Automated Procedure for Conditioning of Normal Conducting Accelerator Cavities

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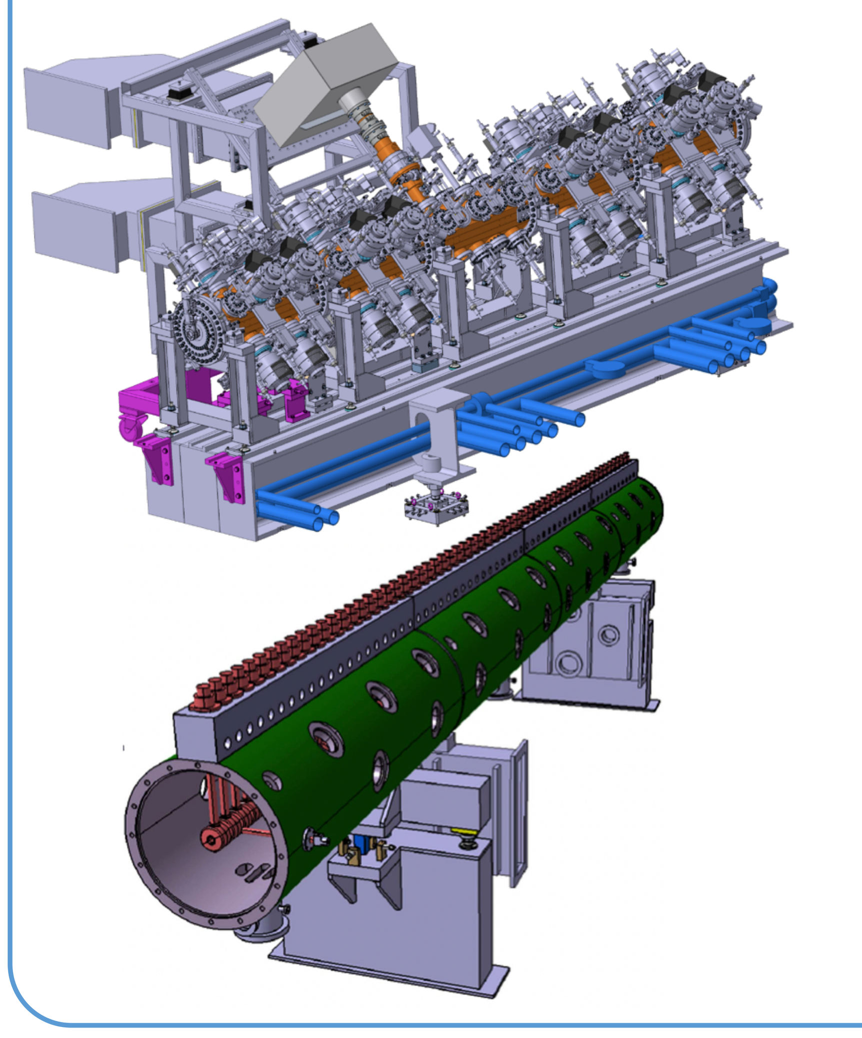
Abstract Radio frequency (RF) conditioning is an essential stage during the preparation of particle accelerator cavities for operation. During this process the cavity field is gradually increased to the nominal parameters enabling the outgassing of the cavity and the elimination of surface defects through electrical arcing. However, this process can be time consuming and labor-intensive, requiring skilled operators to carefully adjust the RF parameters. This contribution presents the software tools for the development of an automatized EPICS control application with the aim to accelerate and introduce flexibility to the conditioning process. The results from the conditioning process of the ESS Radio-Frequency Quadrupole (RFQ) and the parallel conditioning of DriftTube Linac (DTL) tanks will be presented demonstrating the potential to save considerable time and resources in future RF conditioning campaigns.

Introduction



Radio-Frequency Quadrupole (RFQ)

-In Kind collaboration from CEA-Saclay
-5 sections, total length of 4.55m.
-Beam Energy: 75 keV-3.6 MeV protons
-Resonance Frequency: 352.21 MHz
-RF pulse: 780 kW, 3.2 ms, 14 Hz
-Inter-vane voltage: 80-120 keV
-Installed in 2019, Conditioned in summer 2021.
-First proton beam injected in October 2021.

