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Development of a control system for the fourth-harmonic cavity of the HLS storage ring

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Abstract Harmonic RF cavities are commonly used in storage rings to lengthen the bunches and thus suppress the beam's instabilities and increase its Touschek lifetime. The voltage and phase of the electromagnetic fields in the harmonic cavity are of great importance for stretching the bunch. In the Hefei Light Source storage ring, a passive fourth-harmonic cavity is installed, and the cavity is monitored and controlled by an analog control module provided by its manufacturer. To vary and maintain the voltage of the harmonic cavity in a more effective way, a digital proportional, integral, and derivative feedback system based on the Experimental Physics and Industrial Control System is developed on top of the analog control module. This paper reports the details of the development of this voltage control system. Some test and operational results are also presented.

Keywords Bunch length · High-harmonic cavity · EPICS · PID feedback

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1 Introduction

In storage rings, the electron distribution is determined mainly by the magnet lattice, the electromagnetic fields in the RF cavities, the synchrotron radiation, the intrabeam scattering, and various beam instabilities. Among these factors, the electromagnetic fields in radio-frequency (RF) cavities play a key role in defining the phase space volume occupied by the bunched electron beam. Because the synchrotron radiation changes the momenta of the electrons in all directions, and the RF fields change only the longitudinal momenta, the oscillations of the electrons are damped to an equilibrium state, resulting in a finite beam emittance. In the longitudinal direction, the amplitude of the electric fields, or the voltage across the RF cavity, can be used to manipulate the bunch length. By using the RF fields in the fundamental cavity and high-harmonic cavity (HHC), the electron bunch can be lengthened or shortened by adjusting the relative phase advance and voltage ratio of the cavities. The lengthened bunch undergoes less Touschek scattering, and thus, the beam lifetime is longer. By increasing the synchrotron tune spread, the harmonic cavity, also known as the Landau cavity, can be used to suppress the collective beam coherent instabilities and increase the beam current threshold [1, 2]. Further, the harmonic cavity can also help suppress the transverse emittance blowup by alleviating the intrabeam scattering, which is especially important for storage rings with ultralow beam emittance [3].

HHCs have been adopted in many synchrotron light source facilities [1, 2, 4–8]. Obvious bunch lengthening has been observed, and a significant lifetime increase has been achieved [1, 2, 4–6]. Recently developed storage rings with ultimately low emittance, which are known as diffraction-limited storage rings, require a longer bunch length to accommodate more charges in each bunch and increase the Touschek lifetime. HHCs are becoming an essential component of next-generation storage ring-based synchrotron radiation light sources [9–11].

The storage ring of Hefei Light Source (HLS) is operated at a relatively low energy of 800 MeV. The Touschek effect will be the main factor that limits the beam lifetime, and the coupled-bunch instabilities can strongly affect the beam dynamics owing to the lack of natural damping. For these reasons, a passive fourth-harmonic RF cavity was installed in the storage ring during a major renovation of the light source from 2010 to 2014 [7, 12]. The fourth-harmonic cavity of the HLS storage ring was manufactured by the Budker Institute of Nuclear Physics (BINP) in Russia. In this paper, “HHC” refers to the fourth-harmonic cavity unless otherwise specified.

It is known that the voltage ratio of the HHC and the fundamental cavity should be properly set in order to stretch the bunch. The main HLS RF cavity operates at a cavity voltage of 180 kV. With the aid of a low-level RF control system, its voltage stability is better than 0.06 kV (rms). The HLS HHC can operate only in the passive mode, and its voltage is controlled by the cavity tuner. The tuner is driven by a servo motor system and controlled by an analog control module. However, owing to the noisy nature of the measured voltage signal, this control module cannot effectively stabilize the HHC voltage. To better stabilize and adjust the HHC voltage, a digital feedback system based on the Experimental Physics and Industrial Control System (EPICS) [13] is developed at the National Synchrotron Radiation Laboratory (NSRL).

EPICS is commonly used as a standard control model for accelerators and other large-scale scientific facilities. The fundamental unit of EPICS is the record. The EPICS database, which consists of a large set of records and is managed by input/output controllers (IOCs), performs the tasks needed to control the facility. These tasks include basic control and monitoring of the devices, as well as advanced controls such as digital filtering and proportional, integral, and derivative (PID) feedback. The EPICS-based PID controller has been used to control various devices in a number of facilities [14, 15].

