TRIUMF

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TRI-DN-12-22 - E-linac Strong Dipoles EABT:MB0, EHDT:MB2, EHBT:MB25/29/33/37, & EHBTE:MB6 Design Note

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History of Changes

Release Number	Date	Description of Changes	Author(s)
01	2013/04/05	Initial Release	T. Planche

Contents

1 Basic Magnet Requirements

Magnet type	H-frame rectangular dipole
Maximum bending angle	34°
Maximum electron energy (corresponding rigidity $B\rho$)	75 MeV (0.2519 T.m)
Full gap height	53.2 mm
B_{max}	≥ 0.67 T
Field quality requirement: sextupole components	≤ 3.5 rad.m^{-2}
Particular case of EABD:MB0: sextupole components	≤ 20 rad.m^{-2}

Table 1: Basic magnet requirements.

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

$$\int_{-\infty}^{+\infty} B\mathrm{d}l = B\rho\ [\mathrm{T.m}] \times \text{bending angle}\ [\mathrm{rad}] \simeq 0.1495\ [\mathrm{T.m}]. \tag{1}$$

The increment dl is taken along the electron path.

2 Constraints

Design constraints are listed in Table 2.

Maximum power consumption	2200 W
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	$\leq 7.10^{-4}$ T
The vacuum chamber must fit	see EABD:MB0 vacuum chamber design (Fig. 9)

Table 2: Design constraints.

3 Parameters of our Design

3.1 Summary Table

Coil	
Ampere turns per coil	14420 A.t
Minimum inner dimensions [mm] (Given by the pole dimensions, see Fig. 2)	180 × 193 (x×y)
Maximum outer dimensions [mm] (Given by the yoke, clamp and pole dimensions, see Fig. 2 & 3)	329 × 303 × 127 (x×y×z)
Pole dimensions (see Figs. 1 & 3)	
Pole width (**pw**)	180 mm
Pole length (**pl**)	193 mm
Pole height (**ph**)	127 mm
Chamfer height (**chh**)	10 mm
Chamfer angle (**cha**)	30 deg.
Yoke dimensions (see Figs. 1 & 3)	
Magnet width (**mw**)	479 mm
Return yoke thickness (**yt**)	75 mm
Magnet height (**mh = 2*ph + 2*yt** + gap)	457.2 mm
Field clamps (see Figs. 1, 3 & 5)	
Clamp thickness (**clt**)	15 mm
Clamp width (**clw**)	170 mm
Magnetic connection clamp-yoke thickness (**cct**)	20 mm
Thickness of the gap between yoke and clamps (**tgt**)	0.1 mm
Magnet length (**ml**) (see Fig. 1)	333 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.

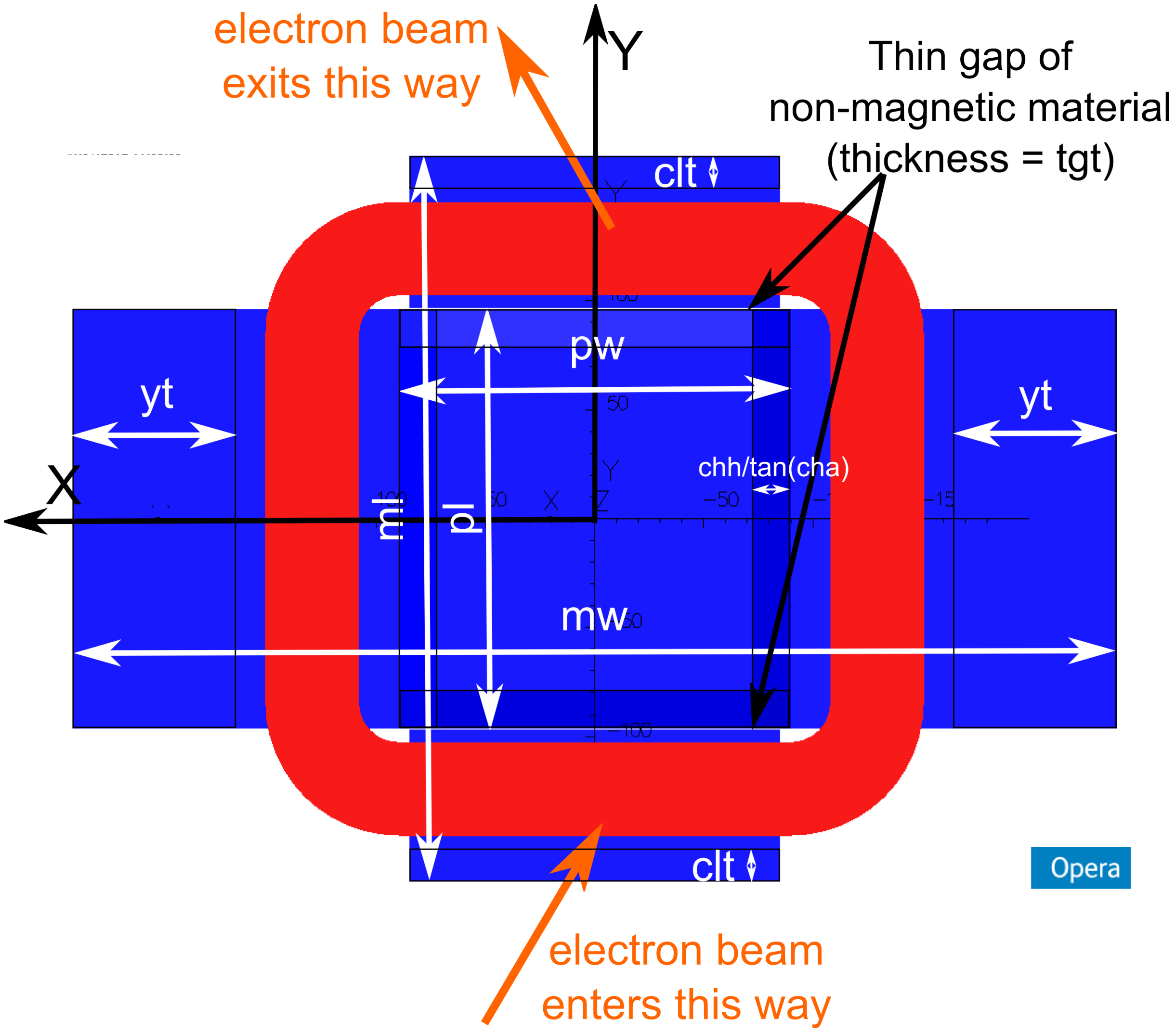

Figure 1: `OPERA-3D` model: plan view of half of the magnet. Steel volumes are in blue, coil is in red. Note: the chamfer goes all the way around the pole.

