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ADVANCED PROCESS CONTROL TOOL FOR MAGNET MEASUREMENT AT PSI

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Abstract

Magnet measurements at the Paul Scherrer Institute (PSI) are performed with the use of a process control tool (PCT), which is fully integrated into the PSI control system. The tool is implemented as a set of user friendly graphical user interface applications dealing with particular magnet measurement techniques supported at PSI, which include advanced Hall probe, vibrating wire, and moving wire methods. The core of each application is the state machine software developed by magnet measurement and control system experts. Applications act as very efficient assistants to the magnet measurement personnel by monitoring the whole measurement process on-line and helping to react in a timely manner to any possible operational errors. The paper concentrates on the PCT structure and its performance.

INTRODUCTION

Charged particle accelerators and their experimental stations at PSI contain a number of various magnetic field generating components: dipoles, quadrupoles, solenoids, etc. The quality of these components, which are usually referenced as magnets, strongly affects the accelerator and experiment capabilities. To assure that all magnetic field quality specifications are met, such components are systematically measured at the PSI magnet measurement laboratory (MML). The equipment of this laboratory was significantly upgraded few years ago. In parallel with this upgrade, an advanced magnet measurement data acquisition and control system (MMDACS) was created. The system was implemented as a part of the PSI controls environment, which is based on EPICS [1].

Major features of this system were presented at the ICALEPCS'13 conference [2]. Since then, the system was consistently showing its high efficiency and reliability in all magnet measurements at the MML. It was also successfully adapted to an advanced 3D Hall probe setup and a new 64 bit Linux PC platform at PSI. The main activities around MMDACS, though, were concentrated on the development and enhancement of user friendly control applications that can efficiently assist operators in routine magnet measurement procedures. The result of such activities is a magnet measurement process control tool (PCT). The tool consists of a set of applications specialized in particular magnet measurement techniques supported at PSI, which include Hall probe, vibrating wire, and moving wire methods. The core of each application is the state machine software designed by magnet measurement and control system experts.

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HALL PROBE MEASUREMENT COMPONENTS AND PROCESS CONTROL APPLICATION

Magnetic field mapping at the PSI is performed by Hall probes. Measurements are done with the use of a Magnet Measurement Machine (MMM). To provide stable long-term measurement conditions, the machine is located in a temperature controlled (±0.1° C) room. A magnet is positioned on the measurement bench with the use of the extremely accurate portable coordinate measuring system FaroArm Quantum system.

Five MMM stepper-motors can move a Hall probe, which is mounted on a titanium arm, in three translation directions or axes (X, Y, Z) as well as rotate it in the horizontal plane and around the arm. Since rotations are used only for proper probe positioning in space, any particular measured field map at the PSI corresponds to a line, a plane, or a volume in the Cartesian coordinate system (X, Y, Z). The measurements are performed in a "continuous scan on the fly" mode, which means that the MMM doesn't stop to make a particular measurement. This allows one to finish a complex field mapping process for each magnet in a relatively short time period, which is typically one day or less.

The MML possesses a set of classical Hall probes, which are sensitive to only one magnetic field component or one-dimensional (1D) by design. Recently, this set was enhanced by an innovative, in-house developed, high accuracy 3D Hall probe [3]. This probe consists of three pairs of 1D Hall probes forming a sub-millimeter cubic active volume (see Fig. 1) and, therefore, is sensitive to all three magnetic field components.

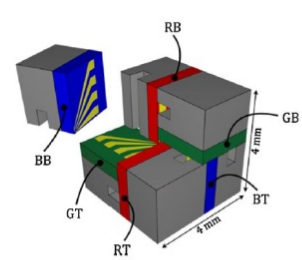

Figure 1: PSI 3D Hall probe structure. For clarity, pairs of 1D Hall probes sensitive to the same direction of the magnetic field are shown in the same color (blue: sensors BB and BT, green: sensors GB and GT, red: sensors RB and RT).

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The MMM measurement equipment consists of PSI digital power supply controllers (DPSC) with their external interface modules PSC-IP implemented in the Industry Pack (IP) standard, a set (one dedicated for 1D and six others for 3D probes) of Agilent 3458A digital multimeters (DMM devices) that can be remotely controlled over the GPIB bus, Hytec 8505 IP modules providing a variety of DIO signals required for MMM operations (e.g. DMM triggering) and a MAXv-8000 VME card (from Pro-Dex) with its transition module to interface MMM stepper-motors and their extremely accurate (~0.5 µm) encoders. The DMM devices are accessed via E5810B LAN/GPIB gateways (from Keysight Technologies) connected to the computer network.

