Modelling BL4N Magnets Using *Opera* to Assist with Quantifying Leakage Fields along the EHBT Line

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1 Abstract

The close proximity of Beam Line 4 North (BL4N) to the Electron High Energy Beam Transport (EHBT) line indicates possible interference with the EHBT line's electron beam due to BL4N's quadrupoles' and dipoles' magnetic fields. It is of interest to quantify these leakage fields in order to assess the field strength along the EHBT line as well as to assist with the design of shielding where these field strengths are above an acceptable value. To calculate the magnetic fields of BL4N's magnets, the finite element analysis software *Opera-3D* is used. Five quadrupole magnets, including the 4Q14/8, the 4Q8.5/8.5, the University of Alberta (UoA) 4Q12/6, the Danfysik TUDA Short, and the Danfysik L5 quadrupoles, as well as two dipole magnets, including the 4VB1 35° bending dipole and a preliminary design for a 45° bending dipole, are modelled in *Opera*. The results of these models are found to be in good agreement with the existing field survey data for each magnet. Leakage fields are extracted for the 4Q14/8 quadrupole at an excitation of 340 A, for the 4Q8.5/8.5 quadrupole at an excitation of 200 A, and for the 4VB1 dipole at an excitation of 820 A, and the integrated field strength of each quadrupole at their respective excitations are provided. The present design features of the 45° bending dipole are discussed. Design changes are suggested for the Bonnie dipole to retrofit the magnet for use as an inflector assembly test stand.

2 Introduction

2.1 Objective of Magnet Modelling

BL4N and the EHBT line are presently in construction through TRIUMF's North-South tunnel. Within the tunnel, BL4N will sit three feet vertically above the EHBT line, sometimes directly above the EHBT line and sometimes within a few horizontal feet [1, 2]. When completed, BL4N will carry a proton beam and the EHBT line will carry an electron beam. Accordingly, the magnets used in BL4N will be much stronger than those used in the EHBT line due to the huge mass difference between protons and electrons. As the EHBT line and BL4N are in close proximity through the North-South tunnel, a concern is that the leakage fields from BL4N's magnets will interfere with the electron beam orbits in the EHBT line and result in distortions [2]. The EHBT line has been designed to maintain proper steering for ambient fields of up to 100 mG [2]. It is therefore of interest to quantify the leakage fields along the EHBT line due to BL4N's magnets using computer simulations of those magnets [2]. The magnets to be used in BL4N are in surplus and include the 4Q14/8, the 4Q8.5/8.5, the UoA 4Q12/6, the Danfysik TUDA Short, the Danfysik L5, and the KEK QA-I quadrupole and the 4VB1 35° bending or C15 III 57R/15 dipole, in addtion to a 45° bending dipole which has yet to be built [2].

The objective of this report is to provide computer simulations for these magnets and to verify the accuracy of the simulations by initially comparing their results to existing field data. The leakage fields may then be extracted along the position of the EHBT line as detailed in Ref. [2]. To perform these simulations, we will be using Cobham's finite element analysis software *Opera* and in particular its three dimensional (3D) modeller and solver, *Opera-3D*.

2.2 *Opera* and Finite Element Analysis

Finite element analysis (FEA) is a computational method of obtaining approximate solutions to boundary value problems (BVPs), such as solving Laplace's equation for magnetic or electric fields. FEA relies on the discretization of the BVP's domain into a finite number of interconnected elements or nodes [3]. The equations governing the problem are then solved at each element and the boundary conditions are satisfied [3]. The user is then able to extract the solution at every element and interpolate the solution between elements as necessary [3].

Our use of *Opera* first consists of using Pre-Processor in which a model of a particular magnet is built and in which the material properties are added to the model along with the boundary conditions. The elements are distributed throughout the domain of interest by first performing surface meshing followed by volume meshing. *Opera*'s magnetostatic solver, TOSCA, is then used to solve our governing equation. Finally, we may extract the field data from the simulation in the Post-Processor.

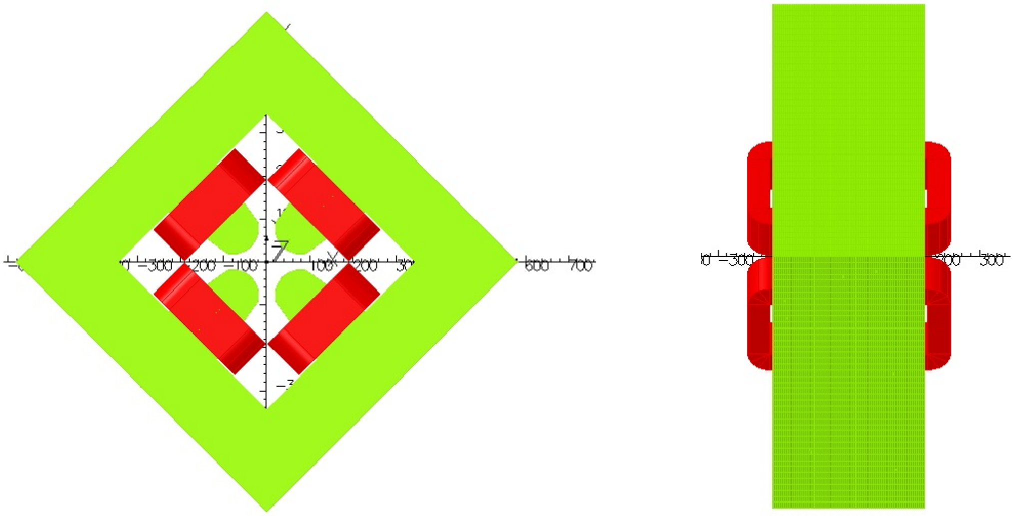
3 Models and Results

There are a number of general features for all of our quadrupole models. The beam direction is always defined as the axis of rotational symmetry; this direction points along the z-axis in our *Opera* models. The x- and y-axes are perpendicular to each other and perpendicular to the z-axis and each intersect edges of the yoke parallel to the z-axis. Only one-sixteenth of a given magnet is modelled because of the 2-fold reflection symmetry and the 4-rotational symmetry each of the quadrupoles possess. The origin is chosen to be where the two reflection planes of symmetry intersect with the axis of rotational symmetry. Each quadrupole is appropriately rotated so that the poles appear to have an "X" shape when viewing the magnet along the beam direction. Additionally, when looking down the negative z-axis, each magnet has a north pole in the first quadrant of the x-y plane; the other poles are given appropriately.

Concerning the dipole models, the y-axis is always parallel to the physical vertical axis. For C-frame dipoles, only one quarter of a magnet is modelled because of its 2-fold reflection symmetry. For H-frame dipoles, only one eighth of the magnet is modelled because its 3-fold reflection symmetry.

3.1 4Q14/8 Quadrupole

The 4Q14/8 quadrupole has simplest design of the quadrupoles modelled, with the ends of the poles flush with the ends of the magnet along the beam direction. The dimensions of the 4Q14/8 quadrupole were obtained through drawings of the magnet [4, 5, 6]. The magnet is composed of C1010 steel and so the nonlinear analysis in *Opera* uses C1010 BH data [7]. Images of the model are shown in Fig. 1. The .comi file used to build the model in *Opera-3D* is presented in Appendix A.1.



(a) (b)

Figure 1: (a) A front view of the 4Q14/8 quadrupole model in *Opera*, looking down the negative z-axis, and (b) a side view of the same model, looking down the positive x-axis. The yoke is shown in green and the coils are shown in red. The two images do not necessarily have the same scale.

In Doug Evans' median plane field survey for this magnet, 02041088, the magnet was operated at 340 A [8]. To ensure our model was reliable, we simulated the fields at 340 A, extracted the fields from *Opera* over the survey's domain, and compared the results to the field survey data, as shown in Figs. 2, 3, and 4.

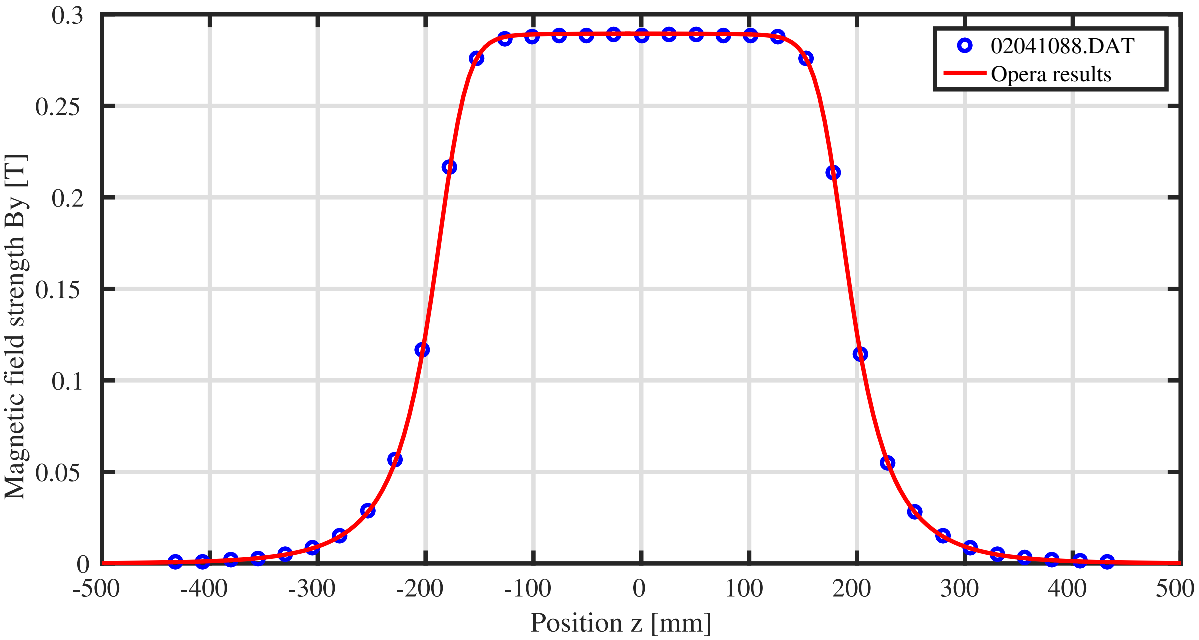


Figure 2: The median plane field survey data 02041088.DAT, plotted along $(x, y) = (25.4, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (25, 0)$ mm and scaled by -1, for the 4Q14/8 quadrupole at an excitation of 340 A.

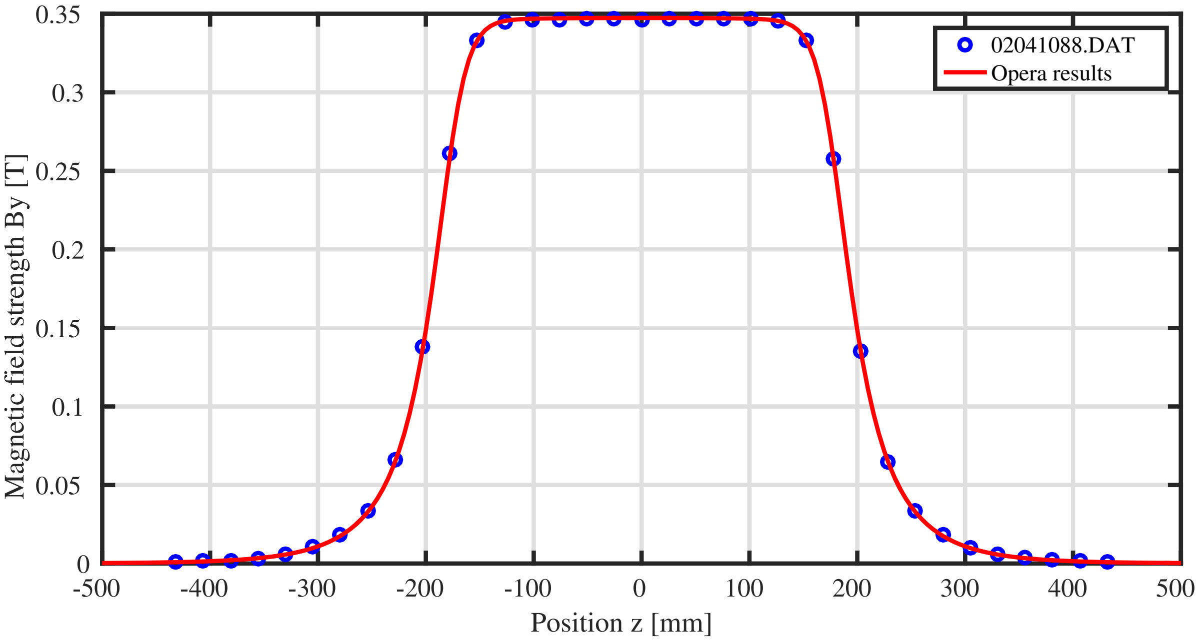


Figure 3: The median plane field survey data 02041088.DAT, plotted along $(x, y) = (30.48, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (30, 0)$ mm and scaled by -1, for the 4Q14/8 quadrupole at an excitation of 340 A.

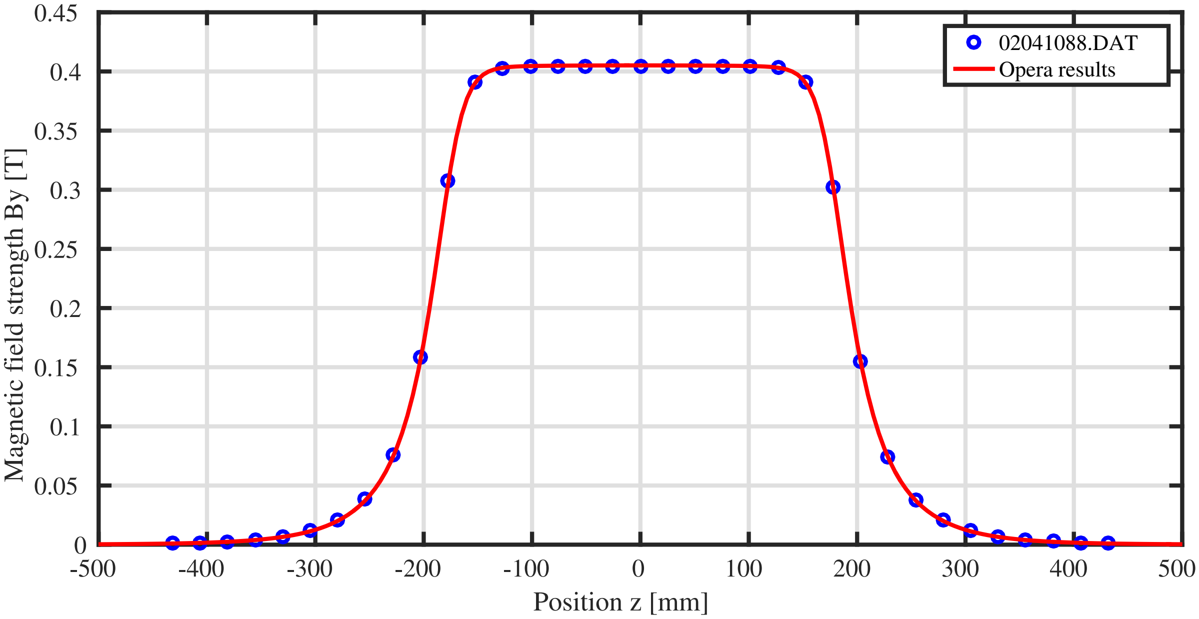


Figure 4: The median plane field survey data 02041088.DAT, plotted along $(x, y) = (35.56, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (35, 0)$ mm and scaled by -1, for the 4Q14/8 quadrupole at an excitation of 340 A.

By visual assessment, the agreement between the *Opera* simulation and the survey data at 340 A is quite good. It is reasonable to conclude that our *Opera* model can accurately provide magnetic field data for other excitations as well, assuming the current is such that the coil shape is unimportant.

Now, the 4Q14/8 quadrupoles in BL4N will sit 914.4 mm directly above the EHBT line [2]. To examine the field due to the 4Q14/8 magnet along the EHBT line, we extracted the three components of the magnetic field at $x = 0$ mm, $y = -900$ mm and between $z = -2700$ mm and 2700 mm in steps of 30 mm. The reason for not choosing $y = -914.4$ mm exactly was because the element size of our model's mesh in the region of interest is 30 mm and so all of the field data was chosen such that the vertices of every point extracted were in multiples of 30 mm to avoid interpolation. A similar rationale is used when extracting the field data from every model discussed in this report. It was found that the y- and z-components of the magnetic field were utterly negligible compared to the x-component B_x, being on the order of 10^{-22} to 10^{-21} G, and so they were ignored. The resulting B_x data is shown in Fig. 5, referred to as Model 2 within that figure. Looking at B_x versus z, we see that the field never exceeds 100 mG along the EHBT line, as required by Ref. [2]. The magnet will actually be operating at a current of 400 A [9], but even at that excitation the field will scale from its maximum magnitude of $\sim$60 mG at 340 A to $\sim$70 mG at 400 A, which is still below the threshold of 100 mG.

Opera was also used to calculate the integrated field strength of the 4Q14/8 quadrupole at 340 A by integrating the y-component of the magnetic field B_y along a line parallel to the z-axis at $(x, y) = (10, 0)$ mm. The integration limits were such that the field was approximately zero at the first limit and approximately zero at the second limit, and the resulting integral was divided by 10 mm to yield an integrated field strength of -4.70 T at 340 A. This value is roughly consistent with the required integrated field strengths given in Ref. [2].

It is interesting to note the effect of having too small of an outer boundary for a model. In Fig 5, Model 1 refers to an *Opera* model with an outer boundary extending to approximately 1 m in each direction from the centre of the magnet, and so the field data is only shown for $z = -990$ mm to 990 mm. There is a clear deviation in the field values for Model 1 as compared to Model 2, which has an outer boundary extending to approximately 3 m in each direction from the centre of the magnet. This is because boundary conditions in the smaller model play a larger role in determining the field outside of the magnet. In general, the outer boundary should be many times larger than the dimensions of the magnet in each direction to ensure accurate results. This is less important when one is interested in the fields inside the magnet but is essential when examining leakage fields. The only issue with models with large boundaries is that they typically take a very long time to run.

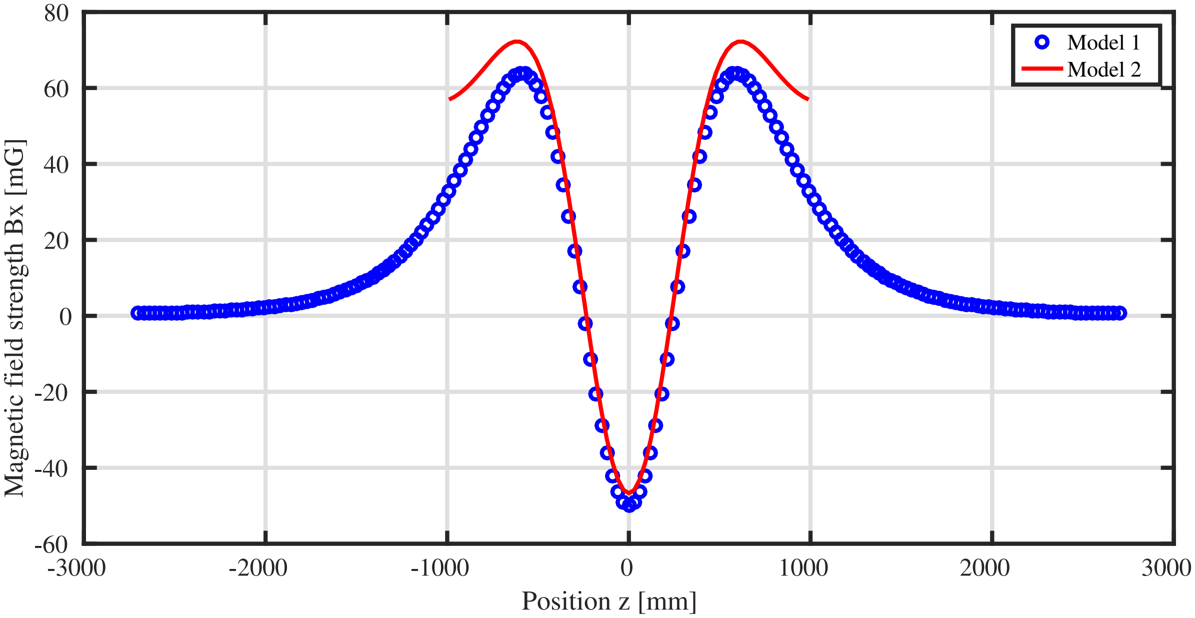


Figure 5: The x-component of the magnetic field B_x of a BL4N 4Q14/8 quadrupole at an excitation of 340 A plotted along the EHBT line at $(x, y) = (0, -900)$ mm. Model 1 refers to a model with an outer boundary that extends to $\sim$1 m in each direction and Model 2 refers to a model with an outer boundary that extends to $\sim$3 m in each direction.

