

RF SYSTEM STATUS FOR PERLE*

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Abstract

The PERLE project consists of a 5 MW at 250 MeV Energy Recovery Linac (ERL) demonstrator, with the accelerating cavities operating at 801.58 MHz and 2 K. The superconducting cavities need to be regulated in terms of amplitude, phase and frequency due to perturbations such as microphonics, Lorentz forces and Beam loading. New developments dedicated to PERLE are in progress in order to achieve the performances. Firstly, a Distributed Master Oscillator (DMO), White Rabbit (WR) protocol based allowing to distribute a reference and to generate locally the synchronized RF signals and clocks needed. It is also associated to a timing system using the same WR enhanced hardware (IDROGEN Board) to produce the synchronized timing triggers and gates for all the machine. In addition, a new C&C board of the Frequency tuning system is developing to increase the ecosystem around the IDROGEN board. The LLRF Feedback system is also MTCA based using Off the shelf boards from IOXOS technologies, associated to a RF power Solid state amplifier prototype from JEMA FRANCE upgradeable from 8.8kW to 60kW. An overview and a status of these systems and their implantations will be presented with some outlooks.

INTRODUCTION

The PERLE project aims to build and operate of a 5 MW at 250 MeV Energy Recovery Linac (ERL) demonstrator, with superconducting cavities operating at 801.58 MHz and 2 K with accelerating gradients up to tens of MV/m (cf. Table 1 parameter list). The RF power values are given for a 20 mA beam, without margins.

As shown in Fig. 1, PERLE is composed in a photocathode gun [1] providing 0.3MeV followed by a Low Energy Transport Line allowing to bunch and focus the beam, and measuring some parameters using the beam diagnostics presents on this LEBT. A cryomodule called “Booster” integrating four superconducting mono-cells cavities increase de beam energy to 7 MeV before the injection into the Linac using a merger [2]. In the ERL section a second cryomodule said “Linac cryomodule” is integrated with four superconducting 5-cells elliptic cavities allowing the energy to be increased by 82MeV with each acceleration

paths (3-loops planned in the Phase 2 project to achieve ~250 MeV).

Table 1: Elliptic Cavities Parameters

Parameters	Single Cell	Five Cell
Frequency [MHz]	801.58	801.58
Bandwidth [Hz]	471.5	100
G	257.6	274.5
R/Q@ $\beta=1$ [Ohm]	108.5	523
Lacc=(n. β . $\lambda/2$) [m]	0.187	0.935
Q ₀	1E+10	3E+10
Q _{ext}	1.7E+6	8E+6
E _{acc} [MV/m]	9.5	21.9
RF power [kW]	40	25

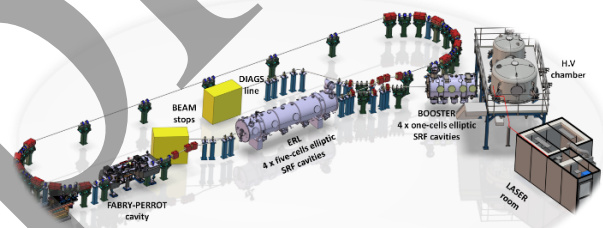


Figure 1: PERLE ERL Phase 1, 1-loop.

Radiofrequency (RF) accelerating cavities and amplitude, phase and frequency control systems require advanced and ongoing R&D due to the ever-increasing performances and accuracy requirements of accelerators to ensure an efficient, reliable and sustainable operation of such high power superconducting accelerators like PERLE.

To limit the joule heating losses and therefore cryogenic consumption, a superconducting cavities quality factor of around 1×10^{10} is required for the Booster, while for the ERL Linac this requirement is set to the challenging value of 3×10^{10} . The external coupling was chosen to minimised the RF power consumption and adds to the operation of some cavities (Linac cryomodule) with a narrow bandwidth (~100 Hz) [3].

