PROGRESS ON PULSED MULTIPOLE INJECTION FOR THE MAX IV STORAGE RINGS

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Abstract

Injection into the MAX IV storage rings will not make use of a conventional local injection bump with four dipole kickers. Instead, pulsed multipole injection will be applied. Previously, it was foreseen to use a pulsed sextupole magnet similar to what KEK had originally designed for the PF ring. But after seeing encouraging results with a prototype nonlinear kicker magnet developed for BESSY II, pulsed multipole injection for the MAX IV storage rings was revisited. A nonlinear kicker magnet similar to the BESSY-type can be realized for both MAX IV storage rings. Such a nonlinear kicker offers a broad zero-field region around the center which does not perturb the stored beam, while offering a high-field region around the location of the injected beam making it ideal for top-up injection. This paper summarizes the proposed kicker magnet design and shows beam dynamics results from multi-particle tracking studies. A comparison with the previous PSM design is also included.

INTRODUCTION

Early in the design process of the MAX IV storage rings it was considered that injection into the rings could be performed using a single dipole kicker installed downstream of the DC Lambertson septum. In the meantime, detailed studies have demonstrated feasibility [1] and fabrication of these dipole kickers is well underway. However, a single dipole kicker is not suitable for top-up injection because injection and capture cannot be made transparent to users. Therefore, injection with a pulsed sextupole magnet (PSM) was studied as a means to perform fully transparent top-up injection. This avoids having to balance the four dipole kickers and pulsers required to cleanly open and close a local injection bump over prolonged periods of time. Detailed analysis [2] revealed the great potential of PSM injection and a reference design for the magnet was initiated following the experience gained at KEK in the design of the PSM for the PF ring [3].

The MAX IV storage rings require roughly the same kick from the PSM as the PSM in the KEK PF. However, the position of the injected beam in the MAX IV PSM's is only a third of that in the PF and therefore the required sextupole gradient in the MAX IV PSM is considerably higher. On the other hand, the aperture requirements in the MAX IV storage rings are significantly lower, thus allowing a reduction of magnet aperture and an increase in field strength. An initial reference design for a 300 mm long solid iron magnet (cf. Fig. 1) supplied roughly 1.2 mrad kick (at 3 GeV) at −4.7 mm from the center. The bore is 32 mm leading to a pole-tip field roughly 0.5 T. A single coil per yoke called for 2125 A current. With a stored energy of 20.6 J, the required pulser voltage was 19.3 kV for single-turn injection into the MAX IV 3 GeV storage ring. For the MAX IV 1.5 GeV storage ring a similar magnet was designed which relies on 1527 A current at 400 mm length. Here, however, single-turn injection calls for 640 ns pulse length which increases the required pulser voltage to 92.9 kV. Although two-turn injection is possible and reduces the voltage requirement by 50%, it remains desirable to further reduce this voltage, i.e. lower the inductance of the PSM. However, since the magnet bore already lies within only several mm of the beam-stay-clear area, a significant reduction of the inductance could not be expected for this type of magnet.

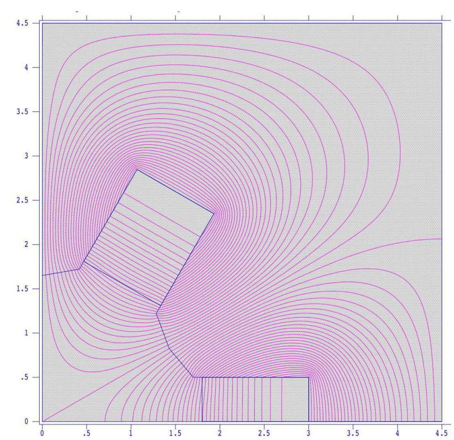

Figure 1: Pulsed sextupole magnet reference design for the MAX IV 3 GeV storage ring. One quarter of the magnet is shown. Scales are in cm. The magnet bore is 32 mm.

NONLINEAR INJECTION KICKER

Around the same time, first reports appeared of a novel nonlinear injection kicker (NLK) developed for BESSY II [4]. This kicker design expands on the original PSM idea to have a high field at the injected beam while keeping the field at the stored beam close to zero. It makes use of a stripline-like design with a geometry intended to create a high-field area strongly localized around the injected beam while suppressing the field at the stored beam through symmetry. Figure 2 shows an initial reference design for the MAX IV 3 GeV storage ring along with the

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generated field profile in the midplane compared to that of the PSM and a pure octupole.

