LLRF Topical Workshop - Timing, Synchronization, Measurements and Calibration

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INFN Frascati National Laboratories

Book of Abstracts

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SRF Cavity Resonance Control by Machine Learning

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For advanced high-Q SRF linacs like LCLS-II, achieving precise control of cavity resonance is crucial to ensuring stable operations. Inadequate control can lead to a substantial increase in RF power demands, thereby escalating both operational and capital expenses due to the need for additional RF power sources. To tackle this challenge, we have developed an innovative cavity resonance controller that leverages a data-driven approach, incorporating a highly efficient surrogate model designed to manage the complex dynamics of cavities under the influence of microphonics and non-linear Lorentz forces. This model's efficacy has been thoroughly validated with real SRF cavities at SLAC. We are currently integrating this controller into the hardware, specifically the existing LLRF system of LCLS-II. This foundational work paves the way for expanding the model to broader motion control applications where extremely low-tolerance vibration control is essential. In this presentation, we will showcase the model and share the latest test results.

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Development of a Cavity Resonance Monitoring System for RAON SCL3

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Recently the accelerator operation for user beam service are planned in 2024. The SCL3 RF operating frequency are 81.25 MHz and 162.5 MHz. All cavities are controlled independently for the acceleration of the various A/q ions. Because all RAON SCL3 cavities are the superconducting cavities and the planned beam current is not so high, the control bandwidth which is defined by the loaded Q of the power coupler are not so wide and the suppression of the mocriphonics is one of the important topics for the stable operation. There are a slow cavity resonance frequency drift caused by the long-term LHe pressure drift, fast cavity resonance frequency fluctuation caused by short-term LHe pressure variation or mechanical vibration transferred through the ground. It is required to measure the shifted cavity resonance frequency and to suppress such microphonics which affects the stable RF operation. We developed a cavity resonance monitoring system for RAON SCL3. The shifted cavity resonance frequency is measured and stored by the LLRF. Also a python based tool to transfer and to analyze this data is developed. In this presentation the status and test result of cavity resonance monitoring system for RAON SCL3 will be described.

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Phase distribution system of HEPS

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HEPS is a new built 6GeV 4th-gen synchrotron radiation light source and under beam commissioning right now. The phase distribution system includes master oscillator system and phase reference line system. The DDS-based MO generates 499.8MHz and 166.6MHz, then distributes to Linac, booster RF and storage ring RF, beam station, as well as BI electronics clock around the facility. The 499.8MHz reference signals are transfered >400m by phase stablized optical fiber and CW lasers. The 499.8MHz jitter at end point is <36fs(10Hz-1MHz), the phase drift is <120fs(peak-to-peak). The whole reference frequency/phase generation and distribution system will be introduced.

Timing / 12

Relative Timing Issues and Mitigations in SwissFEL RF System

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The relative timing between different subsystems of SwissFEL is critical for a fast recovery of operation after a machine shutdown or a restart of any subsystem. For the LLRF system, deterministic phase measurements and stable macro-pulse timing w.r.t the trigger are critical for stable beam acceleration with pulsed RF stations. The phase and macro-pulse timing uncertainties are introduced either by the frequency dividers in the local oscillator and clock generator or the racing conditions between the trigger and clock. The relative timing between the RF and the Gun laser is another issue affecting the beam performance. Re-locking the Gun laser to the RF reference may cause the electron-bunch timing to jump to a different RF bucket, resulting in errors in the RF fields seen by the beam. Multiple measures have been developed to mitigate these issues, including reference tracking, trigger-clock race handling, Gun laser bucket detection and correction, and beam-based feedback. The issues, mitigations, and test results at SwissFEL will be reported in this contribution.

Measurements and Calibration / 13

Beam-based Stability Evaluation in the LINAC of European XFEL

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The linear accelerator of European XFEL exhibits an outstanding phase and amplitude stability using state-of-the-art low-Level RF (LLRF) controls in combination with an optical synchroniation system. The achieved RF field regulation precision is well within design criteria, chosen to reach an electron bunch arrival time stability on the 10fs rms level. However, the high complexitiy of the vector sum RF

field regulation and involved subsytems requires a careful monitoring and optimisation of regulation parameters to keep an optimal operation point. To reach ultra-low arrival time stability to the level better than 5fs rms, beam-based error signals are integrated into the LLRF control loops for a beam-based RF field control with >10kHz regulation bandwidth, acting mainly on the amplitude.
We present latest record timing stability values and discuss which external and in-loop disturbances deteriorate this performance, in order to identify further means of improvement.

Timing / 14

IETS: The new APS Injection-Extraction Timing and Synchronization System

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The new APS storage ring has about 40 cm smaller circumference than the ring it replaced. Consequently, the 6-GeV Booster synchrotron is no longer able to operate at the same rf frequency as the storage ring. Rather than rebuilding the Booster, a novel synchronization system (IETS) was developed that dynamically modifies the Booster rf frequency using a cosine-like frequency program, thus aiming the bunch in the Booster into any desired rf bucket in the storage ring. While the storage-ring frequency was raised by about 140 kHz, the PAR accumulator ring remains at its previous frequency, and the Booster starts synchronous to the PAR but then ramps following the pre-calculated frequeny program. The IETS system allows to change the Booster rf frequency at extraction, moving the beam off-momentum and thus allowing reduction of the momentum spread of the extracted beam. A considerable complication arises from the existing line synchronization of of the Booster magnet ramp, which causes Booster injection to occur at seemingly random times relative to the rf. The whole system includes triggering and rf-reference generation. The presentation will cover theory, development and commissioning of the system that is now in operation at the APS.

Synchronization / 15

Timing and Synchronization in the LLRF systems of the Fermilab PIP-II Linac

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The PIP-II Accelerator is an 800 MeV superconducting Linac in the injection chain of the Fermilab accelerator complex. The LLRF systems for the 125 cavities which include a few normal conducting cavities in the warm front-end section, use a variety of LLRF hardware components and sub-systems that are part of the timing and synchronization system. This includes a master oscillator and phase averaging reference line, a beam pattern generator to enable beam transfer between non-harmonic RF systems and beam loading compensation systems synchronized to a start of beam trigger. The timing signals are based on a 650 MHz clock with manchester encoded event information and data provided over optical fiber. The timing and synchronization systems and their performance parameters will be described here.