The MMM measurement equipment control software is a part of the MMM server program. This program is executed on a VME-64x process control computer (also referenced as an Input Output Controller or IOC), which is a MVME-5100 single board CPU running the VxWorks real time kernel and a memory resident EPICS database handling MMM measurement equipment components and measurement data.

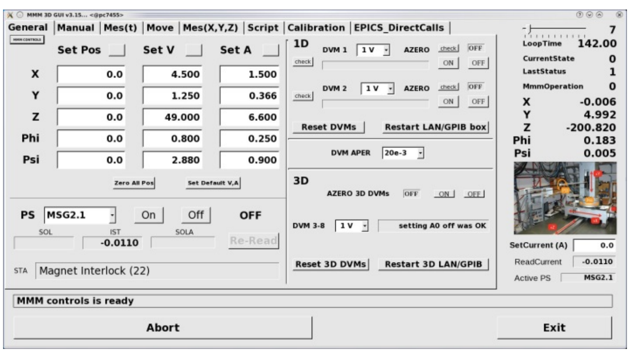

Figure 2: The mmmgui screen overview.

A specially designed control screen **mmmgui** (see Fig. 2), is a graphical user interface representation of the MMM client program. The screen is based on a Qt framework [4], which automatically makes it computer platform independent. The MMM client program runs on one of the MML Linux PC consoles. It is multi-threaded. Each thread deals with a particular MMM operational mode, which is handled by the state machine software associated with this mode and available from a dedicated standard Qt tab panel on the **mmmgui** screen. Threads talk to each other over a shared memory synchronized with the MMM EPICS database.

The MMM state machine software is developed by magnet measurement and control system experts, which makes it highly optimized and extremely efficient for all MMM operations.

The MMM client and server programs communicate via EPICS. They both are combined into the Hall probe process control application, which can handle a variety of basic operational modes.

For instance, consider a frequently used "driving along the Z axis" mode, in which the Hall probe goes through the next steps:

- moves to a specified point sPos and stops there;
- moves in Z direction from sPos to another specified point ePos and measures its potential in M equidistant points during the move;
- stops at ePos.

This mode can be executed from a Mes(X,Y,Z) mmmgui panel (see Fig. 3).

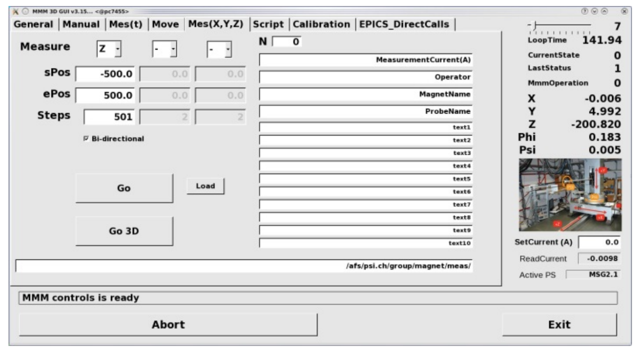

Figure 3: The Mes(X,Y,Z) panel of the mmmgui.

At its bottom, the panel has the MMM operational status line, which is continuously updated by the Hall probe process control application.

Before running the MMM, its user has to define the start (sPos) and end (ePos) points for the measurements, the Z motor acceleration and maximum speed, the number of measurement points M, and the magnet power supply current value. Based on this information, the MMM client program makes a number of calculations, data verifications, and system settings. In particular, assuming that the measurement points are equidistant, their coordinates are defined and immediately become a part of the MMM EPICS database. Also, the MMM server program is instructed to set the required power supply current and Z motor motion parameters and to report setting results.

The mode execution starts by pushing the "Go" button in case of a 1D probe or the "Go 3D" button if the probe is 3D. We remind that in the last case six DMM devices are used for measurements. They all are arranged to be triggered simultaneously.

The MMM client commands the MMM server to move the probe to the specified point sPos and then waits until it is done. Talking to the MAXv-8000 card, the server moves the motor to the point sPos and makes sure that the probe stops at this point. When the motion is completed, the client is informed that it is done and the operational status is set to OK. However, if any operational error occurs, the probe is stopped immediately, the error is reported to the client, and the mode is aborted.

