COMMISSIONING OF THE SHANGHAI LIGHT SOURCE

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Abstract

The Shanghai Synchrotron Radiation Facility (SSRF) is an intermediate energy, third generation light source. In December 2007, electron beam was stored and accumulated in the SSRF storage ring. Since then the accelerator commissioning and beam line installation have continued toward the scheduled user operation from May 2009 onwards. This paper presents an overview of the SSRF status and preparations for user operations.

INTRODUCTION

The SSRF project was proposed by Chinese Academy of Sciences and Shanghai Municipal Government in 1995, it was followed by a dedicated R&D with a budget about 12M USD from 1999 to 2001, and finally the SSRF project was launched by Chinese Central Government in 2004. On Dec. 24, 2007, within three years after the project ground breaking, the electron beam was stored and accumulated in the storage ring and the first synchrotron light was observed[1]. The accelerator and beamline commissioning continued through the end of April 2009, when the SSRF project inauguration held. The construction and commissioning of all the SSRF accelerators have been completed to within their design specifications, and currently the storage ring is operating at an energy of 3.5 GeV with a beam current of 200 mA and an emittance ~3.9 nm-rad. Seven beamlines have been commissioned to their acceptance specifications, and the SSRF user pre-operation was scheduled to begin on May 6, 2009.

The SSRF commissioning started with the 150MeV electron linac on May 15, 2007 and ended with the in-vacuum undulator based macromolecular crystallography beamline in phase-I on April 13, 2009, when the SSRF started its performance measurements for evaluation of the facility readiness to start the user operation. The initial SSRF storage ring commissioning was performed at 3 GeV using three KEK-PF retired cavities from December 2007 to June 2008, the commissioning at 3.5GeV with superconducting RF cavities started on Aug.5, 2008. The 50mA and 100mA stored beam current were obtained on Aug.8 and 10, 2007 respectively, and on Spet.30, 200 mA stored beam current at 3.5 GeV was achieved.

The commissioning of the first SSRF bending beamline, small angel X-ray scattering beamline, started on May 9, 2008, it was followed by the commissioning of the high-resolution X-ray diffraction beamline in June 2008. Two wigglers, W80 and W140, were installed into the storage ring on Sept. 9 and 12, 2008, the commissioning of the XAFS and the medical X-ray image beamlines started on Oct. 4, 2008. The elliptically polarized undulator of 4.2m long was installed into the storage ring on Oct.30, 2008, and it was commissioned with beam on Nov.7, 2008. Then the commissioning of the EPU based soft X-ray spectromicroscopy beamline started on Dec.26, 2008. The first in-vacuum undulator was installed on Jan.28, 2009, and the beamline commissioning started a few days later on Feb.3, 2009. The second in-vacuum undulator was installed on Feb. 29, 2009, and the commissioning of the associated macromolecular crystallography beamline started on March 7, 2009.

CONTROL SYSTEM AND DIAGNOSTICS

The SSRF control system is a hierarchical standard accelerator control system based on EPICS with three sub systems for the linac, the booster and the storage ring. The high level physical application environment is set up by using the MatLab 2007a with Accelerator Toolbox (AT) and the middle layer (MML) with MatLab Channel Access (MCA) connected component MCA/LabCA, and a number of development toolkits are used at SSRF, such as EDM, MatLab, Borland C++, Visual DCT, TCL/Tk, Gcc/G++ and Borland Delphi. Based on the MML&AT developed at ALS and SPEAR3, a few of additional applications have been developed for the SSRF accelerator commissioning, including matchgui.m for twiss parameter matching in transport lines, betameas.m for online beta function measurement, timing.m for timing adjust and injection control, backupgui.m and restoregui.m for lattice configuration saving and restoring, SRtune.m for tune measurement.

The diagnostics available during the SSRF injector commissioning were 3 Bergoz ICTs, 11 WCMs, 16 screen monitors, 3 slits, 2 stripline tune drivers, a Bergoz DCCT and 43 stripline BPMs. The diagnostics available during the storage ring commissioning were a Bergoz DCCT, 2 screen monitors, 2 stripline tune drivers, a visible synchrotron light monitor, a vertical/horizontal combined scraper, 140 BPMs, 2 interferometers, a streak camera and a fast gated camera. The transverse beam feedback system was implemented in December 2008.