Poster Session II (Measurement and calibration) / 16

Calibration and Measurement techniques in the LLRF systems of the Fermilab PIP-II Linac

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The PIP-II Accelerator is an 800 MeV superconducting Linac in the injection chain of the Fermilab accelerator complex. The LLRF systems are a based on two different hardware platforms controlling a variety of cavity types and resonance control systems including temperature, pneumatic and piezzo tuners. The various calibrations required prior to beam operation include, signal power, gradient, amplifier characterization, cavity Q measurement and detune constants. Measurements such as piezzo capacitance, cavity piezo transfer function help in determining tuner health and in devising microphonics control strategies. These measurement and calibration methods of the PIP-II LLRF system are discussed here.

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Phase Noise Cancellation Impact on IQ Measurement Accuracy in LLRF Systems with Frequency Downconversion

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High performance synchrotron light sources like Soleil2 or Lunex5 require LLRF systems with high IQ accuracy: typically 0.01° RMS in phase and 1e-4 relative error in amplitude. This accuracy may be ultimately limited by the phase noise of the reference signal. In most LLRF systems, frequency downconversion to an IF signal of10 MHz is used before the digital IQ-demodulation. It can be shown experimentally or based on numerical simulation that the phase noise information is largely lost when the local signal is produced by mixing the reference RF signal with a spectrally ultrapure 10 MHz-signal. In that usual case, the RF and local signals have almost the same phase noise, which will cancel out in the downconversion process. Phase noise measurements for frequency offsets from carrier in the range of 3 Hz to 1 MHz, with a signal analyzer showed up to a factor 4 of reduction in the phase jitter for the IF signal as compared to the RF signal. Meanwhile, the IQ-demodulation followed by phase rotations is subjected to other noise or error sources, which lead to an overestimation of the phase error. The impact of those uncertainties on the operation of an accelerator will be discussed.

Synchronization / 18

Timing and synchronization experience and future plans at LNF

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New experiments and particle accelerator R&D programs at LNF are pushing the requests on beam stability and reliability towards the limit of the present technology. This drives the study on timing (event management and trigger distribution, down to ps scale) and synchronization (high frequency reference signal generation and distribution, down to fs scale). This presentation will give an overview on the challenges that we are facing and on the techniques and methods that we are adopting to meet the experiments demands. Future plans for new developments and installations are also reported.

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Toward ultra-low timing-jitters for beam-driven plasma accelerators

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Recent advances of plasma-based accelerators showed the feasibility to generate multi GV/m gradients for ultra-short electron bunches to be used for user-oriented applications. The shot-to-shot stability of the plasma-accelerated beam is of fundamental importance and represents the last gap to fill to fully compete with state-of-the-art radio-frequency accelerators. In this context we discuss the required stability in terms of timing-jitter that is foreseen for the development of a plasma accelerator facility.

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Recent results and future perspective in the search for Axion dark matter at LNF

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In recent years, we witnessed an increasing interest in the search of light Dark Matter (DM), addressing in particular axions. Axion existence would untie the long-standing DM problem. Its cosmological evolution and astrophysical constraints indicate a favorable mass range between 1 μeV < ma <

10 meV.
The axion observation technique is based upon its inverse Primakoff conversion into one photon, stimulated by a static magnetic field. The elements required to run a haloscope are a strong magnetic field, a microwave resonant cavity, an ultra-low noise receiver, a tuning mechanism to control the frequency of the cavity and dilution cryostat.
We report on the first operation of the new QUAX haloscope located at LNF. The experiment is conducted using a resonant cavity equipped with a tuning rod mechanism allowing to exclude the existence of dark matter axions with coupling g_a down to 0.861×10^{-13} GeV^{-1} in the mass window (36.5241 – 36.5510) μeV [1]. We also report on future development in the haunt for axions showcasing the features of FLASH, a future experiment that will be host at LNF [2].

[1] A. Rettaroli et al. PRD 2024
[2] D. Alesini et al. Physics of the Dark Universe 2023.

Poster Session I (Synchronization and Timing) / 21

The CEBAF Accelerator MO System Upgrade

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The CEBAF accelerator at Jefferson Lab relies on precise frequency references distributed throughout the site. CEBAF's infrastructure has aged from decades of successful operation, and grounding issues have made the system susceptible to electromagnetic interference. This weakness is particularly noticeable during lightning storms. To address this, the Master Oscillator (MO) system was upgraded by replacing some coaxial lines with modern RF over fiber (RFoF) systems. These fiber-optic links provide noise immunity and reliability, helping to preserve the integrity of its frequency references for the accelerator's LLRF systems. The poster will explain the specific modifications to the frequency distribution system, including the adoption of RF over fiber technology and the implementation process.

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LCLS II precision timing system

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In 2023, LINAC Coherent Light Source II achieved first light, spanning over 5 km from injector to the experiment hall. The goal of achieving 10fs relative jitter between the experiment laser and the x-ray led to the development of new systems. We will present the timing system design, architecture, key commission results and challenges along the way.
The challenge of reference distribution in the harsh environment of the klystron gallery was addressed by using a multi-drop coaxial cable for the superconducting LINAC and stabilized radio frequency over fiber systems for the experimental hall. An in-house laser locker synchronizes the experiment laser to the reference signal, and an S-band beam arrival monitor determines the electron beam's correlation against the reference. A star topology optical timing reference is distributed throughout the soft x-ray experiment hall for synchronization and detection.

Commission results show a laser-to-x-ray jitter of ~60 fs, a significant improvement over the ~200 fs jitter of LCLS. Optical phase synchronization is expected to further enhance jitter performance. As LCLS-II HE progresses, a plan is proposed to enhance the SLAC global timing system to meet the demands of four new hard x-ray instrument hutches.

