FIRST OPTICS AND BEAM DYNAMICS STUDIES ON THE MAX IV 3 GeV STORAGE RING

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Abstract

We present results from beam commissioning of the MAX IV 3 GeV storage ring as well as a summary of the beam dynamics studies that have so for been carried out. We report on injection and accumulation using a single dipole kicker, top-up injection, slow orbit feedback, restoring the linear optics to design, effects of in-vacuum undulators with closed gaps, and adjusting nonlinear optics to achieve design chromaticity correction as well as dynamic aperture sufficient for high injection efficiency and good Touschek lifetime.

INTRODUCTION

The MAX IV 3 GeV storage ring is the first light source to make use of a multibend achromat lattice (cf. Fig. 1) to reach ultralow emittance [1–6]. Beam commissioning in the MAX

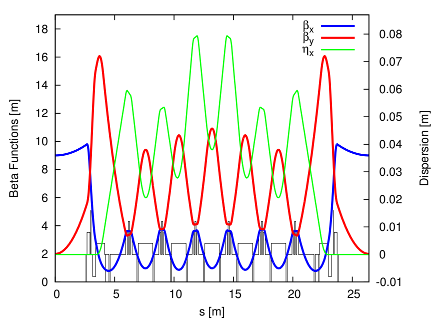

Figure 1: Design optics in one achromat of the MAX IV 3 GeV storage ring. Magnetic lattice indicated at the bottom.

IV 3 GeV storage ring started in August 2015 [7, 8]. First stored beam was achieved on September 15 and on October 8 first stacking was demonstrated. This then allowed many orbit and optics studies to be carried out in the bare machine. On November 2 first light was observed on the first diagnostic beamline in the storage ring. By the end of November top-up injection was being employed and the slow orbit feedback (SOFB) loop had been closed. The first in-vaccum IDs were installed in February 2016 and reached 4.5 mm gaps before the MAX IV facility was inaugurated on June 21, 2016.

This paper will not report on the commissioning of various sub-systems as this can be found elsewhere, e.g. [9–14]. The following sections will instead focus entirely on beam commissioning results and tuning efforts.

INJECTION & ORBIT CONTROL

Once first electron bunches were guided through the entire 3 GeV transfer line, the current transformer at the end of the transfer line was showing a net charge of about 400 pC (at 0.5 Hz).

First Turns & Closed Orbit

All magnets in the storage ring had been set to design optics for the bare lattice at 3 GeV [5], i.e. power supply currents according to magnetic measurement data for all magnets [15]. All ring correctors were set to zero. The single dipole injection kicker was set to $\approx$ 4 mrad kick strength. Without excitation of a single ring corrector magnet, a first turn through the entire storage ring was detected using single-pass data from the ring BPMs. Manual tweaking of transfer line and ring corrector magnets was used to to increase the number of turns recorded in the storage ring. Finally, 500 turns in the ring could be detected and a corrector setting for the closed orbit was established.

Stored Beam, RF Cavity Phasing & Stacking

With three (out of six) cavities delivering 15–20 kW attempts to store beam were made by phasing each cavity individually while observing the storage ring DC current transformer. In the late hours of September 15, 2015 beam was stored for the first time in the MAX IV 3 GeV storage ring. By lowering the voltage on the dipole injection kicker, accumulation was then attempted. During the late hours of October 8, 2015 first stacking to 4.3 mA was observed. Using one ring BPM connected to a spectrum analyzer the synchrotron tune could be measured. The phases of the three cavities were then tuned individually to maximize the synchrotron tune. The three cavity phases were then adjusted coherently with respect to the RF chopper in the injector [16–18] in order to maximize the injection/capture rate. In this way, it became possible to inject and store several mA of current at a rate of over 4 mA/min which corresponded to a capture efficiency of about 30%.

BPM Offsets & Orbit Correction

At 3 mA the integer tunes were confirmed at their design values 42 (H) and 16 (V). An initial attempt was made to determine the offsets for the 200 ring BPMs. The measured offsets showed rms values of 114 μm (H) and 108 μm (V). In the following months these measurements were repeated in order to asses reproducibility, drift, temperature stability, current-dependence, etc. Orbit correction to BPM offsets typically leads to rms orbits of < 1 μm (H) and 41 μm (V) where the latter is caused by a larger number of BPMs than vertical correctors. The SVD routine in the applied MML [19] orbit correction has been modified to apply a weighting where orbit errors in BPMs in the long straights (where the IDs are located) are heavily emphasized at the ex-

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pense of allowing for some vertical orbit excursion throughout the arc.

