A method for minimizing the magnetic cross-talk in twin-aperture $\cos\theta$ superconducting dipoles

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Introduction

In this poster, we present a new method to minimize the magnetic cross-talk in twin-aperture $\cos\theta$-type dipoles. In single-aperture $\cos\theta$ layout, the coil design can be performed with an analytic approach based on a sectors dipole. The great advantage of this method is a rapid evaluation of the field harmonics, which permits an almost exhaustive scan on positions and dimensions of the sectors for coil layouts with different number of sectors. In twin-aperture arrangement as the 16 T bending dipole of the Future Circular Collider (FCC), the magnetic cross-talk between the two coils isn't negligible and requires an extension of the single-aperture sectors model. The analytical scan has permitted to find alternative coil designs for the FCC bending dipole.

Extended sectors model

Twin-aperture magnets have to accommodate two closed apertures surrounded by coils inside a common iron yoke. In the FCC-hh $\cos\theta$ layout, the two coils are mirrored and their cross-section is left-right asymmetric to minimize the magnetic cross-talk. Introducing the sectors model, we can write the normal multipoles of each right coil sector as

$$\begin{aligned} B_n^r(\phi,\psi,m) = {} & \frac{\mu_0 J R_{ref}^{n-1}}{2\pi n(n-2)}\left(\frac{1}{(R+w)^{n-2}} - \frac{1}{R^{n-2}}\right) \\ & \times \left[\sin n(\phi + m\,d\phi) - \sin n\phi - (-1)^n\left(\sin n(\psi + m\,d\phi) - \sin n\psi\right)\right] \quad n \neq 2 \end{aligned} \tag{1}$$

and

$$\begin{aligned} B_2^r(\phi,\psi,m) = {} & \frac{\mu_0 J R_{ref}}{2\pi}\ln\frac{R}{R+w} \\ & \times \left[\sin 2(\phi + m\,d\phi) - \sin 2\phi - \sin 2(\psi + m\,d\phi) + \sin 2\psi\right], \end{aligned} \tag{2}$$

where ϕ and $\phi + m\,d\phi$ are the beginning and final angles respectively of each sector on the right side, ψ and $\psi + m\,d\phi$ are the beginning and final angles respectively of each sector on the left side, m is the turns number of each sector and $d\phi$ is the "quantum" of angle occupied by each turn.

The left coil is described approximating each conductor by a single current line flowing in the center of the turn itself. So, the normal multipoles of each left coil sector, produced in the right coil aperture, follow from the formula of the current line harmonics, summed on the sector turns number:

$$B_n^l(\rho_1,\theta_1,\ldots,\rho_m,\theta_m) = -\frac{\mu_0 I R_{ref}^{n-1}}{2\pi}\sum_{i=1}^{m}\frac{\cos n(\pi-\theta_i)}{(\rho_i)^n}, \tag{3}$$

where the coordinates ρ_i and θ_i of each current line are linked to the angles (ϕ,ψ) of the corresponding right coil sector, by trigonometric formulas.

