement system. The new measurement system primarily includes a rail base, a moving platform, and a rotating shaft. For the first time in the magnetic field measurement system, a motion mode combining translational and rotational movements was adopted, replacing the traditional movement method based on Cartesian coordinate positioning. The new system has a translational stroke of 4300 mm and a rotating shaft length of 280 mm (replaceable), enabling high-precision and rapid measurement of large dipole magnet fields.

After system debugging, a magnetic field measurement of an SRing dipole magnet was conducted, and the testing accuracy and efficiency of the test system were verified through comparison and analysis with traditional Hall probe measurement systems. On this basis, magnetic field distribution and integral excitation curve measurements of an HFRS warm iron superconducting dipole magnet were carried out and completed, achieving the testing objectives for the warm iron superconducting dipole magnet.

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Hall mapper for sorting permanent magnets

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attachment

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Results of the Magnetic Measurements of the Super-FRS First-of-Series Dipole Magnet.

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Abstract—The facility for Antiproton and Ion Research (FAIR) is an international superconducting accelerator facility currently under construction at Helmholtz Center for Heavy Ion Research (GSI) in Darmstadt, Germany [1]. The main part of the FAIR is the Superconducting Fragment Separator (Super-FRS) - a powerful two-stage, large-acceptance, in-flight separator made of 197 superferric magnets. Measurements of all the magnets are taking place at CERN in a dedicated cryogenic facility[3]. The first Series Dipole magnet (Type 2 - 11 degrees bending) was delivered at CERN at the beginning of 2022 and underwent extensive magnetic measurement testing [5]. The second type of the main dipole magnet (Type 3 - 9.5 degrees) was delivered in February 2024. The magnetic field was scanned using a new dedicated system developed by CERN, the so-called Translating Fluxmeter [6]–a PCB coil array installed on a moving trolley that passes through the magnet aperture.

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Latest Developments in Magnetic Measurements

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This abstract presents Metrolab's recent advancements and innovations in NMR and Hall magnetometry, along with our pursuit of ISO 17025:2017accreditation. We introduce the MFC8246 motorized mapper, designed for precise electromagnetic field mapping within small bore magnets. Furthermore, we discuss the HallinSight technology, a significant advancement in three-axis Hall magnetometry, which providesrealtime, high-resolution magnetic field measurements across various configurations. Additionally, we compare the previous generation of continuous wave NMR magnetometers, PT2025 and MFC3045, with the new PT2026, which employs pulsed wave techniques. The ongoing developments in the PT2026, particularly its Revision 2024, are aimed at further enhancing hardware and computational performance, with evaluations expected to be completed by the end of 2024.

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Measurement of Electromagnets and Tuning of Permanent Magnets based on Rotating Coils for the Upgrade of the Swiss Light Source (SLS2)

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The upgrade of the Swiss Light Source (SLS2) has been one of the major projects at the Paul Scherrer Institute (PSI) during the last years. One key element to provide higher photon flux and brilliance for the beamline users is the extremely dense lattice arrangement with a total of 888 electromagnets and 450 permanent magnets, all designed and measured at PSI.
This contribution focuses on the measurement series conducted with a rotating coil measurement system designed and manufactured in collaboration with Elettra Synchrotron Trieste. The system consists of 5 radial coils having each 120 turns, a reference radius of 18 mm and an active coil length of 500 mm, which allows the digital bucking of dipole and quadrupole field components. With a 1-σ repeatability < 0.05 %, this measurement system has allowed us to determine the transfer function (for electromagnets), the main field (for permanent magnets), the harmonics, the roll angle and roughly the magnetic axis. The first part will focus on the measurement of the SLS2-electromagnets, detailing the measurement procedure and showing exemplary results of the Sextupoles, combined function Octupole-Normal Quadrupole-Skew Quadrupoles and the combined horizontal and vertical Correctors. In the second part, the measurement, tuning and fiducialization of the Quadrupole-SLS2-Permanent magnets of type AN, ANM and VE will be explained, and exemplary results will be shown.

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Precise Magnet Alignment for SPring-8-II and Beyond

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Precise magnet alignment based on a vibrating-wire method has been developed for the storage ring of an upcoming fourth-generation light source, SPring-8-II. All the multipole magnets in each straight section placed on a common girder will be aligned with an accuracy of ±0.005 mm or better with magnetic centers detected by the wire outside the machine tunnel before the installation. The same alignment procedure has been successfully applied to Japan's newly launched compact 3 GeV light source, NanoTerasu. Based on the magnetic centers measured by the vibrating wire method, we also discuss a correlation between the magnetic centers and the mechanical bore centers of multipole magnets. An innovative vibrating wire method to align magnet arrays containing permanent magnets is proposed for future accelerators. Proof-of-principle experiments and feasibility studies are underway. The proposed scheme and preliminary results will be presented at the workshop.