Accumulation & Capture Improvements

With a well corrected orbit, injection efficiency started to improve. In order to further raise the level of current that could be injected and stored, the injection kicker pulse length was adjusted from 3.5 μs to 1.5 μs which also caused a reduction in maximum kick from 5.1 mrad to 2.4 mrad, very close to the optimum accumulation setting of 2.1 mrad calculated in [20]. The RF chopper was adjusted to limit the injected bunch train length (energy spread) and to allow a maximum of three S-band bunches to be injected into each of the ten storage ring bucket per shot, taking into account the limited phase acceptance of the storage ring at injection [21]. With these modifications, very high capture efficiencies could be demonstrated (cf. Fig. 2, left) and the injection rate could be increased from 0.5 Hz to 2 Hz.

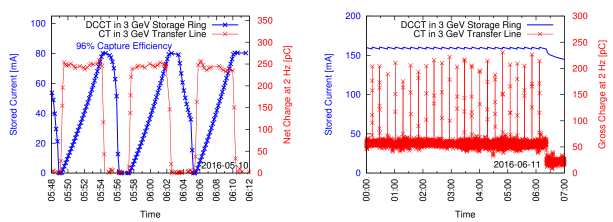

Figure 2: Current in storage ring (blue) and injected charge per shot from linac transfer line (red). Left: increased capture efficiency. Right: top-up operation over night.

Top-up Injection

In November 2015 top-up injection with closed shutters was taken into operation. An example for an entire night shift with current held constant at 159–160 mA by top-up injection is displayed in Fig. 2 (right). The top-up script can inject according to current drop or top-up time interval. It allows adjusting the desired fill pattern. The bunch pattern is monitored routinely by the oscilloscope signal from a ring BPM button. The top-up script also monitors top-up efficiency and suspends top-up injection if the amount of injected charge falls below a pre-defined threshold.

Slow Orbit Feedback

The slow orbit feedback (SOFB) was designed to run at 10 Hz making use of all 380 correctors in the storage ring. In commissioning so far, the SOFB has relied on an MML routine that achieves about 0.5 Hz correction rate. An example for the performance of this SOFB is shown in Fig. 3. Across individual ID straights orbit stability of 200–400 nm rms has been measured in both planes when the SOFB loop is closed. The SOFB has been routinely run during ID and beamline shifts.

OPTICS TUNING

In order to carry out balancing/symmetrization of the optics as well as determine the optical functions, LOCO [22]

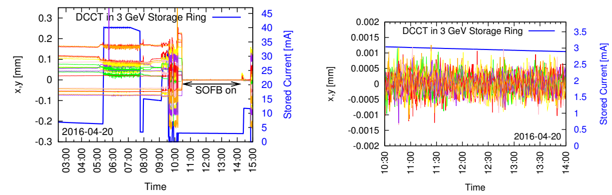

Figure 3: Position readings from BPMs in ID straights. Left: results over a 12-hour period showing drift during decaying beam, jitter during top-up injection, and stable orbit while the SOFB is running. Right: magnified view over the period while the SOFB is running.

was performed. LOCO fitting parameters were restricted to 378 BPMs (gain and coupling), 379 correctors (strengths and coupling), and all upright quadrupole gradients (84 independent power supplies). The largest required gradient change was below 1.5%. At this stage, only quadrupole gradient circuits were adjusted. After a couple of iterations of this quadrupole gradient circuit symmetrization, the difference between measured and model orbit response matrix became as low as 0.7 micron rms in both planes. Applying these adjustments to the power supplies results in a correction of the tunes to better than 10^{-2} of their design values, a substantial reduction of beta beating (residual in both planes is 1% rms) and dispersion beating as well as spurious vertical dispersion (cf. Fig. 4).

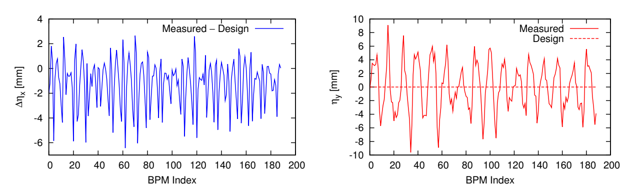

Figure 4: Horizontal dispersion beating (left) and spurious vertical dispersion (right) after downloading results of LOCO fitting to the quadrupole power supplies.

Coupling & Effect of Insertion Devices

In order to further reduce the spurious vertical dispersion as well as suppress coupling, a skew quadrupole correction will be required. This is presently being carried out. First results indicate peak residual vertical dispersion can be lowered from 8 mm to 2 mm. In commissioning so far, two IVUs (18 mm period, 2 m length) have been installed and commissioned. Feed-forward tables have been recorded for local correction of first- and second-order field integrals at all gap settings down to 4.5 mm. During beamline commissioning, application of this feed-forward correction in conjunction with the SOFB has shown to reduce residual orbit deviations to a level of ≈ 1 micron when the gap is closed. However, the feed-forward for the local optics correction as well as the global optics correction (tune feedback) have so far not been operated [23, 24]. Nevertheless, no significant change in tune has been observed when closing the gaps of these devices. No signs of beta beating as a result of the not yet

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operational local optics correction feed-forward has been observed either.