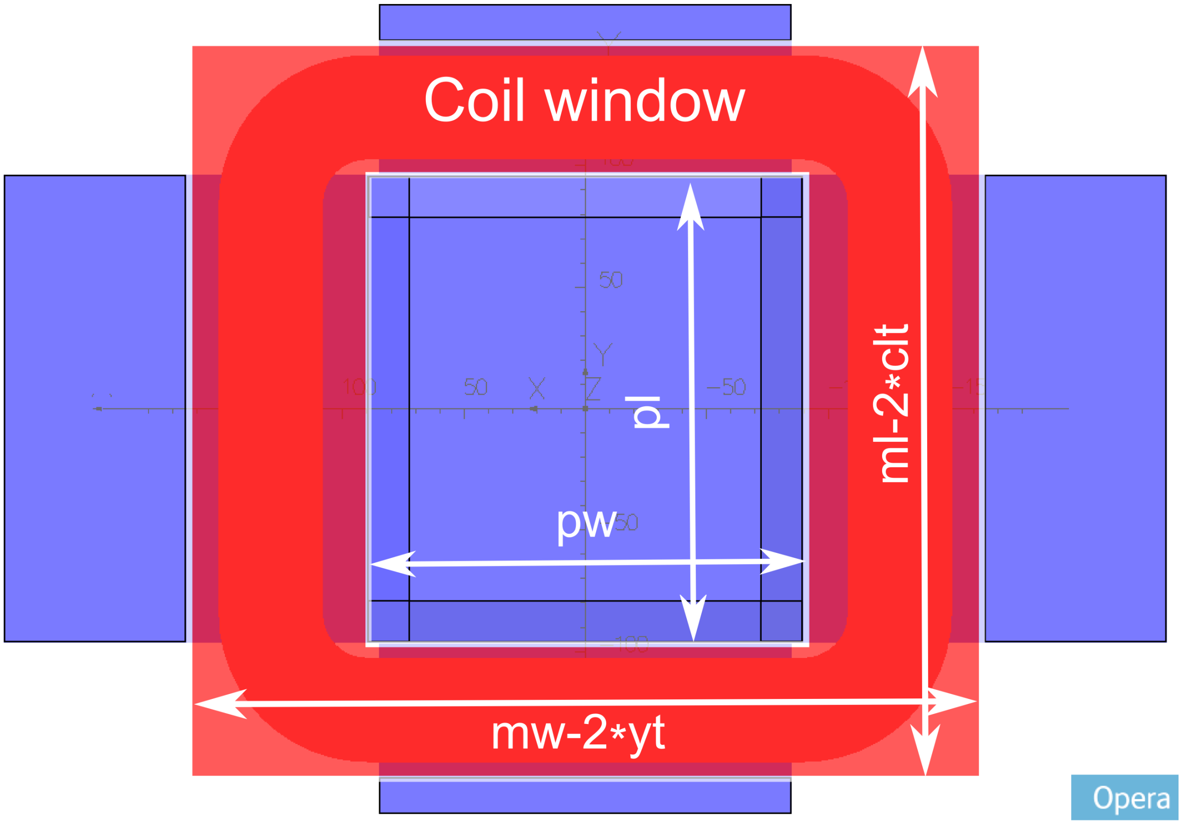

Figure 2: Schematic showing maximum dimensions **mw-2*yt** and **ml-2*clt**, and minimum dimensions **pw** and **pl**.

