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A&T Sector Note

Title: Design and cost estimation of corrector dipoles (PXMCCAVWAP) for the AD machine

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Summary

This note describes the design and cost estimation of two corrector magnets **(PXMCCAVWAP)** needed upstream and downstream of the CERN AD electron cooler. These magnets provide fields for both horizontal and vertical deflection.

Contents

1. INTRODUCTION

Two new combined horizontal and vertical deflection corrector magnets are needed to replace existing magnets, which are situated upstream and downstream of the CERN AD electron cooler. The existing magnets do not fulfil the current requirement.

2. DESIGN REQUIREMENTS

The requirements for the horizontal and vertical planes differ with a larger integrated field needed for the horizontal compared to the vertical, 0.028 and 0.016 T.m respectively. However, a symmetrical design is preferred and the minimum requirement will be that of the horizontal plane. The magnets shall provide a deflection of 28 mrad in both directions for antiprotons of 300 MeV/c. The space available for the correctors in the ring is limited axially and also vertically because existing support tables already installed in the ring shall be reused. The aperture must be large to accept the vacuum pipe with its heater jacket. Table 1 details the magnet requirements and space limitations.

Deflection angle	28	mrad
Beam momentum	300	MeV/c
Beam rigidity	1.0	T.m
Free aperture diameter	190	mm
GFR (Good Field Region)	180	mm
Axially available space	440	mm
Distance Table to Beam	300	mm

Table 1: Requirements and space limitations

If possible existing power supplies will be reused, 25 A / 120 V and 10 A / 40 V for the horizontal and vertical planes respectively. The expected operational field ramp rate is in the order of 167mT/second (48 A/s); this is derived from the worst case scenario with a change from negative to positive full field in 0.6 seconds.

3. COIL AND YOKE DIMENSIONS

The proposed design is to use a laminated steel core made from four quadrants, each equipped with a main excitation coil and two compensation coils all connected in series as displayed in Fig.1. The current density for the desired field is adequately low that air cooled coils can be used. The wire used will have a cross-section of approximately 10.7 mm^2 for the main excitation coils and 8.2 mm^2 for the compensations coils. The main excitation coils will be wound with between 46 and 62 turns of 11 layers, whilst the two compensation coils will be wound with between 20 and 23 turns of 4 layers each. Each coil shall be insulated to the mass by means of woven glass fibre board with a minimum thickness of 2.5 mm, while the wire insulation will consist of a 0.1 mm thickness of a high temperature varnish type Thermex 200. The thickness of the coil head (at the magnet ends) amounts to approximately 50 mm, when taking into account a minimum bending radius of the conductor, conductor insulation and ground insulation.

With the limited space available and the coil dimensions stated above this leaves a maximum of 310 mm for the yoke length, allowing a margin of 10 mm either side of the magnets. Using a minimum thickness for the yoke of 33 mm and the values above allowing for the free aperture diameter of 190 mm, the total height / width comes to 464 mm. This dimension allows approximately 70 mm between the magnet and the support table for an intermediate alignment table.

4. EXCITATION CURRENT AND FIELD DISTRIBUTION

To obtain the effective length of the magnet, a 3D simulation of the magnet has been completed.

The result is l_{eff} = 562 mm (see Fig.3). From $l_{eff} = \alpha.\rho$ and $B.\rho = 1.0$ T, we get $\alpha = 28$ mrad: $\rho = 20.1$ m and $B = 0.05$ T. The form of the quadrant and the use of the combined main and compensation coils all connected in series has been optimised to produce a large good field region +/- 90 mm with a maximum deviation of 0.5 % from B_0 where $X = 0$. This field is achieved with the number of coil turns, 584 = 53*11 (on average) for the main coil and 2 times 86 = 4*21.5 (on average) for the compensation coils (total = 756 turns) with an excitation current required of 14.3 A. The resulting current density is 1.3 and 1.7 A/mm^2 for the main and compensation coils respectively. The 3D simulation has given approximately 0.55 T for the flux density in the yoke.

Fig.2 shows the 3D model of the corrector magnet. Fig. 4 shows the transversal field distributions, while Fig.5 shows the integrated field distribution for the horizontal plane and integrated field error on quadrant where r = 90 mm. Fig.6 shows the excitation curve to the point of saturation.

