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First optics and beam dynamics studies on the MAX IV 3 GeV storage ring

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A B S T R A C T

The MAX IV 3 GeV storage ring is the first light source to make use of a multibend achromat lattice to reach ultralow emittance. After extensive commissioning efforts, the storage ring is now ramping up its user program. 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, adjusting nonlinear optics to achieve design chromaticity correction and dynamic aperture sufficient for high injection efficiency and large Touschek lifetime.

1. Introduction

The MAX IV 3 GeV storage ring is the first light source to make use of a multibend achromat lattice to reach ultralow emittance. First ideas for what would become the MAX IV 3 GeV storage ring were discussed as early as 2002 [1,2] but design efforts intensified during 2006–2009 [3]. Funding for the MAX IV facility was granted in April 2009 and construction started during the summer of 2010. In March 2014, commissioning of the MAX IV linac started with the RF conditioning of the 19 RF stations. Actual beam commissioning of the MAX IV linac started in summer 2014 and lasted until April 2015 when the transfer line to the 3 GeV storage ring was installed. Beam commissioning in the MAX IV 3 GeV storage ring started in August 2015 [4,5]. The MAX IV facility was inaugurated on June 21, 2016 and the first user data was taken in December 2016.

This paper summarizes the events and first results of beam commissioning in the MAX IV 3 GeV storage ring. The next two subsections cover design optics and injection. They are followed by a subsection summarizing the timeline of events during commissioning. The following sections then cover initial injection, orbit measurement and control, linear optics tuning, chromaticity measurement and nonlinear optics tuning, and a few first results concerning emittance, coupling, and lifetime. The final section shall give an overall summary and point out the next studies to be conducted.

1.1. Design optics

The MAX IV 3 GeV storage ring employs a multibend achromat lattice to reach ultralow emittance. An initial lattice was published in [6] and used as the baseline lattice for the Detailed Design Report released in 2010 [3]. This design was later improved and studied in more detail [7–12]. Here we shall not go into any lattice details. Instead, the optics and magnetic lattice are displayed in Fig. 1 and the most important storage ring parameters are summarized in Table 1.

1.2. Injection with a single dipole kicker

The design of the MAX IV 3 GeV storage ring foresees use of a nonlinear kicker magnet for full-energy injection from the MAX IV linac [13]. However, from its inception, this injection was considered too demanding for the first stages of commissioning. Therefore, an injection based on a single dipole kicker was designed [14] and implemented in the MAX IV 3 GeV storage ring. The main idea is to rely on an individual dipole kicker in order to inject both on- and off-axis, as well as to enable accumulation in the storage ring without, however, having to require tight orbit and optics control as in the case of a nonlinear kicker injection scheme. Furthermore, the dipole injection kicker has been installed very close to the injection point (IP) which is defined as the magnetic end of the Lambertson septum, in order to further increase the robustness of injection during initial phases of commissioning.

Details for this injection scheme have been published in [14] and shall not be repeated here. Instead, Fig. 2 shows where the dipole injection kicker is located in the storage ring, as well as the trajectories for the injected and any already stored beam. The dipole injection kicker is excited using a half sine with a base length of 3.5 μs (corresponding to two revolution periods). The situation displayed in Fig. 2 corresponds

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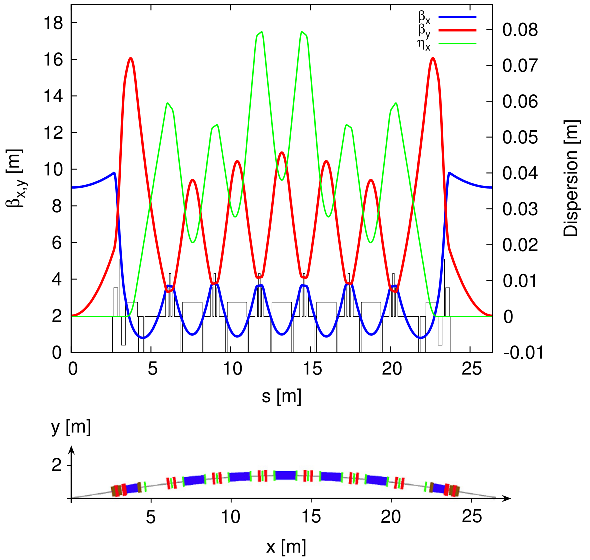

Fig. 1. Design optics in one achromat of the MAX IV 3 GeV storage ring. Top: machine functions. Bottom: magnetic lattice.

Table 1
MAX IV 3 GeV storage ring design parameters.