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Cryogenic Tests of Electronic Components and Sensors for Superconducting Magnet Instrumentation

Authors: Lucio Fiscarelli[1]; Marco Buzio Buzio[1]; Unai Martinez[1]; Vincenzo Di Capua[1]

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This research explores the development of advanced electronic systems for magnetic measurements under various operating conditions. The study focuses on two main areas:
Characterization of electronic components and sensors in extreme temperature environments, from cryogenic to room temperature.
Development of electronics for standard magnetic measurements and quench localization techniques at room temperature.
The aim is to identify and optimize suitable components for advanced instrumentation in the field of magnetic measurements, with particular attention to the performance of amplifiers, passive elements, digital components, and various types of sensors.
Experimental results show how some components maintain functionality across a wide temperature range, while others require specific adaptations. In parallel, innovative solutions for precise magnetic measurements and early quench detection techniques at room temperature are presented.
This research contributes to the advancement of electronic systems for magnetic measurements in various applications, from superconductor technologies to high-energy physics, medical imaging, and advanced materials science.

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Alignment measurements of HL-HLC superconducting quadrupole cryo-assemblies at CERN

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Within the framework of the HL-LHC project at CERN, the rollout of the series production of the superconducting Nb3Sn quadrupole magnets (MQXFB) is 60 % complete. In parallel, the cryo-assembly LMQXFB (Q2) series production has begun. The Q2 cryo-assemblies consist of a cold mass containing an MQXFB quadrupole and a nested orbit corrector dipole, MCBXFB. Three cryo-assemblies were fully tested at 1.9 K and nominal current: LMQXFB01, LMQXFB02, and LMQXFB04. Alignment measurements were performed using a rotating-coil scanner at room temperature to characterize the bare cold mass and the stretched-wire system to characterize the cryo-assembly at room and cryogenic temperatures. Cryogenic measurements were performed at nominal current. This presentation reviews the measurement procedures and the relative challenges to reaching the stringent measurement requirements.

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Latest Developments in Magnetic Measurements

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Abstract—This abstract presents Metrolab's recent advancements and innovations in NMR and Hall magnetometry, along with our pursuit of ISO 17025:2017 accreditation. We introduce the MFC8246 motorized mapper, designed for precise electromagnetic field mapping within small bore magnets. Furthermore, we discuss the HallinSight technology, a significant advancement in three-axis Hall magnetometry, which provides real-time, high-resolution magnetic field measurements across various configurations. Additionally, we compare the previous generation of continuous wave NMR magnetometers, PT2025 and MFC3045, with the new PT2026, which employs pulsed wave techniques. The ongoing developments in the PT2026, particularly its Revision 2024, are aimed at further enhancing hardware and computational performance, with evaluations expected to be completed by the end of 2024.
Keywords—Magnetic Measurements, NMR, Hall, ISO

Full abstract in attachment

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Magnetic Measurement Activities by the ID Group at the National Synchrotron Light Source-II

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The Insertion Device (ID) Group at the National Synchrotron Light Source-II (NSLS-II) has been actively engaged in upgrading the existing ID measurement system, including enhancements to the pulsed wire bench. The group is also focused on developing a new superconducting adaptive gap undulator (SC-AGU) [1] and its measurement system. A new measurement system is needed for the 4-meter-long cryogenic permanent magnet undulator, which is planned for the Experimental Tools III (NEXT-III) project [2]. Additionally, we have adopted a rotating coil/wire system, originally developed by APS, for the measurement of permanent magnet (PM) focusing quadrupoles as part of the NSLS-II upgrade. This paper reports on these activities.

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Magnet group activities at ALBA

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In this contribution we will describe the activities of the Magnets and Insertion Devices group at ALBA since 2022 and the plans for the future. The ALBA synchrotron light source is undergoing a significant upgrade to transition into a fourth-generation facility by 2031, with a key goal of reducing its emittance by at least a factor of 20. The Magnets group at ALBA is responsible for the design, procurement, and validation/characterization of the magnets for the new accelerator, and is currently working on the production of the first prototypes. We will discuss the technical requirements, challenges, and initial strategies for magnet characterization.

Additionally, we will present recent upgrades and improvements to ALBA's magnetic measurements laboratory, along with upcoming enhancements. We will also report on the magnetic measurements performed for external clients, including companies and research institutions.

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Measurement Reports and Lab Upgrades at HZB

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The measurement campaign of a UE51 APPLE II device will be discussed, from individual magnet block measurements to final device shimming and installation.
Progress on adapting measurement systems of the magnet measurement lab will be reported, specifically the adaptation of the Helmholtz Coil measurement system to an EPICS based control system from a legacy OS/2 system.
The status of the pulsed-wire system and in-vacuum Hall probe bench will be presented, alongside the goals for their use with the upcoming measurement campaign for the in-vacuum APPLE II project IVUE32.

