# Development and Test of a $P_kQ_L$ Control Procedure at KEK STF

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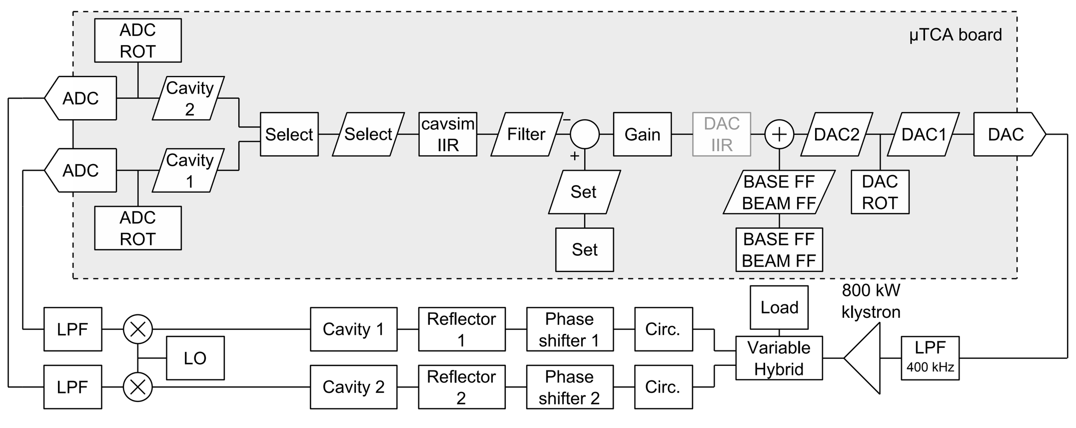
## Introduction

In order to operate the superconducting cavities at the International Linear Collider (ILC) [1] near their maximum gradients, cavity input ($P_k$) and cavity loaded Q ($Q_L$) have to be controlled individually ($P_kQ_L$ control [2]). In this scope an automated beam compensation procedure and a fully automated $P_kQ_L$ control were developed and demonstrated.

In preparation of ILC the Superconducting RF Test Facility (STF) is operated at the High Energy Accelerator Research Organization (KEK). In the configuration for the quantum beam project [3] the linear electron accelerator consists beside others of two super conducting 9-cell TESLA type L band cavities driven by a single klystron in the Distributed RF Scheme (DRFS) and operated using digital Low Level RF (LLRF) control techniques [5].

