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History of Changes

Release Number	Date	Description of Changes	Author(s)
01	2012/11/02	Initial Release	T. Planche

Contents

1 Basic Magnet Requirements

Magnet type	H-frame rectangular dipole
Maximum bending angle	32°
Maximum electron energy (corresponding rigidity $B\rho$)	15 MeV ($5.17\ 10^{-2}$ T.m)
Full gap height	53.2 mm
B_{max}	≥ 0.19 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:

$$\int_{-\infty}^{+\infty} B\mathrm{d}l = B\rho\ [\mathrm{T.m}] \times \text{bending angle [rad]} \simeq 2.89\ 10^{-2}\ [\mathrm{T.m}]. \qquad (1)$$

The increment $\mathrm{d}l$ is taken along the electron path.

2 Constraints

This magnet will be (in phase 2) part of an extremely congested beam line, which implies that the major design constraints are its insertion length and width. The other design constraints are listed in Table 2.

Maximum power consumption	350 W
Steel magnetization	≤ 1.4 T
B(I) linearity over the whole range	within $\pm$ 2%
Fringe field extent: remaining field at 0.2 m from the magnet center	 $\leq 3.10^{-4}$ T
The vacuum chamber must fit	see PHASE-II vacuum chamber design (Fig. 9)

Table 2: Design constraints.

3 Parameters of our Design

3.1 Summary Table

Coil	
Ampere turns per coil	4140 A.t
Minimum inner dimensions [mm] (Given by the pole dimensions, see Fig. 2)	130 × 128.2 (x×y)
Maximum outer dimensions [mm] (Given by the yoke, clamp and pole dimensions, see Fig. 2 & 3)	236.4 × 194.2 × 70 (x×y×z)
Pole dimensions (see Figs. 1 & 3)	
Pole width (**pw**)	130 mm
Pole length (**pl**)	128.2 mm
Pole height (**ph**)	70 mm
Chamfer height (**chh**)	5 mm
Chamfer angle (**cha**)	30 deg.
Yoke dimensions (see Figs. 1 & 3)	
Magnet width (**mw**)	270.4 mm
Return yoke thickness (**yt**)	17 mm
Magnet height (**mh = 2*ph + 2*yt** + gap)	227.2 mm
Field clamps (see Figs. 1, 3 & 5)	
Clamp thickness at the top (**clt**)	5 mm
Clamp width (**clw**)	110 mm
Magnetic connection clamp-yoke thickness (**cct**)	10 mm
Magnet length (**ml**) (see Fig. 1)	204.2 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.

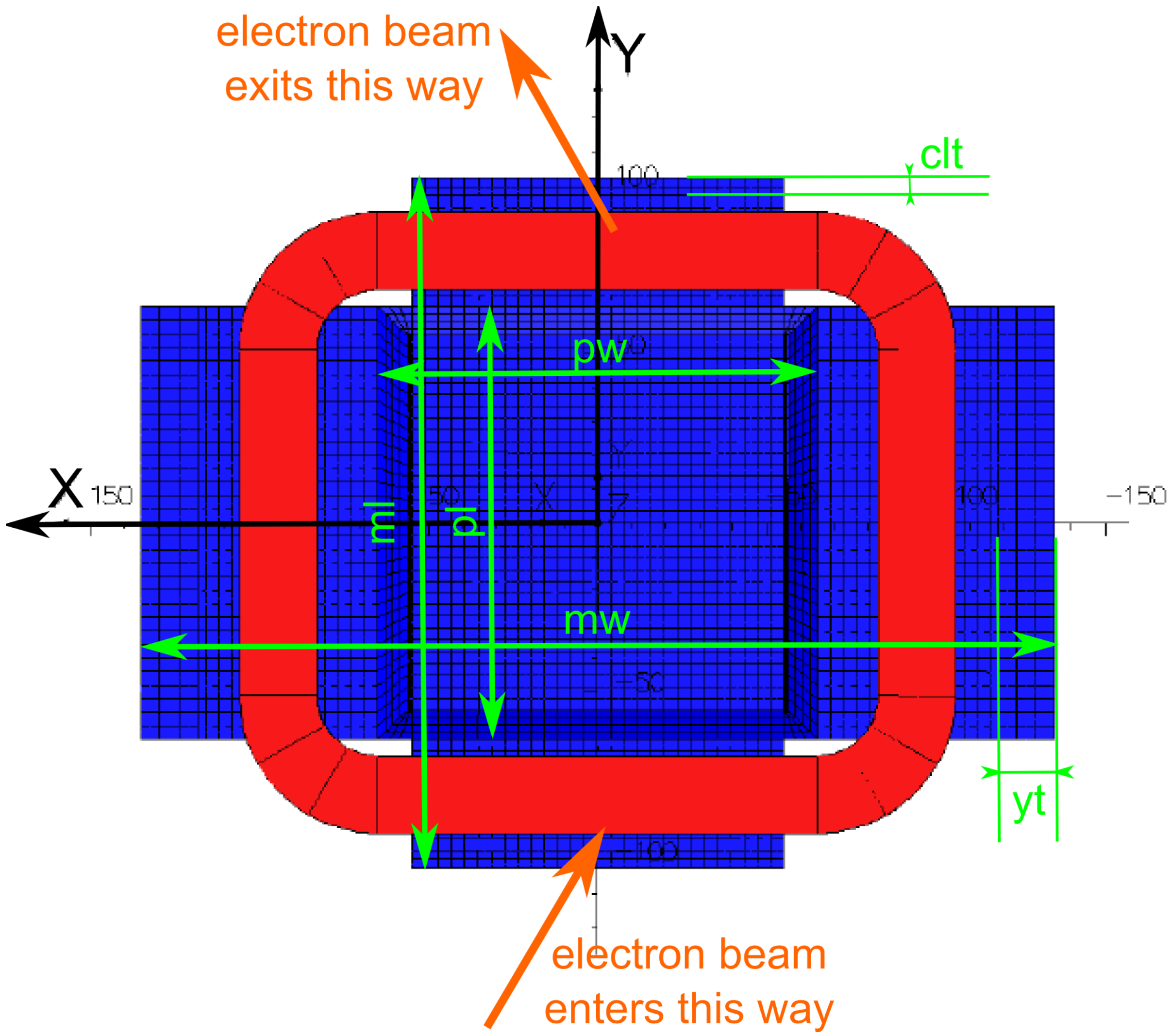

Figure 1: `OPERA-3D` model: plan view of half of the magnet. Steel volumes are in blue, coil is in red. Note: the chamfer goes all the way around the pole.