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Update of the magnetic measurement benches of the ESRF

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Abstract —This talk gives an overview of the update of both the hall probe measurement bench, and the stretched wire measurement bench. These benches were developed in house at the ESRF during the last decades mainly to measure permanent magnet undulators. The new hardware of both benches was chosen to improve their ergonomics, safety and ease of use, as well as the versatility and accuracy of the measurements. The hall probe bench in particular was redesigned with the hybrid undulator assembly process in mind. It will integrate a quick mounted touch probe to align magnet modules and measure magnet and ferric pole positions in the assembly. A new measurement software is being developed using Python, providing the motion control, the measurements acquisitions and various data analysis tools. It will handle single magnet measurements, magnet list sorting, and undulator assembly and optimization all in the same place, with a modern UI.

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Advances in Stretched Wire Tomography at Kyma

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Previous IMMWs showed that stretched wire tomography is a viable measurement technique for measuring magnetic fields near the magnet surface. This method takes advantage of standard stretched wire measurement and uses field integrals as the input information for tomographic image reconstruction. Rotating the magnet around the axis perpendicular to the stretched wire and measuring field integral profiles creates a sinogram of an object. A two-dimensional magnetic field profile is reconstructed by applying different algorithms to the obtained sinogram.

In this article, we present the improvements to the stretched wire tomography setup in Kyma. The quality of the reconstructed magnetic field image stems from the setup components' characteristics, motion control, synchronization, and data post-processing. Focusing on the latter, we present some of the obtained magnetic field images and how post-processing parameters (e.g., data spectral filtering and rotation center determination) and the choice of image reconstruction algorithms affect the discrepancy from the results obtained measuring with a standard Hall sensor.

Furthermore, we discuss the main advantages and drawbacks of the current setup and suggest possible solutions to the issues.

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Towards the magnetic characterization of a meter-long bulk high-temperature superconducting undulator

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Please find the document attached.

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INFN –LNF Magnetic Measurement Laboratory Status and Upgrade

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Abstract—Magnetic Measurements Laboratory at the Frascati National Laboratories (LNF) of INFN played a crucial role for magnets characterization of the whole LNF accelerators apparatus (DAFNE [1], SPARC_LAB [2], BTF [3]) and also for external user (i.e. CNAO [4]) leading to an extensive expertise acquisition in the recent past. In the last years, a revamping phase of the instrumentation was necessary to continue the measurements avoiding an expertise loss. This upgrade [5] has been started thanks to several co-funding projects such as LATINO [6], IRIS [7] also with the INFN internal funding support. The revamping was oriented both towards the update of the old instrumentation, i.e. a Hall probe measurement bench, and towards the purchase of new equipment like a new rotating coil, a Single Stretched Wire Bench, a Pulsed Wire bench, a probe calibration system, and 3D Hall probe mole system. Moreover, several infrastructure works are planned to improve the organization of laboratory spaces. All these interventions are oriented to guarantee a high flexibility of the measurements requirements covering a wide range of magnets type for external user and for the future projects at LNF like EuPRAXIA [8].

Keywords—Hall Probe, Rotating Coil, Single Stretched Wire, Calibration System, Magnetic Laboratory Facility

I. INTRODUCTION (HEADING 1)

The Frascati National Laboratories (LNF) of INFN have extensive experience in measuring magnets for particle accelerators. They have conducted tests, with deep magnetic characterization for various projects including the DAΦNE collider, the Beam Test Facility and the SPARC_LAB linear accelerator of LNF, CNAO, and other experiments.

Aiming to face new projects and to keep the laboratory up to date with current technologies in the magnetic measurement scenario, a consistent instrumentation and infrastructure upgrade has been started in the last years. This has been possible also thanks to co-funded projects such as the LATINO project, supported by Regione Lazio under the POR-FESR 2014-2020 program. In this framework, a rotating coil system and a stretched wire bench were purchased, and civil and plant engineering works were executed. The goal of the project was to establish a magnetic measurements laboratory as part of an open research infrastructure aimed to support industries and the scientific community. Another very important pillar of this upgrade is the IRIS project who has the goal to create a distributed infrastructure for applied superconductivity. The INFN-LNF pole is in charge to provide magnetic measurement laboratory specifically devoted to testing superconducting coils and magnets at room temperature. The project allows to purchase a 3D hall probe mole system, a pulsed wire bench, several DC power converters of various power sizes, a probe calibration system and to upgrade the linear stages of the current Hall probe stage. Moreover, a mezzanine will be realized inside the laboratory aiming to allocate all the power converters, the electronic boards and power electronic components spare parts separately from the instruments and the workbenches.

The requirements of all the instrumentations have been defined in order to have a high flexibility in terms of magnets specifications that could be measured aiming to raise up INFN-LNF laboratory as a key provider magnetic measurement for the whole INFN and, in general, for the scientific community. Moreover, several instrumentation requirements have been based on the preliminary design of EuPRAXIA linac.

II. INFRASTRUCTURE

The magnetic measurements laboratory of LNF is hosted in a 200 m2 building and is operated by the Electrotechnical Engineering Group, that is currently composed of seven technicians and three technologists.

A maximum electrical power of 430 kVA is available to feed power converters of various range and a demineralised water-cooling system is available with a dedicated dry-cooler. An overhead crane is installed for the lifting and handling of the equipment with a maxim weight of 20T. In the framework of IRIS project, the construction of a mezzanine is foreseen within the end of next year.

