OFF-PHASE INJECTION SIMULATIONS FOR MAX 4^{U}

A. Dixon[*], M. Apollonio, S. Thorin, F. Lindau, R. Lindvall, E. Mansten, M. Sjöström,
and P.F. Tavares, MAX IV Laboratory, Lund, Sweden

Abstract

The MAX IV injector, including a full energy linac and a photo gun, offers a unique capability to deliver low-emittance, well-timed electron pulses suitable for injection. This makes on-axis, off-phase, on-energy injection an attractive option for future operation of the upgraded 3 GeV storage ring, MAX 4^{U}, where stronger focusing, reduced magnet apertures, and narrow-gap undulators all limit the transverse acceptance and challenge the present off-axis MIK scheme. Additionally, the significantly reduced emittance makes injected beam perturbations less transparent to the beamlines. In this work, we investigate off-phase injection for the technical design lattice candidate (TDR-1) and show through simulations that stable capture is achievable despite the reduced dynamic aperture. We also evaluate how the characteristics of the photo gun beam support the longitudinal phase-space requirements of on-axis, off-phase, on-energy injection. These results indicate that the combination of a full energy linac, photo gun-based injector and off-phase injection provide a promising path forward for injection into a low-emittance storage ring at MAX IV.

INTRODUCTION

In order to remain at the forefront of storage ring light sources an upgrade of the 3 GeV ring at MAX IV has been proposed, referred to as MAX 4^{U} [1]. The technical design aims to reduce the emittance from 328 pm rad to below 75 pm rad. An integral aspect of the design is to enable regular transparent top-up injections to ensure stable operation and near-constant current.

The significant emittance reduction of the upgraded lattice means that transverse perturbations of the injected beam become more apparent due to the larger relative difference between source size and the oscillation amplitude. As such, off-axis injection with a multipole injection kicker [2] is less transparent to the beamlines. Additionally, the proposed lattice leads to a reduction in dynamic aperture (compared to the present ring) due to stronger focusing and allows for smaller horizontal aperture undulators. The reduced horizontal acceptance places further demands on the required multipole kicker, where the kicker would need to provide a strong kick at distances closer to the stored beam. As such, an alternative method must be explored for MAX 4^{U}. The proposed scheme must be also transparent and compatible with regular top-up injections.

An injection scheme that meets these requirements is on-axis, off-phase, on-energy injection, based on the method proposed in Ref. [3]. In a longitudinal injection scheme, the electron beam is injected into the longitudinal acceptance of the storage ring [4], and pulsed kickers are used to bring the beam on-axis in the transverse planes.

In this paper, we investigate an on-axis, off-phase, on-energy injection scheme for MAX 4^{U}, a proposed upgrade to the 3 GeV storage ring. We show that the photocathode gun and full energy injector at MAX IV enable this method of injection.

FULL ENERGY INJECTOR

At MAX IV laboratory, a normal conducting S-band linear accelerator (linac) is used to inject at full energy into both 1.5 GeV and 3 GeV storage rings. The linac is also used to deliver bunches to a spontaneous undulator radiation beamline, i.e. the Short Pulse Facility (SPF) [5].

The linac can be operated with two different electron sources: thermionic gun (TG) [6, 7] and photocathode gun (PG) [8]. The former is typically used inject into the storage rings. The latter is used to drive the SPF, however injection with the PG is currently under development. When operating with the TG a chopper system is used to produce bunch trains with 10 ns time separation to match the time separation of RF buckets in the storage rings [7]. In comparison to the electron bunches from the TG, the electron bunches from the PG have lower emittance, energy spread and bunch length. The injector parameters are summarised in Table 1.

Table 1: Electron bunch properties and injection parameters for injection with: thermionic gun (TG) and photocathode gun (PG).

	TG	**PG**
Energy [GeV]	1.5/3.0	1.5/3.0
Repetition rate [Hz]	10	10
Charge/shot [pC]	200-500	200
Bunch length [ns]	1.5-70.0	0.005
Emittance [mm mrad]	10	2-3
Energy spread [%]	<0.25	<0.1
Full fill time [min]	10	10

As the photocathode gun and storage ring frequencies are not at multiples of each other, a new system for synchronising the PG and the RF buckets has been developed. A coincidence system is used to synchronise the electron bunch from the photocathode gun and an RF bucket in the ring. The timing of RF buckets is monitored, and injection shots are triggered when RF bucket coincides with the gun pulse. The coincidence system allows a single RF bucket to be targeted for injection, which could be used for various filling patterns.

---

[*] adam.dixon.7536@maxiv.lu.se

OFF-AXIS INJECTION

Multipole injection kickers (MIK) are currently used to inject off-axis into the 3 GeV and the 1.5 GeV rings at MAX IV [2, 9] and are now under consideration for MAX 4^U. In such a scheme, the injected beam is initially far from the stored beam's orbit and when it passes through the MIK it receives a kick towards the stored beam allowing the injected beam to be captured. The injected beam then performs transverse oscillations around the stored beam before they are damped.

