

LLRF AUTOMATION FOR THE 9mA ILC TESTS AT FLASH

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Abstract

Since 2009 and under the scope of the International Linear Collider (ILC) research and development, a series of studies takes place twice a year at the free electron laser accelerator in Hamburg (FLASH) DESY, in order to investigate technical challenges related to the high-gradient, high-beam-current design of the ILC. Such issues as operating cavities near their quench limit with high beam loading or in klystron saturation regime are investigated. To support these studies, a series of automation algorithms have been developed and implemented at DESY. These include automatic detection of cavity quenches, automatic adjustment of the superconducting cavity quality factor, and automatic compensation of detuning including Lorentz force detuning. This paper explains the functionality of these automation tools and shows the experience acquired during the last 9mA ILC test which took place at DESY in February 2012. The benefits of these algorithms and operation experience with them are discussed.

INTRODUCTION

In pulsed accelerators, like FLASH or the ILC, the electric field inside a cavity is ramped up at the beginning of each pulse and then held constant both in amplitude and phase for the entire duration of the beam train. To meet luminosity goals, the vector sum flat top gradient should be regulated and controlled to better than 0.1% in amplitude and 0.1 degree in phase, according to ILC specifications. At FLASH like in the ILC design, one klystron provides power to several cryomodules. Due to performance disparities among cavities, the klystron RF power is distributed according to the individual cavity gradient limits. At FLASH, this is achieved by fixing the waveguide distribution system so that the spread in power distribution matches the spread among cavity gradients within a cryomodule. As a consequence, the beam loading also differs from cavity to cavity, resulting in positive or negative gradient tilts during the flat top while the vector sum of all cavity gradients remains perfectly flat. While this tilting effect is negligible for low beam currents (below 1 mA), it can induce 10 to 20% tilts on single cavities for high beam currents such as the 9 mA ILC upgrade design, as illustrated in Fig. 1. It was demonstrated that a physical misalignment of cavities combined with a gradient tilt during beam acceleration results in a transverse dispersion of the beam [1], and would force lowering the operational gradient in the machine.

One of the goals of the ILC 9mA runs at FLASH was to demonstrate the flattening of individual beam-induced

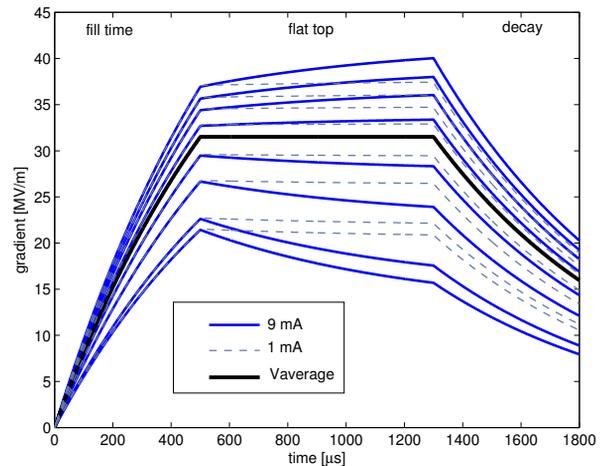


Figure 1: Cavity gradients for one cryomodule (8 cavities) with 1 mA (dotted) and 9 mA (solid) beam currents. The normalized vector-sum gradient is shown in black.

cavity tilts using loaded quality factor (Q_L) adjustments. The test was carried out on the last two cryomodules of the accelerator (ACC6 and ACC7), which contain the cavities with the highest gradient performance and are equipped with motorized controllers of the cavity Q_L .

AUTOMATION

Automation for Machine Operation

Automatic Q_L control. Gradient flattening studies require frequent changes of the cavity Q_L , so the automation of these settings was necessary. A middle-layer DOOCS [2] server was implemented for this purpose. When a new Q_L setting is requested, the server compares it to the current Q_L value, which is computed for all cavities and at each RF pulse. The server then moves the coupler motor to modify the position of the coupler antenna, effectively changing the cavity Q_L and bandwidth, until the measured Q_L value matches its setting. A discrete-time feedback control scheme is applied, where the input error is the difference between measured Q_L and setting, and the controller output directly drives the coupler motor. To avoid over exercising the coupler motor, a move is only requested if the Q_L error exceeds a certain threshold. The server robustness was improved by taking into account exceptions such as out-of-range Q_L settings, invalid Q_L measurements or motor reaching the end of its excursion, etc. A complete description of the automatic Q_L server is found in [3].

