DESIGN, TUNING AND RESULTS OF THE PULSED MAGNETIC SYSTEMS FOR THE BEAM INJECTION IN THE SOLEIL STORAGE RING OPERATED IN 'TRANSPARENT' TOP UP MODE

P. Lebasque, R. Ben El Fekih, M. Bol, J. Da Silva Castro, A. Hardy, C. Herbeaux, J.-P. Lavieville, A. Loulergue, J.-L. Marlats, D. Muller, G. Renaud, J.-P.Ricaud,
Synchrotron SOLEIL, Gif-sur-Yvette, France

Abstract

From the beginning, the SOLEIL Storage Ring was designed to operate in Top Up injection mode. So all equipment involved have been specified to generate as small as possible beam perturbations of the stored beam during the electron beam injection. This concerns many aspects of the design and realization of the injection pulsed magnets (kickers and septa), their vacuum chambers, their pulsed power supplies and timing electronics. Despite quite satisfactory results of pulsed magnetic measurements in laboratory, too large perturbation was still observed on the electron beam orbit during the Storage Ring commissioning. Therefore an extensive work of systematic measurements, analysis of each phenomena, tuning or modification of each device was led until reaching rather good and acceptable performances. This paper will present the results obtained. At this stage, the Storage Ring beam orbit is sufficiently stable in Top Up injection mode so that it is almost transparent to the 24 beam lines, even for the most sensitive ones. After a summary of the main significant topics, the developments foreseen to further improve the performances and make a new step towards a "perfect" Top Up injection are presented.

INTRODUCTION

The Top-Up injection mode is now adopted by a large number of synchrotron light source. So a "clean" injection, with a minimum perturbation of the stored beam orbit constitutes a significant challenge for these facilities.

The Pulsed Magnetic Systems designed, realized and tuned at SOLEIL are not perfect, because a residual perturbation of the electron beam orbit can be still measured at each new injection. But the results are satisfactory as the Top Up injection is routinely used without noticeable perturbation on the beam lines. Up to now no beam line expressed the need of using the available gating signal. The Infra-Red beam line AILES, when working with a long interferometry scan over 15 min, feels these perturbations, but is able to remove it.

The relevant aspects for the Top Up injection are the Septum stray field level, the identity between the four Kickers fields, the time jitter of each pulser and the long term stability. SOLEIL has defined the target as a maximum orbit perturbation of 10% of the RMS beam size in vertical and horizontal planes. Expressed in terms of magnetic values, it was estimated as 12 µT.m maximum of stray field for each septum magnet, and an identity tolerance $\leq 10^{-3}$ between the four kickers fields.

SEPTUM MAGNETS

Injection from the Booster to the Storage Ring at SOLEIL uses two successive Septum magnets: an out-vacuum direct-drive thick septum acting as pre-septum, followed by an in-vacuum eddy current thin septum for the beam injection in the Storage Ring. Of course they have to hit the basic magnetic requirements corresponding to the accelerator physics specifications: field amplitude, integrated field, and transverse field homogeneity. But concerning the septum magnets, the main challenge is on the low value of stray field or other cause of perturbation on the stored beam orbit.

The basics of this question refer to a good screening of the septum yoke and coil, and a good magnetic shielding of the vacuum chamber where the stored beam circulates. On that topic there are supporters of diverse technical solutions: direct drive or eddy current septum, out- or in-vacuum.

Thin Eddy Current Septum in Vacuum

SOLEIL experience is excellent concerning the thin septum (<3.5mm of effective thickness with magnetic shielding) which give an integrated stray field lower than 2 µT.m (<10 ppm of the main integrated field magnitude in the gap) with a very flat distribution over the full width experienced by the stored beam [1]. This septum magnet, when excited, has no measurable effect on the stored beam orbit.

This result is due to the screening effect of eddy current in the septum area, specifically with a full sine current excitation, and to the very effective magnetic shielding which completely surrounds the inner vacuum chamber of the stored beam. Fundamentally this excellent result is possible because the structure of in-vacuum eddy current magnet permits to make a total separation of the electrical and magnetic domains of the septum and of the stored beam chamber. So the stray field and perturbation can be close to zero.

Thick Septum Out-Vacuum

Our direct-drive out-vacuum septum is not so 'perfect'. This magnet was measured alone in laboratory and met the specification after installing some complementary shielding: a stray field of ±11µT.m in bipolar pulse. But when installed on the Storage Ring, a significant bump of the beam orbit of 800µm in horizontal was measured. So a long work of analysis, measurement and modification of this magnet has been undertaken.

