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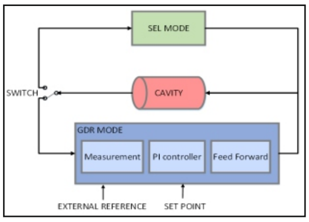
प्रोटॉन त्वरकों हेतु निम्न स्तरीय आरएफ नियंत्रण एवं सुरक्षा प्रणालियाँ

आलोक आगाशे[1], सुजो सी. आई.[2], संदीप भराडे[1], आर. टी. केशवानी[1], जी. डी. रंडाले[2], सैनी एस. एस.1, राधिका नासेरी1, सत्यम रावत[2], निबंध कुमार[1], प्रशांत कुमार[1], ज्योति पी.[1], एम. एम. सुतार[2] और परेश डी. मोतीवाला[1]

[1]प्रगत इलेक्ट्रॉनिकी अनुप्रयोग अनुभाग, भाभा परमाणु अनुसंधान केंद्र, ट्रांबे, मुंबई-400085, भारत
[2]एत्वरक नियंत्रण प्रभाग, भाभा परमाणु अनुसंधान केंद्र, ट्रांबे, मुंबई-400085, भारत



जीडीआर वास्तुकला का मूल ब्लॉक आरेख

सारांश

आधुनिक आरएफ त्वरकों में, निम्न-स्तरीय आरएफ नियंत्रण और सुरक्षा प्रणाली महत्वपूर्ण उप-प्रणालियों, नामतः एलएलआरएफ नियंत्रक, अनुनाद नियंत्रक, आरएफ सुरक्षा एवं समय नियंत्रक का एक निर्बाध एकीकरण है। इस प्रणाली के प्रदर्शन का किरणपुंज की गुणवत्ता, प्रचालन स्थिरता, मशीन की उपलब्धता और समग्र त्वरक प्रदर्शन पर सीधा प्रभाव पड़ता है। एलएलआरएफ नियंत्रक किरणपुंज भरण, माइक्रोफोनिक्स, लॉरेंट्ज़ बल डिट्यूनिंग और घटक संवहन जैसी विसंगति की उपस्थिति में सटीक आरएफ क्षेत्र आयाम और चरण स्थिरता बनाए रखता है। अनुनाद नियंत्रक यांत्रिक एवं तापीय प्रभावों से उत्पन्न होने वाले गुहिका अनुनाद में गतिशील भिन्नताओं को पाटने का कार्य करता है, जिससे प्रचालन के दौरान इष्टतम गुहिका ट्यूनिंग सुनिश्चित होती है। आरएफ सुरक्षा उप-प्रणाली असामान्य प्रचालन परिस्थितियों और दोष की घटनाओं के विरुद्ध गुहिकाओं, आरएफ युग्मकों, आरएफ विंडो और उच्च-शक्ति प्रवर्धकों सहित महत्वपूर्ण आरएफ घटकों की सुरक्षा करता है। इसके अलावा, एक उपयुक्त समय नियंत्रक विश्वसनीय मशीन प्रदर्शन हेतु सभी त्वरक उप-प्रणाली के तुल्यकालिक प्रचालन को सुनिश्चित करता है। यह लेख संक्षेप में इन उप-प्रणालियों का एक अवलोकन प्रस्तुत करता है जिसमें महत्व, कार्यप्रणाली और हार्डवेयर वास्तुकला को भी शामिल किया गया है।

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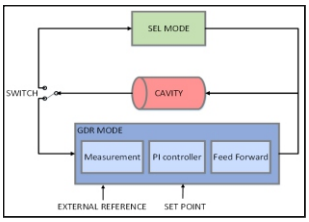
Low Level RF Control and Protection Systems for Proton Accelerators

Alok Agashe[1*], Sujo C. I.[2], Sandeep Bharade[1], R. T. Keshwani[1], G. D. Randale[2], Saini S. S.[1], Radhika Nasery[1], Satyam Rawat[2], Nibandh Kumar[1], Prashant Kumar[1], Jyothi P.[1], M. M. Sutar[2] and Paresh D. Motiwala[1]

