PXIE MEBT Triplets, Doublets, and Dipole Correctors

Vladimir Kashikhin, FNAL, December 12, 2012

The MEBT quadrupoles and dipole correctors should be designed for FNAL PXIE project. The short available slot length and specified high integrated fields drive the design to the short magnets with relatively high power losses. Below investigated the variant with quadrupoles and dipole correctors wound from the solid copper conductor. These air cooled magnets will be simpler for fabrication but constrained by the maximum achievable heat removing. These magnets specifications provided by A. Shemyakin are shown in Table 1.

Table 1

Parameter	**Unit**	**F-Quad**	**D-Quad**	**V/H-Dipoles**
Quadrupole peak integrated gradient	T	1.5	0.85	
Dipole peak integrated field	T-m			0.0021
Pole tip radius (min)	mm	17		17
Yoke length	mm	100	50	
Separation between quad centers in triplets	mm	145	145	
Separation between quad centers in doublets	mm	170	170	
Dipole corrector space with quad coil end	mm			75
Diameter of good field area	mm	23	23	23
Integrated field homogeneity in the good field region	%	1.0	1.0	5.0
Radius of the space free of windings	mm	35	35	35

Because the slot length for magnet allocation is strongly limited there was used an integrated approach combining the magnetic design in the single package including: F and D quadrupoles , V and H dipole correctors.

Triplet Magnetic Design

The quadrupole Triplet consists of center F-Quadrupole and two D-Quadrupoles on both sides. Magnet centers separated with the distance 145 mm. Each quadrupole magnet has a conventional four pole type configuration. In the proposed design the magnet yoke splitted on four sections. Quadrupole coils mounted in each part of the yoke by sliding them along poles. The center F-Quadrupole has the 100 mm yoke length, and side D-Quadrupoles only 50 mm. The magnetic field was simulated by TOSCA code. The simulation results are shown in Fig. 1 - 6.

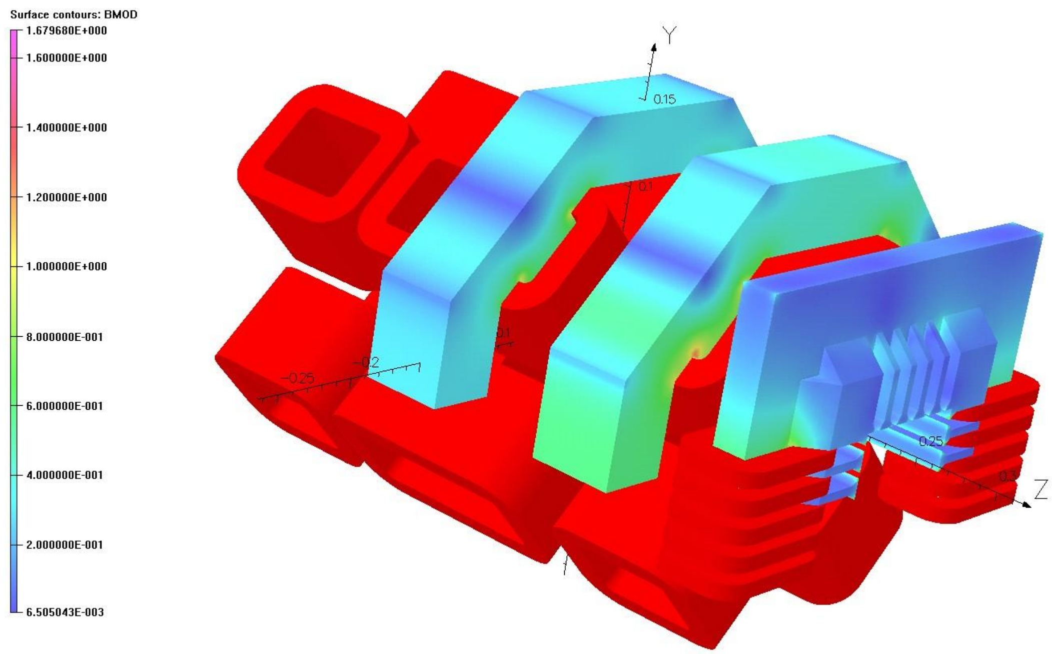

Fig. 1. Triplet model for the magnetic design. Bmax in the yoke is 1.68 T.

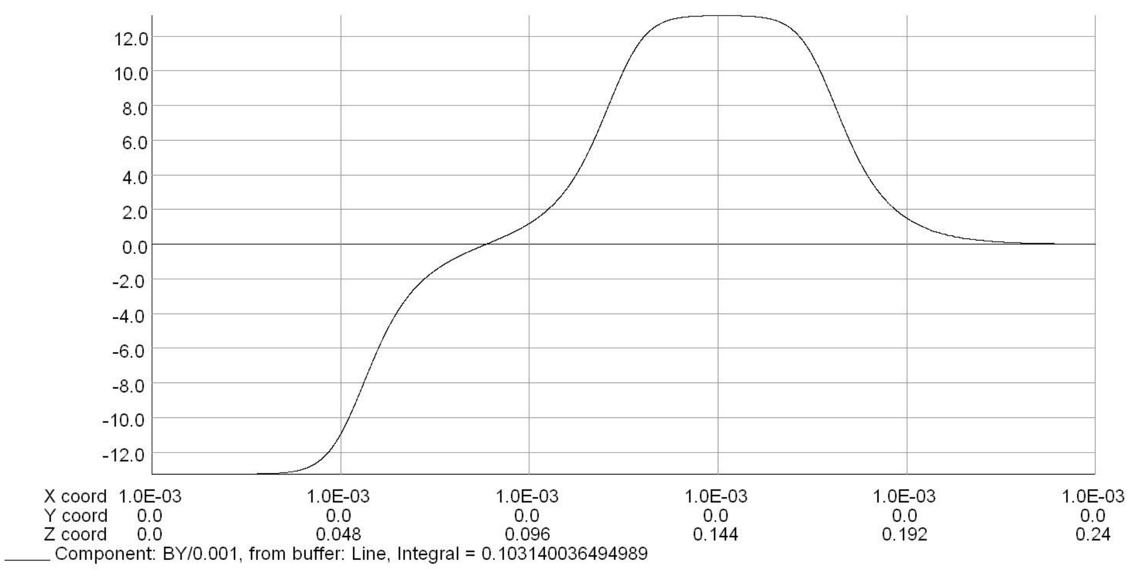

Fig. 2. Triplet field gradient distribution with the dipole corrector yoke.