It is important to note that our *Opera* model for the 4Q14/8 quadrupole with the larger outer boundary did not properly converge during analysis. This is likely due to the huge number of points within our model's volume which our governing equation must be solved at and so the maximum number of iterations allowed for the nonlinear analysis will likely need to be increased to achieve the desired convergence. However, the convergence indicators for the analysis were all nearly below their respective thresholds required for the analysis to output a proper solution, each being within approximately a factor of 10, and so the solution is accurate enough for our purposes.

We have also plotted the magnitude of the field inside the magnet at an excitation at 340 A, as shown in Fig. 6. The field inside the yoke is approximately 0.6 T and the field inside the poles is approximately 1.5 T. At 400 A, the field inside the poles will be approximately 1.8 T and so the poles will be saturated, but the yoke will remain unsaturated with a field of approximately 0.7 T. This is desirable as the leakage fields should remain negligible at 400 A for a relatively unsaturated yoke.

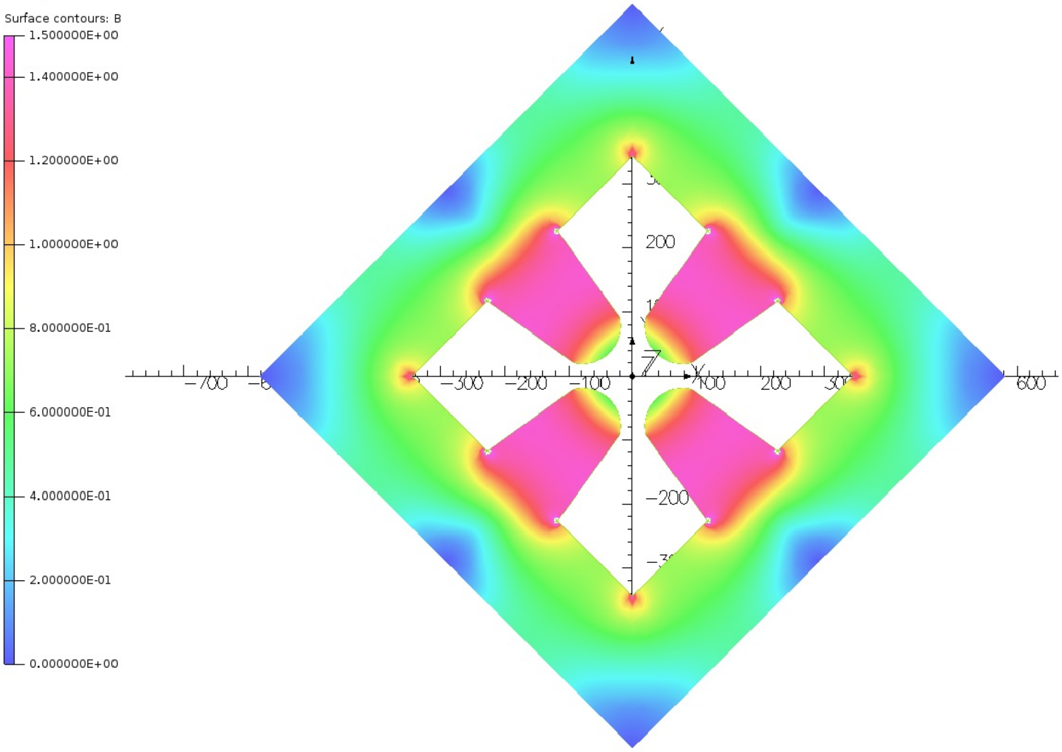


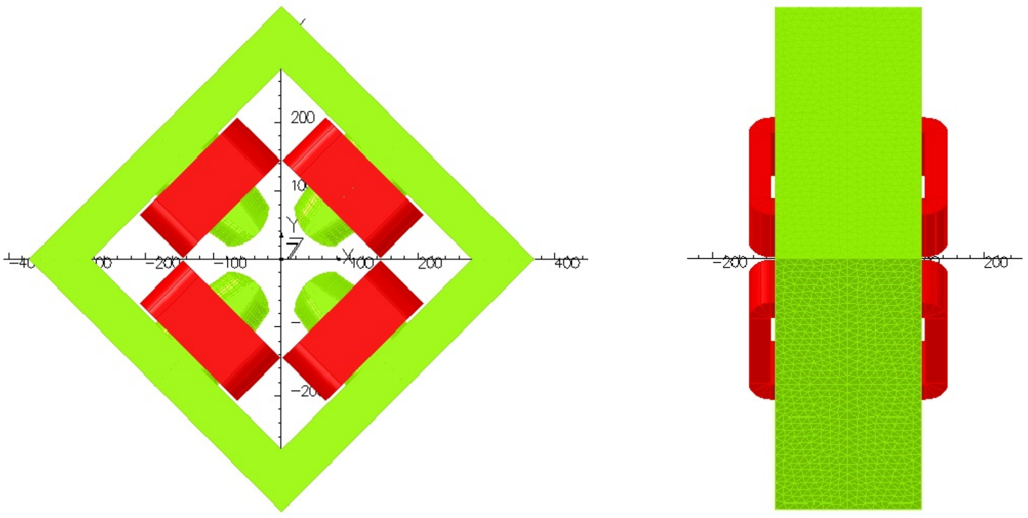
Figure 6: A contour plot of the magnetic field strength B inside the 4Q14/8 quadrupole at an excitation of 340 A in *Opera*. The slice is taken at $z = 0$ mm. The field has units of teslas.

3.2 4Q8.5/8.5 Quadrupole

The main difference between the 4Q8.5/8.5 quadrupole and the 4Q14/8 quadrupole is that the former has poles with rounded edges on their ends while the latter has poles with straight edges on their ends. This added an additional complication when modelling as these rounded edges must also taper as they reach the pole tip. The rounded edges were achieved by using the *BLEND* option in *Opera*. The dimensions of the 4Q8.5/8.5 quadrupole were obtained through drawings of the magnet [10, 11, 12, 13]. The magnet is composed of C1010 steel and so the nonlinear analysis in *Opera* uses C1010 BH data [14]. Images of the model are shown in Fig. 7. The .comi file used to build the model in *Opera-3D* is presented in Appendix A.2.

In Doug Evans' median plane field survey for this magnet, 051498, the magnet was operated at 150 A [15]. To ensure our model was reliable, we ran the model at 150 A, extracted the fields from *Opera* over the survey's domain, and compared the results to the survey data, as shown in Figs. 8, 9, and 10. This was the same procedure used for the 4Q14/8 quadrupole.

By visual assessment, the agreement between the *Opera* simulation and the survey data is quite good in Fig. 8. The agreement between our simulation and the field survey is somewhat poorer around the top of each profile in Figs. 9 and 10. The survey data is much flatter at the top of the profiles in each of these figures. This suggests the presence of shims on the pole tips as shims improve field uniformity, but these shims must have been added after the magnet was manufactured as they were not described in the drawings. Additionally, there is also noticeable angle to the top of each profile from the survey data; the reason for this is unknown. However, the simulation does agree well with the survey data in the fringe field region in all of the figures. As we are interested in extracting leakage fields outside of the magnet, the agreement is good enough for our purposes and we can be confident in our model.



(a)

(b)

Figure 7: (a) A front view of the 4Q8.5/8.5 quadrupole model in *Opera*, looking down the negative z-axis, and (b) a side view of the same model, looking down the positive x-axis. The yoke is shown in green and the coils are shown in red. The two images do not necessarily have the same scale.

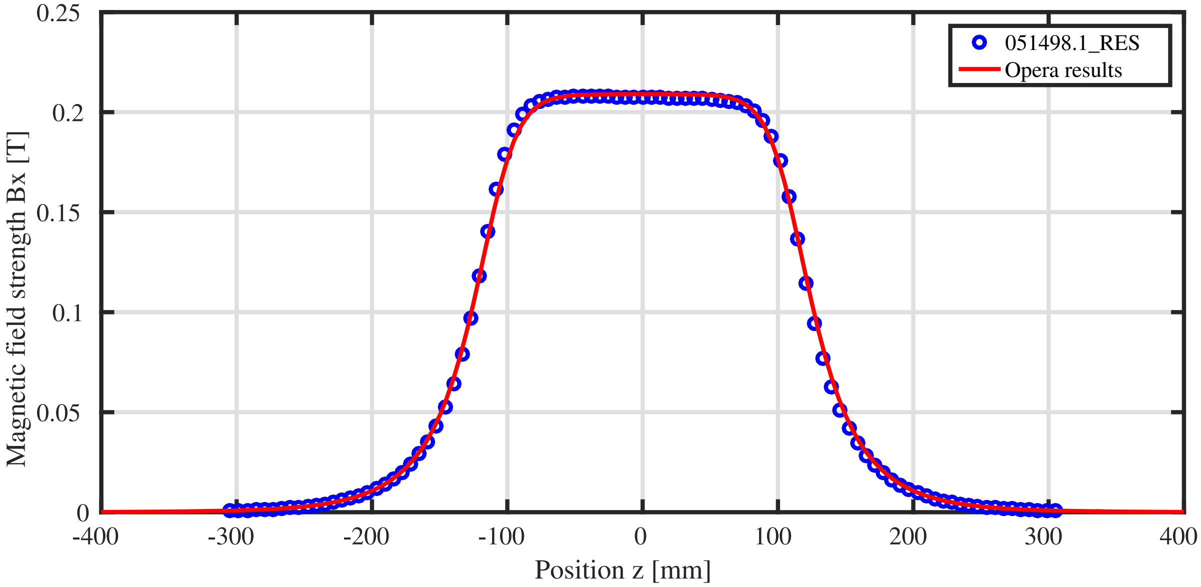


Figure 8: The median plane field survey data 051498.1_RES, plotted along $(x, y) = (25.4, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (25, 0)$ mm and scaled by -1, for the 4Q8.5/8.5 quadrupole at an excitation of 150 A.

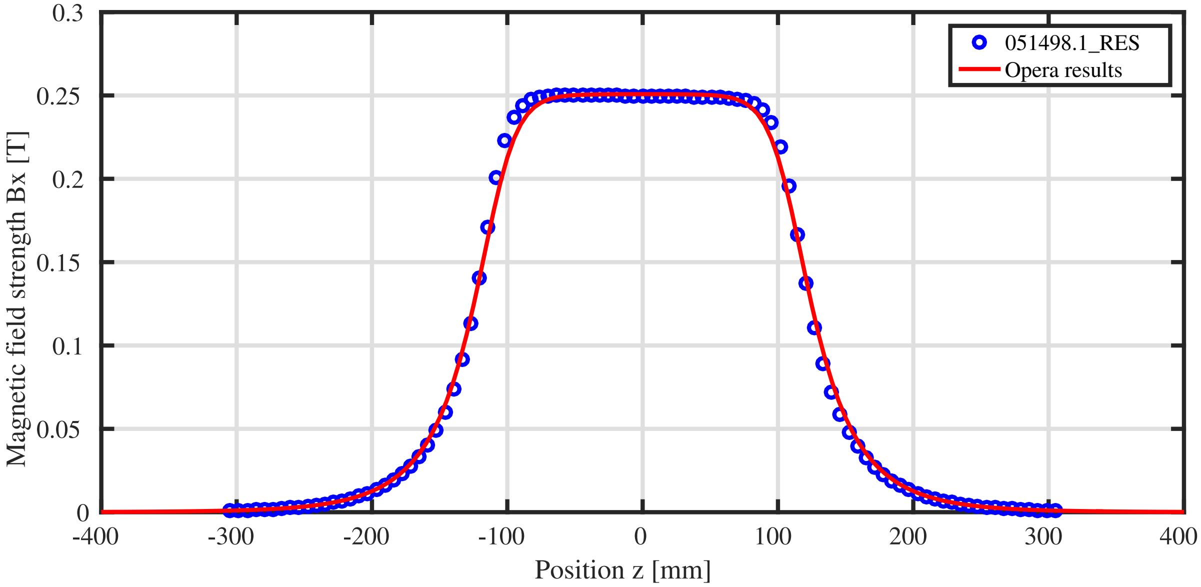


Figure 9: The median plane field survey data 051498.1_RES, plotted along $(x, y) = (30.48, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (30, 0)$ mm and scaled by -1, for the 4Q8.5/8.5 quadrupole at an excitation of 150 A.

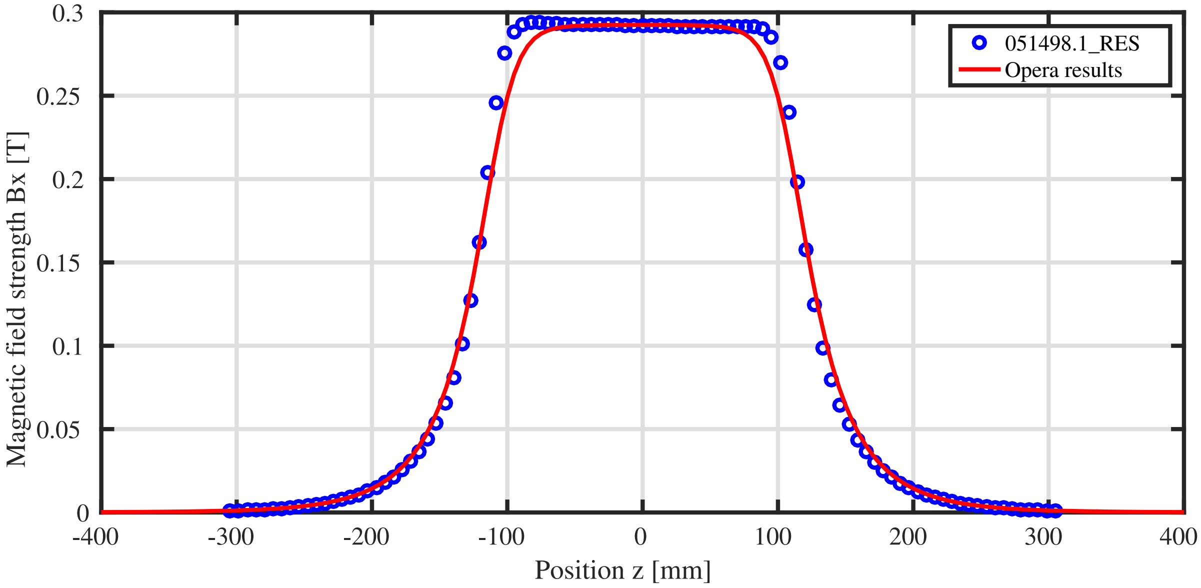


Figure 10: The median plane field survey data 051498.1_RES, plotted along $(x, y) = (35.56, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (35, 0)$ mm and scaled by -1, for the 4Q8.5/8.5 quadrupole at an excitation of 150 A.

The 4Q8.5/8.5 quadrupole will be run at an excitation around 200 A [9]. The magnet will sit 914.4 mm directly above the EHBT line like the 4Q14/8 quadrupole. To examine the field due to the 4Q8.5/8.5 quadrupole along the EHBT line, we extracted the three components of the magnetic field at $x = 0$ mm, $y = -900$ mm and between $z = -2700$ mm and 2700 mm in steps of 30 mm for a model run at 200 A with a large outer boundary. As was the case for the 4Q14/8 quadrupole, it was found that the y- and z-components of the magnetic field were utterly negligible compared to the x-component B_x, and so they were ignored. The resulting B_x data is shown in Fig. 11. Looking at B_x versus z, we see that the field never exceeds 100 mG along the EHBT line, as required by Ref. [2]. Like, with the 4Q14/8 quadrupole, the 4Q8.5/8.5 quadrupole model with a large background did not converge properly. However, the convergence indicators for the analysis were all nearly below their respective thresholds required for the analysis to output a proper solution and so the solution is accurate enough for our purposes.

The integrated field strength for the 4Q8.5/8.5 quadrupole running at 200 A was found to be -2.90 T, calculated in the same way as for the 4Q14/8 quadrupole. This value is consistent with the required integrated field strengths given in Ref. [2].

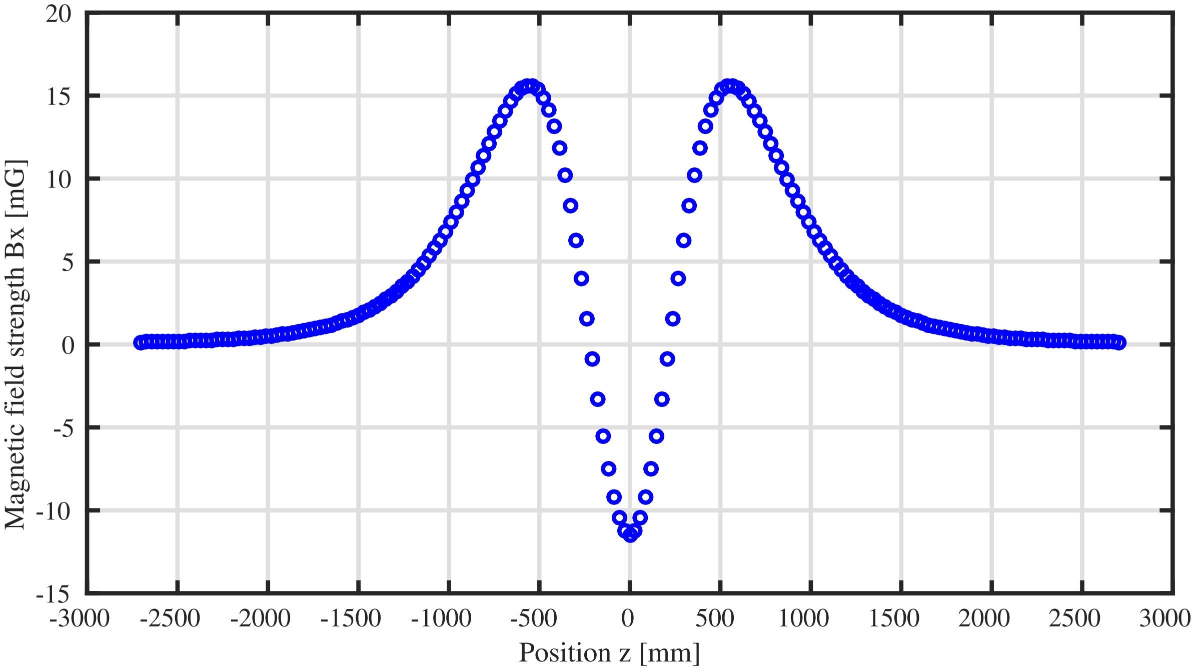


Figure 11: The x-component of the magnetic field B_x of a BL4N 4Q8.5/8.5 quadrupole at an excitation of 200 A plotted along the EHBT line at $(x, y) = (0, -900)$ mm.