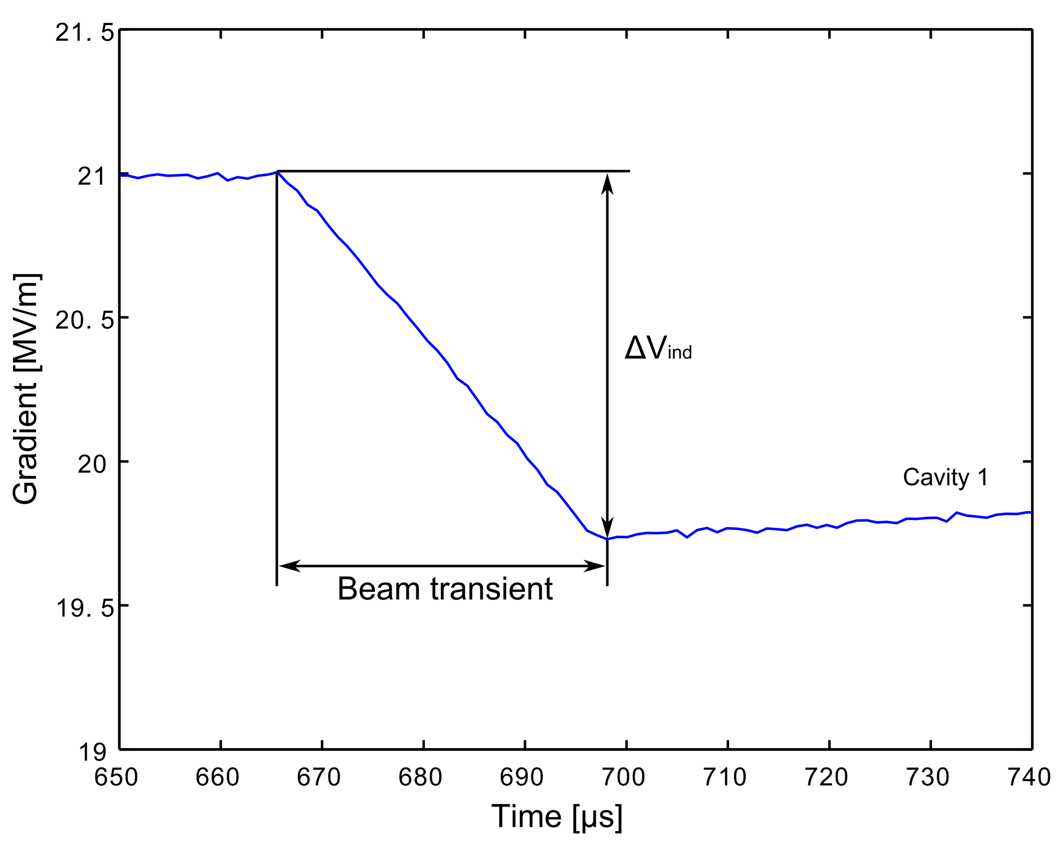



Schematic of the digital LLRF feedback loop controlling two superconducting cavities at STF. Hardware and software components are represented by squares, data channels accessible on the µTCA board via EPICS by rhombi.

## Beam Loading

Beam loading induces a drop $\Delta V_{ind}$ in the cavity gradient, which can be derived from the cavity differential equation by considering only the beam contribution.

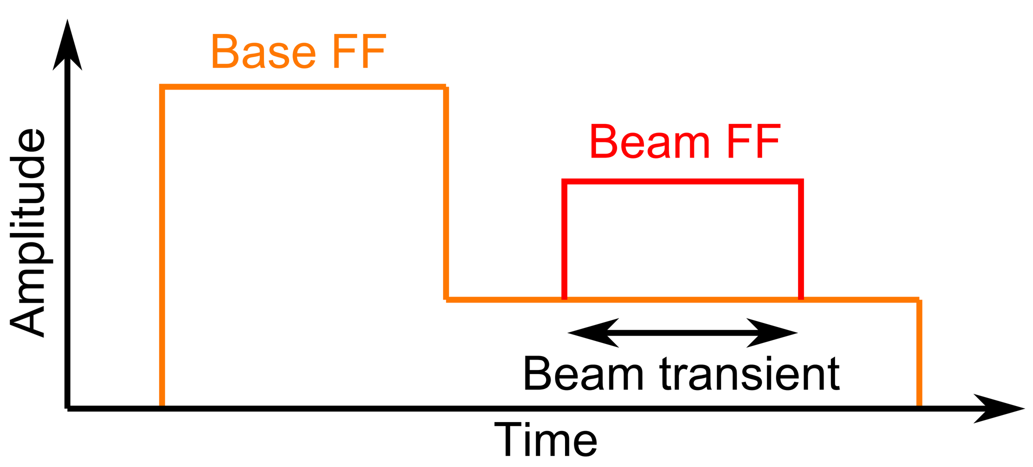
$$\Delta V_{ind} = \pi \frac{r}{Q} f_0 I_{b0} \Delta t$$