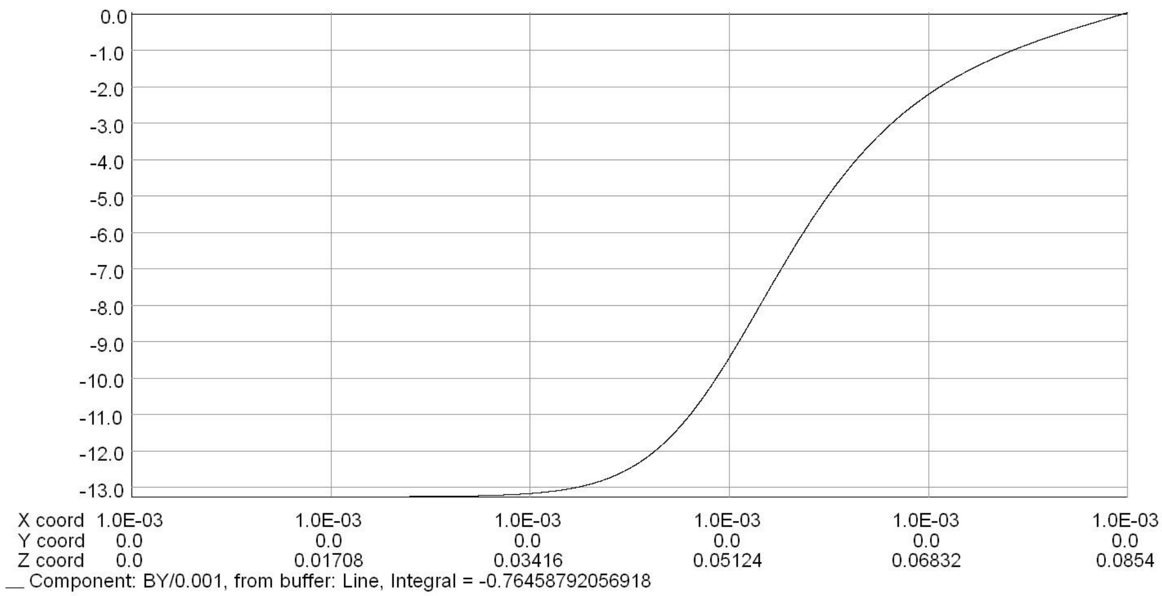

Fig. 3. F-Quadrupole field gradient distribution with the dipole corrector yoke. The integrated gradient is 1.53 T at 1500 A/coil.

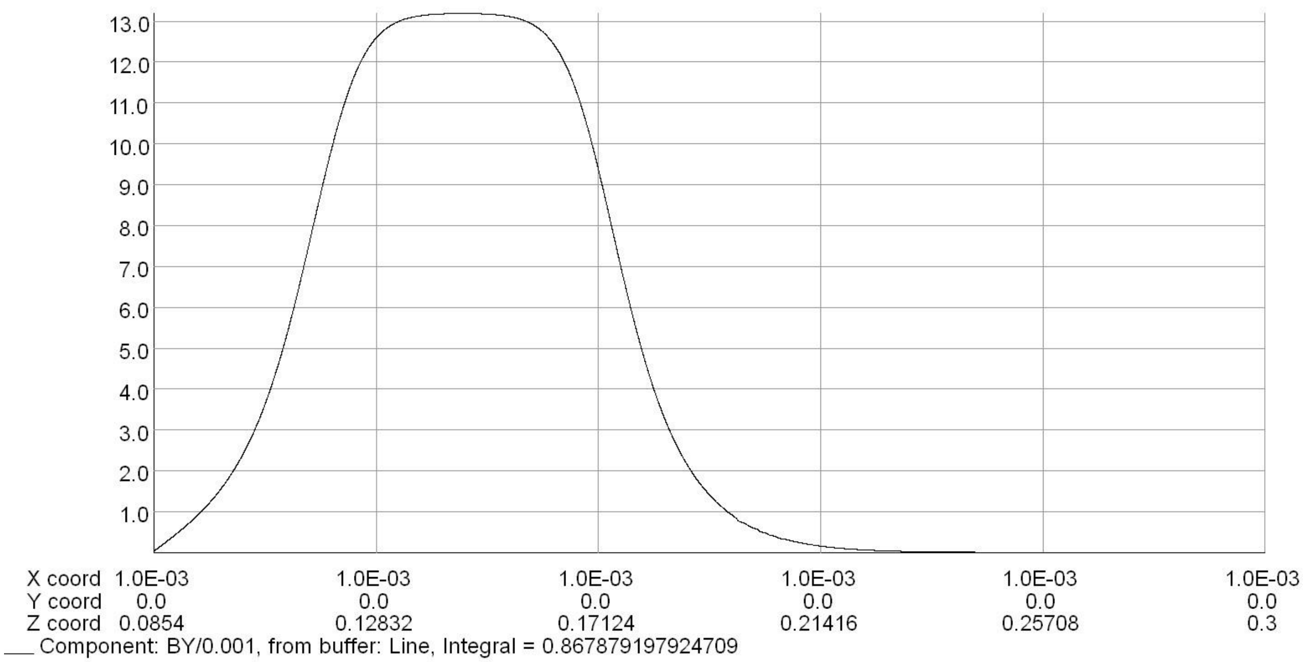

Fig. 4. D-Quadrupole field gradient distribution with the dipole corrector yoke. The integrated gradient is 0.87 T at 1500 A/coil.

