

HIGH POWER CONDITIONING OF CLARA'S RF STRUCTURES

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Abstract

In April 2024, work began at Daresbury Laboratory on the high-power conditioning of CLARA's (Compact Linear Accelerator for Research and Applications) radio-frequency (RF) structures using proprietary automated RF conditioning software, NO-ARC (No Operator Automated RF Conditioner) to attain operational powers and pulse lengths. The four types of structure conditioned were an S-band standing-wave photoinjector (PI), known as the High Repetition Rate Gun (HRRG); four S-band travelling-wave linacs (L01-4); an S-band standing-wave transverse deflecting cavity (TDC); and S-band waveguides under vacuum. Here we present the conditioning progress for each structure in terms of power, RF pulse length, number of pulses and total breakdown count. Key features are highlighted and discussed, along with fallback conditioning strategies.

INTRODUCTION

After the successful build of CLARA Phase-II, including the Full Energy Beam Exploitation (FEBE) branch [1] [2], the next step before beam commissioning and a friendly user experiment run [3] was the high power conditioning of the RF structures. The process of RF cavity conditioning is one where power is gradually introduced into the structure until the nominal operating power and pulse length are reached. If power is applied too aggressively then breakdowns (BDs) can occur; electrical arcing which can damage the internal surface of the structure and even encourage more arcing at the now discontinuous BD site.

Conditioning began in April 2024 on L02 and L03 and proceeded with the other cavities as all necessary systems came on-line. All cavities were conditioned using ASTeC's automated conditioning software, NO-ARC [4], at a pulse repetition rate of 100 Hz. See table 1 for a summary of CLARA cavities' RF parameters.

RF Conditioning Algorithm

Conditioning algorithms can vary greatly, but for this body of work we used the general algorithm outlined in figure 1, referring to the terms defined in table 2.

Put simply, the power is ramped at a given pulse length until nominal peak power is reached then the pulse length is increased and power ramped back up from a minimum peak power, this is repeated until the operational peak power, pulse length and optimal BDR (see table 2) are met.

Table 1: CLARA RF Cavity Design Parameters

Parameter	Unit	HRRG	L01	L02-4	4HC	TDC
Cavity type	–	SW	TW	TW	TW	SW
f	GHz	2.9985	2.9985	2.9985	11.994	2.9985
Q_0	–	13800	14200	12800	7150	16000
R_{sh}	M Ω /m	60	54	62	68	5
Phase advance	rad	–	$2\pi/3$	$2\pi/3$	$5\pi/6$	–
Cells	–	1.5	61	122	72	9
Active length	mm	–	2033	4066	750	–
RF pulse width	ns	2500	540	955	105	3000
$E_{acc,nom}$	MV/m	100	17	20	12	–
$E_{acc,max}$	MV/m	120	25	25	30	–
Deflecting kick	MV	–	–	–	–	10
$P_{RF,nom}$	MW	7	23	36	6	7
$P_{RF,max}$	MW	9	32	57	29	9

Table 2: Definition of RF Conditioning Terms Used in Fig. 1

Term	Definition
Frontier power	Power level immediately preceding a breakdown event.
Logarithmic ramp	Rapid initial recovery with a progressively slower approach to target power.
BDR	Breakdown rate. How many breakdowns per 10^5 or 10^6 pulses.
Acceptable BDR	≤ 1 breakdown per 10^5 pulses.
Optimal BDR	≤ 1 breakdown per 10^6 pulses.
Ramp rate	Fixed power increment applied every n_{pulses} , provided the BDR is acceptable.

Conditioning Infrastructure

Many systems are necessary for conditioning to be implemented, three of the most critical (NO-ARC, BADAS and RF-API) are briefly introduced here.

Since 2016, ASTeC have developed an automated RF conditioning software application called NO-ARC, with the latest v5 being deployed during this conditioning period. NO-ARCv5 is now a configurable finite state machine, coded in object oriented Python, see [4] for a detailed overview of this system.

CLARA's breakdown detector (Breakdown Anomaly Detection And Sampling, BADAS) is a trace violation system whereby a 1 dimensional time series comprising 1017 samples with a 9 ns sampling interval generated from directional couplers in the waveguide, or probes within the cavity, are averaged over the last four pulses and an incoming trace is compared to this averaged form. If the new trace lies outside a configurable window formed around the average trace a