Voltage adjustment and stabilization of the harmonic cavity in the HLS storage ring is also realized using EPICS records. A preliminary report was presented in the IPAC2016 proceedings [16]. This paper reports the development of the digital feedback of the HHC voltage in detail.

2 The fourth-harmonic cavity at HLS

The HLS HHC system consists of a fourth-harmonic cavity and an analog control module. Both the cavity and control module were manufactured by the BINP. The cavity can operate only in passive mode, i.e., when the electromagnetic fields in the cavity are excited by the stored electron beam itself. The main parameters of the fourth-harmonic cavity and the HLS storage ring are listed in Table 1. The shunt impedance is defined as $R_s = V_c^2/2P_c$, where V_c is the effective cavity voltage, and P_C is the power dissipation. The measured temperature stability of the HLS harmonic cavity is better than 0.3 °C (rms).

The control module is used to measure key parameters of the harmonic cavity such as the voltage and frequency. The control module can also be used to control the resonance condition of the cavity. It has two working modes, the voltage mode and plunger mode. When operating in voltage mode, the control module maintains the cavity voltage at a designated value using an analog feedback loop. When it operates in plunger mode, the feedback loop is open, and the tuner plunger can be manually moved in and out to a designated position. Both the voltage setpoint and plunger position are controlled by direct current (DC) voltage signals fed to specific input ports of the control module.

The analog feedback loop has been used to control the HHC voltage. However, it moves the tuner plunger too frequently because of its noisy input signal, resulting in serious damage to the driving motor system. Furthermore, the analog feedback lacks flexibility, such as the ability to integrate the beam parameters into the control system. To make the system more reliable and convenient to use, a digital PID feedback loop based on EPICS is developed. This feedback system is described in the following sections.

Table 1 Main parameters of the HLS storage ring

Name	Value
Beam energy (MeV)	800
Ring circumference (m)	66.13
Fundamental RF freq. (MHz)	204
RF harmonic number	45
HHC resonance freq. (MHz)	816
HHC quality factor	18,000
Shunt impedance (MΩ)	2.5
HHC operation mode	Passive

3 The EPICS-based cavity high-voltage control

A functional sketch of the HHC control system is shown in Fig. 1. The RF signal of the HHC is out-coupled using a built-in electrode in the cavity. The out-coupled signal is processed by the BINP control module. An analog DC voltage signal from one of the output ports indicates the high voltage of the HHC. This analog voltage signal is then digitized by an analog-to-digital converter (ADC) module in a programmable logic controller (PLC). The digitized voltage signal is monitored by an analog input (AI) record inside an EPICS IOC. The IOC and PLC communicate with each other over the local area network of the HLS control system. Inside the IOC, an enhanced PID (EPID) record is employed to adjust or maintain the high voltage of the HHC.

3.1 The HHC voltage signal

The voltage signal from the output of the control module is very noisy. To understand the noise, the time-domain voltage signal is measured using a digital oscilloscope, and the frequency-domain signal is calculated via a fast Fourier transform. Both the time-domain and frequency-domain signals are shown in Fig. 2. The results indicate that most of the spectral power of the voltage signal is in the range from DC to 200 Hz. Because we need only the DC component of the signal to perform feedback, a low-pass filter (LPF) is used to mitigate the alternating current (AC) component. To make the signal even smoother, a set of data compression records called COMPRESS records, which collect data into arrays and average the data using specified algorithms [17], are employed to perform simple digital filtering. The unfiltered and filtered voltage signals are compared in Fig. 3, which shows that these filtering methods are effective in eliminating the AC component of the voltage signal.

