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Influence of 3D effects on field quality in the straight part of accelerator magnets for the High Luminosity Large Hadron Collider

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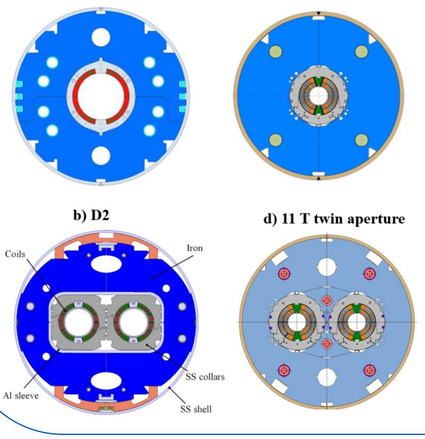
Abstract

Magnetic measurements in the short model of the D1 beam separation dipole developed at KEK showed a large difference (tens of units) between the sextupole (b_3) harmonic in the straight part and the 2D calculation. This difference is correctly modelled only by a 3D analysis: 3D calculation performed with OPERA-3D and ROXIE show that the magnetic field quality in the straight part is influenced by the coil ends, even for the 6.7 m long magnets. The effect is even more remarkable in the short model.

We investigate similar 3D-effects for other dipoles: the 11 T dipole for the HL-LHC for which the effect is clearly visible for the single aperture model. On the other hand in the double aperture configuration with field in opposite direction the effect is negligible. We also consider the case of the 4.5 T recombination magnets for HL-LHC (D2), where the larger space between coil and iron makes this effect less important, but still visible.

Overview of dipole magnets studied in this work

Cross section layouts of the (a) D1 separation dipole, (b) D2 recombination dipole, and the 11 T dipole in single (c) and double (d) aperture:



Main magnet parameters:

	11T 1in1	11T 2in1	D1	D2
Bore field at I_{nom} (T)	11.2	11.2	5.6	4.5
Nr. of apertures	1	2	1	2
Beam separation (mm)	-	194	-	188
Aperture radius (mm)	30	30	75	53
Coil width (mm)	31	31	15	15
Spacer coil to yoke (mm)	31	31	21	36
Yoke inner radius (mm)	92	-	111	-
Yoke outer radius (mm)	255	275	275	307
Short model length (m)	2.0	2.0	2.2	1.6
Full magnetic length (m)	5.6	5.6	6.7	7.8

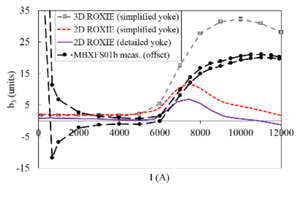
Conclusions

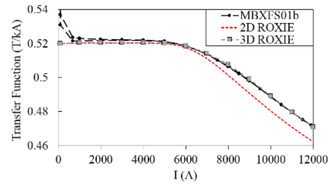
The influence of coil end effects on field quality in the straight part of the D1, D2 and 11 T dipoles is studied. Significant difference between 2D and 3D models are found on the single aperture short models for transfer function and sextupole component.

- For the **D1 dipole** tens of additional units of b_3 were measured in the magnet center of the 2 m model. This result is reproduced by ROXIE and OPERA-3D models.
- In single aperture **11 T dipole** a weaker, but still visible effect is found. In double aperture the effect is negligible.
- Parametric study shows that the layout of single aperture dipoles can be optimized in order to minimize the influence of magnet ends on the magnetic field in the straight section. Critical parameters include the magnet length, the distance between coil and yoke and the area of the yoke cross section.

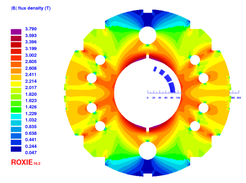
The D1 separation dipole

- 3D effects add 180 units on transfer function and 26 on b_3 in the center of the magnet .





ROXIE @ I_{nom} units at R_{ref}=50 mm	2D		3D		Diff 2D→ 3D	
	b_3	b_5	b_3	b_5	Δ b_3	Δ b_5
Coil only	-32.2	8.6	-32.4	8.4	-0.3	-0.2
Simplified yoke	1.8	-2.4	28.1	-0.1	26.4	2.3
Full yoke geometry	-1.3	-2.0	--	--	--	--

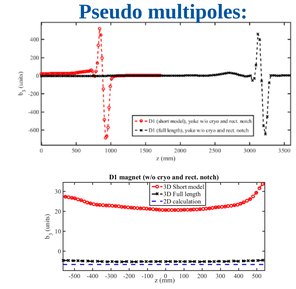


- Full length magnet: Effect smaller but visible.
- Pseudo multipoles are enhanced in the magnet center.
- Integrated values are within tolerances due to compensation from magnet ends.

