

# RF-API: A MODULAR CONTROL FRAMEWORK IN EPICS FOR RF SYSTEMS AT CLARA\*

N. Y. Joshi<sup>†,1,2</sup>, A. E. Wheelhouse<sup>1,2</sup>, J. Wilson<sup>3</sup>, W. Edward-Olaniyi<sup>3</sup>

<sup>1</sup>ASTeC, STFC Daresbury Laboratory, Warrington, UK.

<sup>2</sup>The Cockcroft Institute, STFC Daresbury Laboratory, Warrington, UK.

<sup>3</sup>Technology Department, STFC Daresbury Laboratory, Warrington, UK.

## Abstract

The CLARA facility has been upgraded in Phase II to deliver electron bunches up to 250 MeV using a standing wave photo-injector gun, four linac structures and a fourth harmonic lineariser cavity. A transverse deflecting cavity is also employed to measure key bunch parameters. To support reliable and efficient operation, a comprehensive RF Application Programming Interface (RF-API) has been developed within the EPICS control system. This API provides an intuitive interface for operators and serves as a foundation for higher-level machine control applications. It also enhances operational safety by monitoring unintended performance or configuration deviations in the RF systems, automatically alerting RF experts to potential degradation. This paper presents the design, capabilities, and performance of the RF-API and its associated user interface.

## INTRODUCTION

The CLARA (Compact Linear Accelerator for Research and Applications) facility is being developed in multiple phases to support the investigation of advanced accelerator technologies relevant to future large-scale facilities [1–3], including the proposed UK XFEL [4, 5]. In addition, CLARA provides electron beams for a wide range of experimental applications, including radiotherapy and plasma-based acceleration studies.

In its Phase II configuration, CLARA employs a normal-conducting S-band standing-wave gun, four travelling-wave linac structures, and an X-band lineariser to accelerate electron bunches to energies up to 250 MeV. Key beam parameters, including bunch length and arrival time, are measured using an S-band RF transverse deflecting cavity (TDC).

Each RF cavity is powered by an independent klystron-modulator system, delivering RF pulse powers in the range of 7–36 MW at the cavity input. The interfaces between RF subsystems are illustrated through a block diagram in Fig. 1. The low-level RF (LLRF) system [6] generates the initial RF signal, which is subsequently amplified through a pre-amplifier and klystron. The amplitude and phase of the RF pulse are primarily controlled via LLRF setpoints, but are also influenced by variations in the high-voltage power supply (HVPS), including cathode voltage and current. Although HVPS parameters are typically adjusted only under

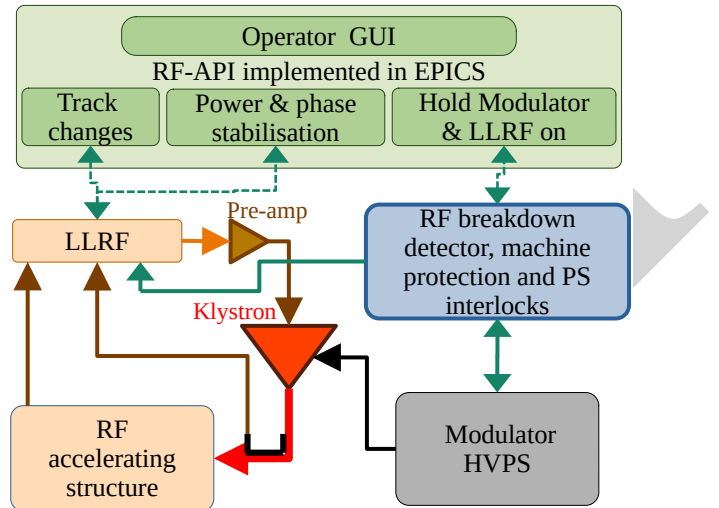


Figure 1: Block diagram of an RF system hardware, protection interlocks and interface with RF-API based control software.

specific conditions, thermal drifts within the system can introduce measurable variations in RF output.

