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Probing LINEAR Collider Final Focus Systems in SuperKEKB

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Absract

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SuperKEKB will be correcting high levels of chromaticity using the traditional scheme which has been also proposed for the CLIC FFS. We present early simulation results indicating that lowering β^*y in the SuperKEKB Low Energy Ring might be possible given on-axis injection and low bunch current, opening the possibility of testing chromaticity correction beyond FFTB level, similar to ILC and approaching that of CLIC.

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Abstract

A challenge for future linear collider final focus systems is the large chromaticity produced by the final quadrupoles. SuperKEKB will be correcting high levels of chromaticity using the traditional scheme which has been also proposed for the CLIC FFS. We present early simulation results indicating that lowering β_y^* in the SuperKEKB Low Energy Ring might be possible given on-axis injection and low bunch current, opening the possibility of testing chromaticity correction beyond FFTB level, similar to ILC and approaching that of CLIC.

1. Introduction

CLIC has two proposed schemes for correcting the natural chromaticity coming from the final doublet (FD), containing the final focusing quadrupoles before the IP. One is based on the design of [1] where the chromaticity is corrected using sextupoles interleaved with the FD, with the main advantage of having a shorter length and a reduced cost. The second, traditional scheme, uses two dedicated sections to correct the horizontal and vertical chromaticity separately. Each section includes two identical sextupoles placed where the dispersion and respective betatron functions are large, as well as with a -I transformation in between to cancel geometrical aberrations. The advantage of the traditional scheme is that it is easier to tune [2].

A final focus system implementing the traditional scheme was tested at FFTB [3] where a vertical beam size of 70 ± 7nm was achieved, while correcting large chromaticity using the compact scheme is currently being tested at ATF2 [4]. The chromaticity of the FFS scales approximately as L^*/β_y^*, with L^* being the length of the last drift between the FD and the IP. Table 1 shows a comparison of the FFS chromaticities for CLIC, ILC, ATF2, FFTB and the SuperKEKB [5] Low and High Energy Ring (LER/HER), respectively for positrons and electrons.

Table 1: Comparison of chromaticity for CLIC, ILC and the Low/High Energy Ring in SuperKEKB.

	L^*[m]	$\beta_y^*[\mu m]$	$\xi_y \sim (L^*/\beta_y^*)$
CLIC	3.5	70	50 000
ATF2	1	100	10 000
ILC	3.5 /4.5	480	7300 /9400
FFTB	0.4	100	4 000
SuperKEKB LER	0.935	270	3 460
SuperKEKB HER	1.41	300	4 700

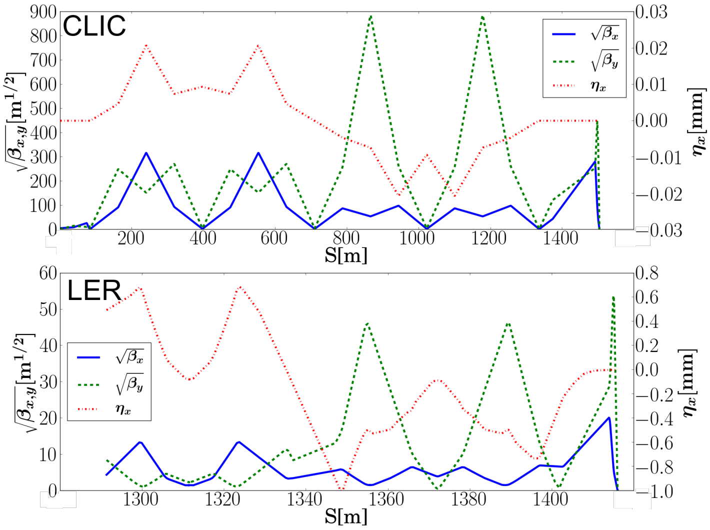

Figure 1: Optical functions in the FFS of SuperKEKB LER (lower plot) and CLIC with the traditional chromaticity correction (upper plot).