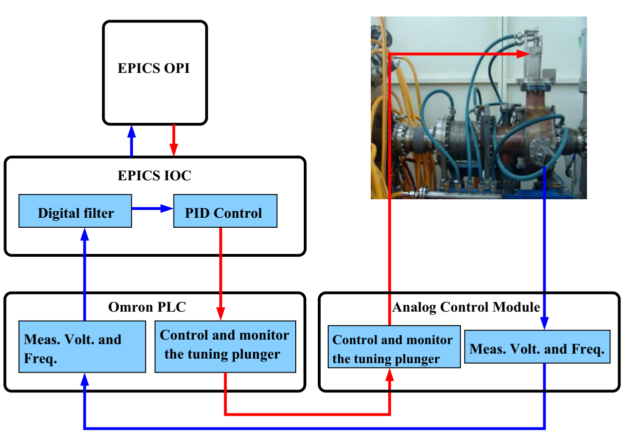

Fig. 1 Overview of the voltage control system for the HLS fourth-harmonic RF cavity (Color online)

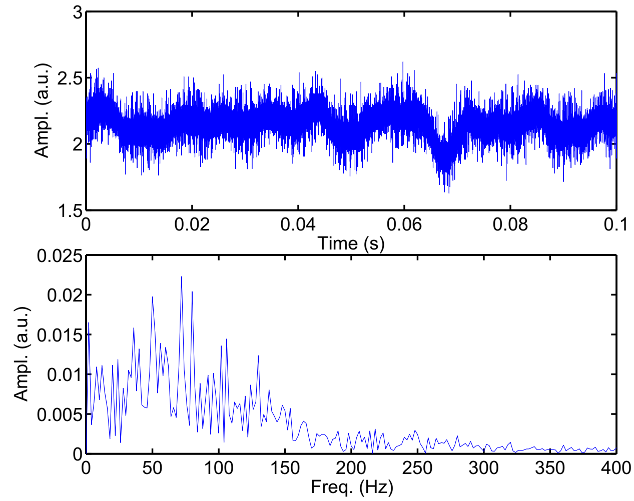

Fig. 2 HHC voltage signal from the output of the analog control module. (Top) Time-domain voltage signal measured using an oscilloscope; (bottom) frequency domain of the measured voltage signal (Color online)

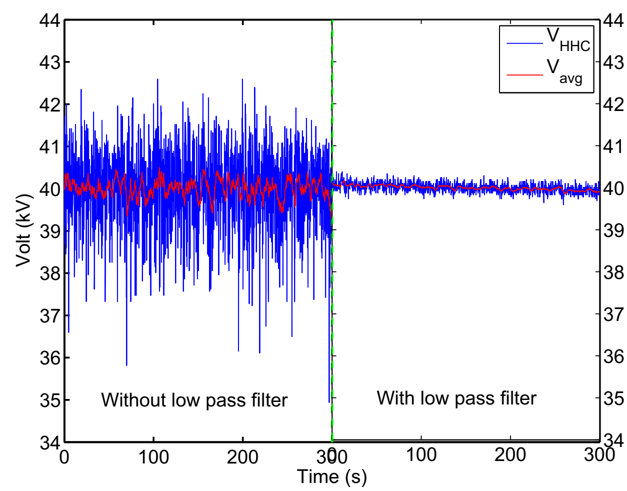

Fig. 3 HHC voltage signal measured using the PLC ADC: (Left) Without LPF and (right) with LPF. Both are measured at a beam current of approximately 210 mA (Color online)

3.2 The PID feedback loop

Feedback of the HHC voltage is realized using a set of EPICS records. As mentioned in a previous section, the core of the feedback loop is an EPID record. It uses the real-time HHC voltage V_{hhc} from an AI record and the voltage setpoint V_{set} from an analog output (AO) record as its inputs. Using the difference between V_{hhc} and V_{set}, the EPID record calculates the manipulated variable to control the tuner plunger. The PID gains, including the proportional gain K_p, integral gain K_i, and derivative gain K_d, are determined on the basis of experimental data and preset to the corresponding fields of the EPID record. To make the feedback robust, a set of AO records holding some critical control parameters is used in the system. These parameters include:

- the lowest beam current (I_{low}) and highest beam current (I_{high}) between which feedback is enabled;
- the lowest position (P_{low}) and highest position (P_{high}) that the tuner plunger can reach;
- the voltage threshold (ΔV) beyond which the feedback would act.

The feedback procedure is controlled by a set of records, as shown in Fig. 4. A FANOUT record [17] is used to judge whether to perform PID feedback according to the value of its SELN field. PID feedback is performed when SELN equals 1, and only the voltage error ($V_{hhc} - V_{set}$) is calculated when SELN equals 2. The FANOUT record works in Specified mode; that is, it triggers only the forward link specified by the value of its SELN field, which is read from the SELL link. The SELL field is linked to an AO record named PID:TRIGN. A genSub record, with its OUTA pointing to the PID:TRIGN record, is used to control the SELN value of the FANOUT record.