Given the diversity of RF hardware deployed across CLARA, direct low-level control by operators would be impractical and error-prone. To address this, a unified RF Application Programming Interface (RF-API) and graphical user interface (GUI) have been developed using EPICS and Control System Studio (CS-Studio) [7] respectively.

## OPERATOR GUI INTERFACE

The operator GUI panels for all seven RF systems are standardised and presented within a single interface to ensure a consistent and efficient user experience, as shown in Fig. 2. The GUI is organised into functional sections, including modulator control, manual override capability, and power and phase adjustment.

Real-time system status is provided through numerical readbacks, status indicators, and colour-coded visual elements, enabling rapid assessment of system status. An interlock tree representation has been implemented to allow operators to efficiently trace the root cause of system trips.

An integrated notification panel displays command status, error messages, and suggested recovery actions via a rolling buffer. In addition, an embedded plotting interface enables short-term monitoring of RF powers, phases, and cavity temperatures.

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<sup>†</sup> Nirav.Joshi@stfc.ac.uk

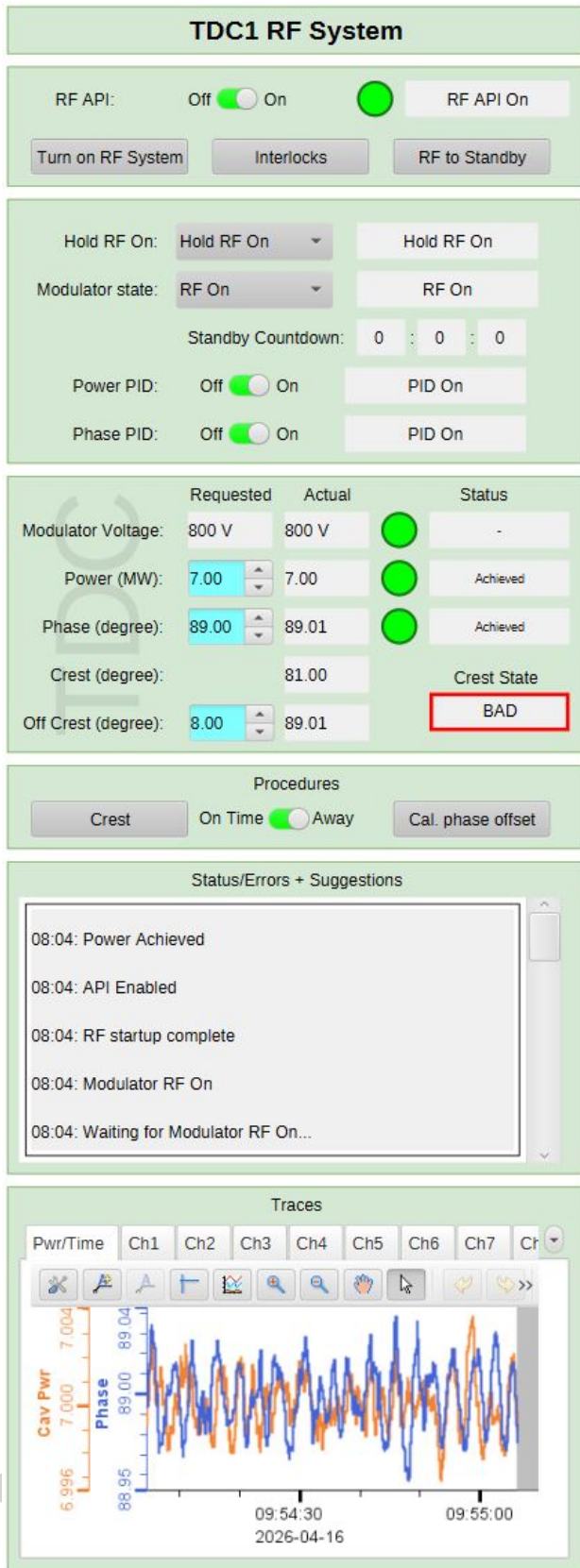


Figure 2: Operator GUI panel to control the RF system for the TDC.

