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HIGH ENERGY PHOTON SOURCE CONTROL SYSTEM DESIGN*

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Abstract

A 6-GeV high energy synchrotron radiation light source is being built near Beijing, China. The accelerator part contains a linac, a booster and a 1360-m circumference storage ring, and fourteen production beamlines for phase one. The control systems are EPICS based with integrated application and data platforms for the accelerators and beamlines. The number of devices and the complexity level of operation for such a machine is extremely high, therefore, a modern system design is vital for efficient operation of the machine. This paper reports the design, preliminary development and planned near-future work, especially the databases for quality assurance and application software platforms for high level applications.

INTRODUCTION

An ultra-low emittance and high brightness 4th generation synchrotron light source, the High Energy Photon Source (HEPS) designed by the Institute of High Energy Physics (IHEP), has started its construction since June 2019. The main parameters for HEPS are listed in Table 1 which contains many challenging goals. It is necessary to have accurate installation, state-of-art equipment and high precision controls with high reliability. The control systems and related computing facilities are extremely important for the HEPS which includes not only traditional control architecture design but also quality control for the project. Also, the HEPS control systems support not only the accelerator but also 14 beamlines which will be constructed at the same time. To build such a complex accelerator-based user facility, it is necessary to have an overall complete design for the control systems.

Table 1: HEPS Main Parameters

Main Param.	Value	Unit
Top beam energy	6	GeV
Main Ring circumference	1360.4	m
Emittance	<60 (<40 with anti-bend)	pm-rad
Beam current	200	mA
Brightness	$>10^{22}$	Phs/s/mm^2/mrad/0.1%BW
Injection	Top-up	
Bunch structure	680 (high-brightness mode), 63 (timing mode)	

The HEPS control system which considers of data for future machine learning (ML) capability is designed. Accelerator and beamline controls are coordinated together for the design. Quality control tools are under development at this early stage of the project. Also, due to tight schedule, a test bench is essential for mimicking online environment and perform parallel test work to save overall construction time.

The basic design principles for HEPS Control Systems are listed below:

- Top-down architecture design: understanding the big picture
- Distributed control systems
- Integrated development tools (GUI code editors, repository management…) for higher software quality
- Choosing advanced yet matured technologies
- Using industrial standards, choosing commercially available products first for lowering costs
- Considering expandability at design, balancing the price and performance while satisfying physics requirements
- Collaborating with other accelerator projects
- Possible commercialization for R&D results

DATABASES

Accelerator generated data, from design to operation, should be captured and saved systematically as much as possible. Furthermore, applications to utilize the saved data should be developed as well. However, due to the large data-base scale and tremendous amount of work, it is necessary to divide the entire database into many nearly independent sub-database modules and connect them via API (Application Programming Interface) or services. Optionally, one can join some sub-databases together with minor modifications in the schemas. This way the database module development work can be shared independently by many institutes and also avoid overwhelming complexity for a single monolithic database.

Based on IRMIS [1] which is a good overall database system for accelerators, as listed in Table 2, there are 17 sub-database modules identified. At this stage of the project, i.e. the design and early implementation phase, databases such as Parameter List, Naming Convention, and Magnet have been developed to suit the project's current needs. In addition, colleagues from another IHEP facility, the China Spallation Neutron Source (CSNS) is collaborating with the HEPS team to develop a Log-book and Issue Tracking database and application for CSNS's early operation need. Besides the four database modules currently under development, a few others like Accelerator Model/Lattice, Physics Data and Machine State, and Work

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Flow Control/Traveler have been developed by colleagues for other projects which can be migrated here easily. The rest of the database modules listed in Table 2 will be developed at later times while they are needed. HEPS select MySQL as the database primary tool. Details for the three currently under developing databases are described below.

Table 2: Planned database work

Parameter List	Logbook and Issue Tracking	Cable
Naming Convention	Maintenance/Operation	Security
Magnet	Inventory	Alarm
Accelerator Model/Lattice	Survey and Alignment	Machine Protection/Interlock
Equipment and Configuration	Work Flow Control/Traveler	MPS Postmortem
Physics Data and Machine State	Document DB	

ACCELERATOR CONTROL

HEPS accelerator controls is EPICS-based, distributed systems. The system design principles are applying industrial standards, global timing system for both accelerator and experiments, and modularized subsystems for easy upgrade and maintenance. The overall accelerator control system architecture is shown in Fig. 1 with typical Device, Middle, and Presentation layers. The Device layer provides the control interface, such as μTCA, PXI or PLC, to devices. The Middle layer performs data assembly and persistence, and online analysis computation. Details for some critical control system components are described below.