[1]Advanced Electronics Application Section, MRG, Bhabha Atomic Research Centre, Trombay, Mumbai-400085, INDIA
[2]Accelerator Control Division, MRG, Bhabha Atomic Research Centre, Trombay-400085, INDIA



Basic block diagram of GDR architecture

ABSTRACT

In modern RF accelerators, the Low-Level RF Control and Protection System is a seamless integration of the critical sub-systems, namely, LLRF Controller, Resonance Controller, RF Protection, and Timing Controller., The performance of this system has a direct impact on beam quality, operational stability, machine availability, and overall accelerator performance. The LLRF Controller maintains precise RF field amplitude and phase stability in the presence of disturbances such as beam loading, microphonics, Lorentz force detuning, and component drifts. The Resonance Controller compensates for dynamic variations in cavity resonance arising from mechanical and thermal effects, thereby ensuring optimal cavity tuning during operation. The RF Protection subsystem safeguards critical RF components, including cavities, RF couplers, RF windows, and high-power amplifiers, against abnormal operating conditions and fault events. In addition, an appropriate Timing Controller ensures synchronized operation of all accelerator subsystems for reliable machine performance. This article briefly presents an overview of these sub-systems dwelling a little bit into their importance, functioning and hardware architecture.

KEYWORDS: *Generator Driven Resonance (GDR), RF Control, Proton Accelerators*

**Author for Correspondence: Paresh Motiwala*
E-mail: parmot@barc.gov.in

Introduction

Particle accelerators rely on precisely controlled electromagnetic fields to transfer energy to the charged particle beam, making stability and accuracy of Radio-Frequency (RF) systems the fundamental requirements for their operation. Low Level RF (LLRF) Controller serves as the core control layer responsible for regulating the amplitude and phase of RF field inside accelerating cavities. Even small deviations in these parameters can lead to beam energy spread, emittance growth, and overall degradation of accelerator performance, particularly in high-intensity accelerators. The LLRF system is designed to operate in either or both operating modes namely; Self Excited Loop (SEL) and Generator Driven Resonance (GDR). It is also operated in open-loop for cavity conditioning. Cavity detuning caused due to mechanical, thermal, and electromagnetic perturbations can significantly impact RF performance in Superconducting and Normal-conducting particle accelerators. The primary objective of Resonance Controller or the Resonance Control System – (RCS) is to maintain the cavity's resonant frequency at the desired operating frequency, while countering the detuning effects. The high power RF subsystems, responsible for transfer of RF energy from RF source to beam being accelerated, must be protected and in the event of an unacceptable scenario quick response needs to be generated. The RF Protection and Interlock (RFPI) System is suited for this. It is fast, scalable, expandable, multi-channel and reliable.

A simplified block diagram of Low Level RF Control and Protection System is shown in Fig.1

LLRF Control System

An RF cavity needs to be driven with different signals for testing and conditioning purpose. For successful operation of a particle accelerator, finding and correcting the resonance frequency of a cavity is essential. Also, modern accelerators operate under a wide range of conditions, including continuous wave (CW) and pulsed modes, each introducing distinct challenges in RF control. Effects such as beam loading, microphonics, thermal drift, Lorentz force detuning etc. continuously perturb the cavity fields, requiring fast and accurate compensation mechanisms. LLRF systems address these challenges through a combination of open-loop, feedback [1] and feedforward control techniques, enabling real-time correction of disturbances and ensuring stable operation.

