PIP-II Beam Transfer Line Large Bore Quadrupoles

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There needed 2 large bore quadrupoles with the effective length of 0.4 m, integrated gradient 2 T, the magnet aperture 80 mm, good field region 150mm x 10mm with the field non-linearity in the good field region 0.1%. There were investigated number of variants including indirect and direct water cooling. After discussions was chosen the magnet with direct water cooling which parameters presented in Table 1. Two large bore Transport Line quadrupoles will be connected in series and powered by a single power supply.

Table 1

Parameter	**Units**	**2 Large Bore Quadrupoles**
Pole tip radius	mm	80
Integrated gradient	T	2
Effective length	mm	400
Center field gradient	T/m	5.0
Pole tip field	T	0.2
Coil ampere-turns/pole	A	3200
Coil peak current	A	114
Coil copper conductor	mm	8x8, dia. 5
Coil number of turns		28
Yoke length	mm	400
Winding resistance	Ohm	0.069
Magnet voltage	V	8.2
Magnet power	W	940
Number cooling circuits		1
Cooling hole diameter	mm	5
Water pressure drop	MPa	0.5
Water temperature rise	C	11.9
Number magnets in string (max)		2
Voltage for the string	V	16.4
Total string power	kW	1.88

Results of preliminary 3D magnetic field analysis shown in Fig. 1 – Fig. 2. Fig. 1 shows that the iron yoke is not saturated. Fig. 2 shows longitudinal field distribution at the reference radius of 12 mm for 0, 30 deg., 45 deg. angles.

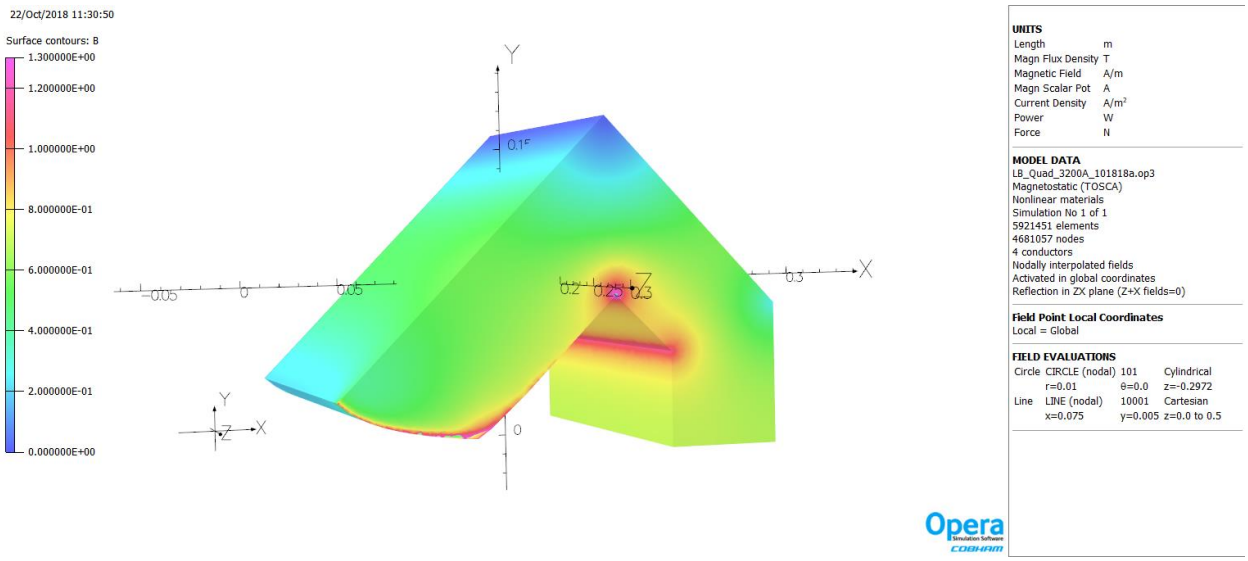

Fig. 1. Flux density in the magnet iron yoke is less than 1.3 T.

