ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-TUPDP080

AUTOMATED PROCEDURE FOR CONDITIONING OF NORMAL CONDUCTING ACCELERATOR CAVITIES

E. Trachanas*, G.Fedel, S. Haghtalab, B. Jones, R. Zeng
European Spallation Source, ESS-ERIC Lund, Sweden
A. Gaget, O. Piquet- CEA-IRFU, University Paris-Saclay, Gif-sur-Yvette, France
Luca Bellan, Carlo Baltador, Francesco Grespan- INFN/LNL, Legnaro

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 (Experimental Physics and Industrial Control System) 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 Drift-Tube Linac (DTL) tanks will be presented demonstrating the potential to save considerable time and resources in future RF conditioning campaigns.

INTRODUCTION

The European Spallation Source (ESS) linear accelerator is designed to accelerate a 62.5 mA, 2.86 ms, 14 Hz proton beam up to 2 GeV to the entrance of a rotating tungsten target and is divided in a normal-conducting (NCL) and a superconducting part (SCL). The normal conducting part is comprised of electromagnetic cavities at room temperature operating at 352.21 MHz containing the ion source, a Low Energy Transport (LEBT), a Radiofrequency Quadrupole (RFQ), a Medium Energy Beam Transport (MEBT) and five (5) Drift-Tube Linac (DTL) tanks (as shown in Fig. 1) [1].

The ESS RFQ was delivered by CEA-Saclay equipped with four (4) modulated vanes and a total length of 4.55 m accelerating the proton beam up to 3.6 MeV with an inter-vane voltage of 120 keV and a duty cycle of 4% [1]. The ESS RFQ was installed at ESS accelerator tunnel in 2019 and following the local and integrated testing phase, power conditioning was successfully completed in summer 2021 (see Fig. 2) and the first proton beam injected in the RFQ in October of the same year [2–4].

The Drift Tube Linac (DTL) is an in-Kind collaboration from INFN composed of five (5) tanks of 8 m each accelerating the beam up to 90 MeV. DTL 1 has been conditioned and commissioned with beam in summer 2022 [5, 6] followed by the installation of DTL tanks 2,3,4 in late 2022. The RF conditioning process for DTL 2,3,4 along with beam commissioning process started at the beginning of 2023 and completed in late summer of the same year [7,8]. DTL 5 was installed at the ESS accelerator tunnel in September 2023 and the preparatory testing phase before RF conditioning is ongoing.

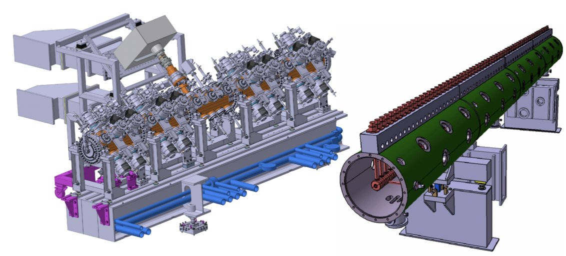

Figure 1: The ESS Radio Frequency Quadrupole and an ESS Drift Tube Linac tank.

RF conditioning is a time consuming and challenging process that lasts for several weeks and requires multiple parameters constant monitoring especially when performed for multiple cavities simultaneously. RF conditioning is a standard process before operation where the cavity field is progressively increased to the nominal level.

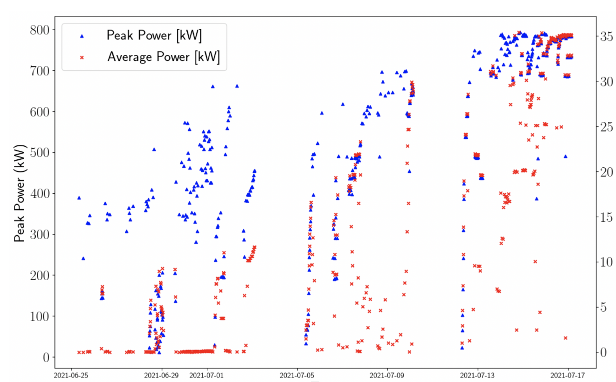

Figure 2: Peak and Average power in the RFQ cavity between 25-06-2021 – 17.07.2021 showing the gradual increase of cavity field to the nominal values.

