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DESIGN AND COMMISSIONING OF A MULTIPOLE INJECTION KICKER FOR THE SOLEIL STORAGE RING

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Abstract

In third generation synchrotron light sources, achieving injection with an orbit distortion lower than 10% of the stored beam size is very challenging. The standard injection scheme of SOLEIL is composed of 2 septum and 4 kicker magnets installed in a 12-meter long straight section. Further tuning of the 4 kicker devices, to reduce perturbations, has proven to be almost impossible since it requires having 4 identical magnets, electronics and Ti coated ceramic chambers. To reach the orbit stability requirement, a single pulsed magnet with no field on the stored beam path can replace the 4 kickers. Such a device, called Multipole Injection Kicker (MIK), was developed by SOLEIL and successfully commissioned in the MAX IV 3 GeV ring where it is used in daily user operation, reducing the beam orbit distortion below 7 µm RMS value in both planes. A copy of the MIK was installed in a short straight section of the SOLEIL storage ring in January 2021. We report MIK simulation studies, the constraints of the project, sapphire chamber coating challenges and the first commissioning results.

INTRODUCTION

Developing transparent injection schemes has been an active field of research and development for the last few years, as it is a strong requirement for 3rd generation synchrotron light sources and crucial for the 4th generation. This paper tackles the issue of injection transparency in the scope of R&D for the current 2.75 GeV storage ring of SOLEIL [1,2] (see Table 1) and its Upgrade project [3,4]. We report the main steps leading to the installation and the commissioning of the MIK for SOLEIL, as a reliable transparent injection system for user operation.

INJECTION SCHEMES FOR TOP-UP OPERATION AT SOLEIL

Current Off-Axis Injection Layout

The current off-axis injection system used at SOLEIL for Top-Up operation is based on a thick and a thin septa and on four dipole kickers installed in a 12-meter long straight section [5]. When injecting, the stored beam is kicked horizontally thanks to the first two kickers to bring it as close as possible to the injected beam, while the injected beam is brought parallel to the stored beam thanks to the consecutive kicks of the septa (see Table 2). Eventually, the stored beam is kicked back to its original orbit thanks to the last two kickers. The injected beam oscillates in the horizontal plane with an amplitude of 10 mm and undergoes radiative damping. Although the septa have been heavily shielded and the kickers finely tuned, a residual closed orbit distortion (cod) is still measured (37% and 275% of the beam size in the horizontal and vertical planes, respectively) [6–9]. It is detrimental for the infrared beamlines which use a gating injection signal and will be unacceptable for many beamlines of the SOLEIL Upgrade. Since the kickers account for the major part of the distortion, especially in the vertical plane, their replacement with a MIK should be very beneficial.

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Table 1: Main Parameters of the SOLEIL Storage Ring

Parameter	Value
Energy (GeV)	2.75
Circumference (m)	354.1
Revolution period (µs)	1.18
Harmonic number	416
Hor. emittance (1% coupling) (nm rad)	3.9
Hor./vert. radiation damping time (ms)	6.9 / 6.9
β_x / β_z at MIK (m)	13.5 / 3.2
β_x / β_z at injection straight center (m)	12.1 / 8.1
Injected beam hor./vert. pos. at MIK (mm)	10.3 / 0.0

Table 2: Main Characteristics of the Injection Devices

Parameter	Thick/thin septa	Kickers
Pulse duration (µs)	$3.3{\cdot}10^3$ / 120	7
Deflect. angle (mrad)	110 / 25	8
Max hor. cod (µm)	20 / $\ll$ 1	100
Max vert. cod (µm)	5 / $\ll$ 1	50

Off-Axis MIK Injection Layout

The MIK is a pulsed magnet that replaces the four kickers and is installed in the second straight section of the ring, 32 m away from the injection point. Its magnetic field is zero at its center, so as not to disturb the stored beam. In addition, the magnetic field provides a horizontal deflection to the injected beam when it passes through the MIK at a target position of 10.3 mm in the horizontal plane (see Figs. 1 and 2), where the kick is as uniform as possible considering the size of the injected beam (σ_x = 1.2 mm and σ_z = 0.4 mm at 20% coupling). The MIK aims to minimize the injection invariant, from typically 55 nm rad to 7 nm rad, by canceling the horizontal angle of the injected beam at the MIK position. Thus, the horizontal oscillation amplitude of the injected beam passes from approximately 25 mm, in the free oscillation region before the MIK, to about 10 mm after the MIK [10] (see Fig. 3).