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LINAC Locking Commissioning and Operation for the Phase Reference Line Synchronization between LCLS-I and LCLS-II at SLAC*

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Abstract
Since June 2024, LCLS-II has been providing users with an X-ray laser that features a higher repetition rate and more intensity compared to LCLS-I. This advancement offers users a broader range of X-ray free electron laser (FEL) options and significantly reduces data collection time. Existing photon instruments and beam diagnostic systems for LCLS-I must be able to detect the X-rays or electron beams from both LCLS-I and LCLS-II LINAC, which has different reference systems. Synchronization of the phase reference systems between the two machines is essential to achieve this goal. The LINAC Locking System at SLAC has replaced the LCLS-I stand-alone 476 MHz master oscillator with an ultra-low noise frequency synthesis system derived from the LCLS-II 1300 MHz phase reference signal. Phase initiation is achieved by aligning the timing of the LCLS-I LINAC event generator (EVG) with the LCLS-II timing pattern generator (TPG) using a common subharmonic frequency. The new low-noise 476 MHz phase reference is distributed to FACET and the LCLS-I LINAC via the existing Main Drive Line (MDL). This paper presents the system design architecture and operational experience of the LINAC Locking System.

Synchronization / 24

All-fiber optical-microwave phase detector for laser-RF synchronization

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To explore the implementation of laser-RF synchronization with femtosecond-level precision and stability, we proposed and demonstrated a Sagnac loop-based all-fiber optical-microwave phase detector (AFOM-PD). The repetition rate of the reference laser is 29.134 MHz, and its RIN has been suppressed by 40 dB at 1 Hz offset frequency. A 1.311010 GHz (2.855132 GHz) RF signal was synchronized with integrated RMS timing jitter from 1 Hz to 1 MHz of 18.6 fs (6.0 fs) and long-term timing drift of 15.8 fs (12.5 fs) over 6 h. The experiments were conducted in a standard laboratory environment with temperatures ranging from 23℃ to 28℃ and humidity varying between 28% and 33%,

demonstrating the feasibility and stability of this laser-RF synchronization system under non-ideal conditions.

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Femtosecond Synchronization System for Free Electron Laser

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Free electron laser has the characteristics of extremely high peak brightness, ultra-short pulse and high coherence, providing unprecedented research opportunity for physics, chemistry, biomedicine, materials science and energy science.
Large-scale free electron laser and its time-resolved pump-probe experiment requires femtosecond-level synchronization. Optical and RF synchronization technologies play important roles for large facilities.
The tasks of the femtosecond synchronization system: To produce a clock reference source with femtosecond level accuracy; 10 fs-level synchronize several hundred clients for Laser, LLRF, Diagnostic, and Timing system with different requirements (optical/RF reference, frequency, power, accuracy, etc.). Femtosecond synchronization system is the core system to ensure the free electron laser facility can work and run stable for a long time.
We built two systems for Dalian Coherent Light Source (DCLS) and Dalian Advanced Light Source (DALS). Both of them are optical system and work well.
Shenzhen Superconducting Soft-X-ray Free Electron Laser (S³FEL) is a high repetition rate soft-X-ray super-conducting free-electron laser facility that consists of a 2.5 GeV CW superconducting linear accelerator and three initial undulator lines, which aims at generating X-Rays between 40 eV and 1 keV at rates up to 1MHz. An optical and RF combined synchronization system is under designing.

Measurements and Calibration / 26

On-line Beam Synchronous Phase Measurement Using Deep Learning Models

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The traditional method for determining the synchronous phase (SP) of beam typically relies on "phase scan method". Despite its high precision and reliability, this method requires a significant amount of runtime. Processes such as phase drift caused by environmental disturbances or rapid recovery after cavity faults (such as Quench) necessitate repeated execution of the phase scan procedure. In modern large-scale accelerator facilities, which often contain dozens or even hundreds of radio-frequency (RF) cavities, the time-consuming nature of phase scanning severely reduces machine availability. This fact highlights the necessity of developing online beam information measurement algorithms. Recently, we introduced an AI-based beam information measure model that uses transient beam loading information as input while simultaneously predicting beam intensity and SP. This method employs Long Short-Term Memory (LSTM) to extract multi-dimensional RF time-series signal features and incorporates an attention mechanism to evaluate the weights of RF waveforms

at different times. The method can work in complex operating conditions such as open-loop, closed-loop, and with or without cavity detuning, and has higher precision and stronger generalization capabilities compared to other online calibration method of SP (such as those based on cavity differential equations or RF beam vector).

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Measurement of Cavity-Loaded Quality Factor in Superconducting Radio-Frequency Systems with Mismatched Source Impedance

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Precise measurements of the cavity-loaded quality factor (QL) is crucial for monitoring the performance of superconducting radio-frequency (SRF) cavities. The conventional "field decay method" cannot be used to measure QL accurately when the impedance is mismatched. This can lead to nonzero forward signals (Vf), which significantly affect the measurement accuracy. To address this limitation, we developed a modified "field decay method" based on the cavity differential equation, enabling precise calibration of QL even with impedance mismatch conditions. This method was validated on the SRF cavities of the Chinese ADS Front-End Demo Linac (CAFe) and further tested at the European Spallation Source (ESS) TS2 facility. TS2 facility which is equipped with a high-power circulator having an adjustable reflection coefficient, provides increased experimental flexibility for validating the proposed algorithm. The results confirmed the effectiveness of our approach in accurately calibrating QL under mismatched conditions, demonstrating the practicality and reliability of the proposed algorithm.

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The LNF flagship project EuPRAXIA@SPARC_LAB: a novel FEL radiation source based on a plasma accelerator

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Plasma acceleration is paving the way for new compact accelerators aiming at reducing the scale of the facilities needed by free electron laser (FEL) or high energy physics by employing accelerating gradients much larger than conventional RF structures. The EuPRAXIA Design Study is dedicated to realizing a distributed FEL facility powered by plasma acceleration in the European framework (it is included in the ESFRI roadmap).

As part of the EuPRAXIA project, Frascati National Laboratories propose hosting a cutting-edge facility named EuPRAXIA@SPARC_LAB, tailored to meet these specific requirements with a unique combination of a high-brightness X-band RF linac driving a plasma-accelerator-based FEL. We plan to realize a FEL in the XUV (3-15 nm) and we are studying the possibility to have a second beamline beamlines in the VUV (50-150 nm). We are preparing a Technical Design Report, while the building is in the executive drawing phase.