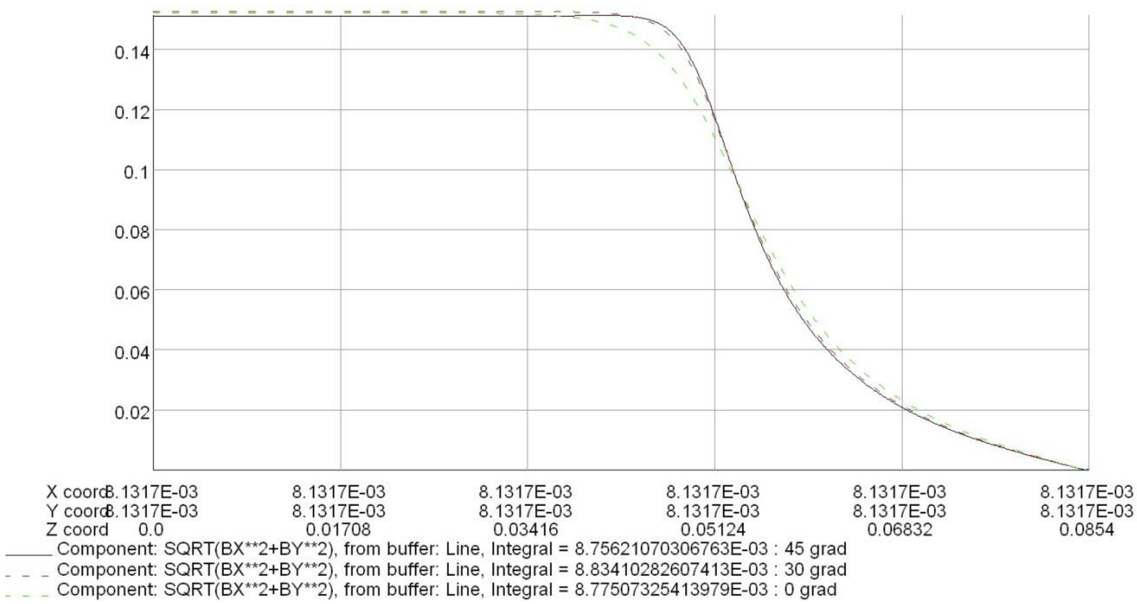

Fig. 5. F-Quad integrated field distribution at 23 mm diameter in Triplets with the dipole corrector yoke.

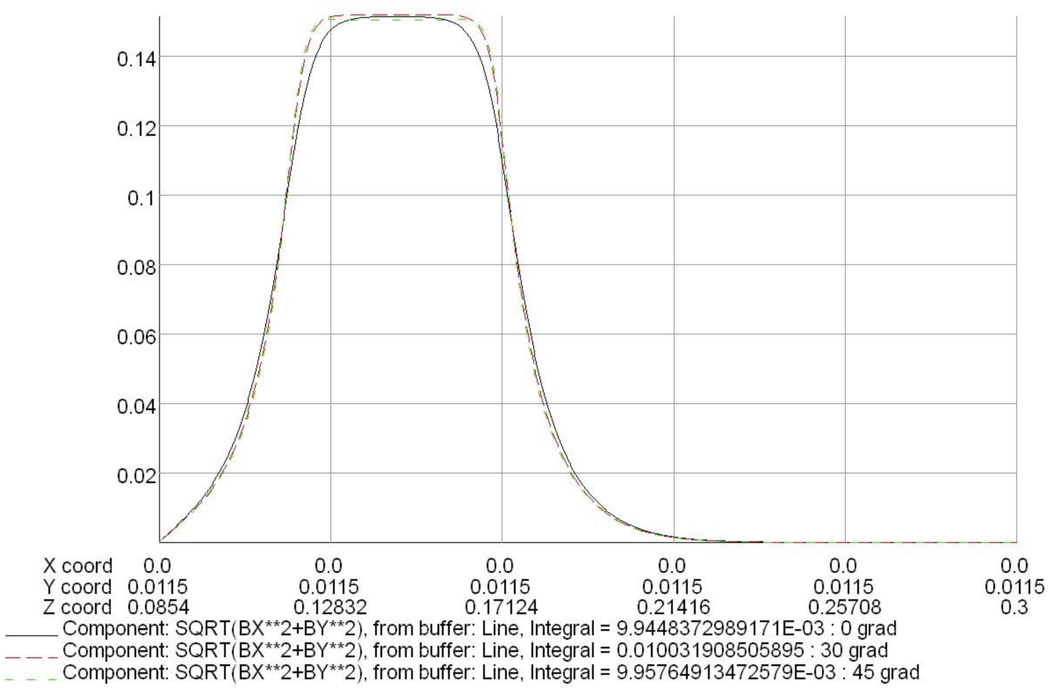

Fig. 6. D-Quad integrated field distribution in Triplets at 23 mm diameter with the dipole corrector yoke.

Table 2

Parameter	Unit	F-Quad	D-Quad
Quadrupole peak integrated gradient at 1500A/pole	T	1.53	0.87
Distance between pole tips	mm	34	34
Yoke length	mm	100	50
Yoke width	mm	300	300
Integrated field homogeneity at 23 mm diameter	%	0.7	0.9
Copper conductor dimensions #10	mm	2.59 (square)	2.59(square)
Copper area	mm^2	6.56	6.56
Number of turns/pole		150	150
Quadrupole peak current	A	10	10
Current density	A/mm^2	1.52	1.52
DC resistance /magnet	Ω	0.6	0.43
DC voltage	V	6.0	4.3
Power losses/magnet	W	60	43
Coil temperature rise (estimated) at the air cooling	°C	55	52

Quadrupole Doublet

The quadrupole Doublet consists of two quadrupoles identical to the F-Quadrupole in the triplet. The only difference that these magnet centers separated at 170 mm (See Table 1).

