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ARIEL Dogleg Vertical Dipoles
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History of Changes

Release Number	Date	Description of Changes	Author(s)
1	2013/12/06	Initial Release	Thomas Planche

ARIEL Dogleg Vertical Dipoles design note

EHBT:MB0 & EHBT:MB5A

Thomas Planche

November 25, 2013

Contents

1 Basic Magnet Requirements

Magnet type	H-frame rectangular dipole
Maximum bending angle	6.715°
Maximum electron energy (corresponding rigidity $B\rho$)	75 MeV (0.2519 T.m)
Full gap height	53.2 mm
B_{max}	≥ 0.35 T
Field quality requirement: sextupole components	≤ 3.5 rad.m^{-2}

Table 1: Basic magnet requirements.

From the rigidity and bend angle, the required field integral is:

$$\int_{-\infty}^{+\infty} B\mathrm{d}l = B\rho\ [\mathrm{T.m}] \times \text{bending angle}\ [\mathrm{rad}] \simeq 0.02952\ [\mathrm{T.m}]. \tag{1}$$

The increment dl is taken along the electron path.

2 Constraints

Design constraints are listed in Table 2.

Maximum power consumption	≤ 1.6 kW
Steel magnetization	≤ 1.4 T
B(I) linearity over the whole range	within ± 2%
Fringe field extent: remaining field 0.1 m away from the magnet edge	$\leq 4.10^{-4}$ T

Table 2: Design constraints.

3 Parameters of our Design

3.1 Summary Table

Coil	
Ampere turns per coil	7880 A.t
Minimum inner dimensions [mm] (Given by the pole dimensions, see Fig. 2)	140 × 55.8 (x×y)
Maximum outer dimensions [mm] (Given by the yoke, clamp and pole dimensions, see Fig. 2 & 3)	246.4 × 129.8 × 77.8 (x×y×z)
Pole dimensions (see Figs. 1 & 3)	
Pole width (**pw**)	140 mm
Pole length (**pl**)	55.8 mm
Pole height (**ph**)	77.8 mm
Chamfer height (**chh**)	5 mm
Chamfer angle (**cha**)	30 deg.
⇒ Chamfer width (**chw = chh/tan(cha)**)	≃ 8.660 mm
Yoke dimensions (see Figs. 1 & 3)	
Magnet width (**mw**)	338.4 mm
Top/Bottom yoke thickness (**yta**)	46 mm
Side yoke thickness[1] (**ytb**)	46 mm
⇒ Magnet height (**mh = 2*ph + 2*yt** + gap)	300.8 mm
Field clamps (see Figs. 1, 3 & 5)	
Clamp thickness (**clt**)	9 mm
Clamp width (**clw**)	140 mm
Magnetic connection clamp-yoke thickness (**cct**) Thickness of the gap between yoke and clamps (**tgt**)	46 mm 0.2 mm
Magnet length (**ml**) (see Fig. 1)	147.8 mm

Table 3: Detailed parameters of our design.

Detailed parameters of our design are given in Table 3. According to `OPERA-3D` simulations, this design satisfies all the requirement and constraints listed above. Illustrative views of the model are shown in Fig. 1, 2, 3 , 4, 5, and 6.

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[1] This dimension may be increased for radiation shielding purposes.