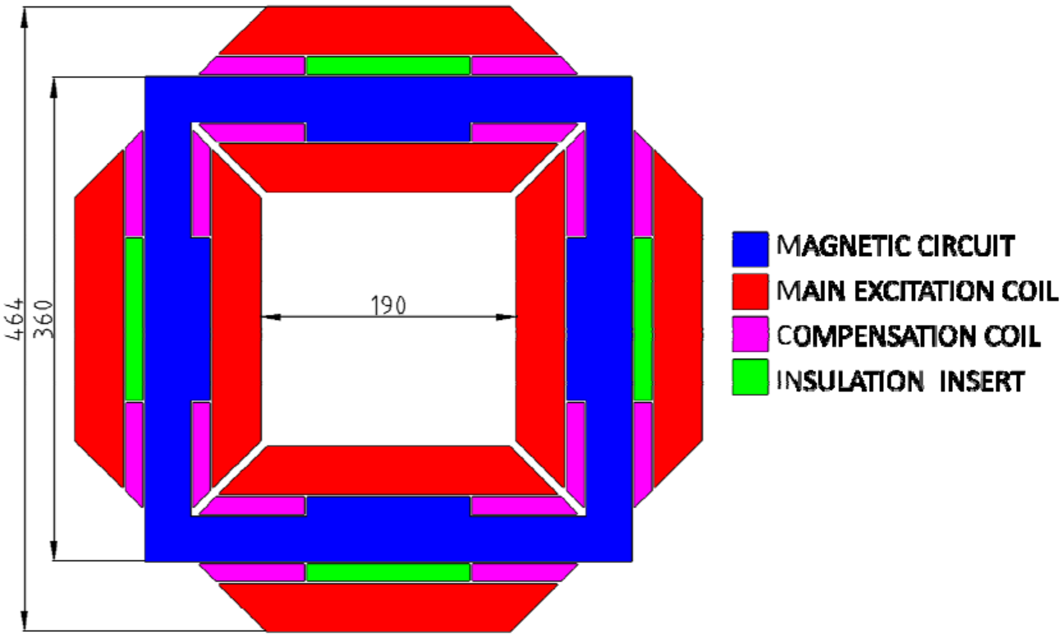
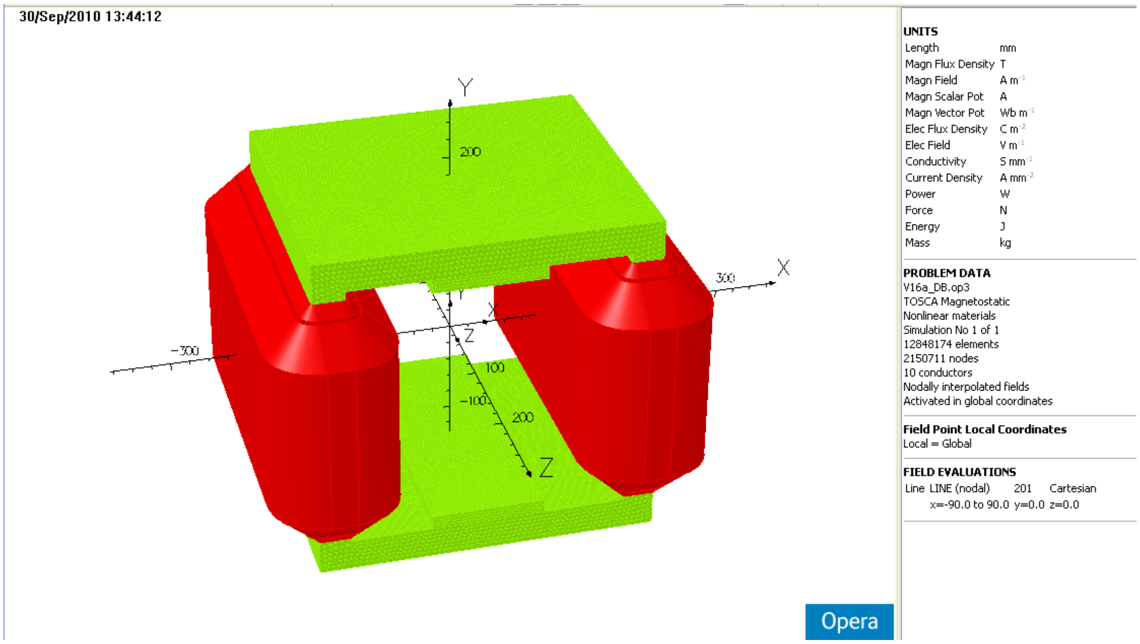