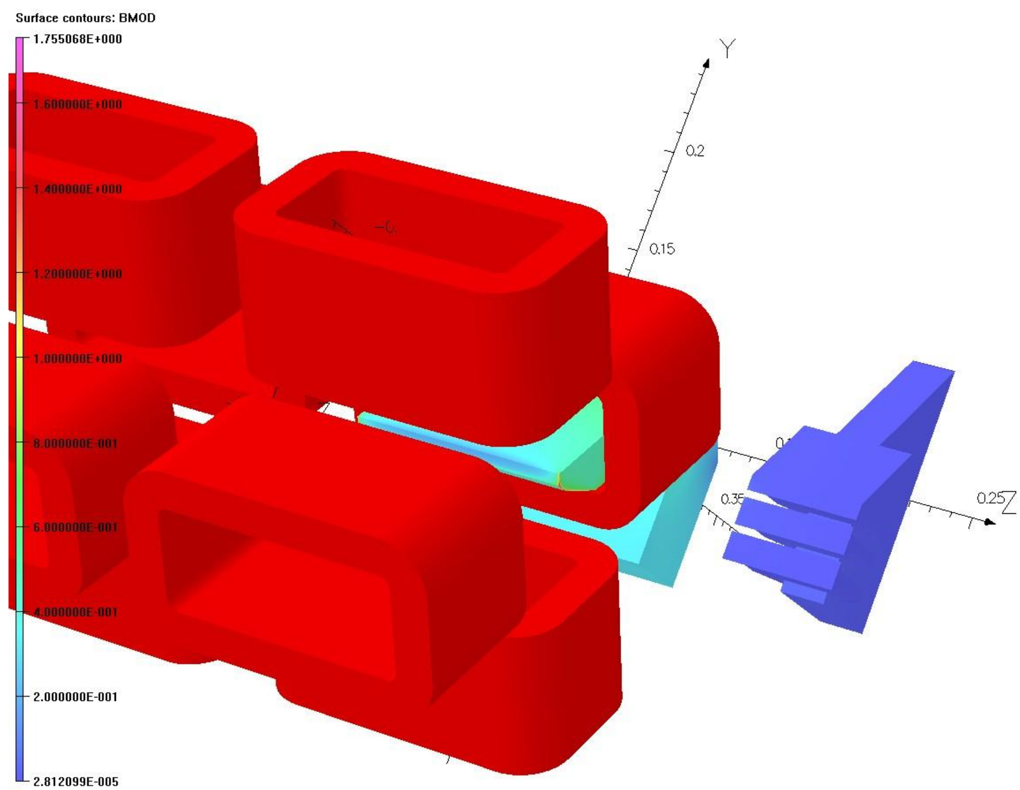

Fig. 7. Doublet model geometry with the corrector yoke.

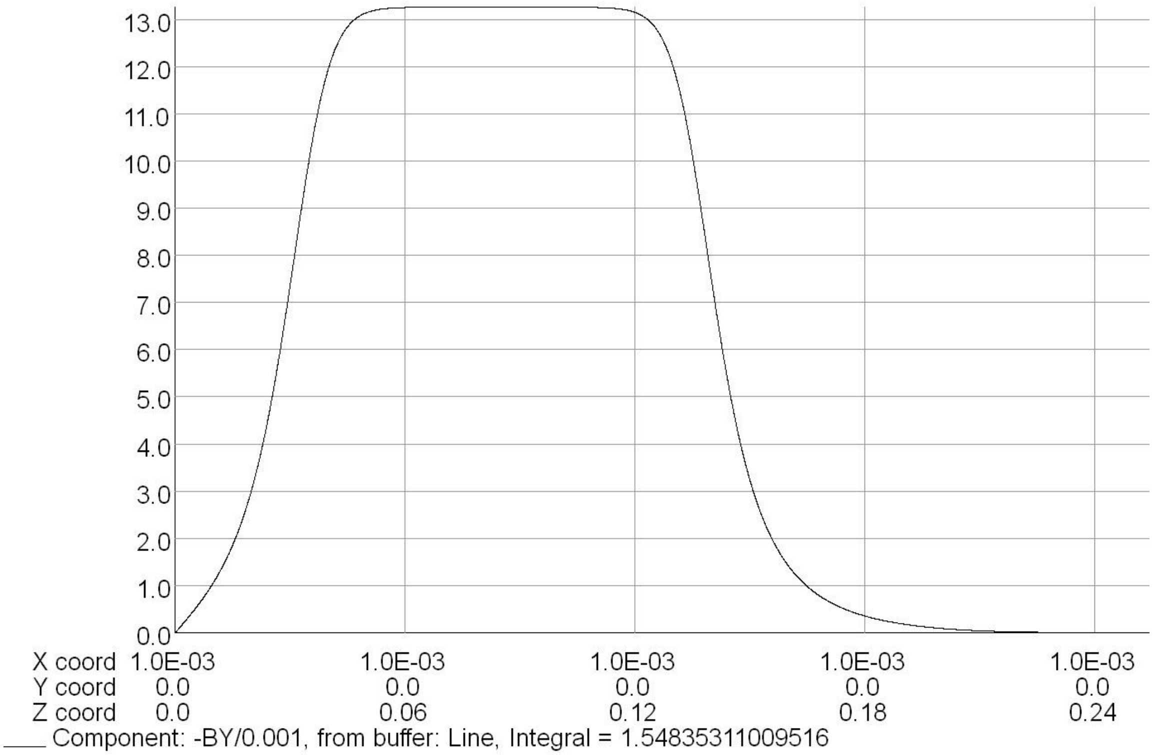

Fig. 8. Doublet field gradient along Z-axis. The integrated gradient is 1.55 T at 1500A/coil.

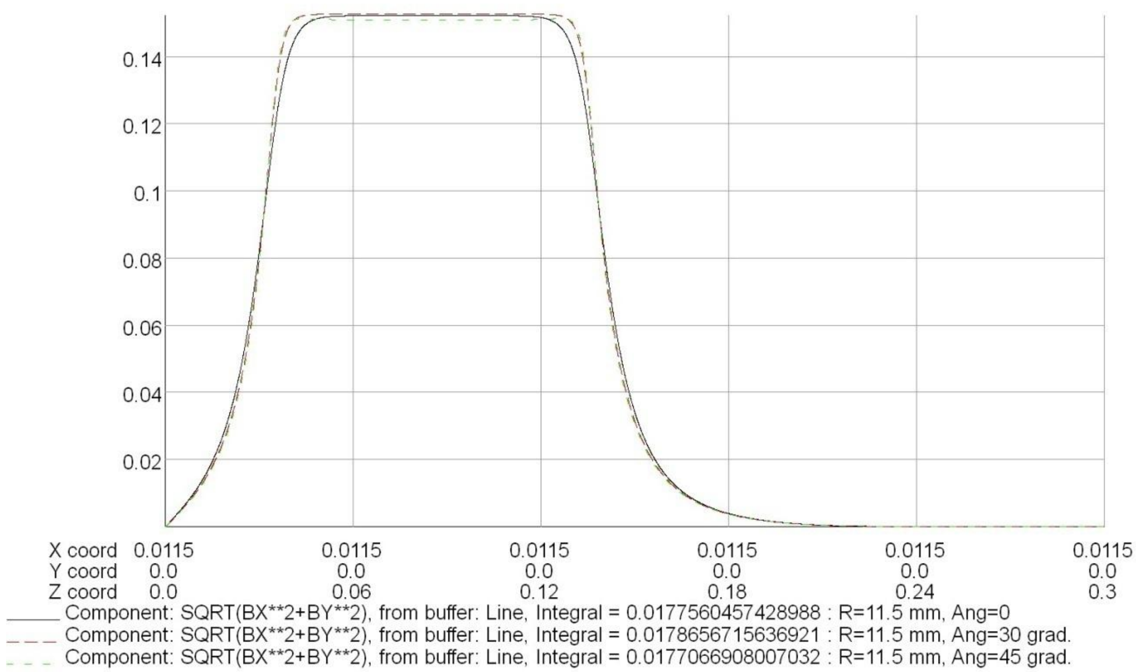

Fig. 9. Doublet transverse field distribution at 23 mm diameter. The integrated field homogeneity is 0.9 %.