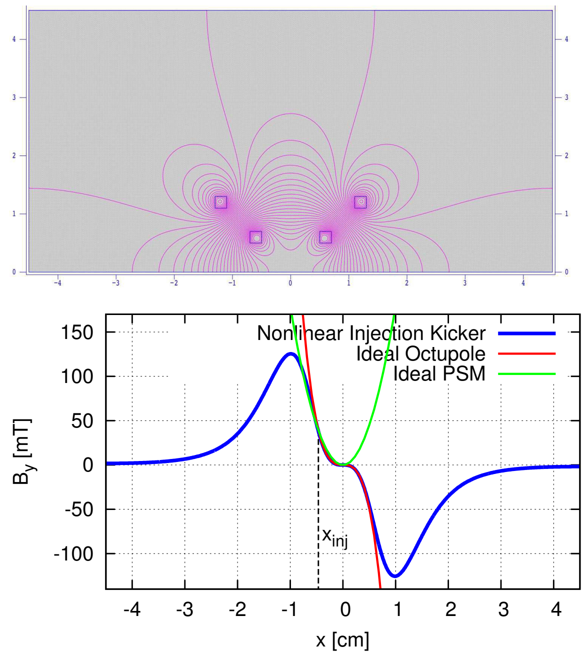

Figure 2: Upper half geometry (top) and resulting field profile in the midplane (bottom) of the reference design for a nonlinear injection kicker for the MAX IV storage rings calculated in POISSON. The design is adapted from the NLK developed for BESSY II.

Such a NLK has several distinct advantages over a PSM. Around the center the field is zero and flat. Between the center and the high-field area the profile is octupole-like (cf. Fig. 2, bottom). This leads to very small perturbations of the stored beam which is crucial given the very tight stability tolerances in MAX IV [2]. While imperfections in the PSM can lead to residual dipole kicks to the stored beam [5, 6], the field in the NLK always has a zero-crossing and therefore offers a field-free area for the stored beam. This area can be found with stored beam via orbit bumps thus enabling beam-based re-alignment of the magnet.

In principle, another advantage of the NLK is the flat area around the field maximum. Ideally the injected beam passes the NLK at this location thus enabling good capture efficiency even for injection of high-emittance bunches. In MAX IV, however, this NLK property cannot be exploited as there is an inherent trade-off between vertical position of the inner rods (in Fig. 2 they are 6 mm from the midplane) and the horizontal position of the field maximum (in Fig. 2 at 10 mm from the center). Since the injected beam in the MAX IV storage rings lies at roughly 5 mm from the stored beam, the inner rods would have to be brought so close to the midplane that the kicker would encroach into the vertical acceptance. On the other hand, as previous studies had demonstrated [2], with the low-emittance beam injected into the MAX IV storage rings[1], capture does not suffer from the gradient sampled in the PSM. Therefore, it was expected that the injected beam can sample the gradient of the NLK field, despite its steeper slope, without suffering significant smearing. This is confirmed by the comparison shown in Fig. 3: although NLK injection increases smearing compared to the PSM, the effective emittance of the injected bunch is still dominated by the large injection amplitudes. The gradient of the NLK at the injected beam does not lead to decreased capture efficiency.

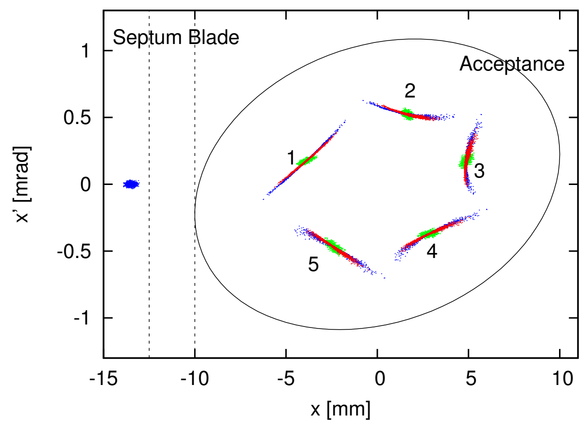

Figure 3: Tracking of the injected bunch with DIMAD during the first five turns in the MAX IV 3 GeV storage ring using single-turn injection. Injection with the NLK (blue) is compared to the PSM (red). For reference, a pure dipole kick (green) has been included. The latter is has no gradient, but it does not allow for transparent top-up injection.

The NLK can therefore be operated in the MAX IV storage rings with the injected beam on the slope. Although such application of the NLK does not exploit the elegant BESSY concept to full extent, it allows using the low-inductance NLK design for pulsed multipole injection (PMI) in MAX IV. The reference design for a NLK adapted to the MAX IV 3 GeV storage ring (cf. Fig. 2) calls for 2855 A and has a stored energy four times lower than the solid iron PSM. The pulser voltage[2] is estimated to be 5.7 kV. In the MAX IV 1.5 GeV storage ring the required current reduces to 1790 A and, with a required pulser voltage of 19.5 kV, single-turn injection becomes feasible. With the NLK two-turn injection is no longer feasible in the MAX IV 3 GeV storage ring as originally designed [2] because the kick of the NLK on the second turn has the wrong sign. However, with the relaxed voltage requirements, this is not considered a problem. For the MAX IV 1.5 GeV storage ring two-turn injection remains feasible as it relies on negligible amplitude of the injected bunch at the kicker during the second passage.

