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BEAM DYNAMICS OF THE TRANSPARENT INJECTION FOR THE MAX IV 1.5 GeV RING

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Abstract

Following the successful operation of the Multipole Injection Kicker in the MAX IV 3 GeV storage ring, we plan to introduce a similar device in the MAX IV 1.5 GeV ring. In order to assess the effectiveness of such device and to define its working parameters, we performed a series of studies aimed at understanding the beam dynamics related to the injection process. In this paper we describe the optimisation of the MIK working parameters, we study the resilience to tune shifts for a chosen injection scheme and illustrate some tests conducted to evaluate the ring acceptance. We conclude with remarks about the effects of magnet errors on key performance parameters such as the injection efficiency and perturbations to the size and divergence of the stored beam and a brief discussion on future work.

INTRODUCTION

At the MAX IV complex in Lund, Sweden [1, 2], two storage rings (SR) are operated, fed by a common LINAC injector. The first ring, R1, receives a 1.5 GeV beam, while the 3 GeV ring, R3, is injected further downstream. Both SRs operate in top-up mode, albeit at different rates (half an hour for R1, 10 minutes for R3) and currents (400 mA and 300 mA respectively). To allow injection and alleviate the effects of top-up transients on the stored beam, R3 makes use of a Multipole Injection Kicker (MIK), thoroughly described in [3]. These pulsed magnets generate strong spatially dependent multipole fields, mainly acting on the off-axis injected beam, whereas the nearly zero field at the nominal orbit highly suppresses any disturbance on the circulating beam. This is highly valued by photon beamlines, especially at fourth generation SRs, where beam reduced dimensions can exacerbate the perturbations produced in the top-up phase. After the early implementations at KEK, first with a pulsed quadrupole [4] and then with a pulsed sextupole [5], whose use was initially considered at MAX IV [6] instead of a more conventional four-bump injection, studies at BESSY [7] first demonstrated a scheme based on a 8-wire iron-free concept, further developed through a collaboration with SOLEIL and installed and commissioned at MAX IV in 2018. Since then, the MIK has been working very successfully, being the first application of this technology on a fourth-generation SR.

A Multipole Injection Kicker for R1

Following the positive results with R3 MIK, MAX IV has recently considered to adopt the same technology for the low-energy ring R1, a 12-DBA lattice [1], whose main parameters are summarized in Table 1. The beam from the

Table 1: MAXIV R1 Ring Global Parameters

E_e (GeV)	1.5
L (m) / T (μs)	96 / 320
ϵ_x (nm)	5.9
$\nu_{x,y}$	11.22 / 3.15
$\xi_{x,y}$	1.5 / 1.8
$\Delta E/E$ (%)	0.075
α_C	3.05e^{-3}

LINAC proceeds towards an extraction line (TR1) located below the ring main floor, hence it is deflected vertically by means of a chicane set-up, reaching a septum whose inner wall is 13.5 mm in the horizontal plane from the nominal orbit. At the septum exit we expect a horizontal separation of 17 mm between the incoming beam and the stored one. The injected beam is then strongly deflected while crossing the magnets in achromats one and two, until reaching a dipole kicker (DK) located in straight 3, 14.8 m from the centre of the injection straight, imparting a correction while also disturbing the incoming stored beam. The aperture sharing regime allows an effective stacking, however beam stability is lost at each top-up. The R1-MIK will be located 90 cm past the DK, in the same straight.

Injection Dynamics

Accelerator Toolbox (AT) [8] was used to investigate the beam dynamics of R1 when injecting with the MIK. The model for the multipole was introduced as a rescaled kick-map after a campaign of measurements by SOLEIL done to characterize the kicker for R3 [9]. A matlab [10] script utilizing AT was developed to visualize the process of injection and correction of the incoming beam, as illustrated in Fig. 1. On the top-left we see a beam of 100 electrons with a phase-space distribution taken from the LINAC parameters as it enters R1 from the outer part of the septum (cyan tracks), −17 mm from the nominal orbit. In addition to the (B_x, B_y) field map as a function of the position of the beam, the model comprises a time wave-form (bottom-left), taking into account the duration of the pulse, here set at 1.28 µs or four periods of the ring. Past the septum, electrons undergo strong deflections due to the magnets crossed at large horizontal displacements, until they reach the MIK where they receive a first kick (K1) imparting an initial correction to the injected beam. On the following turn the beam reaches the crossing point at another horizontal position