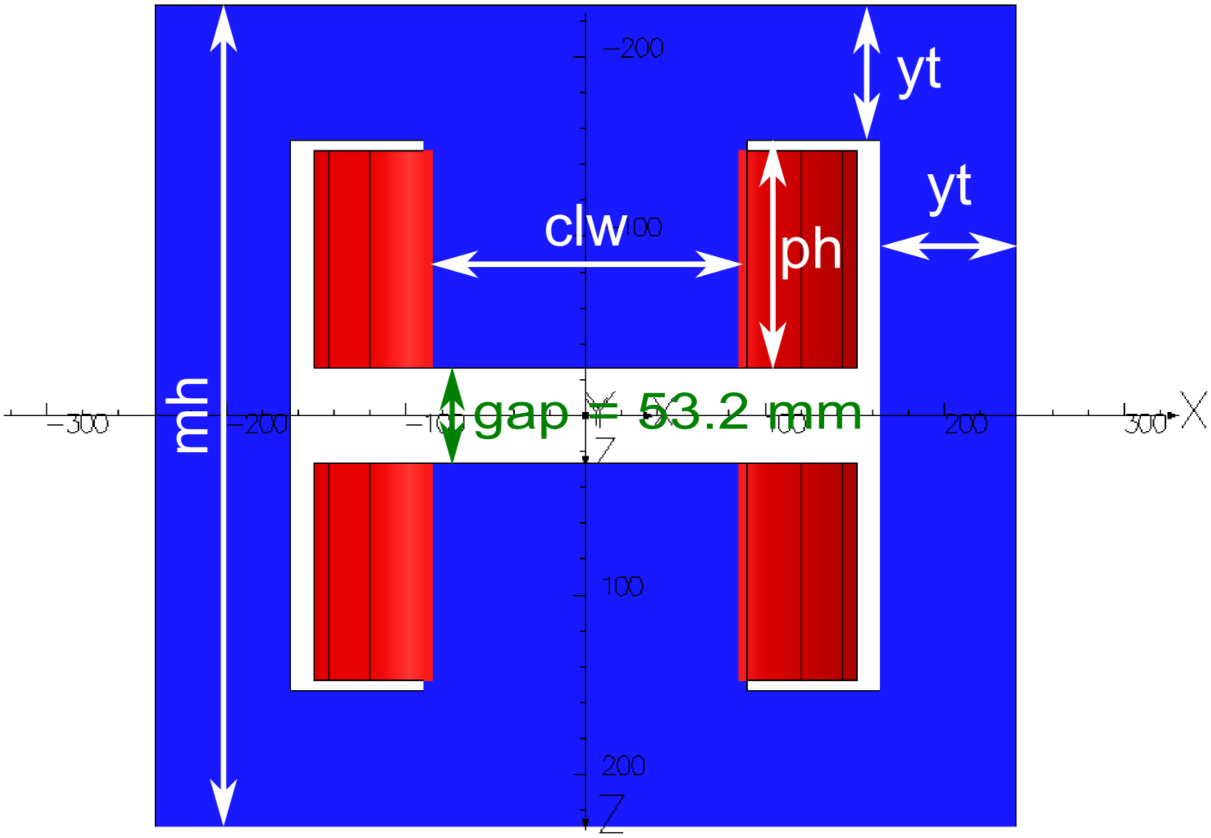

Figure 3: `OPERA-3D` model: front view of the whole magnet. Steel volumes are in blue, coils are in red. Note: the piece of steel which connect the clamp to the yoke lines up with the inside edge of the yoke.

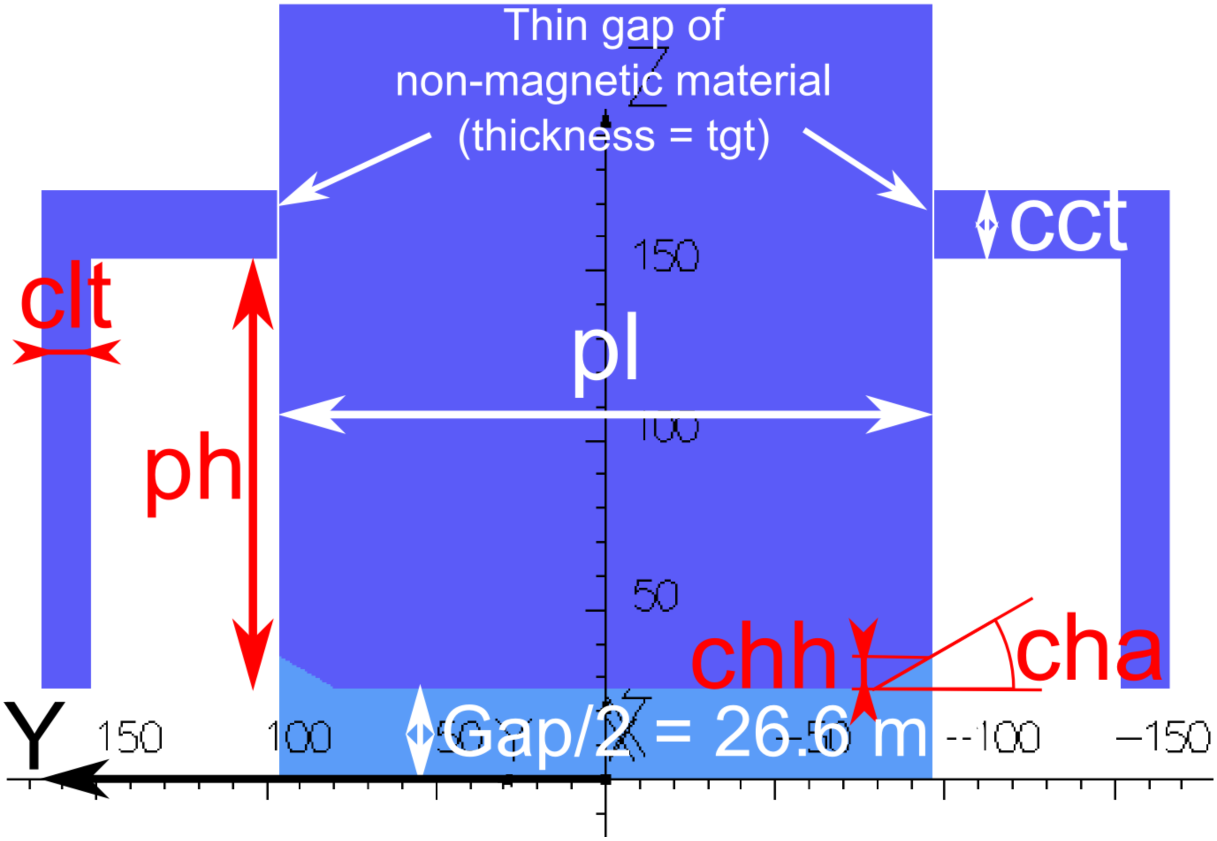

Figure 4: `OPERA-3D` model: Side view of one quarter of the magnet. Only steel volumes are shown.