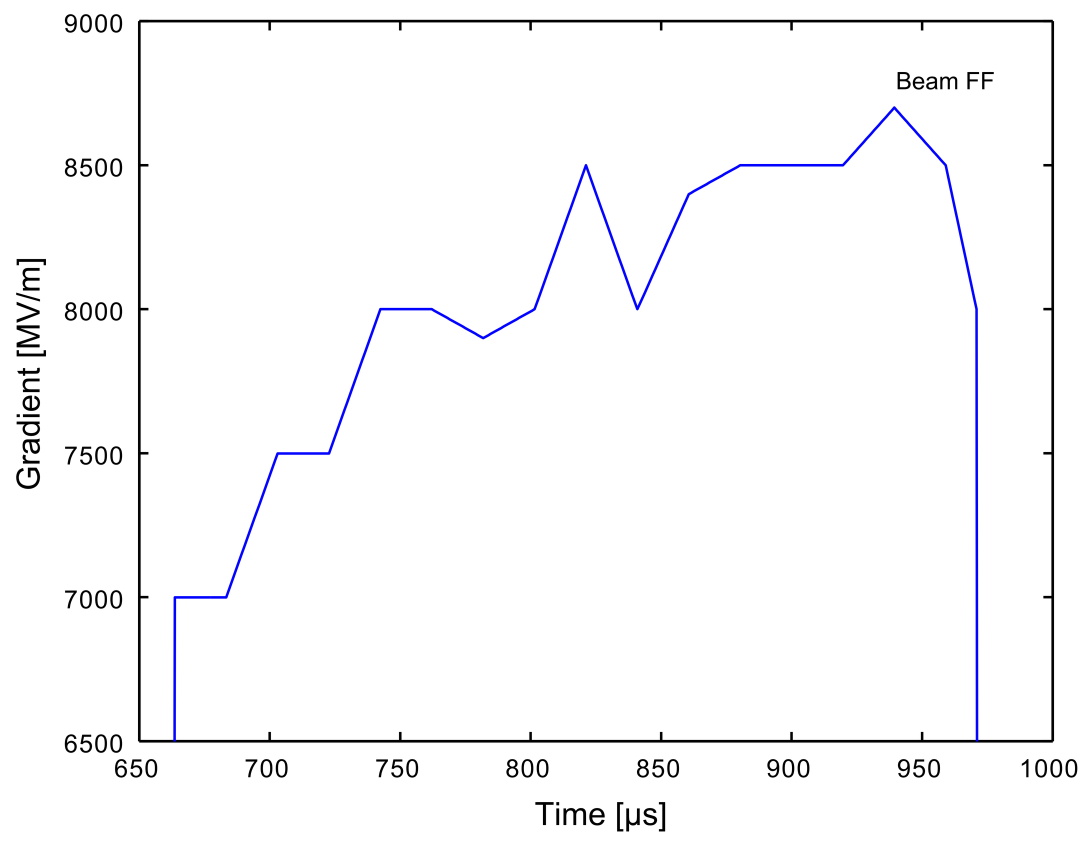

Cavity 1 gradient [MV/m] versus time [µs] during the flattop covering the beam transient, during which beam loading induces the gradient drop $\Delta V_{ind}$.