ATF2 is designed to have a similar chromaticity to ILC while the value for CLIC is 5 times larger. An ongoing study aims to test correction of chromaticity levels even closer to those of CLIC in ATF2 by using an ultra low β_y^*, recent results are given in [6]. The FFS chromaticity of both HER and LER are comparable to that of FFTB and similarly they both utilize a traditional correction scheme. Therefore, if a factor 3 reduction of β_y^* could be achieved at SuperKEKB the traditional correction scheme could be tested for chromaticity levels beyond FFTB, similar to ATF2/ILC and approaching those of CLIC. We present in this paper the results of initial simulations with reduced β_y^* in LER including the impact on dynamic aperture and lifetime, indicating that a factor 3 increase of chromaticity might be possible with low current and single turn injection. In Figure 1 the FFS betatron functions and horizontal dispersion are displayed for both LER and the CLIC design using the traditional scheme, showing the similarity between the two.

2. Reducing β_y^* in SuperKEKB

To explore the possibility of correcting chromaticity levels even closer to those of CLIC using the traditional correction scheme, the program SAD [7] is used to match a LER lattice for several reduced values of β_y^*. The main machine parameters for SuperKEKB are given in Table 2. The nominal value for β_y^* in LER is 270 μm while the target values for the reduced β_y^* are 135 μm, 108 μm and 90 μm, giving a decrease in β_y^* and an increase in chromaticity of a factor 2, 2.5 and 3, respectively. To ease the matching β_x^* is increased from 32 mm to 48 mm. The strengths of the final quadrupoles are all changed less than 0.1%, the main change being an increase of β_y in the magnets by a factor approximately equal to the factor of reduction in β_y^*. To model the IR of SuperKEKB [8], the magnetic multipole fields up to 44-order are divided into 10 mm slices with constant field within 4 m on both sides of the IP. This includes fringe fields from the final quadrupoles as well as the magnetic field from the detector solenoid, compensation solenoids and corrector coils. Figure 2 shows a layout of the IR. Figure 3 shows the beta functions in the last 4 m before the IP together with the array of multipole elements used in SAD to model the magnetic fields. Red rectangles indicate the place where multipole elements from the final quadrupoles are interleaved with those containing the fields originating from the detector solenoid and the solenoid corrector coils. During matching the quadrupole field partitions of the final focusing magnets are changed while higher order components are kept constant. The coupling is found to grow when lowering β_y^* and increasing β_x^*, and it is minimized by varying vertical displacements of sextupole magnets. The remaining coupling is shown in Figure 4. For $\beta_y^* = 270$ μm the coupling is 0.036% while for $\beta_y^* = 90$ μm it is 0.12%. These values are for the error free lattices and without beam-beam interaction. The value for the nominal machine when including realistic errors and the beam-beam effect is 0.27%. Nonlinearities in the IR and coupling originating from the IR solenoid fields are discussed in [9].

Table 2: Main parameters of SuperKEKB [5].

	LER (e^+)	HER (e^-)
E [GeV]	4.000	7.007
I [A]	3.6	2.6
Number of bunches	2 500	
Bunch current [mA]	1.44	1.04
Circumference [m]	3 016.315	
ϵ_x/ϵ_y [nm/pm]	3.2/8.64	4.6/12.9
Coupling [%]	0.27	0.28
β_x^*/β_y^* [mm]	32/0.27	25/0.30
Crossing angle [mrad]	83	
α_p	3.18×10^{-4}	4.53×10^{-4}
σ_δ	8.10×10^{-4}	6.37×10^{-4}
V_c [MV]	9.4	15.0
σ_z [mm]	6.0	5.0
ν_s	-0.0244	-0.0280
ν_x/ν_y	44.53/46.57	45.53/43.57
U_0 [MeV]	1.86	2.43
$\tau_{x,y}/\tau_z$ [msec]	43.2/21.6	58.0/29.0
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.807
Luminosity [cm^{-2}s^{-1}]	8×10^{35}	

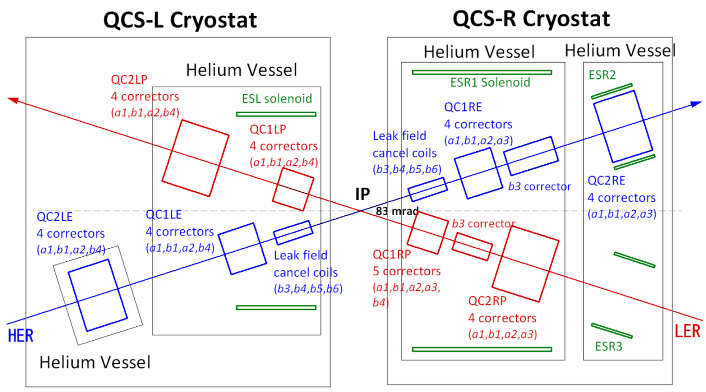

Figure 2: Illustration is taken from [10]. It shows the layout of main optic elements in the SuperKEKB IR, including final quadrupoles, compensation solenoids, corrector coils and leak field cancel coils.