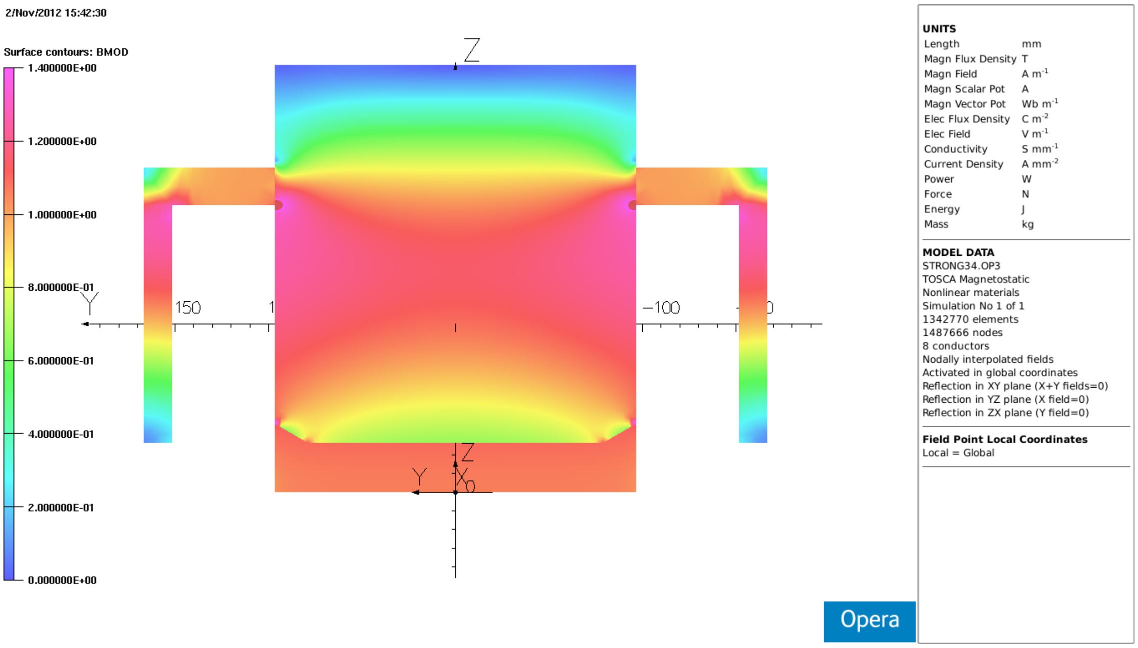

Figure 5: `OPERA-3D` model: Side view of one quarter of the magnet, showing field level in the steel.

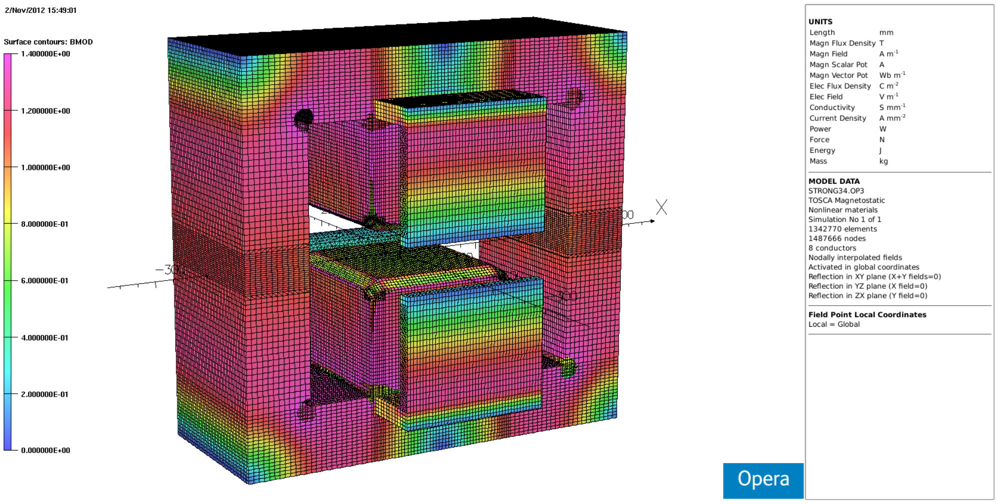

Figure 6: 3D view of the model showing the field level on the surface of the steel + mesh.

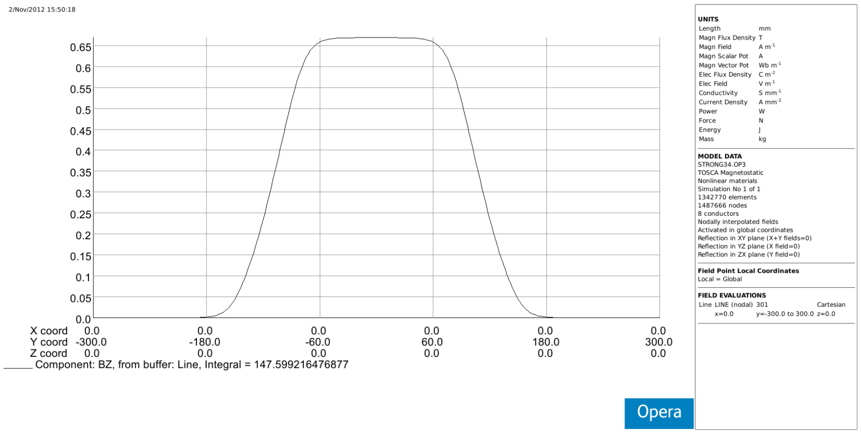

Figure 7: From our OPERA-3D model: vertical component of the magnetic field along the y axis (at x=0 & z=0).

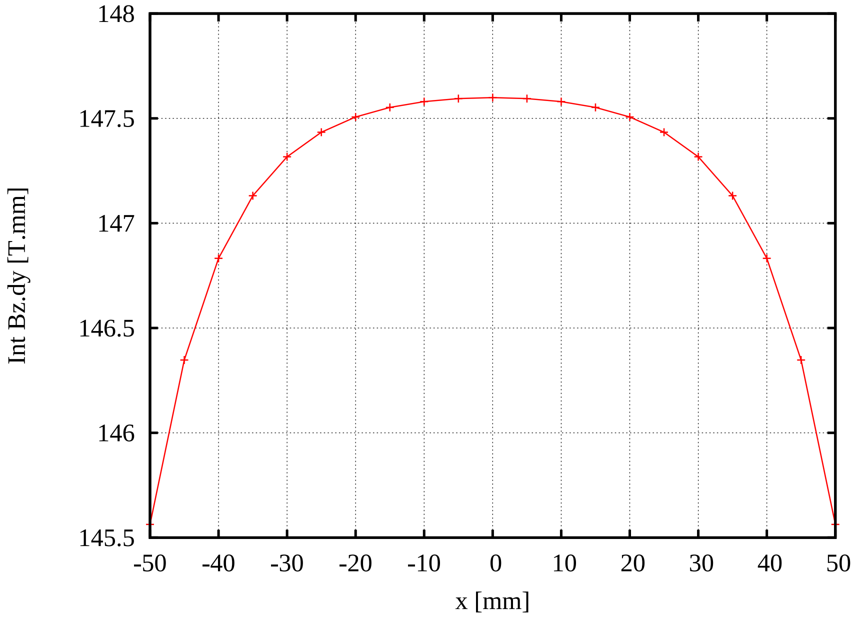

Figure 8: $\int B_z \mathrm{d}y$, along straight lines, as described in Fig. 20 (see Section 4.2).