During this process, different mechanisms such as outgassing, multipacting or field emission can lead to electrical arcing which to some degree is a desirable effect for surface defect elimination. Extensive arcing and vacuum breakdowns can potentially lead to cavity and equipment damage, making the need for a versatile interlock system essential. In

* Emmanouil.Trachanas@ess.eu

19th Int. Conf. Accel. Large Exp. Phys. Control Syst. ICALEPCS2023, Cape Town, South Africa JACoW Publishing
ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-TUPDP080

order to reduce the amount of work and time needed on that process facilities around the world have implemented automatized procedures based on different control frameworks and algorithms [9–15]. Moreover, there is a growing interest on predicting cavity breakdowns and interlocks employing machine learning techniques that could be potentially used in the future in tandem with automatic conditioning algorithms for further improving the efficiency of the process [16, 17]. The conditioning process for RFQ and all DTL tanks is performed using a Python and EPICS based automatised procedure in an effort to accelerate and optimise the process. The automated sequence and logic was based on the RFQ coupler test stand conditioning algorithm from CEA [18] which except the NCL warm cavities was also adapted and implemented by *Wang et al.* at TS2 for ESS cryomodule conditioning [19, 20]. Mainly the RF conditioning campaign is divided in thee different stages: i. low power conditioning, ii. high power conditioning and iii. nominal operation. Although this distinction is rather a simplification, each stage requires a different conditioning strategy with fine-tuning of interlock and conditioning sequence thresholds.

SYSTEM ARCHITECTURE

ESS RF Control system architecture is comprised of the cavity Local Protection System (RFLPS) and the Low-Level RF (LLRF) system. Local protection system follows a state machine configuration and is based on a PLC Slow Interlock Module (SIM) and a MicroTCA Fast Interlock Module (FIM) able to shut-off the RF power on the cavity in less than $10\mu s$. The RF control system monitors and controls the different interlocks in the entire system chain (e.g forward and reflected power levels, cavity field, arc detectors, electron pick-ups) in a centralised and structured way [21]. During RFQ and DTL cavity operation the Low-Level RF system (LLRF) adjusts the amplitude and phase of the cavity employing a feedback control loop that compensates the frequency detuning due to cavity heating. The ESS vacuum control system is interlinked with RFLPS offering cavity vacuum pressure readbacks and vacuum interlock handling.

The automated conditioning procedure was developed as an Experimental Physics and Industrial Control System (EPICS) Input-Output Controller (IOC) using the ESS EPICS environment (e3) and written in State Notation Language (SNL). ESS has deployed the ESS EPICS environment (e3) as a toolkit and interface with the the goal to facilitate control application development by simplifying and abstracting EPICS functional layers [22]. SNL is a language that permits the implementation of complex control procedures directly developed on EPICS base utilizing EPICS Channel Access network protocol for Process Variable (PV) updates [23]. The SNL code is comprised by six (6) states that perform different functions (Init, Cycle Start, Power Control, Nominal, Plateau, Re-arm) and at every state the RF and Vacuum control systems are monitored. The main GUI (OPI) was designed using the Phoebus CStudio [24]. Conditioning IOC was designed in order to be generic, flexible and easily adaptable to any RF cavity using macros and changing the PVs for setpoints and monitoring from dedicated start-up scripts. The IOC configuration of the conditioning algorithm is presented in Fig. 3. The developed conditioning algorithm and GUI (OPI) are available at the GitLab repository of this study [25].

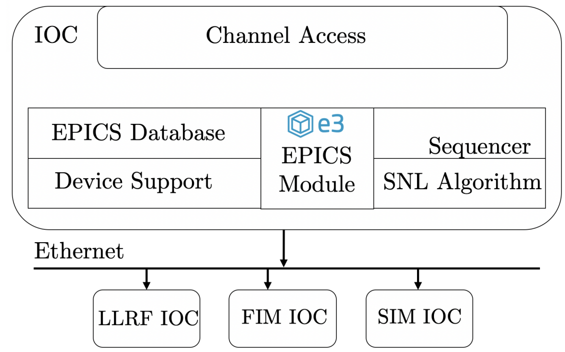

Figure 3: Conditioning algorithm IOC structure.

The developed code stands as a top level IOC and interfaces with RF and vacuum control systems. IOC sets the RF pulse power level (P), pulse length (w) and repetition rate at LLRF level and monitors cavity response and Breakdown Rate (BDR) via the status of FIM and SIM state machines along with the vacuum pressure levels provided by the vacuum control system. The algorithm implements severity level interlock segregation that leads to different response in the context of the selected conditioning strategy and offers the possibility to re-arm the LLRF and RFLPS state machines. The simplified overall system architecture is presented in Fig. 4.