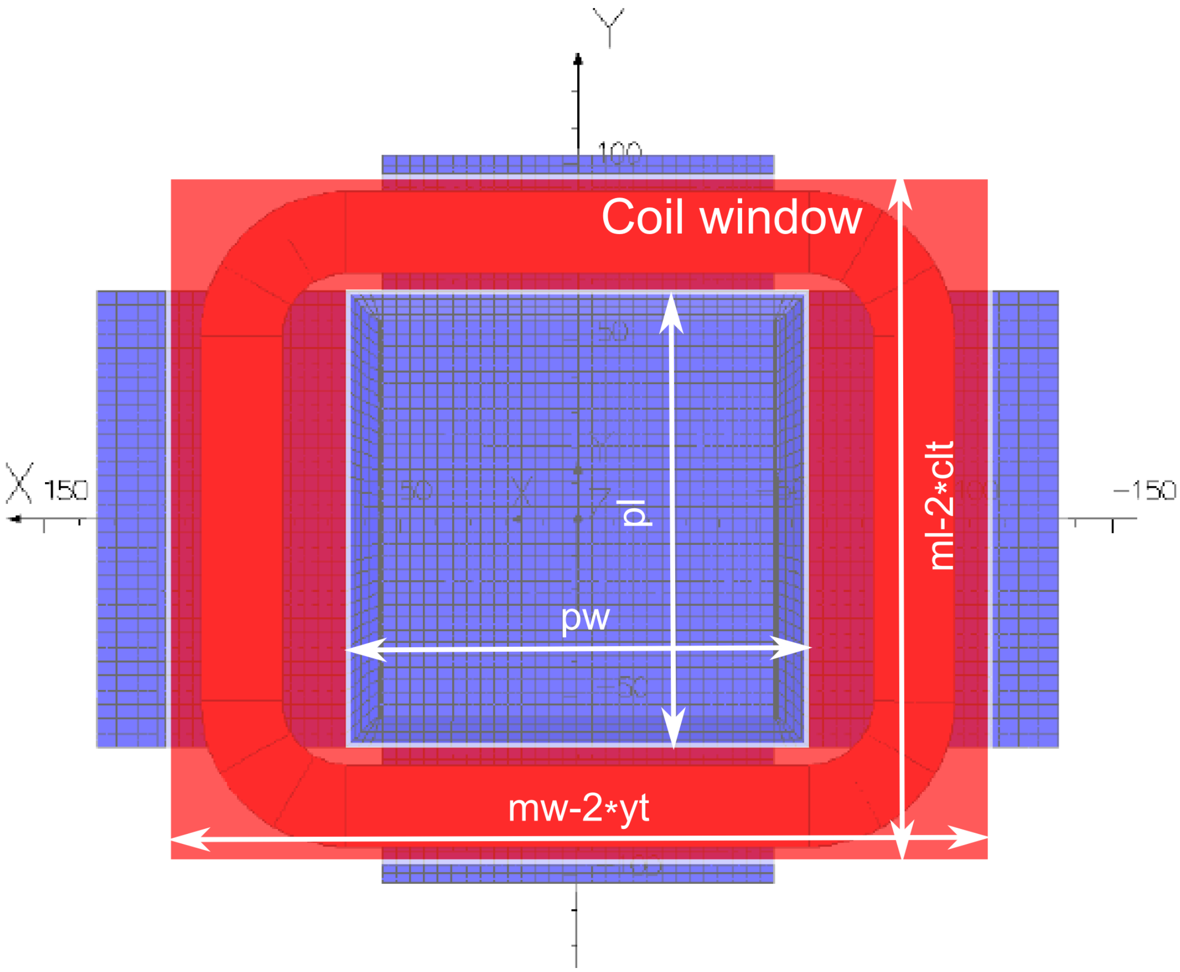

Figure 2: Schematic showing maximum dimensions **mw-2*yt** and **ml-2*clt**, and minimum dimensions **pw** and **pl**.

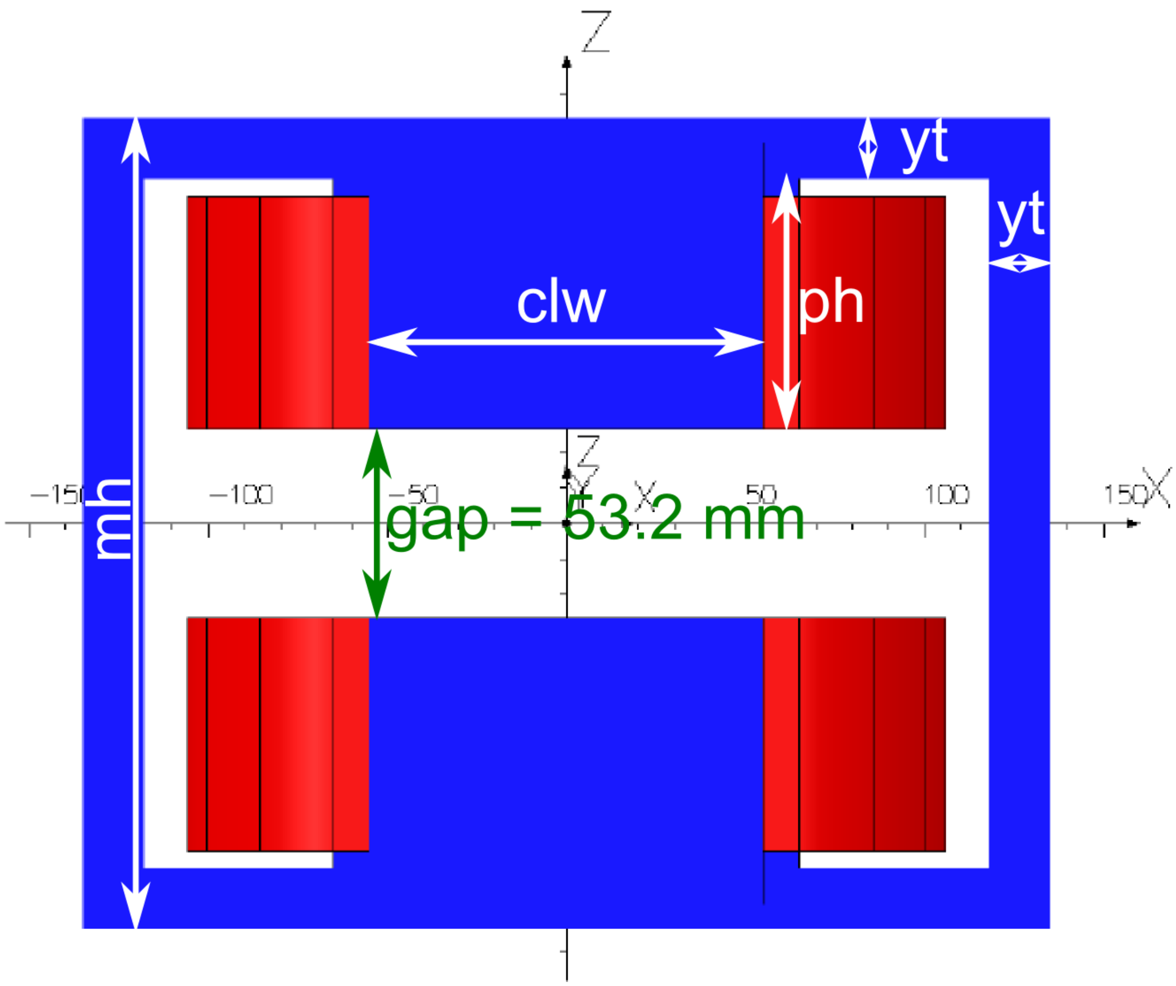

Figure 3: `OPERA-3D` model: front view of the whole magnet. Steel volumes are in blue, coils are in red. Note: the piece of steel which connect the clamp to the yoke lines up with the inside edge of the yoke.

