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PULSED MAGNETS AND POWER SUPPLIES FOR INJECTION & EXTRACTION IN THE SOLEIL II PROJECT

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Abstract

It is a rare opportunity in an engineering career to redesign entirely the injection and extraction systems for a new or upgraded particle accelerator. This paper describes how the beam injection and extraction schemes for the SOLEIL II project have guided the choices, main characteristics, and R&D work for the pulsed magnets & power supplies.

ABOUT BEAM DYNAMICS

The SOLEIL II project will see the two main accelerators – the booster and storage rings – entirely rebuilt, while the LINAC and the two transfer lines will benefit from various equipment upgrades. The new booster lattice will be based on a multi-bend achromat (MBA) lattice to achieve a beam emittance as low as 5.5 nm.rad at 2.75 GeV, as presented in [1]. The new storage ring aims to reach an emittance of around 80 pm.rad at 2.75 GeV will also use an MBA lattice with a succession of 4- and 7-BA cells concatenated with straight sections for various insertion devices as presented in [2]. For these new generation accelerators, injection or extraction efficiency are more sensitive to beam and equipment errors and jitters.

From the point of view of beam dynamics, the main properties that directly translate into pulsed magnet specifications are:

- Required deflections versus available space, including beam stay clear and vacuum chamber dimensions.
- Multipole decomposition of the magnetic fields.
- Reproducibility of the pulsed magnetic field, i.e., shape, peak value & timing jitters.
- Transparency of the injection / extraction processes.

The last aspect is crucial in the case of the Top-Up injection in the storage ring: re-injecting particles without any – or minimal – disturbance of the already stored beam is mandatory in the next generation of synchrotron light sources. Virtually all the Top-Up injection schemes are transparent by design, and it is the actual performance of the manufactured equipment (kicker, septum, etc..) that cause the stored beam to oscillate and thus degrade photon beam quality on the experiments.

INJECTION IN THE BOOSTER

The LINAC is planned to be increased in output energy from current 110 MeV to 150 MeV, which is beneficial to the booster beam dynamics. On-axis & on-momentum injection of the electron beam from the transfer line in the upgraded booster require a septum magnet and a fast dipole kicker magnet.

The existing septum magnet is an eddy current septum magnet powered with a resonant capacitive discharge pulser. The existing kicker magnet is a window-frame lumped topology with a one turn coil with 8C11 type ferrite yoke. It is powered through a matched pulse forming line (PFL) discharge pulser, as detailed in [3].

Both systems have operational margin above 200% and therefore can be reused in the upgrade of SOLEIL II, considering the extra strength needed due to the increased injected beam rigidity. The operations that are planned for the upgrade booster injection pulsed systems are:

- Pulser qualification and verification to allow reliable operation at higher voltages and currents.
- Design of vacuum transitions for the kicker and septum magnets.
- Improved thermalization of magnets & pulser units to improve the pulse-to-pulse reproducibility to $2*10^{-4}$ (1σ) over weeklong operation.

Timewise, it is planned to have prepared the injection pulsed systems for operation for the 150 MeV beam before the dark period which will see the new booster & storage rings installed in lieu of the current accelerators.

EXTRACTION FROM THE BOOSTER

The existing extraction pulsed magnets - three slowly ramped bumpers, a single fast dipole kicker and a duo of thin and thick septum magnets – could not be recycled in the upgrade booster as they could not be made to work with the new optics and accelerator integration.

Instead, a direct extraction scheme is proposed for the new booster. A series of fast dipole kickers will directly kick the beam to a single thick septum magnet at the start of the transfer line. All the pulsed systems will be installed in a dedicated long straight section.

The main specifications for these magnets, derived from beam dynamics are detailed in Table 1 and 2.

The existing ceramic chambers have the proper titanium coating (200 nm) to allow the fast magnetic pulses to transit into the aperture and as such will be reused in the design of the new dipole kickers.

The pulse flat-top duration is related to the long pulse mode of the injected beam, i.e., 104 consecutive bunches at the storage ring frequency (352 MHz). To preserve the quality of the flat-top throughout the propagation of the current pulse in the magnet, it is foreseen that the magnet type should be of transmission line dipole kicker.

To power these four extraction kickers, two solutions of pulsers for each individual magnet are proposed.

