# EDDY CURRENT SEPTUM MAGNETS FOR BOOSTER INJECTION AND EXTRACTION, AND STORAGE RING INJECTION AT SYNCHROTRON SOLEIL

P. Lebasque, P. Gros, J.P. Lavieville, J. Da Silva Castro, A. Mary, D. Muller
Synchrotron SOLEIL, Saint-Aubin, France.

*Abstract*

Eddy current thin septum magnets are used to inject or extract the electron beam to/from the Booster and to the Storage Ring (SR) of SOLEIL. Good transverse homogeneity in the gap for injected beam, and low leakage field on circulating beam is needed, as well as pulse stability. The **Top Up injection** mode of the Storage Ring needs a **very low level of leakage field on the stored beam path**. Operating currents are from 2000 A and 3000 A for Booster injection and extraction, to 5100 A for SR injection. This contribution will describe the magnets and the pulsed power supplies design. The electrical and magnetic measurement results will be presented, with a specific emphasis on the improvements needed to reduce the level of leakage field of the SR septum magnet.

## MAGNETS DESIGN

A specific development was done by the collaboration SATURNE-LURE during the preliminary phases (1996-1998) of SOLEIL design. A prototype of Eddy current septum magnet was built for a complete analysis and measurements (vacuum, thermal, field, leakage field). [1]

From this development, we designed the three septum magnets necessary for SOLEIL, taking account of its solutions: choice of the magnetic core sheets; a copper septum optimized at 3 mm thickness for a good screening of the leakage field by Eddy currents, reinforced by a Mumetal sheet; a copper box enclosing the iron sheets core to contain and dissipate the Eddy current loop generated by the pulsed field; choice of a ~60µs half-sine excitation to avoid excessive thermal dissipation in vacuum; electrical connections by copper elastic pieces.

The SOLEIL's three septum magnets have the same cross-section, which gap is optimized on Storage Ring injection needs. The Booster's have a length of 300 mm, and the SR injection one is 600 mm long.

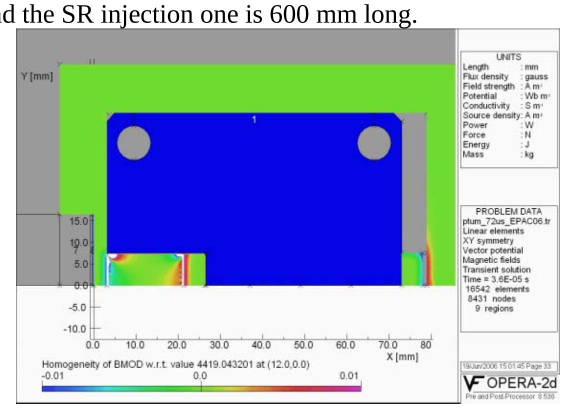


Figure 1: Field homogeneity and current calculations

Insulations are made by alumina plasma deposit: on the electric coil, on inner surfaces and below the copper box. Such a dielectric insulation is expected to have low gas desorption level in the vacuum.

Beam screen monitors are installed into the Booster extraction and the SR injection septum chambers, at the exit of the magnet box.

For the SR septum magnet, it's of great importance to preserve the continuity of vacuum chamber impedance along the stored beam path, and also to improve the vacuum level. So for this, a specific stainless steel chamber was added against the septum, fixed on the magnet. It has an aperture close to the SR chamber dimensions, with RF fingers connections at each end. The whole vacuum chamber that enclose the septum magnet, its connexions and the beam screen monitor, is pumped by a 600 l/s ion-pump, but in addition a dedicated pumping system is connected to this inner chamber in order to keep the vacuum at the SR vacuum level ($10^{-10}$ mbar).