III. EQUIPMENT

A. Hall Probe Bench

The current Hall probe bench is composed of two linear stages that allow the vertical (z-axis) and longitudinal (y-axis) translations of a Hall probe holder. These two stages are installed over a 3 m long granite bench, with the x-axis operating on planar air bearings. The longitudinal and vertical shift ranges are 1m and 300 mm respectively. Also a manual rotation around x, y and z axis is available.

Several aluminum Hall probe holders have been designed internally by LNF staff with 30 and 25 mm outer diameter. A new probe holder is under design with an internal diameter of 20 mm and it will be realized in carbon fiber.

All the stages are connected to a NewPort XPS control unit while the data acquisition and the control relies on a LabView VI. For this bench, currently, only 1D Hall probes are

available. All probes were provided by Group 3 Company because of their high compatibility with the current LabView VI. The purchasing of new Hall probes is ongoing including new 3D hall probe. The revamping of the bench foresees also the replacement of the current movement systems with new motorized linear and rotational stages as well as upgrading the controller system. With these enhancements, the positioning accuracy will be better than 10 µm for linear stages and better than 10 mrad for angular stages.

The main measurements performed in the last year with the current system include: 3D field mapping of all the magnets of the new transfer line of the BTF facility, the measurements on several magnets of the SPARC_LAB photoinjector [9] , of the new SABINA transfer line [10] , measurements for the STAR facility [11] and for the FOOT experiment [12].

B. Rotating Coil

A rotating-coil measurement system has been specifically designed for the field characterization of small-bore multipole magnets, within the collaboration agreement KR4708/TE between INFN and CERN. The current system [13] is based on a PCB magnetometer with 256 turns for each of the five coils, inserted on a carbon fiber tube, with an external diameter of 26 mm and a total length of 620 mm.

Different configurations of PCB and shaft may be designed in the future to meet specific needs. All connecting components are 3D-printed. The system is equipped with a commercial DC brush-less motor, a high resolution incremental encoder, a through-hole slip-ring, a data acquisition system, a software application for the operations based on LabView and a post processing analysis based on Mathlab.

The system can achieve an absolute accuracy of the main integrated gradient of 50 ppm, with a repeatability of 10 ppm, while the accuracy of high-order compensated harmonics is 100 ppm with a repeatability of 10 ppm. The specifications have been based on the preliminary specifications of the quadrupoles for the new EuPRAXIA linac.

C. Single Stretched Wire Bench

The single stretched wire (SSW) was originally designed and built by ESRF [14]. The system is composed of two pairs of vertical and horizontal linear stages that lie on a 3m long granite bench. They could shift on dedicated rails adjusting the distance between them, depending on the magnet size. They are controlled by a NewPort XPS controller, while the voltage induced on the titanium wire (diameter of 100 µm), is measured by a Keitley 2182 nanovoltmeter.

All the DAQ and stages movements are managed by a dedicated software based on IGOR [15]. The accuracy of the multiple is of the order of few 10-4 while the magnetic center accuracy is about 2 µm and the pitch, roll and yaw angles can be determined with a precision of 0.1 mrad. The precision of the integrated gradient is typically 0.2 Gm.

The main measurements performed in the last years with SSW are the quadrupoles of the new BTF transfer line, several small bore permanent magnet quadrupoles for SPARC_LAB plasma acceleration experiments [16] and also for CECOM company [17].

D. Pulsed Wire Bench

A pulsed wire bench is currently being designed, based on the one described in [18]. The bench is designed with two separate granite pillars to accommodate magnets in a wide range of mechanical lengths. One of the pillars is equipped with pivoting wheels for easy movement. Each pillar has two stages, horizontal and vertical, to support and move wire tensioned along the magnetic axis of the magnet.

These linear stages are identical to those used in the previously described SSW, ensuring compatibility and ease of maintenance. The bench will be equipped with Keysight electronics (pulse generator, voltage analyzer), as well as optical elements for wire position transduction. The technical specifications document is almost completed, while the purchasing phase will start by the end of 2024.

E. Hall Probe Mole System

A Hall probe mole measuring system is currently under design for field mapping of small gap magnets. The goal is to have a travelling probe sliding inside the magnet aperture, in particular for insertion devices measurements. The system will be integrated into the existing Hall probe bench, adding a compact 3-axis Hall probe, mounted on a thin mechanical support, the related Keysight digital multimeter, a mechanical interface between the current linear stages and the probe holder and a dedicated DAQ and data analysis software. Considering the unique and long experience with such systems, this bench is under development with Kyma S.p.A. [19] who has already realized a similar system for measuring undulators and insertion devices, also gaining experience in the development of measurements procedures.