Presently HEPS selects the latest EPICS version 3 as the control system platform. The EPICS-based device control will choose mostly industrial standard with EPICS driver support. Besides fast communication networks for global timing system, fast machine protection system, and fast orbit (FOFB) feedback system, the standard communication is through EPICS Channel Access (CA) protocol.

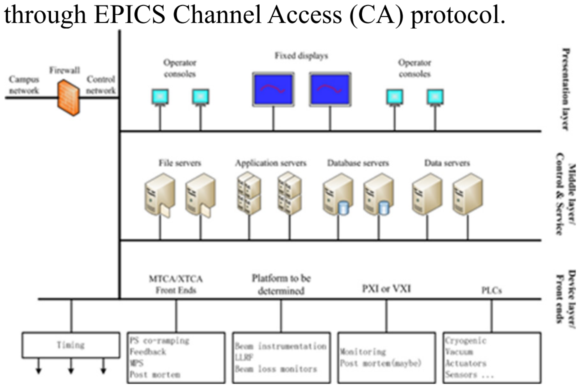

Figure 1: HEPS Accelerator Control System architecture.

Magnet Power Supply Control

HEPS accelerator contains about 2500 magnets which are powered by over 2800 power supplies. For power supplies other than those for the Storage Ring FOFB correctors are through Ethernet interface for data transmission. The generic magnet power supply control system is shown in Fig. 2, which has an Altera Cyclone 5 Field Programmable Gate Array (FPGA) chip and W5500 Ethernet interface.

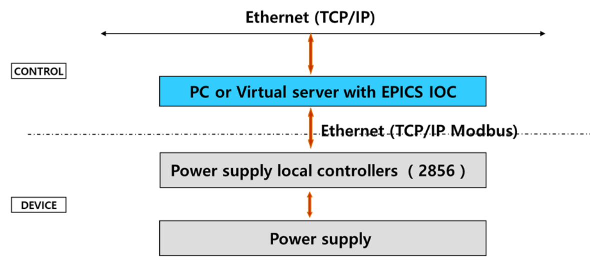

Figure 2: Generic magnet power supply control system.

Because the Storage Ring FOFB correctors are serves for not only for FOFB but also slow correction, the power supply controller for these correctors have additional optical fiber interface as shown in Fig. 3. The "slow" part of the FOFB corrector control is through the basic architecture shown in the left diagram of Fig. 3, and the "fast" part of the corrector is controlled by the right side of the interface in Fig.3.

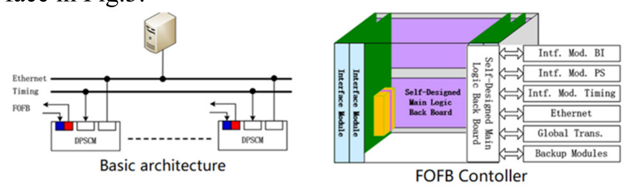

Figure 3: FOFB corrector power supply scheme.

Fast Orbit Feedback System

For the extremely low emittance requirement, an FOFB system is required to correct orbit oscillations caused by ground vibration, magnet power supply ripple and any other possible causes. The orbit stability is to first suppress any known source causing beam oscillation. The FOFB is the last line of defense for beam bunch oscillation, therefore, it should avoid to overdesign the system.

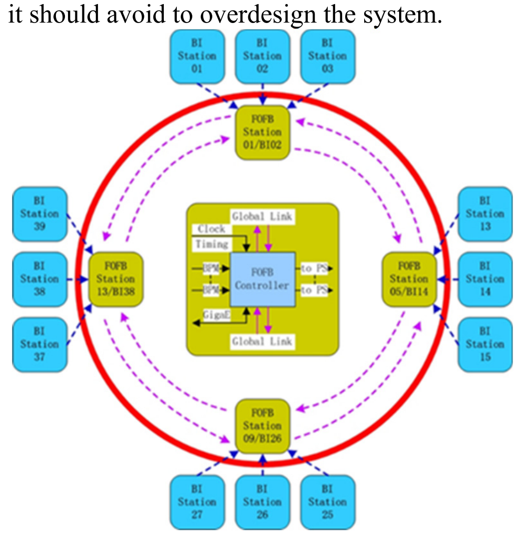

Figure 4: Fast Orbit Feedback System architecture.

