High-gradient near-quench-limit operation of superconducting Tesla-type cavities in scope of the International Linear Collider

Mathieu Omet,^{*} Hitoshi Hayano, Ayaka Kuramoto, Toshihiro Matsumoto,
Shinichiro Michizono, Takako Miura, and Feng Qiu

*The Graduate University for Advanced Studies, Shonan Village, Hayama, Kanagawa 240-0193, Japan
and High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

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We report the successful demonstration of an ILC-like high-gradient near-quench-limit operation at the Superconducting RF Test Facility at the High Energy Accelerator Research Organization (KEK) in Japan. Preparation procedures necessary for the accelerator operation were conducted, such as rf phase calibration, beam-based gradient calibration, and automated beam compensation. Test runs were performed successfully for nominal operation, high-loaded Q (Q_L) operation, and automated $P_k Q_L$ operation. The results are described in terms of the achieved precision and stabilities of gradients and phases.

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I. INTRODUCTION

The International Linear Collider (ILC) [1] is a future high-luminosity linear electron-positron collider with an approximate length of 31 km [2]. Its purpose is high-precision investigation of the Higgs boson, dark matter, and probing of extra dimensions. ILC is based on 1.3 GHz superconducting radio-frequency accelerating technology. The total number of superconducting cavities used will be approximately 16000. The cavities will be driven in a configuration of one 10 MW klystron per 39 cavities. They will be controlled by vector sum. The vector sum is the sum of the complex vectors (in I and Q or amplitude and phase, respectively) representing the accelerating fields in all cavities.

The Superconducting RF Test Facility (STF) is operated at the High Energy Accelerator Research Organization (KEK) in Japan in preparation of ILC. From April 2012 to March 2013 the quantum beam (QB) project [3] was conducted at STF. Its goal was the demonstration of high-brightness x-ray creation by inverse laser Compton scattering. To this end a linear electron accelerator was set up. It consisted of two superconducting nine-cell TESLA-type L-band cavities driven by a single klystron in the distributed radio frequency scheme [4]. The cavities were operated by digital low level radio frequency (LLRF) control techniques [5,6] in a 5 Hz pulsed mode. A simplified schematic of the LLRF control loop is shown in Fig. 1.

The cavity signals were down-converted by mixing them with a local oscillator (LO) signal with a frequency of 1310 MHz. Next, they were filtered (LPF) and digitized by analog-to-digital converters (ADCs) on the μ TCA board [5]. After a signal rotation (ADC ROT) and computation of the vector sum, the signal was filtered (cavsim IIR) and subtracted from the set table. Next, the proportional gain was applied and a base feed forward (FF) as well as beam FF tables were added. The rotated (DAC ROT) and digital-to-analog converted signal was filtered by an analog 400 kHz low-pass filter in order to suppress the excitation of $8\pi/9$ modes [7]. The filtered signal was sent to the klystron, which drives both superconducting cavities. To this end the klystron output power was divided by a variable hybrid, which has a range from 0 to -6 dB for the through port. The cavity phases were set individually by remotely controlled waveguide phase shifters. Since remote control of the coupler positions was not available, remotely controlled waveguide reflectors were used in order to adjust the loaded quality factors (Q_L) of the cavities. The possible range in Q_L was 2.5×10^6 to 5×10^7 . Lorentz force detuning in the cavities was compensated dynamically by piezotuners, which were operated using a sine-wave voltage [8].

ILC will be operated in a pulsed mode with a repetition rate of 5 Hz. Figure 2(a) shows typical cavity gradient shapes without beam, which can be divided into three phases; a filling phase, in which the cavity gradients are built up, a flattop phase, in which the cavity gradients are kept constant, and the decay phase, in which the cavity gradients decay. Commonly the beam is accelerated during the flattop phase. The nominal design gradient for the ILC main linacs is 31.5 MV/m for a beam current of 5.8 mA [2]. A cavity gradient spread of 20% around the average gradient is planned. A further requirement is the operation of all cavities with flat gradients at 5% below their