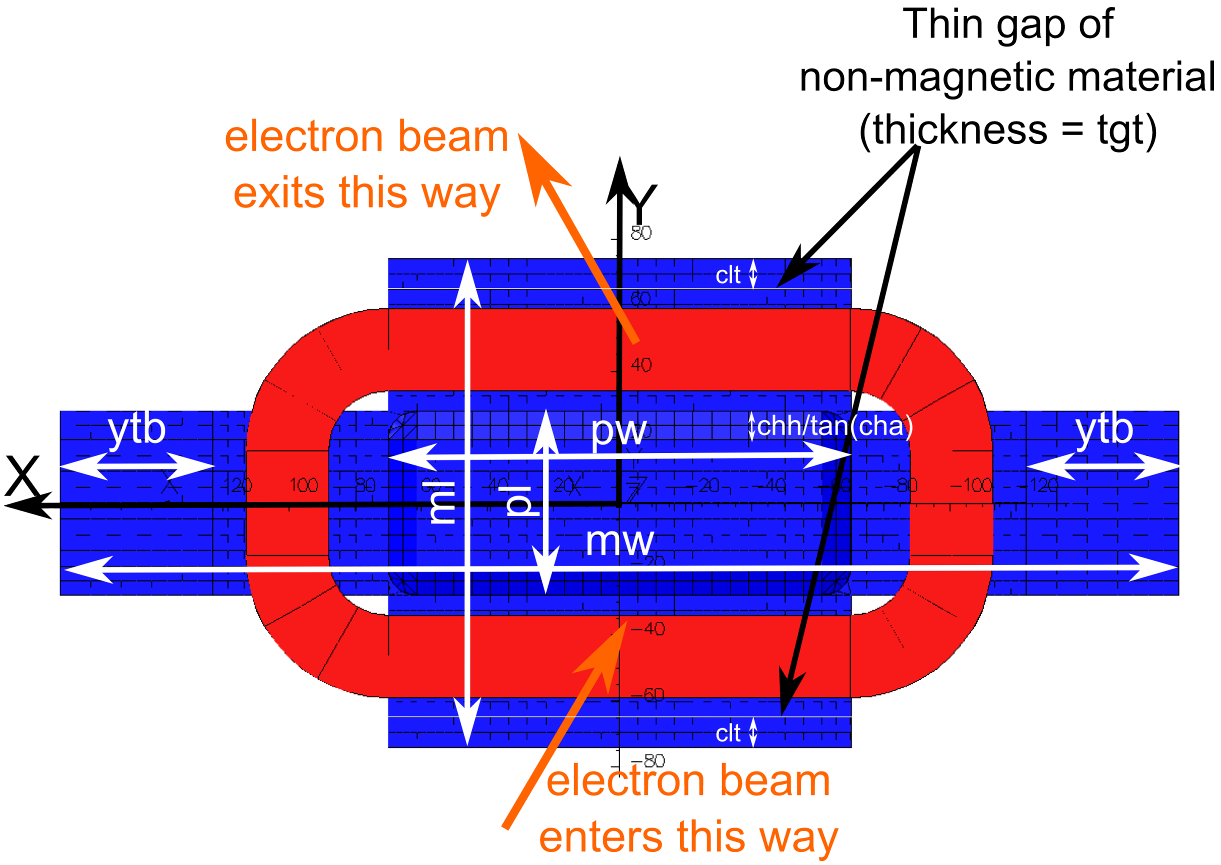


Figure 1: `OPERA-3D` model: plan view of half of the magnet. Steel volumes are in blue, coil is in red.

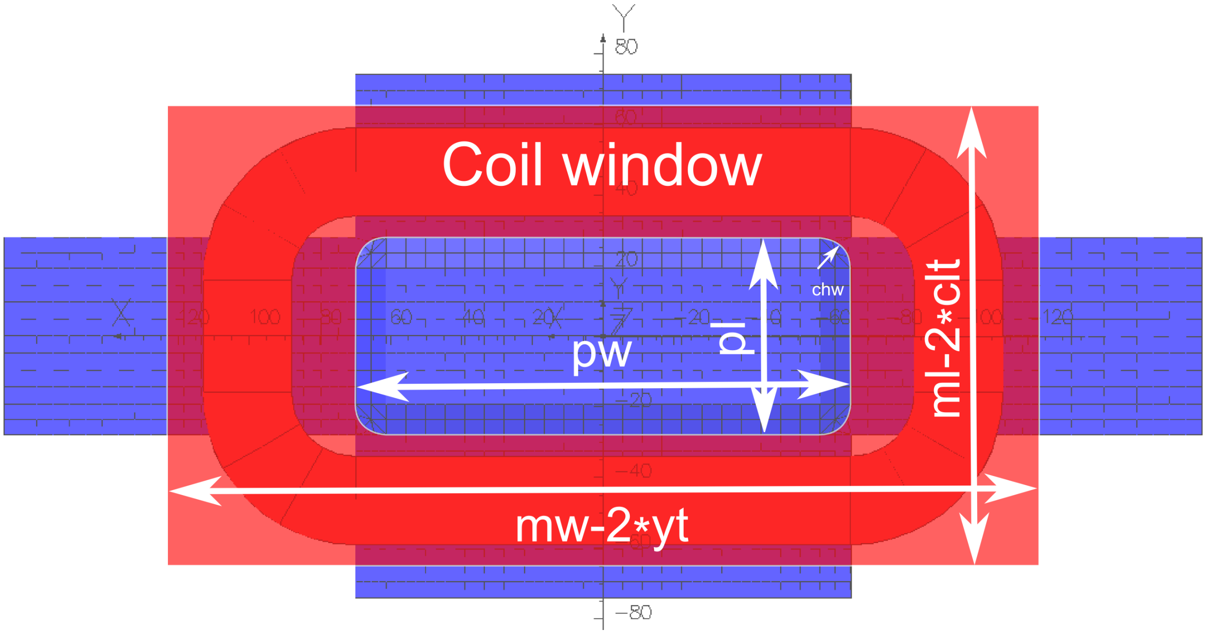


Figure 2: Schematic showing maximum dimensions **mw-2*yt** and **ml-2*clt**, and minimum dimensions **pw** and **pl**.

