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TIME DECAY EFFECT OF THE SUPERCONDUCTING FINAL FOCUS QUADRUPOLE FIELDS ON SuperKEKB BEAM OPERATION

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Abstract

Operation of SuperKEKB with eight superconducting final focus quadrupoles started from 2018, and now the electron and positron beams reached β_y^*= 1 mm and β_x^*= 60 mm at the interaction point (IP). In the operation, we observed a change of vertical tune during a long-time span for the positron ring just after exciting the SC quadrupole magnets. To confirm the source of the tune change, we performed the magnetic field measurements of the R&D and prototype quadrupole magnets, which had almost the same magnetic parameters as the real magnets in the accelerator rings. From the measurements, the tune change was due to the quadrupole field changes in the magnets, occurred from the magnetization change in the NbTi filaments by the magnetic flux creep, and we proposed the magnet excitation process to cancel this field change.

INTRODUCTION

SuperKEKB [1] is the particle collider of electrons (e^-) at 7 GeV (High Energy Ring: HER) and positrons (e^+) at 4 GeV (Low Energy Ring: LER), and it is the innovative collider in the luminosity frontier using the "Nano-beam scheme" [2]. The beam colliding operation of SuperKEKB started in April 2018. Now the peak luminosity has reached 4.678 $\times 10^{-34}$ $cm^{-2}s^{-1}$ with quite expert beam operation [3]. In beam operation, the vertical model tune of LER decreased exponentially with time just after exciting the final focus quadrupole magnets. The studies of beam optics indicated that this change originated from a change in the magnetic field of the final focus superconducting quadrupole magnets. To compare the studies to the real quadrupole magnet field, we performed the magnetic field measurements of the R&D and the prototype final focus quadrupole magnets. The magnetic field changes with time after exciting the magnets were measured and the measured field decay rates were confirmed to be of equal size of the measured tune change during beam operation. We will report the beam tune changes, the magnetic field measurement results and the modified excitation method of the quadrupole magnets to cancel the time decay of the field.

MODEL TUNE CHANGE AFTER EXCITING FINAL FOCUS QUADRUPOLES

Figure 1 shows beam currents and the tunes in the vertical direction of HER and LER during beam operation in November 2021. Figure 1 (a) shows the beam currents of HER and LER shown by the blue and the red lines. Figure 1-(b) and (c) show the vertical tune of HER and LER, respectively. Blue and red plots are the measured and the model tunes. The model tune changed over a week over a long span. The difference between the model and the measured tunes was adjusted with the optics correction. The characteristic change in the LER vertical tune from November 1st to November 8th was measured after the re-excitation of the superconducting magnets following the emergency shutdown of electric power sources. On November 8th, beam operation stopped for the accelerator regular maintenance. At the start of beam operation on November 1st, the tune value of LER was set at 46.598. At the end of beam operation on November 8th, this model value was changed to 46.560. In HER, the vertical tune has the dependence of beam current, and then the change like LER was not observed. The vertical tune change in HER was observed from November 19th to November 24th, where the HER beam current was constant.

The optics studies showed that the changes of the vertical tunes were due to the magnetic field change of the QC1P and QC1E superconducting quadrupole magnets.

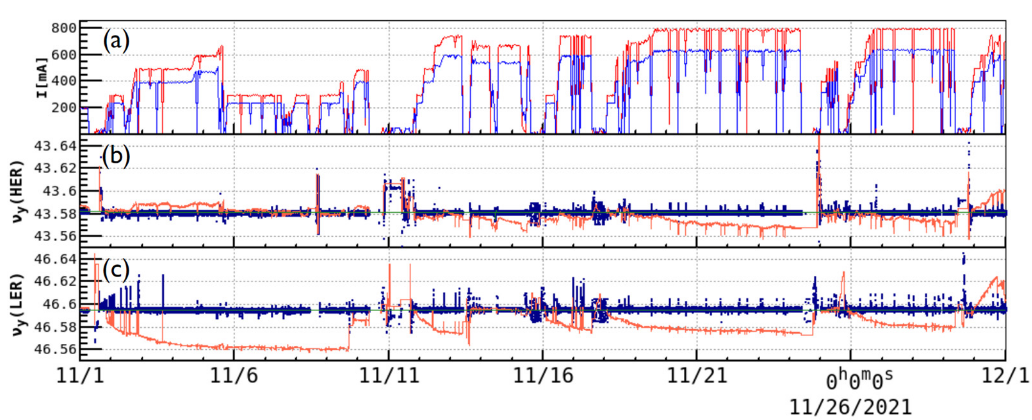

Figure 1: SuperKEKB beam operation status in Nov. 2021. (a) Stored current for LER (red) and HER (blue). (b) Vertical tune for HER. (c) Vertical tune for LER. In (b) and (c), dark blue points are measured tunes, and red lines are model tunes.