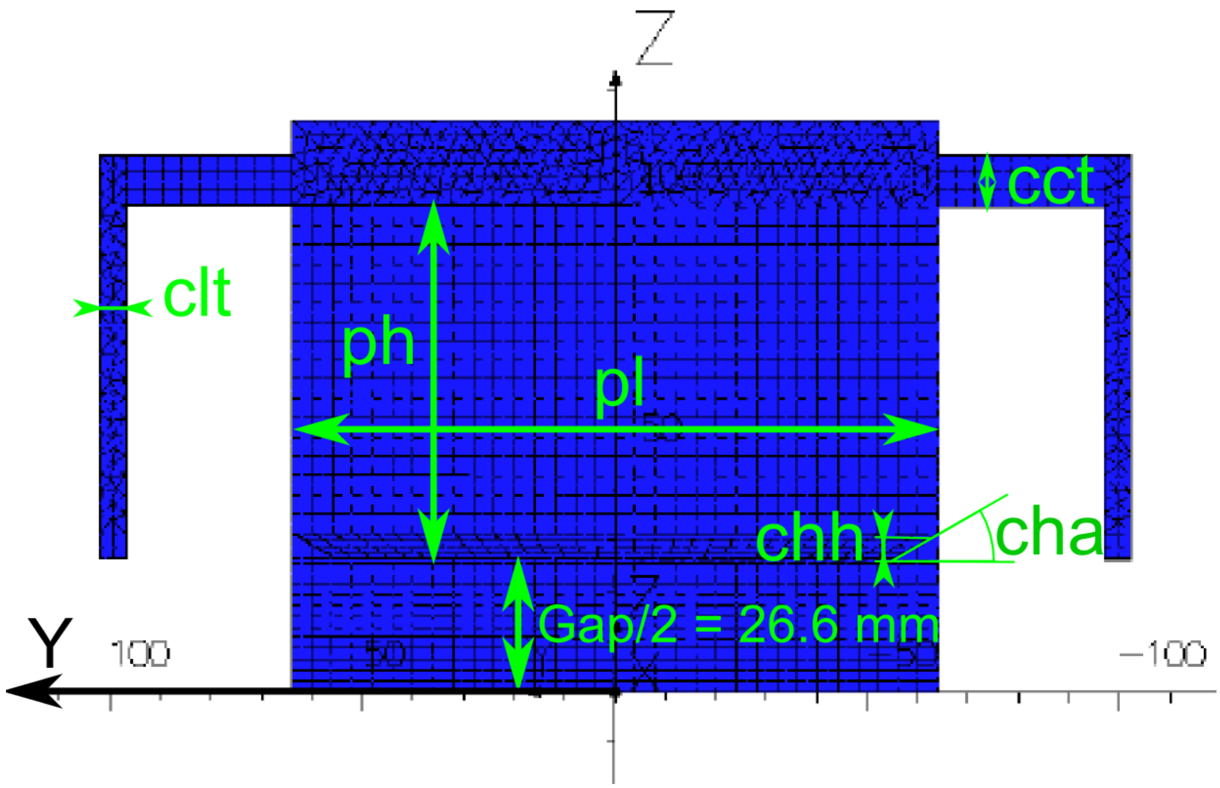

Figure 4: `OPERA-3D` model: Side view of one quarter of the magnet. Only steel volumes are shown. The mesh is also shown (black lines).

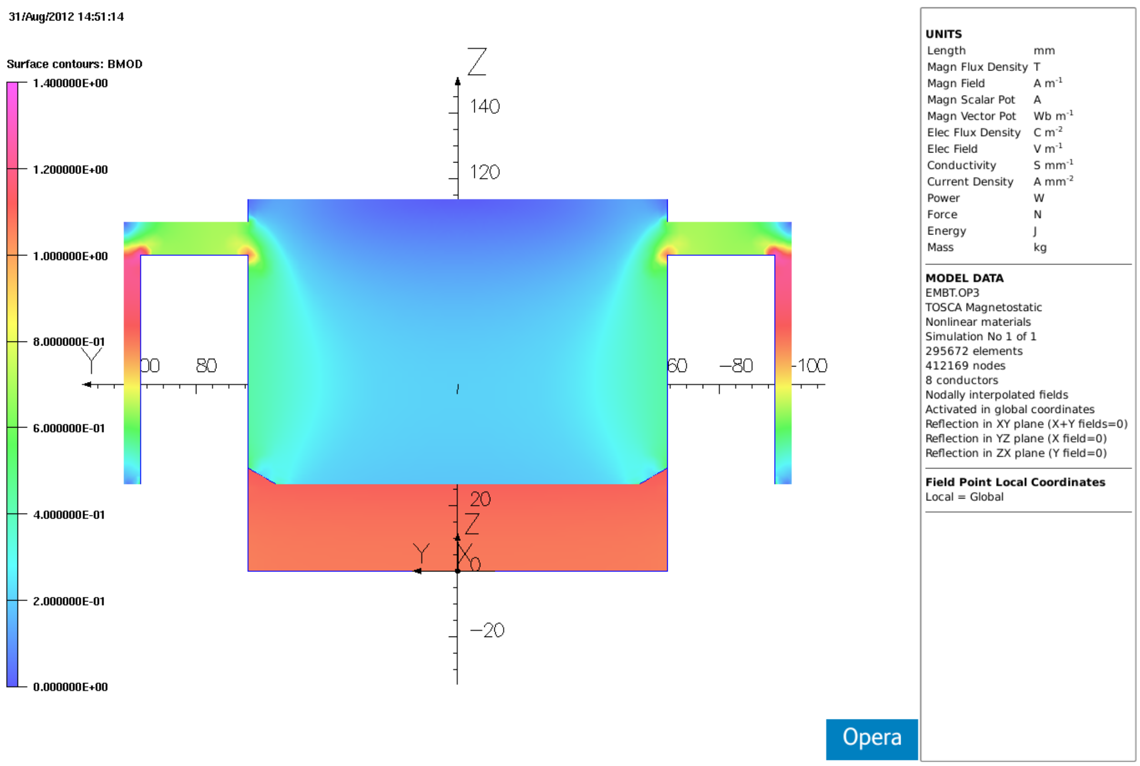

Figure 5: `OPERA-3D` model: Side view of one quarter of the magnet, showing field level in the steel.