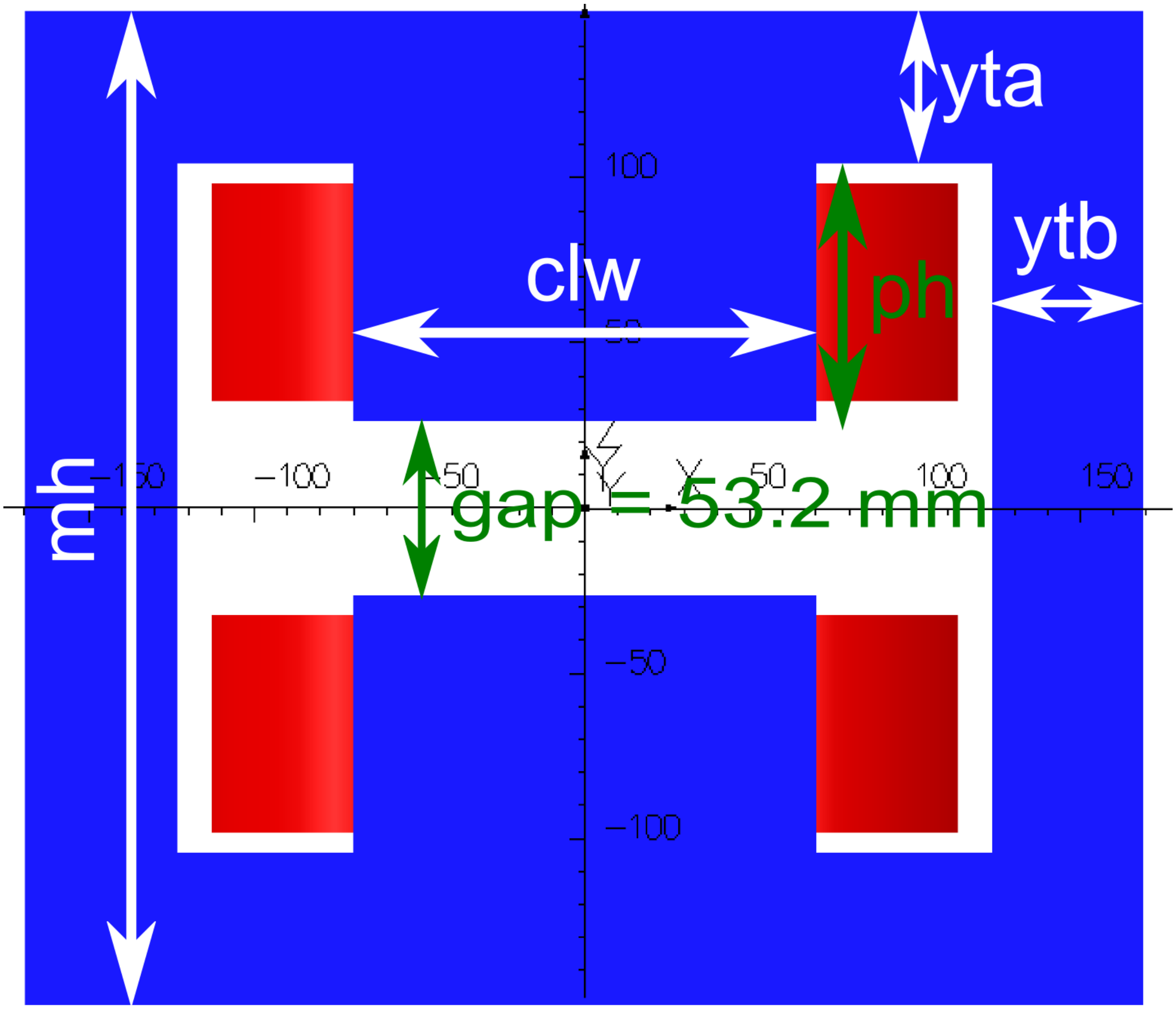


Figure 3: `OPERA-3D` model: front view of the whole magnet. Steel volumes are in blue, coils are in red. Note: the piece of steel which connect the clamp to the yoke lines up with the inside edge of the yoke.

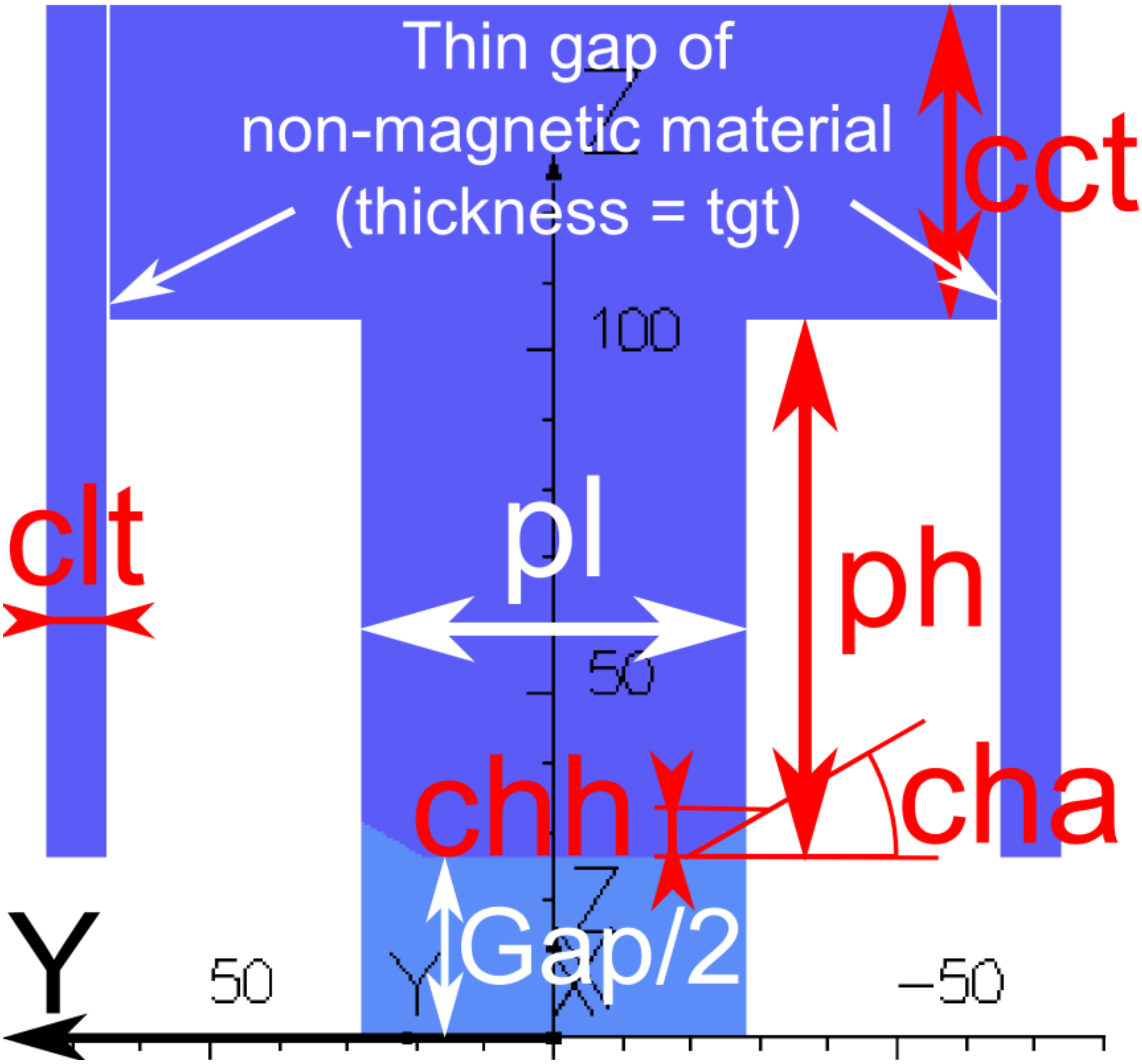


Figure 4: `OPERA-3D` model: Side view of one quarter of the magnet. Only steel volumes are shown.