Drift Tube Linac (DTL)

-In Kind collaboration from INFN
-Total length 40 m, 5 tanks of 8 m each,
-Beam Energy: 3.6 MeV-90 MeV protons
-Resonance Frequency: 352.21 MHz
-Cavity field: 3 MV/m , 3.2 ms, 14 Hz
-DTL 1 Installed, conditioned and commissioned with beam in summer 2022.
-DTL 2,3,4 Installed, conditioned and commissioned with beam in summer 2023.
-DTL 5 Installed at ESS tunnel in September 2023.

System Architecture

Objective: Development of and IOC for automatize cavity conditioning process.

-Slow and Fast (<10 us) interlock handling.
-RF Local Protection system (RFLPS)
- PLC based Slow interlock module (SIM)
- FPGA based Fast interlock module (FIM)

-LLRF for cavity amplitude and phase adjustment.
-RFLPS and LLRF IOC (Input-Output Controller) state machine configuration.

Conditioning IOC gradually increases the power (P), pulse length (w) and repetition rate (f) of the cavity while monitoring the interlocks from RF and vacuum control systems.

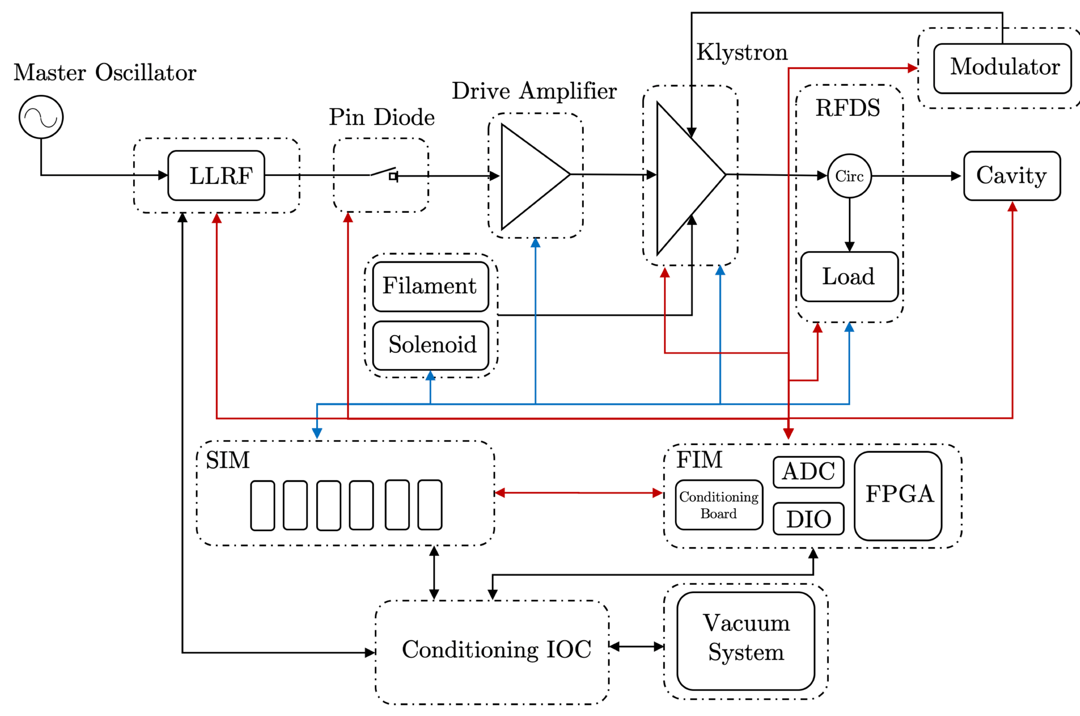


Figure : *RF cavity simplified control system architecture.*

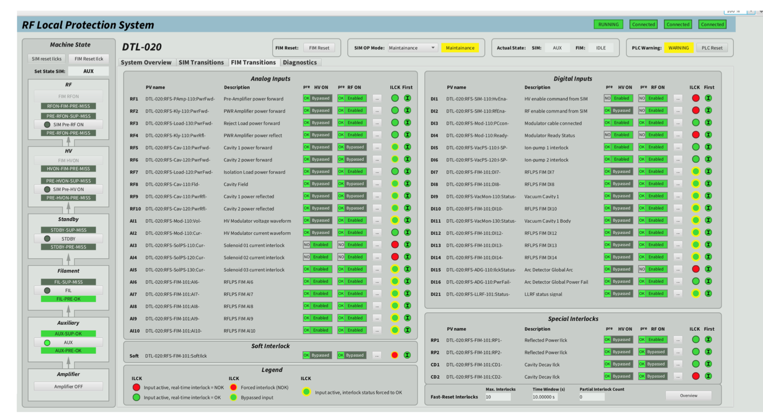


Figure : *RFLPS OPI state machine and interlock panel.*

IOC Structure and Algorithm Description

-Python and EPICS developed IOC using the ESS EPICS environment (e3).
-ESS EPICS environment (e3) developed by abstracting EPICS layers in order to facilitate IOC development and maintenance.
-Conditioning sequence written in State-Notation Language (SNL).
-State Notation Language (SNL) permits the implementation of complex control procedures directly developed on EPICS base utilizing EPICS Channel Access network protocol for Process Variable (PV) updates.
-OPI designed in Phoebus CSStudio.