Two important considerations for the SuperKEKB optics are the dynamic aperture and Touschek lifetime. These are optimized for the reduced β_y^* lattices by using a downhill Simplex routine varying sextupole strengths. There are octupole coils in the IR that can be used to further increase the dynamic aperture that are not adjusted in this report. In addition, the vertical fractional tune ν_y is decreased from 0.57 to 0.56 as this is found to increase the dynamic aperture. To estimate the Touschek lifetime, single particle tracking for 1000 turns is used to determine the dynamic aperture to which an ellipse is fitted. The beam-beam effect is not included. The initial amplitude of the tracked particles are distributed evenly in the horizontal plane, while the initial vertical offset is $\sqrt{\epsilon_y/\epsilon_x}$ times the horizontal one. Figure 5 shows the Touschek lifetimes for the nominal ring and for several reduced values of β_y^*, while the dynamic aperture is shown in Figure 6. The nominal lattice has a Touschek lifetime of 10 minutes and an on momentum dynamic aperture of 25σ which are needed for top up injection.

The physical aperture is limited by the aperture of the final quadrupoles. The nominal horizontal aperture

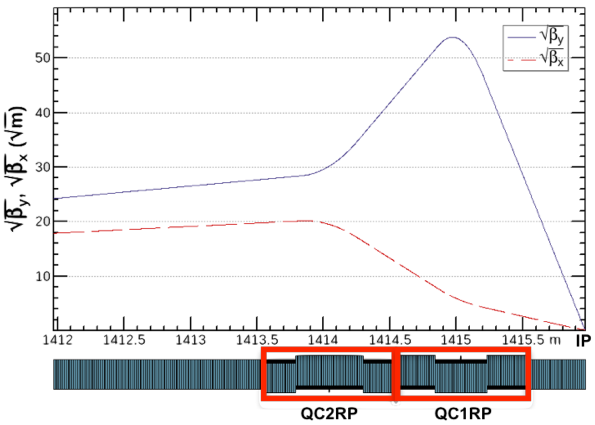

Figure 3: $\sqrt{\beta_y}$ and $\sqrt{\beta_x}$ in LER the last 4 m before the IP with $\beta_y^* = 270\ \mu$m. The magnetic multipole fields up to order 44 are included in the SAD model by 10 mm slices shown beneath the graph. Red rectangles indicate where the elements composing the final quadrupole magnets QC1RP and QC2RP are interleaved with those constituting the total field from the detector solenoid, compensation solenoids and corrector coils.

is similar to the dynamic aperture at $25\sigma_x$, while the vertical is $66\sigma_y$, which means the limitation is in the dynamic aperture. As β_x^* is relaxed when lowering β_y^* the horizontal beam size in the final quadrupoles is reduced. For $\beta_y^* = 90\ \mu$m, β_y in the final quadrupoles is a factor 3 larger than for the nominal machine. If the vertical emittance is increased by 50%, corresponding to a coupling of 0.40%, the vertical aperture would be decreased to $31\sigma_y$ and still larger than the dynamic aperture of 16σ.

Table 3: Tilt and gradient errors added to the quadrupoles and sextupoles in the arc for dynamic aperture calculation. No errors are added in IR elements.