^{*}momet@post.kek.jp

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FIG. 1. Schematic of the digital LLRF feedback loop controlling two superconducting cavities at STF. Hardware and software components are represented by rectangles and the data channels accessible on the Micro Telecommunications Computing Architecture (μ TCA) board via the Experimental Physics and Industrial Control System by rhombi.

respective quench limits, which must never be exceeded. This guarantees that the requirement for flat gradients is fulfilled at the same time. This requirement originates from the fact that cavity gradient tilts and rf fluctuations induce transverse beam orbit changes [9]. Nominal operation covers only the individual adjustment of the cavity driving powers P_k . In this operation mode, only nonflat flattops at different cavity gradients during beam transient can be achieved, as illustrated in Fig. 2. Solely by adjusting the driving power P_k and the Q_L value of each cavity individually ($P_k Q_L$ operation) [10] both requirements, namely different gradients and flat flattops for all cavities, can be fulfilled. In order to establish such an operation, an automated beam compensation and a fully automated setting procedure for $P_k Q_L$ operation had to be developed and tested. The study presented builds up on a collaborative effort driven by the R&D for ILC, to which researchers from several institutes across the world have contributed. A first theoretical approach to $P_k Q_L$ operation was published in 2007 [11]. A partial demonstration of such a kind of operation was performed during the 9 mA ILC tests at the free electron laser in Hamburg (FLASH) at Deutsches Elektronen-Synchrotron (DESY) in 2011 [12]. The present

study describes the development and performance of a full demonstration of a $P_k Q_L$ operation for the first time.

II. IDENTIFICATION OF RF PHASE FOR ON-CREST ACCELERATION

In the initial situation before operation, the rf phases of the cavities were random and needed to be calibrated for on-crest beam acceleration. For this calibration we used the cavity gradient changes induced by beam-loading effects [13]. From the cavity differential equation,

$$\frac{dV_{\text{cav}}}{dt} = -\omega_{1/2} V_{\text{cav}} + R_L \omega_{1/2} (I_g - I_b), \quad (1)$$

where V_{cav} is the cavity voltage, $\omega_{1/2}$ the cavity half bandwidth, R_L the loaded shunt impedance, I_g the generator current, and I_b the beam current, the condition of a constant beam phase at $\phi_{\text{beam}} = 180^\circ$, and substituting R_L and $\omega_{1/2}$, the beam-induced change in the cavity gradient is

$$\Delta V_{\text{ind}} = \pi \frac{r}{Q} f_0 I_b \cos(\phi_{\text{rf}}) \Delta t, \quad (2)$$

where f_0 is the resonance frequency, ϕ_{rf} the rf phase, and Δt the beam transient time. This shows that the change in the cavity gradient has a minimum at the rf phase for on-crest beam acceleration, where the phase difference between the beam and the rf phase is $\phi_{\text{rf}} - \phi_{\text{beam}} = 180^\circ$. By performing an rf phase scan during beam operation, the rf phase for the maximal cavity gradient drop can be found, and thus the rf phase for on-crest beam acceleration. This method was applied in an automated way individually to both cavities at STF. The result is shown in Fig. 3 in terms of the beam-induced change in the cavity gradient, corrected by the beam charge (ADC value/pC) versus the rf phase shift ($^\circ$) for both cavities. The minima were determined by a sine-function fit. A low power measurement after the calibration showed that the deviation of the relative cavity rf phases set was better than 3° .

FIG. 2. Schematic of cavity 1 (yellow), cavity 2 (red), and vector-sum (green) gradients with corresponding rf output for (a) nominal operation without beam, (b) nominal operation with beam, and (c) $P_k Q_L$ operation with beam.

FIG. 3. Beam-induced change in the cavity gradient corrected by the beam charge (ADC value/pC) versus rf phase shift (°) for (a) cavity 1 and (b) cavity 2. The red arrows indicate the locations of the minima.