Table 3

Parameter	Unit	F & D-Quads
Quadrupole peak integrated gradient at 1500A/pole	T	1.55
Distance between pole tips	mm	34
Yoke length	mm	100
Yoke width	mm	300
Integrated field homogeneity at 23 mm diameter	%	0.9
Copper conductor dimensions #10	mm	2.59 (square)
Copper area	mm^2	6.56
Number of turns/pole		150
Quadrupole peak current	A	10
Current density	A/mm^2	1.52
DC resistance /magnet	Ω	0.6
DC voltage	V	6.0
Power losses/magnet	W	60
Coil temperature rise (estimated) at the air cooling	°C	55

Dipole Corrector

Because the space for the dipole corrector is very limited: 75 mm along Z-axis including quadrupole coil end, it was chosen the combined vertical and horizontal dipole corrector configuration.

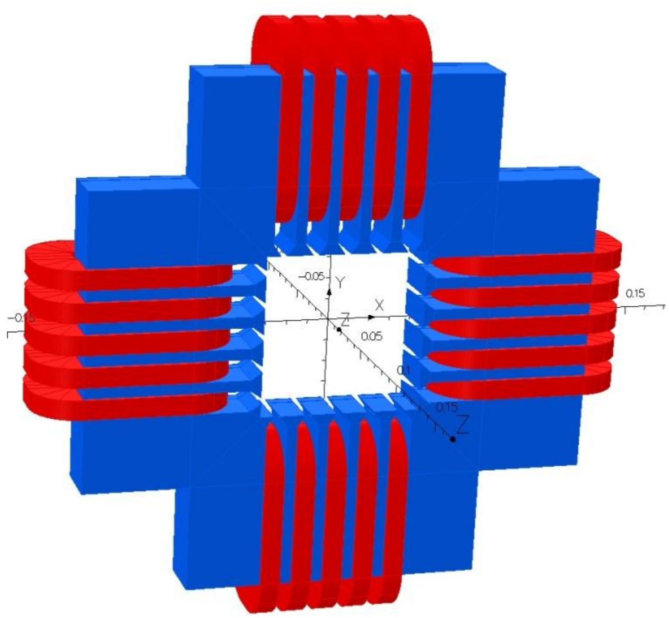

Fig. 10. Dipole correctors model geometry.

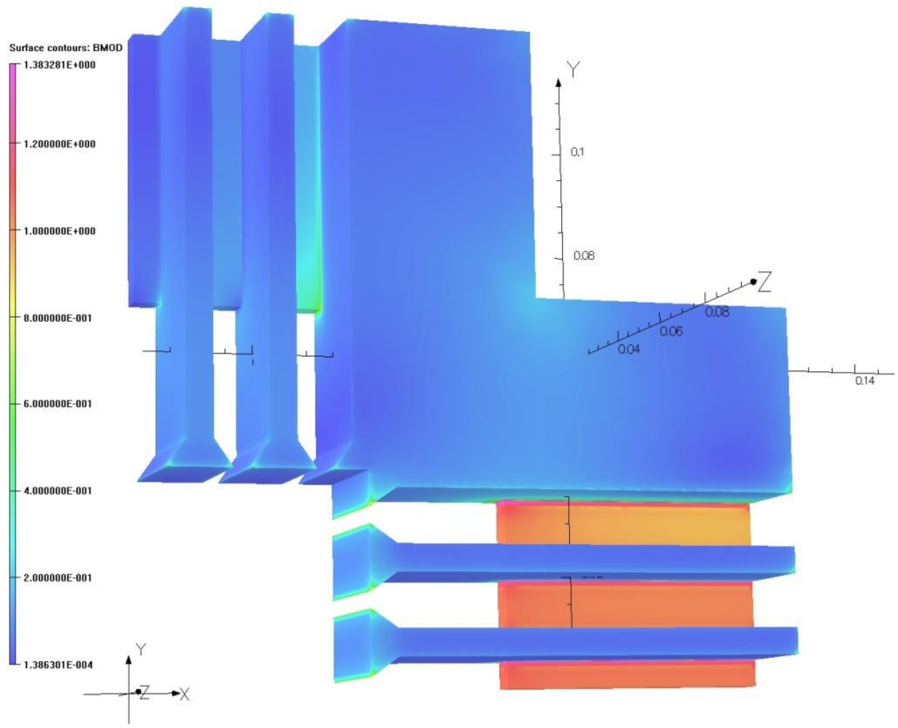

Fig. 11. Dipole correctors geometry and flux density in the iron yoke. Only vertical dipole coils are shown. Bmax=1.38 T.