[1] A benefit of using the MAX IV 3 GeV linac as a full-energy injector into both MAX IV storage rings.

[2] This result relies on preliminary assumptions for the inductance of the circuit which is non-negligible compared to the low inductance of the magnet.

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DETAILED DESIGN PROGRESS

Because of the minimized perturbation of the stored beam as well as the low magnet inductance, it has been decided to use a BESSY-type NLK for injection into the MAX IV storage rings rather than the originally foreseen PSM. For this purpose MAX IV and SOLEIL have initiated a collaboration with the goal to design and build injection kickers for the SOLEIL storage ring as well as the two MAX IV storage rings based on further development of the BESSY-type NLK. The SOLEIL requirements for PMI are similar to those for MAX IV. While PMI in SOLEIL calls for a stronger kick than in MAX IV, the injected beam is farther away from the magnet center. Vertical beam-stay-clear requirements are comparable. In fact, it has been realized that the same magnet can be used for both MAX IV storage rings if the vertical beam-stay-clear aperture is set to 8 mm as a compromise between bringing the maximum kicker field closer to the injected beam and maintaining sufficient vertical acceptance in the MAX IV 1.5 GeV storage ring. Therefore, the only difference between the injection kickers in the two MAX IV storage rings will be the pulsers.

In comparison to the BESSY NLK, the SOLEIL Multipole Injection Kicker (MIK) design [7] foresees a pulser with a single transducer and all four loops connected in series. The parallel connections in the BESSY NLK were suspected of creating a field imbalance leading to residual kicks to the stored beam [8]. Furthermore, the SOLEIL MIK design does not include metallic walls and uses the ceramic chamber as a vacuum vessel allowing for better cooling and access. A large horizontal aperture (45 mm) prevents synchrotron radiation heating of the chamber without increasing the inductance of the magnet. The minimum ceramic thickness is presently being studied as it limits the vertical separation between the inner rods. Any increase of this separation has to be analyzed carefully as it leads to a significant growth of required current.

The ceramic chamber needs a conductive coating. Different coating thicknesses have been studied in terms of heating from ohmic losses, image currents, and Eddy currents. Furthermore the effect of the coating on the field and therefore on the stored beam have been investigated. Presently 5 μm Ti appears to be a suitable choice for the MAX IV 3 GeV storage ring. With such a coating a minor increase in current compensates for field attenuation, but a small quadrupole gradient at the stored beam remains. If any residual kick, $\phi_{\rm res}(\text{at } 1\sigma_x)$, is to be limited in terms of divergence spread, $10\% \times \sigma_{x'}$, it can be shown that the maximum tolerable residual quadrupole gradient is independent of the stored beam emittance: $(\partial B_y/\partial x)_{\rm res} < 10\% \times B\rho/(\beta_x L)$. The SOLEIL MIK with 5$\mu$m Ti coating gives a residual gradient of 0.18 T/m, significantly below the 0.36 T/m [0.28 T/m] acceptable in the MAX IV 3 GeV [1.5 GeV] storage ring. This is corroborated by tracking studies where the effect of such a residual quadrupole gradient on the stored beam has been analyzed (cf. Fig. 4) and shown to be negligible. Another study has indicated that the end geometry of the rods and terminals leads to perturbations on an even lower level.

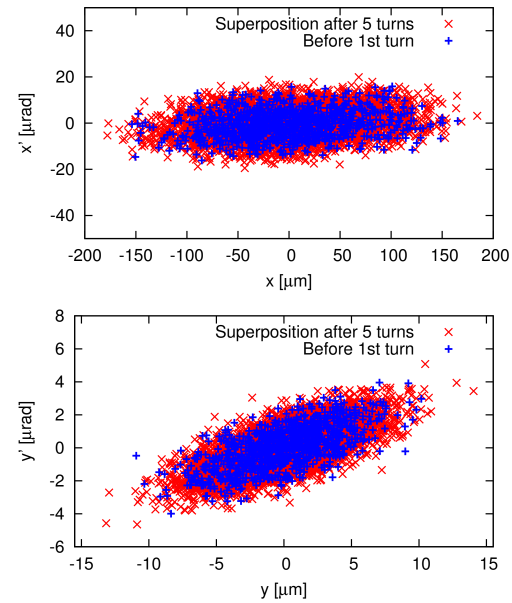

Figure 4: Tracking of the stored beam with DIMAD in the MAX IV 3 GeV storage ring through the SOLEIL MIK in single-turn injection mode. The residual gradient of the MIK leads to negligible perturbation of the stored beam.

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