Figure 1: 2D Magnet Section.



```
UNITS
Length              mm
Magn Flux Density   T
Magn Field          A m-1
Magn Scalar Pot     A
Magn Vector Pot     Wb m-1
Elec Flux Density   C m-2
Elec Field          V m-1
Conductivity        S mm-1
Current Density     A mm-2
Power               W
Force               N
Energy              J
Mass                kg

PROBLEM DATA
V16a_DB.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
12848174 elements
2150711 nodes
10 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Line  LINE (nodal)      201    Cartesian
      x=-90.0 to 90.0  y=0.0  z=0.0
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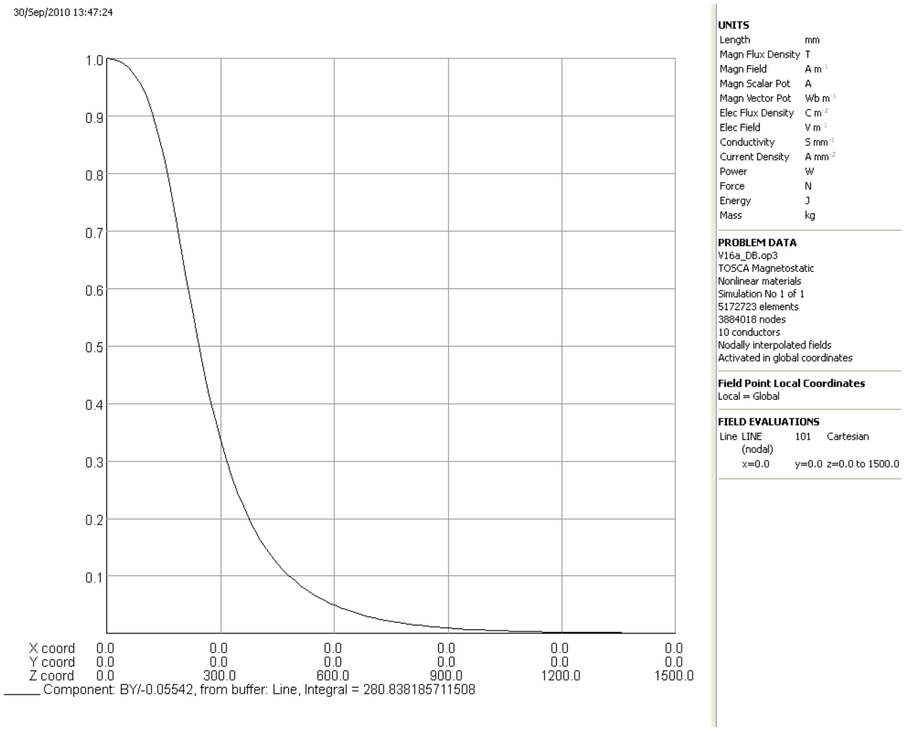
Figure 2: 3D computer model with coil pair for horizontal correction.



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Component: BY/-0.05542, from buffer: Line, Integral = 280.838185711508
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```
UNITS
Length              mm
Magn Flux Density   T
Magn Field          A m-1
Magn Scalar Pot     A
Magn Vector Pot     Wb m-1
Elec Flux Density   C m-2
Elec Field          V m-1
Conductivity        S mm-1
Current Density     A mm-2
Power               W
Force               N
Energy              J
Mass                kg

PROBLEM DATA
V16a_DB.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
5172723 elements
3884018 nodes
10 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Line  LINE        101    Cartesian