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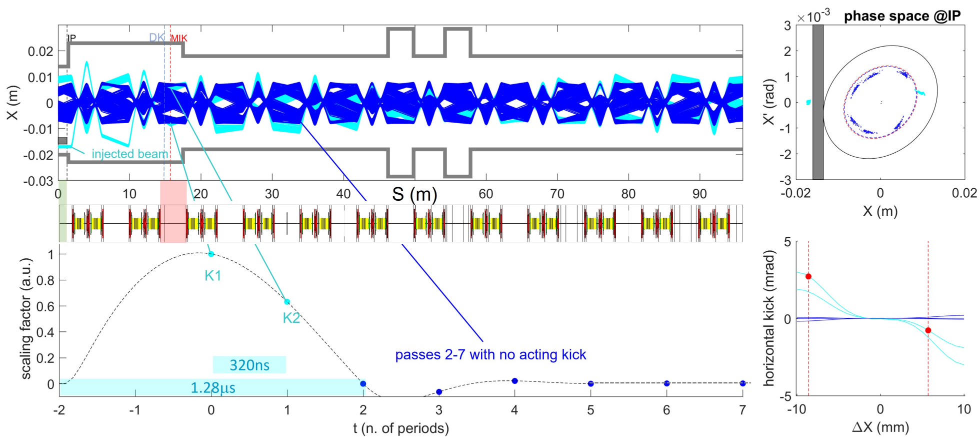

Figure 1: Beam dynamics of an on-crest bunch. Top-left: horizontal trajectories of the first two turns of the injected beam (cyan) with a full kick at injection and a second kick following the MIK time wave-form displayed in the bottom-left section. The following turns (dark blue) take place without MIK action. Top-right: representation of the same seven turn event in the (x, x') phase-space. Bottom-right: MIK field intensity function, showing the two kicking events, K1 and K2.

and undergoes another kick (K2) typically weaker than the initial one, due to the time modulation of the MIK pulse. Considering a bunch originally on-crest of the MIK pulse, no extra kick is imparted after two turns. In Fig. 1 this is represented by the uncorrected motion of the dark blue tracks. The (x, x') recorded at the injection point (IP) shows how the horizontal phase-space can be compressed to a value of about 11.5 mmmrad, making injection and containment of the beam possible throughout many turns. The case seen in Fig. 1 corresponds to a beam injected at −17 mm, with zero slope and at a current of 2.256 kA imparting a first kick of −2.7 mrad at the MIK crossing point. The next paragraph describes the optimisation of the injection into R1.

Optimisation

The optimisation process consists in reducing the Courant-Snyder invariant (CS), by operating on the imparted MIK field and the TR1 injecting parameters, with an eye to the operational limits of these handles. A two-dimensional scan over the injecting angle and the peak current at the MIK illustrates the best regions for an optimised set of parameters. Fig. 2 shows the result of this search, giving a clear indication about the existence of a favoured region in the (x'_{inj}, I_{MIK}) parameter space (dark blue in the assumed color convention), as well as the presence of forbidden regions (yellow) where too large oscillations will make injection impossible. The graph reveals also that the best (x, x') phase-space compression favours large MIK peak currents with large negative injecting angles, however both parameters have physical limitations that must be kept into consideration when discussing the feasibility of the device. The largest I_{MIK} is mainly dictated by the construction limits of the device, whereas the scope of the injecting parameters (x_{inj}, x'_{inj}) is defined by the set of correctors in TR1 and their ability at steering the beam without hitting the outer wall of the septum. A standard minimum search over three parameters was then launched to include the injecting position of the beam, showing how

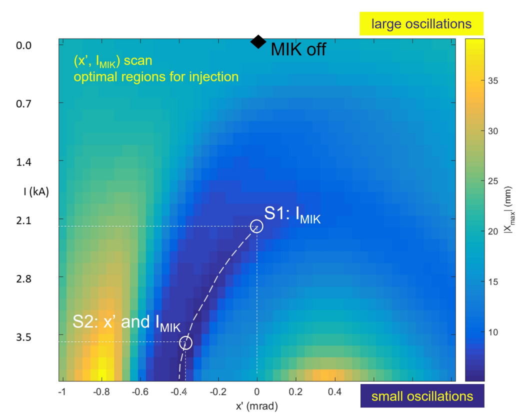

Figure 2: Injection angle and MIK current scan, identifying the best solutions in the (x'_{inj}, I_{MIK}) space in term of maximal residual oscillations over 7 turns. The dashed line guides the eye along the dark blue "valley" of minimum oscillations.