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QC1P/E QUADRUPOLE MAGNETS

In the beam interaction region, 55 superconducting magnets [4] were assembled in the two cryostats for squeezing the e^- and e^+ beams at IP. The QC1P quadrupoles for LER and the QC1E quadrupoles for HER have the function of squeezing beams vertically at the closest positions to the IP for each beam. The optics studies have shown a slight variation in the quadrupole component of the QC1P/QC1E field changes the vertical betatron tune. Figure 2 shows the cross section designs of the magnets To study the magnetic field characteristics of these magnets for a long-time excitation, we measured the magnetic field of the QC1P R&D magnet and the QC1E prototype magnet [5]. These two magnets had the same magnetic parameters as the real magnets except the coil angles to adjust the higher-order multipole fields. Table 1 shows these magnet parameters. The integral field of the QC1P for beam operation is 22.96 T at 1598.3 A, and the fields for the QC1E in the left and right side of the IP is 26.94 T at 1498.6 A and 25.36 T at 1591.0A, respectively. The QC1P is the collared magnet, and during beam operation, the magnet was excited under the solenoid field of 2.6 T by the detector solenoid and the compensation solenoid [4]. On the other hand, the QC1E had the magnetic yokes, and the magnetic effect of the solenoid fields is almost excluded.

The superconducting cable is the NbTi Rutherford cable, which consists of 10 strands. The strand diameter is ϕ 0.498 mm, and the critical current, I_c, in the short sample test is 3170 A at 5 T and 4.22 K. The NbTi filament diameter is ϕ 7.7 µm, and the number of filaments in the strand is 2113.

MAGNETIC FIELD MEASUREMENT SYSTEM

The field measurements of the QC1P R&D magnet and the QC1E prototype magnet were performed in the vertical cryostat. The test equipment is shown in Figure 3, and the QC1P R&D magnet was assembled inside of the superconducting solenoid, whose inner diameter was ϕ 190 mm. The solenoid generated the magnetic field of 2.6 T on the QC1P R&D magnet, the same as the real beam operation. When the QC1E prototype magnet was tested, the solenoid was not excited because the real QC1E is located where the external magnetic field is zero. The magnet was cooled with liquid helium.

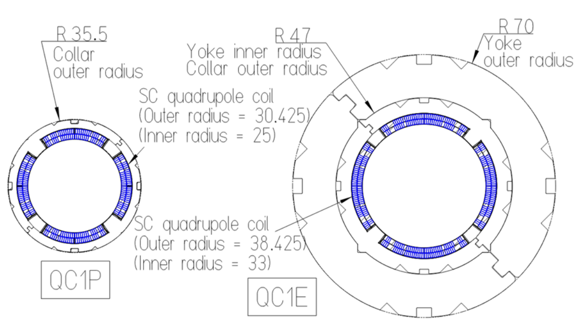

Figure 2: Cross section designs of the QC1P R&D magnet and the QC1E prototype magnet.

Table 1: Magnet Parameters of QC1P R&D and QC1E Prototype Magnets

Magnet	Parameter	Value
QC1P	Design field gradient, T/m	76.37
R&D-magnet	Design current (I_d), A	1800
(No yoke)	Load line ratio at I_d, %	72.3
	Magnetic length, mm	333.6
QC1E	Design field gradient, T/m	91.57
Prototype-	Design current (I_d), A	2000
magnet	Load line ratio at I_d, %	73.4
(With yoke)	Magnetic length, mm	338.3
Cable	Strand diameter, mm	0.498
(NbTi	No. of strands	10
Rutherford	Cu/S ratios	1.0
cable)	Filament diameter, µm	7.7
	No. of filaments	2113
	I_c at 5T and 4.22 K, A	3170

The magnetic fields of the quadrupole magnets were measured with the harmonic coil system which consisted of one tangential coil, three quadrupole coils and three dipole coils [6, 7]. The dipole and quadrupole coils were used as the analogue and digital bucking processes. The harmonic coil temperature was deduced from a harmonic coil's electrical resistance. When converting to the magnet's quadrupole components from the measured harmonic coil voltages, the sensitivity of the harmonic coil was corrected using the winding radius that considers thermal expansion.

FIELD MEASUREMENT RESULTS

The measured quadrupole field changes are shown in Figure 4. The plots show the integral quadrupole field

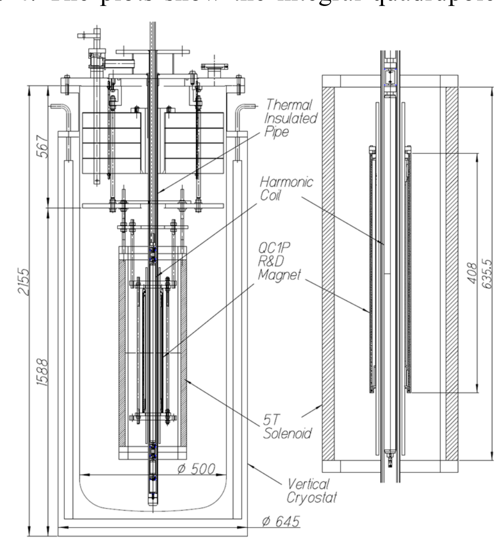

Figure 3: The quadrupole magnet, the solenoid, and the harmonic coil system in the vertical cryostat. The quadrupole magnet is set inside the solenoid magnet bore, as shown by the drawing on the right side.

