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# RF CONDITIONING OF THE CLARA 400 Hz PHOTOINJECTOR

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*Abstract*

Automated conditioning of the 400 Hz photoinjector for CLARA was begun and the conditioning program refined. The conditioning was performed at 100 Hz. Masks were used to detect breakdowns in the reflected power and phase, and the breakdown rate was limited to 5 x $10^6$ breakdowns per pulse. The cavity gradient and breakdown rate evolution over the conditioning time is presented. Post-pulse multipactor and other evidence of electron effects were detected. Possible mechanisms for this are discussed. The conditioning was interrupted by breakdown in the waveguide after reaching 2.5 MW, and will be resumed after the planned 6 month shutdown of CLARA.

## INTRODUCTION

The CLARA 400 Hz photoinjector was developed at Daresbury Laboratory to meet demanding requirements in bunch length and emittance for bunches of up to 250 pC. It is a 1.5 cell normal conducting S-band RF photoinjector [1] which has a dual feed RF input coupler with phase adjustment of each feed to supress any dipole component in the coaxial coupler line. The cavity also features a load-lock vacuum cathode exchange system, and for conditioning a bulk molybdenum cathode plug was inserted. The stored energy in the cavity can be measured via a probe in the full cell. The cavity schematic can be seen in Fig. 1.

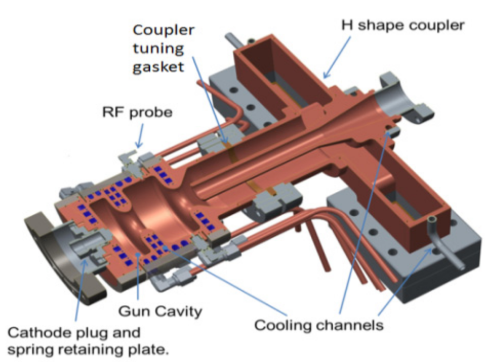


Figure 1: 400Hz photoinjector for CLARA.

For operation at 100 Hz for CLARA FEL experiments the cathode surface electric field required is 120 MV/m. The field is lowered for the 400 Hz mode to 100 MV/m to keep the average power below acceptable limits.

To achieve such a high gradient in an S-band cavity, the surface finish must be highly controlled. The cavity was diamond turned at Research Instruments Gmbh. to a tolerance 0.1 µm. To avoid damage and preserve this surface finish the breakdown rate allowed during the high power RF conditioning process must be tightly controlled.

A program, No Operator Automatic RF Conditioner (NO-ARC) has been developed to automate the conditioning whilst controlling the breakdown rate. RF signals from waveguide couplers and cavity probe, the Wall Current Monitor (WCM) signal, and vacuum levels are all monitored for signs of breakdown. If a breakdown is detected the RF is switched off before more breakdowns can occur. Automation is preferable to operator led conditioning due to the reaction time and repeatability of the automated program. The program was developed and tested on the 10 Hz CLARA gun, and the first CLARA linac [2]. More detail on motivation and background high gradient conditioning science can be found in the same paper. The program is designed to be run unmanned, as machine time for conditioning is very limited, and the bulk must be done overnight and at weekends.

## NO-ARC

NO-ARC is a dedicated control room application suitable for conditioning all RF structures that have a LLRF system similar to the Libera (I-Tech) system employed on CLARA. Here we detail a number of design choices.

### *Modular Design*

Use of a modular design allows for easy refactoring and extension. Modularising different parts of the script is the best path to prepare for future developments and ensure long-term stability. For example, the event detection module currently uses the mask method, described below. We are also working on an improved system using neural networks [3] and when that is operational it should be trivial to implement within the code.

### *CLARA-NET*

Use of our in-house software library CLARA-NET [4] ensures that solutions are shared throughout the entire CLARA project and that multiple developers will be able to work on the code.

### *Configurable Settings*

Settings are configurable through a plaintext configuration file. This includes the RF repetition rate, the rate at which the RF power is increased, and the increase step size, mask parameters for breakdown detection, breakdown detection threshold for dark current and vacuum spikes, traces to monitor for breakdowns and the option to monitor phase as well as power. This allows the program to be easily adapted to condition different RF structures without the need for advanced knowledge of the code.

### *High Repetition Rate Operation*

The higher the repetition rate, the faster the cavity will condition. The Libera system measures the RF pulse amplitude and phase at two directional coupler locations and the cavity probe, and distributes this data to the control system. NO-ARC should monitor traces at the highest pulse

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repetition rate possible, and when a breakdown event is detected switch off the RF before the next pulse. Thorough benchmarking was completed to determine the highest pulse rate possible for operation. At first conditioning repetition rate was limited by the Libera pulse data distribution. All RF traces were distributed individually with no sure way of guaranteeing which trace was associated with which pulse at high repetition rates e.g. 100 Hz. Improvements to the LLRF system were made such that all traces for a particular pulse were sent in the same data-array and in chronological order.