III. BEAM-BASED GRADIENT CALIBRATION

To transform the picked-up, down-converted, and digitized cavity signals to a gradient, the ADC numbers had to be calibrated. For this calibration one can use beam-loading effects as described in the previous section. In the case of an on-crest beam acceleration, Eq. (2) can be simplified to

$$\Delta V_{\text{ind}} = \pi \frac{r}{Q} f_0 I_b \Delta t. \quad (3)$$

Figure 4 shows an example of a cavity gradient versus time with a beam transient of 31 μs . The average beam current was 9.9 mA, which, according to Eq. (3), corresponds to a cavity gradient drop of 1.31 MV/m. The actual drop was 1.26 MV/m, which is within 3.8% of the estimated value. A linear correction function is determined by taking into account the estimated cavity gradient drop, the corresponding change in ADC counts, and the point of origin. This procedure was performed for the digitized pickup signals of both cavities.

FIG. 4. Cavity 1 gradient (MV/m) versus time (μs) during the flattop covering the beam transient, where the beam loading induced the gradient drop ΔV_{ind} .

IV. AUTOMATED BEAM COMPENSATION

For the compensation of the beam-induced gradient drop, additional driving power had to be supplied during the beam transient. This was achieved by the addition of a beam FF table to the base FF table as shown in Fig. 5. Since the beam has a nonconstant structure over the whole pulse, a fully automated beam FF amplitude shape generation was established [10]. Figure 6 shows an example of an automatically generated beam FF table for a 5.5 mA beam with a pulse width of 308 μs . Due to beam current fluctuations during the generation procedure, the beam

FIG. 5. Schematic of amplitude versus time for a base FF table (orange) and a beam FF table (red).

FIG. 6. Amplitude versus time (μs) of an automatically generated beam FF table.

FIG. 7. Vector-sum gradient (MV/m) versus time (μs) after automated generation of the beam FF table during nominal operation.

FF amplitude table is not smooth. Since the cavity itself acts like a low-pass filter, the high-frequency components of this structure are not an issue. Figure 7 shows the vector-sum gradient after the automated generation and the appliance of a beam FF table during nominal operation. The stabilities are presented in the next section (Table I).

V. LONG-TIME NOMINAL OPERATION

In the scope of the QB project, the nominal operation parameters were $V_{\text{Cav}1} = 16 \text{ MV/m}$ and $V_{\text{Cav}2} = 24 \text{ MV/m}$, with $Q_{L,\text{Cav}1} = Q_{L,\text{Cav}2} = 3 \times 10^6$ and a filling time of $540 \mu\text{s}$ [10,14]. The beam compensation was automatically matched to the beam-pulse profile. The vector-sum stabilities during the beam transient achieved in a 1 h long-time run with and without a 6.6 mA beam with a pulse length of $615 \mu\text{s}$ are listed in Table I. A snapshot of the vector-sum gradient is shown in Fig. 7.

VI. HIGH Q_L OPERATION

The operational cavity gradients at ILC will be $(31.5 \pm 20\%) \text{ MV/m}$. The variation of 20% in the gradient stems from the quench limits, which differ between cavities. This requires a Q_L range from 3×10^6 to 10×10^6 [14]. Since $f_{1/2} = \frac{f_0}{2Q_L}$ the cavity bandwidth becomes narrow at high Q_L values (e.g., $f_{1/2} = 32.5 \text{ Hz}$ at $Q_L = 2 \times 10^7$ and $f_0 = 1.3 \text{ GHz}$). Because of this,

TABLE I. Best snapshot vector-sum amplitude and phase stabilities under long-time nominal operation [root-mean-square (rms) values].

Beam	6.6 mA	Off
$\Delta A/A$ vector sum	0.009%	0.008%
$\Delta \phi$ vector sum	0.009°	0.008°

TABLE II. Best snapshot vector-sum amplitude and phase stabilities under high Q_L operation (rms values).

Beam	6.1 mA	Off
$\Delta A/A$ cavity 1	0.12%	0.03%
$\Delta A/A$ cavity 2	0.16%	0.03%
$\Delta A/A$ vector sum	0.011%	0.008%
$\Delta \phi$ cavity 1	0.03°	0.03°
$\Delta \phi$ cavity 2	0.03°	0.03°
$\Delta \phi$ vector sum	0.015°	0.014°

cavity detuning, induced by e.g., microphonics, is expected to become severe.