A typical LLRF system has broadly two modes of operation

- SEL mode
- GDR mode

SEL Mode

The SEL is a control technique used in RF cavity systems to operate the cavity at its natural resonant frequency. In this mode, the system does not rely on any external reference signal; instead, it forms a closed feedback loop using the cavity’s own pickup signal. The loop starts oscillating from inherent noise present in the system, and the oscillation naturally builds up at the frequency where the loop satisfies the required conditions for sustained oscillation. As a result, the SEL inherently locks onto the cavity's instantaneous resonant frequency, ensuring that the cavity is always driven at its natural frequency, even in the presence of detuning effects. The operation of SEL is fundamentally governed by the Barkhausen criterion, which states that sustained oscillations occur when the total loop gain is equal to unity and the total phase shift around the loop is zero or an integer multiple of 2π. In this state, the cavity behaves like a part of an oscillator, and the loop continuously adjusts itself so that the oscillation frequency follows the cavity resonance. It is important to clearly distinguish the role of SEL from that of the resonance controller. The SEL does not force the cavity to operate at a predefined or desired frequency. Instead, it simply ensures

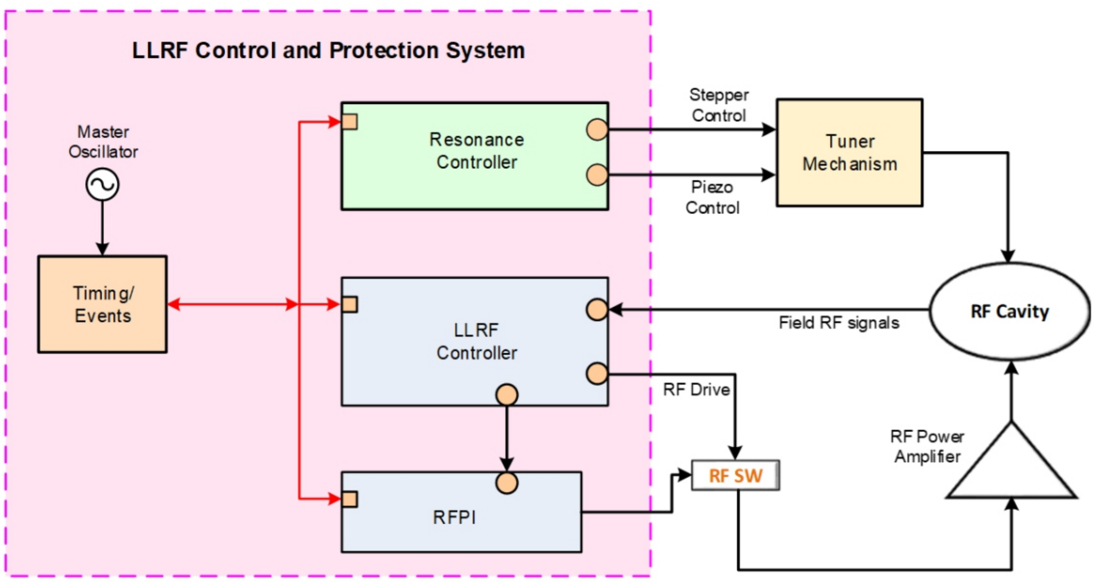


Fig.1: Simplified block diagram of a Low Level RF Control and Protection System.

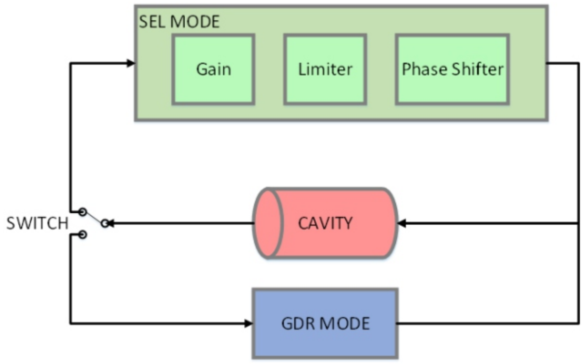


Fig.2: Basic block diagram of SEL architecture.