## Automated Beam Compensation

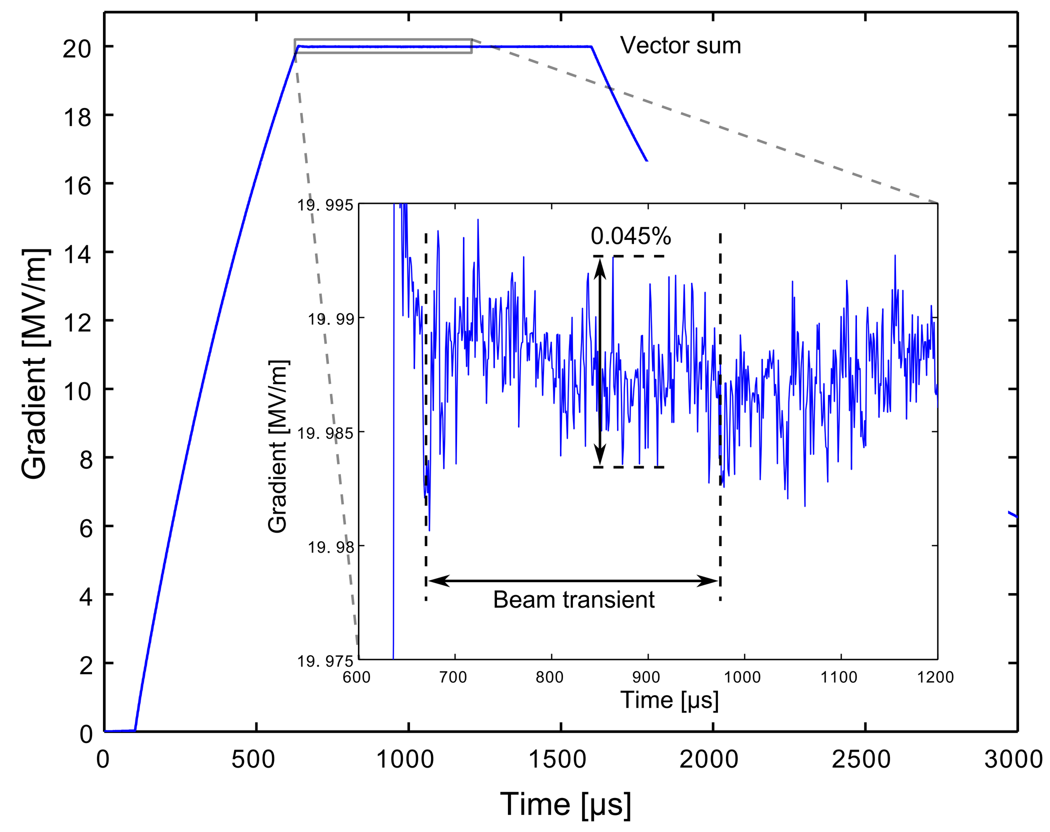
For stable beam acceleration flat gradients are required. These can be achieved by adding a beam feedforward (FF) table to the base FF table. By this additional driving power during beam transient is supplied. Since the beam current profile is not flat a automated beam FF shape generation was established.




Schematic of the amplitude versus time for a base FF table (orange) and a beam FF table (red).




Amplitude versus time [µs] of an automatically generated beam FF table.




Vector sum gradient [MV/m] versus time [µs] after an automated generation of a beam FF table.

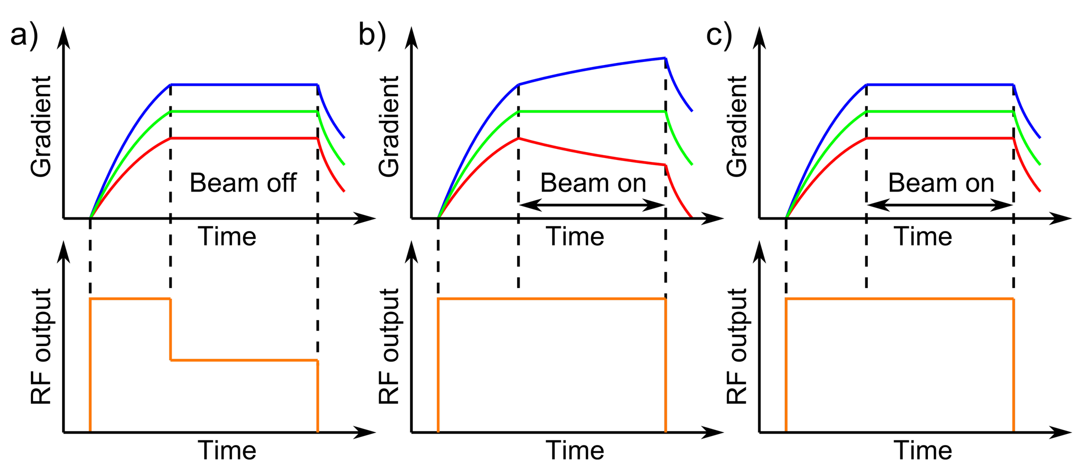
## Nominal Operation

Long time (1 hour) vector sum stabilities under nominal operation ($V_1$=16 MV/m, $V_2$=24 MV/m, $Q_{L1}$=$Q_{L2}$=3e6) with beam compensation.

| | Beam off | Beam on (6.6 mA, 615 µs) |
|---|---|---|
| $\Delta A/A_{RMS}$ | 0.008% | 0.009% |
| $\Delta\Phi_{RMS}$ | 0.008° | 0.008° |

## Fully Automated $P_kQ_L$ Control

The essentials for LLRF cavity control are to operate at flat gradients during beam transient with a constant RF output over filling and flattop time in order to operate the klystron near to saturation. Only in $P_kQ_L$ operation both requirements can be fulfilled. In ILC the cavity gradient spread will be ±20% around the average and all cavities will be operated 5% below their respective quench limits.