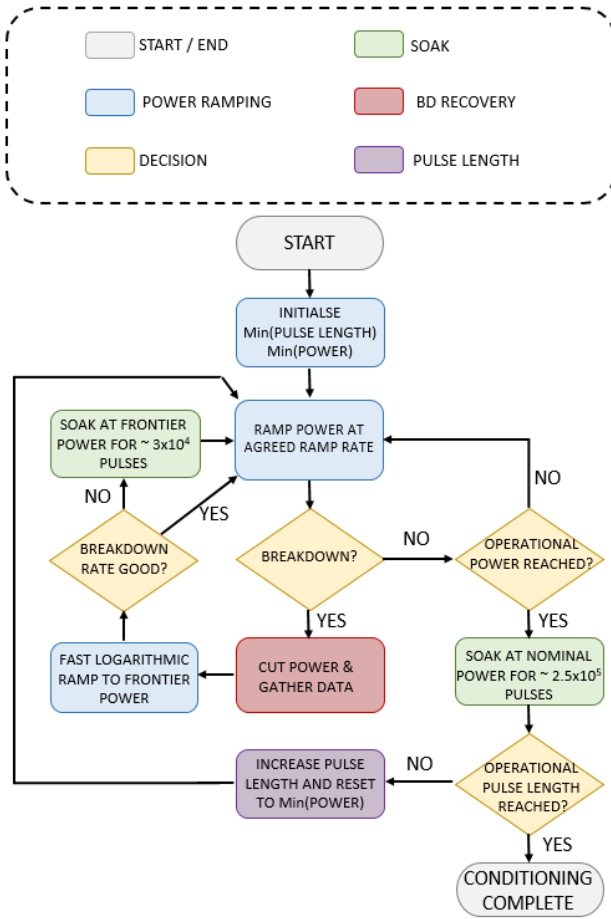


Figure 1: Flow chart depicting the conditioning algorithm applied to all CLARA RF structures via NO-ARC. See table 2 for definitions of terms. Note that if a breakdown occurs during the "soak at nominal power" phase, the power is cut and then log ramped back up to nominal power.

breakdown is declared. At this point BADAS enters a hold state, restoring a default choke mechanism on the LLRF system, attenuating the power by a factor of 1000, guaranteeing that the next pulse is benign. BADAS remains in this hold state until an external reactivation signal is received.

A recently developed modular RF Application Programming Interface (RF-API) has been deployed for RF system control at CLARA, providing a robust, safe, and operator-oriented framework that abstracts hardware complexity while maintaining high performance and flexibility, enabling consistent operation across all RF systems. See [5] for a complete description of this application.

RESULTS

Results are presented for the vacuum waveguides and for each cavity following conditioning. See table 3 for a summary of the main statistics.

Vacuum Waveguide

The waveguide systems for the travelling wave structures (L01 and L02-4) were evacuated to achieve the required

operating vacuum of $< 2 \times 10^{-7}$ mBar. In all cases, the vacuum waveguides needed conditioning before any meaningful power could be delivered to the cavities. This was achieved by increasing the pulse length to the target maximum and proceeding as per the algorithm with respect to peak power and breakdowns. The idea was to maximise the heating of the waveguide for each pulse delivered and encourage sustained outgassing of any volatiles within the waveguide bulk.

HRRG

A key feature of this PI design [6] is the use of an interchangeable photocathode plug based on the INFN design [7], alongside a cathode load / lock system enabling rapid replacement without exposing the PI to air. The conditioning cathode was a hybrid design with a bulk molybdenum (Mo) plug and a diamond-turned copper (Cu) tip as the photoemitting surface.

Conditioning this cavity was challenging and protracted, with numerous breakdowns hindering power ramping.

Post-conditioning inspection revealed scarring on the Mo plug shaft, suggesting sparking in a space-constrained region prone to outgassing accumulation. Similar issues have been reported at other facilities using load / lock systems [8]. This is likely not the sole breakdown mechanism, and further investigation is required.

L01

Conditioning met expectations and BD_{tot} was low, although the process was power limited due to the Klystron (Thales TH2100).

L02

Conditioning was arduous with a high BD_{tot} with various strategies to accelerate progress investigated, see "Conditioning Fallback Strategies" section. The power reflected back from the cavity was a problem and the interlock (set to 1 MW) tripped regularly. After advice from a colleague from PSI (C. Beard, private communication), we increased the interlock to 10 MW. To further minimise reflected power Gaussian pulse shaping was applied to the incident power pulse profile, ensuring the pulse's FWHM matched the required RF pulse length.

L03

Conditioning progressed well with reasonable BDRs and power ramping. Since operational pulse length and peak power were reached ahead of time, the cavity was conditioned beyond specification, aiming to guarantee greater stability during subsequent operation. See figure 2 for an overview of the process.

L04

The cavity was conditioned up to operational parameters, relatively quickly. The elevated vacuum waveguide pressure restricted progress as NO-ARC was set to soak power at waveguide pressures above 2×10^{-7} mBar.