At KEK STF, the range of Q_L values of both superconducting cavities is 2.5×10^6 to 5×10^7 . For the demonstration of high Q_L operation, the Q_L values were set to 2×10^7 . Because of this, the filling time was extended to $800 \mu\text{s}$. Both cavity gradients were set to 20 MV/m . In a 1 h long-time run with a 6.1 mA beam with a pulse length of $615 \mu\text{s}$ and beam compensation and feedback (FB) turned on, amplitude and phase stabilities were achieved as listed in Table II. Figure 8 shows a snapshot of the vector-sum gradient. A run of 20 minutes at the same condition without beam was also performed. The corresponding stabilities are also listed in Table II.

The measured Q_L values of both cavities during beam operation, which were determined by the evaluation of the cavity gradient decays, were on average $Q_{L,\text{Cav}1} = 2.1 \times 10^7$ and $Q_{L,\text{Cav}2} = 2.2 \times 10^7$. The aberrations from the set value originated from an imprecision of the setting method, since the Q_L values in this region were very sensitive to even small changes in the waveguide reflector step motor positions. The Lorentz force detuning compensation was performed with a feed-forward excitation of the piezos. Figure 9(a) shows the detuning for both cavities during the 1 h time span. The corresponding histograms are shown in Fig. 9(b). The standard deviations are $\sigma_{\Delta f,\text{Cav}1} = 10.1 \text{ Hz}$ and $\sigma_{\Delta f,\text{Cav}2} = 4.7 \text{ Hz}$. This shows that the cryogenics

FIG. 8. Vector-sum gradient (MV/m) versus time (μs) during high Q_L operation.

FIG. 9. (a) Detuning [Hz] of both cavities versus time [s] and (b) detuning histogram for both cavities during high Q_L operation.

stability was sufficient so that the average detuning was smaller than the cavity bandwidths. With this a successful demonstration of very stable high Q_L operation of both cavities was allowed, with stabilities comparable to nominal operation.

VII. AUTOMATED PKQL OPERATION

Since the cavity gradient tilts and rf fluctuations induce transverse beam orbit changes [9], a stable beam acceleration requires flat cavity gradients during the beam transient. A further requirement of ILC is to operate all cavities (39 cavities per klystron) at 5% below their respective quench limits over the whole flattop region of the pulse. This can only be achieved with matched conditions for all cavities. Since the beam loading is different for each cavity, the driving powers (P_k) have to be adjusted individually. During the filling time of the pulse, no beam is present. In order to achieve a matched condition right after the filling of all cavities, also the loaded Q values (Q_L) have to be adjusted individually. This operation mode is called $P_k Q_L$ operation. We have successfully demonstrated an automated procedure to engage in $P_k Q_L$ operation and maintaining a long-time $P_k Q_L$ operation [10,14]. The final operation parameters were $V_{Cav1} = 16$ MV/m, $V_{Cav2} = 24$ MV/m, $Q_{L,Cav1} = 9 \times 10^6$, $Q_{L,Cav2} = 3 \times 10^6$, a filling time of $410 \mu s$, an average beam current of 6.4 mA, and a beam pulse length of $615 \mu s$. The virtual quench limits were defined to be 16.8 and 25.2 MV/m, respectively, and were never exceeded.

To engage in automated setting procedure, the working points for the above-mentioned operation parameters first had to be determined in terms of P_k and Q_L . Solving the cavity differential equation [15] yields the required power values during filling and flattop as shown in Eqs. (4) and (5):

$$P_{fill} = \frac{V_{cav}^2}{4 \frac{r}{Q} Q_L [1 + \exp(\frac{-\omega_0 t_{fill}}{Q_L}) - 2 \exp(\frac{-\omega_0 t_{fill}}{2Q_L})]}, \quad (4)$$

$$P_{flat} = \frac{V_{cav}}{4 \frac{r}{Q} Q_L} \left(1 + \frac{\frac{r}{Q} Q_L I_{b0}}{V_{cav}} \right)^2, \quad (5)$$

which hold for the constraints on flat flattops ($\frac{dV_{cav}}{dt} = 0$) and on resonance ($\Delta\omega = 0$). Since both cavities are driven by a single klystron, the power ratio of filling to flattop is the same. Thus, the $P_k Q_L$ working points for both cavities are determined as shown in Fig. 10 ($Q_{L,Cav1} = 9.0 \times 10^6$ and $Q_{L,Cav2} = 3.0 \times 10^6$).