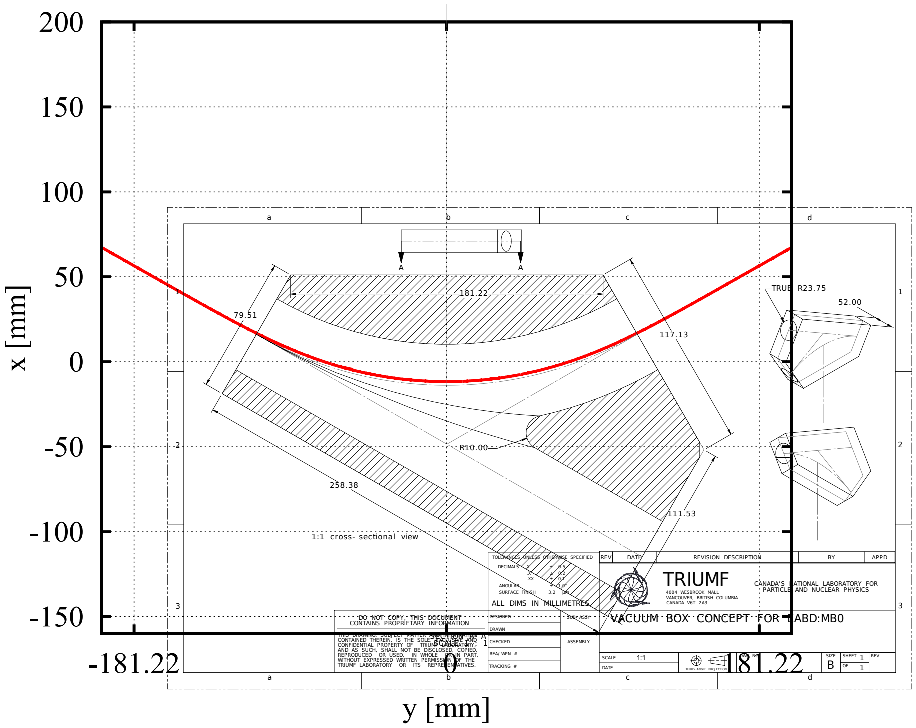

Figure 9: EABD:MB0 reference trajectory (same than in Fig. 16) plotted over a 2D drawing of the vacuum chamber.

3.2 Coil Parameters

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

$$\mathrm{NI}_{\text{per coil}} = \frac{1}{2}\left(\frac{\mathrm{B}_{\max}\ [\mathrm{T}]\ \cdot\ \text{full gap}\ [\mathrm{m}]}{4\pi 10^{-7}}\right) \simeq 14180\ [\mathrm{A.t}] \tag{2}$$

The `OPERA-3D` model of this design used in fact 14420 A.t to produce the required amount of field.

3.3 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 left between the coil and the yoke).

3.4 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 = 170 mm. This comes from a compromize between field quality and reduction of the fringe field extent.
- ◇ A 0.1 mm thin gap of non-magnetic material
- ◇ The Field clamp thickness keeps the maximum field in the clamps below 1.4T (see Fig. 5).

3.5 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.

3.6 Steel Properties

The BH curve used in this model is shown in Fig. 10.

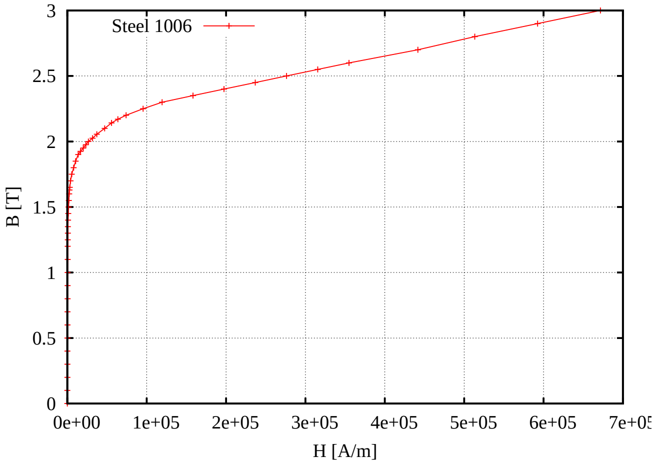

Figure 10: BH curve used in our model (AISI 1006 steel).

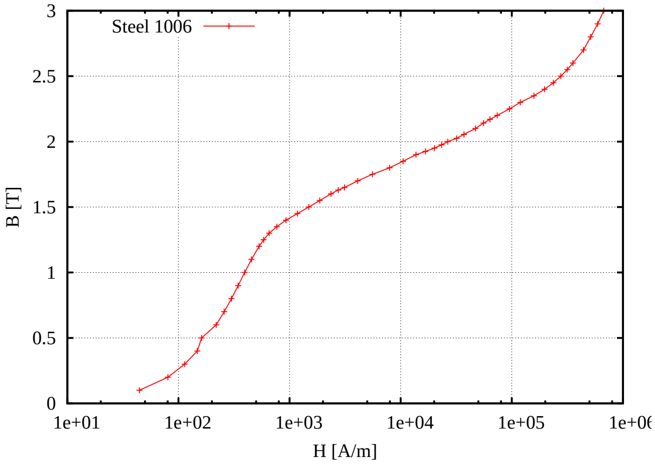

Figure 11: Same as Fig. 10 but with a log scale.

3.7 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 version 9` [1] to track particles of different energies, and from different entry points, corresponding to the two trajectories to be studied (nominal 34° bend at 75 MeV and 60° bend at 30 MeV). Results are summarized in the two following subsections.