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Automatic cavity tuning with piezo. During normal FLASH operation, coarse cavity tuning is performed using the cavity motorized tuner, while fine tuning and compensation for Lorentz force detuning (LFD) is achieved with the piezos mounted onto each cavity tuner structure [4]. A pulsed sinusoidal excitation of the piezo is used to compensate for LFD. A DOOCS server automates this process by computing the cavity detuning during the pulse, and adjusting the piezo stimulus parameters (DC offset, AC amplitude, frequency and pulse delay) to maintain a minimal detuning over the duration of the flat top. This server includes protective measures to prevent over-stressing the piezos. The frequency and the maximum total amplitude of the excitation are limited. Should the cavity frequency drift outside of the safe piezo tuning range, an alert is given to the operator who can then choose to tune the cavity with the motorized tuner, hence, re-centering the piezo correction in its nominal operating range.

Automation for Machine Protection

Cavity gradient limiters. Gradient limiters are implemented inside the controller board, effectively comparing each cavity gradient to a settable threshold for the entire duration of the RF pulse. The RF drive is truncated should one cavity gradient exceed its limiter value. Typically, these thresholds are set to prevent any cavity gradient from going above its quench gradient. 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 feed-forward and in feedback mode.

Cavity gradient pre-limiters. In addition to the cavity limiter described above, each cavity is also assigned a pre-limiter, typically set 0.5-1 MV/m below the cavity limiter. During the RF pulse, every cavity gradient is also compared to its pre-limiter value. If this threshold value is reached (for any cavity), the vector sum set point is lowered within the pulse, by 1 μ sec increments until the cavity gradient falls back into its safe zone, or until a maximum number of steps is reached. The action of cavity limiters and the pre-limiters are depicted in Fig. 2. Because it is acting on the vector sum set point, this action is only effective when operating in feedback mode.

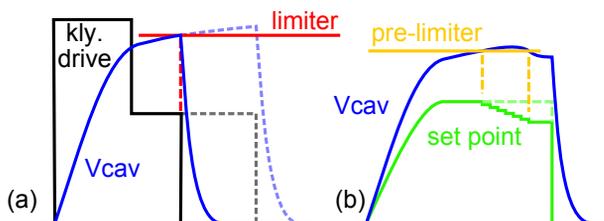


Figure 2: Actions triggered by the cavity limiter (a) and pre-limiter (b).

Quench detection. A quench detection server compares individual cavity Q_L to their previous values averaged over the last N pulses ($N \approx 20$). A sudden drop in Q_L (typically larger than 5×10^5) triggers a quench alert which results in shutting the RF off on the next pulse. Due to server latency, the reaction to a detected quench can be delayed by one RF pulse. The pre-limiters are intended to prevent quenching without tripping off the RF. The limiter and quench server are only triggered if the pre-limiter failed to act.

Tuning Approach

A first attempt at flattening beam-induced gradient tilts was successfully implemented during the 9mA run at FLASH in 2011 [5]. Optimized Q_L values were first calculated for a given beam current using simulations. Setting the predicted optimized Q_L values at FLASH achieved flattening of the gradient tilts to better than 1%. Fig. 3 shows the simulated cavity gradient tilts after Q_L optimization for a nominal beam current of 4.2 mA. Due to their low operating gradients, cavities 5 and 6 of cryomodule ACC6 were not included in the optimization algorithm, however, the net effect of flattening all other cavities combined with the feedback vector sum control contributed to flattening the gradient of these two cavities as well. One set of optimized Q_L values is given in Table 1. When optimized Q_L 's converge toward low values, their implemen-

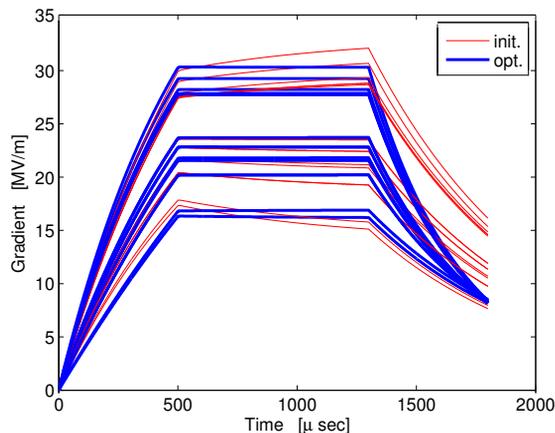


Figure 3: Simulated cavity gradients for ACC6 and 7 before and after Q_L optimization for $I_b = 4.2$ mA.

Table 1: Initial and optimized Q_L values [$\times 10^6$].

ACC6	C1	C2	C3	C4	C5	C6	C7	C8
init	3	3	3	3	3	3	3	3
opt	1.6	1.6	1.7	1.7	3	3	2.1	2.1
ACC7	C1	C2	C3	C4	C5	C6	C7	C8
init	3	3	3	3	3	3	3	3
opt	2	2	1.9	1.9	1.7	1.7	2.2	2.2

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tation at FLASH can be troublesome as some cavities have a minimum achievable Q_L value limited to 1.8 to 1.9×10^6 . The next step was to implement a simple feedback control on individual Q_L settings, using the corresponding cavity gradient tilt as error signal. Proportional gains were chosen conservatively, resulting in slower Q_L adjustments but avoiding over-exercising the coupler motors. This approach was successfully implemented during the last 9mA test at FLASH.