This upgrade enabled several features. The klystron power could be easily checked at the beginning of event detection, and further analysis disabled for that pulse if there was no RF power, preventing false breakdown detections. Additionally, owing to an RF trace buffer, all RF traces could be saved for the pulse that had a breakdown, as well as the two traces before and two after. Time-stamped trace data arrays allowed any changes in the repetition rate of the acquired traces to be flagged, which did occur spontaneously on a regular basis and could be reset programmatically when detected.

After the Libera upgrade detection was demonstrated to work faster than 100 Hz. However the disabling of the RF system was shown to only occur before the next pulse for 42% of the breakdown events, allowing one (or in rare cases 2) more pulses before switch off. It is interesting to note that the pulse after the pulse in which the breakdown was detected shows a breakdown event in 8% of occurrences. This supports the finding in pulsed DC tests that the initial breakdown causes new breakdown emission sites that substantially increase the probability of another breakdown immediately after the initial breakdown [5]. The system relies on the CLARA network, with NO-ARC running in the Main Control Room. Further improvements might be gained if the conditioning script could run on more local hardware.

## MACHINE PROTECTION

In order to guarantee a level of machine protection a number of safety features were implemented. An automated high power RF restart application was written that operated within the CLARA Control system. This application returns the high power RF system to operation after a machine protection interlock trips it off, for example after a large vacuum event. RF power is only returned if the rate of the tripping interlock being triggered was below a level of 3 per half hour. If too many interlocks are triggered or the modulator does not come back on for any reason the klystron filament heater is switched off to protect the klystron.

A conditioning keep-alive-system was created, where the conditioning script continually sends an “alive” signal to the control system. If for some reason the conditioning script fails (e.g. application crashed, host computer crashed, network error etc.) then the control system would turn off the high power RF system.

## BREAKDOWN DETECTION

RF breakdowns were detected via three methods. The most robust method was via the RF traces. Each new RF pulse is compared to the average of the last 5 pulses, and if it differs by a given amount (optionally by percentage or absolute value), it is flagged as a breakdown. This is performed for both the reverse power from the cavity and that measured at the probe. This can be done both for pulse power and phase. The phase is highly sensitive to frequency changes in the cavity, so even minor multipactor events can be detected. To condition through low power multipactor only events seen in the RF power were treated as breakdowns. A breakdown trace with the allowed mask is shown in Fig. 2.

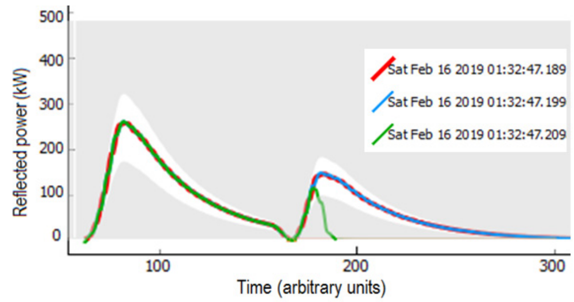


Figure 2: Breakdown event in reflected power trace. The red and blue traces are the normal pulses before the green trace which has a breakdown. Anything outside the white region for a chosen number of points in time is classed as a breakdown.

The secondary method was via dark current measurement at the WCM directly after the photoinjector on the VELA beam line. Spikes in the dark current were detected coincident with some breakdowns, but not all, as breakdowns must occur in a position where the emitted particles can be accelerated out of the cavity to be detected. A WCM trace for a breakdown in the cavity is shown in Figure 3.

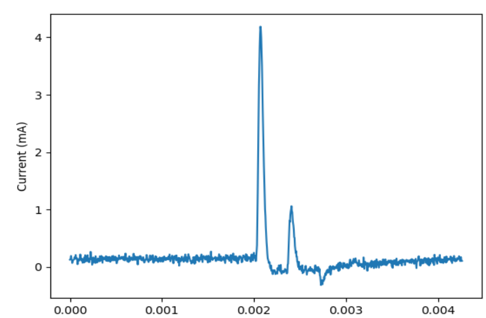


Figure 3: Wall current monitor signal when there was a cavity breakdown.

The final backstop for event detection is changes in the vacuum. This is much slower than the other methods as data is only collected at 1 Hz, but it serves as a safety net in the event of failed breakdown detection by the other means. This has so far not been required.

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## CONDITIONING PROGRESS

The klystron RF power at 750 ns pulse length rose steadily over 64 million pulses to 2.65 MW, with an allowed breakdown rate of 5 x $10^{-6}$ breakdowns per pulse. This is equivalent to approximately 2.5 x $10^{-5}$ breakdowns per pulse per metre of structure length. The scaled gradient [6] over the last 36 million pulses, along with the cumulative number of breakdowns is shown in Fig. 4. Scaled gradient allows comparison between conditioning data at varying pulse lengths and breakdown rates and is defined in Equation 1.

$$E_s = \frac{E_0 \tau^{1/6}}{BDR^{1/30}} \qquad (1)$$

Where $E_0$ is the cavity gradient, $\tau$ is the RF pulse length, and $BDR$ is the breakdown rate.

