# A HOMOGENEOUS SUPERCONDUCTING COMBINED MULTIPOLE MAGNET FOR THE LARGE ACCEPTANCE SPECTROMETER $S^3$, BASED ON FLAT RACETRACK COILS

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## *Abstract*

$S^3$ (Super Separator Spectrometer) [1] is a future device designed for experiments with the very high intensity heavy ion stable beams of SPIRAL2. It will be set-up at the exit of the linear accelerator LINAG at GANIL (Caen, France). It will include a target resistant to very high intensities, a first stage momentum achromat for primary beam suppression, a second stage mass spectrometer and a dedicated detection system. This mass spectrometer includes a set of four large aperture quadrupole triplets with embedded multipolar corrections. These magnets are a combination of three multipoles which could be realized with superconductor wound in flat racetrack coils. To enable the primary beam extraction one triplet has to be opened on one side, which requires a careful design of such a multipolar magnet.

This paper describes the opened multipole geometry. It is adapted to large apertures as demonstrated by Opera-3d$^{\copyright}$ magnetic simulations [2], including harmonic analysis and integral field homogeneity.

## INTRODUCTION

C-shaped quadrupoles are common in magnetic spectrometers. Usually, open quadrupoles are realized with conventional ferromagnetic structure at room temperature. When quadrupole and sextupole fields have to be combined, the sextupole component is obtained by the superposition of two dipolar coils with opposite field, the dipolar field is cancelled and the first sextupolar harmonic is the main component left [3]. One of these dipolar coils, located on the magnet pole, limits the vertical acceptance.

With the 300 mm aperture diameter and the 1.8 Tm maximum magnetic rigidity needed for $S^3$, an increase of the pole tip radius, in order to restore the vertical acceptance, leads to a very bulky and heavy object. Moreover, it is difficult to control the remaining higher harmonics without additional coils which are difficult to place. In the $S^3$ case, the maximum magnetic rigidity requirement means that the saturation is reached in the iron, which contributes to a non-linear behaviour of the magnet. To avoid the problem of iron saturation while respecting a low level of higher multipolar harmonics, novel superconducting solutions are proposed. The use of specific superconducting flat racetrack coil arrangement (MOSAR[#]), instead of usual saddle-shaped coils, achieves similar or even better specifications than conventional technology. Such structure can integrate sets of coils for sextupolar and even octupolar component. A proper control of the harmonics would give a more efficient magnet than in the ferromagnetic design. Moreover the magnet size and weight are notably reduced as well as its power supplies.

Nevertheless, the magnet length and its aperture have the same order of magnitude, leading to difficulties to realize in some cases a large homogenous field area.

## MULTIPOLE GEOMETRY

The magnet geometry is governed essentially by the ±50 mm of the vertical gap used for primary beam rejection. This gap has also to integrate the thickness for mechanical and vacuum components and cryogenic constraint. The total gap is estimated to be ±90 mm.

The quadrupole coils configuration is in standard 45° symmetry but the coil extension is reduced to leave the vertical gap free. Consequently, due to a mismatch between the current distribution and the $\cos(2^*\theta)$ law, the main quadrupole windings create a dodecapole component which is compensated by an opposite quadrupole winding.

Sextupolar and octupolar field can be obtained by different coil arrangements depending on field level, field quality and magnet compactness.

## COMPACT COIL CONFIGURATION

Like in the open classical quadrupole, the sextupole field is obtained by two dipolar windings which create naturally a sextupolar harmonic. In order to cancel the next natural harmonics of the dipole, the decapole, a third dipolar winding is added (see Fig. 1).

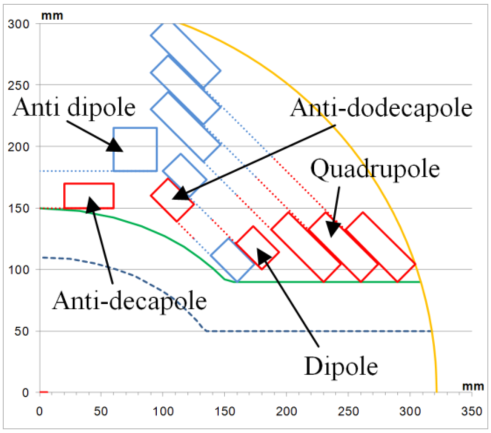

Figure 1: MOSAR compact design. The red and blue colours indicate the different current signs.

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[#] French acronym of *flat Racetrack based large Acceptance Open Superconducting Multipole*

The size, the arrangement and the assembly of the coils is crucial for a good magnetic behaviour and for the limitation of the current density (Table 1).

The use of a staged flat racetrack configuration allows the increase of the straight section of the winding, which effectively creates the wanted field. To obtain that, it is needed to use thin windings to realize the winding ends perpendicularly to the straight part with a low winding radius.