	$\sigma_\theta[\mu$rad$]$	$\Delta K/K$
Normal quad.	100	2.5×10^{-4}
Sext.	100	2.5×10^{-4}

Lattice errors are added to see the impact on dynamic aperture. As no closed orbit correction is done afterwards only errors that do not destabilize the beam are added, this excludes errors in dipole magnets as well as errors in the IR elements. The added errors are listed in Table 3 and consist of strength and tilt offsets of the ring quadrupoles and sextupoles. Figure 6 shows the reduction in dynamic aperture for 110 machines, where each curve represents a separate value of β_y^*. Correspondingly, Figure 5 shows the average reduction in Touschek lifetime when including the errors. Before calculating the dynamic aperture and lifetime, the tune and coupling are corrected. The average coupling after this correction is shown in Figure 4. Introducing quadrupole errors also causes beta beating. Average RMS values for the 110 machines are shown in Figure 7 for both normalized beta beating and normalized dispersion beating. An important remark concerning both the dynamic aperture and the beta beating is that the effects of IR imperfections, which are not included, will be the most enhanced due to the large increase of β_y in the magnets of the IR. Dedicated studies will be carried out to develop a suitable correction algorithm.

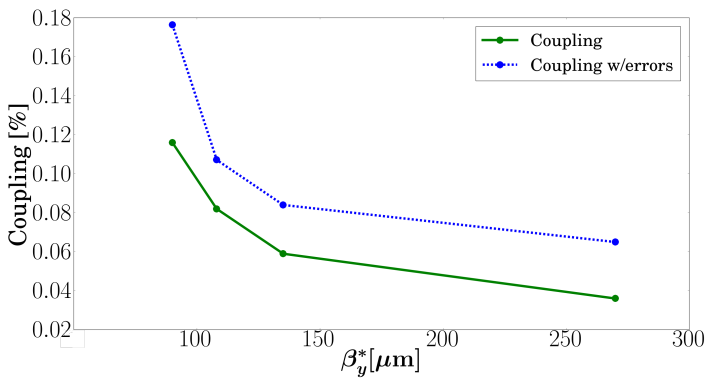

Figure 4: Remaining emittance coupling ϵ_y/ϵ_x after correcting coupling using vertical displacements of sextupole magnets. The solid green line is for lattices without added errors, while the dashed blue line is the average of 110 machines with errors distributed according to Table 3. The tune and coupling are corrected after the errors are added. The beam-beam interaction is not included. The nominal coupling value for the machine with the beam-beam effect and $\beta_y^* = 270\ \mu$m is 0.27%.

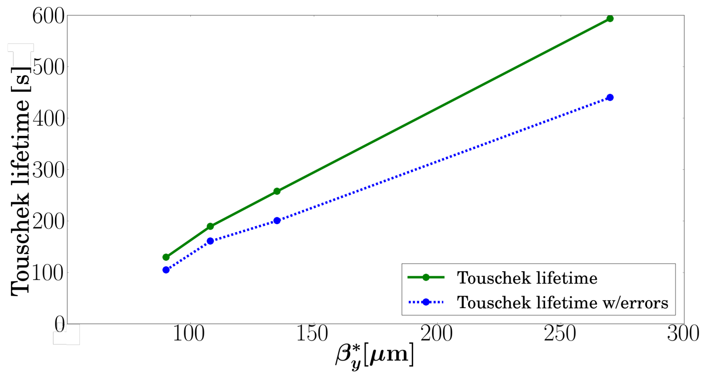

Figure 5: Touschek lifetime for an error free lattice together with the average Touschek lifetime for different values of β_y^* when including errors distributed according to Table 3 in 110 different machines. After adding errors the tune and coupling are corrected.

3. Operational Considerations

For $\beta_y^* < 135\ \mu$m the dynamic aperture becomes insufficient for multi-turn injection, requiring the beam to be injected on the closed orbit. The main parameters of the

