# SUPERCONDUCTING CAVITY QUENCH DETECTION AND PREVENTION FOR THE EUROPEAN XFEL

J. Branlard*, V. Ayvazyan, O. Hensler, C. Schmidt, H. Schlarb, DESY, Hamburg, Germany,
W. Cichalewski, DMCS, Łódź, Poland

*Abstract*

Due to its large scale, the European X-ray Free Electron Laser accelerator (XFEL) requires a high level of automation for commissioning and operation. Each of the 800 superconducting RF cavities simultaneously running during normal operation can occasionally quench, potentially tripping the cryogenic system and resulting into machine down-time. A fast and reliable quench detection system is then a necessity to rapidly detect individual cavity quenches and take immediate action, thus avoiding interruption of machine operation. In this paper, the mechanisms implemented in the low level RF system (LLRF) to prevent quenches and the algorithms developed to detect accidental cavity quenches are explained. In particular, the different types of cavity quenches and the techniques developed to identify them are shown. Experimental results acquired during the testing of XFEL cryomodules prototypes at DESY are presented, demonstrating the performance and efficiency of this machine operation and cavity protection tool.

## INTRODUCTION

The European X-ray Free Electron Laser (XFEL) [1] in Hamburg Germany consists of a pulsed 17.5 GeV electron beam accelerator and an undulator section providing 27,000 photon flashes per second with a wavelength as low as 0.05 nm. The accelerator section comprises 800 superconducting radio frequency (SRF) cavities housed into 8-cavity cryomodules. The XFEL has a total of 25 RF stations, each consisting of 4 cryomodules driven by a single 10 MW klystron. The role of the low level radio frequency system (LLRF) is to control the gradient inside these accelerating structures with an accuracy better than 0.01% RMS in amplitude and 0.01 deg. RMS in phase [2]. Every SRF cavity has a maximum sustainable gradient above which it will quench: the cavity becomes then normal conducting releasing its stored energy in the form of heat dissipated into its surrounding cryogenic helium bath. This results in a loss of accelerating gradient affecting the overall beam acceleration, as well as a disturbance to the cryogenic superconducting cooling circuit, potentially compromising accelerator operation depending on the number and severity of quenches. One important responsability of the LLRF system is hence to prevent, detect and promptly react on cavity quenches, to avoid such events, or to minimize the impact on machine operation if a quench happens anyways.

* julien.branlard@desy.de

## QUENCH PREVENTION

Prior to string assembly and installation into the tunnel, the performance of each cavity is measured to determine its quenching gradient. Except for cavity degradation or contamination, the quench gradient is expected to remain at the same value for a given cavity. The cavity can then be safely operated so long as its nominal gradient remains below its quenching limit. Two sets of gradient limiter mechanisms are implemented inside the LLRF system to guarantee that every cavity be operated lower than its quenching gradient.

### Cavity Gradient Limiters

Gradient limiters are implemented inside the LLRF controller board, effectively comparing each cavity gradient to a settable threshold for the entire duration of the RF pulse. As a compromise between safe operation and performance optimization, the limiters are conservatively set 1-2 MV/m below quench limit for nominal RF pulse length. This action is effective in feedforward and in feedback mode and is illustrated in Fig. 1 (a). The RF drive and cavity gradient profiles with and without cavity limiter action are shown in solid and dashed lines respectively. If the cavity gradient exceeds the limiter value, the klystron RF drive is interrupted, the cavity gradient decays, hence remaining below the cavity limiter value and avoiding a potential quench.

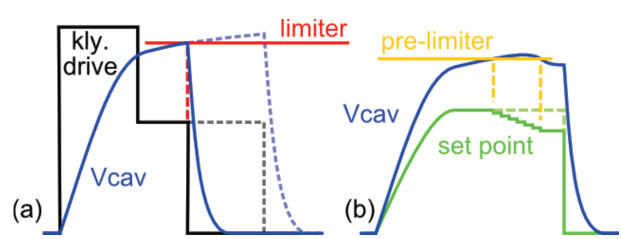


Figure 1: Action triggered by the cavity limiters (a) and pre-limiters (b).

### Cavity Gradient Pre-Limiters

During the RF pulse, each cavity gradient is also compared to a pre-limiter value, typically set 0.5-1 MV/m below the cavity limiter. If this threshold value is reached (for any cavity), the vector sum set point [3] is lowered within the pulse, by 1 $\mu$sec increments until the cavity gradient falls back into its safe zone, or until a maximum number of down steps is reached. The action of cavity pre-limiters is depicted in Fig. 1 (b). Because it is acting on the vector sum set point, this action is only effective when operating in feedback mode.

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## QUENCH DETECTION

Figure 2 illustrates the impact of repeated quenches on the cryogenic system with and without quench detection. Undetected quenches can generate enough heat to perturb the helium flow, preventing machine operations for extended periods of time. Due to the scale of the accelerator and the sensitivity of the cold compressors used for the XFEL, these down-times could be as long as 24 hours and should hence be avoided by every possible measure.