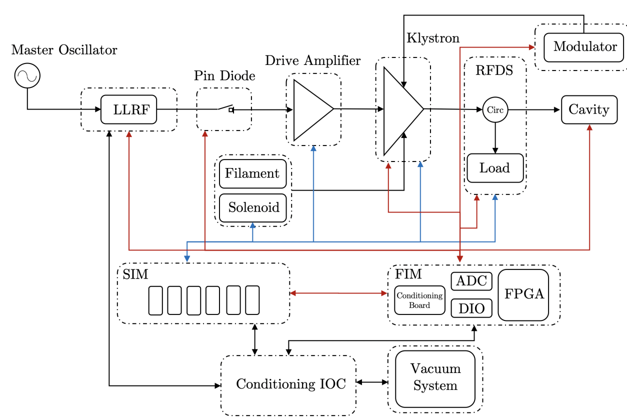

Figure 4: RF cavity simplified control system architecture.

ALGORITHM DESCRIPTION

In order to implement an automated cavity conditioning process the algorithm relies on the definition of a pulse length vector $\vec{w} = [w_{min}, w_2, w_3, w_i, ...w_{max}]$ and a power vector $\vec{P} = [P_{min}, P_2, P_3, P_i....P_{max}]$ is assigned to each w_i (See Fig. 5). Each value of the power vector is assigned to the LLRF setpoint and subsequently to the cavity for a

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number of pulses defined by a *Cycle Duration* time constant. Inside the SNL code the *Cycle Duration* is multiplied with the Repetition Rate to yield the number of RF pulses the power is applied to the cavity.

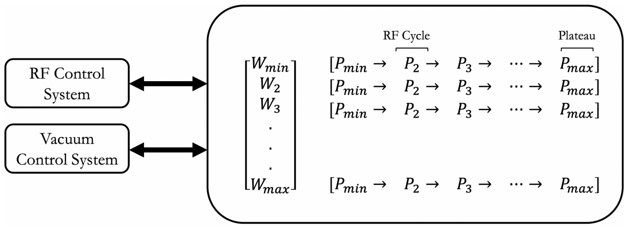

Figure 5: Conditioning application width ($\vec{w}$) and power vectors ($\vec{P}$).

The cavity response is monitored in real-time and in case no interlock is present, the procedure increases the power by $P_{step-up}$ kW until the P_{max} of each width w_i. The P_{max} is applied to the cavity for a *Plateau Time* time constant and then the algorithm proceeds to the next pulse width value (w_{i+1}) increased by $w_{step-up}$ until the end of the width vector (w_{max}). The parameters P_{min}, P_{min}, $P_{step-up}$, w_{min}, w_{max}, $w_{step-up}$, *Cycle Duration* and *Plateau Duration* are set by the operator through the main OPI. The main OPI, employing the automated conditioning algorithm for the simultaneous conditioning of four DTL cavities is presented in Fig. 6. The blue and red trends correspond to the power level setpoint and readback whereas the magenta and light green trends to pulse length and repetition rate setpoints respectively. The green waveform corresponds to the monitored cavity vacuum pressure and the observed slight increase on specific power levels is an indicator of multipacting. This waveform correlation is particularly useful when using the algorithm in order to detect and clean multipacting bands in the low power regime. Pressing the *Infinite Button*, the algorithm can run continuously following the pulse width and power vectors whereas the *Operator Stop* button implements a sequence emergency stop.

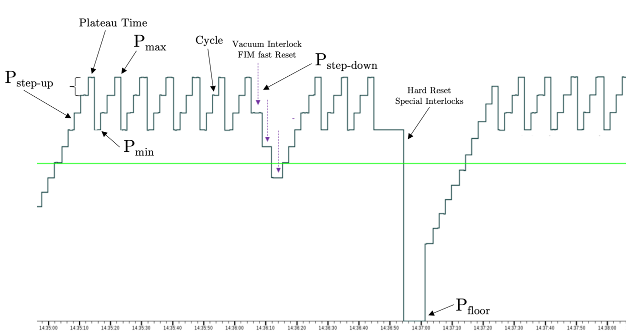

Figure 7: Example from DTL conditioning showing the different algorithm parameters, ramp-up, ramp-down and hard-reset procedures.