We have plotted the magnitude of the field inside the magnet at an excitation at 200 A, as shown in Fig. 12. The field inside the yoke is approximately 1.3 T and the field inside the poles is approximately 1.5 T. These field values should not be large enough to result in saturation of the yoke, which is desirable in minimizing leakage fields.

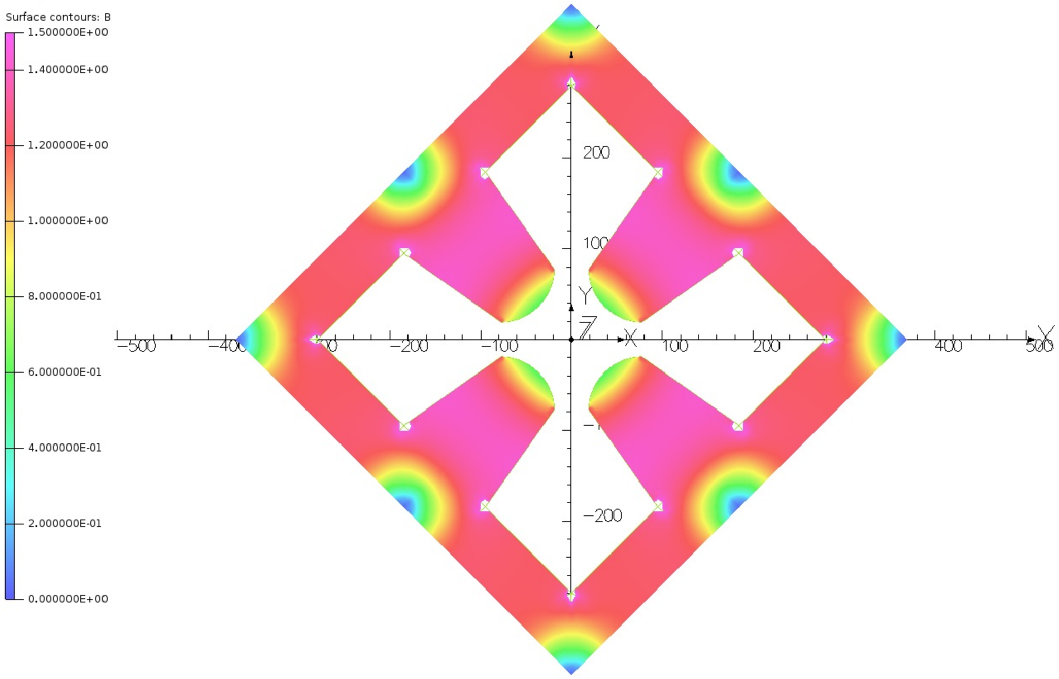


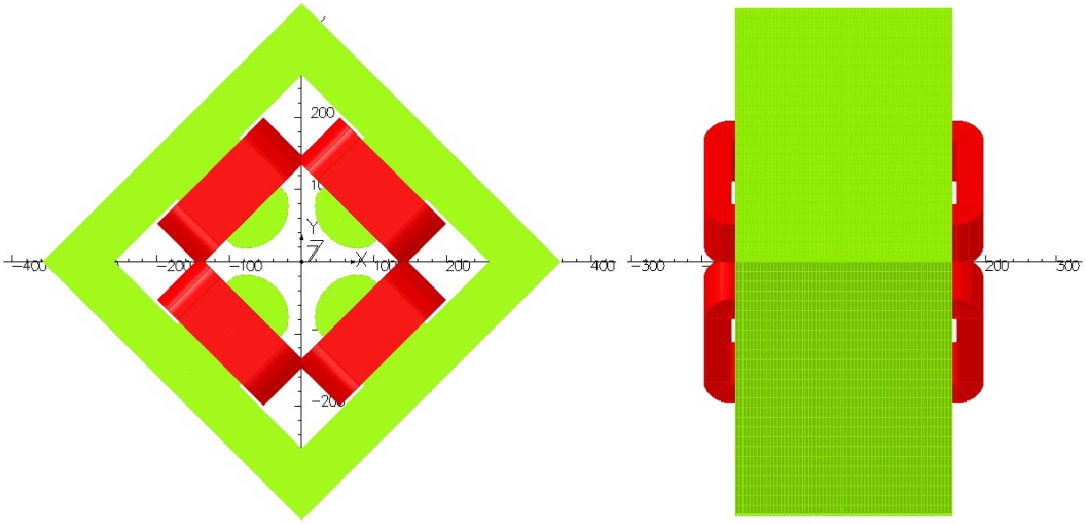
Figure 12: A contour plot of the magnetic field strength B inside the 4Q8.5/8.5 quadrupole in *Opera* at an excitation of 200 A. The slice is taken at $z = 0$ mm. The field has units of teslas.

3.3 UoA 4Q12/6 Quadrupole

The UoA 4Q12/6 quadrupole has the same general shape as the 4Q14/8 quadrupole, with the ends of its poles flush with the ends of the magnet along the beam direction. Some of the dimensions of the 4Q12/6 quadrupole were obtained through the TRIUMF Magnet Index such as its length in the z˙direction as well as its aperture diameter [16], but most of of the dimensions had to be measured using a measuring tape as drawings do not exist for this quadrupole at TRIUMF. It is not clear what the magnet is composed of and so we will be making the assumption that the material is C1010 steel. Accordingly, our nonlinear analysis in *Opera* uses C1010 BH data. Images of the model are shown in Fig. 13. The .comi file used to build the model in *Opera-3D* is presented in Appendix A.3.

In Doug Evans' median plane field survey for this magnet, 01010295, the magnet was operated at 250 A [17], but it is unknown how many turns of conductor exist in the coils and so the number of ampere-turns put through the coils in this survey is unknown. Additionally, the only field survey for the 4Q12/6 quadrupole is a radial field survey, obtained using a rotating coil in a cylindrical frame [18]. A median plane field survey of B_y versus z at $(x, y) = (40.64, 0)$ mm was obtained by Yi-Nong Rao by taking the average of the radial field survey at 0°, 180°, and 360° [18]. We ran our model at an excitation of 250 A with an initial guess for the number of turns of conductor of 50 and extracted the simulated field data along the same line as the survey field data. It was found that the maximum value of the field profile for the simulated data was approximately 1.09 times that of the measured field profile. The model was run again at an excitation of 250 A with the number of turns divided by 1.09: (50 turns)/1.09 $\approx$ 46 turns, and the extracted field data was found to be in good agreement with the survey data without scaling, as shown in Fig. 14. We can therefore be relatively confident in the accuracy of our model; however, it would be good if we had additional survey data to compare our model to.

It should be noted that none of the models for the 4Q12/6 quadrupole properly converged during nonlinear analysis. This is likely due to saturation of the yoke at 250 A, resulting in steel which is highly nonlinear. However, all of the convergence indicators were close enough to their required thresholds and so our solutions should be accurate enough for most purposes. It is possible that convergence may be achieved by increasing the number of iterations.



(a)

(b)

Figure 13: (a) A front view of the UoA 4Q12/6 quadrupole model in *Opera*, looking down the negative z-axis, and (b) a side view of the same model, looking down the positive x-axis. The yoke is shown in green and the coils are shown in red. The two images do not necessarily have the same scale.

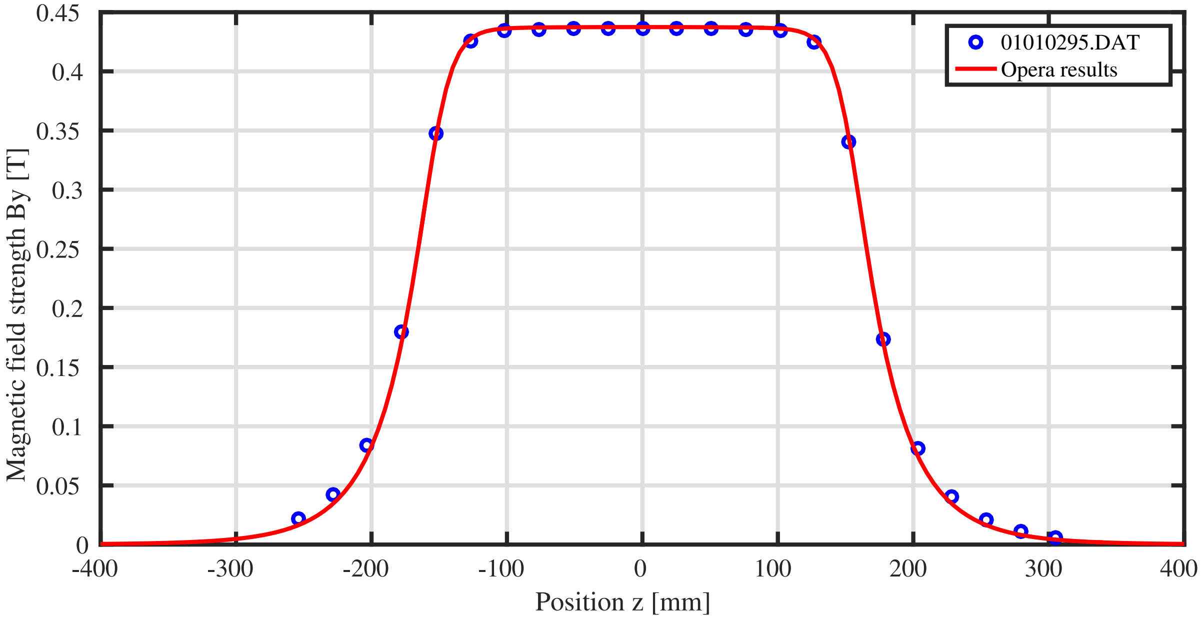


Figure 14: The median plane field survey data 01010295.DAT, plotted along $(x, y) = (40.64, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (40, 0)$ mm, for the UoA 4Q12/6 quadrupole at an excitation of 250 A with 46 turns of conductor in the coils.

The integrated field strength for the 4Q12/6 quadrupole running at 250 A was found to be -3.89 T, calculated in the same way as for the 4Q14/8 quadrupole. This value is roughly consistent with the required integrated field strengths given in Ref. [2].

We have plotted the magnitude of the field inside the magnet at an excitation at 250 A with 46 turns of conductor in the coils, as shown in Fig. 15. The field inside the yoke is approximately 1.1 T and the field inside the poles is approximately 1.5 T. These values are not quite large enough to result in complete saturation of the magnet, but will likely cause the steel composing the magnet to enter its nonlinear regime. The nonlinearity of the steel at 250 A has been verified by reading the BI data for the field near the pole tip and so it is advised that the magnet only be ran at excitations up to ∼200 A [19].

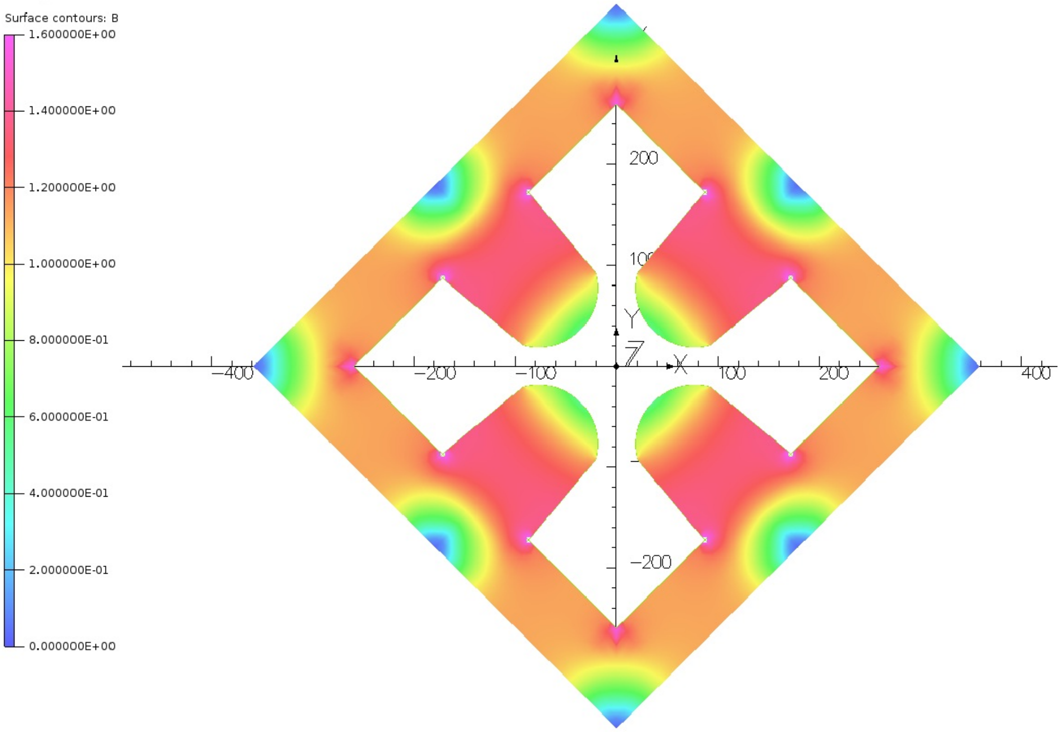
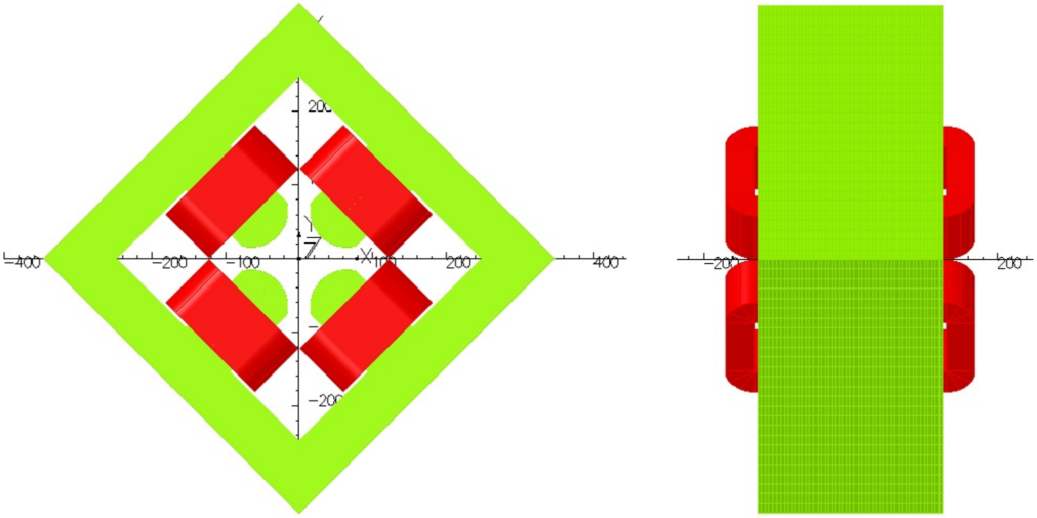


Figure 15: A contour plot of the magnetic field strength B inside the UoA 4Q12/6 quadrupole in *Opera* at an excitation of 250 A with 46 turns of conductor in the coils. The slice is taken at $z = 0$ mm. The field has units of teslas.

3.4 Danfysik TUDA Short Quadrupole

The Danfysik TUDA short quadrupole has the same general shape as the 4Q14/8 quadrupole, with the ends of its poles flush with the ends of the magnet along the beam direction. Some of the dimensions of the TUDA Short quadrupole were obtained through the TRIUMF Magnet Index such as its length in the z-direction as well as its aperture diameter and through email correspondence with Yi-Nong Rao [20, 21], but most of the dimensions had to be measured using a measuring tape as drawings do not exist for this quadrupole at TRIUMF. The number of turns of conductor in each of the coils was determined by counting as the windings within the coils were visible. It is not clear what the magnet is composed of and so we will be making the assumption that the material is C1010 steel. Accordingly, our nonlinear analysis in *Opera* uses C1010 BH data. Images of the model are shown in Fig. 16. The .comi file used to build the model in *Opera-3D* is presented in Appendix A.4.



(a)

(b)

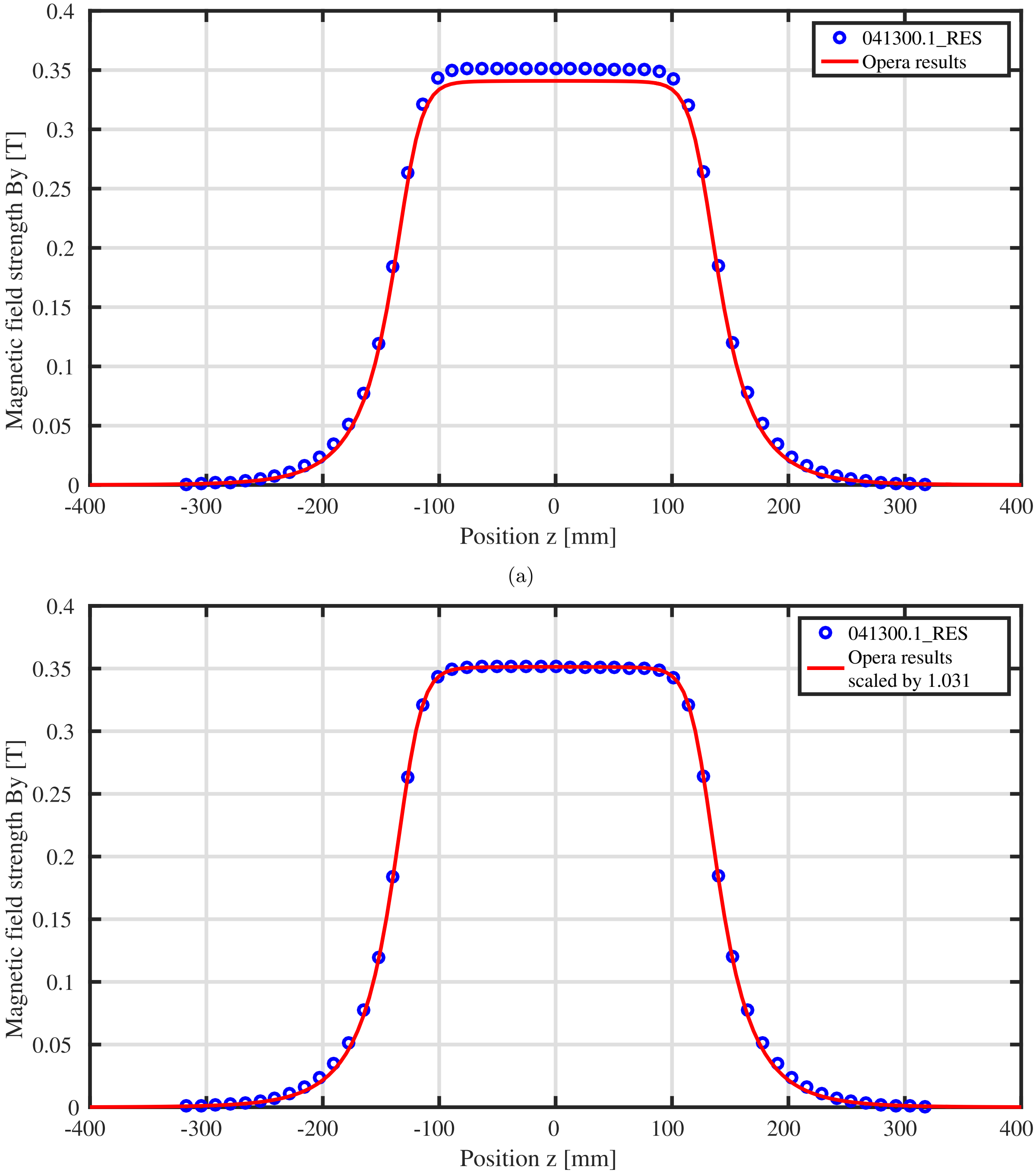
Figure 16: (a) A front view of the Danfysik TUDA Short quadrupole model in *Opera*, looking down the negative z-axis, and (b) a side view of the same model, looking down the positive x-axis. The yoke is shown in green and the coils are shown in red. The two images do not necessarily have the same scale.