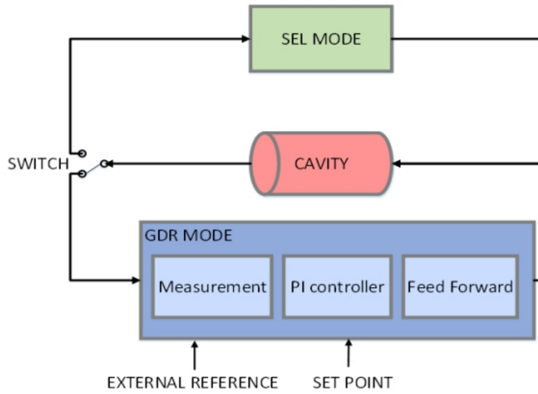


Fig.3: Basic block diagram of GDR architecture.

that the cavity is driven at whatever its current natural resonant frequency is. If this natural frequency deviates from the desired operating frequency, the SEL will still faithfully track this shifted resonance. The task of bringing the cavity resonance back to the desired frequency is performed by the resonance controller, which typically uses electro-mechanical tuners and piezoelectric actuators to physically adjust the cavity parameters. The SEL loop typically consists of three main components: a phase shifter, a gain block, and a limiter. The block diagram of SEL architecture is shown in Fig. 2. The phase shifter ensures that the overall loop phase satisfies the oscillation condition by compensating for delays introduced by system components such as cables and digital processing blocks. The gain block provides sufficient amplification so that the loop gain meets the requirement for oscillation startup and sustainment. The limiter introduces nonlinearity into the loop to stabilize the amplitude of oscillations; without it, the signal amplitude would continue to grow once the loop gain exceeds unity. Together, these components ensure that the loop achieves stable, self-sustained oscillations at the cavity's resonant frequency.

GDR Mode

The GDR mode is a method of operating an RF cavity in which the system is driven by an external RF source at a fixed reference frequency. Unlike the SEL mode, where the oscillation frequency is determined by the cavity itself, GDR mode enforces a predefined frequency, and the cavity is required to follow this reference. The primary purpose of GDR is to achieve accurate control over cavity field amplitude and phase with respect to a global reference, such as a master oscillator. This is particularly important in particle accelerators, where multiple cavities must operate synchronously to ensure proper beam acceleration. In GDR mode, the LLRF control system maintains the desired field by continuously adjusting the drive signal based on feedback from the cavity pickup. GDR mode is typically used after the cavity has been properly tuned, often with the help of SEL. Once the resonance controller aligns the cavity's natural frequency with the desired operating frequency, the system can safely switch to GDR mode. At this point, the detuning is minimal, and the cavity can efficiently accept power from the generator with low reflection. Operating directly in GDR without prior tuning is generally not preferred, as any initial mismatch between the cavity resonance and the drive frequency can lead to high reflected power. In terms of operation, GDR relies on a closed-loop feedback system within the LLRF framework. The cavity pickup signal is compared with the reference signal to generate amplitude and phase error signals. These errors are processed through controllers, typically PI-based, to adjust the drive signal such that the cavity field matches the desired set points. This enables tight regulation of field parameters, which is critical for maintaining beam quality and accelerator performance. The block diagram of GDR architecture is shown in Fig. 3.

Performance of an LLRF System

The performance of an LLRF system is qualified based on its ability to maintain precise control over the amplitude, phase, and frequency of the accelerating RF field under varying operating conditions. Since beam quality and accelerator stability are highly dependent on RF field stability, the LLRF system must demonstrate reliable and repeatable operation within stringent specifications. The qualification of an LLRF system may involve verifying its functionality in SEL and GDR operating modes and its behavior while switching [2] from one mode to another. The performance is quantified using several measurable parameters. The most important among these are amplitude and phase stability, typically specified in terms of RMS or peak deviation over a defined bandwidth. Other important matrices include loop bandwidth, latency, noise floor, dynamic range, cavity field settling time, frequency tracking capability, and suppression of disturbances such as power supply ripple or microphonics. In superconducting accelerators, cavity detuning compensation and field regulation during pulsed operation are also key performance indicators.