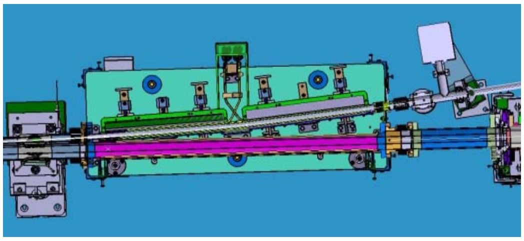

Figure 1: Initial configuration of the thick septum magnet in its environment.

First a µ-metal magnetic shielding is installed around the Storage Ring vacuum chamber parallel to the septum, reducing by a factor 5 the bump (x_{peak}=150µm). Then two magnetic shieldings were installed around the septum yoke: one shielding in Supra-36 (high saturation field material), enveloped by a µ-metal shielding: resulting in only 20% of attenuation (x_{peak}=120µm, z_{peak}=14µm). At that time we understood that the main cause was the strong eddy current generated in the thin-wall stainless steel chamber of the injected beam, located inside the septum gap: 220A peak pulses were measured with Rogowski probe, which flow from the septum gap area to the ground points existing (supports, pump, valve). These eddy current pulses act as a direct perturbation source on the stored beam passing inside the upstream vacuum chamber. So the cure was to place several low impedance grounding connexions on this thin-wall chamber: eddy current was then reduced to 4A peak, and the bump was decreased to x_{peak}=20µm and z_{peak}=20µm [2]. At least the upstream SR chamber was wrapped by an efficient µ-metal shielding: the bump is now x_{peak}=10µm (reduced by a total factor of 80), equivalent to a stray field of ±10µT.m, and z_{peak}=8µm, extended over ~4ms (3500 turns). This result is satisfactory in horizontal (3% of σ_X of the stored beam) but still too large in vertical (40% of σ_Z).

The remaining perturbation is attributed to eddy currents which also flow directly in the downstream flange and chamber (common to injected and stored beam). The only definitive cure will be to modify the vacuum chamber and introduce electrical cuts at each end of the thin-wall chamber, to avoid the extension of these eddy currents.

KICKER MAGNETS

The identity between the four kicker pulsed fields implies the design of all equipment, the ceramic chambers and their coating, the kicker magnets, the pulses and their HV power supplies. So their specifications included strong requirements on their tolerances, and attention has been paid on the manufacturing controls, metrology and alignment of the magnets, on accurate measurements on the HV power supplies and on the pulses. Nevertheless, after installation, a significant residual bump on the stored beam was found, created by the four kicker imperfect matching.

Horizontal Residual Bump Reduction

Successive adjustments have been undergone in order to get a better matching between kickers, acting on all characteristics of the pulses: amplitude (voltage settings), timing (trigger of the pulses), duration (additional capacitors in pulsers), smoothing and shaping (saturating inductor in pulsers). These fine adjustments were done during machine shifts, using the turn by turn data over a set of 8 BPMs to sample the effective pulses profile experienced by the beam [2]. These adjustments were possible only thanks to the location of pulsers out of the vault. The last optimizations conducted until 2009 permit to reduce the residual bump in horizontal plane down to 10µrad (equivalent to 1.3 10^{-3} of the kickers field peak value), injecting an orbit oscillation of 70µm RMS that is damped after a few ms.

Vertical Residual Bump

In the vertical plane, a residual bump is also measured. Initially of 30µrad peak, after correcting the tilt of the four kicker magnets it has been reduced to 10 µrad peak, giving an orbit bump of 40µm.

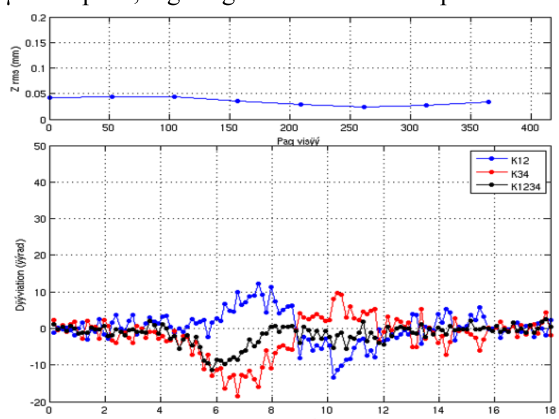

Figure 2: In Vertical plane, RMS residual oscillation (up) and kickers deviations (down).

This residual bump shows bipolar shape over 7µs as it was the derivative of the main pulse. It indicates probably an effect of the eddy current generated in the thin coating of the ceramic chambers. The Titanium coating was calculated to give an attenuation of 0.67% with a coating depth of 2µm in the case of an ideal rectangular chamber. This attenuation is due to the eddy currents which generate a field opposite to the kicker field. A simple calculation gives an estimation of the equivalent kick due to these "eddy currents": with a main kick θ_k=7.6mrad, 0.67%*θ_k =50µrad which is of the same order of magnitude as the measured residual bump. As the chambers have in reality a racetrack profile, the "eddy current" field is not uniform and has a horizontal component. When kicked the stored beam experiences along the four kicker chambers different "eddy current" fields whose integral is not zero. This will be enhanced by the transverse coating profile, which has been chosen to be thicker (+20%) on the chamber axis than in lateral areas, in order to manage the strong mirror current (500mA). This choice was certainly a mistake.