In Doug Evans' median plane field survey for this magnet, 041300.1, the magnet was operated at 235 A [22]. To ensure our model was reliable, we simulated the fields at 235 A, extracted the fields from *Opera* over the survey's domain, and compared the results to the field survey data, as shown in Figs. 17(a) and 18(a).

By visual assessment, the agreement between the *Opera* simulation and the survey data at 235 A is reasonably good. We used the scaling factor between the maximum value of the measured fields at $(x, y) = (25.4, 0)$ mm and the maximum value of the simulated fields at $(x, y) = (25, 0)$ mm, 1.031, to scale our *Opera* results in each of Figs. 17(a) and 18(a), shown in Figs. 17(b) and 18(b), and the agreement is even better. It is reasonable to conclude that our *Opera* model can accurately provide magnetic field data to within approximately 3% of the true field at other excitations as well, assuming the current is such that the coil shape is unimportant. This is good enough for our purposes.

The TUDA Short quadrupole labelled 4NQ21 will be run at an excitation around 180 A [9]. The beam direction through this quadrupole along BL4N is angled at 34° relative to the beam direction along the EHBT line and the centre of 4NQ21 will be 914.4 mm vertically above the EHBT line and a horizontal distance of 570.17 mm away along the x-direction. We have not extracted the field data for the TUDA Short quadrupole. It has a smaller aperture diameter than that of the 4Q14/8 quadrupole but is also shorter along the beam direction and will be operating at a much lower current [6, 20]. Additionally, the nearest point on the EHBT line to the centre of the TUDA Short quadrupole is farther away than the nearest point on the EHBT line to the centre of the 4Q14/8 quadrupole, and so the leakage fields will likely be smaller than those due to the 4Q14/8 quadrupole and therefore smaller than 100 mG. The model should be run with a larger background and the leakage fields should be extracted to confirm this, however. It is also not clear which components of the magnetic field will be non-negligible along the EHBT line.

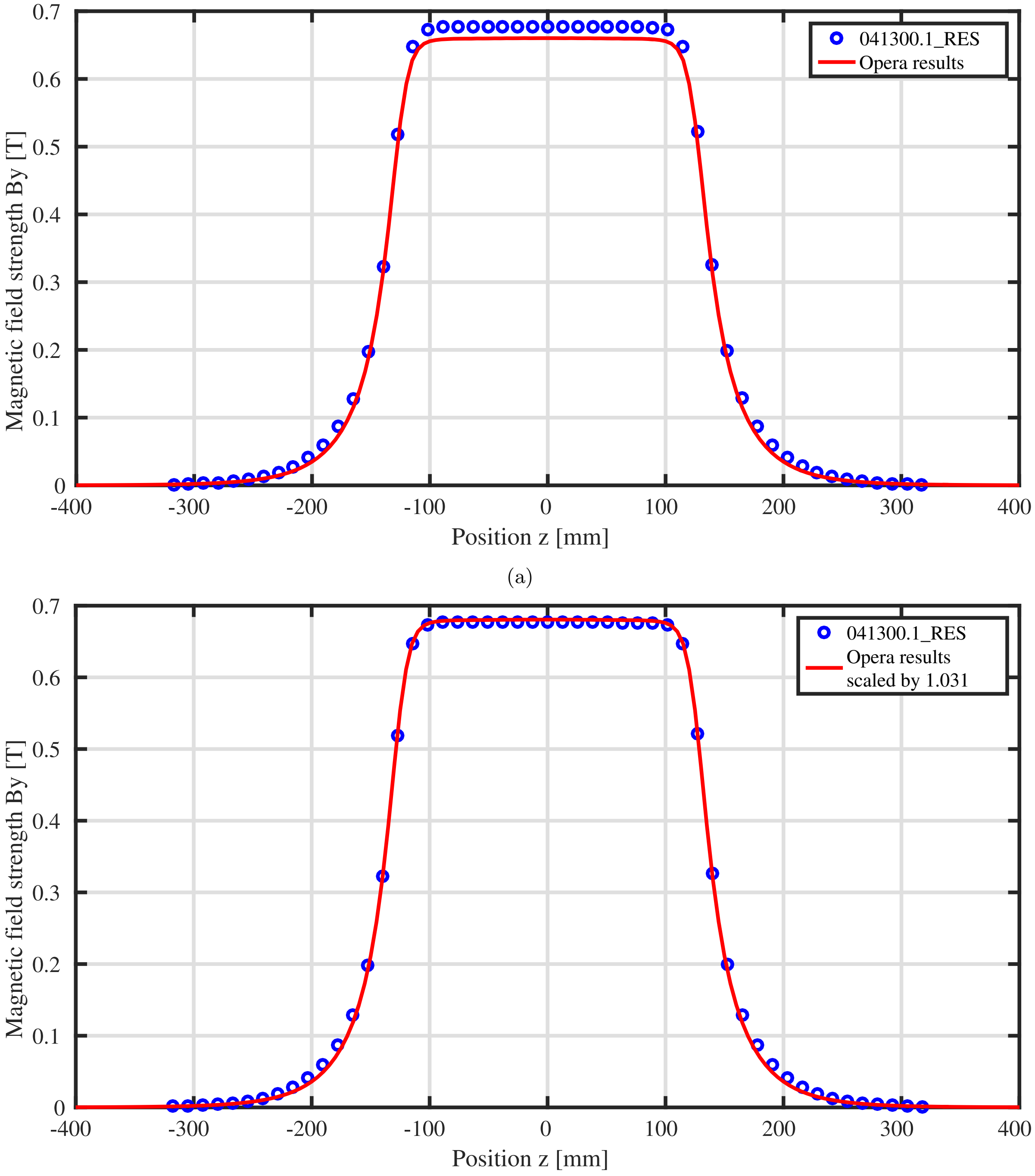
The integrated field strength for the TUDA Short quadrupole running at 235 A was found to be −4.01 T, calculated in the same way as for the 4Q14/8 quadrupole. This value is roughly consistent with the required integrated field strengths given in Ref. [2].



(a)

(b)

Figure 17: (a) The median plane field survey data 041300.1_RES, plotted along $(x, y) = (25.4, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (25, 0)$ mm and scaled by -1, for the Danfysik TUDA Short quadrupole at an excitation of 235 A. (b) The same plot as in (a) but with the *Opera* results scaled by 1.031.



(a)

(b)

Figure 18: (a) The median plane field survey data 041300.1_RES, plotted along $(x, y) = (50.8, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (50, 0)$ mm and scaled by -1, for the Danfysik TUDA Short quadrupole at an excitation of 235 A. (b) The same plot as in (a) but with the *Opera* results scaled by 1.031.

We have plotted the magnitude of the field inside the magnet at an excitation at 235 A, as shown in Fig. 19. The field inside the yoke is approximately 1 T and the field inside the poles is approximately 1.8 T. At 180 A, the field inside the yoke will be approximately 0.8 T and the field inside the poles will be approximately 1.4 T. Each of these values are well below the field values required for saturating the magnet, and so it is likely that the TUDA Short quadrupole will remain in the linear regime when running at 180 A.

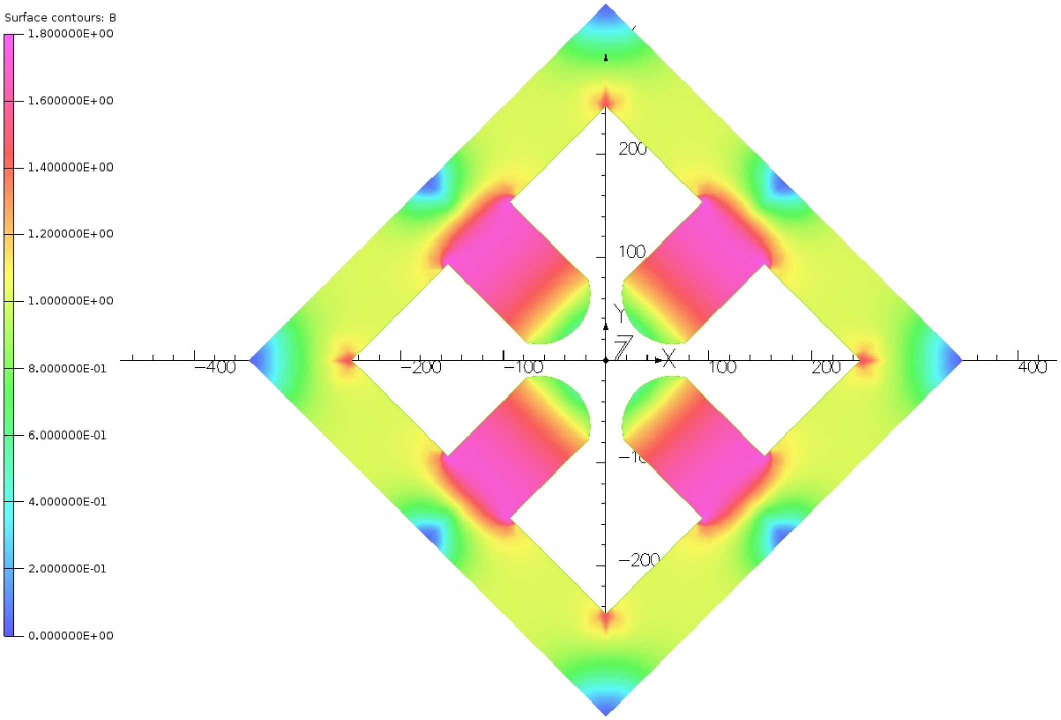
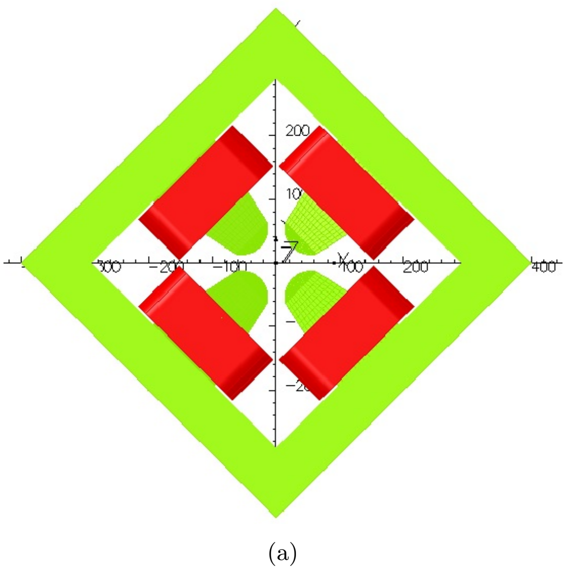


Figure 19: A contour plot of the magnetic field strength B inside the Danfysik TUDA Short quadrupole in *Opera* and at an excitation of 235 A. The slice is taken at $z = 0$ mm. The field has units of teslas.

3.5 Danfysik L5 Quadrupole

The Danfysik L5 quadrupole is similar to the 4Q14/8 quadrupole with the main difference being that the former has angled surfaces on the ends of its poles, resulting in pole tips which are shorter than the yoke along the beam direction, while the latter has poles which are flat on their ends. All of the dimensions of the L5 quadrupole were measured using a measuring tape as drawings do not exist for this quadrupole at TRIUMF. It is not clear what the magnet is composed of and so we will be making the assumption that the material is C1010 steel. Accordingly, our nonlinear analysis in *Opera* uses C1010 BH data. Images of the model are shown in Fig. 20. The .comi file used to build the model in *Opera-3D* is presented in Appendix A.5.

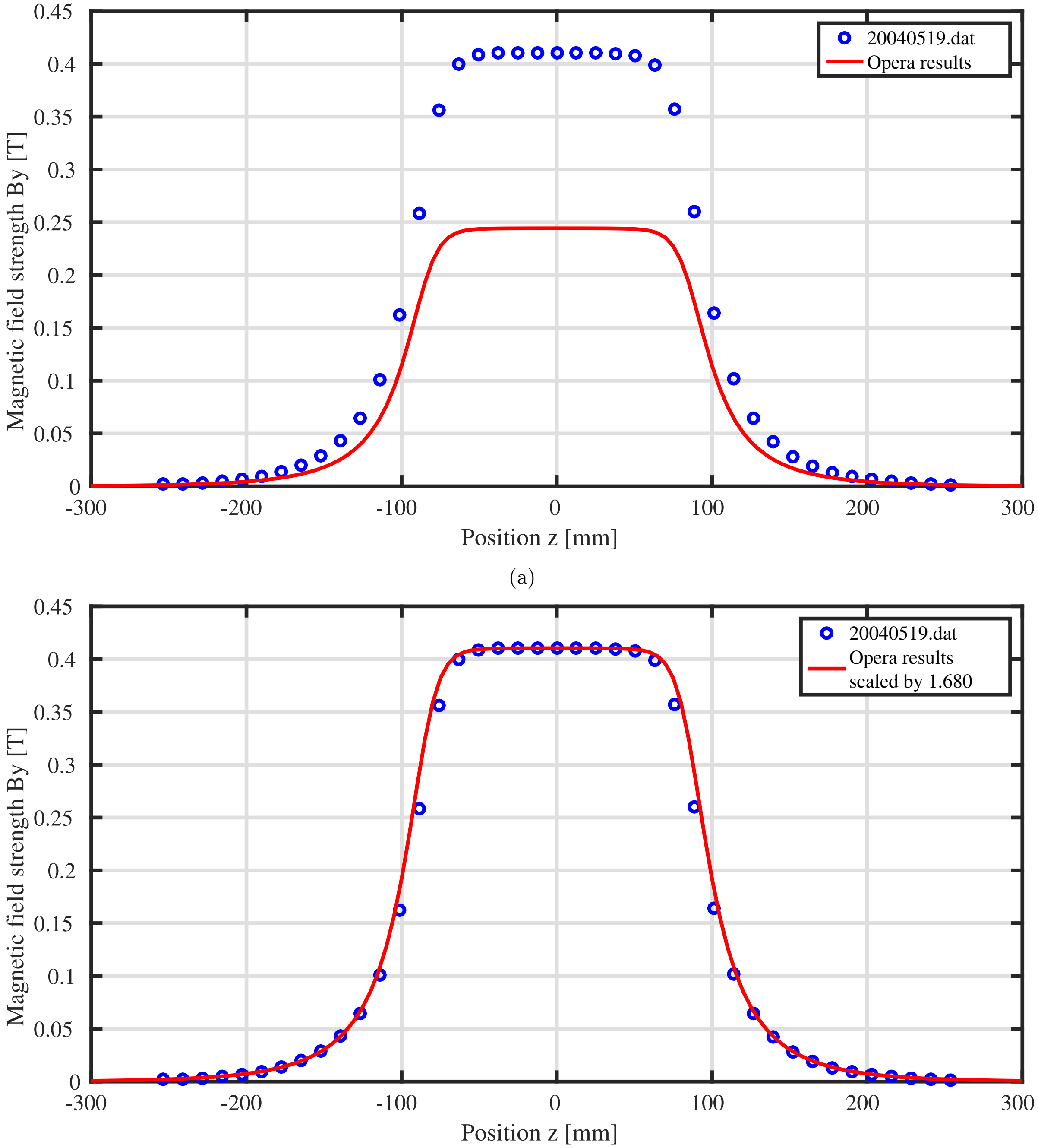


(a) (b)

Figure 20: (a) A front view of the Danfysik L5 quadrupole model in *Opera*, looking down the negative z-axis, and (b) a side view of the same model, looking down the positive x-axis. The yoke is shown in green and the coils are shown in red. The two images do not necessarily have the same scale.

In Doug Evans' median plane field survey for this magnet, 20040519, the magnet was operated at 100 A [23], but it is unknown how many turns of conductor exist in the coils and so the number of ampere-turns put through the coils is unknown. We ran our model at an excitation of 100 A with an initial guess for the number of turns of conductor of 50 and extracted the simulated field data along the same line as the survey field data. It was found that the maximum value of the field profile for the simulated data was approximately 1.680 times that of the measured field profile. The model was run again at an excitation of 100 A with the number of turns multiplied by 1.680: 1.680∗(50 turns) ≈ 84 turns, but the maximum value of the extracted field profile was found to still be slightly smaller than the maximum value of the measured field profile. The unscaled *Opera* results and the scaled *Opera* results along with the survey data are shown in Fig. 21(a) and Fig. 21(b), respectively. It was found that using 85 turns of conductor gave the best visual agreement, as shown in Fig. 22. It is reasonable to conclude that our *Opera* model can accurately provide magnetic field data at other excitations as well, assuming the current is such that the coil shape is unimportant. It would be useful to have additional survey data at other excitations to compare our model to, however.

The L5 quadrupole will be run at an excitation around 100 A [9], and the magnet will sit 914.4 mm directly above the EHBT line like the 4Q14/8 quadrupoles [2]. We have not extracted the field data for the L5 quadrupole along the EHBT line, but we anticipate that B_x will be the only non-negligible component of the field. This magnet does have a smaller aperture diameter than the 4Q14/8 quadrupole but is shorter in the beam direction and it will be run at a much smaller current [6]. As the 4Q14/8 quadrupole run at 340 A produces leakage fields smaller than 100 mG along the same domain, we anticipate the leakage fields due to the L5 quadrupole run at 100 A with 85 turns of conductor to be even smaller and to also satisfy the ambient field requirement for the EHBT line, but this should be verified by running the model at 100 A and 85 turns of conductor with a large background.



(a)

(b)

Figure 21: (a) The median plane field survey data 20040519.dat, plotted along $(x, y) = (26.6192, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (25, 0)$ mm and scaled by -1, for the Danfysik L5 quadrupole at an excitation of 100 A with 50 turns of conductor in the coils. (b) The same plot as in (a) but with the *Opera* results scaled by 1.680.

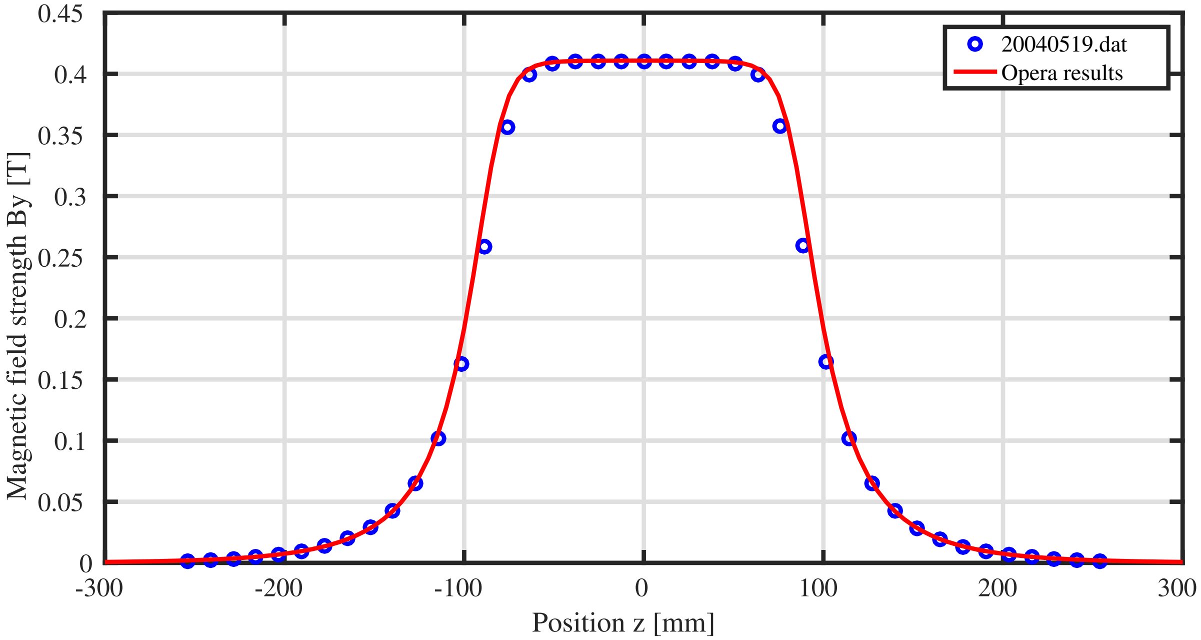


Figure 22: The median plane field survey data 20040519.dat, plotted along $(x, y) = (26.6192, 0)$ mm, and our *Opera* results, plotted along $(x, y) = (25, 0)$ mm and scaled by -1, for the Danfysik L5 quadrupole at an excitation of 100 A with 85 turns of conductor in the coils.