We present the status of the new LNF flagship project EuPRAXIA@SPARC_LAB, that will be challenging for timing and synchronization both on the electron part (for the beam driven plasma acceleration) and on the FEL photon part (for the time resolved user experiments).

Poster Session I (Synchronization and Timing) / 30

RF Phase Reference Distribution System for RAON Heavy-ion Accelerator

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The heavy-ion accelerator of the Institute for Rare Isotope Science (IRIS) has been developed and beam commissioning for the low energy superconducting linear accelerator has been performed. There are three types of SRF cavity, which are 81.25 MHz quarterwave resonator (QWR), 162.5 MHz half-wave resonator (HWR), 325 MHz single-spoke resonator (SSR). There are 22 QWRs and 102 HWRs in the low-energy superconducting linac (SCL3), and 69 SSR1s and 144 SSR2s in the high-energy superconducting linac (SCL2). The RF reference distribution system must deliver a phase reference signals to all low-level RF (LLRF) systems and BPM systems with low phase noise and low phase drift. The frequencies of RISP linac are 81.25MHz, 162.5MHz and 325MHz, and there are 130 LLRF systems and 60 BPMs respectively for SCL3, and 240 LLRF systems and 70 BPMs for SCL2. 81.25 MHz signal is chosen to the reference frequency, and 1-5/8“rigid coaxial line is installed with temperature control. This paper describes the design, test results and operation during the beam commissioning of the low-energy superconducting linac.

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Novel phase-averaging reference system for the CiADS facility

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The China initiative Accelerator Driven System (CiADS) requires a stable phase reference distribution system (PRDS) to provide low-drift reference signals for over 300 radio-frequency (RF) clients on its superconducting linac and beam transport lines. PRDS is realized using a coaxial cable that transmits 162.5 MHz reference signals, and the phase averaging technique will be employed to counteract phase drift caused by changes in the cable length due to temperature variations. To address the limitations of the traditional phase-averaging solutions due to the presence of reflected signals, such as standing wave effects, demanding directivity requirements of directional coupler, and difficulties in phase reference line expansion, we propose an improvement based on a bi-line structure with unidirectional transmission of the reference signal and front-end phase locking. The design of the PRDS for the CiADS and signal processing in the low level RF system are detailed. The feasibility of the new scheme is verified by testing a prototype PRDS.

Timing / 32

RF synchronization and phase recovery using a White Rabbit network for the Large Hadron Collider (LHC) at CERN

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During LHC operations, RF signals are crucial not only for accelerating cavities but also as a clock for experiments, beam instrumentation and the new Crab cavities. We propose a highly scalable method for synchronizing RF generation across the LHC complex, enabling automatic phase recovery.
In the upcoming long shutdown (LS3), scheduled in the period 2026-2028, the analog RF distribution will be replaced by a White Rabbit (WR) network. This network will provide sub-nanosecond clock synchronization, temperature compensation and the RF over Ethernet (RoE) protocol, which facilitates the transmission of Frequency Tuning Words (FTW) and phase information.
In this presentation, we will explore the system architecture and the mechanism used for generating and recovering the RF phase in distributed nodes.

Timing / 35

High-precision clocks and triggers for longitudinal beam measurements in high energy synchrotrons

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High energy synchrotrons, like the Super-Proton Synchrotron (SPS) and the Large Hadron Collider (LHC) at CERN, require high-precision beam synchronous triggers for longitudinal measurements, e.g. to acquire bunch profiles from a wall current monitor pickup. The observation triggering scheme is based on the General Machine Timing (GMT) followed by dedicated trigger units counting the revolution and RF frequency clocks to allow synchronisation to the exact RF bucket. Combined with a programmable fine delay, accurate triggers can be placed at any azimuthal position with a resolution of about 20 ps. The SPS installation is described in detail, including its additional flexibility for measurements at injection, extraction and bunch rotation. The performance and limitations of such an implementation are analysed in terms of jitter with respect to the beam, delay variation due to cable lengths between the clock generation and acquisition with a sweeping revolution frequency. Such varying delays can be compensated with the White Rabbit (WR) technology, and highlights from the recent upgrade in the SPS are presented.

Poster Session I (Synchronization and Timing) / 37

HL-LHC RF distribution over White-Rabbit, the WR2RF and eRTM modules

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The Hi-luminosity Large Hadron Synchrotron (HL-LHC) is an upgrade of the LHC which aims to increase the instantaneous luminosity by 5 to 7.5-fold with respect to the LHC nominal value. During LS3 (2026-2028), Super-conducting crab-cavities will be installed around the ATLAS (point1) and CMS (point 5) experiments which are located several kilometres away from the existing main RF system (point 4). The RF signal distribution for RF users (Experiments, Beam-Instrumentation) will also be upgraded, with use of WR2RF modules, on the RF user side. The crab-cavities LLRF and WR2RF module are synchronized to the main RF system through a White-Rabbit (WR) network. The WR network is used for both clocks and RF synchronization between RF stations. The LLRF electronics is using fixed frequency sampling and processing clocks, and the clocks are reconstructed locally from the WR data stream and a low noise PLL.
The plans of the RF distribution, clock generation and the main hardware modules involved will be presented with results from prototype tests.

Measurements and Calibration / 38

Beam-based gradient calibration at FLASH and EuXFEL

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Based on beam-induced transients observed in open loop, cavity gradients are routinely calibrated at the FLASH and European XFEL accelerators. The method used to perform this beam-based calibration, its accuracy and limitation are presented. The tools developed over the years to support and automate this task are also presented.

Poster Session I (Synchronization and Timing) / 39

Picosecond Timing System Based on White Rabbit for Scientific Facilities

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The timing system is a crucial component in scientific facilities like particle accelerators and laser ignition installations. It ensures that all subsystems within these facilities share a common time reference, enabling coherent operation and accurate tracking of events throughout the machine's operation. Additionally, the timing system generates discrete triggering events and periodic signals required by various subsystems and can also be used for radiofrequency distribution across the facility.

This work presents the architecture of a timing system under development by Safran Electronic & Defense Spain SLU, which is based on White Rabbit technology for the distribution of synchronized triggers. The design and implementation of the hardware, which is FPGA-based, will be discussed in detail.

