MAGNET SERVER AND CONTROL SYSTEM DATABASE INFRASTRUCTURE FOR THE EUROPEAN XFEL

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Abstract

The linear accelerator of the European XFEL will use more than 1400 individually powered electromagnets for beam guidance and focusing. Front-end servers establish the low-level interface to several types of power supplies, and a middle layer server provides control over physical parameters like field or deflection angle in consideration of the hysteresis curve of the magnet. A relational database system with stringent consistency checks is used to store configuration data. The paper focuses on the functionality and architecture of the middle layer server and gives an overview of the database infrastructure.

INTRODUCTION

The European X-ray Free Electron Laser (XFEL) is a research facility currently under construction in close collaboration between the European XFEL Facility GmbH[1] and DESY[2] in Hamburg, Germany [1–3]. It consists of a superconducting linear accelerator delivering an electron beam with particle energies up to 17.5 GeV and a total beam power up to ~600 kW, several long undulator sections enabling the generation of extremely brilliant X-ray pulses at wavelengths down to 0.05 nm, beamlines and setups for photon science experiments, and the associated infrastructure.

The electron beamlines of the European XFEL will be equipped with more than 1400 individually powered electromagnets for beam guidance and focusing. In this paper, we give an overview of the various control system components that work together to provide a uniform interface for controlling and monitoring these magnets. We start at the interface between hard- and software with a short introduction to the server architecture of the magnet power supply system. Above this level, a new magnet middle layer server has been introduced that will be treated in more detail. It gives access to physical parameters like magnetic fields and deflection angles in addition to handling hysteresis effects. The paper closes with a few remarks on the database back-end used for the storage of configuration parameters for these and other systems.

POWER SUPPLY SERVERS

As shown in Fig. 1, distributed front-end servers establish a low-level interface to the magnet power supply controllers (PSCs). There are currently two independent PSC families using different communication protocols and interfacing logic. Most of the main magnets (bending dipoles, quadrupoles) along with some correctors are controlled by PSCs designed at DESY using the industrial CANopen communication protocol [4]. The PSCs of the second family originate from Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia, and use a proprietary protocol [5] which is also CAN-based.

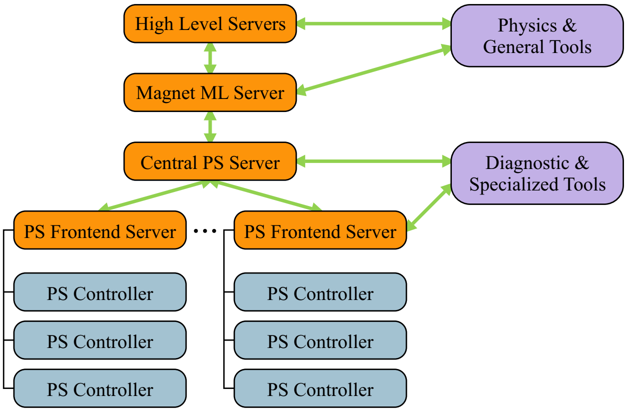

Figure 1: An overview of communication paths between user tools, various server layers, and power supply controller hardware.

An important task of the front-end servers is to hide differences in the interfacing logic and to provide a unified command set that is independent of hardware and communication protocols. The command set covers primitive actions such as switching a power supply on/off, ramping output current, setting current limits, delivering status and error information, and so on. The front-end servers also hide all addressing details, publishing descriptive names of the PSCs rather than their CAN bus identifiers and numbers. The front-end servers can be accessed by a central power supply server (CPSS) as well as by diagnostic applications using the TINE [6, 7] protocol.

The CPSS provides the only access to magnet power supplies for middle layer servers or other clients. It dispatches all requests referring to a single PSC to the corresponding front-end server where they are converted to PSC-specific commands. The CPSS is also capable of accepting composite commands that address PSC groups rather than single units. Such commands are split by the CPSS into several primitive commands and delivered to the front-end servers. The CPSS continuously monitors the front-end servers and collects status information, making it available for middle layer servers and other diagnostic or archiving tools.