Chromaticity

The chromaticity has been determined by measuring the fractional betatron tunes for various ring RF settings where the central ring RF has been matched to the energy defined by the main dipole fields. Both linear chromaticities have been corrected to almost exactly their design values of +1. Within the presently limited fit (less than ±0.4% in energy), the second-order terms show reasonable agreement with design values at −31 and +8

Dynamic Acceptance

Scraper measurements have given insight into the lifetime and dynamic acceptance in the storage ring. An initial set of vertical scraper measurements [25] was used to assess various lifetime contributions (e.g. at 70 mA a total lifetime of 34.4 h of which 63 h is Touschek lifetime) and derive from this the effective pressure the beam encounters at a specific stored current level (e.g. 8.4×10^{-9} mbar at 70 mA). The pressure is derived under the assumption that the beam sees the same rest gas composition as the six rest gas analyzers in the ring, which is highly hydrogen dominated. Finally, LOCO measurement data for the two magnets adjacent the vertical scraper allowed determination of β_y at the scraper. Together with the scraper's limiting aperture, this allows calculation of the storage ring's effective vertical acceptance. An overall vertical acceptance in the storage ring of $A_y = 2.5$ mm mrad has been measured. Similar scraper measurements were also carried in out in the horizontal plane rendering an overall horizontal acceptance of $A_x = 7.0$ mm mrad. Vertical scraper measurements needed to be repeated for several settings of the horizontal scraper, however, to ensure Touschek losses were not collected on the vertical scraper despite the—at this stage—still uncorrected betatron coupling. Both measured acceptances in the storage ring agree very well with results from tracking studies carried out during the design phase of MAX IV [4].

EMITTANCE & LIFETIME

During commissioning several emittance measurements have been carried out using the first diagnostic beamline B320B on the MAX IV 3 GeV storage ring [26]. This diagnostic beamline is still under commissioning, however, first results indicate $\varepsilon_y = 6.4 \pm 0.9$ pm rad (from σ- and π-polarized light at 488 nm [27]) and $\varepsilon_x = 339.4 \pm 7.1$ pm rad (from σ-polarized light at 488 nm [28]). This corresponds to an emittance coupling of $\kappa = 1.9\%$. However, under various initial measurement conditions, coupling as high as $\kappa = 4.6\%$ has been observed. As long as betatron coupling is not suppressed, substantial beam twist is also possible, which could skew apparent vertical emittance results at the diagnostic beamline. More emittance measurements will follow as the diagnostic beamline commissioning progresses.

Lifetime in the storage ring has been improving along with vacuum conditions. As commissioning progressed, especially once top-up injection to higher stored current became possible, the accumulated dose quickly increased. When 100 A h of accumulated dose had been achieved in summer 2016, integrated lifetime as high as $I\tau = 5$ A h [11] (corresponding to the design goal of 10 h at 500 mA) was observed depending on the tuning of the harmonic cavities and the settings of the bunch-by-bunch feedback system. Whereas initial commissioning work at a few mA usually took place with an integrated lifetime around 0.3 A h, commissioning shifts in late 2016 routinely took place at 2–3 A h lifetime. Apart from the pressure reduction associated with improving vacuum, a clear increase of lifetime as a result of bunch lengthening from tuning of the passive harmonic cavities has been observed [12].

CONCLUSIONS & OUTLOOK

Beam commissioning in the MAX IV 3 GeV storage ring has progressed quite well. Injection with a single dipole kicker has proved robust and so far allowed injection and accumulation of up to 198 mA at high capture efficiency. Orbit correction and symmetrization of the linear optics have been successfully carried out. Top-up injection and SOFB are operated routinely and have allowed ID and beamline commissioning to make progress up to the point where actual user data is being acquired at the first two IVU beamlines.

By enabling online display of transverse beam size and bunch length measurements from the two diagnostic beamlines, significant improvements in terms of optics adjustments, RF cavity tuning, and ID compensation should become possible. Furthermore, with an online emittance monitor and bunch length measurement as well as higher single-bunch currents, verification of IBS models as well as experimental investigation of IBS and Touschek lifetime at ultralow emittance and medium energy [29] will for the first time become possible. Finally, first studies of instabilities and collective effects as well as commissioning of the bunch-by-bunch feedback system have started [30].

In the future, we hope to be able to also experiment with a harder focusing optics designed to further increase photon brightness from IDs installed in this storage ring [31–34] to ensure MAX IV remains competitive as other MBA-based storage rings come online.

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