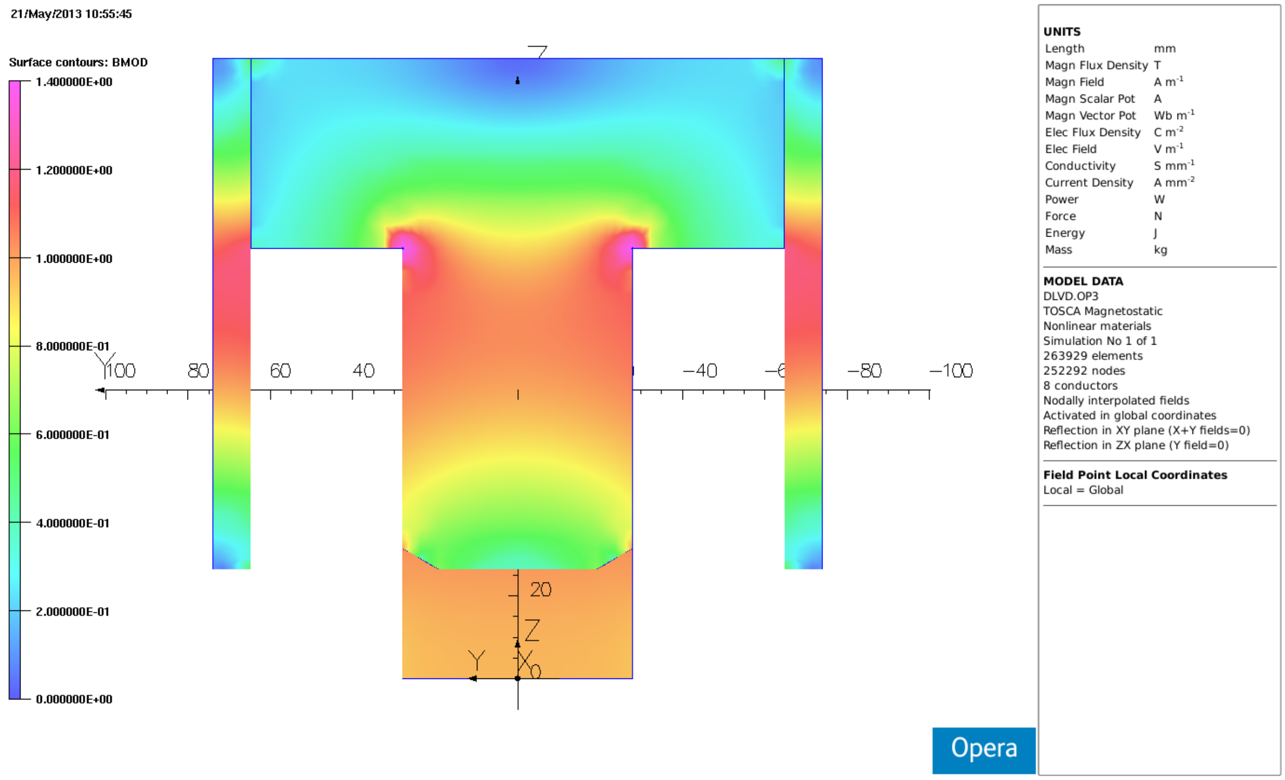


Figure 5: `OPERA-3D` model: Side view of one quarter of the magnet, showing field level in the steel. Color code: goes from 0 (blue) to 1.4 Telsa (magenta).