All BPMs equipped with Libera digital processors could deliver 10Hz closed orbit data, 10kHz fast application data and 694kHz turn-by-turn data at the same time. The typical RMS variation for 10Hz data is 100nm. The noise level for turn-by-turn data is about 3μm.

INJECTOR COMMISSIONING

The SSRF accelerator complex consists of a 150MeV electron linac, a full energy booster and a 3.5 GeV storage ring. The linac commissioning for both single bunch and multi-bunch mode was completed with the performance within its specifications, now it is typically operating at the single bunch mode with an energy of 158MeV, an emittance less than 50 mm-mrad, a bunch charge of

1.06nC, an energy stability less than 0.3% and an energy spread of 0.4%. The achieved maximum bunch charge is 1.6nC [2]. Since Sept. 30, 2007, the SSRF linac has been stably operating for ~9300 hours with high reliability and high reproducibility, its failure time is ~80 hours.

The SSRF booster commissioning started from the linac transport line on September 30 evening, within 60 effective commissioning hours, the 3.5GeV ramped beam were achieved without using any correctors on Oct. 5, 2007. After the installation of the booster to the storage ring transport line, the extracted beam was obtained on Oct. 29, 2007 [3, 4]. Table 1 shows the main achieved booster performance parameters.

Table 1: Achieved Booster Performance Parameters

Parameter		Designed	Measured
Energy (GeV)		3.5	3.51
Charge	Single bunch (nC)	1.0	1.2
	Multi bunch (nC)	5.0	6.0~6.6
Emittance (nm·rad)		108	90~107
Repetition rate (Hz)		2	2
Tune	(H)	8.18,8.42	8.41
	(V)	5.22,5.39	5.27
Current stability (RMS)		---	4%

The entire booster transmission efficiency from the entrance of the LTB transport line to the entrance of the BTS transport line (ratio of two ICTs), including the transport line (LTB) transmission efficiency, the booster injection efficiency, the energy ramping efficiency and the booster extraction efficiency, is larger than 85%.

Since December 21, 2007, the booster has been stably operated as a fully energy injector to the SSRF storage ring with excellent reliability and reproducibility for ~8600 hours.

STORAGE RING COMMISSIONING

The SSRF storage ring commissioning was carried out in three phases. In phase-I, a complete commissioning of the storage ring was carried out at 3GeV with KEK-PF retired copper cavities, and the maximum beam current achieved was 100mA [1, 5, 6]. In phase-II, the storage ring was commissioned at 3.5GeV with superconducting cavities to obtain the high stored beam current, the maximum beam current achieved is 225mA, and there are no technical difficulties for the ring to go even higher current. In phase-III, the commissioning with five insertion devices was performed in parallel with the commissioning of the first SSRF beamlines.

Milestones

The storage ring commissioning is proceed with a fast pace, which also benefits from starting the commissioning by using KEK-PF copper cavities. The main milestones are listed in the following.

- Dec. 21, 2007: commissioning started at 18:20, one turn achieved at 21:08 and multi-turn beam at 21:18;
- Dec. 24, 2007: first stored beam obtained at 06:54
- Jan. 03, 2008: 100mA stored beam achieved at 20:20;
- Mar. 16, 2008: both horizontal and vertical closed orbit corrected to <50 μm (RMS) with 80 correctors (137 BPMs);
- June 2008: a few of microns horizontal/vertical orbit stability achieved;
- Aug. 8-10, 2008: 50 mA and 100mA stored beam at 3.5GeV obtained ;
- Sept. 30, 2008: 200 mA stored beam at 3.5GeV achieved.
- Apri. 29, 2009: 468 A·hrs accumulated beam time obtained.

The commissioning of the SSRF storage ring has been completed to within its design specifications. Table 2 shows the main achieved storage ring performance parameters. The measured beam transmission efficiency from the booster to the storage ring (ratio of two DCCTs), including the booster extraction efficiency, the BTS transport line transmission efficiency and the storage ring injection efficiency, is larger than 95% at ID gaps closed.