In this context, mechanical disturbances such as microphonics caused by the systems surrounding the cavities (e.g., vacuum pumping or helium bath pressure) and radiation pressure can induce a frequency detuning leading to an increase in RF power consumption. To compensate for these variations, which impact beam quality and stability, it is necessary to finely control the accelerating field amplitude (E_{acc}) and phase (ϕ) as well as the resonance frequency of each cavity, and this in real time by controlling

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the associated radiofrequency power source. These control systems, known as Low Level Radio Frequency systems (LLRF), are synchronized with all the machine by a RF Master Oscillator (MO). For PERLE, The LLRF system is μ TCA.4 based with several benefits: a high level of integration, an important available electronic area by slot due to the association into the same slot of front-end and back-end boards and a very high reliability from 99.9% by default to 99.999% with the redundancy capabilities.

DMO AND TIMING

The Distributed Master Oscillator (DMO) is a critical subsystem for the PERLE accelerator, designed to generate and distribute ultra-low-noise reference signals to ensure beam stability and synchronization. The system must provide multiple frequencies, 801.58 MHz (RF), 400.79 MHz (electron gun laser), 200.395 MHz (LLRF clocks), 40.079 MHz (injector), and 10 MHz (instrumentation) while meeting stringent jitter requirements, which vary significantly with frequency (e.g., $\pm 0.1^\circ$ phase jitter corresponds to only 0.346 ps @ 801.58 MHz). The reference oscillator, often based on OCXOs or rubidium standards (e.g., -105 dBc/Hz @ 1 Hz offset), dictates long-term drift and short-term jitter stability, with PLL-based jitter cleaners and noise scaling effects, playing key roles in performance optimization.

RF signal distribution (jitter of 50 to 100 fs) or optical solutions (jitter < 10 fs) introduces additional challenges, increasing the complexity of the overall system design. An innovative solution, originally developed at CERN, enables sub-nanosecond synchronization over long distances but requires hardware improvements to achieve the <350 fs jitter target @ 801.58 MHz-Offset range [1 Hz-1 MHz]. Due to the mixed hardware architecture used (VME + μ TCA), an R&D project was launched at IJCLab through the local use of high-performance fractional PLLs associated to the μ TCA-based IDROGEN board [4]. Using one as Grand Master linked and another configured as a slave, it has been demonstrated that a 900 fs rms jitter at 100 MHz in the offset range [1 Hz-1 MHz] can be achieved, outperforming conventional WR implementations but still falling short of expected requirements. There are still avenues for improvement to explore; however, a new option is already under development in collaboration with le LTE laboratory. This solution is based on a partially optical approach that aims to preserve the advantages of the IDROGEN board and the WR protocol while ensuring jitter < 100 fs. Integration into the REFIMEVE network further enhances stability by distributing atomic clock references (Maser) via fiber optics, while a rubidium-based backup system provides redundancy.

The Timing system also uses the IDROGEN board for the synchronisation of the accelerator with a local regeneration (slaves) of the gates and pulses required for the timing distribution. A μ RTM format board is developing for generating 9 synchronized signals with the delay compensation thanks to the WR protocol and 2.5 ns resolution step. 10 MHz reference and PPS outputs are also planned to be integrated.

LLRF SYSTEM

The field stabilities requirements ($E_{acc} < 0.1\%$ and $\phi < 0.1^\circ$ rms) involve to improve the Signal to Noise Ratio (SNR) and reduce the latency using an oversampling with non-IQ demodulation ratio optimized compared to a previous developed system [5]. The integration of additional commonly used signal processing functions is planned, such as the Self Excited Loop (SEL) or Phase Locked Loop (PLL), which are used to assist cavity start-up, as well as more recent functionalities as Active Noise Cancellation (ANC). Concerning the Hardware, the eco-system is based on a IOXOS technologies [6] solution (Fig. 2) using as a main board referenced IFC1420, composed in an AMC IFC1411 board integrating a PPC6500 linked to an AMD Kintex UltraScale FPGA with two FMC slots, one of which accommodate the DAQ1430 (10 ADCs and 2 DACs channels). The second free FMC slot, is used by a FMC DIO3118 dedicated to interface interlocks to or from the LLRF system. The IFC1420 is provided with a Network on Chip (NoC) based FPGA Design Environment with a specific area for the user. Moreover, The IFC1420 is associated to a RF front-end μ RTM board referenced RDC1470, developed in collaboration for the LLRF operation.