The timing system offers complete configurability of triggering parameters, including direction, pulse count, pulse rate, pulse period, and delay, with a resolution on the order of 5 picoseconds. White Rabbit technology provides sub-nanosecond accuracy and picosecond precision, along with features such as automatic link calibration. The performance metrics achieved by this system will be highlighted in this work.

Poster Session II (Measurement and calibration) / 40

Status of the development of the new digital LLRF for ALBA Synchrotron Light facility

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The Low-Level Radio Frequency (LLRF) system is a critical component in the control infrastructure of any synchrotron, responsible for generating and maintaining a stable electric field within the accelerator cavities by precisely controlling both amplitude and phase.

Safran Electronic & Defense Spain S.L.U. is currently engaged in the development of a new digital LLRF system to upgrade the existing infrastructure at the ALBA Synchrotron Light Source in Barcelona. This project is being executed in accordance with ALBA's technical specifications and will integrate with the ALBA LLRF firmware. On-site testing of the 500 MHz version is anticipated by end of 2024, with the 1.5 GHz third harmonic version scheduled for testing in the first quarter of 2025.

This work will cover the architecture, design, development, and performance evaluation of the LLRF system.

Poster Session II (Measurement and calibration) / 41

Integration of a Digital PLL in LLRF Systems for Advanced Cavity Characterization

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The Low-Level Radio Frequency (LLRF) system is a vital subsystem in particle accelerator facilities, tasked with generating and maintaining a stable electric field within accelerator cavities by precisely controlling both amplitude and phase. As facilities transition from legacy analogue LLRF systems to modern digital counterparts, the enhanced computational power of current Field-Programmable Gate Arrays (FPGAs) presents opportunities to introduce new, sophisticated functionalities.

In this work, we explore the design and implementation of a fully digital Phase-Locked Loop (PLL) integrated within the LLRF system. This digital PLL is capable of automatically tracking the resonant frequency of the accelerator cavities, ensuring that the system continuously adapts to any deviations from the nominal resonant frequency. Moreover, this feature extends beyond simple frequency monitoring; it can also be leveraged for detailed characterization of the magnitude response of the cavity.

The implementation details and performance evaluation of this digital PLL feature will be thoroughly discussed in this work.

Poster Session I (Synchronization and Timing) / 42

Beam Synchronous for the Rest of Us!

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Fermilab's Tevatron Clock (TCLK) infrastructure has been an integral part of the accelerator control network since the 1980's. This 10MHz Manchester encoded protocol has enabled flexible, real-time event distribution for thousands of devices connected to the timing network with a high degree of reliability.

Forthcoming upgrades to the Fermilab complex (PIP-II, LBNF, ACORN) necessitate higher levels of precision to maintain inter-bunch timing for Instrumentation and Control purposes. This presents as an opportunity to refine the event distribution protocol for tighter synchronization between machines, experiments, and eventually far-site operations.

This paper outlines a method by which beam-synchronous events may be distributed through asynchronous serial protocols via integration with local LLRF and global PPS reference signals. This method is ideal for synchrotron machines with aggressive frequency sweeps (such as Fermilab's 38~53MHz Booster) and allows for precision timing to be maintained across machines without specialized hardware.

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White Rabbit application at KEK

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White Rabbit is one of the major timing systems for large-scale accelerators. It precisely synchronizes the FPGA clock of distant hardware modules by its deterministic network protocol. In addition to the timing signal delivery, the fruitful functions that enhance the accelerator operation are provided by this function. The R&D and
application of White Rabbit is an important issue for future accelerator
projects.
We report on the activities of White Rabbit R&D at KEK. The distributed TDC system was developed

and applied to the SuperKEKB accelerator. This system is configured with the SPEC (Simple PCIe Carrier) board which is commercially available. Besides, the feasibility test of the IDROGEN board which has been recently developed at IJCLab is reported. After briefly introducing the IDROGEN specification, the sideband noise level and the accuracy of synchronization of the FPGA clock between the optically connected
distant modules are shown.

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Phase and Amplitude Noise Measurements: Fundamentals and Best Practices

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Accurate phase and amplitude noise measurements are substantial for the advancement of, and academic exchange on low-level RF, (laser) timing synchronization and timing diagnostic systems. However, the notion of phase, timing and amplitude noise, and their various representations can be quite overwhelming for scientists and newcomers to the field without a deep background in electrical engineering and statistics. This, in turn, easily can lead to misunderstandings and can also quickly cause falsification of gathered results due to incorrect measurement setups or inaccurate mathematical processing of collected data. We aim to aid good scientific practice by providing an essential and concise introduction to the art of PM and AM noise measurements, introducing the mathematical foundations that link time domain data and power spectral density estimations, the units involved, as well as standard representation of noise plots. We discuss the operation, settings, and limitations of industry standard phase noise analyzers and common pitfalls in measurement setups for RF and optical systems, covering oscillator stability as well as timing link stability. The discussion also extends to baseband measurements using custom, external timing detectors such as balanced optical cross-correlators.

Poster Session II (Measurement and calibration) / 45

Beam-Based Voltage Calibration for Double-Harmonic RF Systems in the CERN Super Proton Synchrotron

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Accurate knowledge of the voltage and phase in an RF cavity gap is essential to preserve beam quality and to achieve efficient, precise real-time correction with LLRF feedback. Voltage calibration using longitudinal phase-space tomography is a well-established beam-based technique that has demonstrated remarkable precision in determining the RF voltage experienced by a particle bunch. In a double-harmonic RF system, beam-based voltage calibration involves minimizing a four-dimensional parameter space that depends on the phase-voltage parameters of both RF systems. This

process can be computationally challenging, and it is often more practical to perform a sequence of two-parameter voltage measurements, referencing the higher-order cavity system with respect to the main one. The Super Proton Synchrotron (SPS) at CERN is equipped with 200 MHz and 800 MHz cavity systems, that operate in phase at the bunch position for a non-accelerating bucket. In this context, the latest beam-based voltage calibration campaign conducted in the SPS will be presented, comparing different approaches.