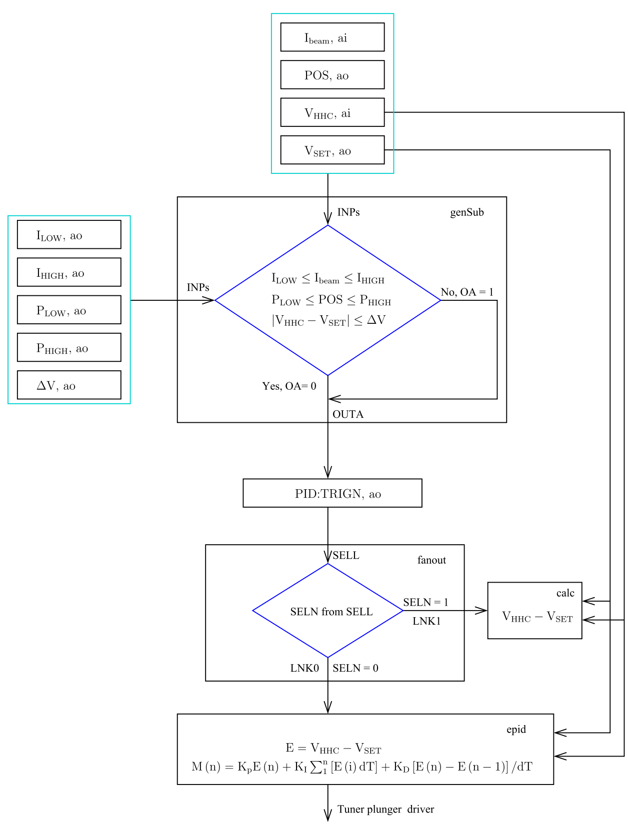

Fig. 4 Functional sketch of the HHC voltage feedback (Color online)

The genSub record monitors the control parameters (I_{low}, I_{high}, P_{low}, P_{high}, and ΔV), the beam current I_{beam}, and HHC parameters including the tuner plunger position P, V_{hhc}, and V_{set}. If these parameters satisfy all the following conditions,

$$\begin{cases} I_{low} \le I_{beam} \le I_{high} \\ P_{low} \le P \le P_{high} \\ |V_{hhc} - V_{set}| \ge \Delta V \end{cases}, \tag{1}$$

the subroutine of genSub assigns a value of 1 to its OUTA; otherwise, a value of 2 is set. All the records in the forward link list are then processed accordingly.

When it is processed, the EPID record uses V_{hhc} and V_{set} to calculate the voltage error and controls the tuner plunger to move the appropriate distance to compensate for the voltage error. This mechanism has been used to effectively maintain the HHC voltage within a designated range, and the tuner plunger is moved significantly less often.

4 Determining the feedback parameters

The PID parameters of the HHC voltage feedback are determined using beam-based experiments. A number of studies, including studies of the reproducibility and linearity of the tuner plunger driving system and the voltage change as a function of the plunger movement, are performed to acquire reasonable PID parameters.

4.1 Reproducibility and linearity of the tuning plunger driving system

The reproducibility of the tuner plunger is an important property of the HHC voltage control system. Because the HLS storage ring now runs with decay of the beam current, the HHC should operate in voltage feedback mode. In this case, a lack of reproducibility due to mechanical hysteresis could be automatically compensated. However, the HLS is undergoing an upgrade project that aims at top-off operation, in which the HHC may run in feedforward mode [18]. This means that the plunger position is fixed according to the beam current. In that case, the reproducibility of the plunger becomes important. To check the reproducibility, the tuning plunger is scanned from one end to the other without an electron beam in the storage ring. The plunger positions are recorded during the scan. Four scans are performed, and the results are plotted in Fig. 5. The results indicate that the reproducibility of the plunger driving system, which has a minor hysteresis effect, is reasonable for controlling the cavity resonance condition. The hysteresis effect also appears in the following test. Fig. 5 also shows good linearity of the motion of the tuning plunger system.