Table 2: Main Achieved Parameters of the Storage Ring

Parameter	Designed	Measured
Beam energy (GeV)	3.5	3.5
Circumference (m)	432	432
Beam current (mA) Multi-bunch Single bunch	 200 – 300 5	 >200 6.5
Natural emittance (nm-rad)	3.9	~3.8
Natural energy spread	0.098%	~0.1%
Coupling	1%	~0.7%
Betatron tunes	22.22/11.29	22.223/11.293
Straight section No.×Length (m)	4×12.0, 16×6.5	4×12.0, 16×6.5
RF voltage (MV)	4.0	>4.2
Beam lifetime (hours)	>10@200-300mA	>15@200mA

Lattice Calibration

Linear optics from closed orbit (LOCO)[7] technique is used for the linear lattice calibration in the SSRF storage ring commissioning. Using LOCO, the RMS beta-beating was sufficiently reduced from 10% to less than 1%.

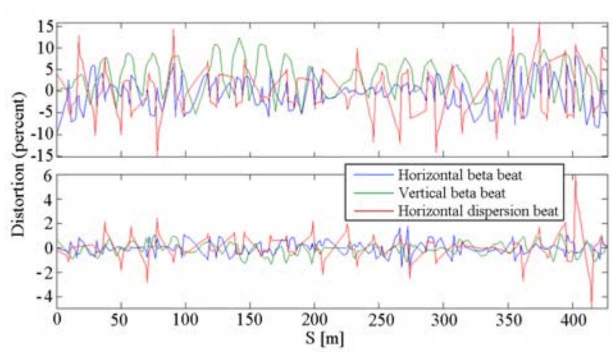

Figure 1: Beta and dispersion beating before (the top plot) and after (the bottom plot) LOCO calibration.

The beam energy is calibrated by the dipole current of the storage ring with an error about 0.5‰. By fitting the spectral flux of the fifth harmonic radiation from an in-vacuum undulator in the storage ring with SPECTRA8.0 [8], the calibrated beam energy about 3.49GeV with an energy spread of ~0.12% is obtained.

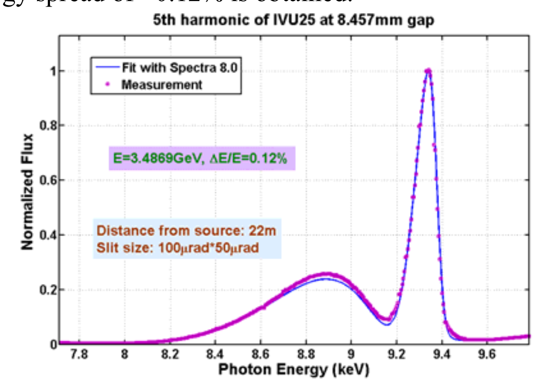

Figure 2: Photon harmonic energy.

The natural emittance is determined by the beam size measurement from an interferometer at 200mA with transverse beam feedback on. The twiss parameters at the source point are given by LOCO, where β_x is 0.544m, η_x is 0.026m , and the theoretical storage ring energy spread of 9.7×10^{-4} is used for calculation. The natural emittance obtained is ~3.8 nm-rad.

The natural and corrected chromaticities measured in horizontal and vertical plane are -44/-14 and 1.6/0.51 respectively. The coupling measured from tune split is about 0.69%. With skew quadrupoles corrections, this coupling can be reduced to about 0.03%.

Orbit Drift and Short Term Orbit Stability

The beam orbit drift changes as the daily temperature variation. Without the RF frequency feedback and the slow orbit feedback (SOFB), the daily orbit drift can reach a few hundreds of microns in the horizontal plane at the locations with large dispersion functions and a few tens of microns in the vertical plane. With SOFB, the RMS orbit variations at all BPM are below 4 µm and 2µm in horizontal and vertical plane respectively under top-up operation (204~205mA) in 18 hours, and the RMS orbit variation of 40 ID BPMs are below 2 µm and 1 µm in each plane respectively at good performance case. In the beam decay operation with SOFB running, they are below 5 µm and 3 µm in each plane respectively during 15 hours as the beam current decays from 170mA to 120mA, and at the same time period, the RMS orbit drifts of the 40 ID BPMs are below 5 µm and 2 µm in each plane respectively.