## CONTROL LOGIC AND FEATURES

The RF-API is designed to provide an optimal balance between automation and operational flexibility. Its control architecture is modular, with individual functional components integrated through EPICS sequencers. Input/output controllers (IOCs) for all RF systems are derived from a generalised template and configured using system-specific substitution files. The development process was significantly accelerated through iterative testing, enabled by a Python-based simulation model developed to reproduce the dynamic response of the klystron. The process logic to turn on an RF system is described in Fig. 3.

Upon an operator request to enable an RF system, the RF-API loads a configuration file corresponding to the selected HVPS voltage. This file contains system-specific parameters, including PID gains for power and phase control, acceptable power tolerances ( $P_{\text{allowed}}$ ), and soaking durations ( $t_{\text{soak}}$ ). The absence of a valid configuration file prevents system activation, thereby enforcing prior validation by RF experts.

Following successful validation, the "Hold Modulator and LLRF on" segment clears machine protection interlocks and enables both the modulator and LLRF subsystems. RF power is then ramped from zero to the operator-defined setpoint ( $P_{\text{operator}}$ ) in a controlled manner.

Power ramping is implemented using discrete increments ( $P_{\text{step}}$ ), with a defined soaking interval at each step. For large power differences, the required LLRF setpoint is estimated using the interpolation coefficients loaded from the configuration file, which are derived from a pre-characterised power response curve. A power response curve for the TDC RF system is plotted in Fig. 4. For smaller adjustments a PID-based approach is employed.

At each step, the deviation between measured and requested power ( $P_{\text{error}}$ ) is continuously evaluated. If  $P_{\text{error}}$  exceeds the acceptable tolerance ( $P_{\text{allowed}}$ ), the ramp sequence is halted and RF expert intervention is requested. A power ramp cycle for TDC from 0 to 7 MW, with soaking for 40 s at each step of 1.5 MW, is plotted in Fig. 5, highlighting recovery in cavity vacuum.

This staged ramping strategy provides several operational advantages:

- Early detection of system gain variations indicative of performance degradation;
- Avoidance of multipacting and RF breakdown regions;
- Stabilisation of cavity vacuum and thermal conditions during operation.

Phase stabilisation is implemented using a PID loop referenced to  $0^\circ$ , thereby mitigating instability associated with phase wrapping near  $\pm 180^\circ$ . Additional compensation mechanisms are incorporated to account for temperature-induced phase variations in travelling wave linacs. In specific cases, stabilisation of a weighted combination of input and output phase is employed, with weighting factors determined empirically.