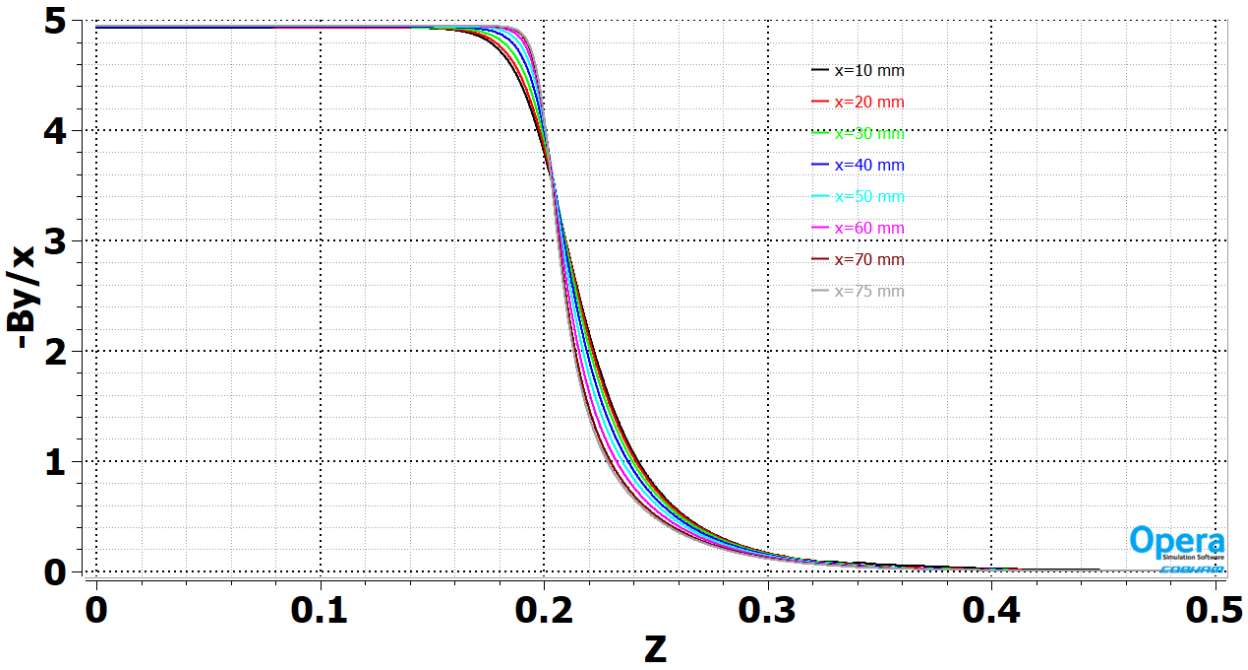

Fig. 2. Field gradients in the magnet mid-plane along Z-axis.

The integrated field non-linearity for this variant (See Fig. 3) is more than the specified 0.1 % value for the good field area 150 mm x 10 mm. Preliminary pole optimization was made to reduce the pole end effects on the field quality.

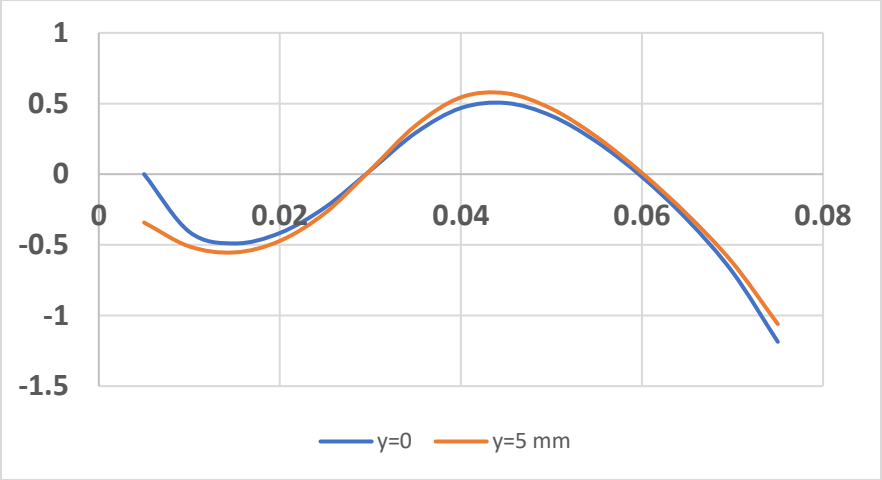

Fig. 3. Integrated gradient homogeneity in % for the area 75 mm x 5 mm in 1/8 of model geometry. X – meters.

Fig. 4 shows the preliminary magnet cross-section.