F. Probe Calibration System

The laboratory will be equipped also with a reference system to calibrate probes and validate measurements. The design and manufacturing of the system has been awarded to Caylar S.a.S [20]. Delivery is expected in February 2025. The system is composed of a 2 T dipole, with a 30 mm gap and a 0,02% field homogeneity over a volume of 15x15x15 mm3. Also included in the system are the 4-quadrant power supply with 10ppm stability, 3 NMR probes to cover the range from 20 mT to 1.8 T and the related gaussmeters for readout. A future upgrade of the system involves the availability of a thermal chamber to guarantee probes calibration with thermal stability at different temperatures.

G. Search Coil for Pulsed Measurements
In the framework of the SIGRUM project [21], LNF is in charge for the characterization of the FeCo material [22] [23]: a serious candidate for the realization of the yoke of scanning magnets part of a superconducting gantry designed for hadrontherapy applications.
A dipole with FeCo yoke, is currently at LNF for testing the eddy current effects in terms of the flux density responses in pulsed current regime. A measurement setup is realized with a search coil provided by CERN, a high-resolution 16-bit DAQ board, a control system based on LabView and a data analysis software based on Mathlab internally designed at LNF.
IV. CONCLUSIONS
The Magnetic Measurement Laboratory at LNF is under a deep revamping phase aiming to face new projects and to keep the laboratory up to date with current technologies. This process involves both the laboratory infrastructure and the equipment. An overview of all these upgrades is given together with a summary of the main measurements performed in the last years. When all the upgrades will be completed, the laboratory aims to perform a wide range of magnetic measurements to support both INFN internal projects and to fulfill a wide range of requirements of possible external users.
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INITIAL MEASUREMENT PLAN FOR SOLEIL-II BY VIBRATING WIRE AND PULSED WIRE MEASUREMENT TECHNIQUES

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The construction of next-generation light sources faces a critical challenge of high-precision alignment of the ring magnets. With the aim to acquire optimal and stabilized synchrotron radiation for upgrade of SOLEIL, the magnetic elements of the synchrotron must be aligned with very high accuracy. The magnetic measurement techniques such as vibrating wire and pulsed wire can be implemented to determine and align the magnetic center of various magnets on a girder simultaneously. SOLEIL is equipped with a pulsed and vibrating wire measurement bench. The vibrating wire magnetic measurement method involves the excitation of harmonics of vibration due to Lorenz forces in the current carrying wire under the influence of magnetic field. By analyzing these oscillation harmonics, the magnetic field can be reconstructed with accuracy. The pulsed wire magnetic measurement is a vital tool for accurately mapping the magnetic fields, offering precision and sensitivity for the measurements. The pulsed wire method operates by sending an electric pulse through a taut wire placed within the magnetic field to be measured. As the pulse travels along the wire, it interacts with the magnetic field, generating a Lorentz force. This force causes a small deflection in the wire, which can be measured using optical detectors. The deflection of the wire is directly proportional to the magnetic field strength at each point along the length of the wire. By recording the wire's motion as a function of the time, the spatial distribution of the magnetic field can be accurately reconstructed.

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Magnetic Measurement Framework for Fully Traceable Measurements

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Magnetic measurements rely on a wide range of measurement setups, sensors, actuators, and post-processing steps. This requires a software framework to manage not only data acquisition but also persistent storage, asset management of sensors (including calibration data), and traceability of measurement results and reports. In this contribution, we present the software used in the TE-MSC-TM section at CERN and show how it supports test engineers and operators in writing reusable measurement applications and creating traceable results from acquisition to measurement reports.

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PM & Fe Material Characterization for PETRA IV DLQ Prototype Magnets

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Material evaluation measurements for soft iron and permanent magnets have been carried out to meet the requirements of the dipole magnets. In particular, three different samples of soft iron material and permanent magnets of SmCo grade are experimentally analyzed and compared with Radia simulations. The analysis and comparison of the measured data will ensure the requirements of field quality and tuning margin for the case of permanent magnet dipoles.

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Magnet Measurements of the ALS-U Magnets

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The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBL) is going through and upgrade where the ALS triple-bend achromat is replaced by a nine-bend achromat storage ring (SR) with on-axis injection using beam swapping from a triple-bend achromat accumulator ring (AR). About 700 accelerator magnets will be used for the ALS-U accelerator systems. The talk gives an overview of the magnet measurement methods and systems used for the magnetic measurements of the ALS-U magnets.

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Magnets for SOLEIL II

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SOLEIL II, the SOLEIL upgrade project aims at reducing the natural horizontal emittance of the storage ring down to 80pm at an energy of 2.75GeV. The storage ring lattice, consisting of alternating 7BA and 4BA High Order Achromat (HOA) type cells, necessitates over a thousand magnets. The magnetic design of dipoles and quadrupoles is based on permanent magnet technology. Correctors, sextupoles and octupoles are resistive magnets. The status of the magnet development is presented.

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Developments Towards a High-Speed/Accuracy Multi-vertex PCB Probe

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The use of Printed Circuit Boards (PCBs) for the inductive pick-up windings of rotating coil probes has made the construction of these precision magnetic measurement devices much more accessible. By combining multiple PCB probes within a single rotating coil structure, potential improvements for both speed and accuracy in harmonic fields measurements is explored.