Table1: Required and calculated characteristics

| | Booster | | Storage ring |
|---|---|---|---|
| | injection | extraction | injection |
| Energy | 110 MeV | 2.75 GeV | 2.75 GeV |
| Deviation | 131 mrad | 9.3 mrad | 27.5 mrad max |
| $\int Bdl$ | 48.3 mT.m | 85.2 mT.m | 252 mT.m |
| Length | 300 mm | 300 mm | 600 mm |
| Peak current | 1922 A | 3390 A | 5015 A |

Table 2: Mechanical data

| | | |
|---|---|---|
| Vertical gap | 15 | mm |
| Horizontal aperture | 18 | mm |
| Turns | 1 | |
| Copper box thickness | 10-12 | mm |
| Septum thickness | 3 | mm |
| Mumetal thickness (initial) | 0.1 | mm |
| Conductor cross-section | 4x14.2 | mm |
| Alumina coatings thick | 0.3±0.03 | mm |
| Cooling on connexions | Air forced | |

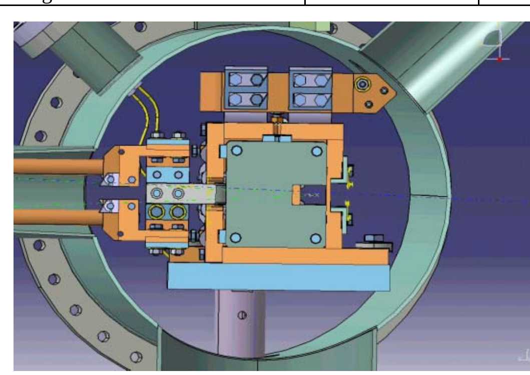

Figure 2: Cross-section of the Booster septum magnets

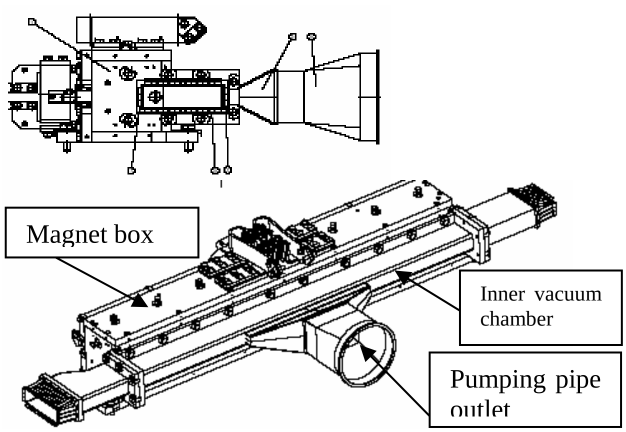


Figure 3: Cross-section of the Storage Ring septum magnet

## PULSED POWER SUPPLIES

The pulsed power supplies are based on the classical LC resonant discharge scheme, with a high current switching thyristor. With a pulse of near 60 µs width, the stored energy is not excessive, so we tried to minimize the charging voltage and capacitors bank value and volume. We are operating with 300V-2A charging power supplies, two PS being set in series for SR injection pulser, and with energy storing bank composed of 47 µF individual capacitors in parallel, which number in parallel is adapted to total inductance (magnet + transmission) of the septum.

To ensure stable shape and low level of EM perturbation we chose coaxial cables for the power pulses from the pulser (in technical gallery) to the magnet (in tunnel). Cables have been chosen relating to their low inductance and low resistance per meter. We use 3 of this cables in parallel for each Booster septum magnet, and 6 cables in parallel for the SR septum magnet, which is working at higher current.

We made a specific study to get thyristors that can support high di/dt, because of the fast rise time of the pulses and of the high currents needed: T1052S, which can accept very high repetitive current pulses and high di/dt, with comfortable margins. It's essential to avoid significant thermal variations in the solid-state junction to get a long life operation: thermal calculations for this thyristor in our operating conditions show that it would stay very thermally constant, even in natural cooling, because of the short pulse width and the low repetition rate (3 Hz).