In case of a fault during power ramping process, the conditioning algorithm segregates the interlocks in three main categories i. *Critical Fault*, ii. *Major Fault* and iii. *Minor Fault*. A Critical fault indicates a fault in the system chain reported by FIM and SIM that leads to the immediate stop of the RF power. During ESS RFQ and DTL conditioning these faults are associated with RF distribution system and in such case the conditioning algorithm waits for the manual reset of the RFLPS and LLRF state machines from the operator or the shift leader. A *Major Fault* occurs when the number of special interlocks like *Reflected power* or *Cavity Decay* surpass a pre-defined threshold in a specific time period. The RFLPS stops the RF power again to the cavity although the conditioning algorithm attempts to re-arm ("hard-reset") the RFLPS state machine and LLRF digitizers.

After the re-arm, the conditioning IOC applies the P_{min} that corresponds to the last executed w_i and follows the defined conditioning sequence. During the RF cycle IOC monitors the vacuum pressures of each tank and if any transcends a threshold defined in the conditioning IOC (Soft Threshold- *Minor fault*) the power is reduced by a predefined value that can be set from the OPI, $P_{step-down}$ for as much time as the vacuum levels are above the threshold (see Fig. 7). Although, the power level cannot go lower than the P_{floor} value that can also be set from the OPI. If IOC attempts to assign P_{floor} power level to the cavity multiple times unsuccessfully the RF power injection is stopped by the algorithm and a manual reset is requested. In case of a hard threshold limit from vacuum control system the IOC waits for a pre-defined amount of time before attempting reset. In the new version of the code deployed for the ESS DTL tanks the *Pulsed Width Reduction* button leads also to the reduction of the pulse length in case of a *Minor Fault*. The *Minor fault* handling routine (power or power/width reduction) also applies in the case of a Special FIM interlocks that do not lead to RFLPS RF power stop.

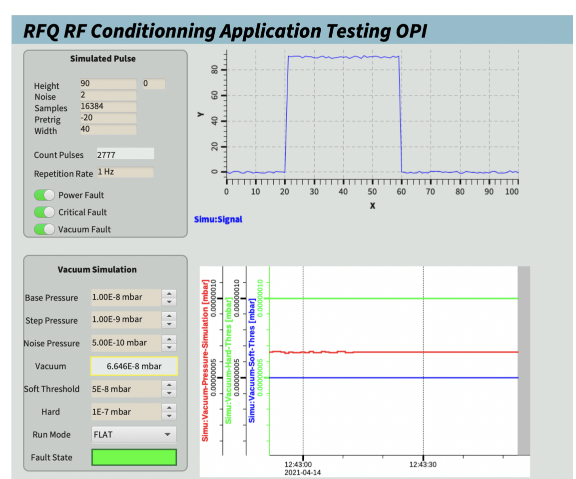

Figure 8: RF conditioning application testing OPI.

Conditioning IOC can be used together with the RF conditioning application testing OPI and IOC that simulates RF pulses and different kinds of faults. Furthermore, it includes a vacuum pressure simulation waveform with properties defined in the vacuum simulation panel. Depending on the

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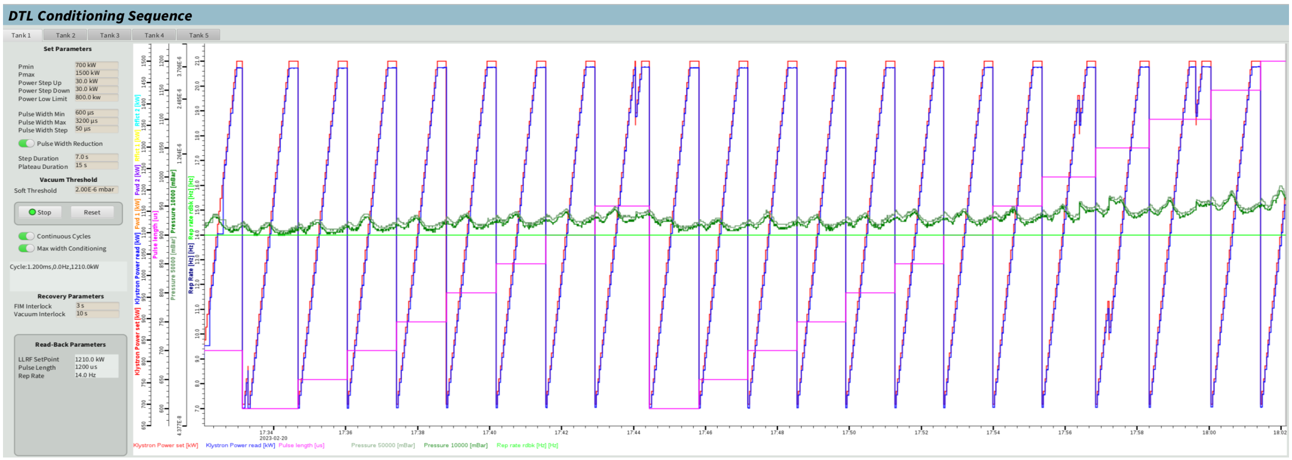

Figure 6: Application of the automated RF conditioning algorithm for the simultaneous conditioning of four DTL Tanks.

entries the new pressure value is calculated simulating an increasing, decreasing or constant vacuum pressure. The OPI for RF conditioning application testing IOC is presented in Fig. 8.

