A PHYSICS BASED CONTROL SYSTEM FOR THE DUKE STORAGE RING *

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Abstract

At the Duke FEL Lab, we have developed a new storage ring control system in terms of the physics quantities of the accelerator. Instead of controlling power supply currents in Amperes, this system controls the effective focusing of magnets. By directly controlling the physics quantities, this control system allows tighter integration of the physics model based high level controls with the EPICS based low-level controls. EPICS events have been extensively used to provide time synchronization during the energy and lattice ramping. This new control system also facilitates the implementation of multiple functions on shared control channels. As a result, the physics based control system simplifies many complex control tasks, improves the beam stability during ramping, and facilitates machine studies. With better understanding of the accelerator, it is possible to fine tune this control system to present users with a virtual accelerator whose operation is independent of the ring energy.

1 INTRODUCTION

The development of modern accelerator control systems has displayed several emerging trends. First, instead of reinventing the wheel, a modern accelerator control system is typically developed based upon a mature and laboratory/industrial standard software infrastructure. The commonly used software infrastructure is Experimental Physics and Industrial Control System (EPICS)[1]. EPICS provides a set of software tools and applications which can be customized to build distributed real-time control systems. Second, the high level controls are developed in a versatile computation environment. The high level physics controls require a flexible programming environment with built-in mathematics and graphics capabilities to allow rapid prototyping, testing, and system integration. An increasing number of accelerator facilities have adopted MATLAB[2] as their preferred software for developing high level controls. Using an interface with the EPICS channel access, MATLAB works seamlessly with the EPICS based control system. Third, the accelerator control system is increasingly integrated with the physics simulation model. The physics model for accelerators has become more accurate in predicting the beam motion thanks to significant advances in accelerator physics in the last decade. For charged particle optics studies, a number of simulation codes have been developed and some of them have been designed with the aim of integrating with the accelerator control system. For example, the PASCAL version of TRACY [3] was developed as an interactive toolkit for storage ring commissioning and tuning. More recently, Accelerator Toolbox (AT) [4] has been developed as a MATLAB toolkit to allow even closer integration between the physics model and control system.

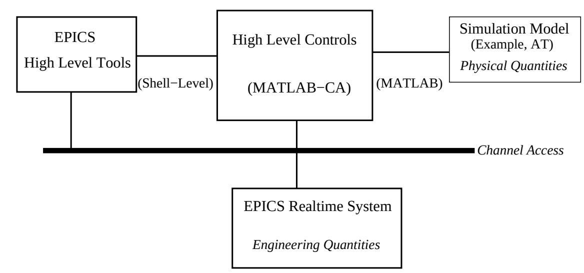

Figure 1: A layout of a typical integrated accelerator control system.

These trends lead to a very flexible but yet very powerful accelerator control system as illustrated in Fig. 1. While MATLAB served as a magic glue for this integrated system, there is an apparent mismatch between the physics model and the the real-time control system. The simulation model works in the physics phase space, for example, using effective focusing strengths for magnets. The real-time control system is typically developed in the engineering space, for example, controlling magnet power supplies in Amperes. The mapping between the focusing strength and the power supply current is typically handled by an add-on high-level program, resulting in a reduced flexibility and efficiency.

Addressing this deficiency, we have recently developed and commissioned a new control system for Duke storage ring based upon the physics quantities. This new approach has simplified many complex operation tasks and resulted in a virtual accelerator directly controlled in the physics space.

2 PHYSICS QUANTITY BASED ACCELERATOR CONTROLS

The physics quantity based control requires accurate measurement data to perform mapping between physics and engineering quantities. For magnet controls, measured magnetic fields data are used to map effective focusing strengths to power supply settings.

The physics quantity based control leads new ways to implement key control functionalities. First, it allows the development of new synchronization methods for energy and lattice ramping. For example, the energy ramping in the storage ring can be achieved by stepping up a single knob, the energy knob, while all necessary power supplies will be updated accordingly in order to maintain the effective focusing for magnets. Second, the physics quan-

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tity based control facilitates the implementation of feed-forward and feedback controls. For example, a corrector magnet control can be split into two soft control channels, one used for closed-orbit correction and the other used in the orbit feedback system. In the following, we will address these issues in detail using the new Duke storage ring control system as an example.

2.1 K-Value to Current Mapping

The most important physics quantities for storage ring operation are the ring energy and effective focusing of dipoles, quadrupoles, and sextupoles. These quantities are also used in the simulation models. In the Duke storage ring control system, the following quantities are controlled directly:

- Ring energy: E [MeV];
- Dipoles, trim controls: K_0, or θ [mrad];
- Quadrupoles, main and trim controls: K_1 [m^{-2}];
- Sextupoles, main and trim controls : K_2 [m^{-3}];
- Orbit correctors: K_0, or θ [mrad].