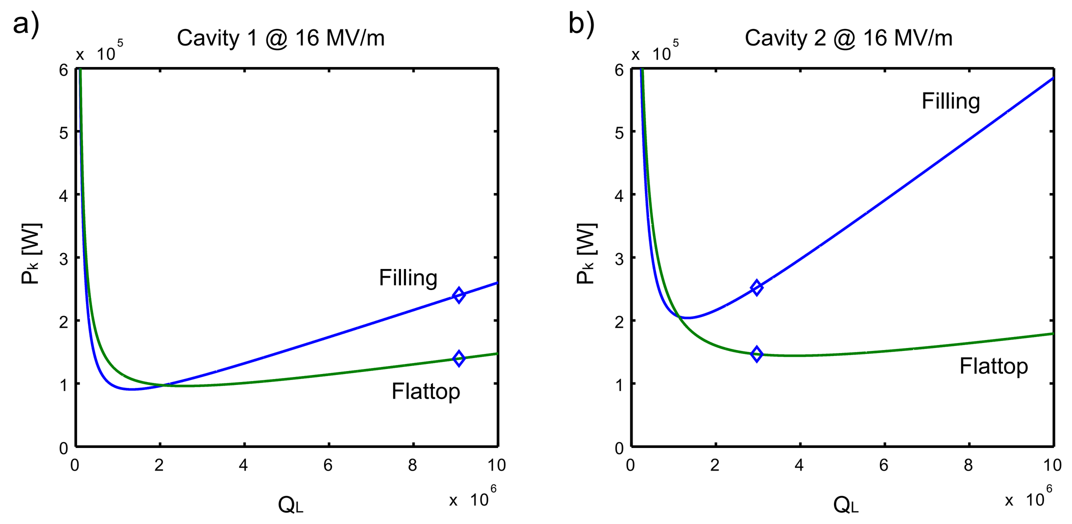



Schematic of cavity 1 (red), cavity 2 (blue), and vector sum (green) gradients with corresponding RF output for a) nominal operation, b) nominal operation with beam, and c) $P_kQ_L$ operation with beam.

Determination of the working cavity points for flat flattops (dV/dt=0) and on resonance (Δω=0):

$$P_{fill} = \frac{V_{cav}^2}{4\frac{r}{Q}Q_L\left(1 + \mathrm{Exp}\left(\frac{-\omega_0 t_{fill}}{Q_L}\right) - 2\mathrm{Exp}\left(\frac{-\omega_0 t_{fill}}{Q_L}\right)\right)}$$