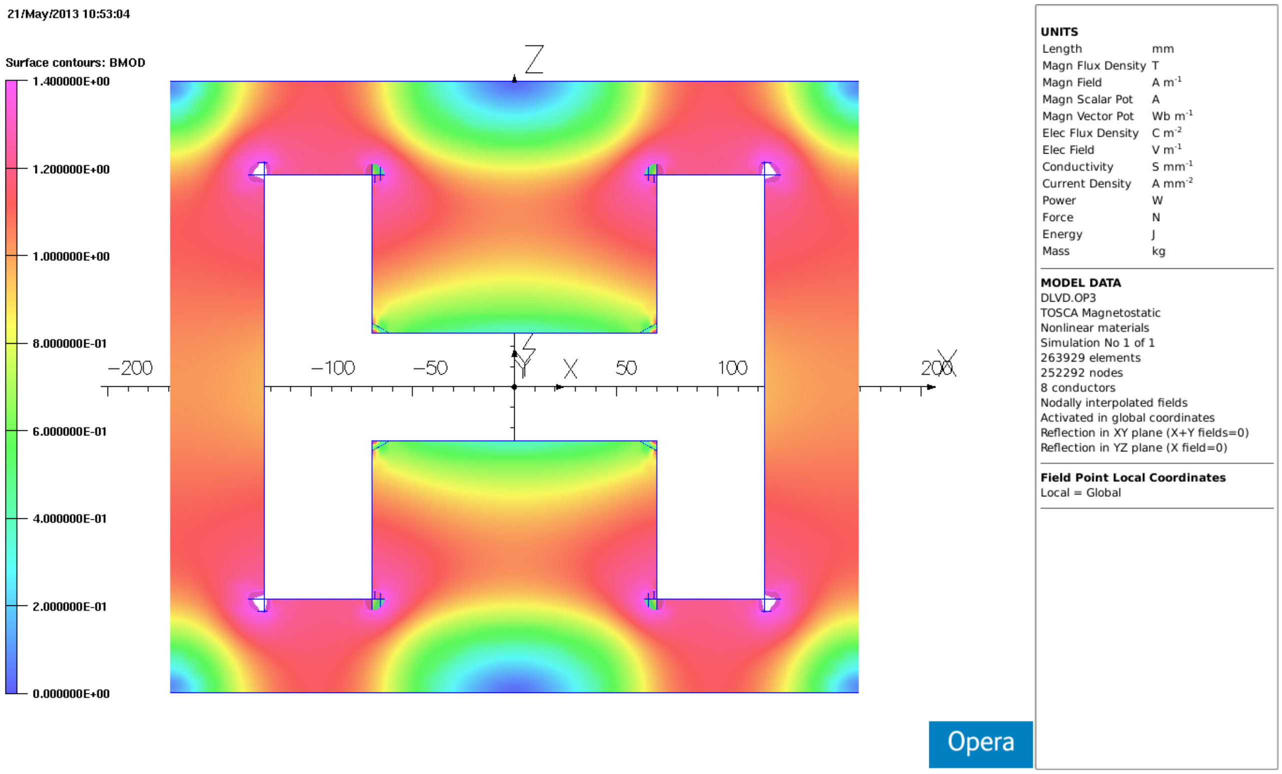
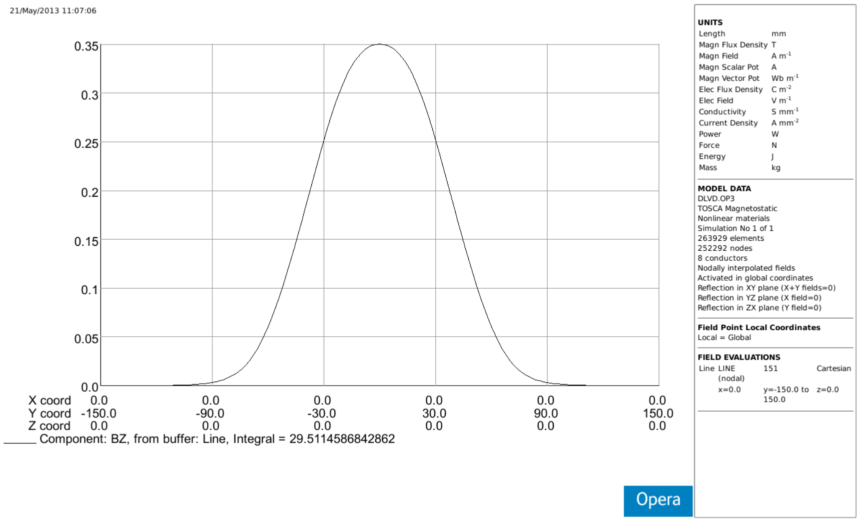


Figure 6: Field level inside the steel along the cut plane y=0. Color code: goes from 0 (blue) to 1.4 Telsa (magenta).



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

MODEL DATA
DLVD.OP3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
263929 elements
252292 nodes
8 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (X+Y fields=0)
Reflection in YZ plane (X field=0)
Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS

Line	LINE (nodal)	151	Cartesian
	x=0.0	y=-150.0 to 150.0	z=0.0

Figure 7: From our OPERA-3D model: vertical component of the magnetic field along the y axis (at x=0 & z=0).

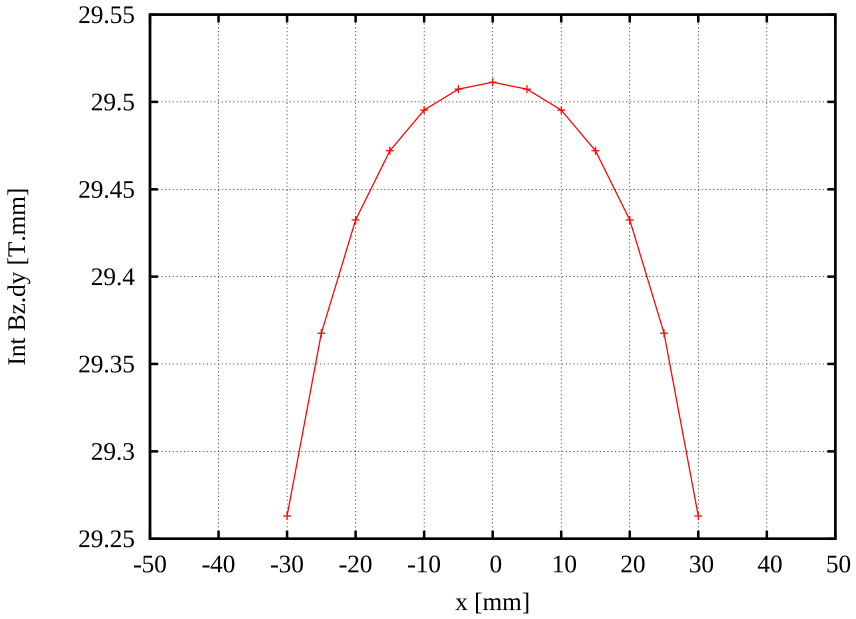


Figure 8: $\int B_z \mathrm{d}y$, along straight lines, as described in Fig. 15 (see Section 4.2).