Achieving very stringent amplitude and phase stability in an LLRF system requires careful optimization of the complete RF control chain, including hardware design, signal processing architecture, feedback algorithms, synchronization systems, and environmental control. Modern particle accelerators and specifically superconducting RF accelerators often demand amplitude stability in the order of 0.01% and phase stability at 0.01 degrees, making the suppression of even small disturbances critically important. One of the primary methods for ensuring high stability of field is the implementation of a high-bandwidth closed-loop feedback system. Although, high bandwidth helps in correcting wide range of disturbances, it amplifies the inherent noise introduced by different components in the RF loop. Therefore, selection of adequate closed loop bandwidth is important to correct disturbances, suppress unwanted noise and maintain closed loop stability.

The quality of the reference clock and synchronization system plays a major role in phase stability. Ultra-low phase noise master oscillators and low-jitter clock distribution networks are essential to minimize phase fluctuations throughout the RF chain. Careful clock tree design further helps to reduce timing-induced errors. High-performance RF hardware is equally important. Low-noise mixers and RF amplifiers with excellent linearity and thermal stability are required to minimize gain variation and measurement noise. Furthermore, temperature-controlled electronics racks, stable and low ripple power supplies, proper grounding & shielding techniques reduce drift and electromagnetic interference.

With the advancements in digital electronics and with the availability of high-speed, high resolution ADC - DAC, LLRF implementation has increasingly transitioned toward System-on-Chip (SoC) based FPGA and DSP-based architectures, allowing high-speed signal processing, flexibility in control algorithms, and improved system integration.

Digitization Schemes

The process of digitization of the RF signal is the first important block in a signal processing chain of a digital LLRF system. Digitization of incoming signal essentially implies conversion of RF to digital quadrature IQ signals. Depending on the application a number of digitization schemes are used for the LLRF with each having its own pros and cons. Selection of the digitization scheme depends upon a number of requirements such as the control precision, control loop bandwidth, system configurability, remote control & data transfer requirements etc. and factors such as development cost, implementation efforts etc. Some of the popular schemes are discussed below.

Baseband Sampling

In this scheme the incoming RF or cavity probe signal is first demodulated using quadrature analog demodulator with the RF Reference. The resultant In-phase and Quadrature (IQ) components are baseband signals which after low pass filtering are digitized using two moderate speed ADCs. The digital and clocking requirements are very simple. This scheme however suffers from I/Q imbalance which needs to be compensated from time to time for good accuracy. Fig.4 shows the baseband sampling scheme.

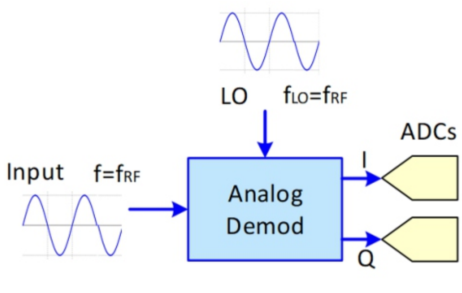


Fig.4: Baseband Sampling scheme.

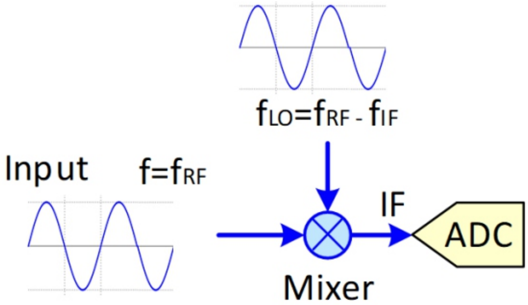


Fig.5: IF Sampling scheme.

IF Sampling

This sampling scheme is suited in applications where the accelerator reference frequency is above several hundreds of MHz and high precision control of RF field is required.

The RF frequency is down converted using a mixer to IF which is generally a few tens of MHz and this IF signal is digitized using IQ sampling or non-IQ sampling scheme. Digitized data is processed and up-converted to the accelerator RF frequency using IQ modulator. This scheme requires additional hardware in the form of down and up-converters but offers very high precision. The scheme is depicted in Fig.5.