optimal solutions still tend to move along the dark blue "valley" seen in Fig. 2, but also hinting at a closer approach towards the outer wall of the septum. The first solution (S1), illustrated in Fig. 2 is the result of a search of the sole MIK current, optimised at 2.265 kA, assuming an ideal parallel injection at −17 mm distance from the nominal beam axis. When adding the injecting parameters, S2 is found which corresponds to a current of 3.565 kA, an initial position of −16.5 mm and an injecting angle of −360 µrad. Fig. 3 shows the (x, x') phase-space past the injection point for two settings of the MIK and of the injection parameters, with the same color code convention adopted in Fig. 1. A bunch in phase with the crest of the MIK waveform, will receive two kicks, with its CS invariant phase compressed towards its final value after two periods. The left side of the figure depicts S1, with a typical CS invariant of about 11.5 mmmrad, comfortably sitting within the septum defined acceptance A_{sept} =29 mmmrad. S2 (right side) obtained by adding the

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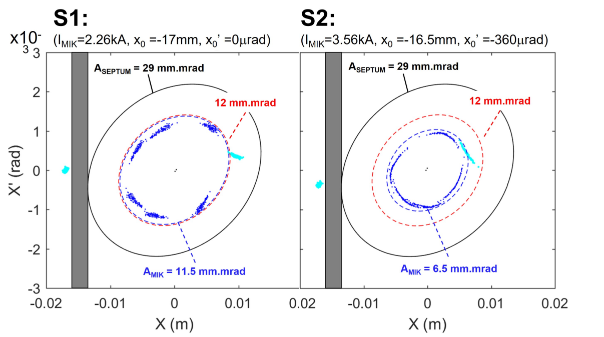

Figure 3: Horizontal phase-space at IP for two optimised solutions: (left) sole MIK current as parameter, (right) MIK current and injection parameters (x_{inj}, x'_{inj}) utilized.

injection parameters in the optimisation process, shows an even better phase-space compression of 6.8 mmmrad.

R1 Ring Real Acceptance

Simulated beam dynamics at injection suggests that there should be enough acceptance to effectively operate the MIK, within a wide range of possible set-ups, from a relatively low to a gradually increasing current, requiring a tuning of the injecting phase-space parameters. These results rest upon the assumption of a perfect machine, whereas we cannot assume that the actual acceptance of the system is as large as A_{sept}. In order to ascertain this important question, we tested the resilience of the stored beam against excitations generated by DK, located 90 cm upstream of the position foreseen for the MIK and presently utilized to compress the phase-space of the injected beam. Fig. 4 shows the current in the machine as a function of a constantly growing DK voltage: at about 6.1 kV (kick of 2.18 mrad), the beam current undergoes a sudden reduction. A simulation of the pulsed dipole acting

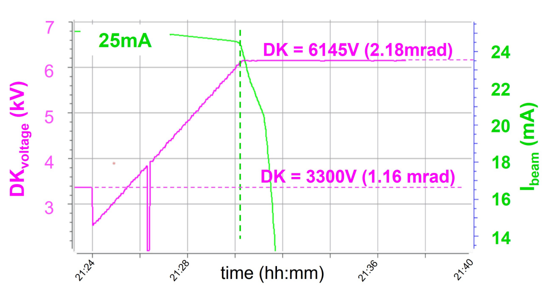

Figure 4: Machine test to verify its acceptance. Seven bunches for a total 25 mA beam (green trace) are probed with the DK at growing currents (pink trace). The I_{beam} sudden drop at 6.15 kV defines the acceptance of the ring.

on the stored beam (Fig. 5), reveals that an excitation of 1.16 mrad, the default value used at injection, corresponds to phase-space acceptance of about 12 mmmrad, allowing acceptance sharing between injected and stored beam. An excitation of 2.18 mrad brings the beam to the inner wall of the septum, confirming the results seen in the machine. Data