The goal of FOFB is to reach 300 Hz – 1 kHz of bandwidth with 576 Beam Position Monitors (BPM) and 192 correctors in each transverse plane. As shown in Fig. 4, The BPMs and correctors are arranged to 16 nodes with each node as star topology, while the 16 nodes are connected in ring topology. The communication among the 16 nodes is bi-directional and through 10 Gigabit Global Links. For

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each node, the FOFB computation is done via FPGA. Studies for better power supply response, computation algorithms are underway.

Global Timing System

HEPS Timing system is responsible for not only the accelerator but also all the beamlines and experiment stations. The overall timing system diagram which includes a distributed event trigger system and a RF reference system is shown in Fig. 5. The red lines in Fig. 5 represents the RF reference lines and the blue lines are event trigger distributions. The main requirements for the HEPS Global Timing System are RF phase stability less than ±0.1 degree peak-to-peak in the Storage Ring, the bottom width of injection kicker pulse less than 12ns, and the phases of reference line clock and event timing system recoverable after power drop. The master clock is running at 499.8 MHz which can be easily up-scaled to 2998.8 MHz for the Linac or down-scaled to 166 MHz for the Storage Ring.

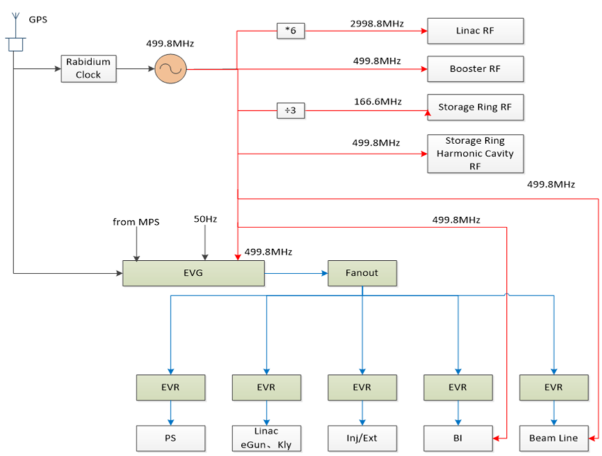

Figure 5: Global Timing System and RF Reference.

The event trigger system is based on the MRF Timing System from the Micro-Research Finland Oy. It is planned to prototype a MicroTCA based Event Receiver (EVR) board which might be implemented in HEPS if schedule allowed.

HEPS needs to deal with very small dynamic aperture for minimizing perturbations to user experiments, and re-charging and re-energizing bunches in the Storage Ring, a complicated swap-out injection as shown in Fig. 6 is designed for top-up operation.

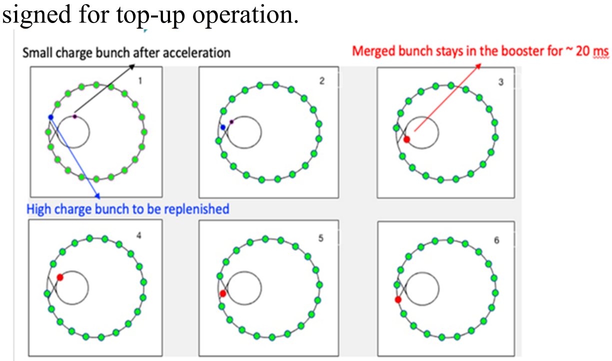

Figure 6: Swap-out injection scheme.

BEAMLINE CONTROL

As shown in Fig. 7, HEPS beamline control system architecture is similar to the accelerator controls'. For better manpower resources sharing, the HEPS optical beamline control is also handled by many accelerator controls experts. Also, it is not practical to have each beamline possessing its own database experts and handle all computing needs, for example. Many tools and platforms built for the accelerator can also be shared by the beamlines. Standards like naming conventions and EPICS supported devices are also shared.

The beamline data may be much more structured than the accelerator data. Therefore, EPICS 7 which support complicated data structure is considered as the data protocol for packaging the beamline and experiment data. Still, the data structure has to be compatible for future mobile applications.

The data acquisition (DAQ) is considered along with the beamline controls. For the nature of fast DAQ and large amount experiment data storage requirements, online data reduction and analysis is essential for the beamlines. Standard data format should be chosen for compatibility with various data analysis tools and shareable among institutes.