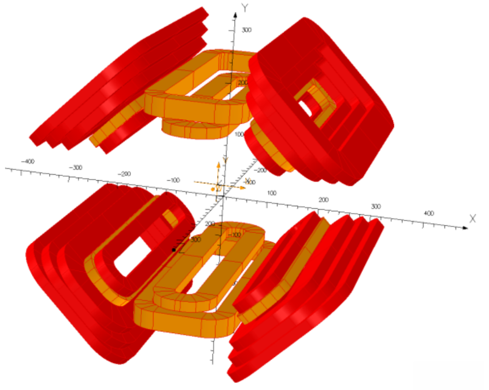

Figure 2: 3D-model of coils using Opera-3d© [2].

Table 1: MOSAR compact design characteristics.

| Coil type | Size (mm) | J (A/mm²) | Gradient | Peak Field (T) |
|---|---|---|---|---|
| Quadrupole | 60 x 20 | 150 | 6 T/m | 5.7 |
| Anti-dodecapole | 30 x 20 | 115 | | 4 |
| Dipole | 30 x 20 | 344 | 11 T/m$^2$ | 6.2 |
| Anti-dipole | 35 x 35 | 244 | | 5 |
| Anti-decapole | 40 x 20 | 210 | | 4 |

The 12-pole component of the quadrupole is cancelled at the magnet center by the dedicated coil, but an amplification of this component arises at the winding ends, as shown on Figure 3. An optimization of the end shape could lower this effect.

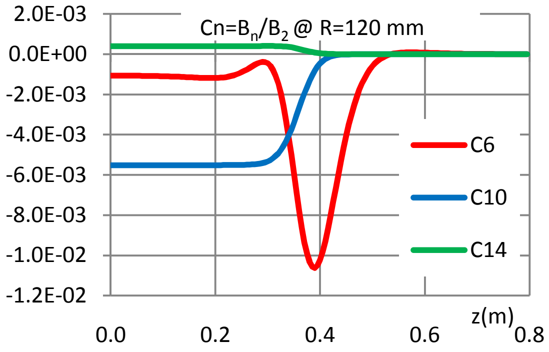

Figure 3: Quadrupole harmonic components along the longitudinal coordinate z on a half-magnet.

About the sextupole, an important number of harmonics remain and for some of them with a relatively high level (Figure 4). This implies a reduction of the transverse sextupolar good field area.

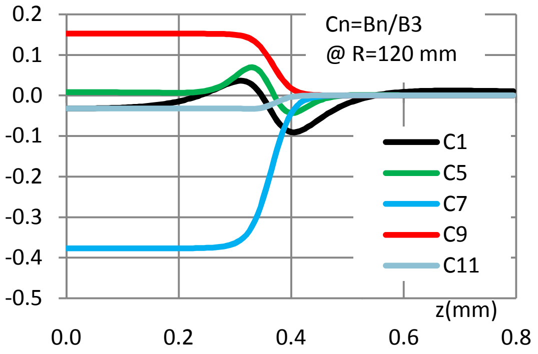

Figure 4: Sextupole harmonic components along the longitudinal coordinate z on a half-magnet.

Moreover as the sextupole is build by combination of two dipolar fields with different horizontal size, a residual dipolar field remains which varies with the horizontal extension (Figure 5).

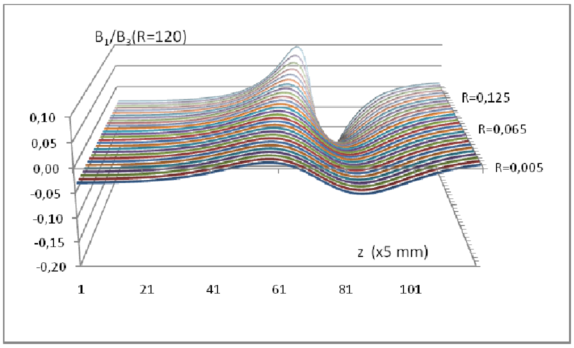

Figure 5: Sextupole residual dipolar harmonic component variation along z on a half-magnet and the magnet radius R.

The sextupole design, which gives a compact multipole magnet, has a relatively small useful horizontal aperture compared with the S$^3$ need.

## SYMMETRIC COIL CONFIGURATION

To extend the sextupolar good field area, it is possible to place the sextupole coils with similar rules than for the quadrupole. The sextupole coils configuration is in standard 30° symmetry and the transverse coil extension is reduced to not overlap with the vertical gap. To obtain sufficient coil aperture the coils distance to the magnet axis is increased (Figure 6). In this configuration, only the first high order harmonic remains at a relative level of $1.4\ 10^{-3}$ at 120 mm radius (Table 2). With symmetric coils, there is no more dipolar component.

With a gap height up to ±90 mm, it becomes possible to insert an octupolar symmetric set of coils (Figure 6) which gives similar behaviour as the sextupole, with only the first natural octupole harmonic at a relative level of $10^{-4}$ at 120 mm.