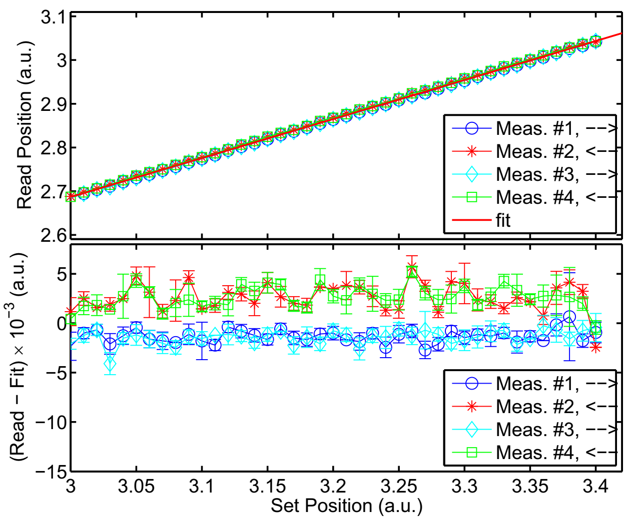

Fig. 5 Reproducibility and linearity of the plunger movement: (Top) Set position versus measured position of the tuner plunger; (bottom) measurement uncertainty (Color online)

The reproducibility is also tested with electron beams in the storage ring because the voltage of the HHC could be very high when the cavity is tuned on its resonance with a considerable beam current. To avoid damaging the cavity, only a small beam current, approximately 3 mA, is stored in the storage ring for these tests. The tuner plunger is scanned inward and then outward. The high voltage of the HHC is measured during the scan. The results of the measurements are plotted in Fig. 6, which shows that the resonance of the HHC can be well reproduced when the plunger moves in the same direction. There are small differences in the resonance points when the plunger moves in different directions. These differences are caused by the hysteresis effect of the mechanical driving system of the tuner. During routine light source operation, the HHC operates far from resonance, as indicated in the figure. Therefore, the hysteresis effect has little impact on the PID feedback.

4.2 Determination of the PID gains

The PID gains of the HHC voltage feedback are determined experimentally by measuring the relationship between the plunger position and the HHC voltage. Because the HLS might be operated in a wide range of beam currents, the experiments are performed at a series of stored beam currents varying from 60 to 280 mA. At each beam current, the tuner plunger of the HHC is scanned to change the HHC voltage in a small range. The plunger positions are linearly fitted as a function of the HHC voltage. The slope of the fitted curve, $\mathrm{d}s/\mathrm{d}V$, is used to determine the proportional term K_p of the feedback loop. One of the measurements performed at 240 mA is plotted in Fig. 7. The measured slopes for different beam currents are summarized in Table 2. The results indicate that the slopes for different beam currents are within a range of -0.004 to -0.002. We select -0.0003, which is 1/10 of the mean value of these slopes, as the K_p value for the feedback to avoid large oscillations. The integral gain K_i and derivative gain K_d of the feedback are also fine-tuned to eliminate overshoot and avoid oscillation; for normal operation, they are 0.3 and 1, respectively.

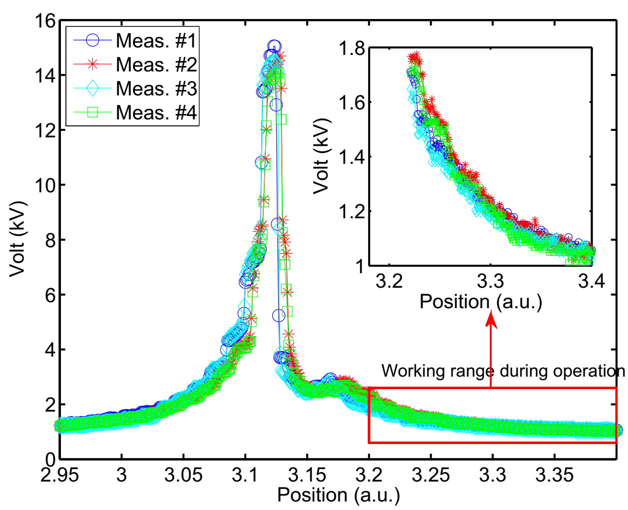

Fig. 6 High voltage of the HHC measured as a function of the tuning plunger position. Data are taken at a beam current of approximately 2.7 mA (Color online)