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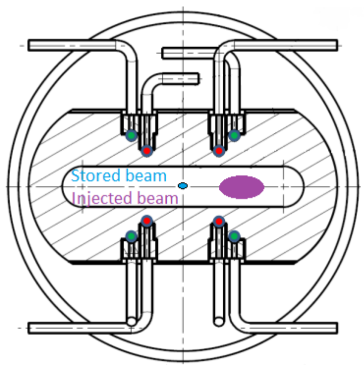

Figure 1: MIK cross section: red and green copper rods, striped sapphire vacuum chamber of the MIK (46.8 mm (H) x 7.8 mm (V)), purple injected and blue stored beams.

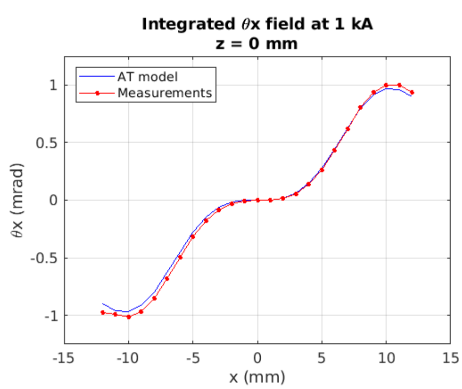

Figure 2: θ_x deflection angle w/ respect to horizontal position: 1 kA supplied MIK (measurements: red, simulated data: blue).

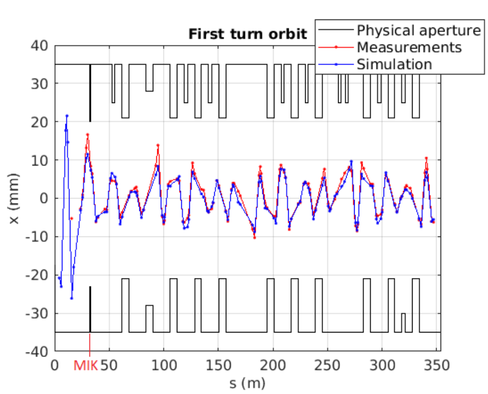

Figure 3: First turn horizontal orbit (measurements : red, and simulated data : blue). The horizontal physical aperture is displayed in black solid lines. Reduction of the oscillation amplitude from 25 mm to 10 mm (MIK voltage = 10.5 kV).

MIK DESIGN

Mechanical Design and Assembly

The MIK magnet installed at SOLEIL is of the same series of MIK magnets designed and manufactured during the 2011-2017 MAX IV – SOLEIL collaboration. The main specifications are summarized in Table 3. Based on the Bessy-II non-linear kicker, the MIK magnet is made of eight copper rods placed in grooves machined in a sapphire vacuum chamber. Its chamber has the narrowest horizontal physical aperture of the ring, reaching ±23.4 mm. Besides, when the in-vacuum insertion devices (IDs) are opened, it also exhibits the narrowest vertical physical aperture (±3.9 mm).

The copper rods are held in the grooves with alumina push-bars and non-conductive and heat resistant epoxy glue (AREMCO-BOND 526N) (see Fig. 1). Precise assembly steps and dedicated equipment such as special clamps ensure that the rods are in the proper position during the curing of the glue. The inside of the sapphire chamber is also coated with a 3.5 µm Ti layer to ensure conduction of the beam-induced current. This step was performed at ESRF [11] in Grenoble using traditional coating methods. More details on the engineering and magnetic measurements of the MIK are given in [12, 13].

Table 3: Main Design Specifications of the MIK

Parameter	Value
Hor./vert. beam stay clear (mm)	46.8 / 7.8
Total length (flange-to-flange) (mm)	400
Magnetic length (mm)	304
Magnetic field at target position (mT/kA)	24.85
Hor./vert. field free region (µm)	800 / 100
Pulse duration (µs)	2.4

Taper and absorber chambers, equipped with ion pumps, are installed upstream and downstream from the MIK chamber to match the physical apertures of the standard 70 mm (H) x 25 mm (V) chamber to the physical apertures of the MIK, to block any synchrotron radiation from the upstream dipole magnet, preventing heating of the MIK, and providing additional pumping capability (low static pressure in the 10^{-10} mbar range). Special tapers were made from CuCrZr alloy: the whole aperture, taper and absorber sections, CF flanges and the water cooling system were all machined from a single bulk bloc. This process reduces the manufacturing steps since no brazing or welding is required.

Magnetic Field Topology

The MIK is powered through a capacitive resonant discharge pulser, providing half-sine current pulses up to 3.6 kA, under 11 kV, and a pulse duration of 2.4 µs. This corresponds to twice the revolution period of the storage ring, in order to lower the perturbations on the injected beam due to the transient field. The MIK generates an octupole shaped vertical magnetic field B_z, with two regions of interest: a field free region of 800 µm on the stored beam path and a peak field of 25 mT/kA at 10.3 mm (see Fig. 2).