As an example, Fig. 2 illustrates the control of a quadrupole in our system. Changes in either the ring energy or the K_1-value of a quadrupole will result in the execution of this portion of the control. Magnetic measurement data are analyzed to provide a lookup table to map the product of the energy and K_1 to a proper current setting, which is subsequently set to the power supply. This approach also facilitates the control of more complex magnetic elements. For example, combined function quad-sextupoles are employed in the Duke ring by asymmetrically driving inner and outer quadrupole coils with two different currents [5]. The sextupole field feed-down effects are properly taken into account by mapping the energy, K_1, K_2 to two power supply currents.

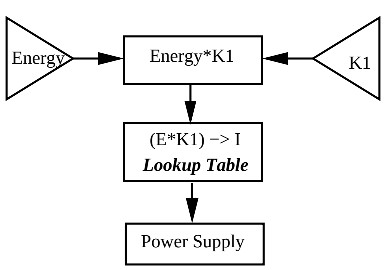

Figure 2: Mapping the energy and K_1 to the current.

Like quadrupoles, the current settings for dipoles, correctors, and sextupoles are properly updated whenever the ring energy and/or relevant K-values are changed. By moving the K-value-to-current mapping down to the lowest level of control in the Input Output Controller (IOC), the mapping efficiency is improved. It also eliminates the potential need to implement multiple copies of the same mapping algorithm on different platforms for high level controls. Most importantly, it allows the lattice ramping to follow the K-value curve instead of the raw current curve, minimizing the tune changes during ramping.

2.2 Energy and Lattice Ramping

Due to the lack of a full energy injector at Duke, most user operations require energy ramping. The energy ramping is performed relatively frequently due to a somewhat short beam lifetime (1–3 hours) in main operation modes. The beam lifetime is limited due to a high peak current in 1-bunch free electron laser (FEL) operation and in 2-bunch gamma-ray operation. In addition to energy ramping, lattice ramping is also commonly performed for FEL wiggler adjustment and lattice tuning. The physics quantity based control leads to a more reliable software based ramping scheme.

Traditionally, the ramping synchronization in a storage ring is provided by either a hardware system or the high-level control software. While providing a high level of synchronization, the hardware based approach is complex, expensive, and less flexible. The software based synchronization is flexible and has been found to be adequate for many storage rings. The downside of this approach is that its timing is less precise and consistent due to performance variations of the local area network, control workstation, and high level software.

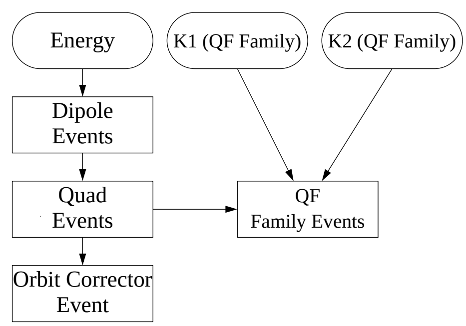

Figure 3: Event-chain in the Duke ring control system.

In contrast, the physics quantity based control facilitates the development of a new type of software based synchronization scheme using EPICS events. For example, an energy event generated by a master IOC is propagated to all related IOCs to signal an energy change. Within an IOC, this event triggers the update of all necessary database records, resulting in ramping relevant hardware. Carried out in the real-time system, the precision of this softwared based synchronization is significantly improved, especially for the case when all IOCs are connected to a way to minimize the unrelated network traffic.

Fig. 3 shows the actual implementation of the EPICS event-chain for the Duke ring. The event based synchronization is chosen to provide flexibility for updating a large number of channels while minimizing the network traffic. The energy event causes the generation of next-level events to update dipole trims, the main dipole, quadrupoles, etc. This multi-layer event-chain system is very flexible for synchronizing a large number of distributed controls during ramping. For example, using the arc QF event, both the energy ramping and lattice ramping (changes in K_1) can be performed simultaneously.

2.3 Multiple Functions of Shared Controls

In many circumstances, a piece of hardware has to be shared by several high-level systems. For example, a quadrupole or a dipole corrector can be used both in the supervisory control and in the feedback or feedforward control. Fig. 4 demonstrates the shared control of a dipole trim in the Duke ring for the following purposes: (1) compensating for the difference in integrated field strength (feedforward); (2) correcting the closed orbit (supervisory control); (3) performing orbit feedback. Because these three types of control functions are performed in the physics space, a simple sum-junction is used to add together the total deflection angle θ_{tot} which is then mapped to the trim current. When operated at 1.0 GeV and above, dipole magnets become highly saturated, resulting in a nonlinear map between the deflection angle and corrector current. The field saturation in the quad-sextupoles is even more complex in the Duke ring. Consequently, without the physics quantity based control, this type of shared controls of a nonlinear device is very difficult to implement in the high-level.