3.2 Coil Parameters

The required Ampere-turns per coil were initially estimated using the relation:

$$\mathrm{NI_{per\ coil}} = \frac{1}{2}\left(\frac{\mathrm{B_{max}}\ [\mathrm{T}]\ \cdot\ \text{full gap [m]}}{4\pi 10^{-7}}\right) \simeq 7410\ [\mathrm{A.t}] \tag{2}$$

The `OPERA-3D` model of this design used in fact 7880 A.t to produce the required amount of field.

3.3 Correction coils

To correct steering errors, as well as to compensate for small differences between dipoles connected in series, each of these magnets will need a pair of correction coils. These corrections coils are intended to modify the field integral by up to 500 G.cm, which corresponds to 132 A.t per correction coil.

3.4 Pole Dimensions

The pole dimensions given above (Table 3) were chosen as follows:

- The pole length results in the required field integral.
- The pole width results in the required field quality (Table 1).
- The chamfers are wide enough to avoid saturation of the steel.
- The pole height results from the coil height used in our model (+6 mm margin on both sides).

3.5 Field Clamps Dimensions

The field clamps are used to meet the required field quality, as well as to satisfy the constraint related to the fringe field extent. The clamp dimensions given above (Table 3) were chosen as follows:

- Field clamp width = 140 mm. This comes from a compromize between field quality and reduction of the fringe field extent.
- A 0.2 mm thin gap of non-magnetic material.
- The field clamp thickness keeps the maximum field in the clamps below 1.4T (see Fig. 5).

3.6 Return Yoke Dimensions

The return yoke dimensions given above (Table 3) were chosen as follows:

- ◇ The return yoke has been made thick enough to keep the field in the steel below 1.4 T (see Fig. 6).
- ◇ The distance between the pole and the return yoke comes from a trade-off between the field quality and the magnet transverse size.

3.7 Steel Properties

The BH curve used in this model is shown in Fig. 9.

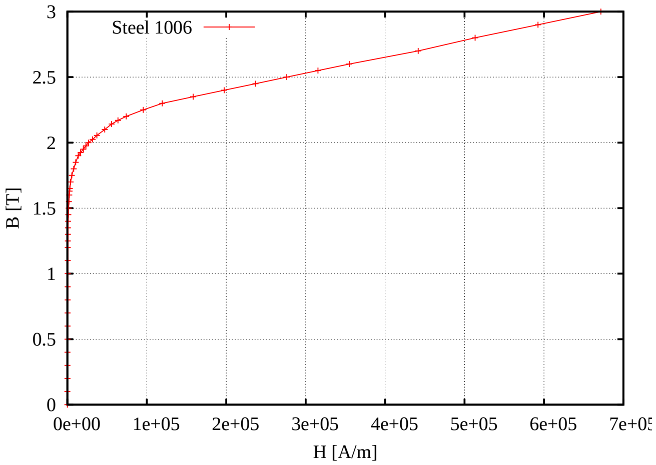


Figure 9: BH curve used in our model (AISI 1006 steel).

3.8 Field Quality from the `OPERA-3D` Model

A 2D field map of the magnet mid-plane has been extracted from the model. The field maps covers an area of 360 mm (in X) by 600 mm (in Y), with a step size of 6 mm in both directions. We used this field map in `COSY INFINITY` [1] to track 75 MeV electrons entering the magnet at an angle of 3.3575°. This way we obtained the transfer map coefficients, calculated around these orbits, as a function of the initial particle coordinate x_0. Results are presented in Fig. 10. One can see on this figure that the sextupole components are minimum around $x_0 \simeq 15$ mm, and values are smaller than required (in Table. 1). The trajectory starting from $x_0 = 15$ mm is our reference trajectory (see Fig. 11). With this reference trajectory, the distance between the magnet center and the cross-over points[1] is 2.6 mm.

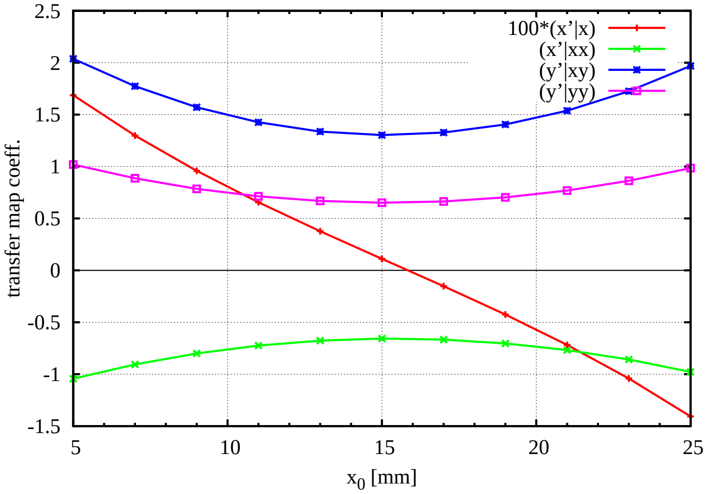


Figure 10: Quadrupole component and major sextupole components calculated around trajectories entering the field map at x_0, with an angle of 3.35757°. The units system used for the coefficient is m & rad.

The magnetic field seen by the particle along this trajectory is shown in Fig. 12. The transfer map calculated (to the second order) around this trajectory is presented in Table 4.

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[1] We call **cross-over** point the point where the line of the incoming beam and the line of outgoing beam intersect.