3.7.1 34° bend

We used this field map in `COSY INFINITY` to track 75 MeV electrons entering the magnet at an angle of 17°. 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. 12. One can see on this figure that the sextupole components are minimum around $x_0 \simeq 65$ mm, and values are smaller than required (in Table. 1). The trajectory starting from $x_0 = 65$ mm is our reference trajectory (see Fig. 13). The magnetic field seen by the particle along this trajectory is shown in Fig. 14. The transfer map calculated (to the second order) around this trajectory is presented in Table 4.

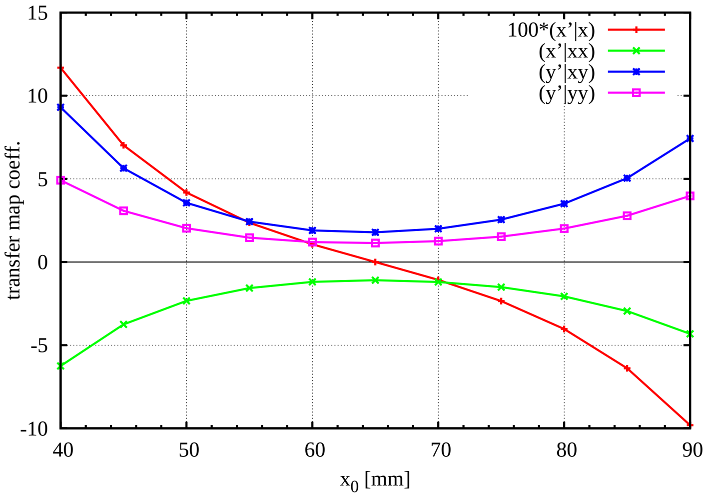

Figure 12: Quadrupole component and major sextupole components calculated around trajectories entering the field map at x_0, with an angle of 17°. The units system used for the coefficient is m & rad.

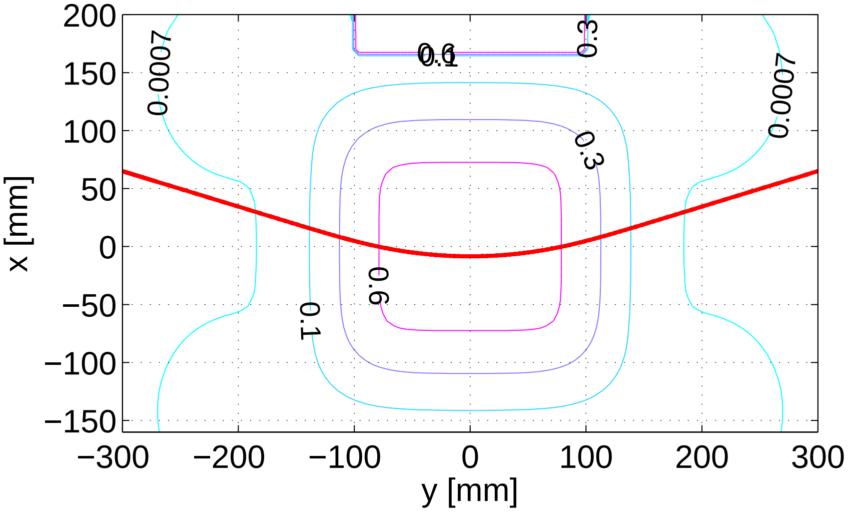

Figure 13: Red line: reference trajectory. Contours represent the absolute value of the magnetic field from the 2D-field map (in Tesla).

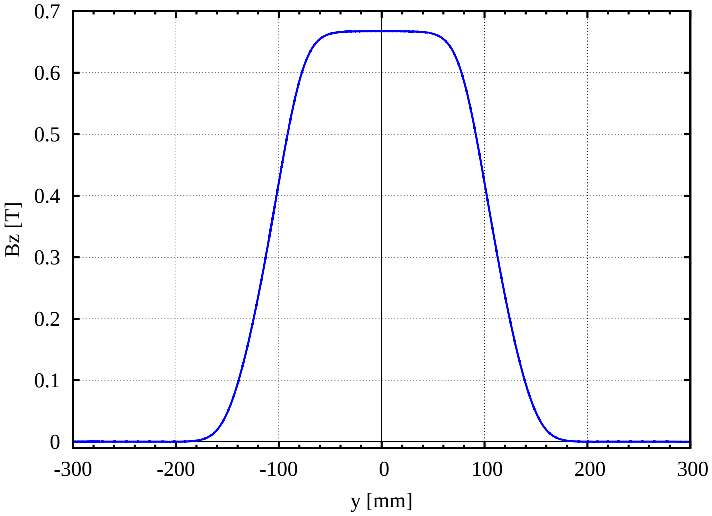

Figure 14: Field **seen by a 75 MeV electron** traveling along the reference trajectory. (Note: only the vertical component of the field is non-zero, since the reference trajectory lies in the mid-plane).

x	x’	y	y’	l	(x|x’|y|y’|l| δ_k)
0.9999907	-0.1290483E-04	0.000000	0.000000	0.6076420	100000
0.6056522	1.000001	0.000000	0.000000	0.1840263	010000
0.000000	0.000000	0.5948272	-1.263477	0.000000	001000
0.000000	0.000000	0.5114667	0.5947501	0.000000	000100
0.000000	0.000000	0.000000	0.000000	1.000000	000010
-0.1839951	-0.6076453	0.000000	0.000000	-0.1378213E-01	000001
-0.3304301	-1.091275	0.000000	0.000000	-0.2678610E-01	200000
-0.8038946	-0.6610005	0.000000	0.000000	-0.1996474	110000
-0.1217468	0.2017831	0.000000	0.000000	-0.3371480	020000
0.000000	0.000000	0.9670443	1.785517	0.000000	101000
0.000000	0.000000	0.9447655	0.5406999	0.000000	011000
-0.6491094E-01	1.144459	0.000000	0.000000	-0.9149373	002000
0.000000	0.000000	-0.1877346	0.9671402	0.000000	100100
0.000000	0.000000	-0.5682441E-01	-0.3590169	0.000000	010100
0.4901073	0.3392116	0.000000	0.000000	0.3548534E-01	001100
0.1996650	0.5357999E-01	0.000000	0.000000	-0.3591097E-03	100001
-0.5533536	-0.1672088	0.000000	0.000000	-0.1391008E-03	010001
0.000000	0.000000	0.5612550	1.043914	0.000000	001001
0.2585218	0.3036437	0.000000	0.000000	-0.2305090	000200
0.000000	0.000000	-0.2923948	0.9575138	0.000000	000101
0.1865315	0.5591118E-01	0.000000	0.000000	-0.3450596E-01	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.