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Table 1: Booster Extraction Kicker Specifications

Number of magnets	4
Deflection per magnet	2 mrad @ 2.75 GeV
Magnetic length per magnet	300 mm
Vac. chamber aperture (H x V)	40 mm x 16 mm
Pulse-to-pulse reproducibility	2 10^{-4} (1σ)
Max. alignment roll	100 µrad
Rise time (0 – 99 %)	200 ns
Flat-top duration and droop	300 ns / 0.1 %

The first solution is an in-house design of PFL pulser. Although it is a traditional concept, the difficulty lays in the mechanical engineering to control all parasitic inductances and resistances that will degrade the pulsed current waveform. The second solution is to develop inductive adders to power the magnets. Recent developments, notably at CERN [4], of this new philosophy to power pulsed magnets have shown their advantage to control the pulsed current waveform, better than passive discharge of a PFL. Furthermore, the options to match in impedance or short-circuit the magnet to gain in current at the expense of a doubled fill time must also be considered. The specified pulse-to-pulse reproducibility is achievable provided thermal management handled correctly and high voltage charging power supply exhibits acceptable pulse-to-pulse precision.

The thick septum magnet for extraction has a twin brother at the end of the booster to storage ring transfer line as one as the last magnets for storage ring injection. As such, they both bare similar specifications presented in Table 2.

Table 2: Thick Septum Specifications

Deflection per magnet	130 to 150 mrad
Deflection accuracy	10 µrad
Max. projected field	1.7 T
Beam minimal separation	16 mm
Stored beam chamber aperture (booster)	dia. 20 mm
Stored beam chamber aperture (storage ring)	dia. 15 mm

The start-to-end calculations for injection efficiency show that the horizontal deflection errors of the thick septum magnets are a major contributor to injection efficiency in the storage ring below 90%. Thus, to maintain efficiency near 100%, the required deflection accuracy for each thick septum should be in the range of 10 µrad with respect to a deflection of 130 to 150 mrad, depending on mechanical integration of the booster to storage ring transfer line. Thus, the pulse-to-pulse magnetic reproducibility, i.e., the accuracy divided by the deflection, is in the range of few 10^{-5}.

To meet such reproducibility with an electromagnetic (EM) thick septum magnet, significant efforts must be placed on:

- The reproducibility of the discharge phase of the pulser into the magnet inductance, including the jitters of semi-conductors.
- The charge-to-charge reproducibility of the charging power supply.
- The proper thermal management of all components (pulser & magnet), including the possible feedbacks to compensate thermal drifts.
- The mechanical design of the magnet with respect to the vibration due to high pulsed currents.

An alternative solution, as studied in [5], is to use a permanent magnet-based (PM) septum magnet. The main advantages are the field accuracy since no DC, ramped or pulsed power supply are required and compactness of the design since coils increase the overall length of the device. To correct the deflection field integral, an external EM dipole or a mobile shunt allows tuning of the field integral to compensate for thermal drift or to improve injection efficiency. In the case of the storage ring injection, a PM septum magnet only exhibits permanent leakage field that can be compensated to some extent by the tuning of the lattice. An EM version will have direct and eddy-current induced leakage fields that are more complex to screen to ensure transparent injection.

At present, the PM solution is the current favored option and preliminary conceptions have been drafted at SOLEIL. Detailed engineering of this solution will continue in the coming years to validate the feasibility of such septum with a high deflection magnetic field. However, an EM version for the thick septum magnet will also be studied as a back-up solution.

INJECTION IN THE STORAGE RING

The current main Top-Up injection is a betatron off-axis on-momentum scheme as detailed in [6].

The booster to storage ring transfer line will end with a thick septum as previous detailed, followed by a thin septum. The final kick on the injected beam is given by a series of multipole injection kickers (MIK) to place the beam within the dynamic aperture. Synchrotron radiation damping over a couple thousand ring revolutions allow the injected beam to combine with the stored beam. The MIK having a zero-field region at center, the stored beam is unperturbed in the final part of the Top-Up injection.

The thin septum is foreseen to be an eddy current septum magnet with detailed engineering of the following aspects to meet the summarized specifications of Table 3.