MAGNET MIDDLE LAYER SERVER

For previous accelerators at DESY, the main magnet-related quantity provided at the control system level was

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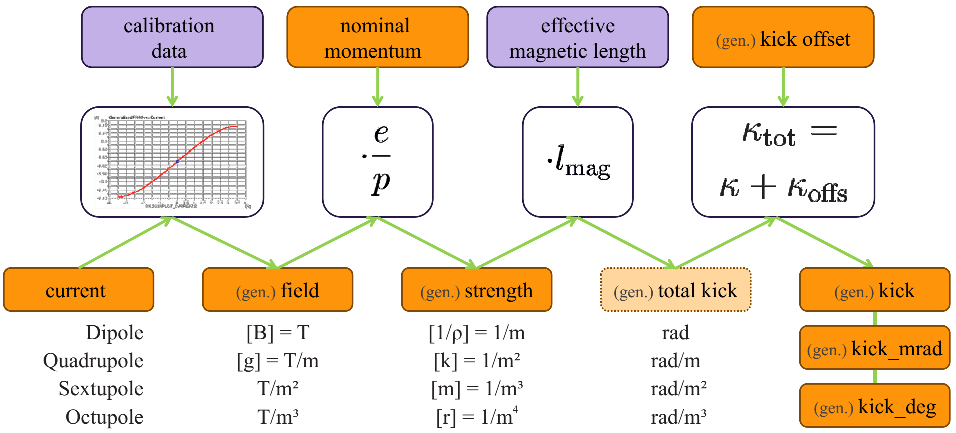

Figure 2: Overview of the various quantities calculated by the magnet middle layer server. User-controllable quantities are shown in orange and static configuration items in purple.

the output current of the power supply. Client software had to rely on additional toolboxes, libraries, or badly maintained ad-hoc code to convert these currents to more physical parameters like fields or deflection angles. At the XFEL, a new magnet middle layer (ML) server has been introduced to provide direct access to these parameters at the control system level. It also offers advanced functionality for the tracking of hysteresis effects, handling of magnet groups and various convenience functions. Where multiple magnets are connected in series to a single power supply, the magnet ML server represents them as individual locations that may or may not have different characteristics.

Implementation

The magnet middle layer server is a DOOCS [8, 9] server written in C++11; as such, it can natively communicate with DOOCS and TINE clients. For back end communication, it maintains a permanent asynchronous TINE link to the central power supply server. The following information is read at a repetition rate of 5 Hz for each power supply:

- current setpoint
- current readback value
- power supply on/off flag
- power supply fault flag
- power supply idle flag

The repetition rate is mainly determined by the maximum read-out rate of the power supply controllers.

Write access from the magnet ML server to the central PS server occurs through synchronous TINE calls and is limited to the setpoint of the current and few special commands.

Physical Quantities

The magnet middle layer server supports the main types of non-pulsed electromagnets used at the XFEL – general multipole magnets (dipoles, quadrupoles, sextupoles, octupoles) and solenoids. As illustrated in Fig. 2, many different physical quantities are calculated from the magnet current and from additional data that is either statically configured or can be changed by the user. To be able to refer to these quantities in a uniform manner across all magnet types, we use a custom vocabulary of generalized quantities:

Generalized field is calculated from the magnet current using a set of calibration curves for the up- and downward current slope (for details see below). For dipoles, this quantity signifies magnetic flux density ($[B] = \mathrm{T}$), for quadrupoles field gradient ($[\mathrm{d}B/\mathrm{d}x] = \mathrm{T/m}$), and so on.

Generalized strength is obtained by multiplying the generalized field by e/p where e is the elementary charge and p is the expected particle momentum at the magnet. This *nominal momentum* p is a setting of each individual magnet and can be changed by the operator maintaining alternatively the field or the strength; usually, it is adjusted to the measured energy profile of the accelerator by a dedicated tool. For quadrupoles, the generalized strength is identical to the k value used in many lattice design and tracking codes.

Generalized kick is defined as the product of generalized strength and effective magnetic length of the magnet. For dipoles, this *kick* actually corresponds to the deflection angle of the magnet, while for other magnet classes it is more commonly referred to as *integrated strength*.