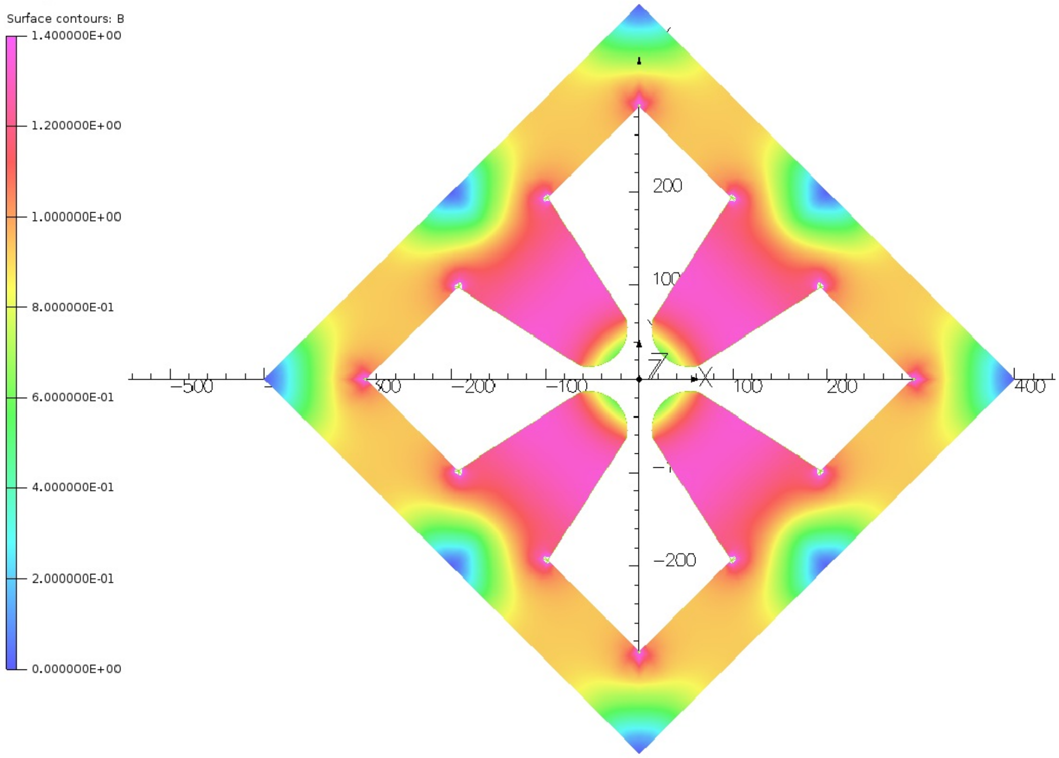


Figure 23: A contour plot of the magnetic field strength B inside the Danfysik L5 quadrupole in *Opera*, running at 100 A with 85 turns of conductor. The slice is taken at $z = 0$ mm. The field has units of teslas.

The integrated field strength for the Danfysik L5 quadrupole running at 100 A with 85 turns of conductor was found to be -3.47 T, calculated in the same way as for the 4Q14/8 quadrupole. This value seems considerably larger than the required integrated field strengths for quadrupoles of this type, which are all close to 1.5 T, as given in Ref. [2]. It is not presently clear why these values are so different and so this disagreement is something to be aware of.

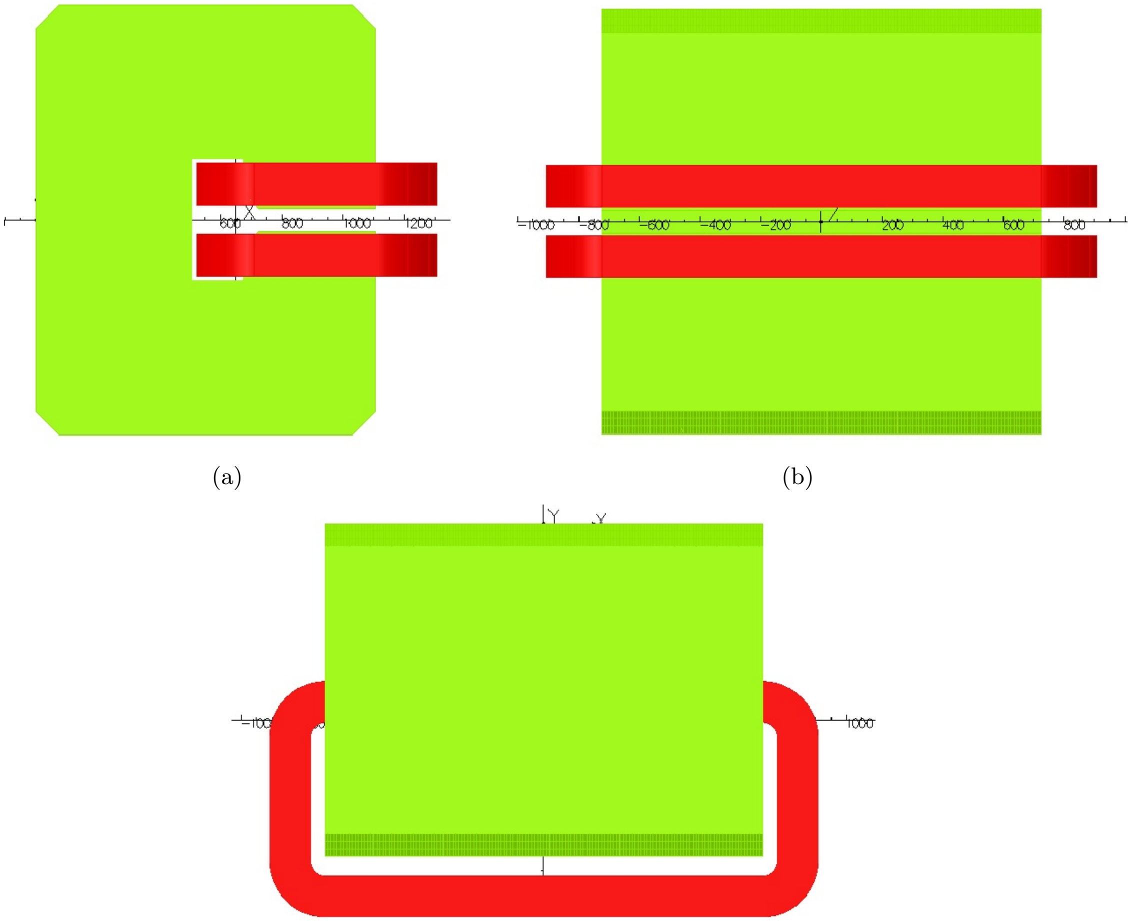
We have plotted the magnitude of the field inside the magnet at an excitation at 100 A with 85 turns of conductor, as shown in Fig. 23. The field inside the yoke is approximately 0.9 T and the field inside the poles is approximately 1.4 T. Each of these values are well below the field values required for saturating the magnet, and so it is likely that the L5 quadrupole will remain in the linear regime when running at 100 A.

3.6 4VB1 35° Bending C-Frame Dipole

The 4VB1 35° bending dipole is a C-frame dipole. The y-axis is as given for all of our dipole magnets and the x-axis is parallel to the beam direction through the magnet, which we are defining to run along the length of the yoke. Accordingly, the z-axis is perpendicular to the x- and y-axes and given appropriately for a right-handed coordinate system. The origin along the y-axis is taken to be halfway between the poles and the orgin along the x-axis to taken to be halfway along the length of the magnet. The origin along z-axis is somewhat arbitrary, but in our model we take it to be on the outermost edge of the return yoke along the z-direction. The corners of the outer yoke of the magnet along the beam direction are chamfered and the interior edges of the pole tips along the beam direction are chamfered as well. All of the dimensions of the 4VB1 dipole were obtained through drawings of the magnet, including the number of turns of conductor in the coils [24, 25, 26, 27, 28]. The magnet is composed of C1010 steel and so the nonlinear analysis in *Opera* uses C1010 BH data [28]. The north pole of the dipole is in the negative half of the y-axis. Images of the model are shown in Fig. 24. The .comi file used to build the model in *Opera-3D* is presented in Appendix A.6.

An interesting feature about all of our dipole models is that they mesh and solve much more quickly than our quadrupole models. As most of the surfaces in the dipole models are parallel to either the x-y, x-z, or y-z planes, it is possible to achieve highly regular meshing, which is desirable.

In Doug Evans' fringe field survey for this magnet, 02290874, the magnet was operated at 392.29 A [29]. It appears that within this survey the origin along the z-axis was taken to be at the pole manifold end, the chamfered end of the pole along the z-direction, and that the origin along the x-axis was taken to be at -254 mm in our model's reference frame. Please refer to Doug Evans' notebook on this date for the details. We have appropriately shifted Doug Evans' x coordinates for his measurements. To ensure our model was reliable, we simulated the fields at an excitation of 392.29 A, extracted the fields from *Opera* over the survey's domain, and compared the results to the field survey data, as shown in Figs. 25(a), 26(a), and 27(a). By visual assessment, the agreement between the *Opera* simulation and the survey data at 392.29 A is reasonably good. It was found that the maximum value of the measured fringe field profile along $(y, z) = (12.7, 179.832)$ mm was approximately 1.015 times that of the simulated field profile at approximately the same position. This scaling factor was used to the scale our *Opera* results in each of Figs. 25(a), 26(a), and 27(a), as shown in Figs. 25(b), 26(b), and 27(b), and provided even better agreement. It is reasonable to conclude that our *Opera* model can accurately simulate magnetic fields to within approximately 1% of the true field at other excitations as well.

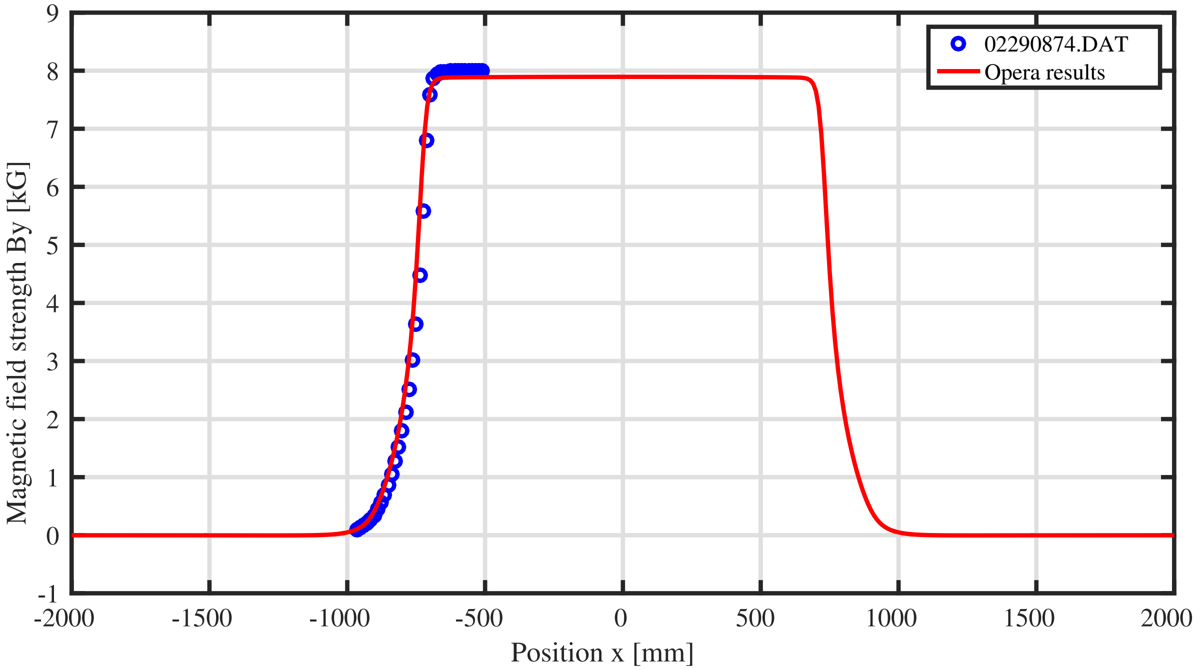


(a)

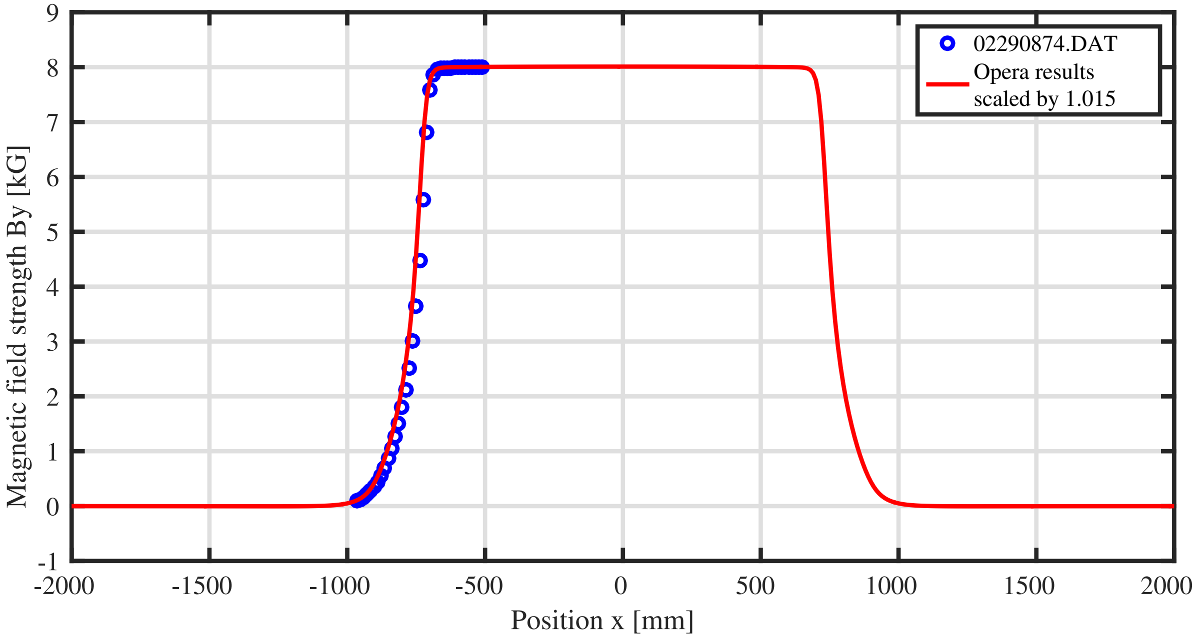
(b)

(c)

Figure 24: (a) A front view of the 4VB1 dipole model in *Opera*, looking down the positive x-axis, (b) a side view of the same model, looking down the negative z-axis, and (c) a top view of the same model, looking down the negative y-axis. The yoke is shown in green and the coils are shown in red. The three images do not necessarily have the same scale.

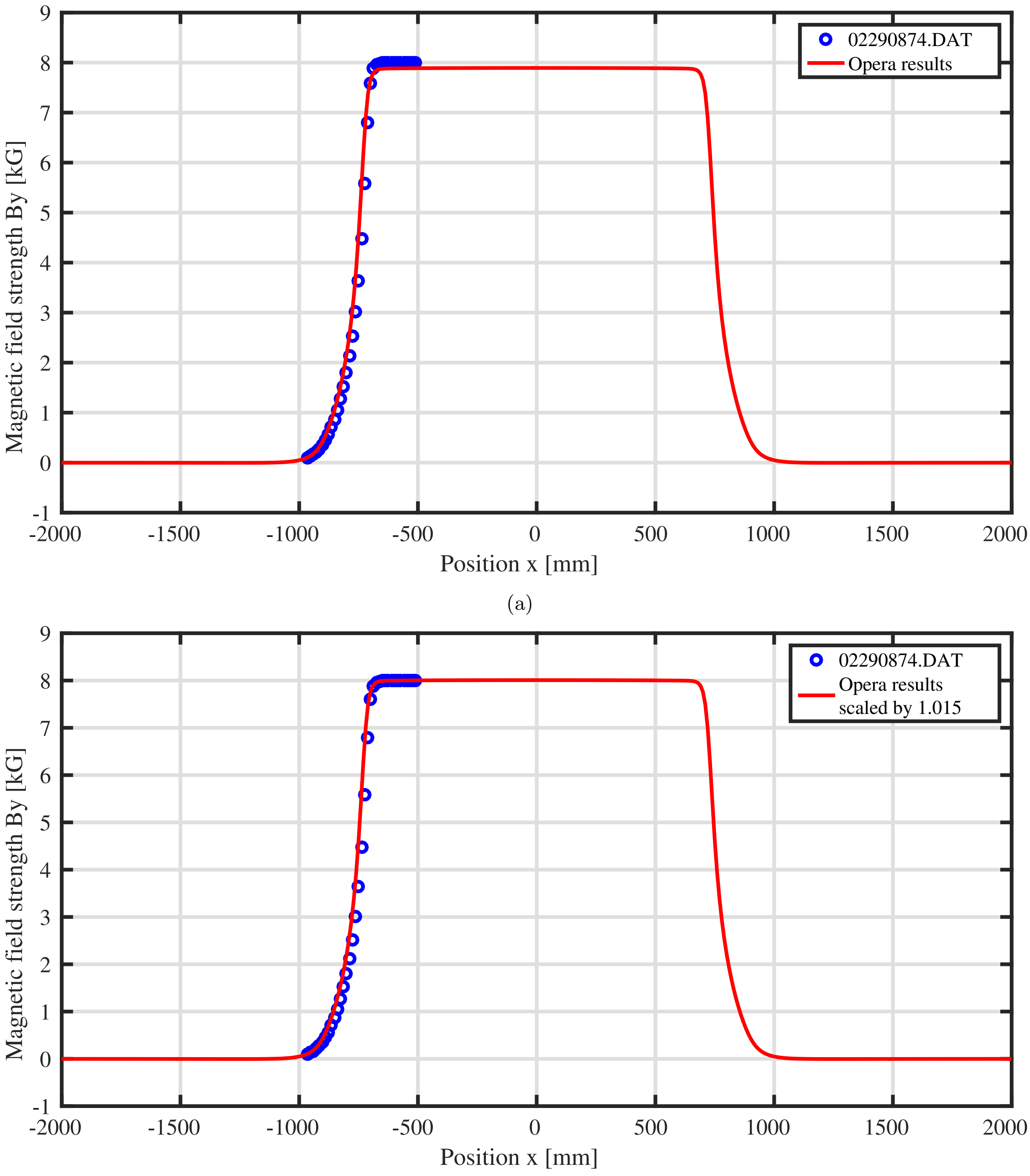


(a)



(b)