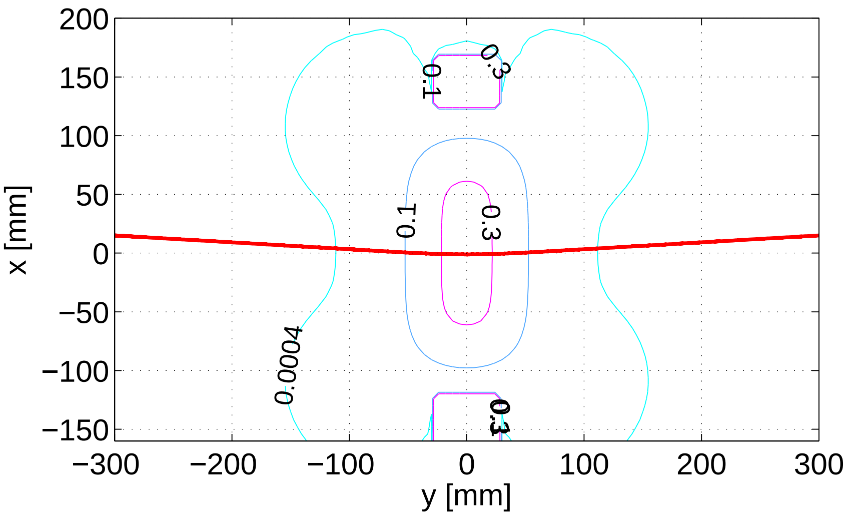

Figure 11: Red line: reference trajectory. Contours represent the absolute value of the magnetic field from the 2D-field map (in Tesla).

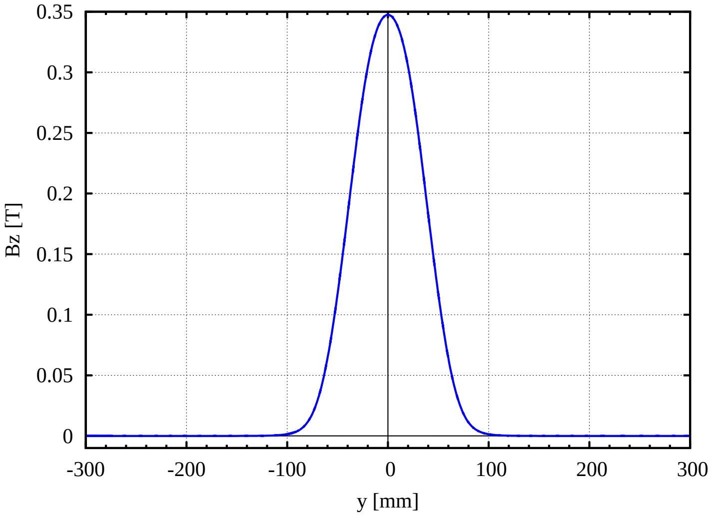

Figure 12: Field **seen by a 75 MeV electron** traveling along the reference trajectory. (Note: only the vertical component of the field is non-zero, since the reference trajectory lies in the mid-plane).

x	x'	y	y'	l	(x|x'|y|y'|l| δ_k)
1.000335	0.1111383E-02	0.000000	0.000000	0.1165447	100000
0.6018363	1.000333	0.000000	0.000000	0.3500091E-01	010000
0.000000	0.000000	0.9634636	-0.1210959	0.000000	001000
0.000000	0.000000	0.5913491	0.9635964	0.000000	000100
0.000000	0.000000	0.000000	0.000000	1.000000	000010
-0.3512817E-01	-0.1165446	0.000000	0.000000	-0.2141701E-03	000001
-0.1980793	-0.6569467	0.000000	0.000000	-0.1165039E-02	200000
-0.2369919	-0.3945890	0.000000	0.000000	-0.7909547E-02	110000
-0.3552253E-01	-0.2429187E-03	0.000000	0.000000	-0.3007312	020000
0.000000	0.000000	0.4001822	1.302736	0.000000	101000
0.000000	0.000000	0.2386175	0.3912406	0.000000	011000
0.1891841	0.6514841	0.000000	0.000000	-0.6078162E-01	002000
0.000000	0.000000	0.5756015E-02	0.3986251	0.000000	100100
0.000000	0.000000	0.1599667E-02	0.1281909E-02	0.000000	010100
0.2301319	0.3847187	0.000000	0.000000	0.6677049E-02	001100
0.7244359E-02	0.2321848E-02	0.000000	0.000000	0.2099155E-04	100001
-0.5969189	-0.6510624E-02	0.000000	0.000000	0.1326949E-03	010001
0.000000	0.000000	0.6450940E-01	0.1163177	0.000000	001001
0.6965719E-01	0.1150780	0.000000	0.000000	-0.2918539	000200
0.000000	0.000000	-0.5663147	0.7805351E-01	0.000000	000101
0.3497070E-01	0.4095972E-03	0.000000	0.000000	-0.1713718E-02	000002

Table 4: Second order transfer map calculated by `COSY INFINITY` around the reference trajectory. The units system used for the coefficient is m & rad.