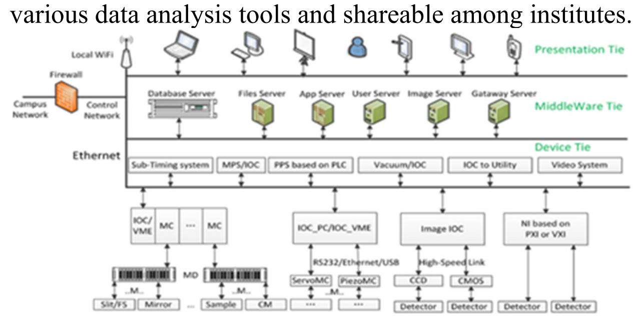

Figure 7: HEPS Beamline Control System architecture.

HIGH-LEVEL SOFTWARE

High-level applications are the tools for operating the HEPS properly. As shown in Fig. 8, the overall high-level application architecture and application flow can be divided into three layers: data, software API or services, and application GUI. For better software architecture, reusability, and easy-to-program purposes, same functions appear in multiple applications should be converted to either regular callable APIs or service APIs in the middle layer. Furthermore, due to the nature of the functions, it is better to separate them in three groups so they don't mixed together and lose the flexibility: control system API, physics and general-purpose API, and ML API. The three API groups are also released independently as separate software packages. Details for these APIs will be de-scribed below.

Control System API

HEPS accelerator as well as optical beamline is based on EPICS control systems. APIs such as CA calls are packaged along with connection exceptions and operation loggings, so application developers do not have to go through tedious details. If there is any need for swapping with another control system, one can simply replace the EPICS

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wrapper with a different one. HEPS is considering CS-Studio API as the control system API platform.

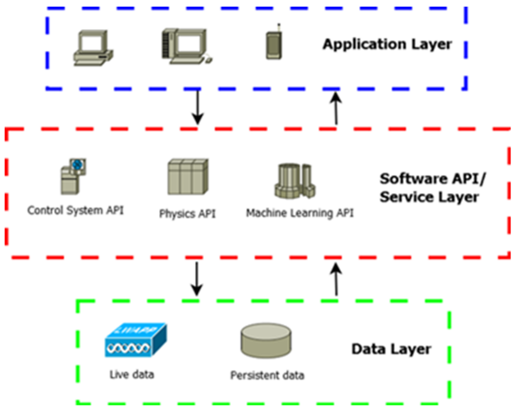

Figure 8: HEPS Control System architecture.

Physics and General-Purpose API

Physics related applications are built with physics API which provides physics specific functions such as online model computations, and general-purpose API supports certain operations like parameter scan or correlation plot. HEPS is considering a Java-based Open XAL [2] toolkit includes not only definitive accelerator data structure but also quite comprehensive functions for most accelerators. On the other hand, beamlines and experiment stations can have similar platforms for their physics needs.

Machine Learning API

Naturally different from the two categories of API mentioned above, ML API is the third API set for high-level applications. A Python-based ML API platform has been tailored for accelerators to access popular ML APIs such as Scikit-Learn and TensorFlow, and accelerator control and experiment data easily. For in-stance, besides the API for calling ML algorithms, APIs for pre-processing raw data from various accelerator data sources, and the computation results showing in visual form for easy read should also be provided. All these can be done with simple APIs to greatly cut development efforts. With such a platform, physicists can use Python, a popular scripting language, to quickly develop ML-based data analysis applications. Also, one can switch among ML algorithms for quick tests. The ML API will also be responsible for converting data format to suit many popular Big Data platforms for further data analysis.

Although HEPS will not have any operation data for ML in a few years, IHEP, fortunately, has another two running facilities, BEPC-II and CSNS, which can pro-vide data for testing ML ideas. So far, there have been two examples done with the ML effort. The first ML example is to align misplaced timestamps for pairs of Linac BPM (beam position monitors) and DC (dipole corrector) signals, and The second ML example is to apply Deep Learning Algorithm to HEPS lattice design for optimizing two competing parameters, the beam dynamic aperture (DA) and its brightness (BN). Both examples have promising results and further development will carry on.

CONCLUSION

The HEPS control systems have been initially designed and a few tasks have been started. Modern technologies will be applied to the actual implementations as further detailed design work done. For the software shareable between accelerators and optical beamlines as well as experiment stations, collaborations are formed. Starting from project supports like databases and project management tools, the controls team is also design and development work in many areas. All the databases are saved in GitHub repository for easy collaboration access [3]. This overall modularized architecture design gives us the most flexibility and efficiency for development yet ensure high-quality and reliable products. Also, researches in new fields such as Big Data analysis have been started for such a future synchrotron light source.

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[3] `https://github.com/AcceleratorDatabase/`