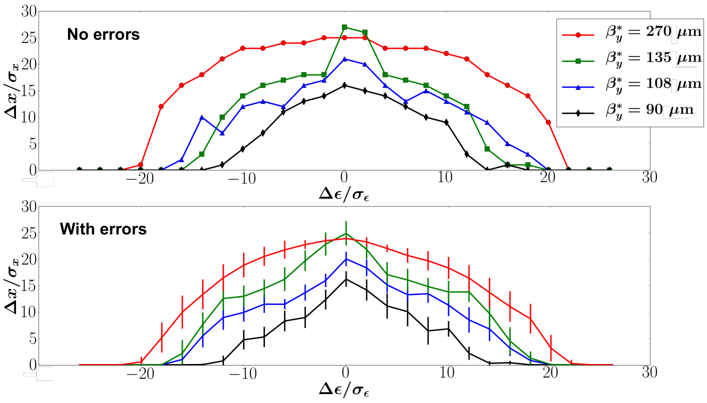

Figure 6: Dynamic aperture for different values of β_y^* for error free lattices is shown in the upper plot. The lower plot shows average dynamic aperture when including errors distributed according to Table 3 in 110 different machines, including error bars indicating one standard deviation. After adding errors the tune and coupling are corrected. The dynamic aperture is calculated using single particle tracking for 1000 turns.

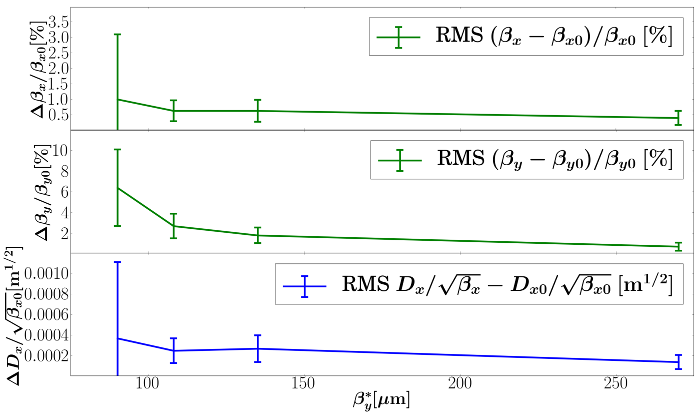

Figure 7: The upper and middle plots show respectively the average RMS horizontal and vertical normalized beta beating when including errors listed in Table 3 and after correcting tune and coupling. The lower plot shows average RMS horizontal normalized dispersion beating. The values are calculated for 110 machines for each value of β_y^*. The standard deviation of the calculated values are shown with error bars.

injector linac are listed in Table 4. Comparing the linac bunch charge with the nominal bunch charge for LER, the maximum bunch charge available for single turn injection is 28% of the nominal value. Lower bunch current increases the lifetime, assuming that the dimensions of the beam stay the same the Touschek lifetime is inversely proportional to the number of particles in the bunch [11]. Reducing the bunch charge to 28% of the nominal value could therefore increase the estimated lifetime by a factor of 3.5. Further, for single turn injection the injection kicker kicks out neighboring bunches, limiting the number of bunches.

Table 4: Main parameters [12] of the injector linac for SuperKEKB. The nominal LER/HER bunch charge are added for comparison.

	e^+	e^-
Energy [GeV]	4	7
Linac bunch charge [nC]	4	5
LER/HER bunch charge [nC]	12.5	10.5
Horizontal emittance [nm]	12.7	3.65
Vertical emittance [nm]	2.56	1.46
Energy spread [%]	0.07	0.08
Bunch length [mm]	0.7	1.3
# of bunches	2	
Maximum repetition rate [Hz]	50	

An important limitation to changing the optics in LER is the beam background in the Belle 2 detector of SuperKEKB, which has to be controlled to protect sensitive components. The background sources include the Touschek effect, beam-gas scattering, radiative Bhabha scattering and synchrotron radiation near the IP. An overview of how these have been estimated for the nominal machine and some implemented countermeasures can be found in [14]. Estimates for the beam background when lowering β_y^* are not made. One possible scenario is reducing β_y^* in stages, checking the background and reducing number of bunches if needed.

4. Validation measures

It is necessary to measure the beam size and β_y at the IP to determine how well the increased chromaticity is corrected. At KEKB, such measurements have been made using free betatron oscillations induced by a kicker magnet [16]. There are 2 BPMs installed between the IP and the quadrupoles closest to the IP in each ring that can be used for this purpose [15]. Two other measurement techniques include beam-beam scan and k-modulation. Future studies will be needed to determine how these techniques are affected by a change in β^*.