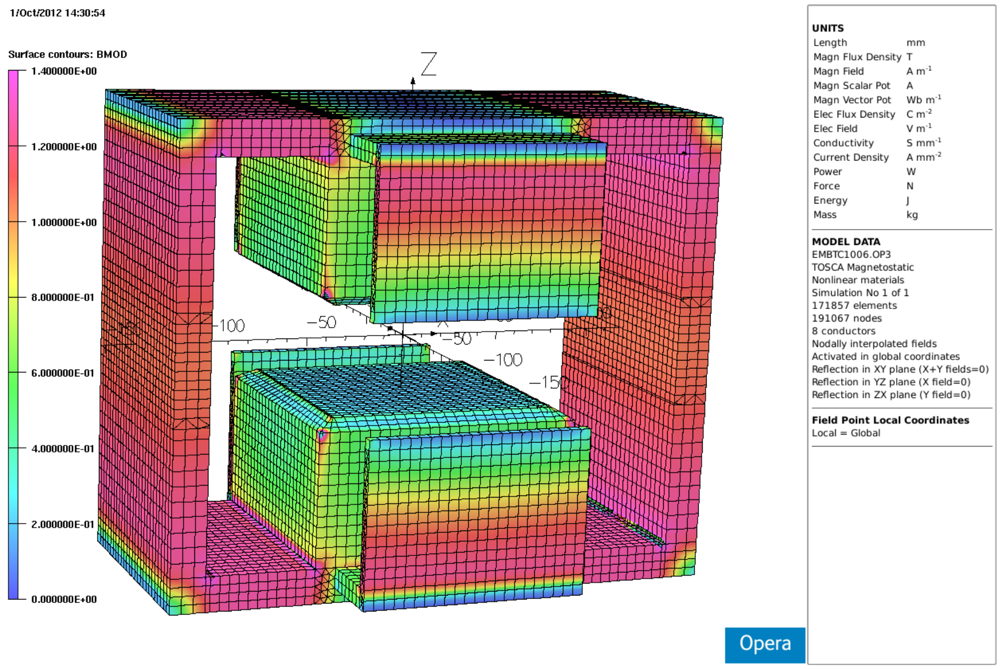

Figure 6: 3D view of the model showing the field level on the surface of the steel + mesh.

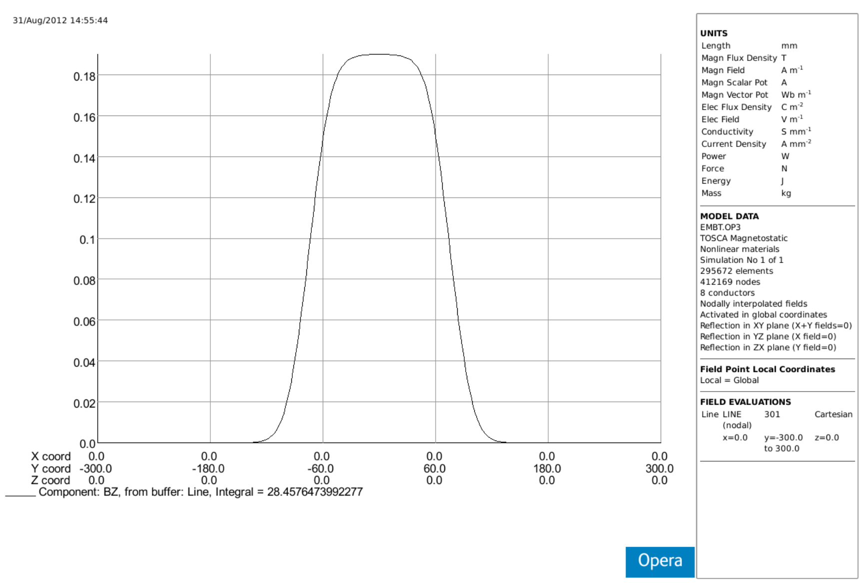

Figure 7: From our OPERA-3D model: vertical component of the magnetic field along the y axis (at x=0 & z=0).

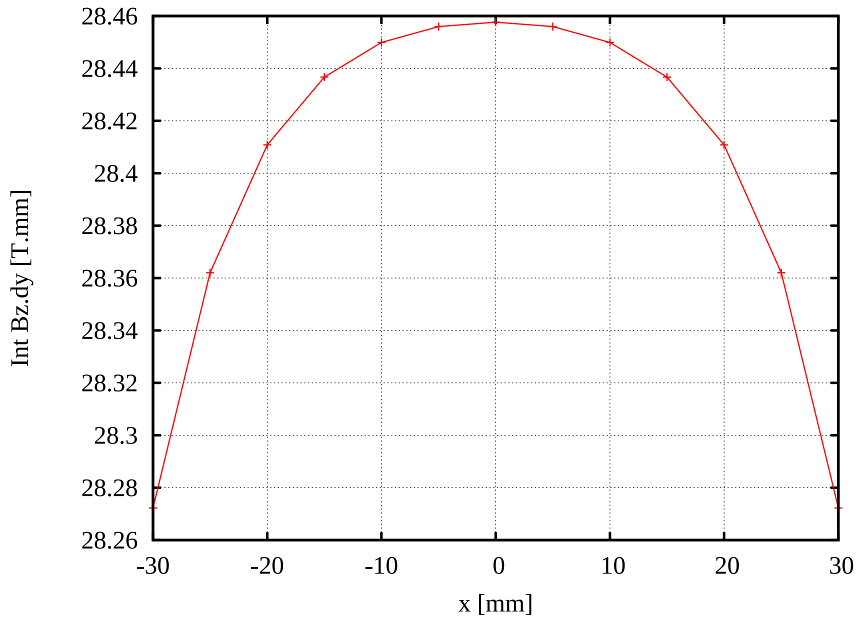

Figure 8: $\int B_z \mathrm{d}y$, along straight lines, as described in Fig. 21 (see Section 4.2).

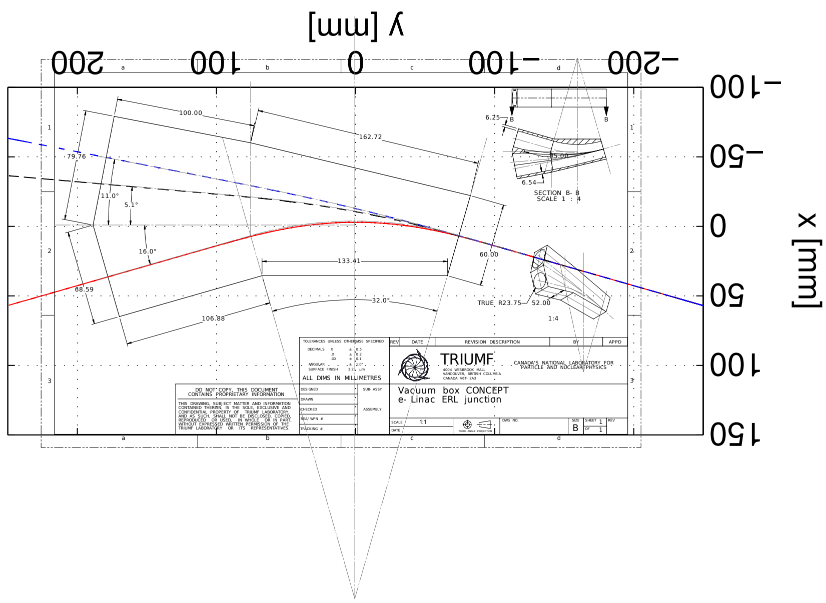

Figure 9: PHASE-II trajectories (same than in Fig. 16) plotted over a 2D drawing of the vacuum chamber.