The LLRF system designed and developed for HTS, RRCAT employs this sampling scheme whereby 650MHz RF is down-converted to an intermediate Frequency of 20MHz for processing and subsequently up-converted back to 650MHz for driving Superconducting RF cavities. The system has been commissioned at HTS, RRCAT and successfully evaluated with Spoke Test Cryostat (STC) at Fermilab, USA. The system tested at STC is depicted in Fig.6.

RF Sampling

In this scheme the RF input signal is directly digitized by high bandwidth ADC using under-sampling technique by carefully selecting the ADC sampling clock. This scheme can be used for improved measurement bandwidth and reduction in

Fig.6: Testing of LLRF system at STC, Fermilab.

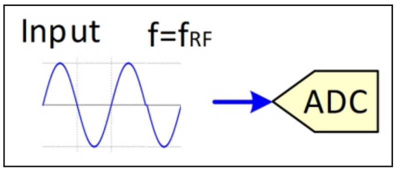


Fig.7: RF Sampling scheme.

frontend RF hardware requirements which in turn reduces errors due to RF-IF conversion. The scheme however requires extremely low jitter clock for the ADC to reduce the phase noise generated as a process of digitization. Thus the scheme may not achieve very tight precision as achieved with IF sampling. However, it can be very conveniently used where stability requirements are around 0.2% in amplitude and 0.2 degrees. in phase. The scheme is depicted in Fig.7.

LLRF systems based on this sampling scheme have been developed and commissioned to control the RF field in Buncher, RFQ, DTL1 and DTL2 within the LEHIPA lattice. Built on the Compact PCI platform, the systems receive 352MHz RF signals and under sample them to generate an intermediate lower frequency image by the way of sampling process. This image is then processed and digitally modulated back to 352MHz. The ADC sampling frequency is judiciously selected based on a variety of system parameters. Operational results demonstrate a field stability of 1% in amplitude and 1 degree in phase.

Every scheme requires a demodulation loop subsequent to the process of digitization and is carefully designed to reduce the effect of local oscillator and clock jitter [1]. Also, use of appropriate digital filters help in suppressing noise components. Feedforward algorithms are often added to compensate for predictable disturbances such as repetitive beam loading or pulsed cavity transients. RCS is additionally employed to compensate cavity detuning. Mechanical and environmental stability are also critical factors. Variations in cable length, vibration, and ambient temperature can introduce measurable phase shifts. Therefore, phase-stable cables, vibration isolation and thermal regulation are commonly adopted to reduce long-term drift.

Fig.8: Two LLRF controllers in a cPCI chassis for LEHIPA.

Another key aspect of performance of a LLRF system is reducing the transients while switching from SEL to GDR mode. A critical aspect of this transition is the difference in phase behavior between SEL and GDR modes. In SEL mode, while the amplitude of oscillation is stabilized by the limiter, the absolute phase is not defined with respect to any external reference; it is effectively arbitrary. In contrast, GDR operation requires a well-defined phase relationship with an external reference signal. At the instant of switching from SEL to GDR, there may be a large phase difference causing abrupt changes in the cavity field. This typically results in high transient in reflected and forward power, which is undesirable and can stress the RF system. Simulation using known algorithms demonstrates reduction in transients to as much as 60% [2].

Resonance Control System

The RCS is an integral part of modern LLRF systems for particle accelerators, where cavity detuning can significantly impact RF performance. The primary objective of RCS is to maintain the cavity's resonant frequency at the desired operating frequency, counteracting detuning effects. Unlike amplitude and phase control, which manage the properties of the RF field itself, resonance control addresses the dynamic physical behavior of the cavity structure, ensuring that RF power is efficiently transferred and the beam receives the intended energy gain. Effective resonance control is especially critical for achieving high RF cavity gradients and high duty cycles, as detuning at high gradients can lead to increased reflected power, reduced operational efficiency, and even cavity quenching in superconducting systems. By stabilizing the resonant frequency under varying operational conditions, the RCS enables sustained high-gradient operation while supporting reliable, continuous beam delivery.

Sources of Cavity Detuning

Several mechanisms can induce detuning in RF cavities:

(1) Thermal Drift: RF power dissipation heats the cavity structure, causing expansion and frequency drift. Even small temperature changes can shift the resonance frequency.