The SSRF is located in urban area and with a soft soil earth condition. The measurements show that the RMS integrated displacement of magnet vibrations on the ring floor between 1 to 100Hz is ~0.2 µm at noisy hours and ~0.13 µm at quiet hours respectively. The cultural noise contribution is mainly in the region of 1~20Hz, while the technical noises are suppressed to a very low level. The short term beam orbit motion is well controlled with RMS integrated displacement of 0.3 µm at quiet hours and 0.5 µm at noisy hours, thanks to the nice correlation between magnets up to 20Hz guaranteed by the thick slab and solid girder design and the aforementioned technical noise suppression. Figure 3 shows the vertical vibration power spectral density comparison of a quadruple magnet and the stored beam in the ring. In addition, the horizontal beam orbit motion is also well controlled within 0.8 µm at noisy hours and 0.6 µm at quiet hours. The fast orbit feedback (FOFB) is under commissioning to further improve the orbit stability performance.

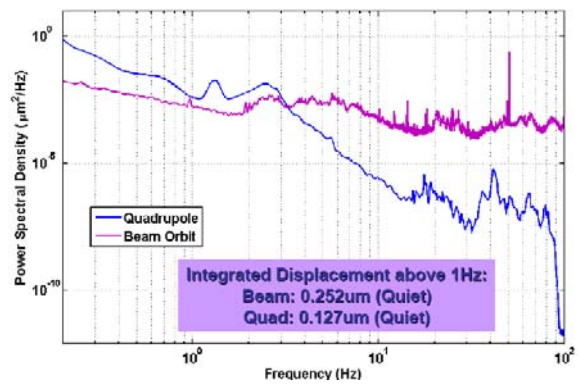

Figure 3: A vertical quadrupole and beam orbit vibration power spectral density comparison at quiet hours.

Collective Effects

The single-bunch and multi-bunch instabilities have been both observed in the SSRF storage ring. Vertical beam blow up caused by the transverse mode coupling instability (TMCI) occurs at the single bunch current of 6mA with a vertical chromaticity of 0.5 (operating mode). The transverse sawtooth instability appears together with the TMCI, the bursting frequency is tens of Hertz. The maximum single bunch current could exceed 10mA when increasing the chromaticity. As shown in figure 4, the bunch lengthening occurs at ~0.8mA/bunch, which may indicate a rough current threshold of the longitudinal microwave instability.

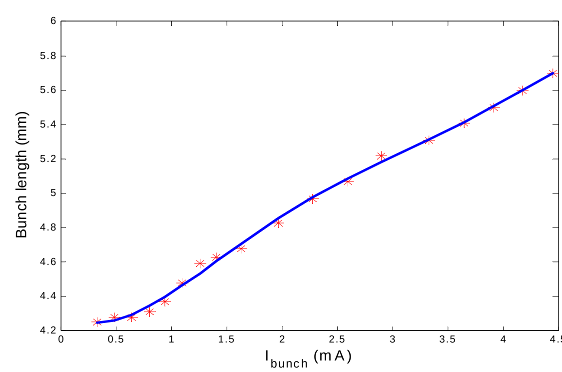

Figure 4: Bunch lengthen with bunch current.

The first appearing multi-bunch instability is fast beam ion instability (FBII) which occurs at about 40mA when vacuum pressure is typically 0.4nTorr. The vertical beam size increases when FBII happens and the vertical oscillation amplitudes observed by the bunch-by-bunch feedback system increases along the bunch train. Short bunch train filling pattern could increase the FBII threshold. The experiments show that the resistive wall instability threshold is ~64mA, which could be identified by the oscilloscope, as shown in figure 5.

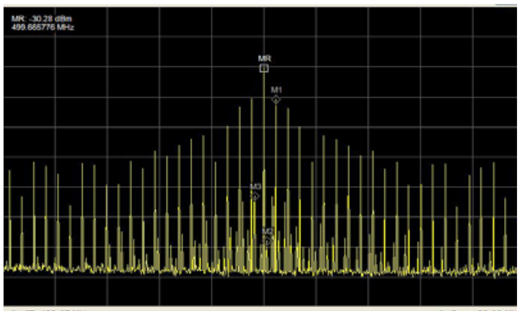

Figure 5: Beam spectrum of the mutibunch fill at 64mA.

The broad-band impedance is measured by the tune changes with the single bunch current. The longitudinal effective impedance is 0.34Ω before the IDs installations. The impedance increased to 0.48Ω after two in-vacuum IDs installed and closed to their minimum gap of 7mm.