3.2 Coil Parameters

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

$$\mathrm{NI}_{\text{per coil}} = \frac{1}{2}\left(\frac{B_{max}\ [\mathrm{T}]\ \cdot\ \text{full gap [m]}}{4\pi 10^{-7}}\right) \simeq 4022\ [\mathrm{A.t}] \tag{2}$$

The `OPERA-3D` model of this design used in fact 4140 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 for a maximum field (in the mid plane) of about 0.190 T.
- ◇ 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 (+5 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 = 110 mm. This has been found to be close to the optimum from the point of view of the field quality.
- ◇ 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 well below 1.4 T (see Fig. 6).
- ◇ The distance between the pole and the return yoke (set equal to the gap height) 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. This BH curve was created at TRIUMF (by Paul Reeve), from the measurement of several samples of AISI 1006 steel.

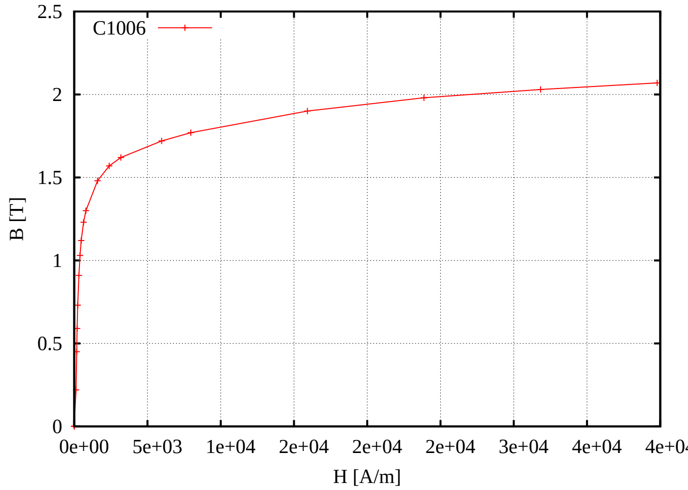

Figure 10: BH curve used in our model (AISI 1006 steel).

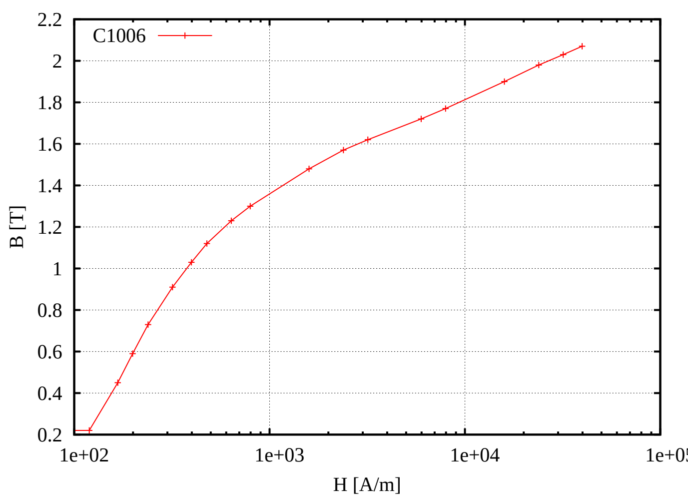

Figure 11: Same as Fig. 10 but with a log scale.

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

This type of magnet will be used in PHASE-I and in PHASE-II in different configurations. To study the optical properties of the magnet in these different configurations, we analyzed the optical properties along four different trajectories.

A 2D field map of the magnet mid-plane has been extracted from the model. The field maps covers an area of ± 100 mm in X and ± 250 mm in Y, with a step size of 5 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 four trajectories to be studied. Results are summarized in the two following subsections.

3.7.1 PHASE-I configuration

In PHASE-I, the nominal bending angle of these two dipoles is only 18°. The field map obtained at nominal current has been scaled by a factor 18°/32°. We used this scaled field map in `COSY INFINITY` to track 15 MeV electrons entering the magnet at an angle of 9°. 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 $x_0 \simeq 31$ mm, and values are smaller than required (in Table. 1). The trajectory

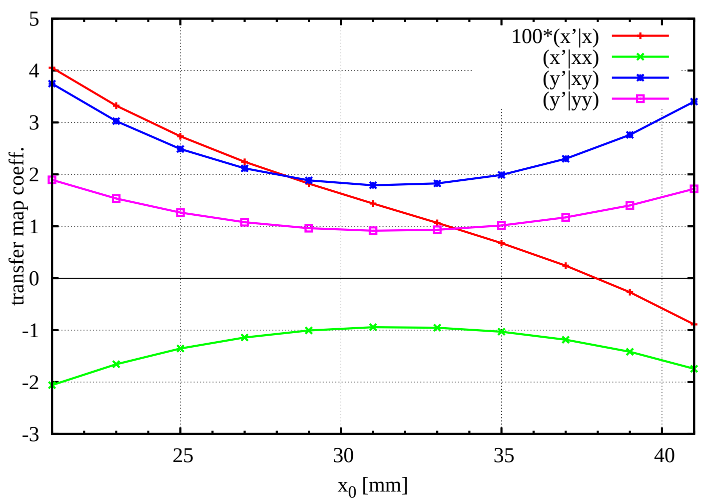

Figure 12: Quadrupole component and major sextupole components calculated around trajectories entering the field map at x_0, with an angle of 9°. The units system used for the coefficient is m & rad.

starting from $x_0 = 31$ mm is the reference trajectory for the PHASE-I configuration (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.

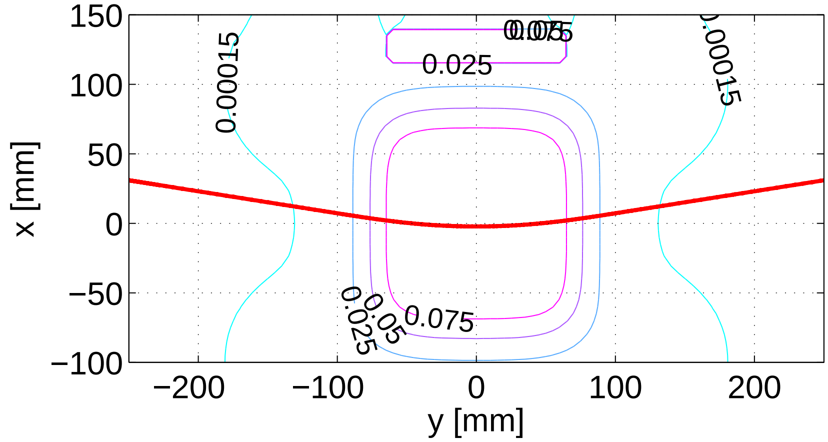

Figure 13: Red line: PHASE-I reference trajectory. Contours represent the absolute value of the magnetic field from the 2D-field map (in Tesla).