3.7.2 Particular case of EABD:MB0 – 30 MeV 60° bend

We have found that the same magnet design could also be used for the EABD:MB0, which is a 60°, 30 MeV dipole.

To study the optical property of this magnet used as a 60° 30 MeV bender, we scaled the original field map by roughly a factor $60°/34° \times 30$ MeV/75 MeV $\simeq 0.7$, and used `COSY INFINITY` to track 30 MeV electrons entering the magnet at an angle of 30°. 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. 15. One can see on this figure that the sextupole components are minimum around $x_0 \simeq 125$ mm, and smaller than the 20 rad.m^{-2} required for this particular dipole (see Table. 1) . The trajectory starting from $x_0 = 125$ mm is our reference trajectory (see Fig. 16). The magnetic field seen by the particle along this trajectory is shown in Fig. 17. The transfer map calculated (to the second order) around this trajectory is presented in Table 5.

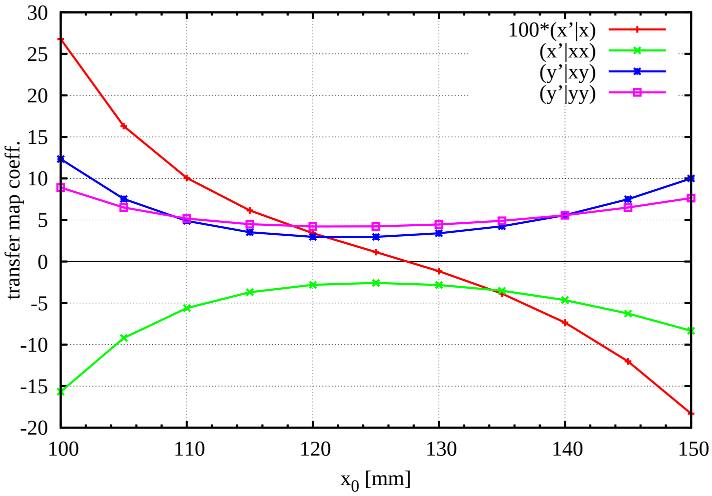

Figure 15: Quadrupole component and major sextupole components calculated around trajectories entering the field map at x_0, with an angle of 60°. The units system used for the coefficient is m & rad.

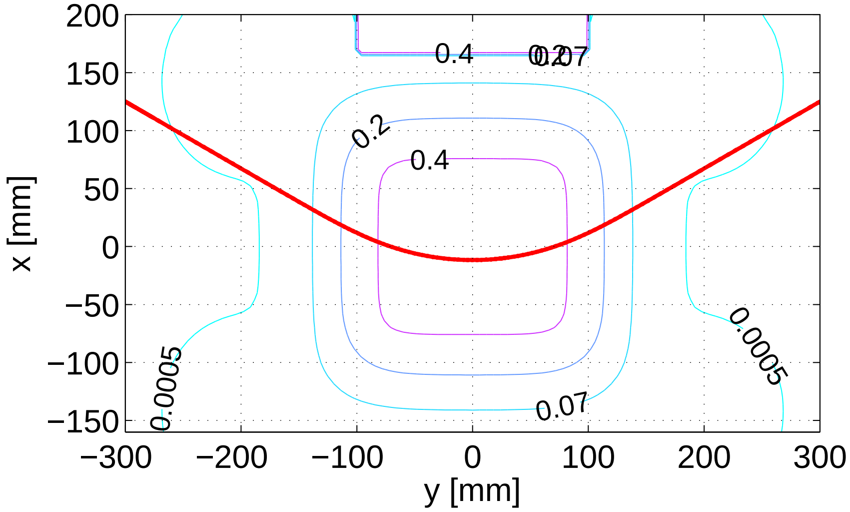

Figure 16: Red line: reference trajectory. Contours represent the absolute value of the magnetic field from the 2D-field map (in Tesla).

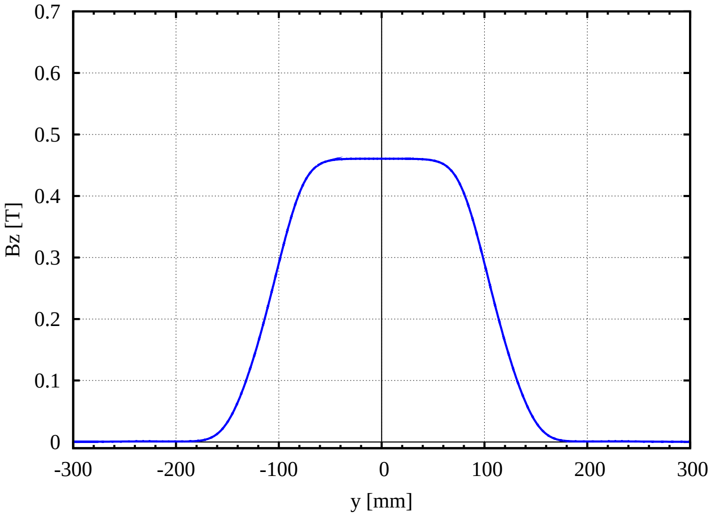

Figure 17: Field **seen by a 30 MeV electron** traveling along the reference trajectory. (Note: only the vertical component of the field is non-zero, since the reference trajectory lies in the mid-plane).