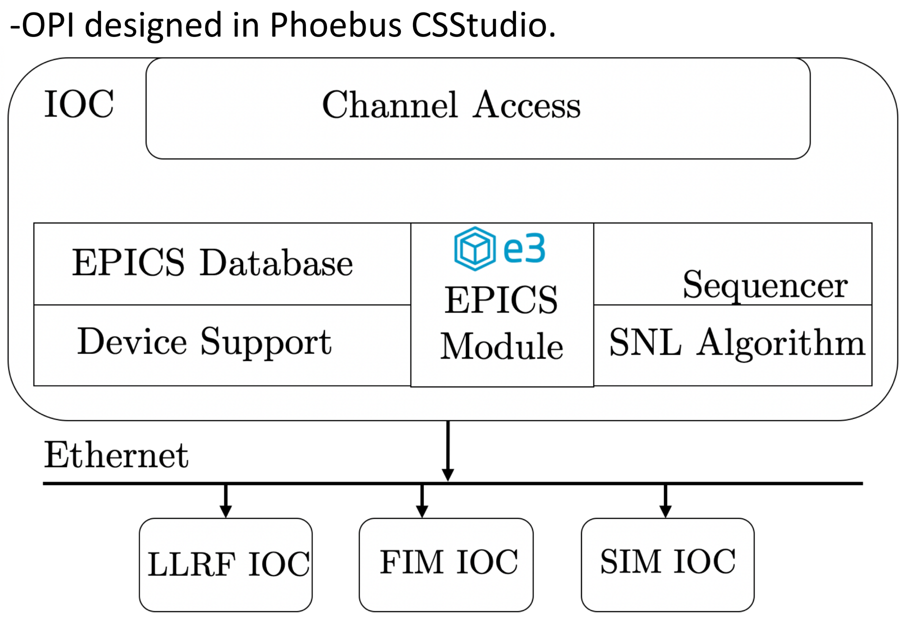


Figure : *Conditioning Algorithm IOC structure.*

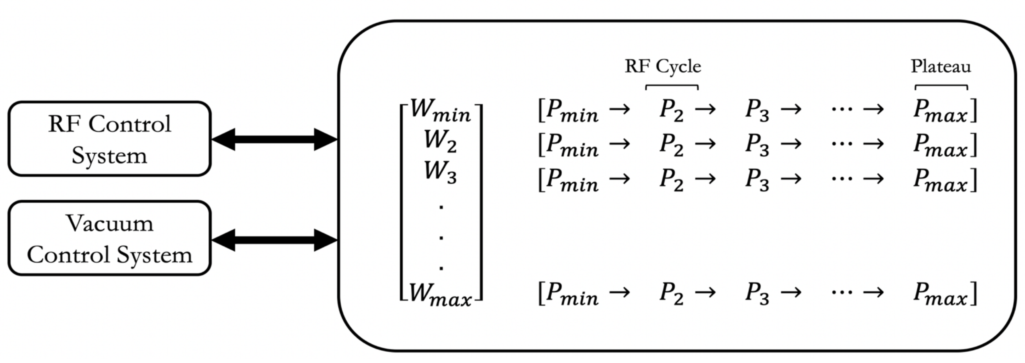


Figure : *Conditioning Algorithm vectors and sequence.*

-6 states for parameter set and interlock handling routines
-*Start*, *Operator stop*, *Reset* and continuous operation buttons.
-A power vector **P i**s assigned to each pulse length vector **W.**
-Starting from P_{min} power is gradually increased to P_{max} by $P_{step\text{-}up}$.
-Starting from w_{min} pulse length is gradually increased to w_{max} by $w_{step.}$