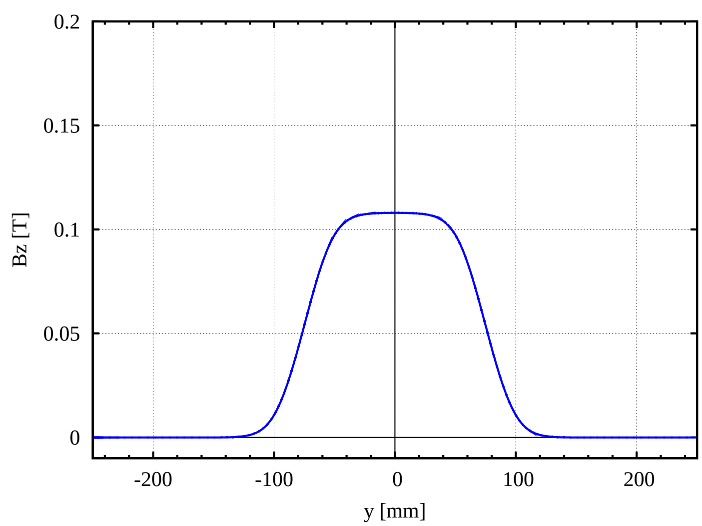

Figure 14: Field **seen by a 15 MeV electron** traveling along the PHASE-I reference trajectory. (Note: only the vertical component of the field is non-zero, since the reference trajectory lies in the mid-plane).

x	x'	y	y'	l	(x|x'|y|y'|l| δ_k)
1.003616	0.1438749E-01	0.000000	0.000000	0.3069777	100000
0.5028674	1.003606	0.000000	0.000000	0.7702556E-01	010000
0.000000	0.000000	0.8568956	-0.5620544	0.000000	001000
0.000000	0.000000	0.4726613	0.8569756	0.000000	000100
0.000000	0.000000	0.000000	0.000000	1.000000	000010
-0.7706502E-01	-0.3069766	0.000000	0.000000	-0.2002172E-02	000001
-0.2394906	-0.9444077	0.000000	0.000000	-0.5321875E-03	200000
-0.4538753	-0.4739317	0.000000	0.000000	-0.5492283E-01	110000
-0.5692085E-01	0.1073864	0.000000	0.000000	-0.2523850	020000
0.000000	0.000000	0.5422012	1.788906	0.000000	101000
0.000000	0.000000	0.4774614	0.4488960	0.000000	011000
0.1337341	0.9152969	0.000000	0.000000	-0.3098724	002000
0.000000	0.000000	-0.1411201	0.5370676	0.000000	100100
0.000000	0.000000	-0.3545194E-01	-0.2066425	0.000000	010100
0.3892482	0.3841109	0.000000	0.000000	0.3490710E-01	001100
0.4784963E-01	0.2774166E-03	0.000000	0.000000	0.1628773E-03	100001
-0.4789894	-0.5457682E-01	0.000000	0.000000	0.7888173E-04	010001
0.000000	0.000000	0.2179440	0.5113129	0.000000	001001
0.1280011	0.1882804	0.000000	0.000000	-0.2203673	000200
0.000000	0.000000	-0.3941497	0.3226049	0.000000	000101
0.7536098E-01	0.8306453E-02	0.000000	0.000000	-0.8510117E-02	000002

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

3.7.2 PHASE-II configuration

We used the field map obtained at nominal current in `COSY INFINITY` to track 15 MeV electrons entering the magnet at an angle of 16°. 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 $x_0 \simeq 57$ mm, and values are smaller than required (in Table. 1). The trajectory starting from $x_0 = 57$ mm is the PHASE-II reference

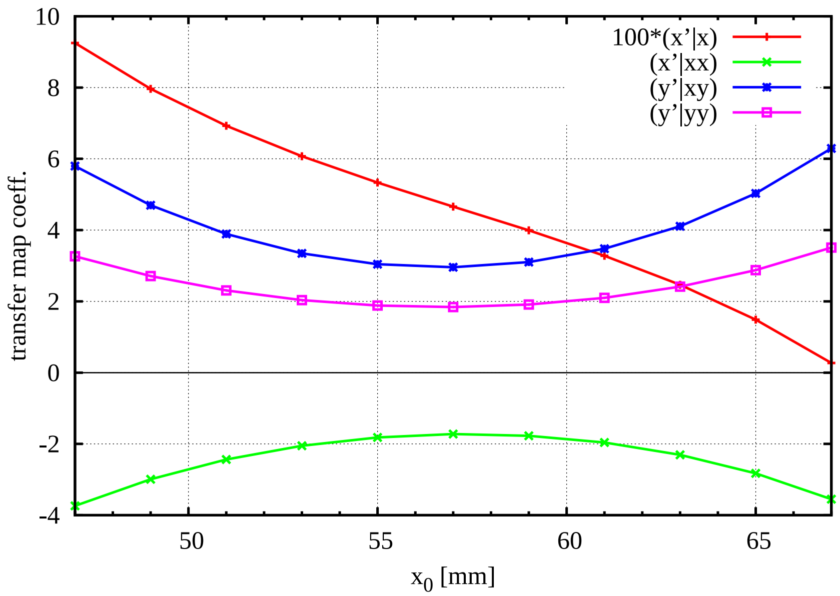

Figure 15: Quadrupole component and major sextupole components calculated around trajectories entering the field map at x_0, with an angle of 16°. The units system used for the coefficient is m & rad.

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.

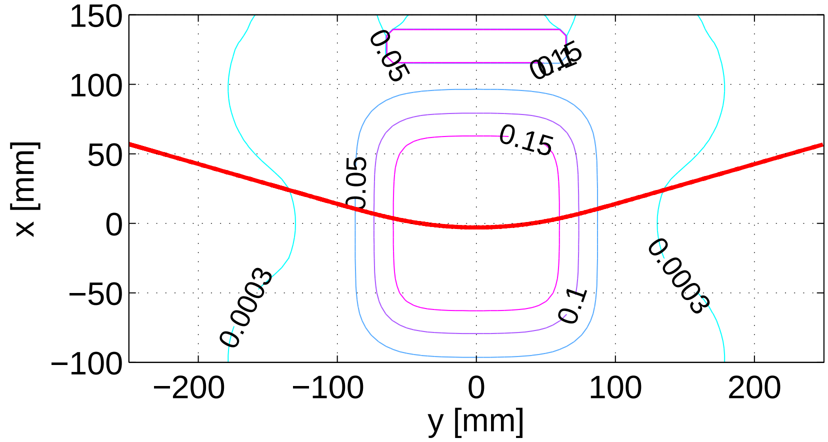

Figure 16: Red line: PHASE-II reference trajectory. Contours represent the absolute value of the magnetic field from the 2D-field map (in Tesla).