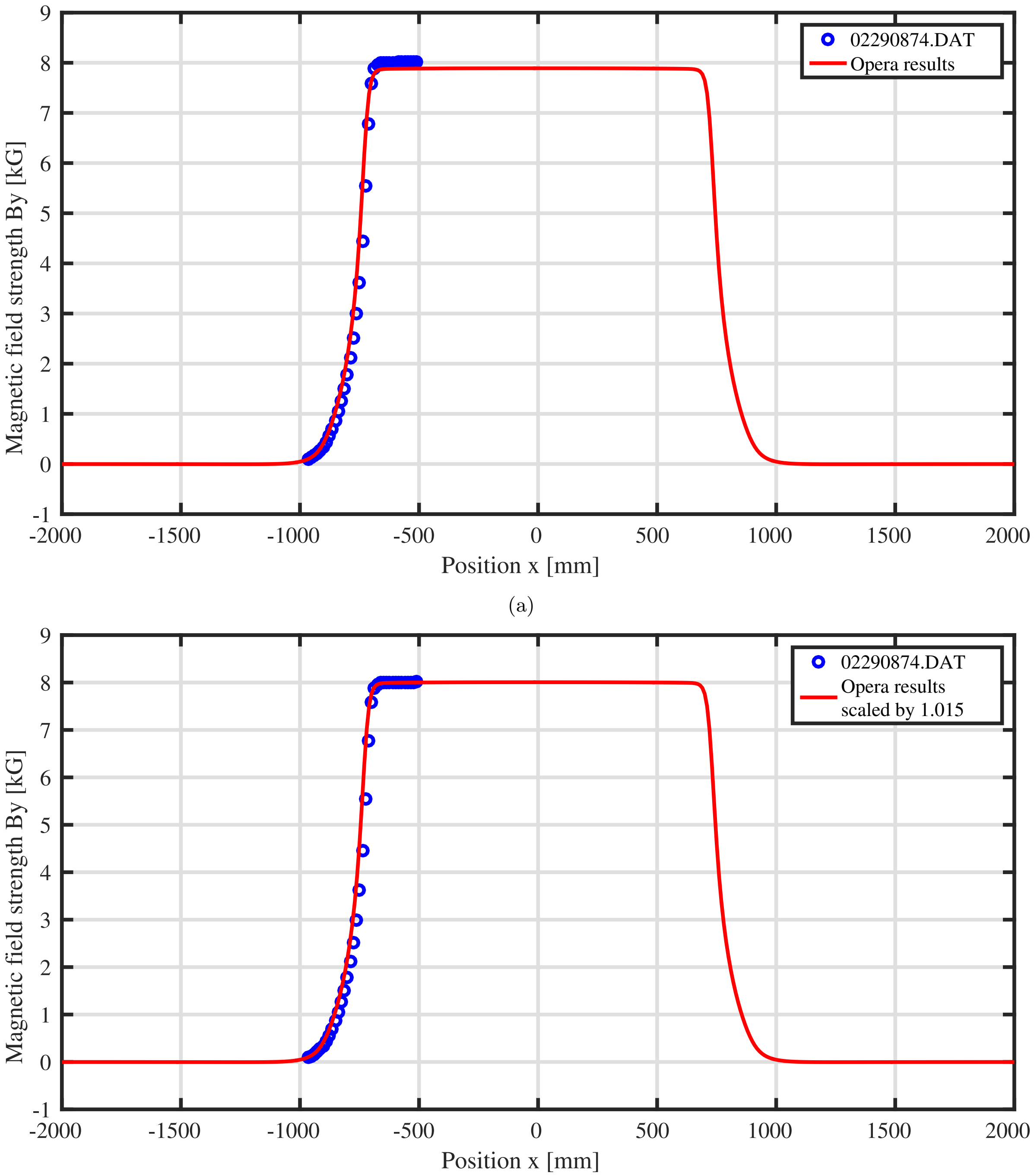
Figure 25: (a) The median plane field survey data 02290874.DAT plotted along $(y, z) = (12.7, 129.032)$ mm, and our *Opera* results, plotted along $(y, z) = (10, 130)$ mm, for the 4VB1 dipole at an excitation of 392.29 A. The coordinate z is relative to the pole manifold end. (b) The same plot as in (a) but with the *Opera* results scaled by 1.015.



(a)

(b)

Figure 26: (a) The median plane field survey data 02290874.DAT plotted along $(y, z) = (12.7, 179.832)$ mm, and our *Opera* results, plotted along $(y, z) = (10, 180)$ mm, for the 4VB1 dipole at an excitation of 392.29 A. The coordinate z is relative to the pole manifold end. (b) The same plot as in (a) but with the *Opera* results scaled by 1.015.



(a)

(b)

Figure 27: (a) The median plane field survey data 02290874.DAT plotted along $(y, z) = (12.7, 230.632)$ mm, and our *Opera* results, plotted along $(y, z) = (10, 230)$ mm, for the 4VB1 dipole at an excitation of 392.29 A. The coordinate z is relative to the pole manifold end. (b) The same plot as in (a) but with the *Opera* results scaled by 1.015.

The 4VB1 dipole will be run at an excitation around 820 A to result in a bending angle of 34°, according to Yi-Nong Rao. The magnet will sit 914.4 mm directly above the EHBT line and at angle of 17° to the EHBT line, with its return yoke facing the EHBT line [2]. The distance from the centre of the 4VB1 magnet's pole, which we are taking to be 381 mm wide along the z-direction, to the EHBT line will be $(1828.14 \text{ mm}) - (1447.8 \text{ mm})/2 * \tan(34°/2) = 1606.82$ mm along the z-direction, where 1447.8 mm is the length of the magnet in the beam direction and 34° is the required bending angle. [2, 30]. Within our model, this position corresponds to $z = -692.42$ mm. As we wish to extract data 2 m in either direction along the EHBT from this point, we will be collecting data along a straight line connecting the points $(x, y, z) = (1913, -914, -108)$ mm and $(x, y, z) = (-1913, -914, -1277)$ mm within the reference frame of our model. We ran our model with an excitation of 820 A and made the outer boundary extend to $\sim$5 m in each direction to ensure accurate results. At this excitation, the maximum field strength B_y between the poles is approximately 1.5 T. We collected 80 data points along the domain of interest, extracted the buffer corresponding to the data from *Opera*, and projected the three components of the field onto the EHBT line using the unit vectors for the EHBT line in our model's reference frame. We let the z-axis in the EHBT line's reference frame point along its beam direction, the y-axis in the EBHT line's frame match that of our model, and the x-axis in the EHBT line's reference frame be appropriately given for a right-handed coordinate system. The unit vectors for the EHBT line, $\hat{\mathbf{X}}$, $\hat{\mathbf{Y}}$, and $\hat{\mathbf{Z}}$, given terms of the unit vectors for our model, $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$, are $\hat{\mathbf{X}} = -\sin(17°)\hat{\mathbf{x}} + \cos(17°)\hat{\mathbf{z}}$, $\hat{\mathbf{Y}} = \hat{\mathbf{y}}$, and $\hat{\mathbf{Z}} = -\sin(73°)\hat{\mathbf{x}} - \cos(73°)\hat{\mathbf{z}}$. The resulting three components of the magnetic field, given in the frame of the EHBT line, are shown in Fig. 28. It is also important to note that these field components are correctly signed as the field inside the dipole has the correct sign for bending the protons in BL4N in the desired way.

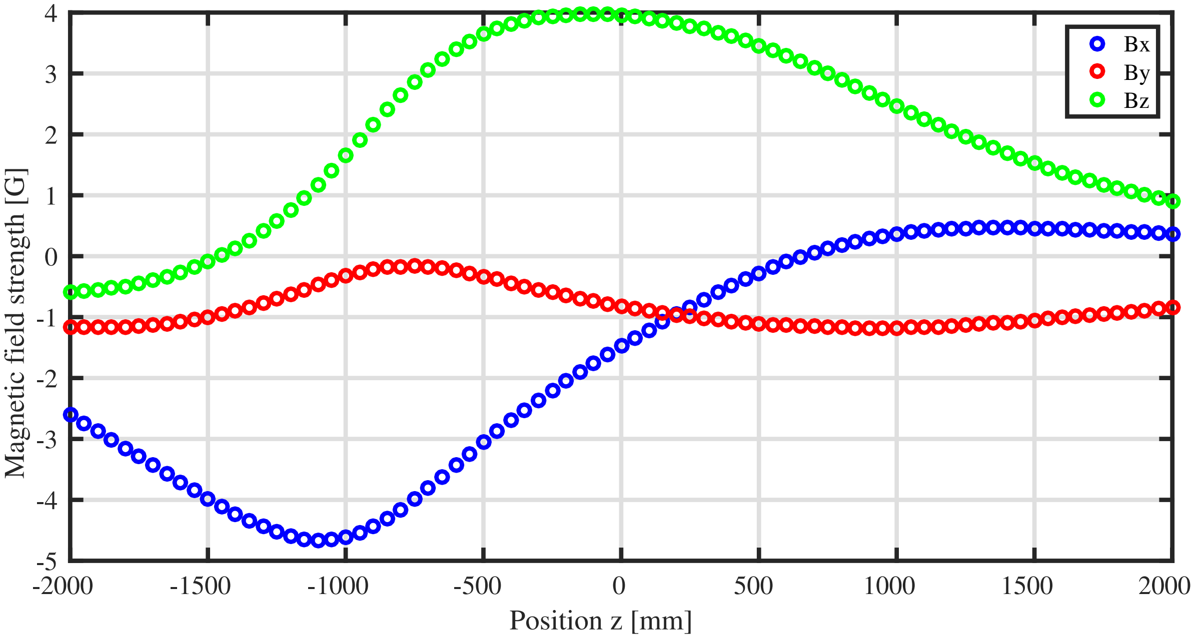


Figure 28: The x-component B_x, the y-component B_y, and the z-component B_z of the magnetic field due to the 4VB1 dipole magnet with an excitation of 820 A long the EHBT line as described in Ref. [2]. The coordinate z denotes the position along the EHBT line in the beam direction with the origin taken to be at $(x, y, z) = (0, -692.42, -914.4)$ mm within the reference frame of our model, referred to as the point "R2" in Ref. [2]

It is clear from Fig. 28 that all three components of the field are non-negligible along the EHBT line due to the 4VB1 dipole running at 820 A. Moreover, all three of the components tend to remain well above 100 mG in magnitude, with B_x nearly achieving -5 G and B_z achieving 4 G. Therefore, shielding will be important near this magnet as the ambient fields are higher than the 100 mG threshold required to maintain proper electron steering [2].

We have plotted the magnitude of the magnetic field inside the magnet at an excitation at 820 A, as shown in Fig. 29. The field inside the yoke is approximately 1.6 T and the field inside the poles is approximately 1.9 T. For field values this high, the magnet's steel is very likely in its nonlinear regime and the yoke is nearly saturated.

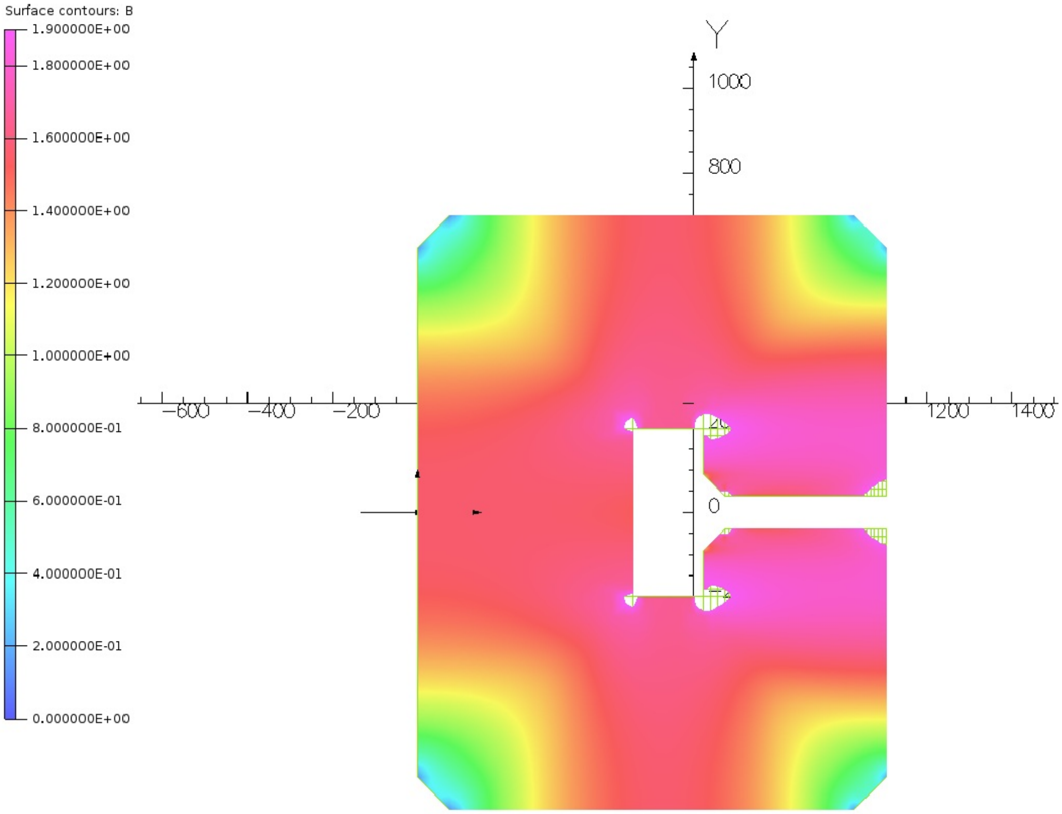
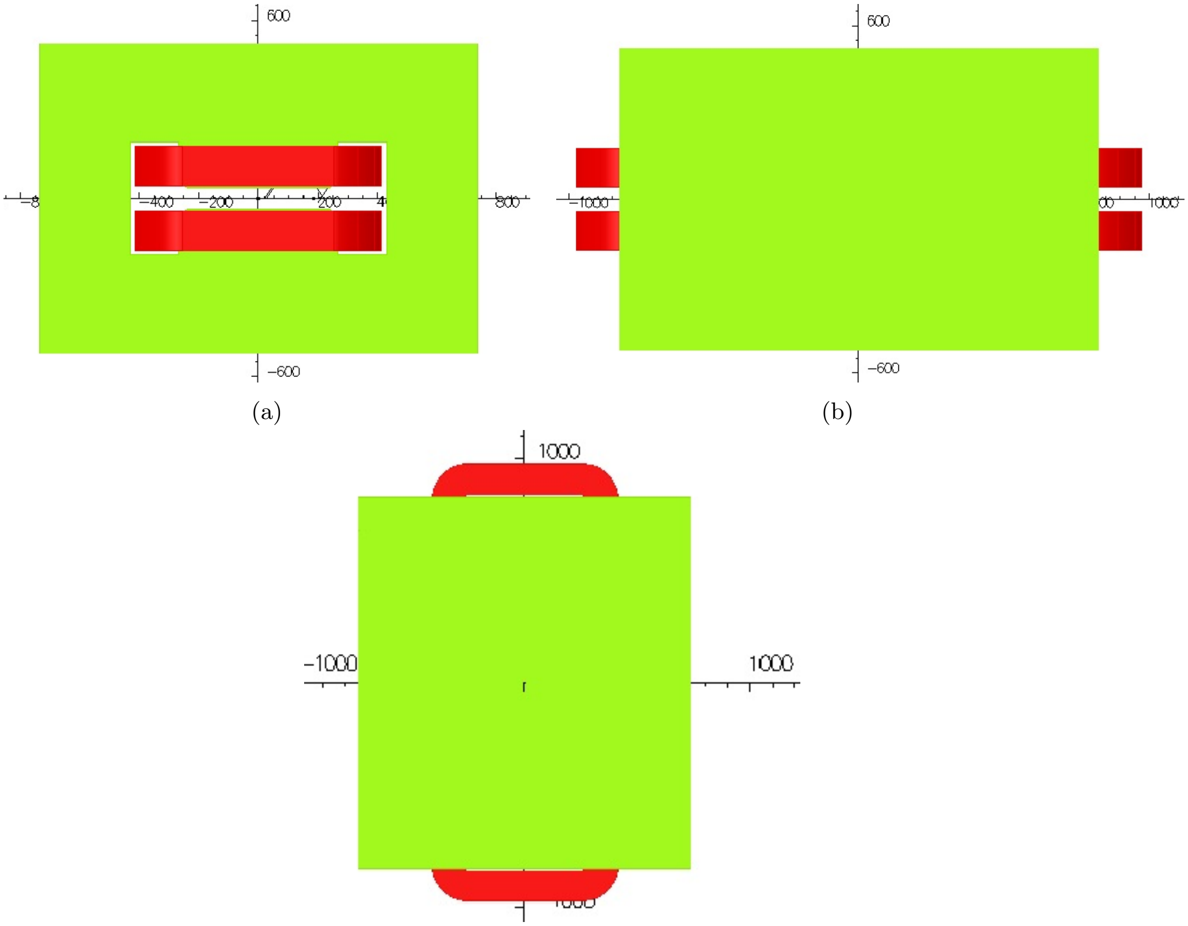


Figure 29: A contour plot of the magnetic field strength B inside the 4VB1 dipole in *Opera* and at an excitation of 820 A. The slice is taken at $z = 0$ mm. The field has units of teslas.

3.7 Preliminary 45° Bending H-Frame Dipole

We have also worked on a preliminary design for a 45° bending dipole with an H-frame yoke in *Opera-3D*, two of which will be needed in BL4N [31]. The magnet can have a maximum length of 1.85 m in the beam direction, which is the z-direction in our model, and a maximum height of 1.30 m in the vertical direction, which is the y-direction in our model [32]. The x-direction is appropriately given for a right-handed coordinate system and the maximum width of the magnet in the x-direction is 1.27 m [32]. The origin in the x-, y-, and z-directions is taken to be at the centre of the dipole where the three reflection planes of symmetry intersect. The north pole of the dipole is in the positive half of the y-axis. We have assumed the magnet will be made of C1010 steel, which is a pessimistic assumption as C1010 steel tends to result in lower quality fields due to its high carbon content. As a result, we used C1010 BH data for the nonlinear analyses associated with this model. Images of our preliminary design are shown in Fig. 30. The .comi file used to build the model in *Opera-3D* is presented in Appendix A.7.