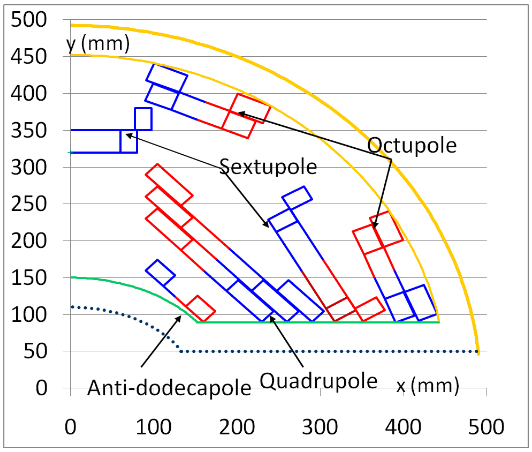

Figure 6: MOSAR design with octupole. The red and blue colours indicate the different current signs.

Table 2: MOSAR symmetric design characteristics.

| Coil type | Size (mm) | J (A/mm²) | Gradient | Peak Field (T) |
|---|---|---|---|---|
| Quadrupole | 60x20/30x20 | 150/115 | 6 T/m | 5.9 |
| Sextupole | 20x30 | 280 | 11 T/m$^2$ | 5 |
| Octupole | 43x25/34x25 | 180 | 18 T/m$^3$ | 5.9 |

In this case the maximum peak field is about 5.9 T located on the quadrupole and octupole coil ends.

The sextupolar correction satisfies $S^3$ requirement in terms of gradient. But for the octupole the maximum octupolar "gradient" is limited.

## SPECIFIC OCTUPOLAR DESIGN

With an increase of the free gap up to ±96 mm, the previous octupole design leads to excessive values for the peak field and the current density. To keep the octupolar component available, an original design with "radial coil arrangement" is studied. The principle is to put coils by pairs at an angular position where the amplitude of both $\cos(12^*\theta)$ and $\cos(20^*\theta)$ are minimized and $\cos(4^*\theta)$ is quite high. An octupole could be obtained by using 8 pairs of coils alternatively polarized (Figure 7).

If now we suppress one set of coils with the same polarity, we still obtain an octupole but with half the amplitude by the field superposition principle. We can remove the horizontal and vertical coil pairs to create an opened octupole close to the magnet axis. Because the geometrical symmetry of the quadrupole is compatible with this specific octupole coils geometry, it is possible to insert these coils inside the quadrupole coils and above the anti-dodecapole coils (Figure 8). The octupolar field is then enhanced with lower current density and the peak field remains acceptable (Table 3).

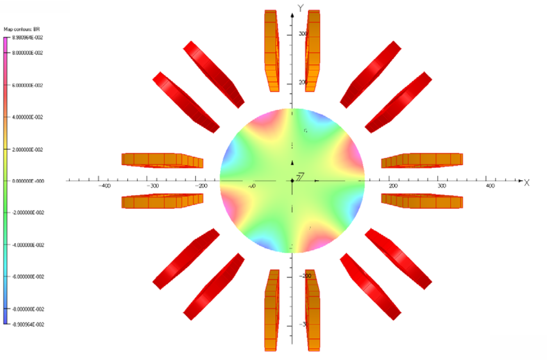

Figure 7: "Radial coil" octupole configuration. The red coils are turned on, the orange are turned off.

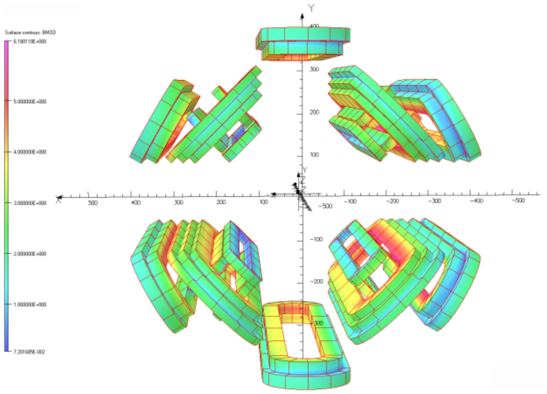

Figure 8: MOSAR with "Radial coil" octupole.

Table 3: "Radial coil" octupole design characteristics.

| Coil type | Size (mm) | J (A/mm²) | Gradient | Peak Field (T) |
|---|---|---|---|---|
| Quadrupole | 44x19/32x11 | 225/170 | 6 T/m | 6.2 |
| Sextupole | 40 x 28 | 190 | 11 T/m$^2$ | 6.2 |
| Octupole | 35 x 20 | 120 | 25 T/m$^3$ | 4.2 |

## CONCLUSION

We have studied different magnetic designs to realize an open superconducting multipole for $S^3$ able to include quadrupolar, sextupolar and octupolar components. The use of flat racetrack coils will give easier winding. As the coils arrangement depends strongly on the free vertical gap size, the magnet final design will be determined by the cryogenic and mechanical space constraints and needs. These studies are still ongoing.

## REFERENCES

[1] A. Drouart *et al.*, Nucl. Phys. A 834 (2010) 747c.
[2] Opera-3d: http://www.vectorfields.com.
[3] M. Barthes, A. Dael, J.P. Pénicaud, M. Tkatchenko, Proceedings of the 9th International Conference on Magnet Technology, Zürich, 1985.