The client program configures the used DMM devices to collect M data values. Then it instructs the server to move the probe in Z direction from point sPos to point ePos with triggering DMM devices in all previously calculated measurement points and waits until it is done. The

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server monitors the probe motion progress and generates DMM trigger signals exactly when the probe reaches such points. Each time the DMM device is triggered, the actual probe potential is written into its internal memory buffer. Simultaneously, the corresponding time stamp, which is obtained directly from the VxWorks operating system, and the probe Z coordinate, which is DMA transferred from the VME memory associated with motor encoder data, are written in the MMM EPICS database. The MMM server program assures all necessary real time constraints on the whole data acquisition process. When the motion is completed, the client is informed about it. And again, in case of any operational error, the probe is stopped immediately, the error is reported to the client, and the mode is aborted.

The above mentioned actions of the Hall probe process control application for handing the "driving along the Z axis" mode disclose the algorithm, which is implemented in the state machine software for this particular mode. All other MMM basic operational modes are implemented in a similar way.

The Hall probe process control application acts as a very efficient assistant to MMM operators during magnetic field mapping procedures. All **mmmgui** panels are extremely easy to use. Any MMM operational failures are monitored and registered in the EPICS database, which immediately makes them available for review and troubleshooting.

MOVING WIRE SETUP AND ITS PROCESS CONTROL APPLICATION

Harmonic measurements in multipole magnets at PSI use a single moving wire method when a stretched wire moves over a cylindrical surface in the magnet aperture and the magnetic flux change is measured as a function of the rotation angle.

The moving wire setup consists of a dedicated DMM device and a high performance multi-axes Newport XPS motion controller/driver unit. The unit can precisely control complex motion sequences, which makes it especially valuable for implementing any advanced wire trajectory and device synchronization features. Two pairs of linear motorized stages Newport M-ILS150CC are connected to the XPS unit. In each pair, one stage moves vertically (Y direction) and is attached to the second one, which in turn moves horizontally (X direction). The wire is stretched between two holders mounted on vertical stages. The stages are configured (as XY groups) to synchronously move both ends the wire along a specified arc. As a result, the system gets ready to execute any cylindrical wire motion.

The measurements are handled by the moving wire process control (MWPC) application that communicates with the XPS unit and DMM device over the computer network.

The application is based on the EPICS synApp software package [5]. The XPS support part of this package was modified to fit PSI data acquisition and measurement requirements and to run reliably on any (32 or 64 bit) Linux PC.

The application is accompanied by a set of MEDM and caqtdm graphical user interface (GUI) panels, which are very easy to use. They guide a user through a sequence of required measurement and data acquisition steps, which are controlled by the state machine software. These steps can be described as follows.

A desired wire trajectory is defined. The trajectory is a set of reference points through which the wire has to be moved as well as a number of equidistant points in which the XPS unit will generate trigger signals for the DMM device and write corresponding wire coordinates into its local memory buffer.

The wire trajectory information is saved into a wire trajectory definition file. Based on this file, the MWPC application configures the XPS unit to execute the specified trajectory.

The MWPC application sends the command to the XPS unit to execute that trajectory.

The XPS unit executes the specified wire trajectory. The XPS external trigger signals are caught by the DMM device, which saves the information about the flux change induced voltage of the moving wire at trigger moments into its internal buffer. The MWPC application assures that the DMM device configuration follows the XPS unit settings.

When the wire motion is finished, the MWMC application transfers the XPS and DMM device internal memory buffers to the EPICS waveform records associated with a 2D wire trajectory representation and corresponding wire voltages, which immediately makes all measurement data available for archiving, processing, modelling, etc.

VIBRATING WIRE SETUP AND PROCESS CONTROL APPLICATION

The vibrating wire process control application implements the fundamental idea of the vibrating wire method. If a stretched wire is excited by an alternating current (AC), then it starts oscillating in a static magnetic field. The AC frequencies corresponding to natural wire resonances cause especially large vibrations, which makes such a system extremely sensitive to the existence of the magnetic field along the wire. Essentially, the fact that the wire stretched in a multipole magnet stops vibrating means that the effective magnet axis and the wire are aligned. So, to locate this axis one should move the wire until its oscillations vanish.