The procedure to engage in $P_k Q_L$ operation covers the following steps: (i) setting the Q_L values using waveguide reflectors (Q_L control, automated), (ii) detuning compensation using piezotuners (automated), (iii) setting the cavity gradients by adjustment of the ratio of the variable hybrid and the feed-forward amplitude (P_k control, automated), (iv) phase compensation using waveguide phase shifters (automated), (v) turning on feedback (manually), (vi) turning on beam (manually), (vii) turning on beam compensation (manually), (viii) simultaneous extension of the beam pulse and cavity gradient flattop lengths (automated).

The manual steps were not automated because of machine protection concerns. A snapshot of the cavity 1, cavity 2, and vector-sum gradients during $P_k Q_L$ operation is shown in Fig. 11.

Figure 12 shows the gradient stabilities for cavities 1 and 2 versus time for a 800 s sample time span of the performed 1 h long-time operation with beam. The mean-vector-sum stabilities were $\Delta A/A_{Cav1,mean} = 0.211\%$ and $\Delta A/A_{Cav2,mean} = 0.132\%$ and the best $\Delta A/A_{Cav1,best} = 0.041\%$ and $\Delta A/A_{Cav2,best} = 0.031\%$.

Figure 13 shows the vector-sum gradient and phase stabilities during the beam transient versus time for the same 800 s sample time span. The vector-sum amplitude and phase stabilities are listed in Table III. These are comparable to the stabilities during nominal operation and hence allow a very stable actual $P_k Q_L$ operation, demonstrated for the first time here.

FIG. 10. Power (kW) versus Q_L for (a) cavity 1 and (b) cavity 2. The working points are marked by blue diamonds.

FIG. 11. Cavity 1, cavity 2, and the vector-sum gradients (MV/m) versus time (s) during $P_k Q_L$ operation. The dashed lines indicate the virtual quench limits of 16.8 and 25.2 MV/m, respectively.

FIG. 12. Cavity 1 (left) and 2 (right) gradient stabilities during beam transient versus time (s) in $P_k Q_L$ operation.

FIG. 13. Vector-sum gradient and phase stabilities during beam transient versus time (s).

The dominant source for the cavity as well as vector-sum stability fluctuations was a beam current fluctuation of about 20%. Even under this condition, the average vector-sum stabilities, indicated as “mean” in Table III, were maintained. If the beam current could be controlled precisely and the matched condition maintained, the

vector-sum stabilities would be as good as the ones indicated “best” in Table III for the whole time.

VIII. SUMMARY AND OUTLOOK

We have successfully demonstrated ILC-like near-quench-limit operations at KEK STF, using two superconducting nine-cell cavities driven by a single klystron. The rf phases of the cavities for on-crest beam acceleration were determined and set with a relative aberration of less than 3° . The cavity gradient measurement by the down-converted and digitized pickup signals was calibrated with an error of 3.8%. An automated beam compensation was implemented, yielding vector-sum-gradient and phase stabilities for a long-time (in the scope of the QB project) nominal operation with beam of $\Delta A/A = 0.009\%$ rms and $\Delta\phi = 0.009^\circ$ rms. In a long-time high Q_L operation ($Q_{L,Cav1} = Q_{L,Cav2} = 2 \times 10^7$, $V_{Cav1} = V_{Cav2} = 20$ MV/m) with beam the vector sum stabilities were $\Delta A/A = 0.011\%$ rms and $\Delta\phi = 0.015^\circ$ rms. An automated $P_k Q_L$ setting procedure led to $V_{Cav1} = 16$ MV/m, $V_{Cav2} = 24$ MV/m, both gradients 5% below their respective virtual quench limits, $Q_{L,Cav1} = 9 \times 10^6$, $Q_{L,Cav2} = 3 \times 10^6$. The vector-sum-gradient and phase stabilities for the long-time $P_k Q_L$ operation during the beam transient were $\Delta A/A = 0.009\%$ rms and $\Delta\phi = 0.009^\circ$ rms, comparable to those under nominal operation.