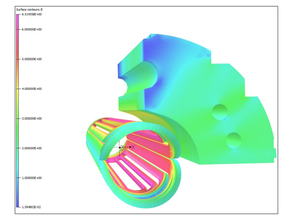
Integrated multipoles:

	Straight part		Ends				Integral	
			Connection side		Non-connection side			
	Short model	Full length	Short model	Full length	Short model	Full length	Short model	Full length
L_m (m)	0.1	4.7	0.8	0.8	0.8	0.8	**1.7**	**6.3**
b_3	27.2	3.1	0.6	-20.0	-4.9	-26.6	**-0.1**	**-3.7**
b_5	-0.2	-2.4	0.3	-1.9	-3.3	-5.5	**-1.4**	**-2.7**
b_7	0.2	0.3	-1.5	-1.3	-3.3	-3.2	**-2.2**	**-0.4**
a_1	0.3	0.1	-34.8	-30.4	0.2	0.0	**-16.2**	**-4.0**
a_3	0.1	0.0	12.5	11.8	0.0	0.0	**5.9**	**1.6**

Pseudo multipoles:



Benchmark of results with OPERA-3D model:

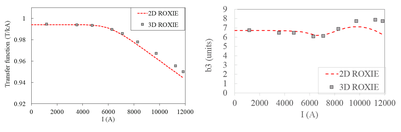


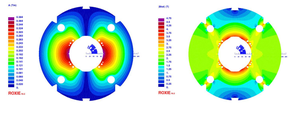
units at Rref=50 mm @ I_{nom}	2D		3D		Diff. 2D → 3D	
	B_1 (T)	b_3 (units)	B_1 (T)	b_3 (units)	ΔB_1	Δ b_3
OPERA	5.556	-5.9	5.683	24.5	0.13	30.4
ROXIE	5.567	-6.8	5.675	21.3	0.11	28.1
diff. models	-0.01	0.8	0.01	3.2	--	--

The 11T short model dipole

Single aperture

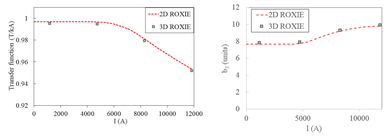
- Transfer function: +60 units.
- b_3: +2 units.

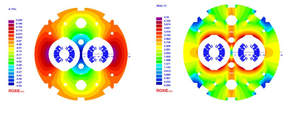




Double aperture

Iron saturation well captured by 2D model.

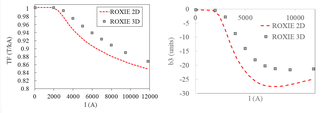


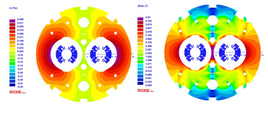


Exercise! ***Inverse the current direction in one aperture of 11 T.***

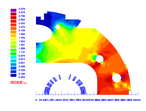
3D effects kick in at around 4 kA. At 12 kA:

- ΔB_1 = 200 units.
- Δb_3 = 3.5 units.



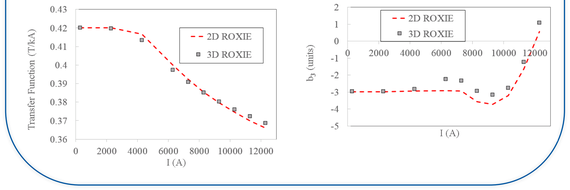


The D2 separation dipole

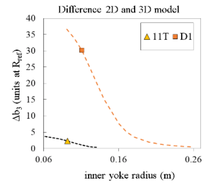


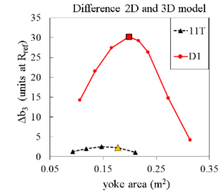
For the short model at I_{nom} 12.3 kA and R_{ref} = 35 mm

- ΔB_1 = 70 units.
- Δb_3 < 1 unit.



Parametric dependencies of yoke layout





The 3D effects are strongly dependent on:

1. The distance between the coil and yoke,
2. The coil aperture,
3. The area of the yoke cross section.

The small space between inner yoke radius and coil is the main reason for the strong 3D effects in D1.