RESULTS

Fig. 4 shows the three step Q_L optimization sequence for the cavities of ACC6 and ACC7. The gradients are normalized to their beam arrival time value. Also shown in thick is the toroid signal, scaled for comparison with the cavity gradients. Initially, all cavities have their Q_L set to the default 3×10^6 value. The beam train is kept short (400 μsec) and the gradient tilts induced by the beam loading are clearly visible during the first 400 μsec of the flat top, Fig.4(a). The individual cavity Q_L are then optimized automatically so that all gradients are flat with beam, Fig.4(b). While the optimized Q_L values flatten the gradients with beam, they also worsen the tilts in the flat top region where no beam is present. In the last step (c), the beam train is extended to its full 800 μsec . While this Q_L optimization scheme had been previously simulated and its feasibility verified, it is the first time that it was successfully imple-

mented at FLASH. With optimized Q_L , all gradients were kept flat with a 0.2% peak-to-peak accuracy, while accelerating a full 800 μsec beam train. To complete the test, the laser was blocked and later unblocked, to simulate a beam-off / beam-on scenario. This was done keeping all Q_L optimized for full beam conditions. When the beam was switched off, all cavities gradient tilted. The cavities with a positive tilt exceeded their pre-limiter threshold resulting in the automatic lowering of the set point (during the same RF pulse), hence, avoiding any quench scenario. This protective measure is a direct result of the cavity pre-limiters, as explained in the previous section. When the beam was re-enabled, all cavities returned to their flat gradient profile; no beam was lost, no cavity quenched during this exercise.

One key lesson from this test is the importance of precedence among automation algorithms. "Run-away" scenarios were experienced during the Q_L optimization phase. Indeed, changing Q_L will affect the cavity gradient, influencing the Lorentz force detuning, which in turn will trigger a counter action from the piezo automation, resulting in a positive feedback situation for the Q_L automation algorithm. To prevent such a situation, careful exception handling needs to be implemented. For example, one can wait until the piezo feedback is finished compensating for Lorentz force detuning, before applying the next iterative step of Q_L optimization. The feedback gains on automatic piezo control and Q_L control are also of crucial importance and should be chosen so as not to make the system unstable. These issues will be investigated during the next 9mA test scheduled for September 2012 at DESY.

SUMMARY AND OUTLOOK

A series of automation tools were developed to support the high-gradient, high-beam current conditions required for the ILC 9mA studies at FLASH. These tools are implemented as a combination of firmware modules and high-level software. The functionality of these automated tools was explained and the results they allowed to achieve were presented. A key conclusion from this study is the importance of arbitrating between these various automation tools, as they can have conflicting actions and jeopardize the machine stability. Priority among automation servers and exception handling are two key topics on the agenda of the next 9mA study scheduled for September 2012.

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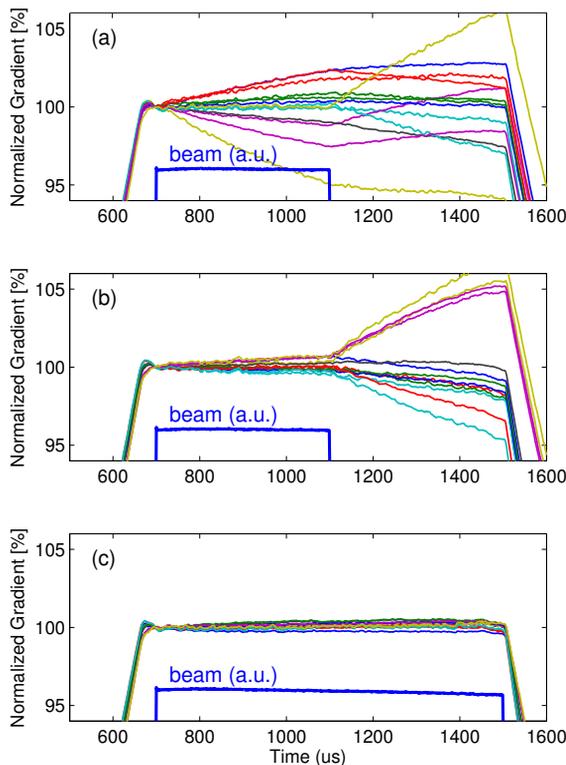


Figure 4: ACC6 and ACC7 normalized cavity gradients with default Q_L values (a), after optimization (b) and with full beam train length (c).