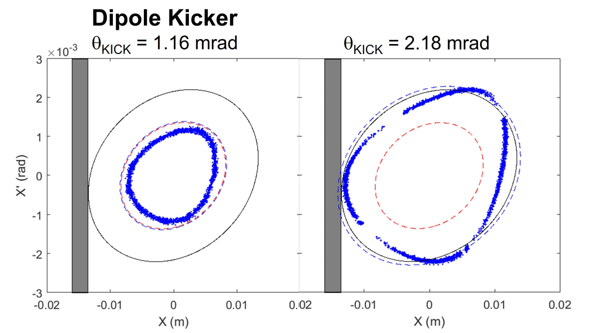

Figure 5: Resilience to DK excitation in the AT model. Left: DK angle at 1.16 mrad (standard injection value). Right: DK angle at 2.18 mrad, with the (x, x′) phase-space at IP shaving the inner wall of the septum.

suggest that the present machine has a sufficient aperture to use a MIK operating at low current, where an acceptance of about 11.5 mmmrad is needed.

Resilience to Tune Shifts

Changes in the tune working point may occur, either for a deliberate choice or for external causes, *e.g.* a non completely compensated change in the ID gaps during operations. It is therefore important to assess the effect of such changes in the process of injection with the MIK, since the phase advance between the injection point and the device crucially defines the crossing point and so the effectiveness of the kick. In Fig. 6 a scan of the horizontal tune is plotted against the

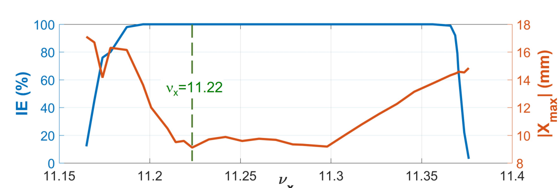

Figure 6: Horizontal tune and its effect on residual oscillations and injection efficiency.

residual oscillation of the injected beam and the injection efficieny, showing a tune outside the [11.19, 11.37] range may result in a dramatic drop of efficiency.

CONCLUSIONS AND FUTURE WORK

The study of beam dynamics for a MIK injection into R1 at MAXIV, corroborated with machine tests, allowed to assess its feasibility in terms of machine acceptance and main performance of the MIK, defining a region of optimal parameters. Installation of the device is meant to start during the summer shutdown. Further studies are foreseen to evaluate the effect of IDs when operating the MIK, and to assess the impact of mis-alignments of the copper rods defining the field of the device, which translates into field distorsions potentially affecting both the injected and the stored beam.

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REFERENCES

[1] MAX-IV collaboration, "MAX-IV Detailed Design Report", August2010. https://www.maxiv.lu.se/accelerators-beamlines/accelerators/accelerator-documentation/max-iv-ddr/

[2] P. F. Tavares *et al.*, "Commissioning and first-year operational results of the MAX IV 3 GeV ring", *J. Synchrotron Radiat.*, vol. 25, part 5, Sept. 2018, pages 1291-1316. doi:10.1107/S1600577518008111

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

[4] K. Harada, Y. Kobayashi, T. Miyajima, and S. Nagahashi, "New injection scheme using a pulsed quadrupole magnet in electron storage rings", *Phys. Rev. ST Accel. Beams*, vol. 10, p. 123501, Dec. 2007. doi:10.1103/PhysRevSTAB.10.123501

[5] H. Takaki, N. Nakamura, Y. Kobayashi, K. Harada, T. Miya-jima, A. Ueda, S. Nagahashi, M. Shimada, T. Obina and T. Honda, "Beam injection with a pulsed sextupole magnet in an electron storage ring", *Phys. Rev. ST Accel. Beams,* vol. 13, p. 020705, Feb. 2010. doi:10.1103/PhysRevSTAB.13.020705

[6] S. C. Leemann, "Pulsed sextupole injection for Sweden's new light source MAX IV", *Phys. Rev. ST Accel. Beams, vol.* 15, p. 050705, May 2012. doi:10.1103/PhysRevSTAB.15.050705

[7] O. Dressler, T. Atkinson, M. Dirsat, P. Kuske, and H. Rast, "Development of a Non-Linear Kicker System to Facilitate a New Injection Scheme for the BESSY II Storage Ring", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper THPO024, pp. 3394–3396.

[8] Accelerator Toolbox Collaboration, http://atcollab.sourceforge.net/

[9] R. Ben El Fekih, "Short Note on MAX IV MIK-2, Magnetic Measurements Report", SOLEIL internal note

[10] MATLAB, version 9.8.0 (R2020a) Natick, Massachussets: The MathWorks Inc. 2020, https://in.mathworks.com/