While off-axis injection with the MIK currently provides excellent transparency, the magnetic field at the centre of the MIK is never exactly zero, so it can never be fully transparent. Additionally, as the beam emittance is decreased for MAX 4^U, the relative difference between the stored beam size and the oscillation amplitude of the injected beam becomes larger and the injection process is less transparent. Additionally, the smaller dynamic aperture of the upgraded lattice makes off-axis injection with the existing MIK more challenging, however this could be solved with a re-designed MIK which provides a transverse kick at smaller transverse offsets.

OFF-PHASE INJECTION

Due to the challenges presented by off-axis injection, e.g. less injection transparency, smaller physical and dynamic apertures, an alternative system, based on longitudinal injection described in Ref. [3], is proposed. In the injection scheme proposed for MAX 4^U, the beam is injected on-axis, off-phase, and on-energy. The longitudinal acceptance of the TDR-1 lattice is shown in Fig. 1.

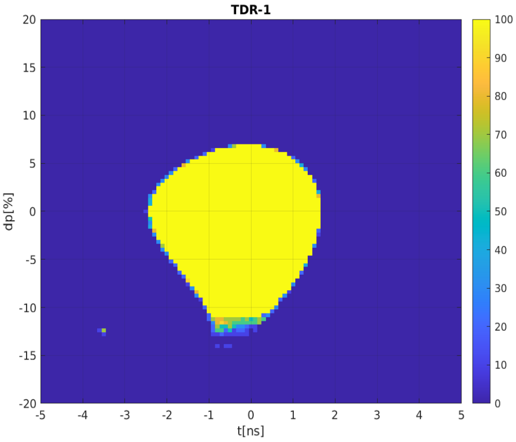

Figure 1: Phase acceptance of the TDR-1 lattice with 30 error seeds. The acceptance is determined by whether a particle injected with specific phase-energy coordinates survives.

The injected electron bunches are brought on-axis using a series of fast stripline kickers (SLK), eliminating transverse oscillations of the injected beam. The amplitude of the kicker falls to zero before the stored beam passes through the modules, and so does not disturb the stored beam. The short (5 ps) bunch lengths from the photocathode gun are a good candidate to be used with the short pulsed kicks from the stripline kickers.

For the TDR-1 lattice, the injected beam has horizontal position $x = -12.25$ mm and angle $x' = -2.4$ mrad at the exit of the septum. A total kick of 2.5 mrad is applied by the stripline kickers (in the straight following the injection straight) to the injected beam. The kick is distributed equally among 8 modules, each of which is 15 cm long. The stripline modules lead to an aperture restriction of ± 6 mm.

The phase acceptance is determined by varying the phase of the injected bunch relative to the synchronous particle and calculating the injection efficiency (IE). Phase jitter generated from a Gaussian distribution with 100 ps RMS width was applied to every particle in the injected bunches as a method of estimating the injection efficiency averaged over many injected bunches.

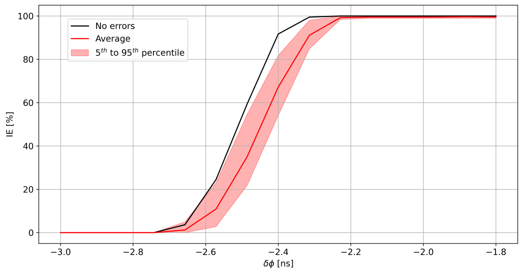

Figure 2: Phase acceptance of the TDR-1 lattice. Black line shows the lattice without errors. Red solid line shows the average of 30 lattices with errors, and the red transparent band show the $5^{\text{th}} - 95^{\text{th}}$ percentile range.

The phase acceptance (shown in Fig. 2) indicates that a phase offset of -2.2 ns is required to reach close to 100 % IE averaged over all seeds. As such the fast kickers would require a falltime that is shorter than 2.2 ns otherwise the residual field would disturb the stored beam, and an injection process that is no longer transparent.

The injection dynamics is evaluated by performing particle tracking simulations of the injection process and the subsequent turns in the storage ring. The particles were tracked for 6000 turns after injecting with a phase offset of -2.2 ns. The injection efficiency averaged over 30 lattices with errors was 99.42 %.

The horizontal (blue) and vertical (red) beam envelopes are shown for all 30 lattice error seeds (top left of Fig. 3). The horizontal envelope of the beam immediately after injection is shown as a cyan line, where we see that the beam is horizontally offset at the exit of the septum ($s = 0$ m) and is brought on-axis at the location of the stripline modules (vertical pink dashed line).

The synchrotron oscillations performed by the injected beam are shown in the longitudinal phase space plot (bottom right of Fig. 3). The amplitude of the synchrotron oscillations reduces as the turn number increases due to radiation damping.