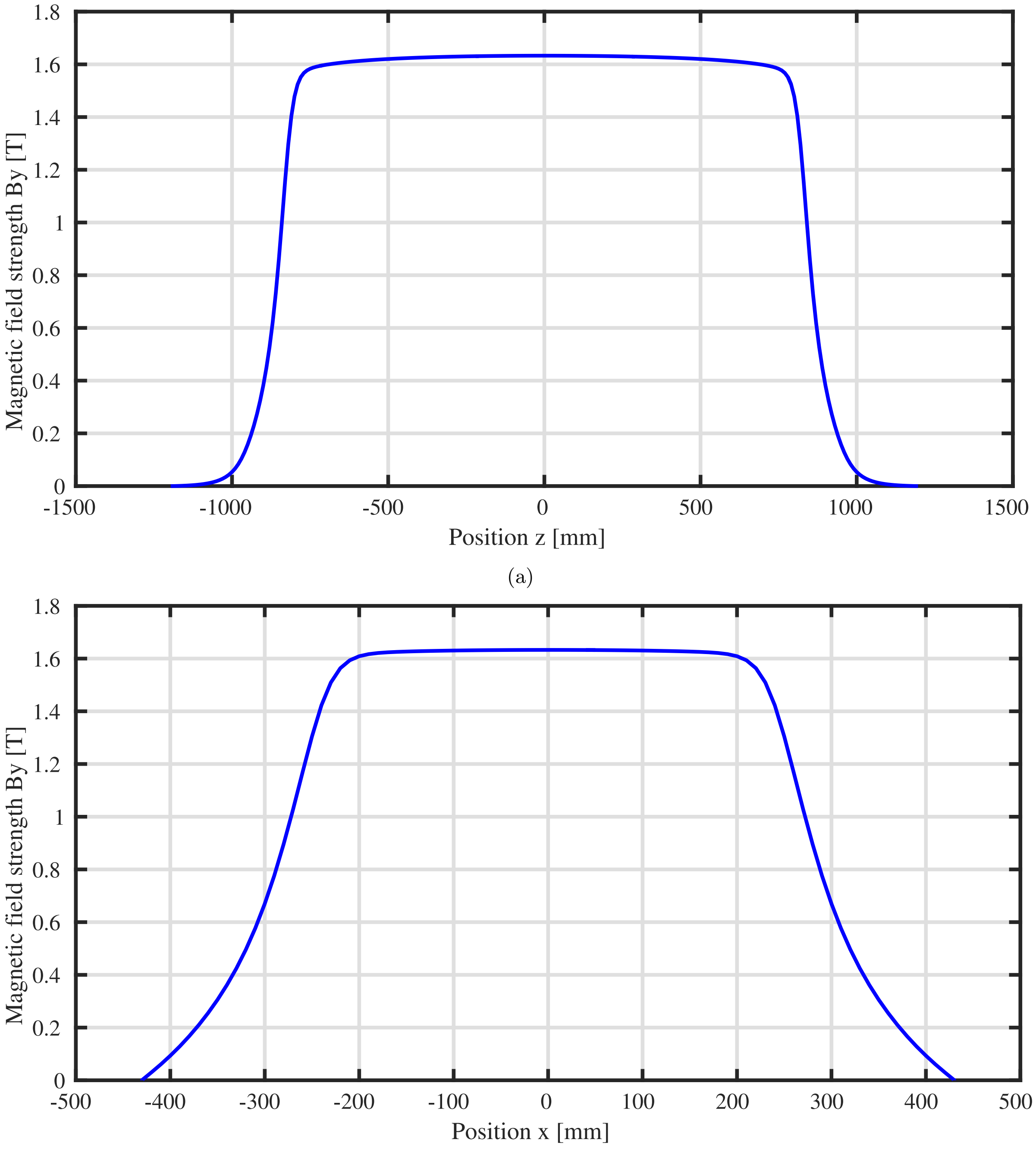


(a) (b)

(c)

Figure 30: (a) A front view of the preliminary 45° bending dipole model in *Opera*, looking down the negative z-axis, (b) a side view of the same model, looking down the positive x-axis, and (c) a top view of the same model, looking down the negative y-axis. The yoke is shown in green and the coils are shown in red. The three images do not necessarily have the same scale.

Presently, the magnet has a pole width of 482.6 mm at the tip and a pole gap width of 76.2 mm. The length of the yoke in the z-direction is 1651 mm, the width of the magnet in the x-direction is 1473.2 mm, and the height of the magnet in the z-direction is 1041.4 mm. The total length of the magnet in the z-direction, including the overhang of the coils, is 1945.64 mm. The length and the width of the magnet are larger than the maximum values permitted for each. We have also chamfered the edges of the pole tips along the beam direction through the magnet. The coils have a cross-sectional area of width 134.62 mm and of height 134.62 mm with 64 turns of conductor assumed to pass through this area, which is a similar turn density to that of the 4VB1 35° bending dipole to make our model realistic [27]. At 850 A, the magnet achieves a maximum magnetic field strength B_y of $\sim$1.6 T. Plots of B_y as a function of z and x on the median plane of the dipole are shown in Fig 31(a) and Fig. 31(b), respectively.



(a)

(b)

Figure 31: (a) The y-component of the magnetic field B_y of our 45° bending dipole, scaled by a factor of -1, as a function of (a) position z along $(x, y) = (0, 0)$ mm and (b) position x along $(y, z) = (0, 0)$ mm. The magnet is operating at an excitation of 850 A. Note the difference in scales along the horizontal axis in each plot.

We used COSY INFINITY to find the reference trajectory for a particle through the dipole in the median plane $y = 0$ mm using the fields obtained from our *Opera* simulation. We used a 500 MeV proton as our reference particle and assumed the reference trajectory to have its turning point exactly halfway along the length of the dipole at $z = 0$ mm. The turning point was decided to be the value of x_0 which roughly minimized the first order transfer map coefficient A_x, where $\Delta x' = A_x x$, and which roughly minimized the second order transfer map coefficients A_{xx}, A_{xy}, and A_{yy}, where $\Delta x' = A_{xx} x^2$, $\Delta y' = A_{xy} xy$, and $\Delta y' = A_{yy} y^2$. The prime denotes angle in the specified direction. We scanned through a range of x-coordinates to locate the turning point $x = x_0$, first with a course step size and again with a finer step size near the approximate value of x_0. It was found that $x_0 = -110$ mm best satisfied these requirements. For $x_0 = -110$ mm, the transfer map coefficients were $A_x = 0.00796\ \mathrm{m}^{-1}$, $A_{xx} = -0.301\ \mathrm{m}^{-2}$, $A_{xy} = 0.376\ \mathrm{m}^{-2}$, and $A_{yy} = 0.214\ \mathrm{m}^{-2}$. It is important to note that $A_{xx} = -0.301\ \mathrm{m}^{-2}$ does not satifsy the requirement of being smaller in magnitude than one fifth of -0.869 m^{-2}. This is requirement is specified in order to minimize beam emittance growth through the magnet, as described in Ref. [33]. The fields were scaled by 0.99312 to result in a bending radius of 44.9998° along this reference trajectory. A plot of the transfer map coefficients as a function of x_0 near $x_0 = -110$ mm is shown in Fig. 32. A plot of the reference trajectory through the dipole is shown in Fig. 33.

We repeated the same procedure for finding the reference trajectory and for finding the second order transfer map coefficients for that trajectory as described above for the pole tip widths of 15.0 inches, 17.0 inches, and 21.0 inches in addition to the pole tip width of 19.0 inches (482.6 mm) we used in our model. We plotted these coefficients for each width as shown in Fig. 34. As apparent from the plot, increasing the width of the pole does result in second order coefficients which are closer to zero, which is desirable in reducing aberrations through the magnet; however, the rate at which these coefficients converge to zero decreases with increasing pole width.

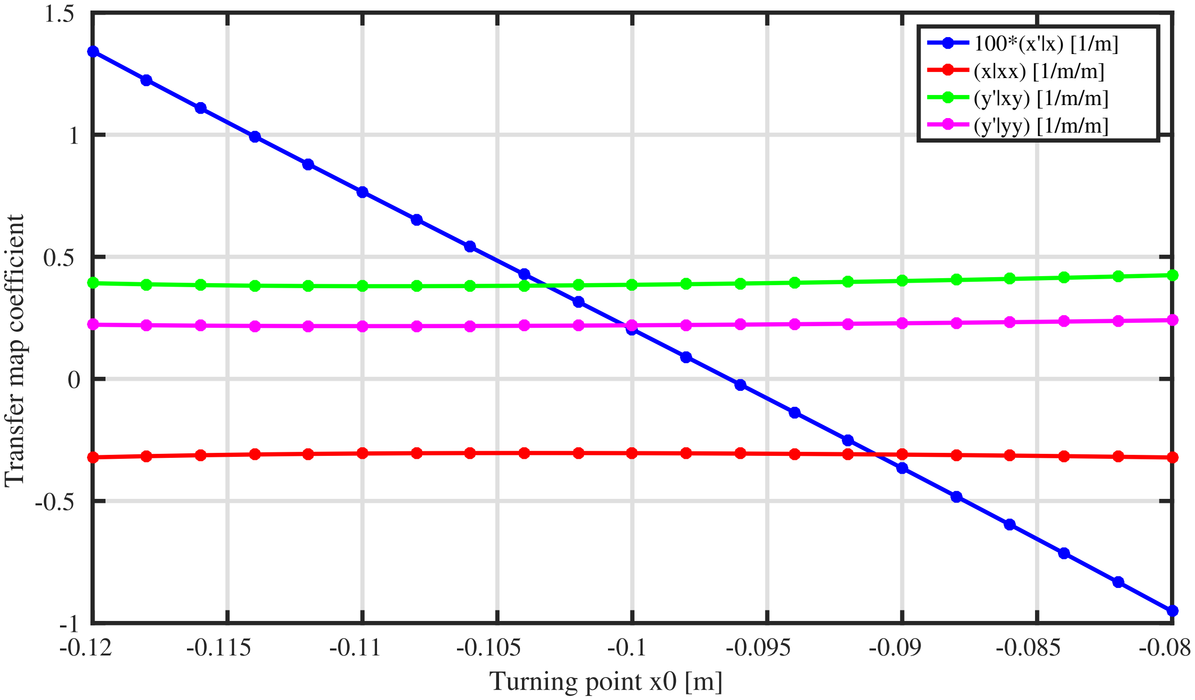


Figure 32: The transfer map coefficients for the particle trajectory through our dipole as a function of x_0, where x_0 is the x coordinate of the turning point in the reference trajectory $(x, y, z) = (x_0, 0, 0)$ mm.

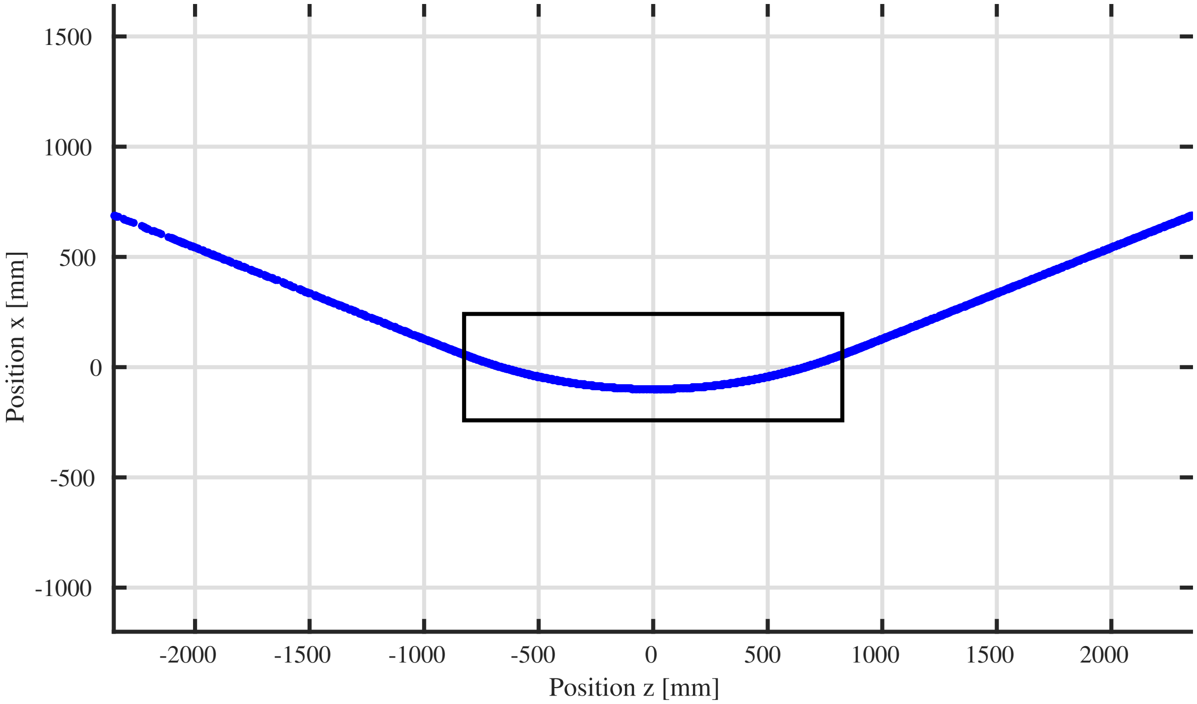


Figure 33: The COSY INFINITY reference trajectory through our dipole in the median plane for a 500 MeV proton, shown in blue. The dipole is excited at 850 A and its fields are scaled by 0.99312 to result in a bending angle of 44.9998°. The black box denotes the surface of the pole tip.

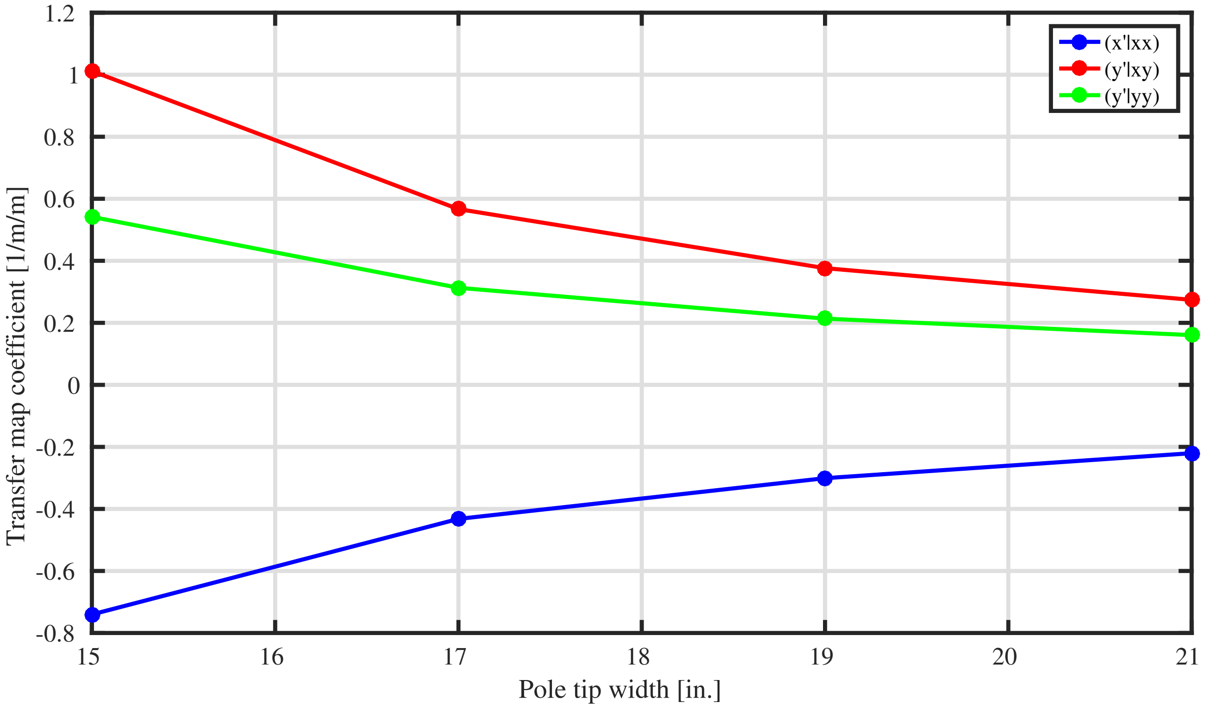


Figure 34: The second order transfer map coefficients for the reference trajectory through our 45° bending dipole operating at 850 A as function of the width of the pole tip.

While we have not extracted leakage fields along the EHBT line due to this magnet from our model, we have plotted the magnitude of the magnetic field inside the dipole at an excitation at 850 A, as shown in Fig. 35. The field inside the yoke is approximately 1.6 T and the field inside the poles is approximately 2 T. The magnet's poles are completely saturated and the yoke of the magnet is nearing saturation and very likely in the steel's nonlinear regime. As a result, it is possible that there will be leakage fields of a relatively high magnitude along the EHBT line due to this magnet.

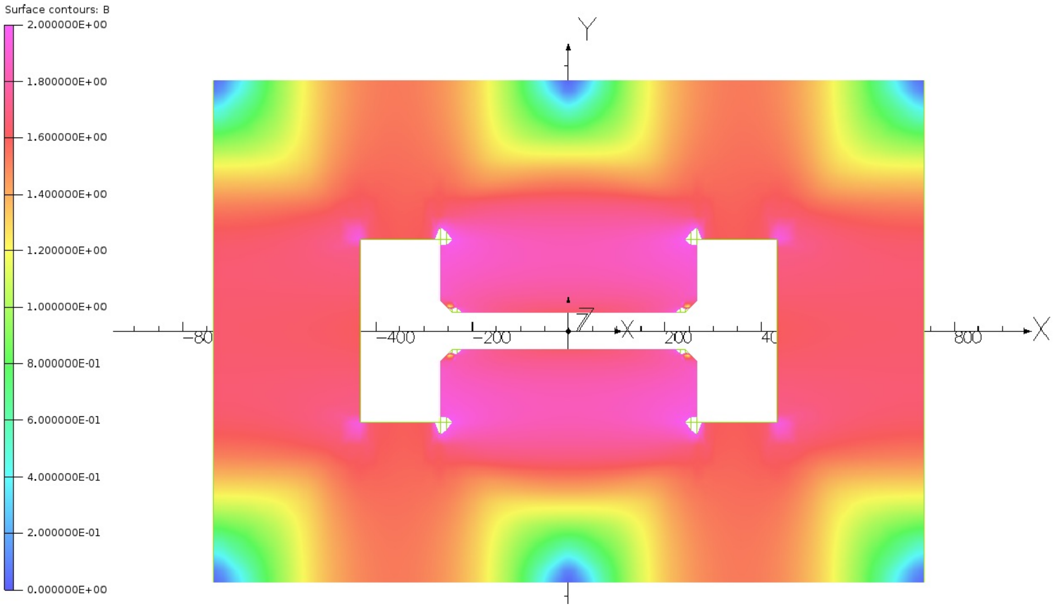


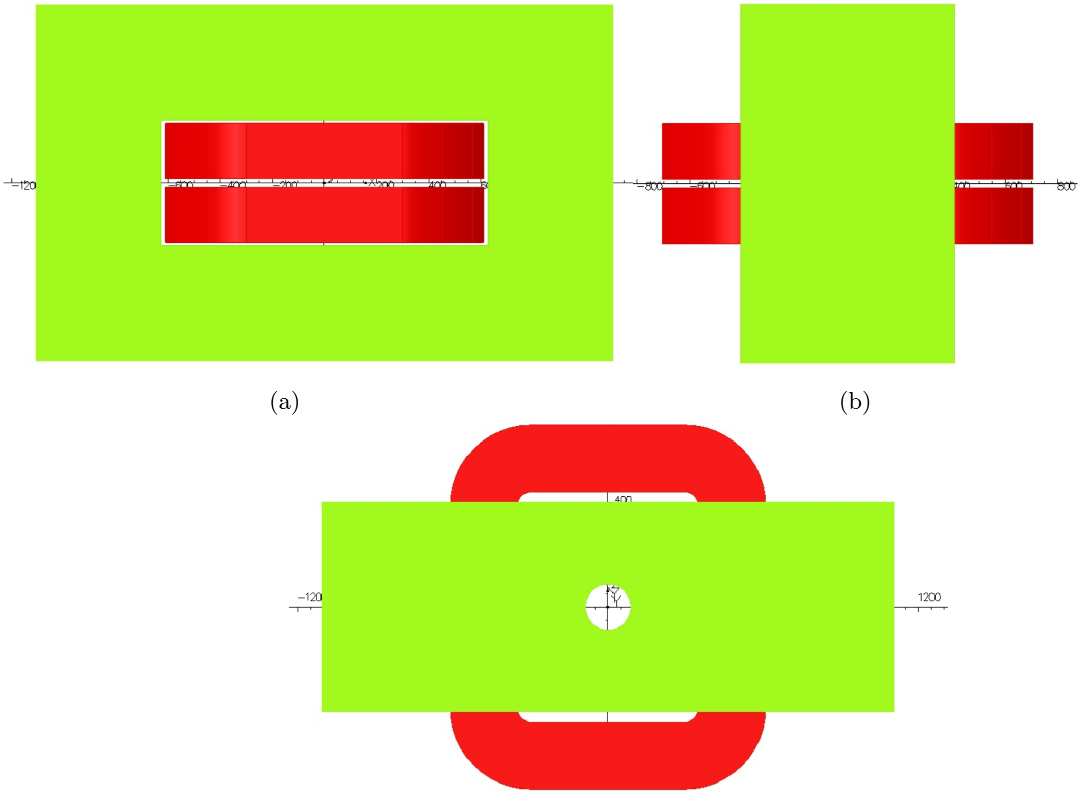
Figure 35: A contour plot of the magnetic field strength B inside our 45° bending dipole in *Opera* and at an excitation of 850 A. The slice is taken at $z = 0$ mm. The field has units of teslas.