Poster Session I (Synchronization and Timing) / 46

Control & Monitoring Software for Fibre Optic Link Stabilization

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The CLARA Accelerator at Daresbury Laboratory requires timing information to be distributed to locations up to 100m apart with femtosecond accuracy. This information is delivered as laser pulses via 6 stabilized fibre optic links. Each link uses 3 main subsystems which condition and modify the laser pulses: a piezoelectric fibre stretcher provides closed loop length stabilization to compensate for timing jitter (up to ~5kHz) and drift produced along the transmission fibre; a motorized optical delay stage is used for calibration and to prevent saturation of the fibre stretcher; and an amplification stage is used to maintain sufficient signal strength (~10mW) through the link. Each of these components requires software control, however code that was previously used was fragmented, basic and not suited to use for multiple links simultaneously.

We have developed a new single piece of software to control and monitor these systems concurrently. As CLARA is transitioning to user operations, this software needs to have high reliability, operating 24/7 with minimal intervention. To facilitate commissioning of the systems, it will also automate calibration procedures. This poster presents an outline of the requirements; tools and techniques used to develop the software; and discussion of testing performed to date.

Synchronization / 47

Optical Synchronisation Systems for the CLARA facility

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The Compact Linear Accelerator for Research and Applications (CLARA) is a 250 MeV ultrabright beam test facility at STFC Daresbury Laboratory. Originally conceived as a free electron laser test facility, timing is based on an actively stabilised optical timing architecture, incorporating opto-electronic systems for beam arrival diagnostics and laser/RF client synchronisation. The facility is undergoing commissioning in preparation for user exploitation, scheduled to begin mid-2025, which includes plans for combined laser-electron beam experiments with strict demands on synchronisation. We report the status of the CLARA facility, focussing on the development and installation of systems for timing and synchronisation, and provide an outlook towards the start of user operations.

Poster Session I (Synchronization and Timing) / 48

Coherent Electron Cooling (CeC) - Timing and Synchronization

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Coherent Electron Cooling Proof-of-Principle (CeC PoP) is an experimental accelerator system currently commissioned at Brookhaven National Laboratory (BNL). The purpose is to demonstrate cooling of a single hadron bunch circulating in the relativistic heavy ion collider (RHIC) with co-propagating electron beam. To support CeC operation, FPGA based LLRF Controllers provide system controls, monitoring, RF references and instrumentation timing signals. Synchronization between the Laser source, photocathode electron gun, buncher and SRF accelerator cavity is achieved by broadcasting revolution frequency and resets to each LLRF controller through a high-speed fiber link. CeC is one of the essential techniques being studied for high energy strong hadron cooling, to increase the integrated luminosity goal of the future Electron-Ion Collider (EIC) at BNL.

Poster Session II (Measurement and calibration) / 49

Mitigation for a shorted cavity probe at EuXFEL

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Since the commissioning of the EuXFEL free electron laser, one of the 784 superconducting cavities of the linac has a short circuit at the probe connector. For this reason, its signal cannot be used for field regulation. Instead, the signal coming from a high order mode (HOM) coupler antenna is included in the vector sum regulation. This cavity shows a direct impact on the beam arrival time profile along the bunch train. In this work, limitations and operational solutions are described.

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Reliable, Optically Augmented RF Reference Distribution with Femtosecond Stability

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State of the art Free Electron Lasers have rigorous electron beam stability requirements. To fulfill these requirements the low-level RF systems rely on a phase stable RF reference. Classical coaxial RF distribution systems have low complexity and thus offer excellent reliability and also a good short-term performance. However, their long-term stability does not meet today's requirements of large-scale FELs. Optical reference distribution methods offer significantly superior long-term stability but are also more expensive and complex to implement and maintain. Our optically augmented RF distribution system features drift compensation of the RF signal at the client with respect to a drift-free optical reference signal. The key component of the RF re-synchronization module is an opto-electrical phase detector based on a commercial Mach-Zehnder based amplitude modulator - for which we show few femtosecond long-term stability. Our augmented system offers the advantages of a coaxial RF distribution system while providing the femtosecond stability of a pulsed optical synchronization system to those clients with a high stability requirement. We present the topological advantages of an augmented RF distribution in terms of reliability, scalability, costs, and performance.

Poster Session II (Measurement and calibration) / 51

Influence of environmental parameters on calibration drift in superconducting RF cavities

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Precisely calibrating RF superconducting radio-frequency linear accelerators is crucial for accurately assessing cavity bandwidth and detuning, which provides valuable insights into cavity performance, facilitates optimal accelerator operation, and enables effective fault detection and diagnosis. In practice, however, calibration of RF signals can present several challenges, with calibration drift being a significant issue, especially in settings prone to humidity and temperature fluctuations. In this study, we delve into the effect of environmental factors on the calibration drift of superconducting RF cavities. Specifically, we examine long-term calibration drifts and explore how environmental variables such as humidity, temperature, and environmental noise affect this phenomenon. The results show that environmental factors, particularly relative humidity, significantly influence calibration drifts. We also examine the distribution of temperature and humidity throughout the linear accelerator and their correlations with specific locations, providing both a global and localized understanding of environmental impacts. This insight aids in developing targeted solutions for specific segments of the accelerator. Finally, by analyzing the correlation between the environmental factors and calibration drift, appropriate compensation algorithms can be designed to mitigate and eliminate these effects, thus optimizing calibration accuracy and stability.

Poster Session I (Synchronization and Timing) / 52

Characterization and Improvement of Phase Noise in the RHIC 197 MHz RF System

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The Relativistic Heavy Ion Collider (RHIC) is a high energy collider currently in operation at Brookhaven National Lab that collides both proton beams and heavy ion beams at energies of up to 250 GeV. The use of a low phase noise RF system is important to the operation of the collider, as phase noise will cause beam emittance growth as beam is circulated and collisions occur. In an effort to reduce the phase noise seen by the beam, an ultra-low phase noise source consisting of a DAC being clocked by an ultra-quiet 2 GHz clock was developed and tested for RHIC's 197 MHz RF systems. Using this source, the current High Level RF system's phase noise performance was characterized. This source optimized noise performance at high frequency offsets, while the current RF system is optimized for low frequency offsets. It will have applications in the future Electron-Ion Collider Crab Cavities, as wideband noise is critical in limiting the transverse emittance growth of the beam.