      (nodal)
      x=0.0       y=0.0  z=0.0 to 1500.0
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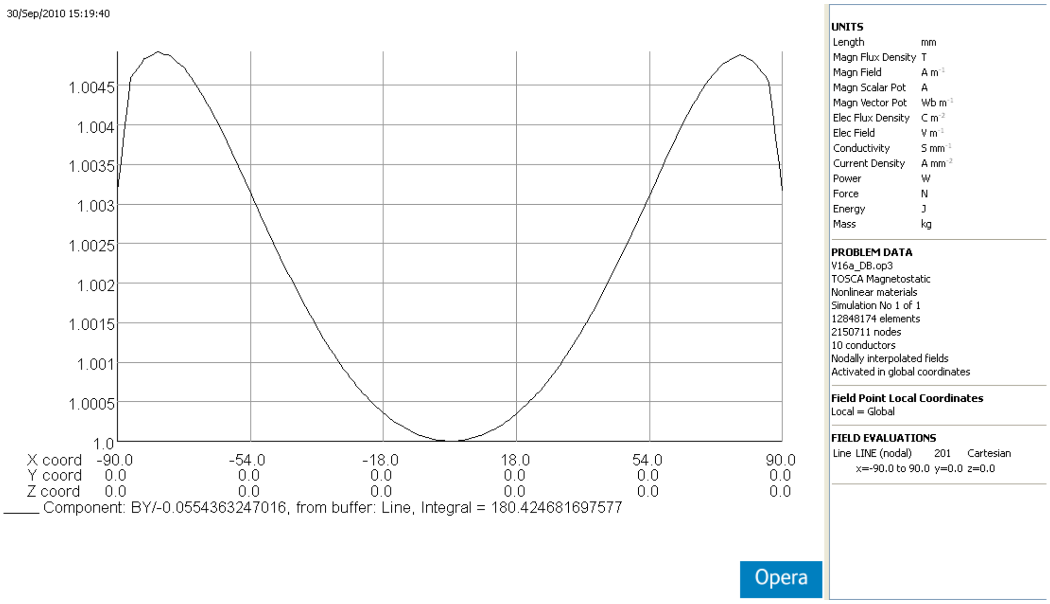
Figure 3: Field distribution along magnet axis (for half of the magnet), normalized to unity in its centre.



UNITS

Length	mm
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
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Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Line LINE (nodal) 201 Cartesian
x=-90.0 to 90.0 y=0.0 z=0.0

Figure 4: Field distribution shown for horizontal plane only as magnet is symmetrical, normalised to unity in the centre.

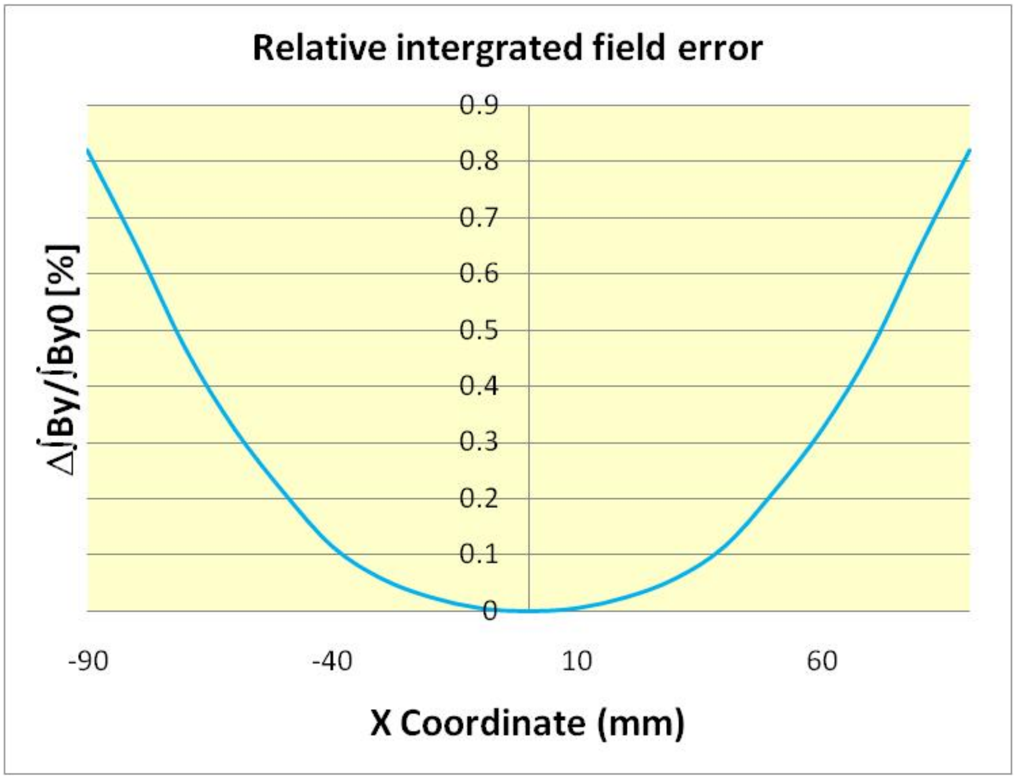

Figure 5a: Relative integrated field error on the horizontal axis.

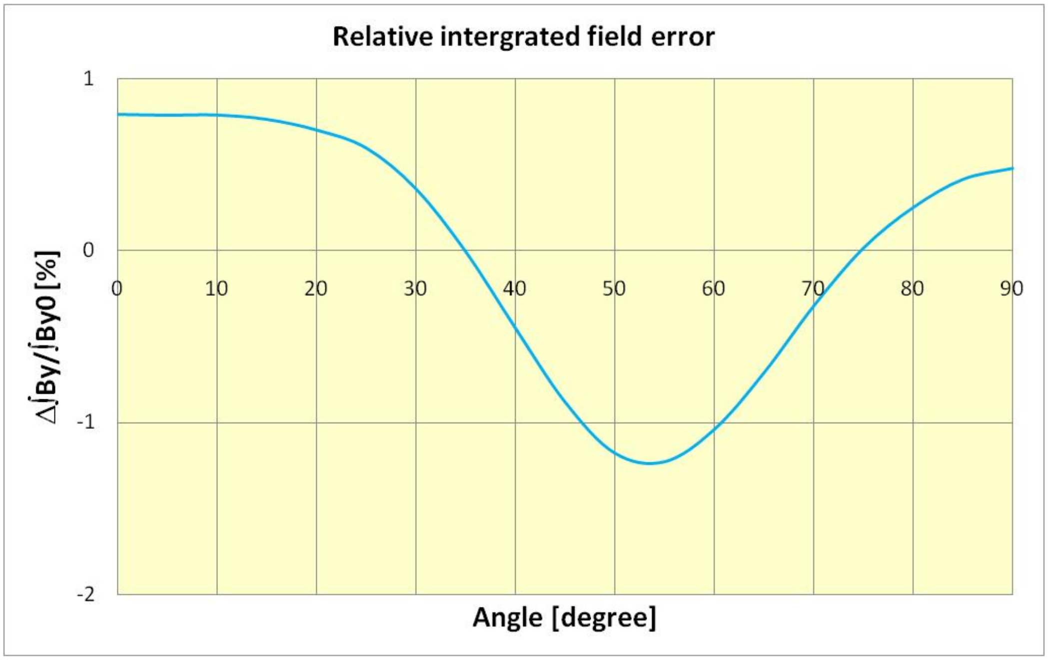

Figure 5b: Relative integrated field error on quadrant where r = 90 mm.

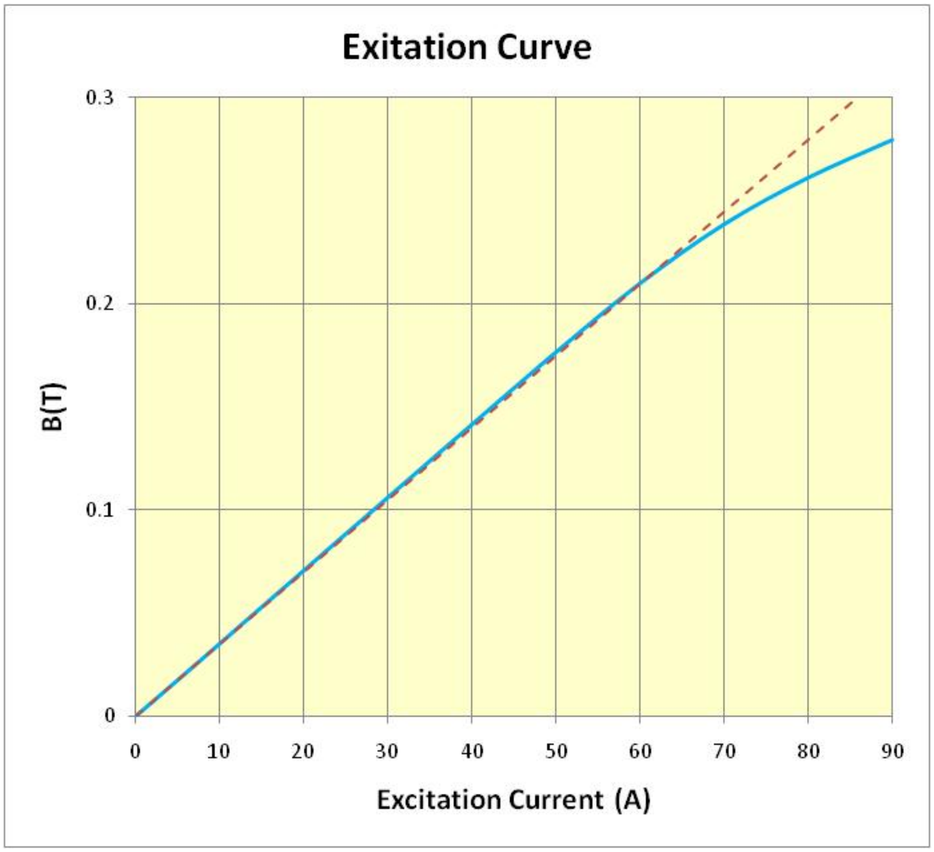

Figure 6: Excitation curve, Current (Amps) vs. Field (Tesla).

5. PARAMETER TABLE

Magnet characteristics

Number of magnets	2 + 1	spare
Number of power supplies per magnet	2	
Number of coils per magnet:		
Main excitation coil	4	
Compensation coil	8	
Bending angle	28	mrad
Free aperture diameter	190	mm
Effective magnetic length	562	mm
Normal magnetic field	0.05	T
Normal integrated field	0.0281	Tm
Good Field Region (% of free aperture)	95	%
Field homogeneity in GFR	±1	%

Magnet dimensions

Magnet overall length	420	mm