During RFQ and DTL cavity conditioning it was observed that during the automated rearm or *hard-reset* process the cavity could not restart when receiving multiple sequential interlocks. In order to address this issue conditioning algorithm attempts to send the minimum pulse length ($10\mu s$) in order for the cavity to recover. Failure to restart the cavity with $10\mu s$ leads to RF power stop to the cavity by the algorithm. The simplified flowchart for the conditioning algorithm is presented in Fig. 9.

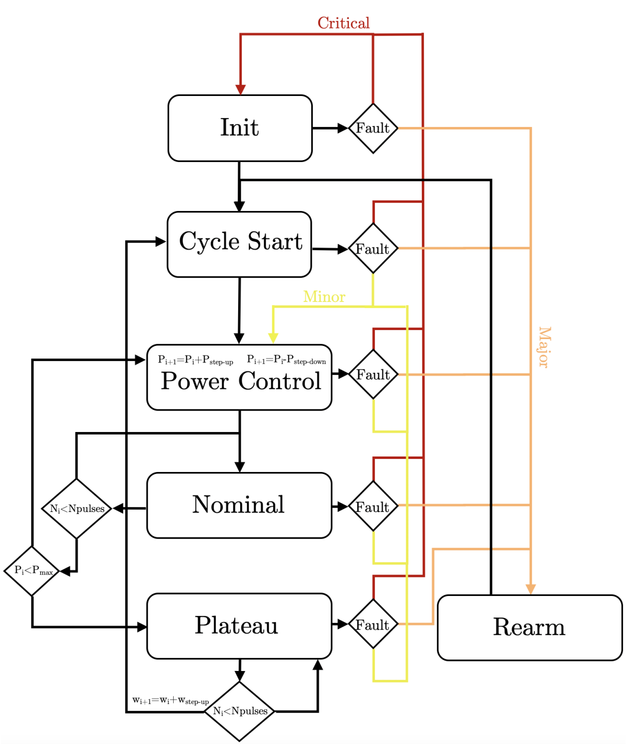

Figure 9: RF conditioning algorithm flowchart.

CONSIDERATIONS AND CONCLUSIONS

The simple, yet flexible algorithm designed and tested at ESS was extensively used in the last commissioning rounds, especially the last round completed in August 2023 where RFQ and DTL1 had to be re-conditioned in parallel to the simultaneous conditioning of the DTL tanks 2,3 and 4. At this point, and following the reports from other facilities [10, 11, 15, 26] some important considerations need to be taken into account. Firstly, it is particularly challenging to design a standard conditioning procedure applicable to different cavities rather than the strategy and subsequently the algorithm need to be adjusted in a case-by-case basis. Cavity response and conditioning times might differ from one cavity to another and there is a great interest in algorithms and strategies that will improve and streamline the process [26]. Following the lessons learnt during the ESS conditioning process we can distinguish three conditioning regimes: i. *Peak Field* - where the pulse length is kept constant and the power level is increased until we reach the nominal cavity field, ii. *Pulse length increase*- where the power is kept constant and pulse length is increased in order to trigger cavity outgassing and iii. *Low Power-fixed pulse length* for multipacting bands cleaning. The algorithm was adapted to implement these regimes and react to cavity responses for a number of different scenarios. A robust version control scheme and a flexible approach that permit easy modifications and adjustments on the code is essential in order to address day-to-day challenges.

Secondly, an automated conditioning algorithm indeed increased substantially the efficiency and the time spent on the conditioning process, although the design of a fully automated procedure still remains challenging [10, 11].In order to further reduce cavity trips that will inevitably lead to an accelerated conditioning process predictive modeling and machine learning algorithms might also provide the tools in order to detect present patterns in large datasets obtained during conditioning periods at ESS. The conditioning process was accelerated via the automated conditioning sequence, although additional work and further studies are needed in order to completely automatize the process, act preemptively and reduce operator engagement time.

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