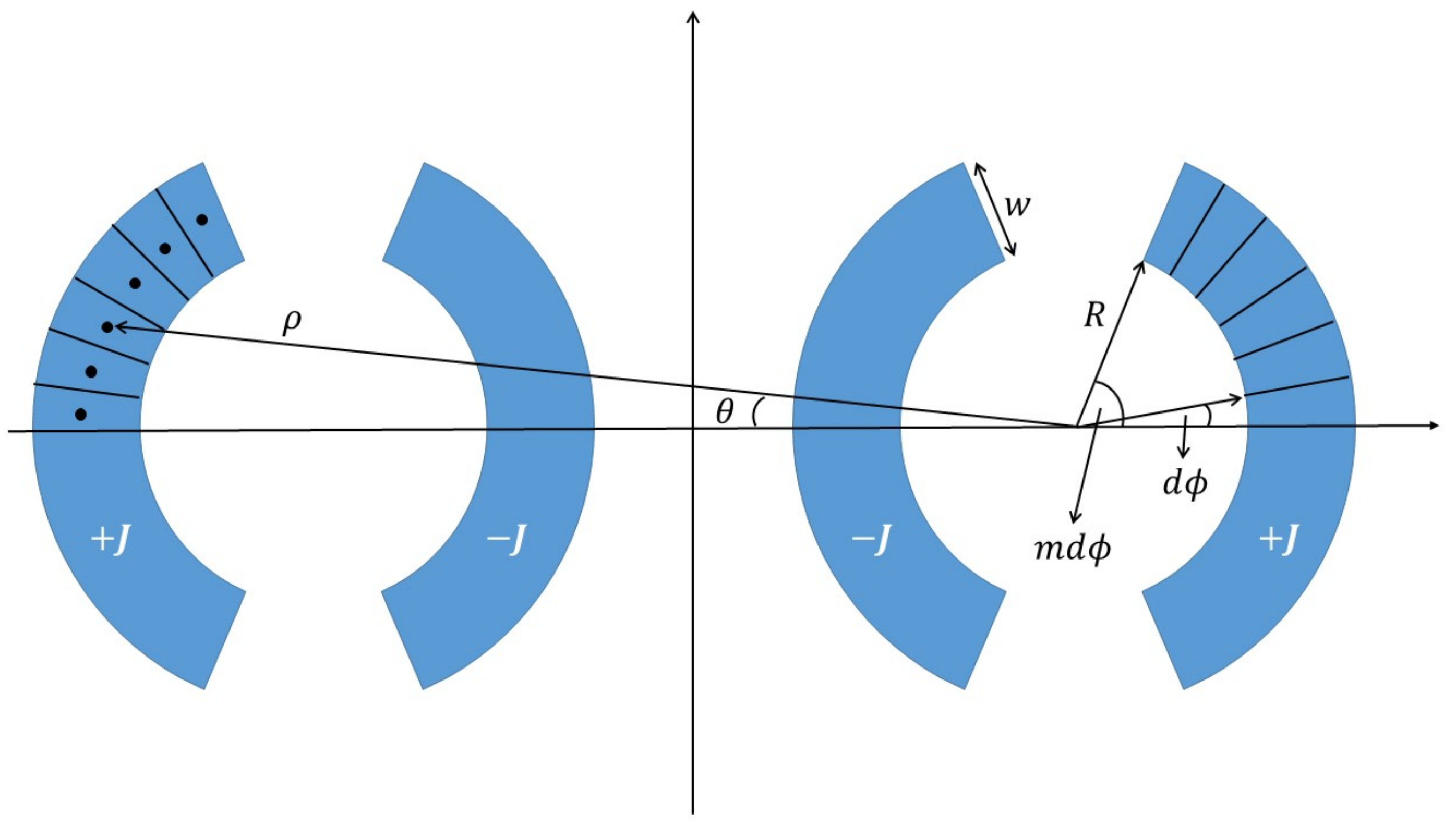

Figure 1: Sketch of twin-aperture dipole.

The normalized normal harmonics, produced in the right coil aperture by the two coils, are

$$b_n(\phi_1,\psi_1,m_1,\ldots,\phi_N,\psi_N,m_N) = 10^4\,\frac{\sum_{p=1}^{N}\left[B_{n,p}^r(\phi_1,\psi_1,m_1,\ldots,\phi_N,\psi_N,m_N) + B_{n,p}^l(\phi_1,\psi_1,m_1,\ldots,\phi_N,\psi_N,m_N)\right]}{\sum_{p=1}^{N}\left[B_{1,p}^r(\phi_1,\psi_1,m_1,\ldots,\phi_N,\psi_N,m_N) + B_{1,p}^l(\phi_1,\psi_1,m_1,\ldots,\phi_N,\psi_N,m_N)\right]}, \tag{4}$$

where N is the sectors number. Eq. (4) is minimized by an iterative method: first, we generate a random left coil configuration $(\phi_1,\psi_1,m_1,\ldots,\phi_N,\psi_N,m_N)$ and compute the contributions $B_{n,p}^l(\phi_1,\psi_1,m_1,\ldots,\phi_N,\psi_N,m_N)$; then, we find a right coil configuration $\left(\phi_1',\psi_1',m_1',\ldots,\phi_N',\psi_N',m_N'\right)$ for whom the multipoles $B_{n,p}^r\left(\phi_1',\psi_1',m_1',\ldots,\phi_N',\psi_N',m_N'\right)$ delete the contributions $B_{n,p}^l(\phi_1,\psi_1,m_1,\ldots,\phi_N,\psi_N,m_N)$. After, we update the left coil contributions $B_{n,p}^l\left(\phi_1',\psi_1',m_1',\ldots,\phi_N',\psi_N',m_N'\right)$ and we find a second right coil configuration $\left(\phi_1'',\psi_1'',m_1'',\ldots,\phi_N'',\psi_N'',m_N''\right)$ for whom the harmonics $B_{n,p}^r\left(\phi_1'',\psi_1'',m_1'',\ldots,\phi_N'',\psi_N'',m_N''\right)$ delete the contributions $B_{n,p}^l\left(\phi_1',\psi_1',m_1',\ldots,\phi_N',\psi_N',m_N'\right)$. We repeat these steps until the configuration doesn't change anymore.