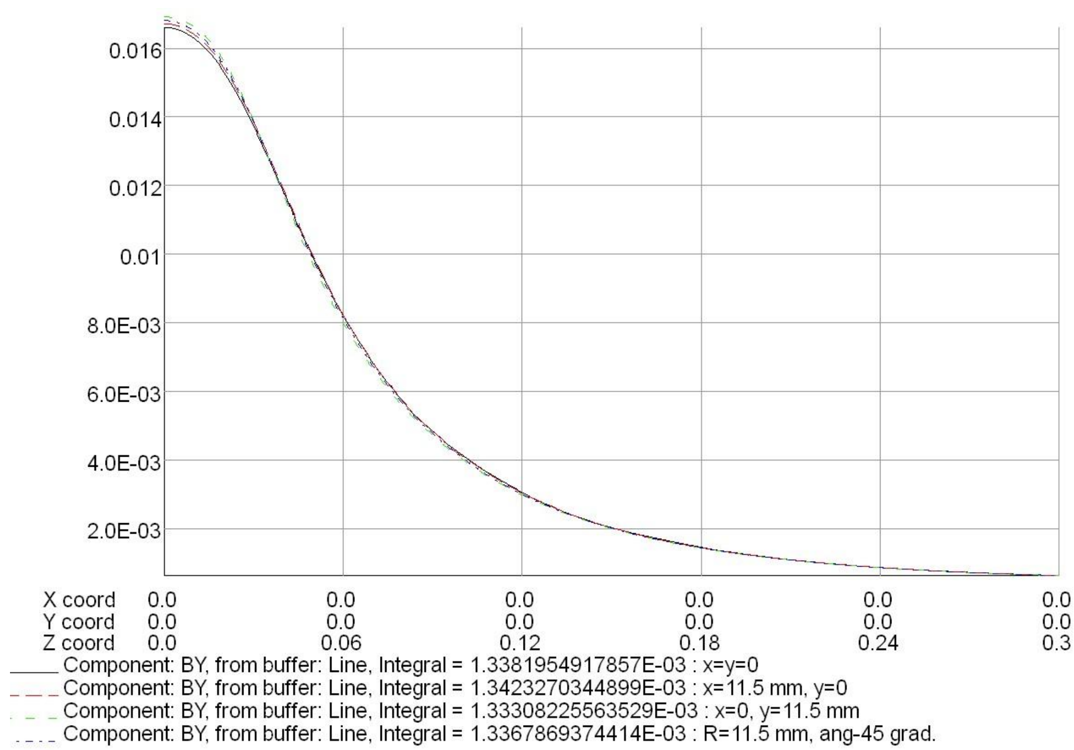

Fig. 12. Vertical dipole corrector field along Z-axis.

As shown in Fig. 12 the integrated field homogeneity for the dipole corrector at the reference radius 11.5 mm is 0.7 % which is well below of specified 5% value. The integrated field is 2.6 mT-m (specified is 2.1 mT-m). The iron yoke peak field was checked for both VD and HD correctors powered. The peak field is below 1.5 T. It is possible to reduce this field by increasing the area of yoke back legs.

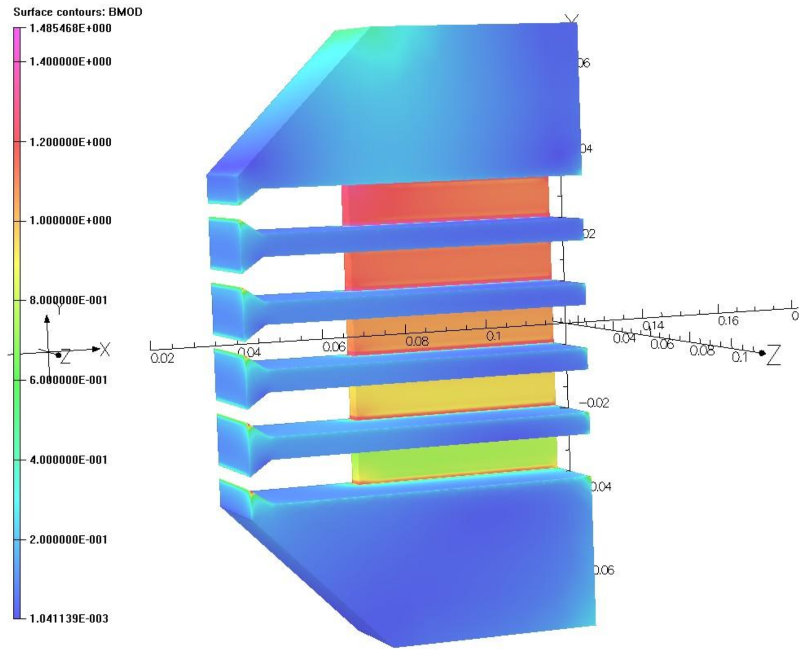

Fig. 13. Flux density in the yoke at both correctors peal current. Bmax=1.48 T.

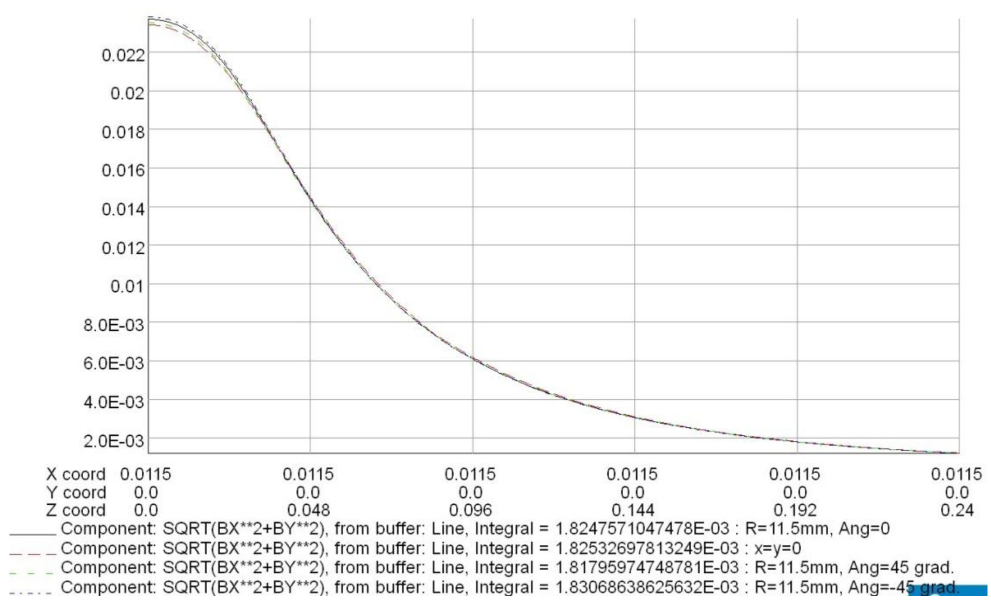

Fig. 14. Both correctors field distribution at 1100 A/pole.

The integrated field with both correctors at peak current 1 A is 3.6 mT-m, and the field homogeneity is 0.7 %.