We note that the vibrating wire method is one of the most accurate techniques to determine the magnetic axes of multipole magnets.

The PSI vibrating wire measurement setup includes the next equipment components.

- A magnet measurement bench with the integrated reference rail and the FaroArm Quantum system. Following specifications from a manufacturer, a magnet is precisely positioned on the bench with its specified axis directed along the reference rail.

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- Two pairs of linear motorized stages Newport M-ILS150CCL with their controller units SMC100, which have a serial (RS232) external interface. Analogously to the case of the moving wire, in each pair, one stage moves vertically and is attached to the second one, which in turn moves horizontally. The wire is stretched between two holders mounted on vertical stages. Practically in all measurements, the controller units are configured to move two horizontal and two vertical stages simultaneously. This allows one to easily keep the wire inside the magnet aperture and directed along the reference rail (or the magnet axis specified by the manufacturer).

- A novel PSI inductive detector consisting of four pick-up coils placed radially around the wire, with 90° angles between the coils. It is worth to note that in addition to wire vibration characteristics, the signals from the coils contain the information about the wire position in the magnet aperture.

- A lock-in amplifier HF2LI (from Zurich Instruments). The instrument is set up to use its oscillator to generate the output voltage to power the wire and its demodulators to measure wire vibrations and positions in both horizontal and vertical planes. For its remotely controlled operations, the amplifier provides a USB external interface.

We note that the HF2LI control software was significantly modified in the last two years. Now it allows one to reliably communicate with such amplifiers on any Windows and Linux computer over local USB ports.

Based on the used magnet measurement setup and its characteristics, the implemented vibrating wire state machine software performs the next basic functions.

- Power the wire by the HF2LI amplifier with a specified AC.

- Move the wire to a specified horizontal and vertical position inside the magnet aperture.

- Measure and record the demodulated horizontal and vertical wire coordinates as well as amplitudes of pickup coil signals in some predefined time interval (e.g. several seconds).

- Calculate the average values of the recorded amplitudes.

- Plot the average amplitudes against the position of the wire in the magnet.

- Define the magnetic axes of the magnet. As the amplitude is always a positive number, there are two linear fits, one with a negative and one with a positive slope. The intersection point of these two fits is taken for the magnetic axis. In particular, for quadrupoles such a plot looks like one shown in Fig. 4, which is the result of a horizontal scan through a quadrupole magnet. As close to the magnetic axis the vibration is too small to measure without significant errors, one skips measuring these points and instead fits a linear function to the data measured further away from the magnetic axis.

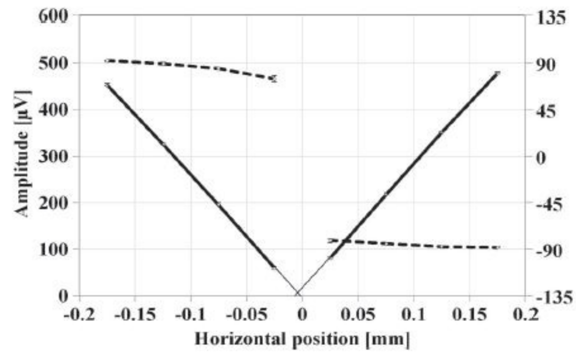

Figure 4: A typical graph of wire vibration amplitude and phase in quadrupole magnet. The amplitude is represented by solid lines. Thin lines show a linear function fit of the amplitude.

CONCLUSION

The presented in this paper PCT has been in use for magnet measurements at PSI for about one year. Developed by magnet measurement and control system experts and implemented as user friendly GUI panels and powerful state machine software behind them, the PCT consistently shows its high reliability. It acts as a very efficient assistant that guides magnet measurement operators through the most optimized steps for each measurement method.

REFERENCES

[1] EPICS, `http://www.aps.anl.gov/epics/`

[2] P. Chevtsov *et al.*, “SwissFEL Magnet Test Setup and its Controls at PSI”, in *Proc. ICALEPCS’13*, San Francisco, CA, USA, Oct. 2013, pp. 1209-1212,

[3] C. Wouters *et al.,* “Calibration scheme for a new type of 3D Hall sensor”, *Sensors and Actuators*, vol. A257, 2017, pp. 38-46.

[4] Qt, `http://qt-project.org`

[5] synApps, `https://www1.aps.anl.gov/bcda/synapps`