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Recent Magnetic Measurement Activities at Fermilab

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Magnetic measurements are performed at Fermilab for both projects internal to the lab and as well as work for other laboratories. This talk briefly overviews the current projects and types of measurements we're currently involved in, focusing on the more interesting or challenging. Recent projects include the US-LHC Hi-Lumi Accelerator Upgrade Project (AUP), Fermilab's Proton Improvement Plan (PIP-II), and magnets built for Oak Ridge National Lab (ORNL) Proton Power Upgrade (PPU). The measurements domain includes large magnet lengths and apertures, as well as curved magnet trajectories and measurements during AC magnet excitation.

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Magnetic Characterization Proposal of a 6.6 T Superconducting Wavelength Shifter for a Hard X-Rays Synchrotron Beamline

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We present recent developments in characterization approaches for a superconducting wavelength shifter currently being developed for the Brazilian Sirius synchrotron light source. The insertion devices will exhibit 6.6 T peak field with a 7 mm cryogenic magnetic gap leading to a 5 mm vertical gap inside the electron beam chamber. A primary approach based on an anti-cryostat chamber currently being developed is presented along with further developments and considered approaches involving the use of scan coils and in-vacuum printed circuit boards.

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Magnetic Measurement activities at Magnet Division, Brookhaven National Laboratory

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1. Introduction Magnet Division, Brookhaven National Laboratory is one of the world's earliest magnet research and development laboratories. Having played a significant role in early collider projects including the Relativistic Heavy Ion Collider, Large Hardon Collider, and recent Accelerator Upgrade Project, it will play a major role in BNL's Electron-Ion Collider. Contributions to other scientific and industry projects is worth mentioning. For the characterization of magnets, magnetic measurement facilities kept flourishing under the aegis of several projects. Magnet Division has over the last decades maintained high standards of discipline in magnetic measurements and standardization of magnetic measurement procedures. For magnetic field mapping several instruments and facilities are developed. This paper is a report on magnetic measurement operations at Magnet Division along with work underway on hardware and support upgrades of existing systems and development of new technologies for future magnetic measurement systems.

2. Magnetic measurement facilities at Magnet Division, Brookhaven National Laboratory Several magnetic field mapping and measurement systems, developed in due course of time are operational at the Magnet Division. The majority of these include rotating coils, hall probe-based mappers, vibrating wire systems, and stationary coils for ramping magnets. The two variants of rotating coils namely "the moles"which have internal drive and are used for low field measurement in long magnets and "rotating coil"which are externally driven. These systems are built for several reference diameters and lengths. The "moles"and "rotating coils"are multi-loop with a standard design having 5-loop coils and 9-loop coils with digital bucking. Magnetic field mappers using hall probes are in use for field mapping and vibrating wire systems for magnetic axis determination. Magnet Division also has a Stationary multi-coil system for harmonic measurements during magnet ramping. BNL has having facility for the calibration of Rotating Coil and Hall Probes. The facility consists of a large aperture dipole magnet, quadrupole, and sextupole magnet, high rating stable power supply, and NMR sensor. The facility is also supported by various mechanical alignment and transportation systems.

3. Recent Magnet Measurement activities Several magnets are recently measured at the Magnet Division. These are largely from transfer function and harmonic measurement considerations. These include measurement of Dipole Magnet (DX) from RHIC, Rapid Cycling Synchrotron low field dipole test magnet, Refurbished Quadrupole and Sextupole Magnets from Advanced Photon Source, warm measurements of direct wind magnets for Electron-Ion Collider and magnetic measurements on Nb3Sn Quadrupole magnets for Accelerator Upgrade project (AUP). These measurements are being carried out using a combination of "moles", external drive rotating coils, and PCB-based rotating coils.

4. Magnetic Measurement System upgrades Many of the existing magnetic measurement systems at Magnet Division are running on outdated hardware and software causing significant loss of person-hours for repairs and diagnostics. The existing rotating coil systems including both the "mole"and "external drive rotating coil"are proposed to be upgraded. The coil rotating mechanism is proposed to be upgraded using standard rotary stages from reputed suppliers. Rotary stages with rotating speeds as high as 1000° /sec are easily available which is sufficient for present requirements. The data acquisition and processing systems are being planned to be upgraded with modern visual programming platforms. The upgraded system is proposed to have options for both voltage and flux measurement and acquisition and will have the option of both analog and digital bucking. The synchronization between data acquisition systems and rotary stages will be carried out using FPGA-based embedded electronics. The magnetic measurement moles consist of an in-built main motor that rotates the coil and a gravity sensor motor that aligns the mole to gravity. It is the presence of these motors built into the mole which limits the magnetic field strength when the mole is placed in this field. Piezo motors are proposed to replace both of these motors. Analysis programs are also being replaced with one using languages like MATLAB or Python.