-Each power lever is applied for a number of pulses defined by RF *Cycle Duration* in sec.
-P_{max} is applied for a number of pulses defined by *Plateau Time* in sec.
-FIM, SIM, LLRF state machines and vacuum pressures continuously monitored.
-Interlock severity segregation scheme and handling routines.
-10us minimum pulse length mode for cavity recovery.
-Adjustable recovery times for vacuum and FIM, SIM interlocks.

Interlock Handling

Critical Fault

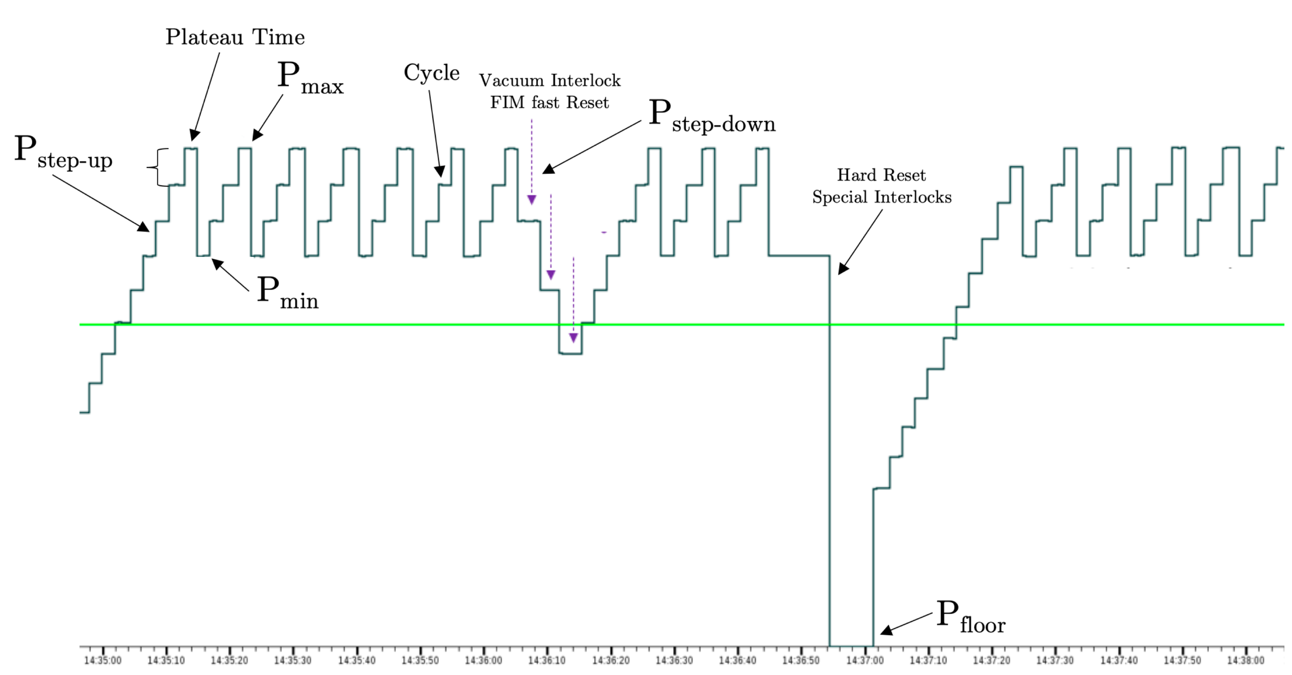
-RF power to cavity revoked.
-Manual Reset requested.
-Klystron, RFDS and modulator interlocks.