Since $P_k Q_L$ operation demands the operation at very specific working points, it is sensitive to operation parameter deviations. Simulations of $P_k Q_L$ operation with ILC parameters showed that deviation limits were $+5.3\%$ for the cavity driving power (P_k), -11.6% for Q_L values, $\pm 13.6^\circ$ for the cavity phase, and -6.3% for the beam current. Exceeding those limits leads to cavity quenching. In the present study all LLRF parameter deviations were within these limits. Only the beam current fluctuation exceeded the limit. In the future an adaptive $P_k Q_L$ operation could be developed, which follows slow beam current changes or drifts. Since step motor positions of the waveguide reflectors cannot be adjusted in a pulse-to-pulse time span a sufficiently stable beam current is nonetheless essential.

TABLE III. Vector-sum amplitude and phase stabilities under $P_k Q_L$ operation (rms values).

Beam	6.1 mA
Best vector sum $\Delta A/A$	0.009%
Mean vector sum $\Delta A/A$	0.016%
Best vector sum $\Delta\phi$	0.009°
Mean vector sum $\Delta\phi$	0.019°

- [1] <http://www.linearcollider.org>.
- [2] The International Linear Collider—Technical Design Report, CERN, FNAL, KEK, 2013.
- [3] A. Kuramoto and H. Hayano, in *Proceedings of the 4th International Particle Accelerator Conference, IPAC-2013, Shanghai, China, 2013* (JACoW, Shanghai, China, 2013), MOPME019, p. 509.
- [4] S. Fukuda, in *Proceedings of the 25th International Linear Accelerator Conference, LINAC-2010, Tsukuba, Japan* (KEK, Tsukuba, Japan, 2010), MOP027, p. 112.

- [5] T. Miura *et al.*, in *Proceedings of the 2nd International Particle Accelerator Conference, San Sebastián, Spain* (EPS-AG, Spain, 2011), MOPC155, p. 445.
- [6] S. Michizono *et al.*, in *Proceedings of the 2nd International Particle Accelerator Conference, San Sebastián, Spain* (Ref. [5]), MOPC157, p. 451.
- [7] E. Vogel, *Phys. Rev. ST Accel. Beams* **10**, 052001 (2007).
- [8] C. Pagani *et al.*, in *Proceedings of SRF2011, Chicago* (JACoW, Geneva, 2011), THIOA01, p. 615.
- [9] K. Kubo, *Effect of Cavity Tilt and RF Fluctuation to Transverse Beam Orbit Change in ILC Main Linac* (KEK, Tuskuba, 2010).
- [10] M. Omet *et al.*, in *Proceedings of the 4th International Particle Accelerator Conference, IPAC-2013, Shanghai, China, 2013* (Ref. [3]), WEPME013, p. 2950.
- [11] K. L. F. Bane, C. Adolphsen, and C. Nantista, in *Proceedings of the 16th IEEE International Pulsed Power Conference, Albuquerque, NM* (IEEE, Piscataway, NJ, 2007), WEPMS037, p. 2424.
- [12] J. Branlard, in *Proceedings of LINAC2012, Tel-Aviv* (JACoW, Geneva, 2012), THPB085, p. 1023.
- [13] M. Omet *et al.*, Development and Application of a Frequency Scan-based and a Beam-based Calibration Method for the LLRF Systems at KEK STF, in *Proceedings of the 9th Annual Meeting Particle Accelerator Society Japan, Osaka, 2012* (Particle Accelerator Society of Japan, Tokyo, 2012), PASJ2012, p. 265.
- [14] M. Omet, T. Matsumoto, S. Michizono, and T. Miura, Demonstration of RF Stabilities in STF 9-cell Cavities Aiming for the Near Quench Limit Operation, in *Proceedings of SRF13, Paris* (JACoW, Geneva, 2013), THIOC04, p. 865.
- [15] T. Schilcher, Ph.D. thesis, Universität Hamburg, 1998.