## MAGNETIC MEASUREMENTS

Magnetic measurements were performed to characterise each septum magnet inside the gap: transverse homogeneity of integral field, longitudinal profile of local field, and effective magnetic length; and outside the gap, the leakage integral field versus distance from the septum.

We built specific probes: a 1 turn long coil of 1,185mm width (made of FR4 circuit reinforced), a short coil of 3mm diameter (machined plastic) and for leakage field a 6 turn long coil of 10 mm width (machined plastic support). Probe signals were digitally integrated by a fast sampling digital scope.

Magnetic measurements were made at higher voltage and current than nominal requirements. Table 4 gives the main results: field integral in the gap at z=0, transverse homogeneity $\Delta\int Bdl / \int Bdl$ versus horizontal position from septum, local field in the central region, magnetic length calculated from local field measurements. Leakage field integral values, out of the gap, are given on the mean path of the circulating or stored beam, with its distance from external edge of septum.

Table 3: Initially measured magnetic characteristics

| | Booster | | Storage ring |
|---|---|---|---|
| | Injection | Extraction | Injection |
| @Voltage | 201.5 V | 290 V | 550 V |
| Peak current | 1941 A | 3604 A | 5040 A |
| $\int Bdl$ center | 54.68 mT.m | 90.37 mT.m | 255 mT.m |
| $\Delta\int Bdl / \int Bdl$ | ±1.2% | ±1.5% | ±0.5% |
| B centre | 176.36 mT | 286.97 mT | |
| Magnetic length | 318 mm | 318 mm | 620 mm |
| Leakage $\int Bdl$ max on beam path | 25 µT.m @x=20mm | 54 µT.m @x=15mm | 409 µT.m @x=25mm |
| Stray/main fields ratio | $0.45\ 10^{-3}$ | $0.6\ 10^{-3}$ | $1.65\ 10^{-3}$ |

The local field measurements along s axis (x= centre of gap) give the longitudinal profile.

The leakage field of septum magnets is maximum 225 µs after the beginning of the main septum field pulse. This delayed leakage field is caused by Eddy current in septum and copper box, that turn off with a specific time constant determined by inductance and resistance in the copper circuit. This time constant imposed a long decay time of leakage field after the maximum. We measured also, near the entrance and the exit of the magnet core, local leakage field pulses, synchronous of the main field, but their contributions to total leakage filed are small.

For the Booster the max leakage field integral was fixed at $\leq$ 200 µT.m, so the results are good.

For the Storage Ring, leakage field results was acceptable for a classical septum magnet, but new calculations for Top Up mode injection fixed the max acceptable leakage field at 12 µT.m (i.e $0.47\ 10^{-4}$ of main field) in order to get a beam position oscillation or less than 10% of beam dimension in any part of the Storage Ring. So a hard improvement of the leakage field has been necessary.

## STRONG REDUCTION OF THE STRAY FIELD

For the SR septum magnet, the stored beam pass through an inner stainless steel (316LN) specific chamber, joined to the magnet box, terminated by rectangular ends with RF fingers, which has a dedicated outlet in the median transverse plan to the pumping system.

First, a complete set of magnetic measurements, local and integral, of the leakage field of the SR septum magnet has been done, to well identify its characteristics and sources. It confirms that delayed integral field regularly decays with the distance from septum. It confirms also that there are some local contributions to leakage field, synchronous of main field, at each extremity of the magnet box and in front of the aperture in the inner chamber for pumping outlet.

Secondly, we modify the pulser in order to get **bipolar full-sine pulses** of power current exciting the magnet [2]. With our 10m transmission, we get **a negative pulse equal to 71% of positive one**. With this modification we get a reduction of the leakage field integral to 53% of initial value, a reduction of the max field integral delay to 135 µs, and above all a faster decaying of the leakage field pulse. But the result was not sufficient to reach our goal.