Triggering Jitter Measurement

The time jitter between the four kickers, and with other equipment is important. It is difficult to make a direct measurement of a very small jitter on the kicker pulses, because they have a 3µs rise time, too slow to permit a sub-nanosecond reliable measurement. So an indirect set of measurement based again on BPM turn by turn has been done. The dispersion in the sample gives a measure of the jitter between kickers. A first measurement in September 2008 showed an abnormal jitter up to 2-3ns, taking into account the timing distribution jitter performance (<100ps RMS). This allowed detecting an inadequate optical transmission of the trigger signals (attenuated and too slow rise time). After refurbishment, the measurement performed in April 2009 showed a strongly reduced jitter, ~500ps peak to peak, below BPMs precision. Electronic measurements have recently been made also in the pulses, but on a derived current, in an R-C series filter, which has a fast rise time. These measurements, performed in August 2011, show low jitter between each pulse current and the timing distribution: jitter peak to peak ≤510ps, RMS ≤84ps.

AVAILABILITY AND LONG TERME STABILITY

The SOLEIL Storage Ring began to be operating in June 2006, and was injected in Top Up mode since March 2009. In fact, no failure occurred on the Pulsed Magnetic Systems of the Storage Ring injection since the beginning. This very good availability is certainly due to the use of solid-state switches and to comfortable technical margins in current and voltage (at least 25%) when dimensioning the components.

The settings of the pulsed magnets stay very stable, in voltage amplitude or time delays. They stay identical during the runs and from run to run, over the technical shutdowns. They are changed only when the Storage Ring optics are modified [3]. From our present experience, these pulsed devices have excellent long term stability.

SOME CONCLUSIONS AND FORESEEN IMPROVEMENTS

Table 1: Injection bumps measured at BPM (β_x=14m, β_z=12m) compared to Top Up targets, and Kickers jitter.

Plane	H	V	Time jitter (max)
Target	~30µm rms	~2µm rms	
Thin septum	~0	~0	
Thick septum	10µm peak	8µm peak	
Kickers	70µm rms	40µm rms	510ps p-p, 84 ps rms

The thin septum magnet demonstrated its unprecedented performances: good field transverse homogeneity, stray field near zero, very thin effective septum wall (3.5mm including shielding). These qualities directly result from the choice of an in-vacuum eddy current magnet, which permits to completely separate the magnet gap and the stored beam path in the electric and magnetic domains. The only remaining question concerned the internal thermal raise when operating at 500mA. In order to limit the magnet heating we replaced the initial air-cooled sinks by water regulated sinks on the thermal drain (out-vacuum). Thus we lowered the internal temperature by 10°C. A further improvement could consist to change the stored beam inner chamber, currently in stainless steel by a copper one.

The thick septum magnet still generates an excessive vertical perturbation on the beam orbit. It should be divided by a factor 4. The out-vacuum design naturally generate eddy current in the vacuum chamber in the gap, and they extend out of the yoke, generating perturbation on the beam orbit. The only definitive cure is to modify the thin-wall metallic chamber to make electrical cuts exactly at input and output of the yoke, to avoid eddy current extension. This modification will be done soon at SOLEIL.

The four kicker systems have now reached a rather good level of matching, close to the target (tolerance of 10^{-3} of the peak field) in the horizontal plane. But the residual bump in vertical plane is still too large (20 times the accepted value), and is a concern, especially in case of providing a beam with smaller vertical beam sizes. Certainly some possibilities of adjustment exist, improving the matching on pulses, developing a new effort on the roll alignment. But there is an unexpected effect due to the eddy currents generated inside the ceramic chambers coating, probably increased by non-uniform coating thickness.

Concerning the kickers matching adjustment, we probably have still margins of improvement, but we are for the time limited by the impossibility to measure the kicker individual contribution. That is because we lack of BPM between the four kickers. So we plan to install one BPM in the middle of the injection straight section. Then the factor 2 on the horizontal residual bump due to kickers, could be gained in order to fulfil the 10% of RMS beam size in orbit stability.

But to reduce efficiently the vertical bump, we think necessary to have an active feed-forward corrector. Its development is under study, based on the idea to drive, by the inverted signal of the residual bump measurement, an "amplifier" supplying a vertical kicker. Its design is not easy because this "amplifier" needs to provide high voltage (~500V) and current (50A) bipolar pulses, with a rather large bandwidth. Certainly it will be necessary to have two feed-forward correctors for the vertical plane in the injection section, to be able to correct both in position and angle.

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