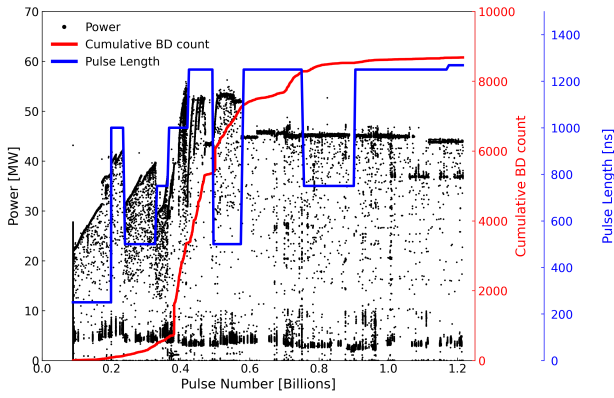


Figure 2: The conditioning performance of CLARA's L03.

TDC

This was a near perfect conditioning run, where BD_{tot} remained low (< 100), no fallback strategies were needed and with the aid of NO-ARC providing round-the-clock conditioning, only 11 calendar days were required to obtain operational parameters. See figure 3 for an overview.

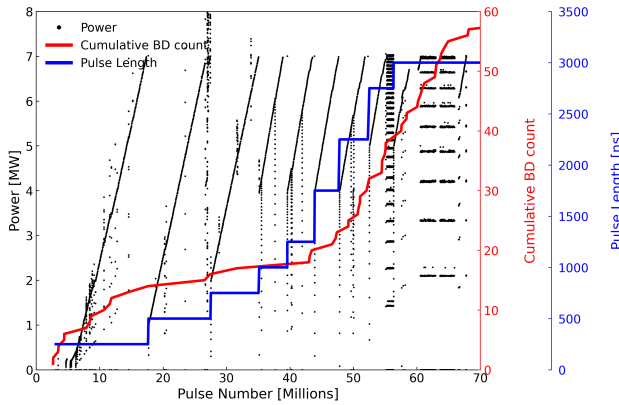


Figure 3: The conditioning performance of the CLARA TDC.

4HC

The 4th harmonic cavity [9] is presently undergoing conditioning. Progress has been severely hampered by problems sealing the X-band waveguide flanges, where we have seen issues with vacuum seals and discontinuities causing waveguide breakdowns. Many complications have been addressed and resolved, but some issues remain.

Table 3: High power conditioning summary for all of CLARA's 7 RF cavities. BD_{tot} refers to the total breakdown count experienced by each cavity.

Cavity	Pulse [μ s]	Power [MW]	BD_{tot}	Pulses [$\times 10^9$]	Days
HRRG	2.5	7.0	62953	1.960	419
L01	1.25	13.0	456	0.133	294
L02	1.25	36.0	74766	1.655	368
L03	1.25	36.0	8680	1.216	328
L04	1.25	36.0	7938	1.133	232
TDC	3.0	7.0	3478	0.068	11
4HC	—	—	—	—	—

CONDITIONING FALLBACK STRATEGIES

A recurring issue, particularly with the HRRG and L02, was the stagnation of frontier power at a given pulse length (typically operational), where a high breakdown rate prevented further ramping. This led to repeated $BD \rightarrow$ power reduction \rightarrow logarithmic ramp cycles (“sawtoothing”), making conditioning at the frontier inefficient.

An effective mitigation strategy was “pulse length recycling,” where the pulse length was reduced and the algorithm restarted, conditioning back up to the operational pulse length. This process was repeated until target power and pulse length were reached (see Fig. 4). This approach enabled conditioning beyond nominal peak power, promoting stable operation.

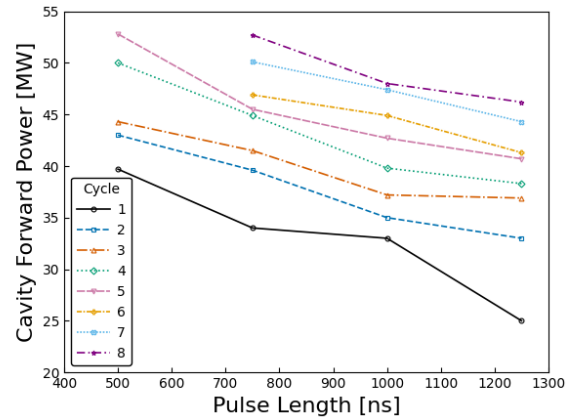


Figure 4: The conditioning fallback strategy of pulse length recycling as applied to L02, showing the peak power attained at each pulse length with improvement observed across successive cycles.

CONCLUSION

Here we have introduced the conditioning algorithm applied to CLARA RF structures via the robust automated conditioning software NO-ARC using associated infrastructure. Cavities that were well-behaved and relatively easy to condition were presented in detail (L03 & TDC), as well as suspected problems and fallback strategies relating to cavities where the process of obtaining operational parameters proved to be more demanding (HRRG & L02). All S-band CLARA cavities have been conditioned to pulse lengths, peak powers, and BDRs sufficient to support beam commissioning, followed by a series of successful experiments during the first friendly user run. [3].

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