Then we build two home-made shielding screens [3, 4] in a magnetic alloy (Imphy from Arcelor) of 0.2mm thickness. One was just a “wall” screen between the inner chamber and the magnet copper box. The second was a screen surrounding as completely as possible the inner chamber. The shaping of these screens needs many folding of the magnetic alloy sheet. We put it in place without thermal treatment of the screens. With these additional screens, we get another reduction of the max amplitude of the leakage field integral, to 29% of initial value: 118 µT.m.

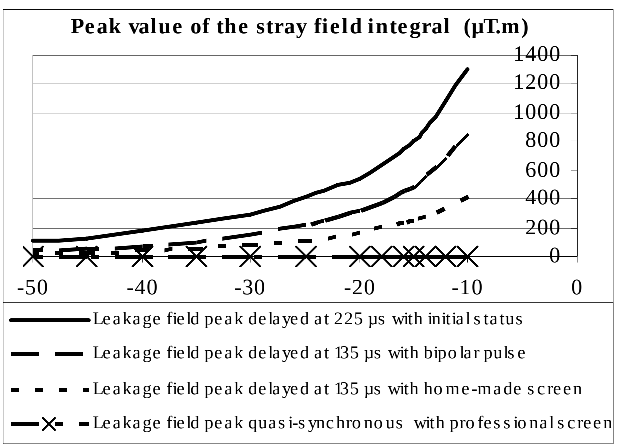


Figure 4: Stray field in different configurations

Finally we contact the company MECAMAGNETIC dedicated in shielding, and they design a shield screen adapted to the inner chamber and magnet box geometry, and to the field pulse frequency characteristics. An essential point is to make an adequate thermal treatment (up to 1100 °C, with specific cycle), after the final shaping of the shielding pieces, in order to recover the complete magnetic permeability of the alloy degraded by diverse folding needed to shape it. The screen shape has to surround totally the inner chamber, even at its ends up to the RF finger and even around the transverse pumping outlet: to get a very low level of leakage field, it is mandatory to screen all the local components of leakage field. We choose a special magnetic alloy, SuperImphy, of greater permeability, with the greatest thickness (0.5mm) compatible with the required distance between the injected beam and the stored beam.

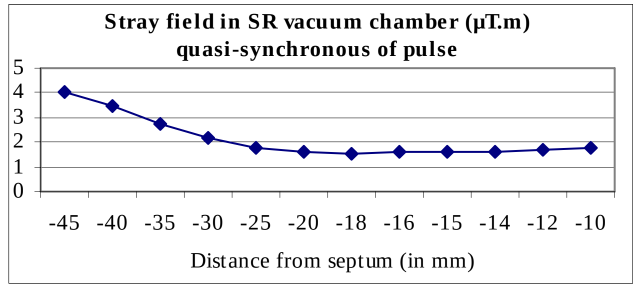


Figure 5: Strongly reduced stray field in final status

So **we could strongly reduce the stray field** integral to **<2µT.m** in most part of the stored beam path, that is only **<10 ppm of main field magnitude**, with a **very flat distribution** which indicates a very good screening. We could understand the small growing of field integral, at distance > 35mm from septum, as an influence of local stray field penetrating by the pumping local aperture.

## CONCLUSION

**In order to get a very low level of stray field** for septum magnets, dedicated to Top Up injection mode of Synchrotron Radiation source, a full-sine current pulse is useful, but it is also necessary to design an adapted shielding screen for the stored beam path region.

**For a very effective shielding screen one has to respect four conditions:**

- a magnetic material with a very strong initial magnetic permeability, taking into account the permeability reduction with the field frequency,
- an adequate thermal treatment at high temperature in furnace after the final shaping of the pieces composing the screen,
- a sufficient thickness of magnetic alloy sheets regarding to the wanted field attenuation, with eventually the best compromise with beam injection geometry,
- a screen geometry able to envelop, in all directions, as totally as possible the stored beam path region.

With such a design, one can obtain very strong field attenuation, which it is possible to estimate even by simple formulas calculation.

## REFERENCES

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