The beam lifetime is dominated by Touschek effect in the SSRF storage ring. The measurements show that the Touschek lifetime is 51.3 hours for 0.3mA/bunch. The gas scattering lifetime is 51.7 hours/nTorr. The beam lifetime for 5mA single bunch is 4.7 hours against the linear scaling value of 3.1 hours due to the bunch lengthening effect. The lifetime for a 200mA beam with 4/5 (600 bunches) filling is 31.1 hours and 18.3 hours respectively for in-vacuum undulators fully opened and closed to their minimum gap of 7mm. At present the beam current for the user experiments is from 120 mA to 90 mA, and the beam lifetime is about 25 hours at 4/5 (600 bunches) filling.

Top up Injection and High Current Operation

Top-up injection was tested during machine studies, and the current stability can be controlled within 0.3% at 200 mA. Figure 6 shows a typical top-up operation at 200mA. After a careful scan of injection kicker's strength, timing and mechanical adjustment of the rolling angles, the maximum transient orbit disturbance on the stored beam during injection is now smaller than 100 μm in horizontal and 30 μm in vertical respectively.

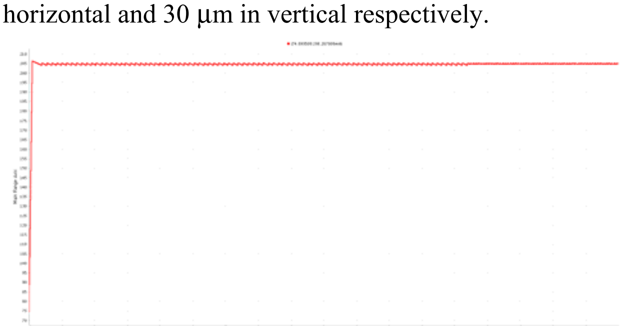

Figure 6: A typical top-up operation test at 200mA.

Efforts have been made to operate the storage ring at high current, including the temperature interlock system setting up, SRF cavity aging, and the transverse beam feedback system (TFB) tuning. The TFB is essential for high current operation, as shown in figure 7, the multi-bunch instabilities at a beam current of 190 mA are heavily damped. Figure 8 shows transverse beam blow up is effectively suppressed by the TFB.

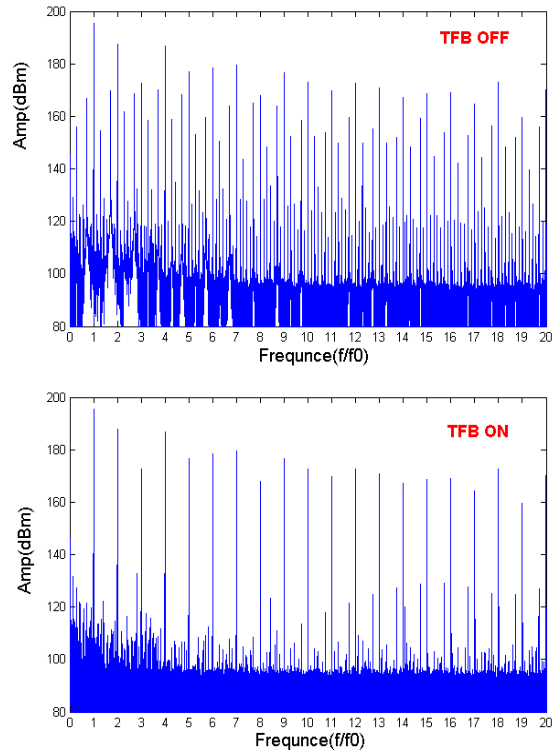

Figure 7: Transverse beam spectrum with TFB off and on (at a beam current of 190mA).

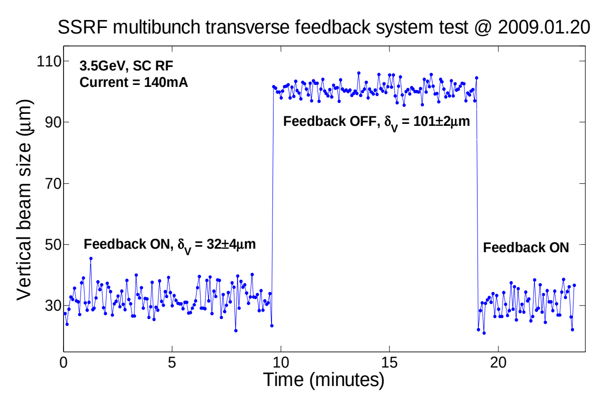

Figure 8: Vertical beam size with TFB on and off.