Electromagnetic design

The analytical scan has found more than 30 possible solutions. We show one of the best design, which is very similar to that presented in the Conceptual Design Report (CDR).

Table 1: Design parameters

Bore inner diameter	50 mm
Beam distance	250 mm
Iron yoke outer radius	330 mm
Material	Nb_3Sn
Bore nominal field	16 T
Operating temperature	1.9 K
Operation on load-line (HF/LF)	86/84.7 %
Operating current	11410 A
Field harmonics (geo/sat)	$\leq 3/10$ units

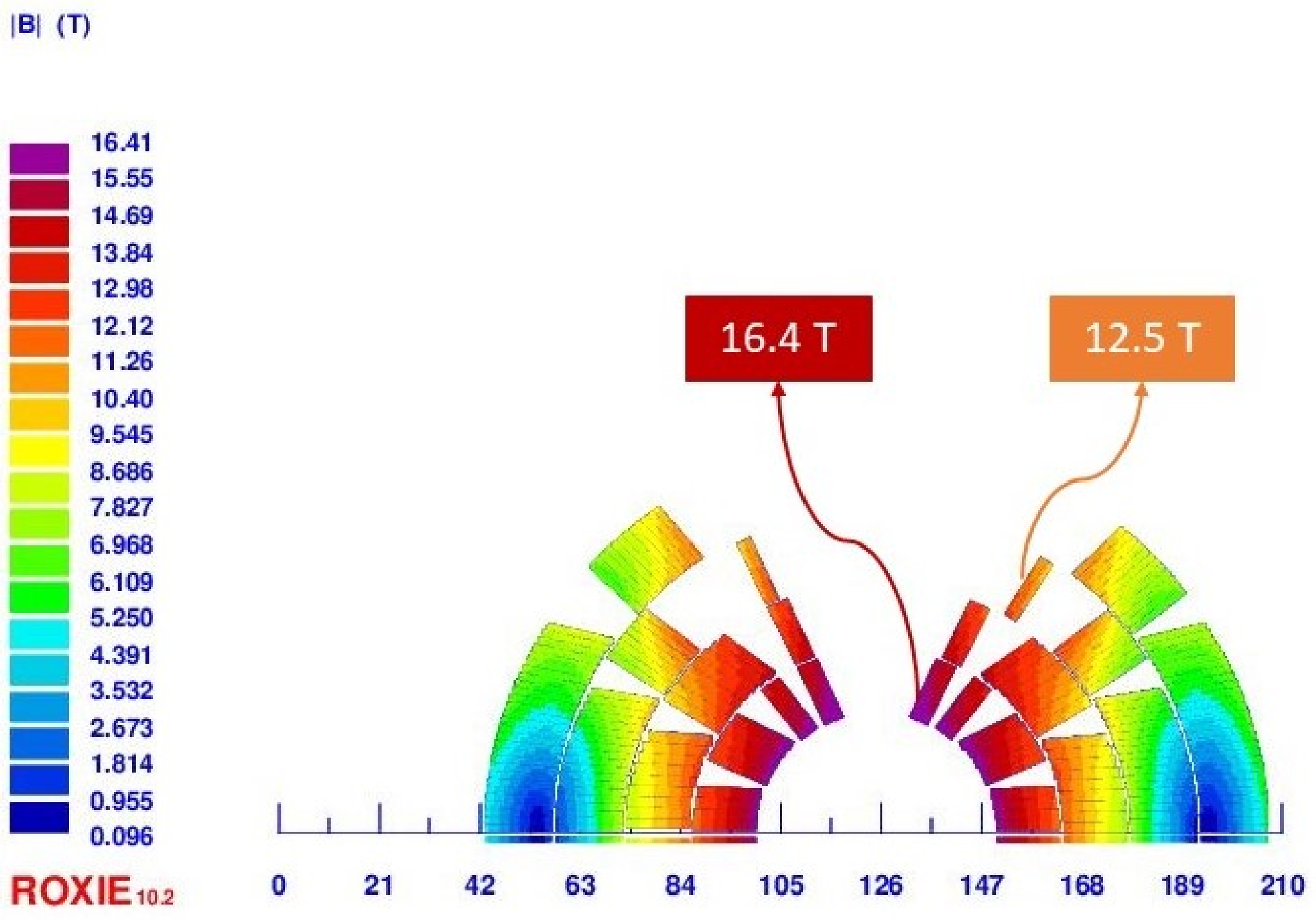

Figure 2: Coil design and magnetic field in the xy-plane.