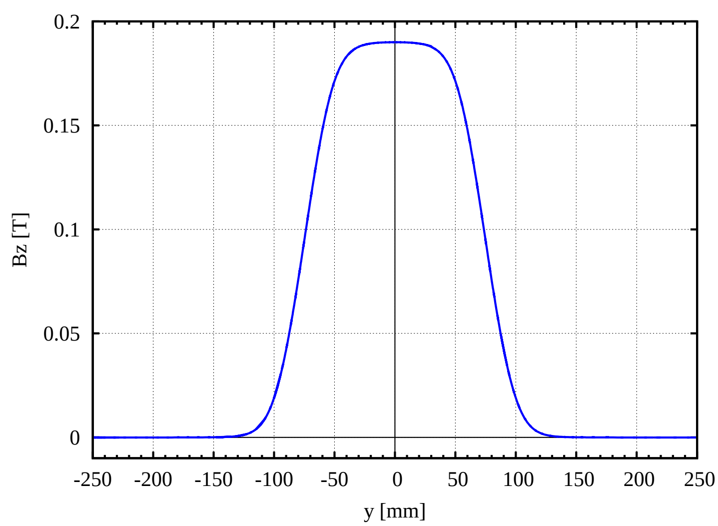

Figure 17: Field **seen by a 15 MeV electron** traveling along the PHASE-II reference trajectory. (Note: only the vertical component of the field is non-zero, since the reference trajectory lies in the mid-plane).

x	x'	y	y'	l	(x|x'|y|y'|l| δ_k)
1.011822	0.4658572E-01	0.000000	0.000000	0.5570365	100000
0.5082627	1.011717	0.000000	0.000000	0.1409224	010000
0.000000	0.000000	0.5578885	-1.673621	0.000000	001000
0.000000	0.000000	0.4118777	0.5568727	0.000000	000100
0.000000	0.000000	0.000000	0.000000	1.000000	000010
-0.1405325	-0.5569983	0.000000	0.000000	-0.7462796E-02	000001
-0.4492737	-1.724324	0.000000	0.000000	0.2776880E-02	200000
-0.8395714	-0.8725398	0.000000	0.000000	-0.1799029	110000
-0.1064154	0.1956936	0.000000	0.000000	-0.2761304	020000
0.000000	0.000000	1.243019	2.958193	0.000000	101000
0.000000	0.000000	0.9646802	0.7493663	0.000000	011000
-0.8060200E-01	1.838881	0.000000	0.000000	-1.219172	002000
0.000000	0.000000	-0.9068984E-01	1.215280	0.000000	100100
0.000000	0.000000	-0.2245591E-01	-0.3423160	0.000000	010100
0.4987121	0.5427197	0.000000	0.000000	-0.1710628E-01	001100
0.1561940	-0.1395477E-01	0.000000	0.000000	0.2145452E-02	100001
-0.4671117	-0.1846940	0.000000	0.000000	0.1593947E-03	010001
0.000000	0.000000	0.6324751	1.385809	0.000000	001001
0.2050421	0.2816337	0.000000	0.000000	-0.1867132	000200
0.000000	0.000000	-0.2015561	0.9964430	0.000000	000101
0.1406402	0.4937580E-01	0.000000	0.000000	-0.2672615E-01	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.

3.7.3 PHASE-II recirculating beam trajectories

The energy ratio between the injected beam and the recirculating beam is expected to range from 7 MeV/47 MeV to 15 MeV/45 MeV. The corresponding beam trajectories are shown in Fig. 18. Transfer maps corresponding to these two recirculating beam trajectories are given in Tables 6 and 7.

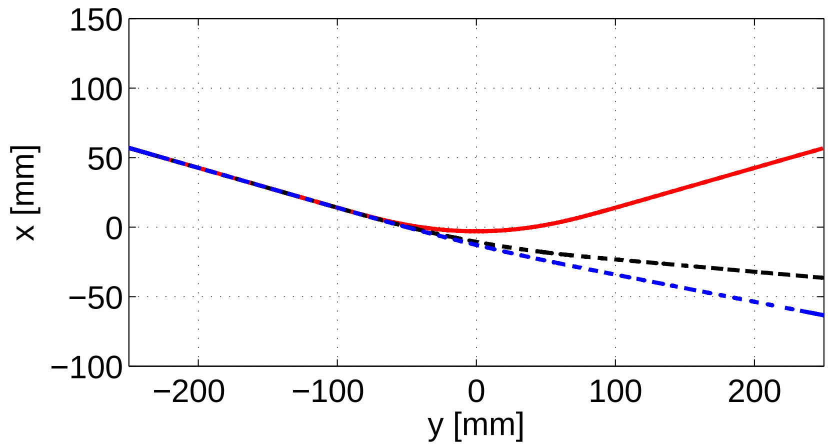

Figure 18: Red line: PHASE-II reference trajectory (same than the one shown in Fig. 16). Dotted blue line: recirculating beam trajectory for a ratio injected energy/recirculated energy = 7 MeV/47 MeV. Dotted black line: recirculating beam trajectory for a ratio injected energy/recirculated energy = 15 MeV/45 MeV. These two ratios span the entire range of operational configurations of the merger.

x	x'	y	y'	l	(x|x'|y|y'|l| δ_k)
1.026385	0.1821922E-01	0.000000	0.000000	0.8709683E-01	100000
0.5161502	0.9834556	0.000000	0.000000	0.2248021E-01	010000
0.000000	0.000000	0.9623505	-0.6408443E-01	0.000000	001000
0.000000	0.000000	0.5110645	1.005090	0.000000	000100
0.000000	0.000000	0.000000	0.000000	1.000000	000010
-0.2188171E-01	-0.8524630E-01	0.000000	0.000000	-0.1955494E-03	000001
-0.2633621	-1.206158	0.000000	0.000000	-0.5033999E-03	200000
-0.2583833	-0.7130031	0.000000	0.000000	-0.3074597E-01	110000
-0.3653539E-01	-0.5613852E-01	0.000000	0.000000	-0.2582614	020000
0.000000	0.000000	0.4990882	2.333637	0.000000	101000
0.000000	0.000000	0.2598636	0.7421918	0.000000	011000
0.2126802	1.113313	0.000000	0.000000	-0.2453925E-01	002000
0.000000	0.000000	0.8093110E-01	0.7126550	0.000000	100100
0.000000	0.000000	0.2882447E-01	0.1208233	0.000000	010100
0.2354270	0.6774761	0.000000	0.000000	0.2993268E-01	001100
-0.2037403E-01	0.8300905E-02	0.000000	0.000000	0.3311043E-03	100001
-0.5137258	0.1457718E-01	0.000000	0.000000	-0.8072133E-03	010001
0.000000	0.000000	0.4247166E-01	0.3522293E-01	0.000000	001001
0.5618054E-01	0.1388096	0.000000	0.000000	-0.2527456	000200
0.000000	0.000000	-0.5024485	0.7806388E-02	0.000000	000101
0.2164323E-01	-0.7116765E-03	0.000000	0.000000	-0.6395166E-03	000002