Table 4

Parameter	Unit	V/H Dipole
VD/HD integrated field at 220 A/coil section, 1100A/pole	mT-m	2.6
VD+HD integrated field at 220 A/coil section, 1100A/pole	mT-m	3.6
Distance between pole tips	mm	76
Pole length	mm	50
Yoke width	mm	240
Integrated field homogeneity at 23 mm diameter	%	0.7
Copper conductor diameter	mm	1.0
Copper area	mm^2	0.785
Number of turns/pole		1100
Dipole peak current	A	1.0
Current density	A/mm^2	1.3
DC resistance /magnet	Ω	9.2
DC voltage/magnet	V	9.2
Power losses for VD+HD	W	20
Coil temperature rise (estimated) at the air cooling	°C	40

MEBT Magnets Mechanical Concepts

There are several issues related to the magnet design and fabrication:

- Very limited slot length for magnets (See Fig. 10, and Fig. 11).
- Small aperture drives the mechanical design to the four separate pole sub-assemblies and as a result to the issue of accurate pole position in the magnet aperture.
- The request to have a possibility to disassemble the magnet without breaking the beam pipe vacuum adds demands to the assembly tolerances.
- The proposed magnet air cooling will strongly depends on the magnet fabrication (thermal contacts coil-yoke), the air convection in the magnet package area. Besides the air temperature in the tunnel and measurement stands may be varied in a large range, and correspondingly the peak coil temperature.
- The magnet reliability should be taken into consideration (peak coil temperature, thermal cycles, reliability of electrical insulation, etc…).

Nevertheless there are some relaxing circumstances:

- This magnets are transport line magnets with the single beam pass. So, the needed field quality is well below synchrotron magnets.
- The magnet position in the space not so critical because of relatively strong dipole correctors.

Below presented mechanical concepts of PXIE MEBT magnets (See Fig. 15-Fig. 19).

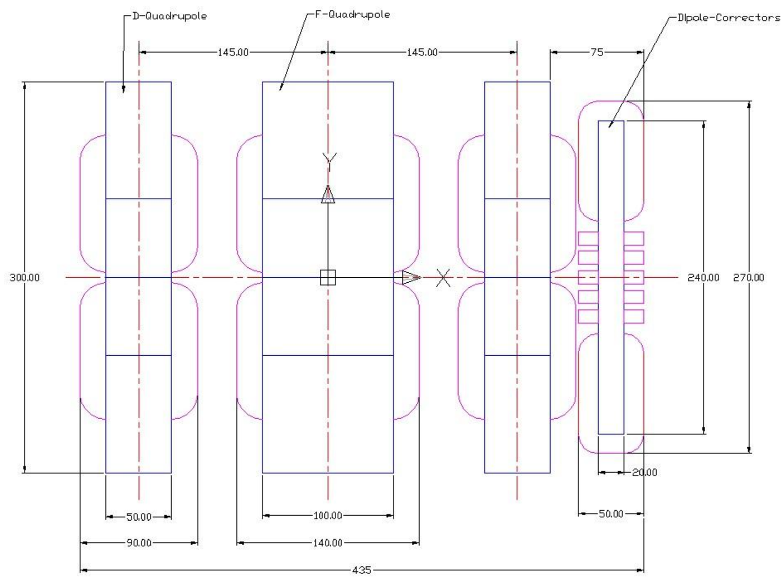

Fig. 15. Triplet and Dipole Corrector top view.

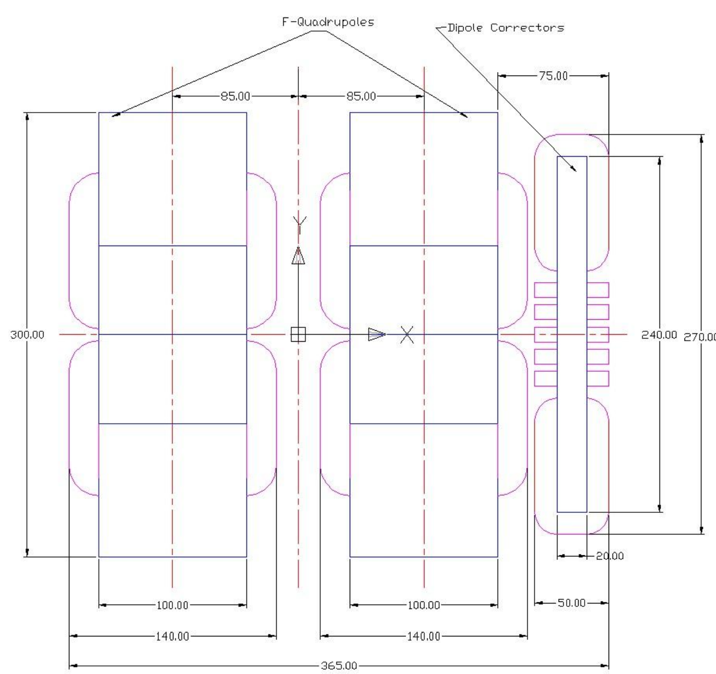

Fig. 16. Doublet and Dipole Corrector top view.

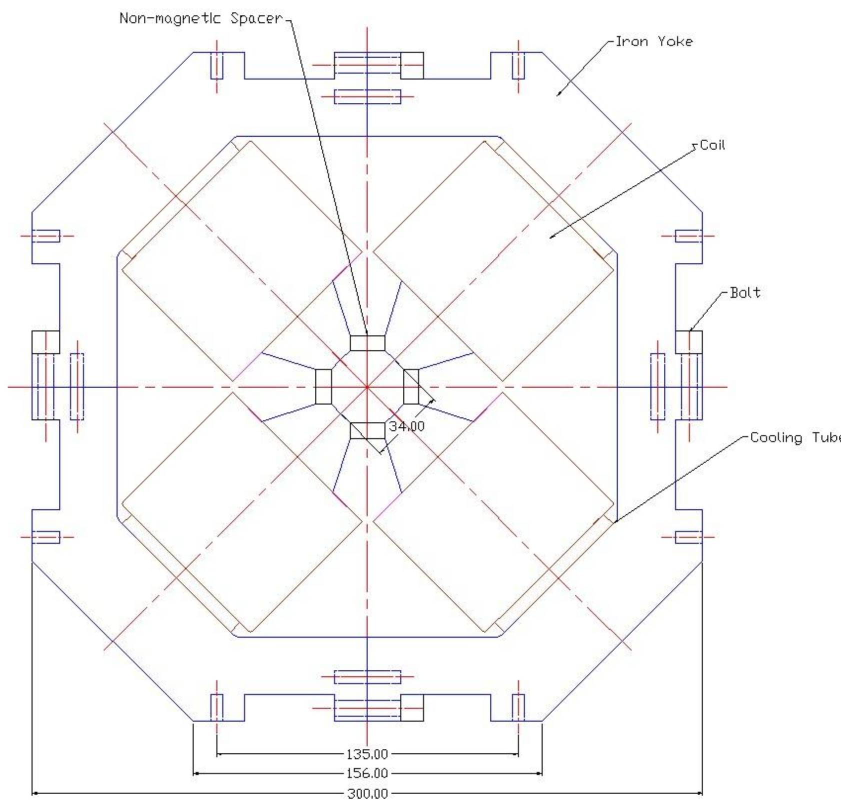

Fig. 17. Quadrupole side view.