Simulated Field The transient non uniform magnetic field of the MIK was simulated with Quickfield™ Professional [14]. Considering that the magnetic length of the MIK

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is 304 mm, the integrated fringe field is negligible compared to the integrated transverse components, B_x and B_z, of the magnetic field. Thus, the simulated field is reduced to the transverse planes (x, z). The unwanted B_x component can perturb the injected beam, adding a vertical angle θ_z of the order of 100 µrad, while B_z deflects the injected beam of a nominal angle $\theta_x \sim 2$ mrad. The pulse-induced current generates weak transient octupolar and a quadrupolar fields, on the stored beam path, at the beginning and at the end of the pulse, respectively. Although the rods were positioned to provide a field free region, a misalignment would generate a weak quadrupolar field too.

Measured Field Prior to installation, the peak B_z field was measured, at 1 kA, to ensure the MIK field met the specifications. The chamber was scanned with an integral pick-up coil along the x and z axes and the signal integrated with a high precision oscilloscope. Precision steppers and careful alignment of the measurement bench and probe improved the accuracy of the measurements: B_z is consistent with the ideal simulated field, as exhibited by Fig. 2.

SIMULATIONS

The feasibility study of the MIK injection scheme was demonstrated using the Accelerator Toolbox (AT) [15, 16] and the TRACY-III code [17]. Firstly, the best available location to install the MIK device was found to be downstream of the first short straight section after the injection point, 32 m from the injection point (Fig. 3). The booster beam is injected horizontally around −25 mm from the longitudinal axis of the ring; it oscillates freely till the MIK with an amplitude just below the physical aperture, after tuning the injection angle. A MIK deflection angle of around 2 mrad minimizes the beam invariant (7 nmrad).

Next, it was verified that the reduction of the physical aperture in the horizontal and vertical planes is not detrimental to the daily operation. This was confirmed with beam-based experiments using the scrapers with a typical ID configuration (Touschek lifetime reduction by 20% w/o IDs and below 3-5% w/ IDs). The beam losses are relocated in the extra-shielded injection section by inserting furthermore the inner horizontal scraper (-21 instead of −27 mm). The theoretical and then measured magnetic field of the MIK were included in the model: its pulse duration is equivalent to 2 turns. The physical aperture of the model was updated, including two photon absorbers, to produce beam loss profiles for the radiation safety group. The best setting was obtained by minimizing the horizontal injection angle and the free horizontal oscillation amplitude of the injected beam, before the MIK. Using Gaussian bunches of 10^4 electrons, the typical injection loss rate is around 1%, with injection parameters $x_{inj} = -26$ mm and $x'_{inj} = 490$ µrad (40% coupling in the booster) and a septum blade inserted 1 mm further than in operation (−18.5 mm instead of −19.5 mm).

FIRST EXPERIMENTS

The MIK device, its reduced chamber and the photon absorbers were installed in January 2021. After vacuum conditioning, the alignment and the magnetic field of the MIK were first characterized using local bumps with the stored beam (15 mA bunch train of 104 bunches). The chromaticities were reduced to use turn-by-turn BPM measurements, and the tunes set to 18.16 and 10.23 in the horizontal and vertical plane respectively. The MIK pulse is very linear and reproducible with respect to the voltage of the pulser; the misalignment is below 100 µm.

At the beginning of April, the beam was injected for the first time using the MIK reaching an injection efficiency of 38% before any optimization. The voltage of the MIK was 4 kV(∼60% of its nominal value). Then, the injection efficiency was increased to 86%, at 10.5 kV. The data analysis confirmed that the injection invariant was reduced; Figure 3 shows the first turn horizontal orbit of the injected beam, passing from 25 mm in the free oscillation area, before the MIK, to 10 mm, after the MIK, in agreement with adjusted simulation data. BPM data revealed that the injected beam had not yet reached the optimal position of 10.3 mm, that should maximize the horizontal deflection angle.

In May, the injection positions and angles of the injected beam, in the horizontal and vertical planes, have been optimized to reach 90% at the nominal voltage of 7 kV, and 96% at 10.5 kV. Further experiments will be done in a few weeks to understand the discrepancy between the nominal and optimal voltages.

CONCLUSION AND PERSPECTIVES

The MIK device enables to inject, store and accumulate a beam into the storage ring with 96% efficiency. Characterization of the perturbation on the stored beam will follow and experiment together with a few beamlines are foreseen. Then injection schemes, such as off-momentum and longitudinal injection, will be experimentally studied in order to get experience for the SOLEIL Upgrade, where a new type of MIK is the key injection element [18].

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