Commissioning of First Insertion Devices

First five insertion devices (IDs) were installed and commissioned at the SSRF storage ring from middle September 2008 to early March 2009, including two wigglers, one elliptical polarized undulator (EPU) and two in-vacuum undulators. A careful investigation of the perturbation on the closed orbit and on the linear optics has been performed for all devices. The minimum gaps are 17mm for two wigglers, 33mm for the EPU and 7mm for two in-vacuum undulators. Closing the IDs to their minimum gaps generates a residual closed orbit distortion of 72μm, 73μm and 37μm in RMS for wigglers, EPU and in-vacuum undulators respectively. The EPU is only commissioned at linear polarized mode as required by the beamline. The trim coils were assembled at two ends of each IDs to compensate the orbit distortion, and the feed forward tables have been set up to correct the orbit disturbance to less than 5μm at all gap values. During the gap moving process, the orbit is well within the ±2mm beam position interlock threshold. The IDs effect on the linear optics was limited, which creates tune shift less than 1×10^{-3}.

The performance of the in-vacuum undulator, which was developed in house at SSRF, was characterized by photon energy scanning of its radiation. Figure 9 shows the radiation harmonics of the in-vacuum undulator.

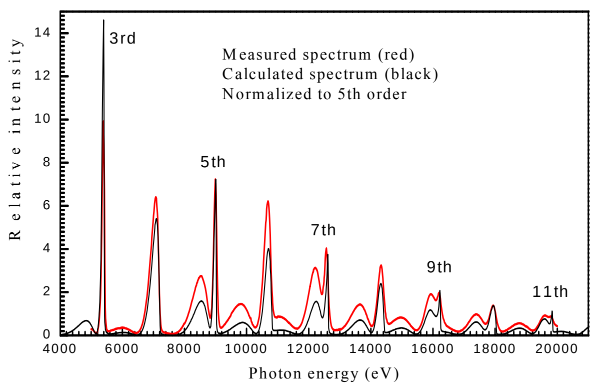

Figure 9: Harmonics of in-vacuum undulator radiation.

BEAMLINE COMMSSIONING

The SSRF beamline commissioning started from two bending magnet (BM) beamlines with sagittal focusing monochromators. Within 60 hours, the focusing mono-beam was observed at the end stations of both the small angle scattering (SAXS) beamline and the diffraction beamline (XRD). The commissioning of the two wiggler based beamlines, the X-ray imaging and Biomedical Applications (XIM) and the XAFS, is straight forward, the mono photon beam was observed at sample point in 2 hours at both beamlines right after the commissioning start. Then the commissioning of the EPU based Soft X-ray Spectromicroscopy beamline and two in-vacuum undulator based beamlines, Hard X-ray Micro-focusing (XMF) and Macromolecular Crystallography (MX), have been completed before April 13, 2009. All seven first phase beamlines have achieved their commissioning goal.

The commissioning of each beamline was divided into two steps. The goal of first step was to obtain monochromatic beam at the sample position. After that the beamline optics and alignments were carefully adjusted to optimize the beamline performance, and then extensive beamline tests were performed. For undulator beamlines, the source characteristics were also carefully tested. The commissioning of various experimental techniques has also been carried out. The commissioning of all beamlines started with beam current less than 10mA, in order to avoid possible heat damage. Now all beamline has been successfully tested and operated under 200mA beam current without heat problems.

CONCLUSIONS

The construction and commissioning of the Shanghai light source are completed successfully within the time schedule. The accelerator complex has been tested and commissioned to the high performance within its design specifications, various machine studies have been carried out and the accelerators have excellent reliability and reproducibility. Seven phase-I beamlines have been commissioned to their acceptance specifications. The SSRF now is ready for the start of user experiments.

ACKNOWLEDGEMENTS

We would like to thank all of our SSRF staff for their dedications and contributions to the construction and the commissioning of the SSRF. The SSRF performance with a fast commissioning speed achieved is a testimony to the highly qualified work that went into designing and constructing the SSRF complex.

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