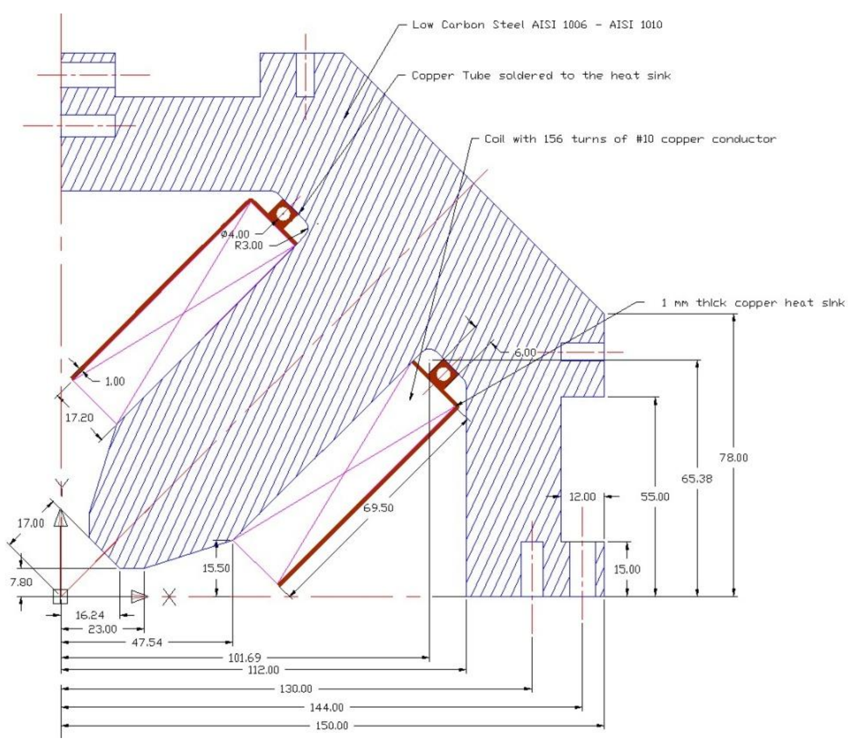

Fig. 18. Quadrupole pole block assembly.

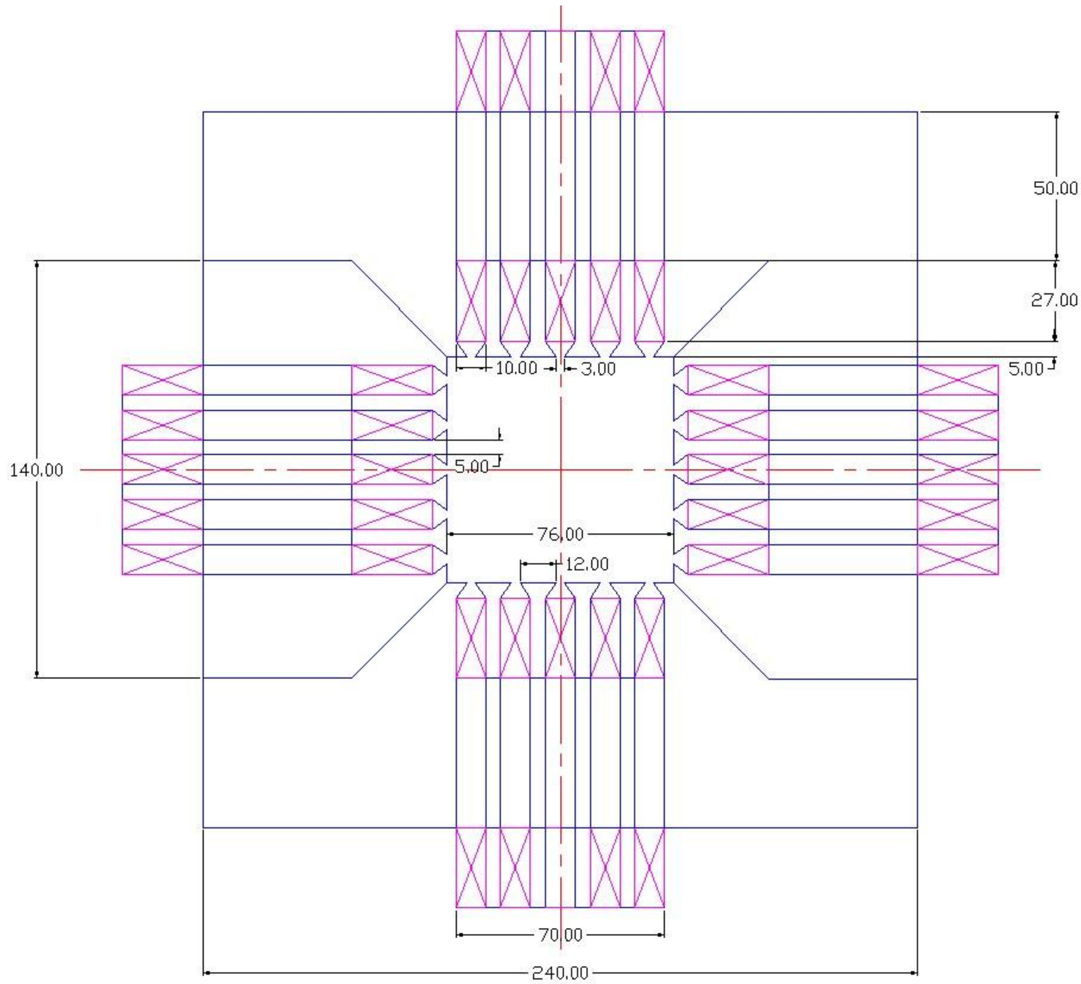

Fig. 19. Dipole corrector cross-section.

In quadrupoles added water cooling tube which will help to make the magnet temperature more stable and independent from the external air temperature and at convection.

The dipole corrector could be assembled from 4 solid iron blocks with machined slots. In this case coils will be randomly wound into slots like in electrical machines stators. Another option to make yoke cuts along the slots. Coils could be fabricated separately, assembled with yoke parts, and bolted all together. The most cost effective approach should be chosen.

Finally, presented concept definitely could be improved by more careful optics analysis, and when available industry technology will be known.