Table 6: Second order transfer map calculated by `COSY INFINITY` around the recirculating beam trajectory for a ratio injected energy/recirculated energy = 7 MeV/47 MeV. The units system used for the coefficient is m & rad.

x	x'	y	y'	l	(x|x'|y|y'|l| δ_k)
1.044398	0.2555027E-01	0.000000	0.000000	0.1932335	100000
0.5158892	0.9701100	0.000000	0.000000	0.4947926E-01	010000
0.000000	0.000000	0.9013882	-0.2415340	0.000000	001000
0.000000	0.000000	0.5006219	0.9752544	0.000000	000100
0.000000	0.000000	0.000000	0.000000	1.000000	000010
-0.4801101E-01	-0.1861935	0.000000	0.000000	-0.9269208E-03	000001
-0.3595977	-1.567160	0.000000	0.000000	-0.1052165E-02	200000
-0.4250677	-0.8905832	0.000000	0.000000	-0.6506904E-01	110000
-0.5800702E-01	-0.2395832E-01	0.000000	0.000000	-0.2597751	020000
0.000000	0.000000	0.6506080	2.934826	0.000000	101000
0.000000	0.000000	0.4423977	1.028903	0.000000	011000
0.1826646	1.345722	0.000000	0.000000	-0.1250192	002000
0.000000	0.000000	0.3578559E-01	0.9164603	0.000000	100100
0.000000	0.000000	0.2248442E-01	0.8676642E-01	0.000000	010100
0.3432737	0.8074083	0.000000	0.000000	0.5809036E-01	001100
-0.2032033E-01	0.1738557E-01	0.000000	0.000000	0.9482503E-03	100001
-0.5076630	0.1504317E-01	0.000000	0.000000	-0.2330166E-02	010001
0.000000	0.000000	0.1242294	0.1761899	0.000000	001001
0.9811067E-01	0.2052749	0.000000	0.000000	-0.2428965	000200
0.000000	0.000000	-0.4695435	0.8926224E-01	0.000000	000101
0.4708462E-01	-0.1513031E-02	0.000000	0.000000	-0.3069520E-02	000002

Table 7: Second order transfer map calculated by `COSY INFINITY` around the recirculating beam trajectory for a ratio injected energy/recirculated energy = 15 MeV/45 MeV. 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. 19

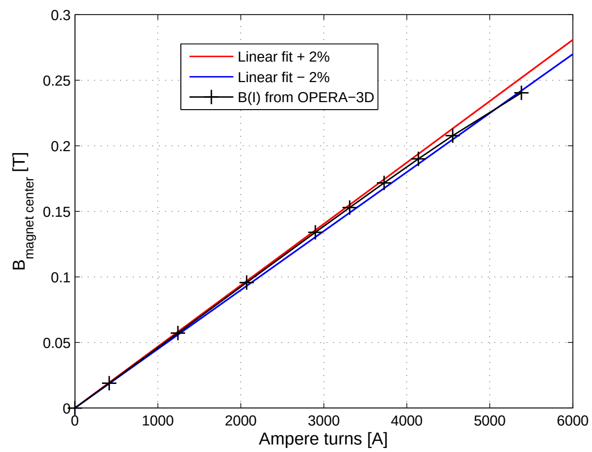

Figure 19: Field value at the center of the magnet, function of the Ampere.turns (per coil).

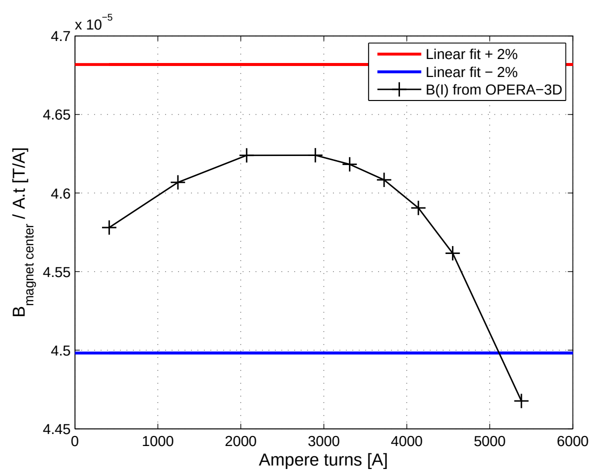

Figure 20: Same as Fig. 19, but for convenience we plot here B/Ampere.turns.

4 Tolerances & Field Measurement Specifications

4.1 Mechanical Tolerances

Tight tolerances ($\sim$ 100 μm) 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 TMD0002D"ARIEL EMBT 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 0.190 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:

- ◇ Find the actual location of the magnetic mid-plane.
- ◇ 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 28.46 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. 21, from x = -30 mm to x = +30 mm. This must be done with the field at the center equal to 0.19 T. The field integrals along these lines may be calculated from the field map and must be identical within $\pm$ 0.5%.
- ◇ If the field integrals satisfy this condition, 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 0.19T.

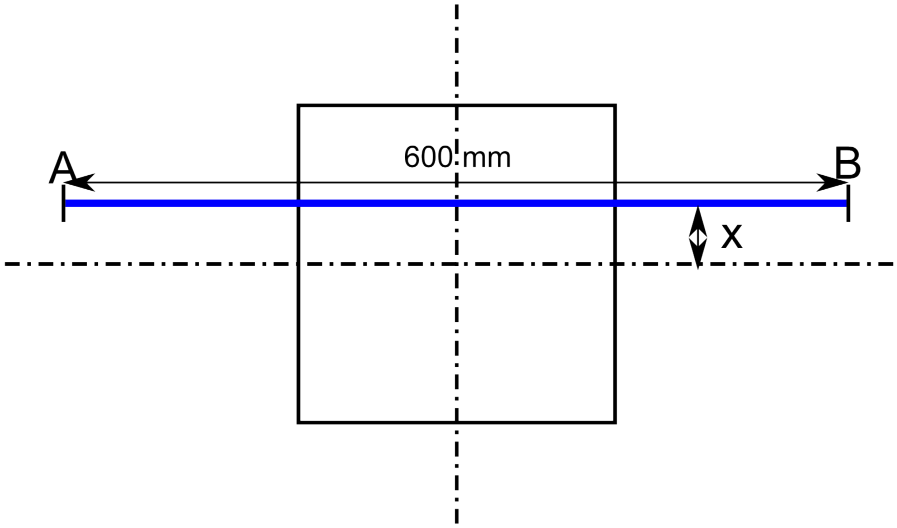

Figure 21: Schematic description of the trajectories along which the field integrals will be measured.

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.