Measurements and Calibration / **53**

Measurements of the PSB LLRF multi-harmonic beam loading compensation system.

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The Proton Synchrotron Booster (PSB) produces a variety of proton beams covering a very large longitudinal parameter space, which are accelerated up to 2 GeV. This low-energy regime requires a significant frequency sweep of the RF system. Finemet-based cavities provide this large frequency range without the need of a tuning loop, but they introduce a significant longitudinal broadband impedance. An ensemble of digital feedback loops therefore compensates the beam-induced voltage at the revolution frequency harmonics. This contribution focuses on measurement techniques used to precisely characterise the signal processing of these loops. First comparisons with beam-based measurements of the transient and steady-state response of the full system are presented. These measurements contribute to a detailed understanding of the LLRF system, necessary to accurately model its behaviour. Moreover possible improvements to the cavity voltage amplitude and phase calibrations in the presence of strong beam loading are highlighted.

Poster Session I (Synchronization and Timing) / **54**

PIP-II Clock and Timing

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The PIP-II timing system is planned to be a two part system consisting of a global timing system (referred to as ACLK) that provides high level, event based timing for the whole Fermilab accelerator complex while the second part is a RF synchronized clock system unique to the PIP-II Linac itself (referred to as LCLK). The ACLK System will make use of an external 10 MHz GPS based signal source as a reference for its 650 MHz phase lock as it is the reference frequency for the TCLK output of the system (needed to support legacy hardware around complex). The LCLK System will use a PIP-II Linac RF reference (162.5 MHz) from the Linac LLRF system to allow beam synchronized event placement. Both the ACLK and LCLK systems will have a clock output with a data frame of 16 event bits + 32 data bits with frames broadcast at 650 MHz, phase locked to the 10MHz reference in the case of ACLK and the PIP-II LLRF sourced 162.5 MHz reference in the case of LCLK.

Poster Session II (Measurement and calibration) / 55

APS-Upgrade Storage Ring RF Noise Reduction for Beam Stability

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The new Advanced Photon Source Upgrade (APS-U) storage ring is now operating and x-ray beamlines are coming back online. Targeted suppression of 60-Hz-harmonic-related rf amplitude and phase noise from megawatt-class klystrons has played a role in achieving orbit stability at the micron level and reducing beam energy fluctuations. Measurements of beam stability are made from an analysis of synchronous beam position monitor data available from the APS-U fast data acquisition (DAQ) system. The design and tuning of the noise suppression system is presented along with its improvement to beam stability.

- Work supported by U. S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357

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An Overview: Reference Distribution and Synchronization Systems, from Sub-picoseconds to Sub-femtoseconds Stability

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Distribution systems are used to provide reference frequencies from a common source to all phase-critical clients at an accelerator. To precisely synchronize remote RF and optical oscillators to the common clock, a combination of phase-stabilized links and phase-locked loops with optimized bandwidth and locking parameters are implemented. A pre-requisite to reach the required phase-stability, is the availability of drift-free phase-detectors with sufficient resolution.
When selecting for a type of reference distribution and synchronization systems, various aspects need to be considered; among those the ultimately required time stability, the scale of the facility and the predominant sources of disturbances. Phase-critical sub-systems at an accelerator are susceptible for noise occurring in various frequency bands from megahertz to millihertz, from sources such as intrinsic noise of electronics and materials, vibrations and environmental conditions.
We present an overview of selected developments for RF and optical synchronization systems, suited for stability requirements in the several 10 fs to sub-fs regime.

Poster Session I (Synchronization and Timing) / 57

Recent Experience in the Operation of FLASH2020+ RF Reference Generation System

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The redesigned RF reference generation and distribution system at FLASH was installed in 2022. The upgrade is based on a European-XFEL-based Main Oscillator (FL-MO1300), Frequency Conversion (FL-FCM), and RF Distribution (FL-DISM) modules. The main 1.3 GHz RF reference signal is synthesized in FL-MO1300, and the remaining signal frequencies are synthesized in FL-FCM and synchronized to the main 1.3 GHz reference. All reference signals are distributed via the FL-DISM. All the modules provide live monitoring of most RF signals and diagnostic information via the DESY DOOCS system. The contribution presents the recent operation experience of the upgraded RF reference system at FLASH, including long-term logged parameters, like main oscillator stability, distribution output power level, and the system modules'temperature stability.

Poster Session II (Measurement and calibration) / 58

Data-driven Model Predictive Controller for SRF Cavity Resonance Control

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For advanced high-Q SRF linacs like LCLS-II, precise cavity resonance control is crucial for ensuring stable operations. Inadequate control can lead to a significant increase in RF power demands, escalating both operational and capital expenses due to the need for additional RF power sources. To address this challenge, we have developed an innovative data-driven model predictive controller that incorporates a highly efficient surrogate model. This model is designed to manage the complex dynamics of cavities affected by microphonics and nonlinear Lorentz forces. Its efficacy has been thoroughly validated with real SRF cavities at SLAC. The MPC is implemented in a soft processor and is currently being integrated into the resonance control of an LCLS-II LLRF-like system. This foundational work paves the way for extending the model to broader motion control applications where extremely low-tolerance vibration control is essential. In this paper, we will showcase the model and share the latest test results

Poster Session I (Synchronization and Timing) / 59

Report on the Development of a Real-time Redundancy Subsystem for the Master Oscillator of the European XFEL

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We present recent advancements in the development of the real-time redundancy subsystem for the Master Oscillator of the European XFEL. This system improves upon the usual method of manually switching to a hot-spare in the event of a failure in the main source. Its primary objective is to maintain uninterrupted operation of the facility by minimizing the impact of potential Master Oscillator failures. By combining continuous monitoring, low-latency switching, and synchronization, the system ensures that failures result in only a brief and minor disturbance instead of a complete loss of a usable signal. As a result, little influence on the downstream systems is expected. We provide examples of the system's operation under laboratory conditions, summarize the achieved performance, discuss encountered issues, and outline further plans.