Additionally, the server splits the setpoint for the generalized kick into an offset and a base part. The base part is used for the normal setup of the magnetic lattice whereas the offset is reserved for small corrections from the trajectory feedback. In this way, the main kick property is kept free of feedback noise.

Calibration Functions and Hysteresis

Practically all magnets at the XFEL, with the exception of only a handful of units, have massive iron yokes and therefore exhibit non-negligible hysteresis effects. In other words, their magnetic field B is not a unique function of the excitation current I, but depends on the magnetization history of the material. A multitude of analytical and numerical methods have been proposed for the modelling of hysteretic

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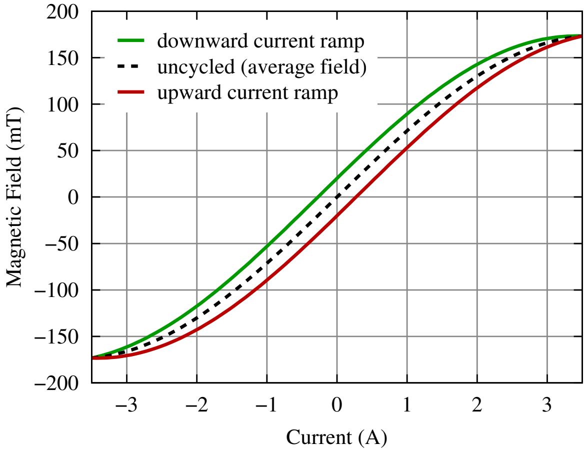

Figure 3: Exemplary calibration curves for a magnet with hysteresis. The opening of the curves has been exaggerated for clarity.

effects in the presence of arbitrary changes of the current or the corresponding magnetizing field H (see e.g. [10–12]), but there is little experience to suggest that these models could satisfy the demanding field precision requirements of the XFEL.

In the development of the magnet middle layer, we have chosen an intermediate approach: The server allows the standardization *(cycling)* of magnets to establish a well-known magnetization state. From this point on, it monitors the current and follows the position on an outer hysteresis curve in the $B(I)$ diagram as shown in Fig. 3. This curve ranges from the minimum of the current, $I_{\min}$, to its maximum, $I_{\max}$, and consists of a branch ramping upwards in current and another one ramping downwards. Both branches are described by independent calibration functions based on fits to measurement data. Currently, 5th-order polynomials are used for most curves. A tanh-based function from [12] finds application for a few magnets with scarce measurement data and bipolar power supplies:

$$\begin{aligned} B(I) = {} & c_0 I + c_1 \tanh\left[c_2\left(I - c_3\right)\right] + \\ & c_1\left(\tanh\left[c_2(c_4 + c_3)\right] - \tanh\left[c_2(c_4 - c_3)\right]\right)/2 \end{aligned}$$

When the user sets the generalized field, strength, or kick, the corresponding current is found numerically using a stable solver based on Newton's method.

Obviously, the magnet only stays on its calibrated hysteresis curve as long as the current is changed *with* the ramp direction of the present branch. If it is changed *against* that direction, the server marks the magnet as *dirty*, i.e. in need of cycling. In this case, the exact field is considered unknown and is approximated by the mean value of the up- and downward calibration curves at the given current.

Cycling, Degaussing, and Other Sequences

A generic sequencing algorithm allows the execution of consecutive operations on a given power supply circuit. Command sequences are defined as comma-separated strings using the commands listed in Table1. There are currently three applications for this server-internal sequencer:

Table 1: Main Sequencer Commands

Command	Description
current *amps*	Ramp to the specified current.
field *val*	Ramp to specified generalized field.
kick *val*	Ramp to specified generalized kick.
max	Ramp to maximum current.
min	Ramp to minimum current.
strength *val*	Ramp to specified generalized strength.
wait *secs*	Wait specified number of seconds.