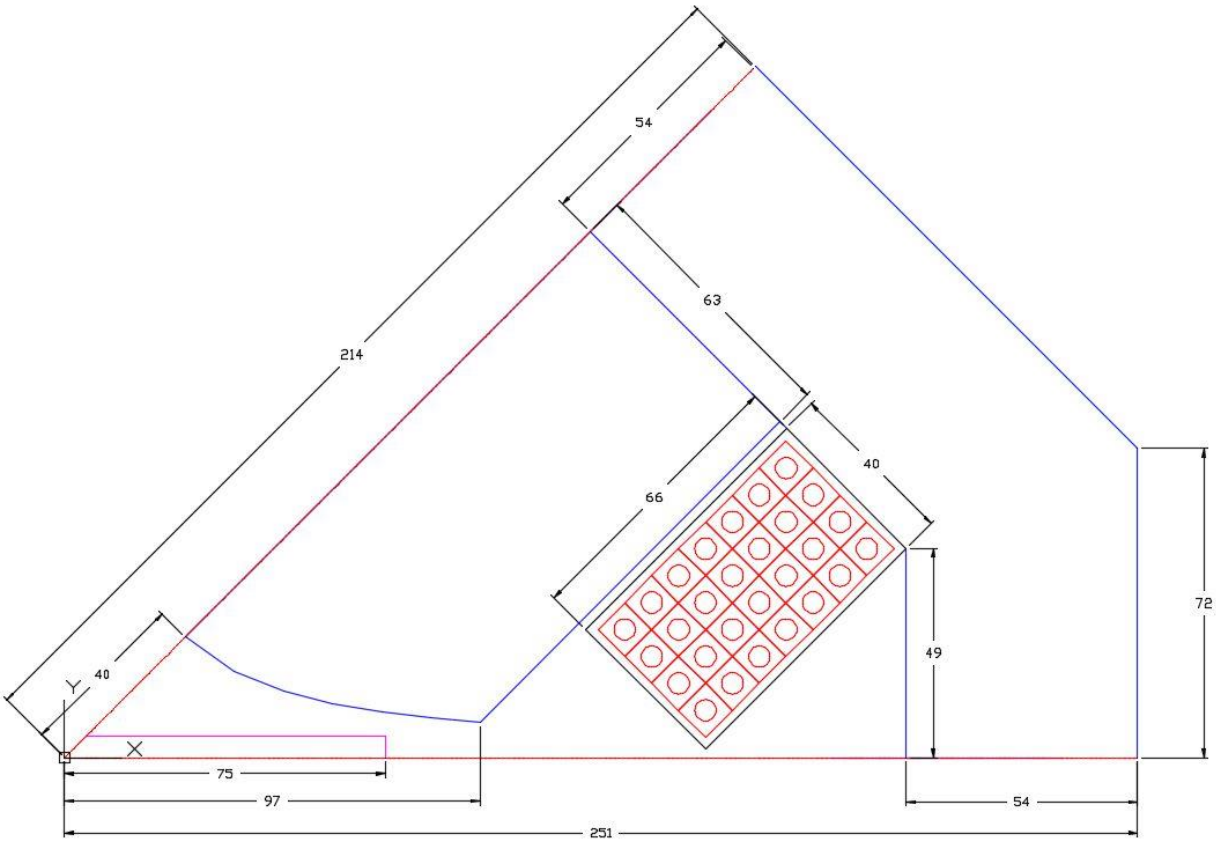

Fig. 3. Quadrupole with the direct water cooling.

The pole profile has hyperbolic form with the analytic formula for X, Y coordinates:

$$X \cdot Y = \boldsymbol{a}^2/2,$$

Where **a** – is a pole tip radius of 40 mm.

Pole tip coordinates shown in Table 2.

Table 2

x, mm	y, mm
28.284	28.284
34.026	23.512
39.767	20.117
45.509	17.579
51.250	15.610
56.992	14.037
62.733	12.752
68.474	11.683
74.216	10.779
79.957	10.005
85.699	9.335
91.440	8.749
97.182	8.232

Summary

For Large Bore Quadrupoles considered water cooled magnets generating 2T of integrated field gradients. The 2D magnet field analysis showed that the field meet specified less than 0.1 % field non-linearity. But 3D field analysis showed increased up to 1 % value. More effort needed to optimize the pole profile configuration.

This note is only for the preliminary mechanical design. Further geometry optimization might be needed. The field quality is very sensitive to the pole end chamfers. For that reason only small chamfers could be used to reduce the coil length. It is supposed that coils wound without inner splices by continuous hollow copper conductor. The conductor dimensions parameters taken from LUVATA table of standard conductors for which they have dies.