5. New Magnetic Measurement Systems New magnetic measurement systems are being planned at the Magnet Division to meet the requirements of upcoming projects. PCB-based analog-bucked rotating coils for dipole and quadrupole magnets are being designed. An integrated dual-rotating coil system is being planned for the z-scanning of a magnetic field inside compensation magnets having longitudinally varying harmonic contents. An integrated facility consisting of vibrating wire, stretched wire and rotating wire is also being planned. Options of liquid helium-compatible rotating coils are being explored for Electron Ion Collider. This paper will discuss them in detail.

6. Summary This paper/talk is a comprehensive coverage of Magnetic measurement capabilities and activities at the Magnet Division at Brookhaven National Laboratory which extends over more than 5 decades. This talk will cover them as described above.

7. Acknowledgement The magnetic field measurement system at Brookhaven National Laboratory is the outcome of tremendous efforts by our former colleagues including Animesh Jain, James Herrera, Richard Thomas, Peter Wanderer, George Ganetis, and John Skaritka. Contribution of Christopher Tamargo and John Cintorino is highly appreciated.

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Magnetic Measurements and Tuning of an APPLE-III Undulator for FLASH at DESY

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An APPLE-III undulator of 2.5m length with a period length of 17.5mm has been developed at DESY within the last years. The device makes use of a magnetic force compensation scheme and provides arbitrarily polarized radiation. The undulator serves as a full-scale prototype for 6 further APPLE-III presently constructed within the FLASH2020+ seeding upgrade program. It has been successfully

commissioned earlier this year as a 3rd harmonic afterburner at the FLASH2 SASE line.
The tuning of individual half-periods of the magnet structure had been implemented by a wedge-driven flexor mechanism in the magnet keepers which carry two half-periods each. Pairing of AB-magnet pairs based on Helmholtz measurements could already reduce the scattering of the magnetic moment across all keepers. For magnetic sorting, all mounted keepers had been individually characterized by a dedicated compact stretched wire built for this project. Tuning of the completed magnet structure as function of gap and phase was accomplished by a Hall probe bench.

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UPRGADE OF HALL PROBES BENCHES FOR CRYOGENIC UNDULATOR BASED-ON SAFALI SYSTEM AT SOLEIL

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The rise of cryogenic undulators requires an adaptation of their measurement benches. The constraints of vacuum, space, and temperature compel us to modify our benches in terms of their configurations and components.
The new Hall probe bench that will be tested on the CPMU12 currently under construction at Soleil is Based on the SAFALI (Self-Aligned Field Analyzer with Laser Instrumentation) System presented at FEL 2007 for IVU24 and CPMU prototype at Spring-8 [1].
This system digitally corrects the position and angle of the Hall probe in Igor Pro, using an active feedback loop that controls piezoelectric motors to adjust the probe's position. At present, it cannot be characterized outside of the vacuum, as air inhomogeneities cause deviations in the laser beam.
The alignment of the laser beams with the other components of the bench has been automated in Python, due to the instability and lack of precision in the manual approach. Initially, the alignment of the probe axis with the electron axis of the undulator was to be ensured by installing fixed irises as references on the undulator chassis. However, this option was abandoned due to space constraints in the vacuum chamber.
In addition, the cinematic of the bench has also evolved from an out-vacuum stepper motor with a metallic belt driving the Hall probe to a linear motor that can be directly embedded in the vacuum chamber to fulfill measurements under vacuum and cryogenic conditions. This configuration should enable to reach better performances mainly a better stability in terms of velocity.

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Vibrating-Wire Magnetic-Axis Measurement of SLS2.0 Multipole Magnets

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A large number of sextupole-octupole pairs are to be installed into the new storage ring of the Swiss light source, SLS2.0. These magnets are measured using vibrating wire technique, and the magnetic axes are found and relatively aligned.

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Magnetic measurement activities at CERN

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This talk presents the current status of magnetic measurement activities at CERN, including ongoing and future projects, major infrastructure upgrades, instrumentation R&D and recent noteworthy results.

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Challenges and Results from the series Measurements of the SLS2.0 Longitudinal Gradient Bends magnets

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The measurement challenges and results from the series tests assessing production quality of the main magnet'assembly, referred to as Triplet, for the upgrade of the Swiss Light Source(SLS)2.0 are described (2.0 stands for the whole renewal of the storage ring). A Triplet, which comes in four flavors, is at the heart of the seven-bend achromatic structure of SLS2.0 [1], implementing a longitudinal gradient bend (LGB) function. The requirement, from beam dynamics, of tuning the integral LGB function with an overall uncertainty of 2·10-3 relative to the nominal design value identifies (or drives) the measurement challenges. The Triplet assembly is composed of three magnets, that is, a central dipole surrounded on each side by two combined function magnets providing quadrupole and dipole components. Each Triplet element is a permanent magnet implemented with NdFeB blocks. In this contribution, a brief overview of the Triplet magnets characteristics is reported and the process of extracting measurement requirements from Triplet Finite Element (FE) simulations is illustrated. Thereafter, the authors'focus goes on the measurement procedure and tuning for both single magnets and an assembled triplet. Then, a comprehensive summary of the series measurements results is discussed.