(2) Lorentz Force Detuning (LFD): High-intensity electro-magnetic fields in superconducting RF cavities generate Lorentz forces that physically deform the cavity walls, shifting the resonant frequency. The magnitude of LFD increases with the square of the accelerating field gradient and can lead to frequency shifts of several hundred Hz in high-gradient cavities.

(3) Microphonics: Vibrations from ambient sources—cryogenic pumps, building vibrations, or by acoustic noise—can induce rapid, small fluctuations in cavity frequency. Microphonics may be broadband or concentrated at specific mechanical resonance modes.

Principles of Resonance Control

The RCS maintains the cavity's resonant frequency by compensating for both fast and slow detuning effects.

(1) Tuner Control: Adjusting the physical geometry of the cavity using mechanical and piezoelectric tuners to correct frequency shifts.

(a) Slow Mechanical Tuners: These devices adjust the cavity geometry over seconds to minutes to correct long-term frequency drifts caused by thermal expansion, cooldown effects, or gradual structural deformation. Mechanical tuners typically use stepper motors or screw-based actuators to change the cavity length, ensuring the cavity resonates near the desired operating frequency.

(b) Fast Piezoelectric Tuners: For rapid disturbances such as microphonics or LFD during pulsed operation, piezoelectric actuators make fine adjustments in sub-millisecond timescales. These fast tuners dynamically compensate small frequency shifts, maintaining high RF efficiency and minimizing reflected power.

The designed and developed RCS has been commissioned at HTS, RRCAT and evaluated at Fermilab. A similar system shall be developed for MEHIPA also. The integrated RF control system commissioned at HTS RRCAT is shown in Fig.9.

(2) Temperature (Thermal) Control: Regulation of the cavity temperature is often done using Low Conductivity Water (LCW) based cooling systems in order to counteract detuning caused by thermal expansion or contraction of the cavity walls. Temperature-controlled LCW circulates through channels in the cavity structure to remove heat. The resonance controller monitors water temperature and flow, integrating this data into feedback and feed-forward loops to compensate for thermal drift. Precise regulation minimizes detuning due to thermal expansion. Apart from manual offline tuning of frequency, this principle for control of frequency is used in LEHIPA to avoid excessive reflected power.

Development of EPICS based Application Software

The control system architectures developed and evaluated leverage the Experimental Physics and Industrial Control System (EPICS) framework, tailored precisely to the specific hardware deployments. At the HTS Facility in RRCAT and STC facility in Fermilab, the LLRF and RCS systems were implemented using the legacy EPICS 3 framework, closely integrated with a customized SoC FPGA platform to handle deterministic and low-latency processing. In this configuration, the LLRF system exhibits high-throughput data handling capabilities, successfully acquiring and processing 40 concurrent waveforms, each with a record size of 1k samples, at a repetition rate of 20Hz. The LLRF system deployed and commissioned at the LEHIPA facility transitions to the modern EPICS 7 framework. This implementation takes full advantage of the high-performance pvAccess (PVA) protocol, which enables structured data types and optimized network streaming to significantly enhance data throughput, multi-variable communication, and overall system scalability. Future developments for MEHIPA will also be planned using EPICS 7 framework.

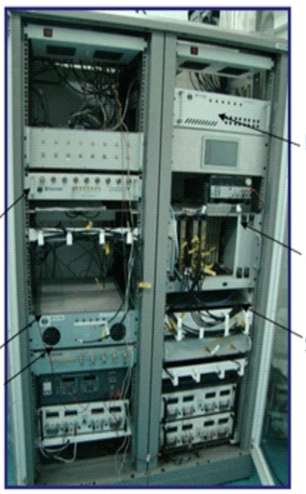


Fig.9: Integrated RF control system commissioned at HTS, RRCAT.