Cycling: A magnet that has left its measured hysteresis curve is in a state where its field is known only with an increased degree of uncertainty. To force the magnet back onto the known curve, it is usually driven multiple times through the cycle from $I_{\min}$ to $I_{\max}$ and back. Each magnet can be assigned an individual cycling sequence. Until better recipes are found experimentally, the default sequence is *"max, wait 1, min, wait 1, max, wait 1, min, wait 1"*, i.e. double cycling ending with a magnet on the upward ramp.

Degaussing: Magnets with iron yokes retain a remanent magnetization even without excitation current. If a bipolar power supply is attached, this magnetization can be eliminated by driving the current to a specific value or in alternating, decaying patterns. If such a procedure is defined, it can be launched through the server's *degauss* command.

Autocycling setpoints: Current, field, strength, and kick can be set through special *autocycle* properties. If these are used, the server makes sure that the requested target value is reached *and that the magnet ends up on its known hysteresis curve.* Depending on the initial state, one of the following procedures is executed:

- If the magnet is marked as *dirty*, the cycling procedure is executed before ramping to the target value.
- If the target can be reached by ramping in the present ramp direction, the value is set directly.
- If the target cannot be reached in the present ramp direction, the current is first ramped to the minimum or maximum and afterwards to the target value (semi-cycle).

Group Functionality

Magnets can not only be controlled individually, but also collectively. For this purpose, the magnet ML server offers an arbitrary number of group locations that can be used to access multiple magnets with a single command. Depending on the operation, these server properties work with arrays of values (e.g. for reading and setting magnet strengths) or with combined single values like collective status flags (e.g. "all group magnets are on"). Many convenience functions are implemented on this level as well. For example, to cycle only the *dirty* (uncycled) magnets in section L1, a single call to CYCLE_DIRTY on the GROUP.L1 location is sufficient.

The server creates a number of groups on startup based on the magnets' associations with accelerator sections and user defined flags. These automatic groups can neither be removed nor can their list of magnets be modified. In addition, arbitrary user-defined groups of magnets can be created and removed through server commands at runtime.

DATABASE INFRASTRUCTURE

Traditionally, control system servers at DESY read their configuration from local files (using XML or a number of proprietary formats). These files are edited by hand, through specialized tools or scripts, or modified by the servers themselves. This approach necessarily leads to friction where different servers need access to the same information—component names, positions, and calibration constants are typical examples. In fact, given the scale of the XFEL project and the sheer number of individual servers and developers involved, inconsistencies in such *shared configuration items* are the rule rather than the exception.

In order to improve this situation, we have started to store selected configuration items in DESY's Oracle 12c database system. As far as practically possible, database constraints are used to keep the stored data consistent in case of modifications. A few tailored libraries/toolkits for C++, Matlab, and Python have been developed and put at the disposal of developers to allow easy access to the database. The usage of these instruments is slowly picking up throughout the codebase, and the magnet middle layer server is the first one to read almost its entire configuration from the database.

Of course, relying on a central instance like the Oracle system—even if geared towards high availability—introduces a single point of failure. Therefore, all servers store the information received from the database also in their traditional local configuration files. In case of connection problems, the locally cached configuration is used.

CONCLUSION AND OUTLOOK

The European XFEL is a facility of considerably higher complexity than all of the other currently operating accelerators at DESY. With respect to these older machines, a slightly different approach is used to control its more than 1400 solenoids, correctors, quadrupoles, and higher order multipole magnets. The servers controlling the magnet power supplies have been stripped of higher level functionality, and a new magnet middle layer server has been introduced to provide access to physical parameters such as field, kick, and nominal particle momentum. This new server also allows to operate magnets on both branches of their calibrated hysteresis curve, offering advanced functionality for cycling and degaussing of magnets when necessary. The server relies heavily on the configuration database infrastructure that has been recently introduced to minimize inconsistency between shared configuration items in control system applications.

Like most subsystems, the magnet middle layer server is going to be used more intensively starting with the commissioning of the XFEL injector at the end of this year. It is also available at the FLASH facility [13–15] with limited functionality. The operational experience from these accelerators is going to influence the features of the software continually. Among several possible future extensions, the tracking of magnetization inside of the calibrated outer hysteresis curve seems most promising, but requires intensive comparison with measurements and is therefore not viable in the short term.

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