Table 3: Thin Septum Main Specifications

Deflection	20 to 25 mrad
Magnetic length	400 mm
Septum effective thickness	1 mm
Beam separation	7 mm
Stored beam location wrt. septum	5 mm
Projected max. leakage field	few µTm

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Firstly, given the targeted beam separation and effective septum thickness, it is planned to use a copper blade that will thin out from 3 mm to 0.5 mm over the length of the magnet. A fast bipolar current pulse, typically 10 to 20 µs maximizes the contribution of the eddy current screening to achieve low-leakage field.

Secondly, mumetal shielding will be used to complement the screening of the leakage field. A thickness of 0.5 mm will complete the septum composition to reach this 1 mm effective thickness. A dedicated set-up is also under study to understand the limitations of mumetal at the pulse frequency, typically between 10 kHz and 500 kHz. The aim is to narrow the ideal frequency that allows the most effective contribution of eddy-current and magnetic mumetal shielding. Mumetal shields will also be used around the magnet, especially to screen the magnet apertures, stored beam pipe, magnet connections and pumping ports. A collaboration with experts of CERN on the design of eddy-current septum magnets will happen over the next two years.

At last, a dedicated feedforward correction, as implemented in [7], could be used to compensate for some residual leakage field to achieve perfect transparency of injection from the point of view of the leakage fields of thick and thin septum magnets.

The SOLEIL pulsed magnet team has gained significant experience in the design and manufacture of MIK systems through the successful collaboration with MAX IV [8] and recently with the commissioning of a twin MIK system on the current SOLEIL storage ring [9]. However, the Top-Up injection scheme requires that the injected beam receive a final deflection free of any gradient, to avoid a larger betatron oscillation of the particles that do not receive an adequate kick. Thus, the magnetic field distribution of the MIK must have a peak located where the injected beam arrives in the magnet, i.e., 3.5 mm.

Reusing the 8-conductor topology of the MAX IV type MIK to move the peak magnetic field from 10.3 mm to 3.5 mm would lead to a magnet with a free aperture for the beams of about a millimeter, impracticable to manufacture. Thus, the pulsed magnet team had to design new topologies to meet the required magnetic field distribution.

The new topologies had to allow sufficient vertical & horizontal aperture (typ. 6 mm (V) x 30 mm (H)) for the beam while allowing a peak magnetic field at +/- 3.5 mm and a zero-field region of octupole type, i.e., with no dipole component and minimal quadrupole component. Up to 20 conductors could be used to form the magnet while keeping an inductance low enough to allow pulsed operation.

Seven topologies were designed with three patented in France – worldwide patent extension is ongoing. The most suitable – topology D – is foreseen to be used for the SOLEIL II storage ring and is shown in Fig. 1 (left): the beam stay clear (green) is 7 mm (V) x 30 mm (H), with the whole assembly being in vacuum. The conductor transverse distribution along the longitudinal “S” axis and polarity are represented with colored dots. The plot on the right presents a comparison of vertical field distribution for a MAX IV type MIK and for the type D MIK, both at 1 kA.

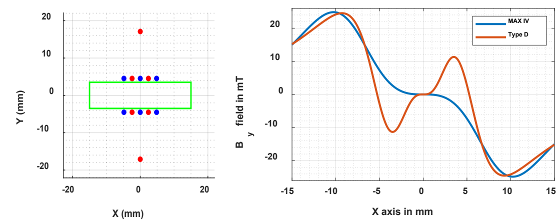

Figure 1: MIK topology D conductor distribution (left) and comparison of field distribution between a MAX IV MIK and type D MIK, both at 1 kA current (right).

A key feature of the type D MIK is the ability to move the two outwards’ conductors at Y = +/- 17 mm to allow for correction the residual dipole & quadrupole at center induced by the manufacturing errors of the magnet. The performances of this feature will be detailed in a future paper.

Ongoing prototyping of the type D MIK includes verification of the high voltage behavior in vacuum, effect of eddy currents in the titanium coating of the aperture on the magnetic field distribution and thermal design to cope with the beam induced thermal loads. At present, all the tests are conclusive. The next engineering steps will also cover the final design of the semi-conductor based pulsers and consultation of ceramic manufacturers to finalize the design the final magnet parts.

CONCLUSION

From the preliminary beam dynamics specifications for injection and extraction in the SOLEIL II project, the pulsed magnet team has been able to propose a solution for every need of pulsed system for quality beam deflection, with a subtle balance between proven solutions and new developments when current technology did not meet the beam dynamics requirements.

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