Stored current I	500 mA
Circumference C	528 m
Main RF f_{rf}	99.931 MHz
Bare lattice emittance ε_0	328 pm rad
Betatron tunes ν_x, ν_y	42.20, 16.28
Linear chromaticity (natural) ξ_x, ξ_y	−50.0, −50.2
Linear chromaticity (corrected) ξ_x, ξ_y	+1.0, +1.0
Linear momentum compaction α_c	3.06×10^{-4}
Energy spread (natural) σ_δ	0.769×10^{-3}
Radiated power (bare lattice) U_0	363.8 keV/turn

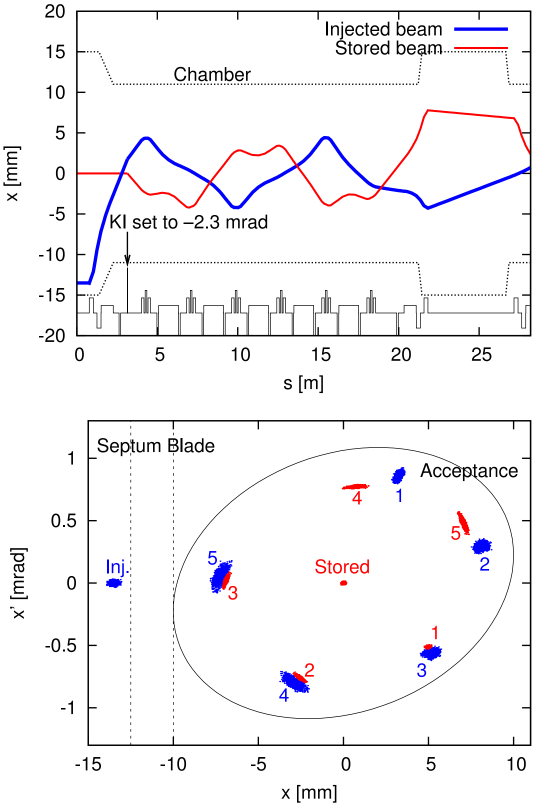

Fig. 2. Accumulation with a single dipole kicker. Top: injection trajectory from end of septum through first achromat with dipole injection kicker (KI) adjusted for accumulation. Bottom: phase space plot at end of septum showing multi-particle tracking data for accumulation case.

to beam accumulation. For initial commissioning, on-axis injection was desired. This can be accomplished by slightly angling the beam at the IP and increasing the injection kick strength.

1.3. Commissioning timeline

Beam commissioning in the MAX IV 3 GeV storage ring started in August 2015 when for the first time electron bunches were guided from the linac extraction area all the way through the 3 GeV transfer line to the Lambertson septum in the storage ring. By August 25 the first turn in the storage ring was recorded and first stored beam was achieved on September 15. First stacking was demonstrated on October 8. 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 applied and the slow orbit feedback (SOFB) loop had been closed.

A first shutdown took place in February 2016 in order to install the first two insertion devices (IDs): two 18 mm period in-vacuum undulators (IVUs) from Hitachi. Once these devices had been commissioned with beam, commissioning of the first two beamlines (frontends, beamline transport, end stations) could be carried out. These two initial beamlines had monochromatic beams at 11 keV in mid May. In June they took first diffraction patterns and by the end of June the gaps had been closed to 4.5 mm. The MAX IV facility was inaugurated on June 21, 2016. During the summer 2016 shutdown the next three IDs were installed: an in-vacuum wiggler (IVW) and two elliptically polarized undulators (EPUs) along with their narrow-gap chambers. By the end of 2016, the two IVU beamlines were routinely taking delivery of 50 mA of beam for beamline commissioning and first experiments, while 198 mA of stored beam had been reached during machine shifts.

This paper will not report on the commissioning of various subsystems as this can be found elsewhere, e.g. [15–21]. The following sections will instead focus entirely on beam commissioning results and tuning efforts.

2. Initial injection & orbit control

Initially, when first electron bunches were guided through the 3 GeV transfer line [13], the signals from the single-pass BPM units installed along the transfer line could be used for beam threading. Once sufficient amounts of charge could be transported all the way to the end of the transfer line, the excitations of the vertical dipoles in the transfer line revealed the extraction energy by fitting to magnetic measurement data. Furthermore, a screen that can be inserted in the high-dispersion area of the transfer line was used to verify the energy spread within and along the individual bunch trains. During this phase, the injector and linac were operating at 0.5 Hz while the RF chopper in the injector area [22–24] was set up to create a roughly 100 ns long bunch train with 500 MHz time structure. This was done in order to increase the signal-to-noise ratio of the BPMs. The linac extraction energy was adjusted to make sure electrons were extracted at 3 GeV to within better than 1%.

The correctors in the transfer line were then adjusted manually in order to decrease the signal on diode rings that had been placed around the vacuum chamber at the downstream end and in the vicinity of the septum. In this way position and angle at the IP were brought closer to design.[1] In a next step, first injections into the storage ring were

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[1] One additional BPM was installed right after the injection septum which, together with the first BPM in the storage ring, allows determining the angle at the IP. In practice, however, this was never used.