Major Fault

-RF power to cavity revoked.
-Algorithm attempts state machine Reset (Hard-reset).
-Special interlocks handling.
-Interlock rate sensitive.

Minor Fault

-Power is reduced with a predefined step.
-Option to reduce pulse length with a predefined step.
-Soft vacuum interlock and pressures
-Special interlocks handling.
-Failure to handle leads to hard reset.



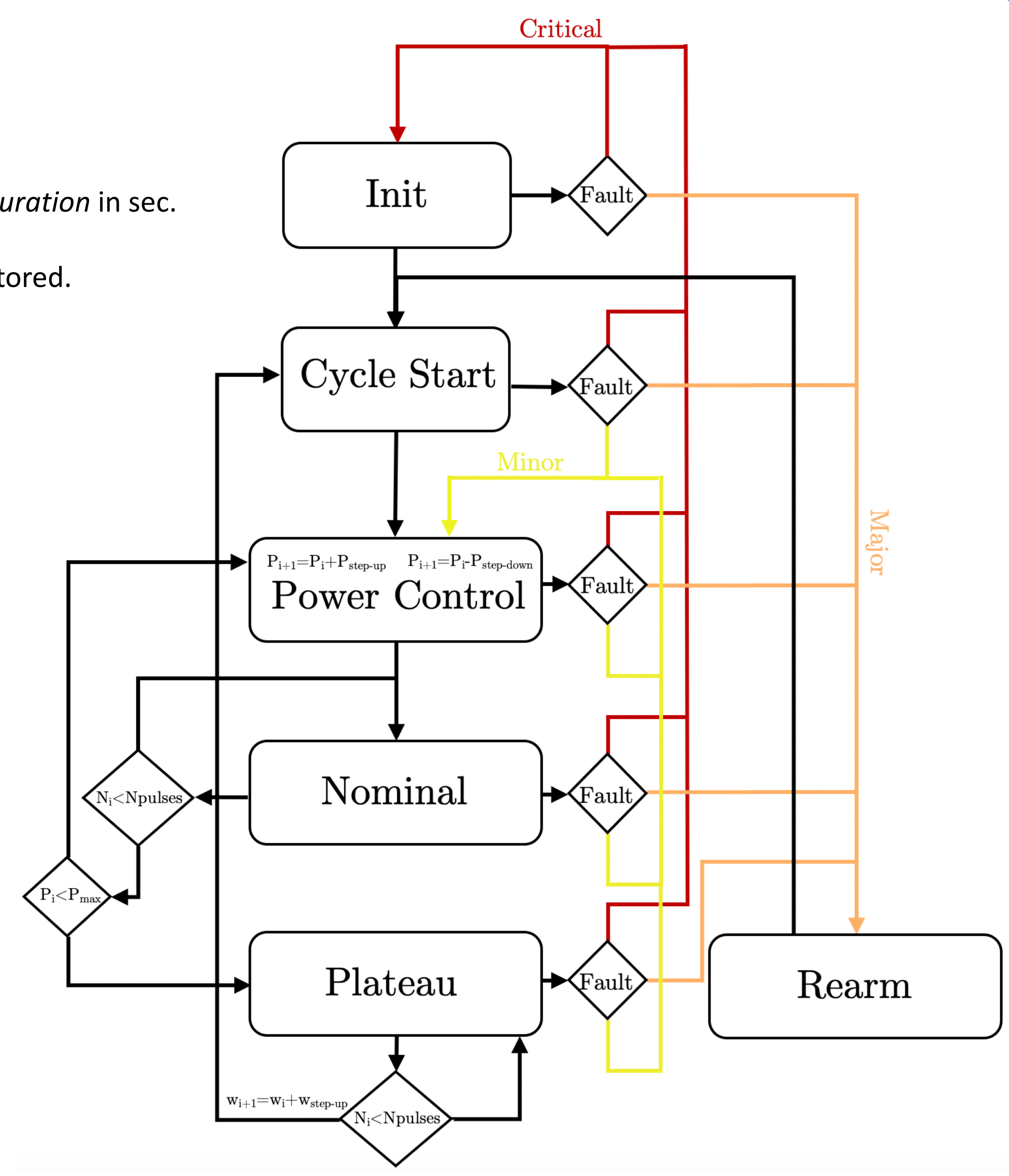
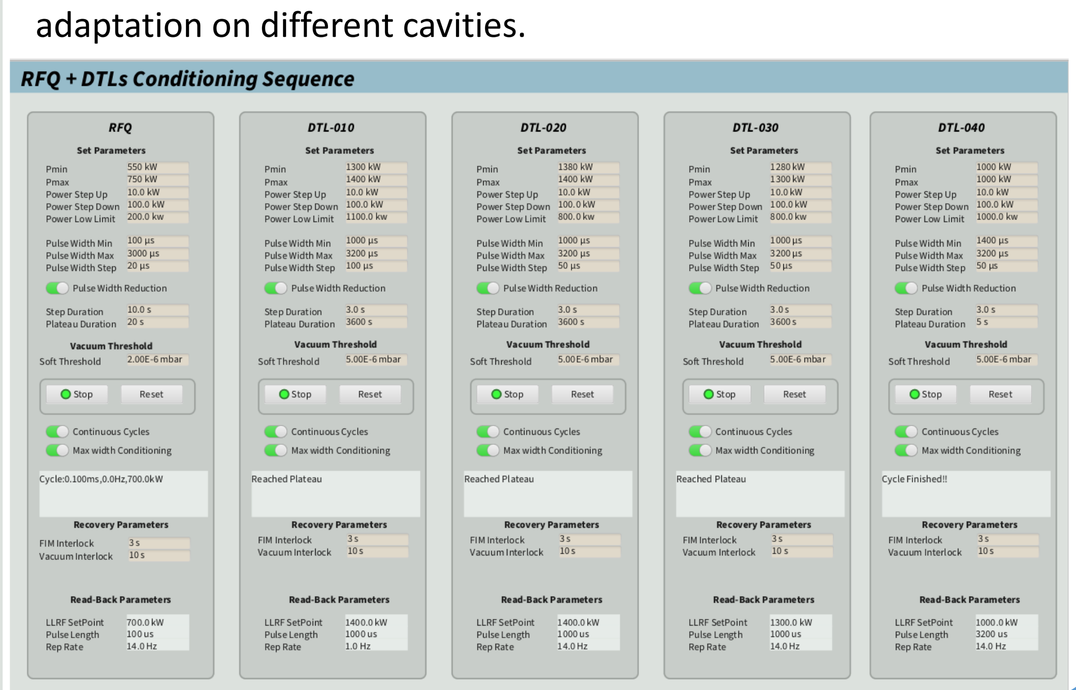


Figure : *RF Conditioning algorithm flowchart.*

-RFQ and DTL Tanks parallel Conditioning conditioning process.
-Tested with simulated interlocks and developed conditioning testing IOC for RF pulse and vacuum pressure simulation.
-"Expert " and Simplified Operator Interface (OPI).
-Fully configurable parameters and Interlock Recovery times for improved scenario adaptability.
-Readback Parameters and correlated waveforms.
-Generic design employing macros and start-up scripts for easy adaptation on different cavities.



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Conclusions

-RFQ and DTL Tanks Conditioning process accelerated with the implementation of the conditioning IOC.
-Reduction of operator engagement and improved efficiency.
-Challenging to develop a standard universal conditioning algorithm as each cavity exhibits different behavior.
-Flexibility, Maintenability and version control are essential to adapt to day-to-day challenges.
-Studies and investigation on going to further improve the process, act preemptively and address occurent issues.