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Performance Evaluation of the ESS Phase Reference Line

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The Phase Reference Line (PRL) of the European Spallation Source (ESS) is a passive system based on a single 1-5/8"coaxial rigid line installed at the tunnel ceiling above the beamline. It is supported by temperature and gas pressure control systems with active electronics installed in the ESS Klystron Gallery Hall. The length of the PRL is around 580 meters. The system is temperature stabilized (+/- 0.1 deg C) and includes an inner-line gas pressure stabilization to assure synchronization accuracy. The PRL was designed to distribute 352 MHz and 704 MHz reference frequencies from a Master Oscillator to 56 tap points in the tunnel. Each tap point has several (3 or 6) signal outputs, giving 294 of the total output number. The system was installed, and the long-term phase drift performance was tested. This contribution covers the summary of the PRL project, including the recent performance test results.

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White Rabbit: status and plans of the technology and the community around it

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White Rabbit (WR) is an open-source (hardware, gateware, firmware and software) technology developed by a community of contributors including laboratories, universities, national metrology institutes and companies. After its standardisation as part of IEEE-1588 (PTP, Precision Time Protocol),

it has seen significant uptake well beyond its initial scope of big scientific facilities. WR is now used in domains as diverse as particle accelerators, telescopes, financial institutions, national time dissemination and telecom.
After a short introduction to the technology and the WR community, we will describe the newly-created WR Collaboration, which aims at ensuring the sustainability of the project and providing good guaranteed support to users and developers of the fundamental building blocks of WR: the WR switch and the WR PTP core, as well as maintaining these two key open-source components in good health.
We will also describe the technological evolution of WR, including future plans, and fundamental performance limits arising from the use of Field-Programmable Gate Array (FPGA) technology for I/O and phase measurement.
We will conclude with a list of topics for further discussion, where potential collaboration with LLRF teams could result in making WR more useful in accelerators and beyond.

Poster Session II (Measurement and calibration) / 62

Preliminary Design of Low Noise and High-Gain Feedback for EIC Crab Cavities

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The Electron-Ion Collider (EIC), a decade-long project at Brookhaven National Laboratory (BNL) funded by the Department of Energy (DOE), aims to design and build a facility for colliding polarized high-energy electron beams with polarized proton and heavy ion beams. The EIC will operate at center-of-mass energies between 20 GeV and 140 GeV and achieve luminosities up to 1034 cm-2s-1. This collaborative effort between BNL and the Thomas Jefferson National Accelerator Facility (Jefferson Lab, JLAB) will use crab cavities to compensate for a 25 mrad crossing angle, thereby maximizing luminosity. These crab cavities require ultra-low noise RF field control to prevent transverse emittance growth. Additionally, the low-level RF (LLRF) system must integrate very low noise performance with high-gain feedback to effectively reduce cavity impedance. We will present preliminary design work on an ultra-low noise LLRF system with high-gain feedback, specifically developed for the EIC crab cavities.

Measurements and Calibration / 67

Improving long-term stability and 1/f amplitude noise using pilot-tone compensation technique in Beam Position Monitors

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In this contribution, we describe the advantages of the pilot tone compensation technique that we have implemented in a new BPM system for Elettra 2.0. The injection of a fixed reference tone upstream of the cables allows for a continuous calibration of the system, compensating for the different behaviour of each channel due to thermal drifts, variations in cable characteristics, mismatches and

components tolerances. Moreover, this approach also reduces the 1/f amplitude noise introduced by the ADCs. Our results show a dramatic improvement over calculated positions, both in terms of long-term stability (slow data with low bandwidth), and noise performance on fast data (10 kHz to 1 MHz data rate), reaching sub-micrometer accuracy over a 24-hour time window, and RMS noise below 100 nm, on a scale factor of 10 mm with 10 kHz data rate.

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The Einstein Telescope Timing issues: picosecond resolution for a billion years journey back in time

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The Einstein Telescope (ET) project is the research infrastructure to host the future European gravitational wave detector and Italy is a candidate to host it in Sardinia. It is a large underground facility for a third-generation gravitational wave detector, which will be able to observe a volume of the universe about one thousand times larger than current instruments. It is considered a flagship project at the international level and it was included in the Roadmap 2021developed by ESFRI.

Italy's candidacy is supported by the Italian government and it is scientifically coordinated by the INFN (the Italian National Institute for Nuclear Physics) through the ETIC project, funded by the Next Generation EU, with two main objectives: carry out a feasibility and analysis study of the Italian candidate site and establish a national network of R&D laboratories.

The ET will face peculiar challenges for data acquisition, synchronization and control systems; several R&D projects are already started in order to identify and test solutions and technologies.
This presentation will give an overview of the ET project, highlighting both scientific goals and technological aspects, then will focus on timing and synchronization aspects, exploring possible common points or interests with the community of this workshop.

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Welcome of the LNF Director

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Basics of RF Reference Signal Generation and Synchronization Systems

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This contribution, planned as a sort of short summary/tutorial, will cover the basics of RF synchronization, starting with theoretical definitions and an attempt to put together and organize concepts and names frequently confused by various people. Items such as the definition of synchronization systems and their accuracy measures will be discussed, followed by sources of instabilities and methods of achieving required precision. The concept of phase drifts and noise will be introduced, followed by basic phenomena influencing these measures in practical systems. Various methods of signal generation and distribution will be shown, including representative examples of passive and active, as well as RF cable and optical fiber-based systems.

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Optical technologies for generating microwaves, time and frequency distribution and synchronization

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With the invention of the frequency comb two decades ago it became possible to easily (and phase coherently) switch between radio and microwave frequencies in the GHz to 10s of GHz range and optical frequencies in the range of several 100 THz.
The much faster oscillations of optical frequencies give us a few orders of magnitude advantage whenever it comes to interferometric stabilization.

Frequency combs also enable the use of optical references in the GHz domain by optical down conversion, i.e. dividing the very stable output of optical cavities with relative stabilities in the 10^{-15} or even 10^{-16} range into the GHz range. With this technique we have generated a world record breaking 10 GHz signal with -173 dBc at 10 kHz from the carrier.

By using the phase information of an optical wave we have transmitted a frequency reference with better than 10^{-19} relative accurcay over a distance of 1920km. Using the same technique of optical carrier phase comparision, it is possible to sychronize two lasers to attosecond precision even over large distances.

By combining these techniques one can envision an optical control system of large accelerator and free electron laser facilities far supperior to any RF only system.