High precision RF control for next generation accelerators

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1. Introduction

One of the essential elements of any successful accelerator facility is to have a comprehensive suite of instrumentation to measure the beam properties, distribute that measured information throughout the facility, and apply that to control and maintain stable operation. An R&D program in accelerator controls and instrumentation (including the low-level RF controls) is urgently needed to develop innovative approaches to instrumenting and controlling these forefront machines. Such a program will yield great benefits to broad accelerator communities due to the common control and instrumentation challenges in particle accelerators, regardless of whether the particles are leptons or hadrons, or whether the accelerator is circular or linear.

Charged particle beams can be manipulated and sensed through their interactions with surrounding environments or devices using radio-frequency (RF) electromagnetic fields; beam signatures are measured, recorded, analyzed and controlled, and signals are transmitted within the facility using modern telecommunication techniques. Modern controllers are almost always based on embedded digital signal processing. There are quantitative differences between different facilities, including the required precision and stability, the carrier frequency and bandwidth of the measurements needed, and the speed with which the information must be applied throughout the facility.

The development of accelerator controls and instrumentation systems has traditionally occurred within the context of a specific project where the performance and requirements of the systems are derived from the project requirements. This leads to the developments of control and instrumentation systems that tend to be pursued after a specific project is approved and during the actual construction and commissioning of the project. Due to the pressing needs and risk management in that phase of the project, the resulting accelerator control and instrumentation systems tend to be those that have already been demonstrated, thus limiting the opportunity to take risks in search of rewards and to adopt state-of-the-art technologies. It is important and beneficial to get ahead of that limitation by performing R&D in specific areas that will provide true advances in accelerator controls and instrumentation for future accelerator projects.

2. Challenges and required technology development

Analog systems need to provide low noise, low crosstalk samples of the signal to be controlled. Analog to digital converters need to maintain the low noise levels. Digital signal processing must have low latency to provide wide feedback bandwidth. Engineering to meet all these requirements simultaneously is more challenging than meeting each one individually.

Current RF control systems use heterodrodyne technology together with FPGA based digital feedback, providing 10^{-4} RF stability to the RF cavity field, or femto-second synchronization between end stations. Crosstalk between signals through wires, cables and EMC/EMI can limit performance. Modular system design is required, minimizing copper interconnect in order to physically separate sensitive signals from noisy environments. Optical fiber can interconnect modules to provide timing and data communication. Good isolation is still needed for the local oscillator distribution line and/or the power cables. We may learn from the LIGO experiment, that used high precision interferometers and cross correlation among signals to mitigate and characterise the 1/f noise of its active components.

Analog to digital converter (ADC) noise is another major noise source for the RF control system. We rely on communication and other industries that keep improving component performance; to have a sustainable effort it is important to evaluate, test and adopt state of the art components. Traditional low noise ADCs have been widely used in many projects. The new generation of RFSoC chips can simplify the system by eliminating the frequency conversion in the analog front end, but the analog performance (including thermal stability and 1/f noise) of the available RFSoC needs to be evaluated for accelerator applications.

FPGA based control systems provide flexible implementation of control algorithms. Most of the current implementations are programmed at a low level with direct RTL. Developing a set of portable and flexible gateware libraries is the key for flexibility and modularity at this stage. For any feedback system, lower latency means wider control bandwidth, so each module needs to be optimized to meet the needs of accelerator systems.

Driving high-Q Superconducting cavities at high gradient is always challenging, and needs more understanding of the interaction among Lorentz detuning forces, the cryogenic system, pressures from Helium flow/bubbles, local mechanical resonances and microphonics etc. Recent testing at JLab's LERF demonstrated some new techniques to support pulse mode on a 16 Hz bandwidth cavity, that could expand the available envelope of stability, loaded Q, and pulse width. Further testing is needed to study the system, including performance and noise interaction.

Compact RF control modules can give more possibilities to improve system performance. The typical form factor for RF control hardware is racks and chassis, either using a network attached device or different industry standards (e.g., TCA series, VME/VXI series, PCIe …). More compact form factors could allow reducing the physical distance between electronics and the signal to be controlled. RF controls cooperate with the timing and synchronization system, using multiple modules separated by function and performance. Interconnection using optical fiber appears to work well and should be developed further. Customized optical transceiver modules may also be helpful.

3. Current status and a path toward

BACI under ATAP of Berkeley Lab is a leading research center for high precision RF control systems. During the past 20 years, FPGA based RF control systems have been widely employed for accelerator low level RF and timing synchronization systems.

We plan to continue conducting research and development on the LLRF design and prototyping by taking advantage of the latest and available chips from industry and integrating them into projects within the DOE Science Office. Sustainable support and R&D efforts are required to continue the open source and modular approach development focusing on the analog performance and overall system optimization. Our ultimate goal is to provide any scientific project with a flexible and well-optimized system that meets the required performance of the project and has a clear path to support future project upgrade requirements.