3.9 B(I) curve

The relation between Ampere.turns and field value at the center of the magnet in our model is presented in Fig. 13

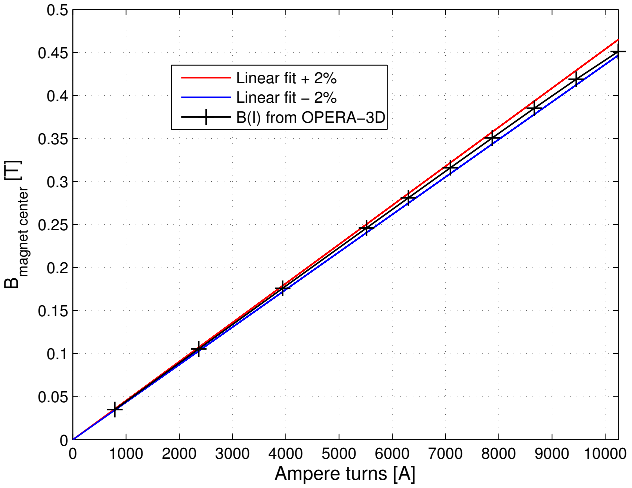

Figure 13: Field value at the center of the magnet, function of the Ampere.turns (per coil).

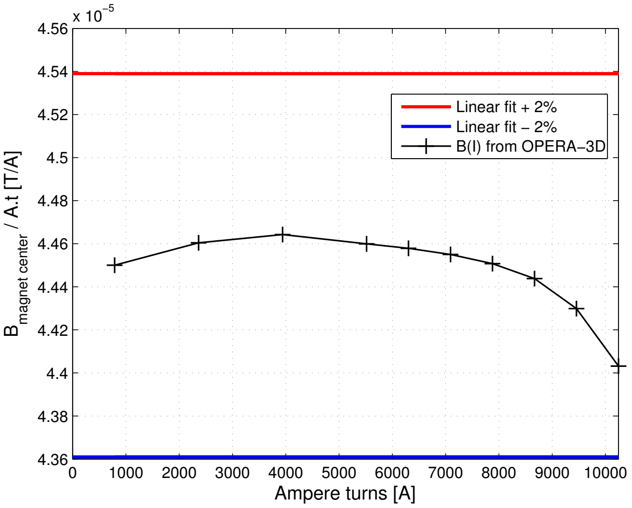

Figure 14: Same as Fig. 13, but for convenience we plot here B/Ampere.turns.

4 Tolerances & Field Measurement Specifications

4.1 Mechanical Tolerances

Tight tolerances ($\sim 100\ \mu$m) must be specified only on the following part:

- ◇ poles flatness,
- ◇ straightness of the pole edges crossed by the beam,
- ◇ shape chamfers,
- ◇ parallelism between the pole edges and the clamps,
- ◇ flatness of the face of the clamps facing the beam.

See TRIUMF drawing TMD0096D Dipole Specification Drawing” for more information.

4.2 Field Measurement

4.2.1 Field strength at the magnet center

- ◇ It must be checked that the field at the magnet center can reach 0.740 T, and run continuously for three hours.
- ◇ We also require a calibration (B vs. I) curve, giving vertical component of the B field at the center of the magnet for at least five different currents.

4.2.2 Field map and integrals

We want a field map in the mid-plane and calculation of straight line field integrals. Proposed measurement procedure:

- ◇ Check that the field integral, in the mid-plane, along a straight line passing by the center of the magnet exceeds the expected value of 29.51 T.mm (see Fig. 8).
- ◇ In the mid-plane only, measure (map) the vertical field every 10 mm along straight lines as described in Fig. 15, from x = -30 mm to x = +30 mm. This must be done with the field at the center equal to 0.350 T. The field integrals along these lines may be calculated from the field map and must be identical within ± 0.55% over ± 30 mm.
- ◇ If the field integrals satisfy these conditions, and if the magnet is built according to the specified mechanical tolerances, then the field quality satisfies our requirements.
- ◇ We also want a similar field map showing the residual fields (I=0) done after operating at 0.350T.

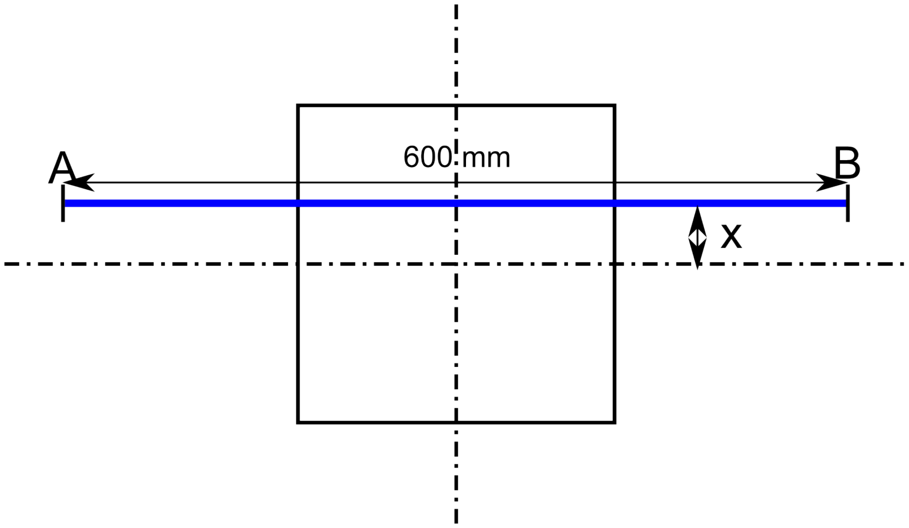

Figure 15: Schematic description of the trajectories along which the field integrals will be measured.

4.2.3 Data

TRIUMF should get a copy of all the measured data, including field components and coordinates (indexed against the physical dimensions of the magnet) for each measurment point.

References

[1] K. Makino, M. Berz, Cosy infinity version 9, Nucl. Instr. and Meth. A 558 (1) (2006) 346 – 350, proc. of ICAP 2004. doi:10.1016/j.nima.2005.11.109.