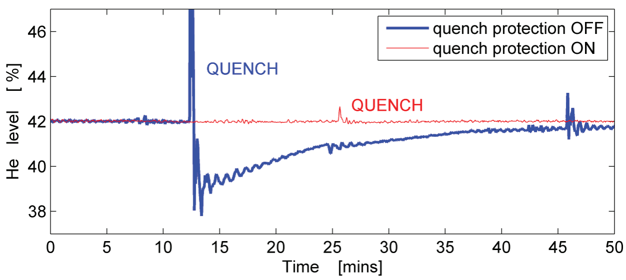


Figure 2: Helium level fluctuations due to undetected repeated quenches (thick) and when the quench detection server is active (thin).

When a cavity quenches, its unloaded quality factor $Q_0$ can drop by several orders of magnitude. For TESLA SRF cavities, this means $Q_0$ goes from $2 \times 10^{10}$ to $10^7 - 10^8$. Due to the external coupling $Q_{\text{ext}}$ of the cavity input power coupler, fluctuations of $Q_0$ cannot be directly seen; instead the loaded quality factor $Q_L$ is measured and used to detect $Q_0$ changes resulting from a cavity quench.

$$\frac{1}{Q_L} = \frac{1}{Q_{\text{ext}}} + \frac{1}{Q_0} \tag{1}$$

Typically, $Q_{\text{ext}} = 3 \times 10^6$, which means that a two-order of magnitude drop in $Q_0$ will only result in $<2\%$ decrease in measureable $Q_L$ while the dissipated heat induced by a quench scales as $1/Q_0$. A precise $Q_L$ measurement is then of paramount importance for any quench detection algorithm. A typical approach consists of computing $Q_L$ from the cavity gradient decay, which follows an exponential curve with a time constant proportional to the cavity $Q_L$ [3]. A complementary approach based on the second order electrical and mechanical model of a SRF cavity will produce a time-dependent $Q_L$ estimation based on the forward, reflected and transmitted cavity signals over the entire duration of the RF pulse [4].

### *Hard Quench*

In the current implementation of the quench detection server, $Q_L$ is measured for every cavity and averaged, $\langle Q_L \rangle$, over the previous $N$ pulses, where $N$ is typically set to 100. For every pulse, the difference between the new $Q_L$ value and the running average is compared to a quench threshold to discriminate pulse-to-pulse $Q_L$ measurement fluctuations from a sudden drop coming from a cavity quench.

A quench is detected if $\Delta Q_L = |Q_L - \langle Q_L \rangle| > 5 \times 10^5$, typically corresponding to a change in $Q_0$ by a factor $>1000$. The measured cavity gradient profile before a quench (0) and for the two subsequent pulses (1) and (2) is illustrated in Fig. 3. The corresponding $Q_L$ values are respectively 3, 1.4 and $1.2 \times 10^6$, the faster gradient decay is a clear signature of a lower $Q_L$.

During nominal operation, the LLRF feedback controller will try to compensate for the gradient drop resulting from a quench. In some cases, the available klystron power overhead is enough to compensate for most of the gradient drop. In other cases, this might lead to avalanche quench effects. When detected, the quench $Q_L$ value is not included in the running average $\langle Q_L \rangle$ and the RF is suspended for the subsequent pulse by turning off the feedforward and changing the amplitude set point to zero. The operator is notified and should recover operating conditions, while taking care not to reproduce the operating conditions which triggered the quench.

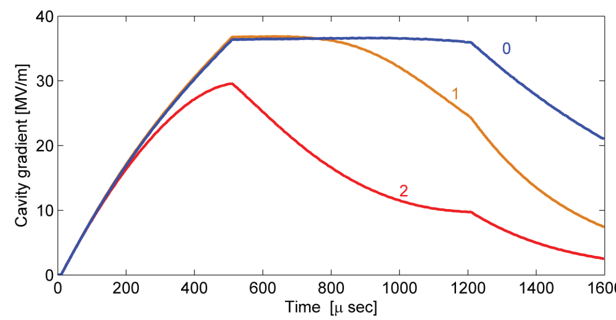


Figure 3: Cavity gradient profile for three successive RF pulses, before (0) and during quench (1) and (2).

### *Soft Quench*

While the majority of detected quenches are "hard" quenches as described above, some cavities have shown a so-called "soft" quench profile. In a soft quench, only sections of the cavities are becoming normal conducting and a smaller drop in $Q_L$ is observed. The challenge is that the soft-quenched cavity gradient profile is seemingly unchanged while its heat load is 10 to 100 fold that of a fully superconducting cavity. After several minutes of operation, an undetected soft quench will eventually result into a cryogenic interlock, producing critical accelerator downtime, just as hard quenches do. Experience has shown that a soft quench can however be identified when the following conditions are met: (1) a sudden and sustained small drop in $Q_L$ combined with (2) an increase in pulse-to-pulse $Q_L$ measurement fluctuations. The example of Fig. 4 illustrates this experience, showing the measured $Q_L$ as a function of pulse number. The cavity started soft-quenching shortly before pulse 400, its $Q_L$ dropped by $1 \times 10^5$ ($\sim$300 fold drop in $Q_0$) and remained lower, while the standard deviation changed from 0.3 to 46e4 (13% increase). After approximately 1000 pulses, the cavity hard quenched.