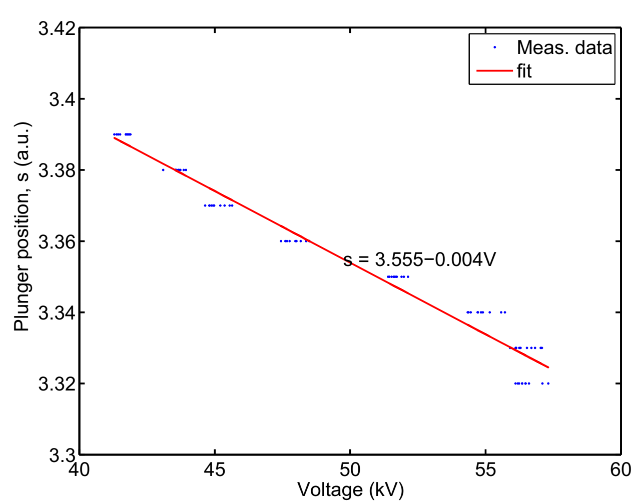

Fig. 7 Plunger position as a function of the cavity voltage. The beam current is approximately 240 mA for this measurement (Color online)

Table 2 Slope of the plunger position as a function of the HHC voltage measured at different beam currents

Beam current (mA)	ds/dV
60	− 0.003
120	− 0.002
160	− 0.003
200	− 0.004
240	− 0.004
280	− 0.004

5 HHC voltage stabilization and adjustment

The HHC voltage feedback system was used to vary/maintain the HHC voltage to/at designated values during routine light source operation and machine studies. At present, the HLS storage ring is operated in a beam current range varying from 100 to 400 mA in decay mode. The voltage of the fundamental cavity is 170 kV. The HHC voltage is optimized to stay at 40 kV to increase the beam lifetime and mitigate the coupled-bunch instabilities. To protect the cavity from damage, the low- and high-current limits are set to 40 and 400 mA, respectively. The low and high limits of the plunger position are set to 3.28 and 3.60, respectively. The voltage threshold, ΔV, is set to 0.5 kV, which is approximately 1.3% of the setpoint value.

As it is a function of the beam current in the storage ring, the HHC voltage decays during operation in decay mode while the feedback loop is open. When the feedback loop is closed, the HHC voltage can be maintained in the range of 40 ± 0.5 kV; see the upper part of Fig. 8. This system can also be used to adjust the HHC voltage by varying the setpoint value of the HHC voltage, as shown in the lower part of Fig. 8.

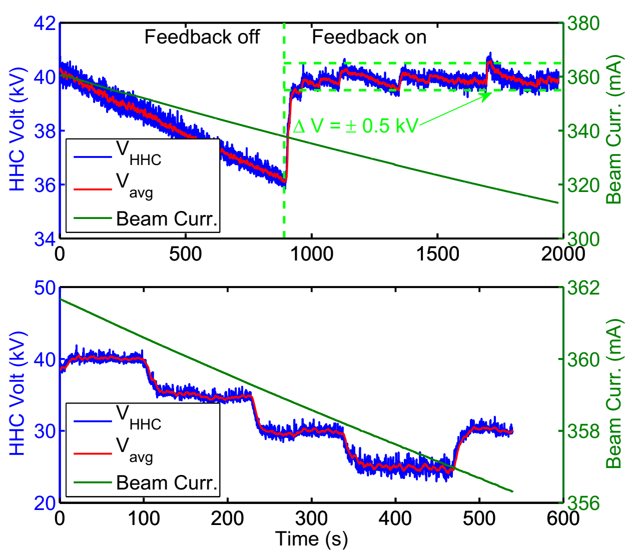

Fig. 8 HHC voltage stabilization and adjustment. (Top) Feedback test; (bottom) voltage adjustment using the feedback system (Color online)

6 Summary

A fourth-harmonic RF cavity is installed in the HLS storage ring to mitigate the beam instabilities and increase the beam lifetime. A digital PID feedback system based on EPICS is developed. This feedback system can effectively maintain the high voltage of the HHC within ± 0.5 kV around the voltage setpoint. The HHC voltage can also be adjusted using this feedback system for various machine studies.

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