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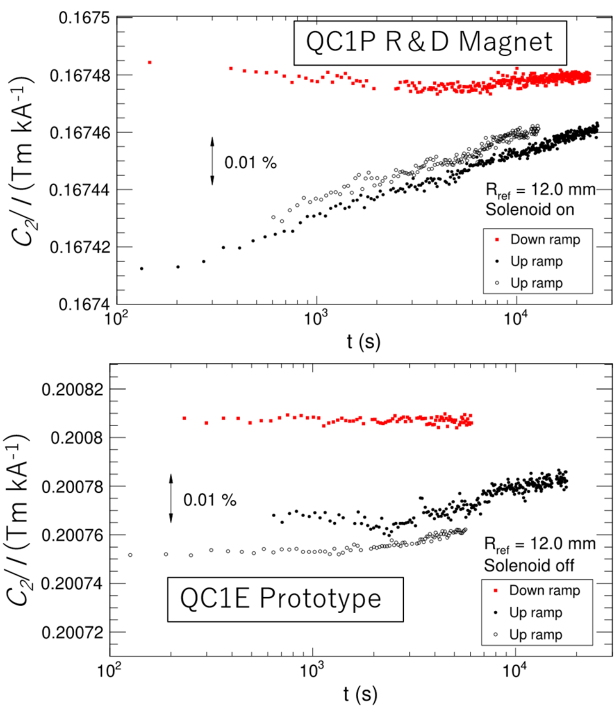

Figure 4: Quadrupole magnetic field changes of the QC1P R&D magnet and the QC1E proto-type magnet.

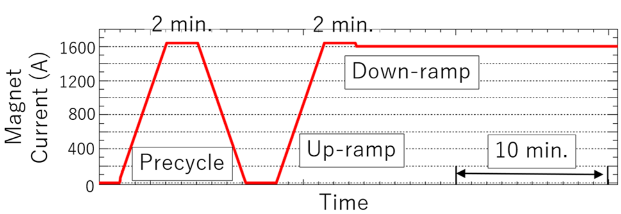

Figure 5: QC1P magnet excitation process

strength at the radius of 12 mm (C_2) divided by the transport current (I). The open and closed black circles correspond to the measured C_2/I where I was increased with 10 A/s to the target current for the field measurement. The horizontal axis is the elapsed time (t) after reaching the target current. The values of C_2/I have a linear relation to the logarithm of t, $C_2/I = a \ln(t) + b$. In the equation, a and b are arbitrary coefficients, and for the QC1P R&D magnet, $a = 9.5\times10^{-6}$ for two measurements. The QC1E prototype magnet has $a = 5.8\times10^{-6}$.

In the QC1P measurements, C_2/I of the closed circles changed from 0.16741 Tm/kA to 0.16746 Tm/kA for 8 hours, and this field change corresponds to the vertical tune change of 0.023. The C_2/I change for eight days is extrapolated to be 0.167495 Tm/kA by the equation, producing the vertical tune change of 0.036. This tune change is comparable to the vertical model tune drift of LER from November 1st to November 9th, as shown in Fig. 1.

The magnetic field change with time in the superconducting magnet was measured due to magnetic flux creep [8], and the influence on the accelerator was measured at first in the Tevatron collider operation [9].

To reduce the magnetic field change with time, we applied the exciting way of the QC1P, as shown in Fig. 5. Before the measurement, the magnet was precycled as the magnetic initialization. Following the initialization, the current was increased to a higher value by 2.5 % than the operation current (up-ramp) and the current was decreased to the target value (down-ramp) for the field measurement. This process generates the additional magnetic flux in the superconducting filaments, which is the opposite direction from the fluxes during the up-ramp process. Red squares show the measured results in Fig. 4. The measured values of C_2/I were almost constant for the QC1P and QC1E magnets. The coefficients of a for QC1P and QC1E were 2.1×10^{-7} and -2.5×10^{-7}, respectively. This magnet excitation process is being used in the real system, and the vertical tune changes in LER and HER due to the QC1Ps and the QC1Es are almost no longer a problem in beam operation.

CONCLUSION

In operation of SuperKEKB, after exciting the superconducting final focus quadrupoles, the vertical model tune drifts of LER and HER over a long-time span were observed. Optics studies pointed out that the tune drifts were due to the field changes of the final focus quadrupoles.

The magnetic field measurements of the quadrupole magnets, which had the same magnetic parameters to the real quadrupoles in beam lines, were performed. We measured the quadrupole field changes of 0.03 % for 8 hours by magnetic flux creeps in the superconducting filaments. The change of the quadrupole field was comparable to the vertical model tune change.

The magnet excitation process to cancel the field change was proposed, and it is now applied in the present magnet system in beam lines.

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