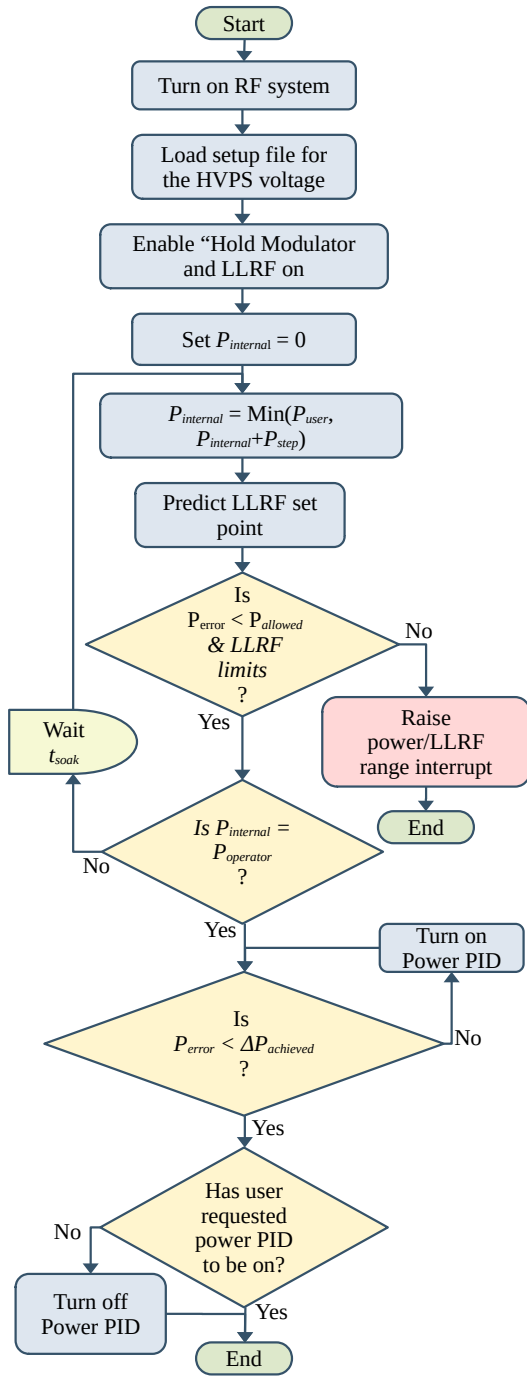


Figure 3: Process flowchart to turn on an RF system in CLARA.

With such implementation, RF-API provides a functional abstract layer for interaction, enabling efficient vertical integration into higher-order control applications, such as automated conditioning of RF structures [8, 9] and beam-based feedback. It provides a standard three level status flag informing the higher-order applications if their request to change the power or phase is still under processing, successfully completed or has encountered an error and failed.

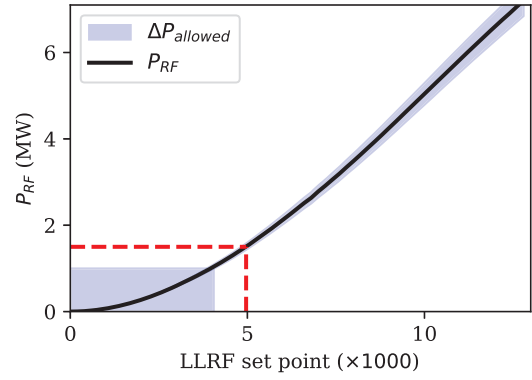


Figure 4: RF power ( $P_{RF}$ ) response of TDC RF system, highlighting acceptable power error ( $\Delta P_{allowed}$ ), and prediction of LLRF setpoint.

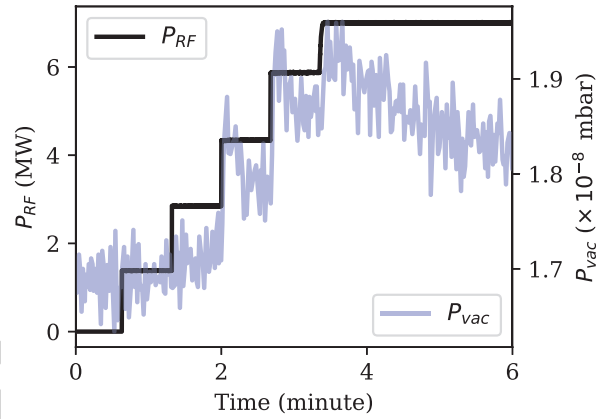


Figure 5: Ramping of TDC RF power ( $P_{RF}$ ), with soaking at each power step, allowing recovery of cavity vacuum pressure ( $P_{vac}$ ).

## PERFORMANCE

The RF-API has demonstrated stable and reliable operation across all RF systems, for more than six months since the start of the phase II technical system commissioning. Typical measured stability over an eight-hour operational period is better than 0.08% in RF power and 0.064° in phase. It has recovered the RF systems from trips within half a minute, minimising impact on the experiments, improving user experience.

## CONCLUSION

A modular RF Application Programming Interface has been successfully developed and deployed for RF system control at CLARA. The system provides a robust, safe, and operator-oriented framework that abstracts hardware complexity while maintaining high performance and flexibility. The RF-API enables consistent operation across heterogeneous RF systems and provides a scalable foundation for future accelerator control developments.

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