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Summary of Projects and Challenges in the Magnet Section at the Paul Scherrer Institute

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Magnetic Measurement Activities by the ID Group at the National Synchrotron Light Source-II

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Magnet group activities at ALBA

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Magnet Measurements of the ALS-U Magnets

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Magnets for SOLEIL II

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Magnetic Measurement activities at Magnet Division, Brookhaven National Laboratory

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Latest Developments in Magnetic Measurements

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SENIS Advanced Sensors and Instruments for Magnetic Field and Electric Current Measurement

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Hall mapper for sorting permanent magnets

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Three-dimensional magnetic field mapping system for large spectrometer magnets utilizing on-fly technology

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Measurement of Electromagnets and Tuning of Permanent Magnets based on Rotating Coils for the Upgrade of the Swiss Light Source (SLS2)

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Challenges and Results from the series Measurements of the SLS2.0 Longitudinal Gradient Bends magnets

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Crosstalk effects measurement on permanent magnets with hall probe mapping for the Upgrade of the Swiss Light Source (SLS2)

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Update of the magnetic measurement benches of the ESRF

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Magnetic Measurement Framework for Fully Traceable Measurements

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Overview of the ITER magnetics diagnostic

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ITER (International Thermonuclear Experimental Reactor) is the world's largest Tokamak fusion project designed to demonstrate the feasibility of nuclear fusion as large-scale energy source.
It will be equipped with a large array of diagnostic instruments to provide the measurements necessary to control, evaluate and optimize plasma performance in ITER and to further the understanding of plasma physics. Magnetics is an essential diagnostic to provide magnetic equilibrium; measure currents in the plasma or in structures; measure plasma stored energy; and it is directly integrated in the plasma control system to provide feedback on plasma shape and position.
It provides high-resolution, real-time measurements of the magnetic fields within and around the plasma, which are critical for maintaining effective magnetic confinement.
The system provides measurements of the magnetic properties of the plasma, from raw parameters (local field and flux changes) through time-integrated quantities (field and fluxes) to complete equilibria and derived plasma properties (shape, position, speed, energy, slow and fast instabilities). To do this, the diagnostic uses more than 2000 sensors, divided in the following groups as subsystems:

- Sets of pick-up coils, saddle and voltage loops mounted on the inner wall of the vacuum vessel;
- Rogowski coils mounted around earth straps of the blanket shield modules;
- Sets of pickup coils, Rogowski coils and shunts mounted on the divertor cassettes;

- Sets of pick-up coils, voltage loops, hall sensors and fiber optic sensors mounted on the outer surface of the ITER vacuum vessel;
- Continuous poloidal Rogowski coils mounted within the TF coil case.

Signals from these sensors are conditioned, calibration factors are applied and plasma properties like position, shape, current and modes are derived, in real-time, quasi-real time and offline using a dedicated set of bespoke integrators boards, which integrate, elaborate the signals during the plasma pulse time and transmit the information to the plasma control system and the archive network.

After a general introduction on the ITER construction status and assembly with focus on the diagnostics, this talk will give an overview on the challenges and technological solution adopted for different the magnetic sensors types, the cabling solutions to bring the signals outside the vessel and the electronics

and the software that will be used to calculate in real-time the plasma parameters.

This talk will also cover other magnetic measurements tools that are not directly involved in the plasma control but are essential to characterize and protect the tokamak like toroidal field mapping system based on NMR sensors and the plasma current measurements system for interlock and safety.

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Recent Magnetic Measurement Activities at Fermilab

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Developments Towards a High-Speed/Accuracy Multi-vertex PCB Probe

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Crosstalk effects measurement on permanent magnets with hall probe mapping for the Upgrade of the Swiss Light Source (SLS2)

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The Paul Scherrer Institut is currently involved in the upgrade of the Swiss Light Source (SLS2) accelerator. The goal is to increase the photon flux and the beam brilliance by keeping the same storage ring dimension. To achieve the new machine performance, a high density of magnets of about 1270 magnets instead of 388 is used. Therefore, the introduction of 372 permanent magnets (PM) was necessary. However, due to the proximity of the PMs to the electromagnets, the crosstalk effect becomes a problem in terms of the reduction of the field strength of the PM. An experimental campaign was carried out with a compact field mapper, using a 3D Hall probe, to assess the influence of the electromagnets on the PM field.

This presentation provides an overview of the crosstalk measurements, the comparison between simulations and experimental results and the adopted strategies for retuning the PMs in the machine.

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New Rotating-coil Chains for the HL-LHC Cryomagnets

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A coil chain is defined as an assembly of rotating coil segments, mechanically connected, that covers the entire field profile of long magnets. Rotating coil chains for field harmonics measurement of superconducting magnets had been heavily used on LHC cryo-magnets at CERN. The Insertion Region magnets for the HL-LHC project, with new geometries and tighter tolerances have required the development of new 10 m coil chains for the characterization of integral and local field. PCB coils in sandwich-type fibreglass assemblies and their calibration method, as well as examples of measurements of the first series magnets will be presented.

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Rotating-coil Chains for the HL-LHC Cryomagnets

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