While the bunch undergoes synchrotron oscillations in the longitudinal phase space, the beams transverse phase

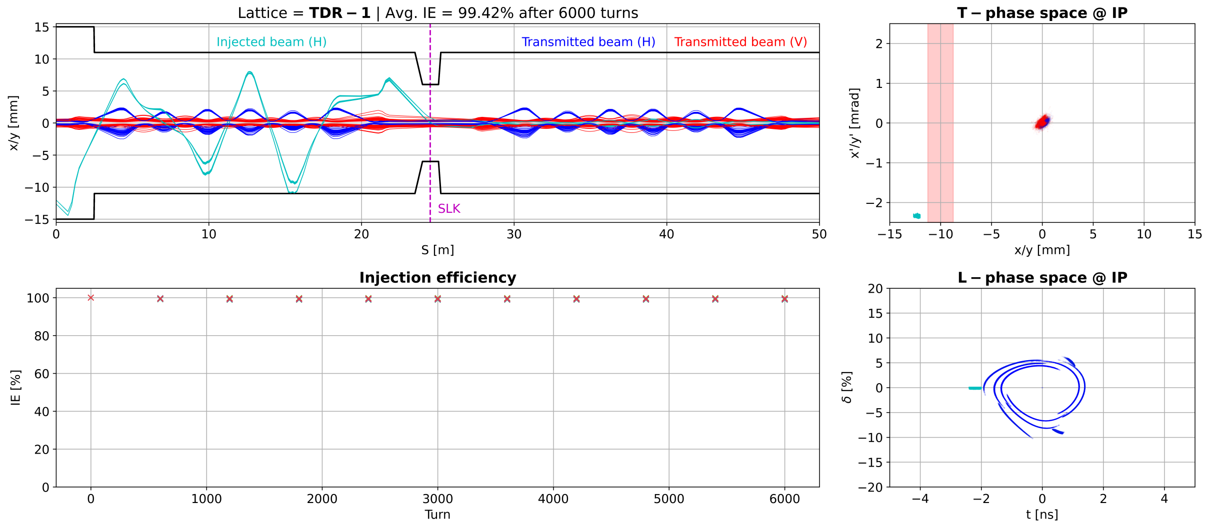

Figure 3: Dynamics of the first 6000 turns after injecting into the TDR-1 lattice: maximum/minimum horizontal and vertical coordinates (top left) during the first turn (cyan/magenta) and last turn (blue/red); horizontal and vertical phase space (top right); injection efficiency vs turn number (bottom left); longitudinal phase space (bottom right).

space (shown in the top right of Fig. 3) does not exhibit any significant oscillations after injection. This provides greater injection transparency, and allows the use of narrow gap undulators.

CONCLUSION

MAX 4^{U} aims to achieve a reduction in emittance from 328 pm rad to below 75 pm rad. Here we demonstrated through simulations that on-axis, off-phase, on-energy injection can be achieved for the TDR-1 lattice. The injection system provides high injection efficiencies with a phase offset of 2.2 ns (or shorter). The lack of injection transient horizontal oscillations leads to greater injection transparency than off-axis injection, and also eases injection into a lattice with a reduced physical and dynamic aperture compared to the existing storage ring. This type of injection scheme is enabled by the photocathode gun, full energy injector, and coincidence system already operating at MAX IV.

REFERENCES

[1] B. Afzali-Far *et al.*, “MAX4U: An Upgrade to the MAX IV 3 GeV Storage Ring”, MAX IV Laboratory, Lund, Sweden, Conceptual Design, Dec. 2025. `https://www.maxiv.lu.se/beamlines-accelerators/max-4u/accelerator-design/`

[2] P. Alexandre *et al.*, “Transparent top-up injection into a fourth-generation storage ring”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 986, p. 164739, Jan. 2021. doi:10.1016/j.nima.2020.164739

[3] M. Aiba, M. Böge, F. Marcellini, Á. Saá Hernández, and A. Streun, “Longitudinal injection scheme using short pulse kicker for small aperture electron storage rings”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 18, no. 2, p. 020701, Feb. 2015. doi:10.1103/PhysRevSTAB.18.020701

[4] P. Kuske, J. Li, and M. Aiba, “Longitudinal acceptance measurement at an electron storage ring”, *Phys. Rev. Accel. Beams*, vol. 23, no. 3, p. 030701, Mar. 2020. doi:10.1103/PhysRevAccelBeams.23.030701

[5] S. Werin, S. Thorin, M. Eriksson, and J. Larsson, “Short pulse facility for MAX-lab”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 601, no. 1-2, pp. 98–107, Mar. 2009. doi:10.1016/j.nima.2008.12.106

[6] J. Andersson, D. Olsson, F. Curbis, L. Malmgren, and S. Werin, “New features of the MAX IV thermionic pre-injector”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 855, pp. 65–80, May 2017. doi:10.1016/j.nima.2016.10.051

[7] D. Olsson, F. Lindau, M. Eriksson, J. Andersson, and L. Malmgren, “A chopper system for the MAX IV thermionic pre-injector”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 759, pp. 29–35, Sep. 2014. doi:10.1016/j.nima.2014.05.052

[8] F. Lindau *et al.*, “MAXIV Photocathode Gun Laser System Specification and Diagnostics”, in *IPAC’17*, 2017. doi:10.18429/JACoW-IPAC2017-TUPAB097

[9] M. Apollonio *et al.*, “Commissioning of the Multipole Injection Kicker in the MAX IV 1.5 GeV ring”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 1080, p. 170620, Nov. 2025. doi:10.1016/j.nima.2025.170620