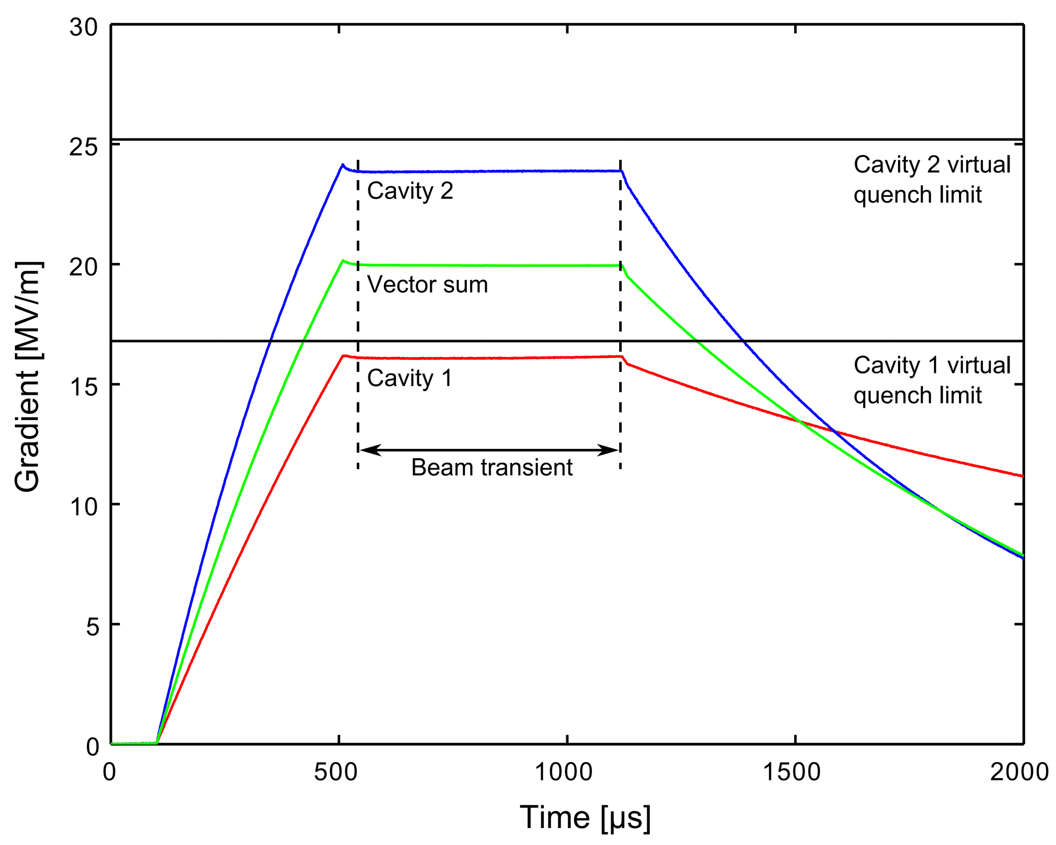
$$P_{flat} = \frac{V_{cav}}{4\frac{r}{Q}Q_L}\left(1 + \frac{\frac{r}{Q}Q_L I_{b0}}{V_{cav}}\right)^2$$




Power [W] versus $Q_L$ for a) cavity 1 and b) cavity 2. Working points are marked by blue diamonds.

Long time (1 hour) stabilities after fully automated $P_kQ_L$ setting procedure ($V_1$=16 MV/m, $V_2$=24 MV/m, $Q_{L1}$=9e6, $Q_{L2}$=3e6) with beam (6.4 mA, 615 µs) and beam loading compensation.

| | Vector sum | Cavity 1 | Cavity 2 |
|---|---|---|---|
| $\Delta A/A_{RMS}$ | 0.009% | 0.041% | 0.031% |
| $\Delta\Phi_{RMS}$ | 0.009° | | |




Gradients [MV/m] versus time [µs] of cavity 1 (red), cavity 2 (blue), and vector sum (green) during $P_kQ_L$ operation with beam. The virtual quench limits are indicated by black lines.

## Conclusion

Digital LLRF control procedures for ILC-like operation covering beam loading compensation, nominal operation, and fully automated $P_kQ_L$ operation have been developed and demonstrated at KEK STF. The vector sum long-time stabilities under $P_kQ_L$ operation were comparable to those under nominal operation. All introduced ILC requirements were fulfilled.

## References

[1] http://www.linearcollider.org
[2] K.L.F. Bane, "RF Distribution Optimization in the Main Linacs of the ILC", Proceedings of PAC07, Albuquerque, 2007, WEPMS037
[3] A. Kuramoto, "Alignment Detection Study using Beam Induced HOM at STF", Proceedings of IPAC13, Shanghai, 2013, MOPME019.
[4] S. Fukuda, "Distributed RF Scheme (DRFS) - Newly Proposed HLRF Scheme for ILC", Proceedings of LINAC10, Tsukuba, 2010, MOP027.
[5] T. Miura, "Performance of the µTCA Digital Feedback Board for DRFS Test at KEK-STF", Proceedings of IPAC11, San Sebastian, 2011, MOPC157.

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