Magnet overall width/height	464	mm
Distance to support table	70	mm
Total weight per magnet	360.5	Kg

Iron core characteristics

Steel type	Stabocor 1200-100A	
Lamination thickness	1.0	mm
Packing factor	97	%
Iron length	310	mm
Magnetic gap height and width	265	mm
Yoke height and width	360	mm
Yoke thickness (minimum)	33	mm
Yoke mass	122	Kg

Coil characteristics

Main excitation coil

Cooling	air, natural convection	
Conductor material	OFE copper	
Number of turns	584	
Number of layers	11	
Number of turns per layer	46 – 62	
Resistance @ 20 °C	0.86	Ω
Current density	1.34	A/mm^2
Conductor cross section	10.7	mm^2
Width	3.7	mm
Height	2.95	mm
Edge radius	0.5	mm
Insulation thickness	0.1	mm
Approximate mass	50	Kg

Compensation coil

Number of turns	86	
Number of layers	4	
Number of turns per layer	20 – 23	
Resistance @ 20 °C	0.14	Ω
Current density	1.75	A/mm^2
Conductor cross section	8.2	mm^2
Width	3.0	mm
Height	2.8	mm
Edge radius	0.5	mm
Insulation thickness	0.1	mm
Approximate mass	5	Kg

Electrical parameters

Nominal current (vertical)	14.3	A	(8.1	A)
Resistance @ 20 °C	2.28	Ω		
Resistance @ 55 °C	2.44	Ω		
Inductance	0.75	H		
D.C. Voltage @ 55 °C (vertical)	34.88	V	(19.8	V)
Inductive Voltage @ 0.167T/s - 48 A/s (vertical)	35.4	V	(20	V)
Total Voltage, inductive + resistive (vertical)	68	V	(39.8	V)
Dissipated Power @ 55 °C (vertical)	499	W	(160	W)

Power supplies