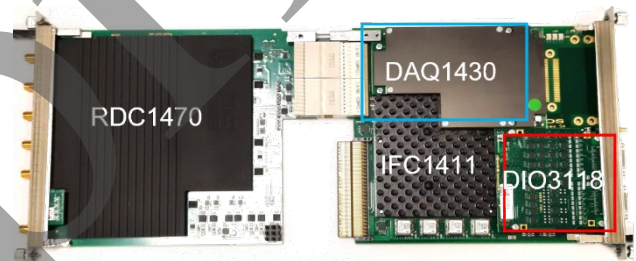


Figure 2: Couple of IFC1420 & RDC1470v2.

Finally, we are currently developing μ RTM format boards to pair with IDROGEN boards in order to take advantage of the White Rabbit's features and performance for the generation and distribution of RF reference and timing signals (cf. part "DMO & Timing"), but also dedicated to the Frequency tuning control.

RF POWER SYSTEM

The RF power system is designed to adjust the RF power delivered to the superconducting cavities, taking into account the performance of both the cavities and their power couplers. This adjustment is also based on RF commissioning results, particularly regulation performance, and the beam current ramp-up while respecting the maximum RF power of the circulators and loads.

The use of solid-state RF transistor technology was selected on the basis of the requirements defined for PERLE [7]. An 8.8 kW amplifier prototype, upgradeable to 60 kW, based on 2.2 kW RF power modules using LD MOS transistors, has been ordered following a contract with JEMA FRANCE.

The RF power circuit therefore consists of a Solid-State Amplifier (SSA) with a WR1150 waveguide output connected to port 1 of an isolator (a circulator with a load on port 3). The isolator's output (port 2) is connected to the power coupler via a waveguide section of less than 20 m combined with a waveguide-to-coaxial transition. The RF power amplifier, as well as the circulator and the load, are cooled via a water-cooling system. Arc detectors will be integrated at the isolator's input and output. The amplifier, for its part, will be protected against abnormally high reflected power within a few microseconds.

Despite the constraints posed by the existing building (Fig. 3), the installation of the system made it possible to integrate the LLRF and RF power systems while minimizing loop delay, thereby ensuring the stability of the accelerator field's amplitude and phase control at high loop gains.

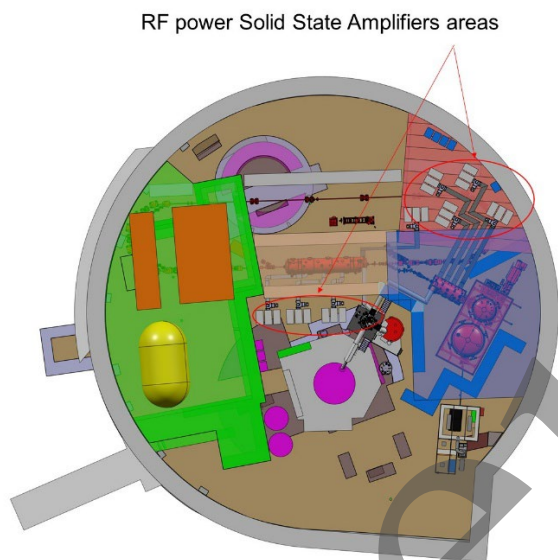


Figure 3: Floor Plan of the IGLOO building, which houses PERLE.

CONCLUSION

The RF system is composed of the LLRF and HLRF systems associated to the timing, the Machine Protection System (MPS), the Personnel Safety System (PSS) and the C&C using EPICS. The design phase is in progress using the current technologies as μ TCA.4 and the White Rabbit protocol.

Some solutions are currently being explored, including those related to the MO and reference signal distribution using the IDROGEN board, which provides excellent performance in pulsed accelerators [8] but has not yet been demonstrated for CW machines such as PERLE.

Another solution, using the new RF front-end board RDC1470v2, which operates over a wide frequency range, could be applied. Moreover, the RF power amplifiers and the associated components as circulators, loads, directional couplers have been defined and close to be ordered. One RF amplifier prototype will be delivered at the end of 2026, followed by an extensive test campaign to characterise and validate it.

There are still significant challenges to address in the IG-LOO building for the installation the machine, in particular regarding the RF systems, the testing series components and the validation of the 2K control system for the super-conducting cavities.

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