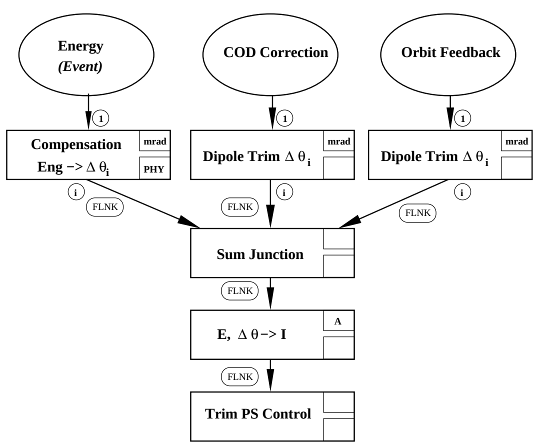

Figure 4: Multiple controls of a shared dipole trim.

3 PERFORMANCE

The present Duke storage ring control system consists of about four thousand EPICS channels. Twelve hundred (1200) of them, concentrated in two IOCs, are associated with the energy and lattice ramping. When optimized, all these channels can be updated at a 5 Hz rate, fully synchronized by the EPICS events. The maximal ramp rate is limited by the IOC CPU load, reaching a peak value of 70% during ramping compared with non-ramping load of about 10%. The ramping IOCs are relatively old computers (MVME167 single board computers) with a 33 MHz CPU. We expect that a higher ramping rate can be achieved using faster IOCs, such as Motorola Power PC boards with 200 MHz to 1 GHz CPUs.

With the physics quantities base control, the stability of beam orbit and beam size has been significantly improved during ramping. The measured beam orbit is shown in Fig. 5 for the energy ramping from 350 MeV to 1 GeV. Horizontally, the maximum and RMS orbit changes are 1.11 mm and 0.24 mm. Vertically, the maximum and RMS orbit changes are 0.54 mm and 0.13 mm.

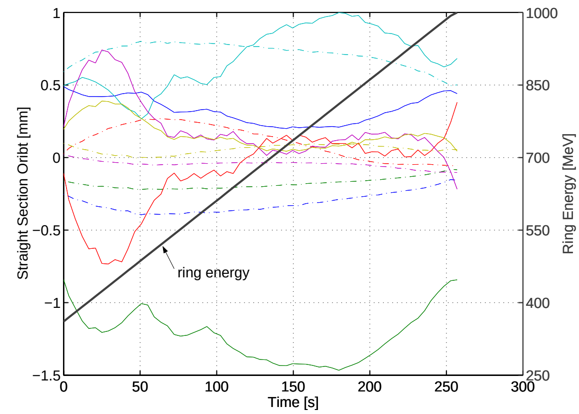

Figure 5: Beam orbit in the wiggler straight section during energy ramping. Solid and dot-dashed lines are horizontal and vertical orbits, respectively.

4 CONCLUSION

We would like to summarize the main benefits of a physics based control system as follows:

- providing closer integration between the simulation model and accelerator control system;
- simplifying and improving the energy and lattice ramping;
- assisting the development of feedback and feedforward systems via shared functional controls;
- allowing independent development of high level controls regardless of the low level details;
- simplifying extrapolating new lattice with different energies using an existing lattice.

These advanced features are great assets in improving the storage ring operation efficiency and reliability and extremely useful in machine studies. With better understanding of the magnetic field hysteresis and saturation, the physics based control can be fine tuned to present the user with an invariant virtual accelerator whose operation is transparent, portable, and independent of the beam energy.

Finally, we would like to thank V. Litvinenko for his encouragement and support and J. Li for his assistance in measuring the control system performance.

5 REFERENCES

[1] See the APS website, http://www.aps.anl.gov/epics

[2] See the MathWorks website, http://www.mathworks.com

[3] H. Nishimura and J. Bengtsson, LBNL, a tracking code in PASCAL, private communication.

[4] A. Terebilo, Proc. of 2001 Particle Accelerator Conference, Chicago, p. 3203 (2001).

[5] V. N. Litvinenko, Y. Wu, B. Burnham, J. M. J. Madey, S. H. Park, Proc. of 1995 Particle Accelerator Conference, Dallas, TX, p.796 (1995).