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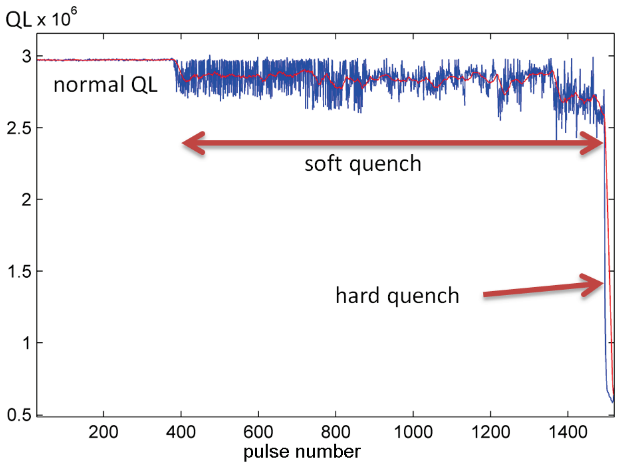


Figure 4: Pulse-to-pulse measurement of $Q_L$ during a cavity soft quench.

Typically, the server will detect a soft quench if the measured cavity $Q_L$ drops between 1 and $5 \times 10^5$, remains lower for 20 consecutive pulses, and a three to five fold increase of the $Q_L$ standard deviation is concurrently observed. Soft quenches are trickier to identify and false alarms should be avoided. The compromise is to wait longer to be certain that a soft quench is taking place, yet not so long as to disturb the cryogenic system beyond recovery. The thresholds, pulse averaging numbers are fine tuned as more experience with different cavities is acquired.

## OPERATION CHALLENGES

The robustness of a quench detection system is also linked to its ability to avoid triggering false alarms when external parameters are changing; for example, when a cavity $Q_{\text{ext}}$ is voluntarily changed by an operator using its motorized coupler. Turning off the quench detection system when running the $Q_{\text{ext}}$ motor is undesirable since the cavity gradient can increase and exceed its quenching limit as a result of motor operations (and $Q_{\text{ext}}$ change). Instead, the quench detection algorithm should differentiate the rate of change of $Q_L$ resulting from a quench from that induced by moving the motorized $Q_{\text{ext}}$. This sets a limit on the maximum speed of change of the external coupler motors. Another example is illustrated in Fig. 5, where the measured $Q_L$ is plotted as a function of cavity detuning. In theory, detuning and $Q_L$ are independent. In practice however, coupling between cavity tuning and loaded quality factor is clearly observed. As the cavity is moved away from its resonance frequency, the resulting gradient is decreased, the $Q_L$ measurement accuracy is diminished, nonlinear effects in the cavity gradient measurement electronics are becoming more significant and coupling effects between adjacent cavities become more noticeable. This last point is especially true when adjacent cavities have significantly different gradient profiles which is the case if one cavity is largely detuned and the other on resonance. To cope with this, the quench detection system typically discards $Q_L$ measurements of cavities which gradient falls below 10 MV/m, or cavities with large detuning (>500 Hz or 1 cavity bandwidth).

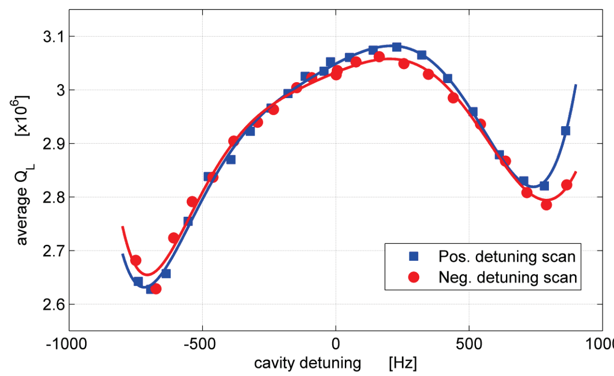


Figure 5: Coupling between cavity detuning and $Q_L$.

The current action when detecting a quench consists of switching the RF off. For accelerator operation, a smarter reaction to a quench is required. For example, lowering the operating point of the current quenching cavity or RF station and having the resulting loss in gradient absorbed by neighboring RF stations would minimize the overall accelerating gradient disturbance and allow for a smooth transport of the beam down the accelerator, maintaining its final energy. This approach also avoids creating large dynamic heat load fluctuations when shutting off an RF station.

## OUTLOOK

The needs for a robust quench detection system for the European XFEL was explained. The gradient limiter prevention techniques were presented, examples of different types of quenches and their characteristic signatures were given. Upgrades of the existing quench detection server include its implementation on the MTCA.4-based LLRF system [2] along with a faster communication between the DAQ and the quench detection server based on zeroMQ [5] protocol. These upgrades should further improve the robustness and performance of this essential tool.

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