x	x'	y	y'	l	(x|x'|y|y'|l| δ_k)
1.003586	0.1134623E-01	0.000000	0.000000	1.140618	100000
0.6222334	1.003462	0.000000	0.000000	0.3535958	010000
0.000000	0.000000	-0.1863676	-3.121929	0.000000	001000
0.000000	0.000000	0.3094070	-0.1827221	0.000000	000100
0.000000	0.000000	0.000000	0.000000	1.000000	000010
-0.3548669	-1.140555	0.000000	0.000000	-0.4253877E-01	000001
-0.8091698	-2.578082	0.000000	0.000000	-0.5027111E-01	200000
-1.707246	-1.598036	0.000000	0.000000	-0.7213692	110000
-0.2639536	0.3551342	0.000000	0.000000	-0.4476298	020000
0.000000	0.000000	2.890101	2.965472	0.000000	101000
0.000000	0.000000	2.270734	0.9201927	0.000000	011000
-0.8260981	4.226893	0.000000	0.000000	-4.136849	002000
0.000000	0.000000	0.6344447	2.871038	0.000000	100100
0.000000	0.000000	0.1951859	-0.4843687	0.000000	010100
0.1973791	1.441177	0.000000	0.000000	-0.7925417	001100
0.7136821	0.9225612E-01	0.000000	0.000000	-0.4451856E-02	100001
-0.4511442	-0.6614949	0.000000	0.000000	-0.1442019E-03	010001
0.000000	0.000000	1.143022	0.9594004	0.000000	001001
0.3697436	0.5057645	0.000000	0.000000	-0.2055353	000200
0.000000	0.000000	0.3235326	2.706185	0.000000	000101
0.3847818	0.3957999	0.000000	0.000000	-0.1304890	000002

Table 5: Second order transfer map calculated by `COSY INFINITY` around the reference trajectory. The units system used for the coefficient is m & rad.

3.8 B(I) curve

The relation between Ampere.turns and field value at the center of the magnet in our model is presented in Fig. 18

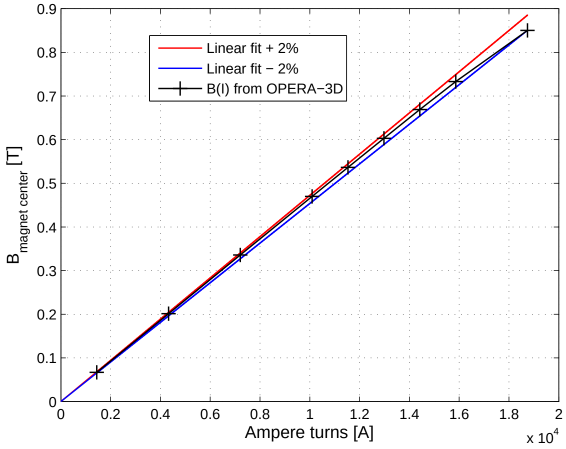

Figure 18: Field value at the center of the magnet, function of the Ampere.turns (per coil).

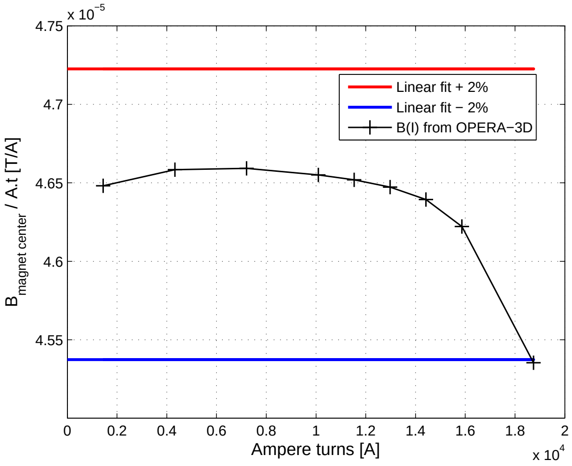

Figure 19: Same as Fig. 18, but for convenience we plot here B/Ampere.turns.

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 TMD0003D“ARIEL S34 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 0.670 T, and run continuously for three hours.
- ◇ We also wish to have 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 147.6 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. 20, from x = -50 mm to x = +50 mm. This must be done with the field at the center equal to 0.670 T. The field integrals along these lines may be calculated from the field map and must be identical within ± 8.0% over ± 50 mm, AND within ± 0.23% 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 0.670T.

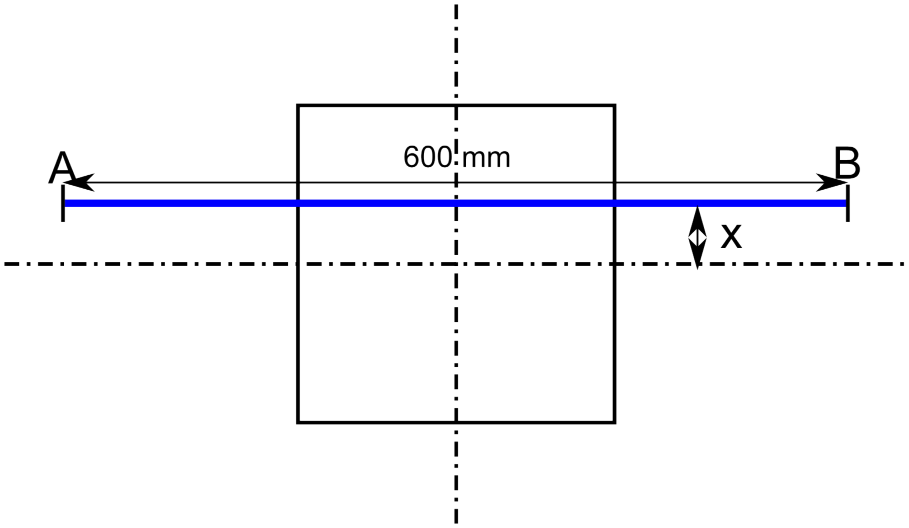

Figure 20: Schematic description of the trajectories along which the field integrals will be measured.

4.2.3 Data

TRIUMF should get a copy of all the measured data.

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`.