RF Protection and Interlock System

RFPI System is responsible for safe operation of expensive RF components through rapid fault detection and protective actions. The system accepts outputs from different sensors and monitors their signal levels against pre-defined settable limits. Based on the results, decision through a pre-configured logic matrix is taken to switch off the RF power to the RF cavity in 1-2μs. Modern RFPI system, employing state-of-the-art FPGAs, are extensive systems that detect and respond to fast events such as cavity arcs, field emissions and slow events such as water pressure, temperature etc. RFPI system also supports acquisition and storage of these signals. Field signals isolation, fast response, modularity, scalability, flexibility, redundancy, and reliability form key parameters of a good RFPI system.

A typical RFPI system [3] has the capability to process:

- Digital status signals from different subsystems including Machine Protection System (MPS), LLRF, vacuum system, cooling system, personal protection system and RF power source. Interlocks between these systems can be implemented by programming the required logic in the controller.
- Forward, reflected and pickup RF signals to/from the cavity.
- Signals from Photo Multiplier Tube (arc detector).
- Field Emission signals from probes.
- Analog signals (4-20 mA/0-5 V) from plant process parameters like temperature, vacuum and flow.

In the event of a fault detection, typically following output signals are generated from the system:

(a) RF Inhibit: This signal can be used to turn off the RF switch placed between the LLRF output and Power amplifier input.

(b) LLRF Inhibit: This signal can be used to notify the LLRF that the RF power to the cavity is switched off enabling the LLRF to initiate suitable action.

(c) PWR Inhibit: This signal can be used to switch Off driver stage of RF power source

(d) MPS Inhibit: This signal can be used to switch off the beam.

Fig.10: VME64x based RF Protection Interlock System.

A VME 64x based RFPI system has been installed at LEHIPA and HTS,RRCAT (Fig.10). The functionalities of the RFPI system have also been demonstrated at Fermilab under IIFC.

Initiatives are underway on developing advanced SoC-FPGA architectures leveraging cutting-edge technologies.

Timing Control System

In high-performance accelerator facilities, precise multi-subsystem timing and synchronization are of paramount importance to ensure robust beam control, deterministic measurement accuracy, and deterministic machine protection. At the core of this synchronization architecture is the Event Generator Board (EGB), which serves as the central orchestration node for real-time signal generation across the entire facility network. By driving a specialized distribution topology, the EGB-centric timing system establishes the rigid real-time framework necessary to coordinate heterogeneous subsystems under strict operational constraints. Specifically, it fulfills four critical functions: ultra-low-jitter clock synchronization, deterministic event generation and distribution, distributed nanosecond-scale time-stamping, and synchronous data transmission. This precise temporal framework directly drives the LLRF systems, enabling deterministic phase and amplitude field control, phase-locked loop stabilization, and tightly coupled RF-to-beam synchronization across the accelerating cavities.

Conclusions

In conclusion, the Low-Level RF Control and Protection System form the backbone of modern particle accelerators by ensuring precise regulation, synchronization, resonance control, and protection of RF systems. The LLRF system plays a central role in maintaining stable amplitude and phase of cavity fields under disturbances such as beam loading, microphonics, thermal drift, and LFD. The SEL and GDR modes provide operational flexibility during cavity tuning, conditioning, and stable beam acceleration. Modern FPGA and DSP based implementations enable high-speed digital signal processing, low latency control, and sophisticated feedback and feedforward algorithms required for stringent accelerator performance. The RCS further enhances operational stability by compensating cavity detuning through mechanical tuners, piezoelectric actuators, and thermal regulation techniques. Simultaneously, the RFPI System ensures safe operation of expensive RF components through rapid fault detection and protective actions. High-quality synchronization, low phase-noise clock distribution, careful grounding, shielding, and thermal management are equally critical in achieving the demanding stability requirements of modern accelerator. The timing and synchronization system based on the Event generation architecture is yet another critical subsystem in high performance accelerator facilities for real-time signal generation across the entire facility network.

The integration of all these subsystems and control through a common EPICS platform enables reliable, efficient, and high-performance accelerator operation while supporting future advancements in high-gradient and high-duty-cycle accelerator technologies.

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