Luminosity is also used to determine beam characteristics at the IP. The luminosity for the different values of β_y^* in error free lattices is estimated using a feature of the beam-beam tracking routine implemented in SAD [13]. A weak-strong model is used where the HER beam is assumed unaffected by the alteration of the LER beam. Even though the HER beam has a larger magnetic rigidity than the LER beam due to the energy asymmetry, the effect on the HER beam should be investigated. A reduction of the LER bunch charge by 72% is included in the calculation, corresponding to on-axis injection as discussed above. Additionally, the number of bunches is lowered to 40. Figure 8 shows the estimated luminosity from tracking 1000 particles around the LER ring when including damping and excitation. The average luminosity is calculated every

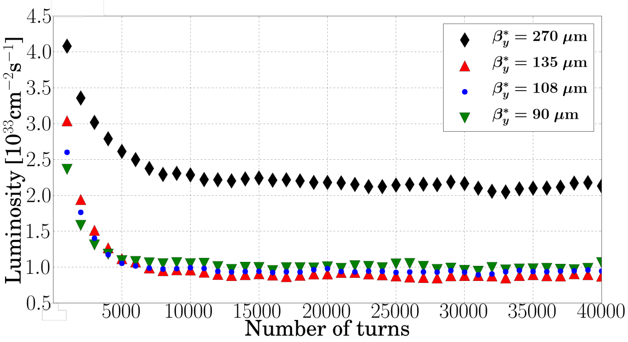

Figure 8: Luminosity during tracking of a distribution of 1000 particles for 40 000 turns using 4 different values of β^*. No errors are added. The average luminosity between 10 000 and 40 000 turns is shown in Table 5. The bunch charge is reduced by 72% to correspond with the largest bunch charge available for single turn injection, while the number of bunches is 40.

Table 5: Estimated luminosity in SuperKEKB for the different cases of β_y^*. The HER beam is assumed unaltered from the nominal case, and LER bunch charge is lowered by 72%. No errors are added in the lattice.

$\beta_y^*[\mu\text{m}]$	270	135	108	90
L $[10^{33}\text{cm}^{-2}\text{s}^{-1}]$	2.1	0.90	0.94	1.0
Bunch current [mA]	0.40			
# of bunches	40			

1000 turns. The average luminosity between 10 000 and 40 000 turns, when the values have stabilized, are shown in Table 5. With regards to the luminosity measurement, the estimated luminosity for different reductions of β_y^* in Table 5 vary by about 5%. One of the luminosity monitors in Belle 2, the ECL luminosity monitor [17], is expected to have an accuracy of 2% for a 100 s measurement if the luminosity is $1\ \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$. A summary of some tentative parameters for such a run with a factor 3 increase in chromaticity from the final quadrupoles is shown in Table 6. The parameters include a change in the vertical tune from 46.57 to 46.56, as well as an increase in coupling from 0.27% to 0.40%.

Table 6: Tentative parameters for a low β_y^* run of LER, where HER is assumed to have the nominal parameters given in Table 2.

β_y^*	90 μm
β_x^*	48 mm
ν_x/ν_y	44.53/46.56
ϵ_x/ϵ_y	3.2 nm / 13 pm
Bunch current	0.40 mA
# of bunches	40
Luminosity	$1 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$

5. Conclusion

Future linear collider FFS have to correct a large chromaticity originating in the strong final quadrupoles and it is important to understand limitations in the proposed correction schemes. SuperKEKB will correct chromaticity of the same scale as FFTB using the traditional correction scheme. Adjusting the optics could test how well the SuperKEKB FFS corrects chromaticity levels comparable to ILC and approaching that of CLIC.

A SuperKEKB LER lattice has been matched and optimized for lower values of β_y^* down to a factor 3 below the nominal value, corresponding to a factor 3 increase in chromaticity from the final quadrupoles. Lowering β_y^* by a factor 3 in LER decreases the dynamic aperture considerably. Considering only strength and tilt errors of quadrupoles and sextupoles in the arcs, the reduction of dynamic aperture and lifetime seem to be manageable if employing on-axis injection and thus at most 28% of the nominal bunch current. An increase in coupling is observed when reducing β_y^*, from 0.036% to 0.12% for the error free lattice without beam-beam interaction, which further increases when errors are introduced. Tentative parameters for low β_y^* optics in LER based on the above results are given in Table 6. Further studies are needed to take into account IR errors, beam background, correction procedures and validation measures.

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