The fractured nature of the conditioning time meant that some reconditioning was required at the beginning of each shift, and for some shifts the klystron was not warm at the beginning of each shift and so took ~40000 pulses to come back to the previous output power for the same set point.

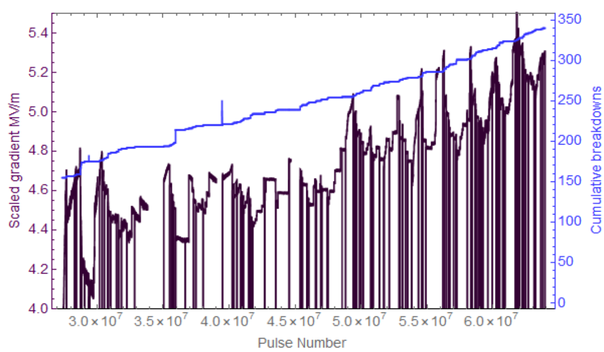


Figure 4: A section of conditioning data showing scaled gradient and cumulative breakdowns.

Some interesting phenomena were observed during conditioning which are now under detailed study. Firstly post-pulse multipactor, as observed in the 10 Hz photoinjector conditioning [2]. This is a phenomenon in which the phase of the decaying cavity field diverges dramatically, at very low power. Secondly a “bump” was observed in the amplitude trace of the probe signal. As no evidence of this phenomenon is seen in the forward or reverse traces, it is currently thought to be dark current being measured directly by the probe, possibly a multipactor band in the first cell. Particle in cell simulation is under way to further understand both.

## WAVEGUIDE BREAKDOWN

Conditioning time was cut short after breakdown products were detected in the $SF_6$ in the waveguide that feeds the RF photoinjector. Analysis showed a level of 55 ppm of $SO_2$. The SF6 was tested two weeks previously and no $SO_2$ was present. The limit for $SO_2$ in our waveguide is 12 ppm, so this necessitated removal, inspection and cleaning of the waveguide. On inspection it was found that the adaptor from the Thales window to the standard CPRG of the waveguide, on the $SF_6$ side of the window, had severe burns from arcing on both sides.

This waveguide connection showed clear burns from arcing as well as evidence of the silicone half o-ring gasket being pinched, which would have occasioned a spark gap across the flange connection. The flange can be seen in Fig. 5. Additionally this spacer piece is flat except for the o-ring groove. It lacks a raised central section to ensure RF contact occurs inside the o-ring groove, along with thin raised edge sections for mechanical stability, both of which the rest of the waveguide has. An example is shown in Fig. 6. These two factors are what lead to arcing in the waveguide at such low power. Less severe marks were seen at some other waveguide joints.

Waveguide breakdown detection via the RF trace at the directional coupler close to the cavity was implemented, but could not detect the breakdowns in this location as it was between the directional coupler and the cavity. A circulator means the reflected power at the klystron is dominated by cross coupling from the forward power and cannot be used for waveguide breakdown detection. Other methods of breakdown detection in waveguide are under study, particularly microphonic detection.

Unfortunately the time required to clean and re-machine the waveguide meant we could not begin conditioning again before the planned CLARA shutdown, and as such it conditioning is planned to continue in the autumn after the shutdown.

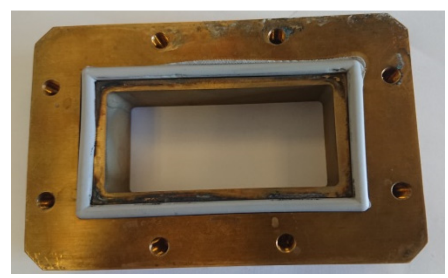

Figure 5: Flange with arcing burns and pinched gasket.

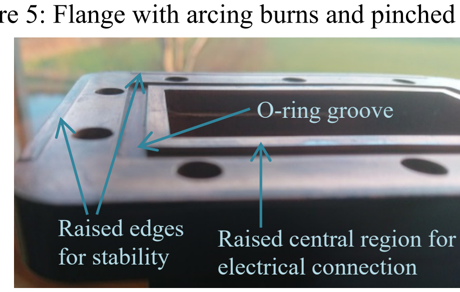


Figure 6: Example flange with raised RF connection.

## CONCLUSION

Work is continuing at Daresbury Laboratory on applying new research to conditioning procedures and employing higher levels of automation. The conditioning program NO-ARC has been used to begin conditioning the 400 Hz photoinjector and was robust enough for unmanned overnight operation. Conditioning will be continued later in the year after the CLARA shutdown.

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