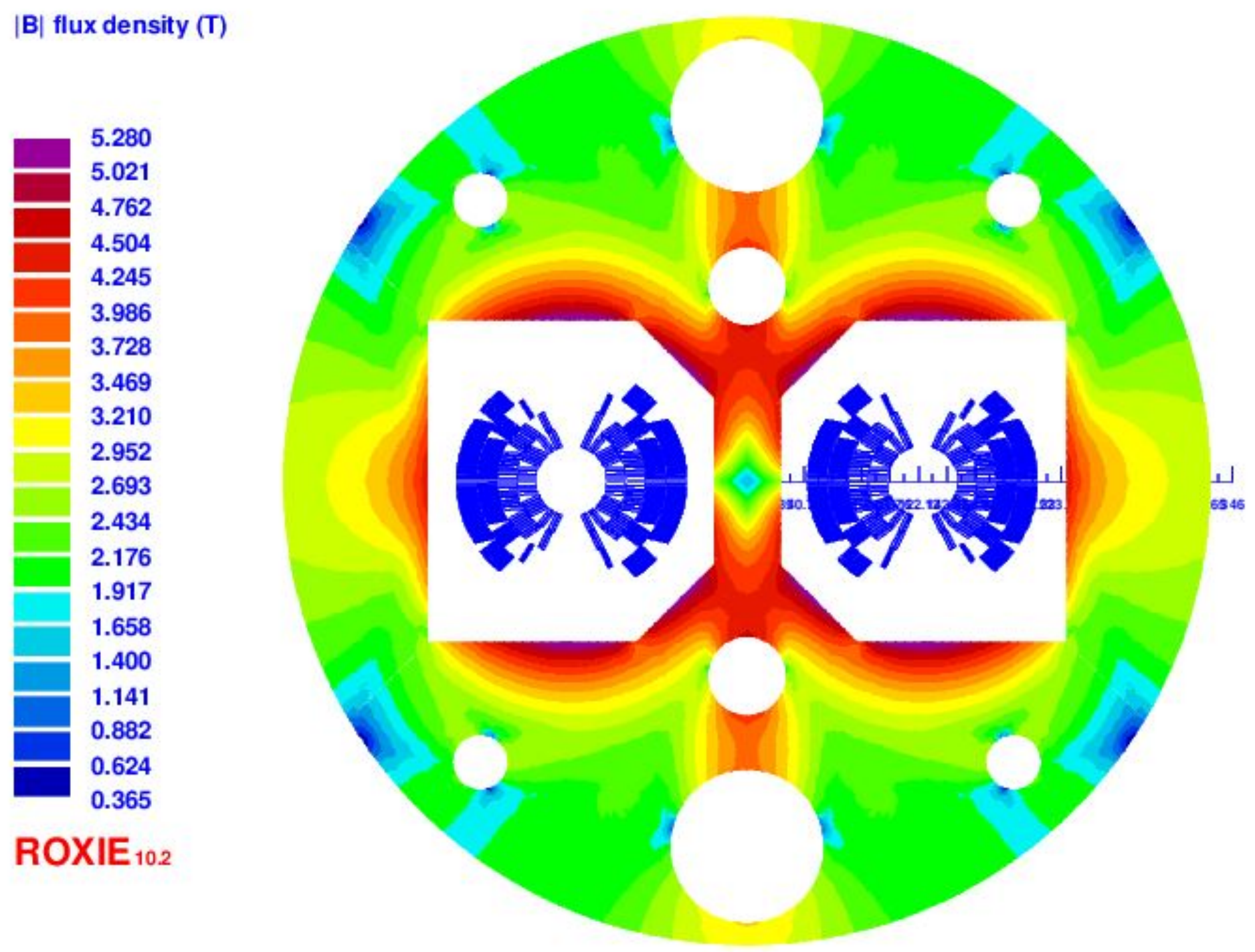

Figure 3: Magnetic field in the iron yoke sorrounding the coils.

Table 2: Normalized normal harmonics at operating current.

b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	b_{11}	b_{12}	b_{13}	b_{14}	b_{15}	b_{16}	b_{17}
0	0	0	0	-0.02	0.5	0.02	-0.25	0.02	1.13	0	-0.25	0	-0.05	0	-0.05

References

[1] A. M. Ricci, P. Fabbricatore and S. Farinon, *Magnetic design of twin-aperture $\cos\theta$ superconducting dipoles with a semi-analytic approach*, ArXiv:1902.02203.