Two types of bipolar power supply exist for the magnets to be replaced, 25A/120V and 10A/40V for the horizontal and vertical planes respectively. As the requirement for the vertical deflection is less than that of the horizontal only 39.8 V should be required at 8.1 A as opposed to the 14.3 A and 68 V for the horizontal, thus allowing both of the supplies to be reused.

6. COST ESTIMATION AND SCHEDULE

The total costs for the magnets including raw materials, magnetic and mechanical design, manufacturing, production follow-up, testing, transport, and acceptance tests at CERN are estimated to be around 70 000 CHF. A price break-down is shown in Table 2. This estimation is based on the assumption that the magnets are supplied by a Western-European manufacturer. The magnet supply does not include supports, vacuum chambers and magnetic measurements.

Table 2: Magnet price break-down

	kCHF
Fixed Costs (design, engineering & follow up)	**19**
Costs per magnet unit (material, manufacture)	**17**
Material costs per magnet (steel, copper)	*7*
Manufacturing costs per magnets incl. Engineering	*10*
Total cost all magnets	**70**

The time from the date of the project approval when the detailed design work can be started until the end of the magnet delivery is estimated to be around 18 months.

The CERN Staff resources would be very limited for this project, and can be covered by the normal operation.

Acknowledgements:

The author would like to express gratitude to M Ebbini for the contributions with OPERA 3D.