3.8 Inflector Assembly Test Stand: Bonnie H-Frame Dipole

The H-frame dipole magnet nicknamed "Bonnie" will be retrofitted for use as a test stand for the new inflector assembly to be installed within the cyclotron. As there is the possibility of the new inflector being damaged due to the conditions inside the cyclotron, it is desirable to have an external setup which can create a field similar to that of the cyclotron for the purposes of testing the new inflector. It is our objective to determine the manner in which the Bonnie magnet will need to be adjusted so that it produces such a field, whose data is given in Ref. [34] as B_y versus y.

We modelled the Bonnie magnet initially in *Opera*'s two dimensional (2D) solver, *Opera-2D*. Thomas Planche and Rick Baartman anticipated that a cylindrical hole cut about the vertical axis of the magnet would siphon the flux in such a way as to result in the desired field. With this in mind, 2D models were used to explore various cylindrically-symmetric hole shapes and diameters as well as different separations between the lower and upper yoke at varying excitations. The poles of the dipole were removed during modelling and the dimensions of the magnet were measured using a measuring tape. However, some of the magnet's dimensions can be found in the TRIUMF Magnet Index [35]. The number of turns of conductor, 94, was calculated by determining the number of turns required to produce a max field of 1.7 T for a 5.5 inch pole gap when the Bonnie magnet is running at 1000 A [35]. It was discovered that certain *Opera-2D* models were capable of producing the desired field profile. It was also discovered that using conical cuts changed the field profile marginally as compared to simply using cylindrical cuts. To make the model more realistic, the magnet was built in *Opera-3D*. The x-, y-, and z-axes are given in the same way as for the 45° bending dipole. The Bonnie magnet was assumed to be made of C1010 steel and so our nonlinear analysis in *Opera* used C1010 BH data. The north pole of the dipole is in the negative half of the y-axis. Through trial and error, the best match to the cyclotron field data was achieved for a cylindrical hole of diameter 7.0 inches cut about the vertical axis of the magnet, a separation between the lower and upper yoke of 19.0 inches, and at an excitation of 625 A. The poles of the magnet were not present in this model. The actual separation between the lower and upper yoke is approximately 16.75 inches and so additional steel will need to be added to the sides of yoke. Images of the model are shown in Fig. 36. The .comi file used to build the model in *Opera-3D* is presented in Appendix A.8. The field profile achieved by the model as compared to the cyclotron field data is shown in Fig. 37(a).

Alternatively, if a 7.0 inch diameter hole is too small for the inflector plug, a plot of B_y versus y for a Bonnie dipole with a cylindrical hole of diameter 8.0 inches cut about the vertical axis of the magnet, a separation between the lower and upper yoke of 18.0 inches, and at an excitation of 600 A is shown alongside the cyclotron data in Fig. 37(b). The matching is only marginally worse than the field achieved in Fig. 37(a).

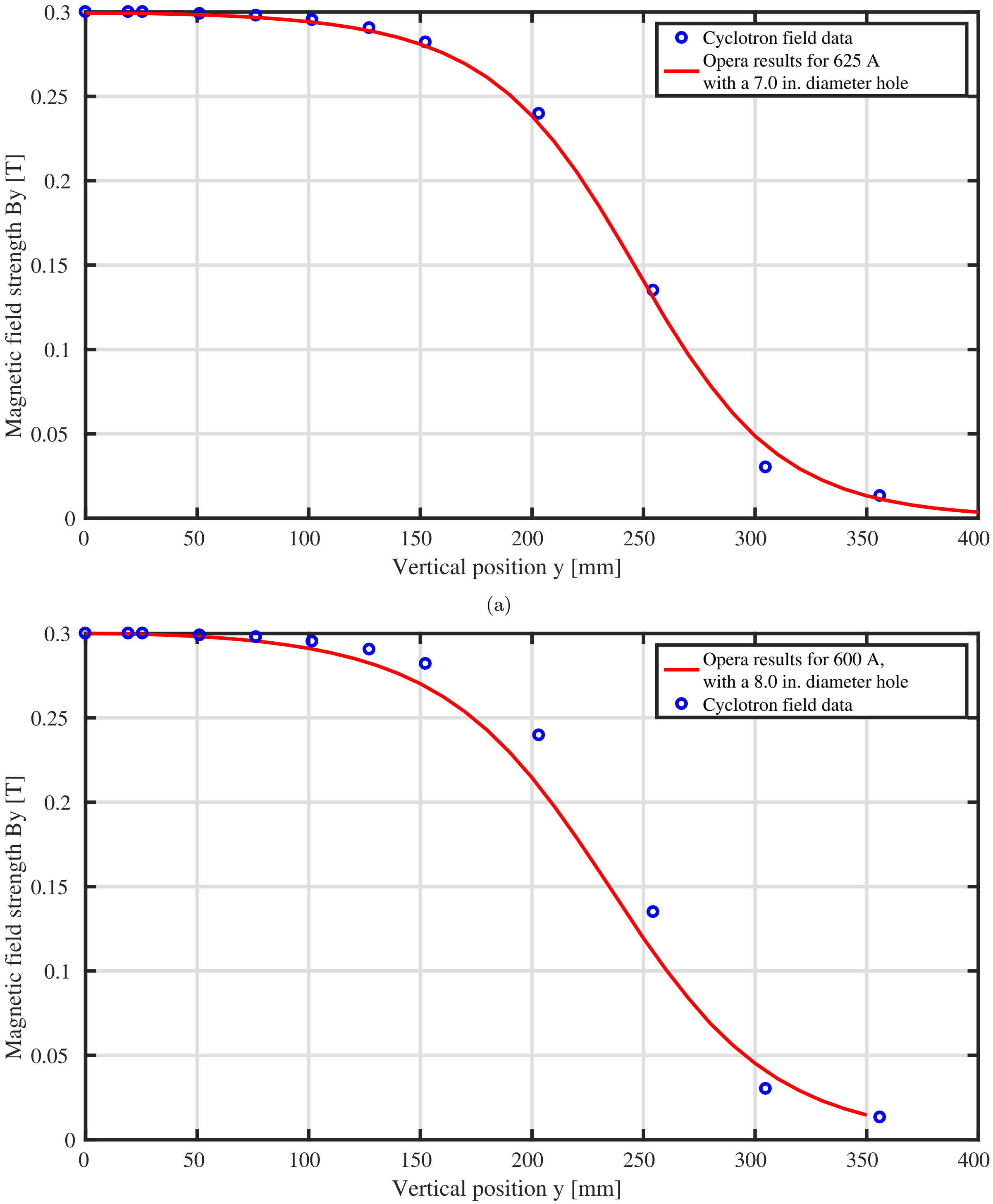


(a)

(b)

(c)

Figure 36: (a) A front view of the Bonnie dipole model in *Opera*, looking down the negative z-axis, (b) a side view of the same model, looking down the positive x-axis, and (c) a top view of the same model, looking down the negative y-axis. The yoke is shown in green and the coils are shown in red. The three images do not necessarily have the same scale.



(a)

(b)

Figure 37: (a) The y-component of the magnetic field B_y plotted as a function of vertical position y from the centre of the Bonnie dipole due to the Bonnie dipole when (a) a 7.0 inch diameter hole is cut about the vertical axis of the magnet, the separation between the lower and upper yoke is 19.0 inches, and the excitation is 625 A and when (b) a 8.0 inch diameter hole is cut about the vertical axis of the magnet, the separation between the lower and upper yoke is 18.0 inches, and the excitation is 600 A. The cyclotron field data is shown in each plot as well.

4 Summary

In this report, we have detailed the use of *Opera* in modelling the magnets to be used in BL4N. We have shown our *Opera* models to be in good agreement with the existing survey data for each magnet. We extracted the leakage fields due to the 4Q14/8 quadrupole, the 4Q8.5/8.5 quadrupole, and the 4VB1 35° bending dipole along the EBHT line operating at 340 A, 200 A, and 820 A, respectively. We found the leakage fields to be smaller than 100 mG for the 4Q14/8 and the 4Q8.5/8.5 quadrupoles, as required to maintain electron steering. The leakage fields due to the 4VB1 dipole were on the order of 1 G and so shielding will be required around these magnets. We have not extracted the leakage fields due to the UoA 4Q12/6 quadrupole, the Danfysik TUDA Short quadrupole, or the Danfysik L5 quadrupole along the EHBT line when each is operating at 240 A, 180 A, and 100 A, respectively, but we anticipate the leakage fields will be smaller than 100 mG for each. The only magnet which has yet to be analyzed is the KEK QA-I quadrupole, but a starting point for a model has been implemented by the author in *Opera*.

We have also presented a preliminary design for a 45° bending dipole to be used in BL4N. The second order transfer map coefficients along the reference trajectory have been provided for examining emittance growth through the magnet, but are not as small as desired. Leakage fields along the EHBT line due to this magnet operating at 850 A have yet to be extracted.

Concerning the use of the Bonnie dipole magnet as an inflector assembly test stand, we have shown that removing its poles, cutting a cylindrical hole of diameter 7.0 inches about the vertical axis of the magnet, increasing the separation between the lower and upper yoke to 19.0 inches, and running the magnet at an excitation of 625 A results in a field B_y as function of vertical position y which matches that of the cyclotron, as desired.

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Appendices

A *Opera* .comi Files Used to Construct the Models

The following appendices include the .comi files used to construct the *Opera-3D* models discussed in this report. These macros may be run from *Opera*'s Comi Editor window or from the Modeller's Console. Each macro has been annotated for clarity.

The models have been parametrized in terms of their dimensions at the beginning of each macro. A magnet with the same general shape as an existing model but with different dimensions may be easily constructed by adjusting these parameters within the macro; the air boxes should scale appropriately. Because of this, the macros used to create the 4Q14/8, UoA 4Q12/6, and the Danfysik TUDA Short quadrupoles are nearly identical.

If linear analysis is chosen, $\mu_r = 2000$ is set for the material composing the magnet, but this can be adjusted as needed. The linear analysis is much faster than the non-linear analysis but should only be valid at low excitations. If non-linear analysis is chosen, the directory pointing to the BH data for the material composing the magnet may need to be updated. All magnets use the BH data for C1010 steel. In all models, μ_r is assumed to be isotropic.

In terms of potential problems which may arise when running the models, sometimes the material properties of the steel are not properly added to the yoke and/or the pole of the magnet and each remains a grey colour identical to that of the background instead of changing to a green colour. Often, this happens when new cuts or air boxes are added to the existing model and the identifiers for the yoke and the pole change, which are separated from one another in each macro in order to add different cell properties to each. The line, *PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=J.00001*, for example, selects the cell of the body "Yoke" which has identifier J.00001, but this identifier could change to K.00001, for example, when adding a new cut plane somewhere in the model. These identifiers can be determined by manually selecting cells within the model using the GUI. This problem can be fixed in the future by specifying the magnet body to be cut into a yoke body and a pole body instead of a yoke cell and a pole cell, which both belong to the same single body. Other things to keep in mind are that all air boxes should be made total potential regions except for the air box which encloses the coils entirely, which should be made a reduced potential region. One also has to ensure the coils do not physically overlap with each other and that the magnet's dimensions are physically possible. All of the models presently mesh without error for the element sizes used in the included macros, but it is possible that adjusting the element sizes may cause volume meshing to fail. Finally, the commands *CLEAR* and *YES* at the top of each macro will need to be commented-out prior to running the model in a Modeller window where there is no existing model and will then need to be un-commented to build updated models in a Modeller window in which there is an existing model.

If one has any questions or concerns about the models, Matthew Basso can be reached by email at mjbasso2012@gmail.com.

A.1 4Q14/8 Quadrupole

```
//4Q14/8 Quadrupole Magnet Model - Prepared by Matthew Basso in Opera 18R1/2
//Please note: this magnet has been almost entirely parameterized. One can enter
parameters for a magnet sharing a similar shape but with different dimensions as
compared to 4Q14/8 and this script should be able to build the new magnet without any
further intervention.

CLEAR |//This command may need to be commented out before initially running the macro.
YES   |//This command may need to be commented out before initially running the macro.

$CONST #MM_PER_INCH               25.4

//The analysis type is specified. If #ANALYSIS_TYPE=0, the analysis type is linear. If
#ANALYSIS_TYPE=1, the analysis type is nonlinear.

$CONST #ANALYSIS_TYPE             1

//The dimensions of the quadrupole as well as the meshing parameters are entered below.
The names have been made as descriptive as possible, but one should refer to the
provided sketches if it is unclear how a dimension is defined.  Where applicable, the
DWG number associated with the drawing from which the dimension was obtained is noted.

$CONST #APERTURE_DIAMETER         4.060*#MM_PER_INCH  |//Obtained from DWG No. E-3638.
$CONST #POLE_LENGTH               7.560*#MM_PER_INCH  |//Obtained from DWG No. D10076.
$CONST #POLE_BASE_WIDTH           6.105*#MM_PER_INCH  |//Obtained from DWG No. D10076.
$CONST #POLE_TIP_WIDTH            4.000*#MM_PER_INCH  |//Obtained from DWG No. D10076.
$CONST #POLE_TIP_RADIUS           2.340*#MM_PER_INCH  |//Obtained from DWG No. D10076.
$CONST #YOKE_EDGE_WIDTH           6.6*#MM_PER_INCH    |//Estimated from DWG No. E-3638
using a ruler.
$CONST #YOKE_THICKNESS            13.810*#MM_PER_INCH |//Obtained from DWG No. E-3638.

$CONST #COIL_OFFSET               5.0                 |//This dimension was arbitrarily
selected. The coils must have some small (nonzero) offset from the poles.
$CONST #COIL_EDGE_WIDTH           2.0*#MM_PER_INCH    |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_LENGTH               4.0*#MM_PER_INCH    |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_CURRENT              340.0 A             |//In Doug Evans' field survey
(02041088.DAT) for this magnet, the current put through coils was 340 A.
$CONST #COIL_TURN_NUMBER          37.0                |//Obtained from DWG No. D.30179.

$CONST #CENTER_BOX_ES             5.0                 |//"ES" refers to "element size".
The "Center box" refers to the body enclosing the good field region at the center of the
quadrupole.
$CONST #POLE_ES                   2.0*#CENTER_BOX_ES  |//The "Pole" refers the body
which makes up the poles.
$CONST #YOKE_ES                   4.0*#CENTER_BOX_ES  |//The "Yoke" refers the body
which makes up the yoke.
$CONST #COIL_BOX_ES               2.0*#CENTER_BOX_ES  |//The "Coil box" refers the body
which encloses the coils and the poles.
$CONST #YOKE_BOX_ES               5.0*#CENTER_BOX_ES  |//The "Yoke box" refers the body
which encloses the coils, the poles, and the entire yoke.
$CONST #BACKGROUND_1_ES           5.0*#CENTER_BOX_ES  |//"Background 1" refers to the
smaller background region enclosing the quadrupole.
$CONST #BACKGROUND_2_ES           6.0*#CENTER_BOX_ES  |//"Background 2" refers to the
larger background region enclosing the quadrupole.

$CONST #POLE_DSL                  6    |//"DSL" refers to "data storage level". The pole
and the yoke have the highest DSLs. Subsequent DSLs are assigned in the order in which
the air boxes are drawn.
$CONST #YOKE_DSL                  5
$CONST #CENTER_BOX_DSL            4
$CONST #COIL_BOX_DSL              3
$CONST #YOKE_BOX_DSL              2
$CONST #BACKGROUND_1_DSL          1
$CONST #BACKGROUND_2_DSL          0

$CONST #XY_SCALING_FACTOR         6.0  |//This factor defines how many times larger
```

```
Background 2 should be in terms of length relative to the side length of the yoke.
$CONST #Z_SCALING_FACTOR          6.0  |//This factor defines how many times larger
Background 2 should be in terms of thickness relative to the thickness of the yoke.

//The following dimensions are implicit from the above dimensions. The current density
in the coils may be calculated given a desired current and knowing the cross-sectional
area of the coils used and number of turns passing through that area. As the analysis
uses SI-MM, the units of current density are A/mm^2.

$CONST #YOKE_OUTER_LENGTH         #APERTURE_DIAMETER+2.0*(#POLE_LENGTH+#YOKE_EDGE_WIDTH)
$CONST #YOKE_INNER_LENGTH         #YOKE_OUTER_LENGTH-2.0*#YOKE_EDGE_WIDTH
$CONST #POLE_TIP_LENGTH           #POLE_TIP_RADIUS*(1-COS(ASIN(#POLE_TIP_WIDTH/2.0/
#POLE_TIP_RADIUS)))
$CONST #BACKGROUND_XY_LENGTH      #XY_SCALING_FACTOR*#YOKE_OUTER_LENGTH/2.0
$CONST #BACKGROUND_Z_LENGTH       #Z_SCALING_FACTOR*#YOKE_THICKNESS/2.0
$CONST #APERTURE_RADIUS           #APERTURE_DIAMETER/2.0
$CONST #COIL_CROSS_SECTIONAL_AREA #COIL_EDGE_WIDTH*#COIL_LENGTH
$CONST #COIL_CURRENT_DENSITY      #COIL_CURRENT*#COIL_TURN_NUMBER/
#COIL_CROSS_SECTIONAL_AREA

//The yoke of the quadrupole is drawn and covered.

WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=0 Z0=0 X1=0 Y1=#POLE_LENGTH
+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z0=0
X1=#YOKE_OUTER_LENGTH/2.0 Y1=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_OUTER_LENGTH/2.0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH
Z0=0 X1=#YOKE_INNER_LENGTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_INNER_LENGTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_BASE_WIDTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_BASE_WIDTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_TIP_WIDTH/2.0 Y1=#POLE_TIP_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_TIP_WIDTH/2.0 Y0=#POLE_TIP_LENGTH Z0=0 X1=0 Y1=0
Z1=0 EDGETYPE=CENTRE X2=0 Y2=#POLE_TIP_RADIUS Z2=0

//The yoke is displaced in the y-direction, rotated around the z-axis, and swept in the
z-direction to create a body. The pole is made using a cut-plane.

PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=DISPLACE DU=0 DV=#APERTURE_RADIUS DW=0
PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=-1.0*#YOKE_THICKNESS/2.0
DRAFTTYPE=NONE
BLOCK UNIQUENAME='Cut' X0=0 Y0=#APERTURE_RADIUS+#POLE_LENGTH Z0=0 X1=#POLE_BASE_WIDTH/
2.0 Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=#YOKE_THICKNESS/2.0
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45

//All four of the coils are built with negative rotational symmetry. A local coordinate
system is used to position the coils.

RACETRACK OPTION=NEW -KEEP XP1=#POLE_BASE_WIDTH/2.0+#COIL_OFFSET YP1=0
WIDTH=#COIL_EDGE_WIDTH THICKNESS=#COIL_LENGTH H1=#YOKE_THICKNESS/2.0+#COIL_OFFSET
R1=0.01*#POLE_BASE_WIDTH INCIRCUIT=NO CIRCUITELEMENT= CURD=#COIL_CURRENT_DENSITY
TOLERANCE=0 DRIVELABEL='Default Drive' THETA2=0 PHI2=-45 PSI2=0 XCEN2=(#POLE_LENGTH
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) YCEN2=(#POLE_LENGTH
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) ZCEN2=0 LCNAME='Global coordinate
system' RXY=0 RYZ=0 RZX=0 SYMMETRY=-4 MODELCOMPONENT=NO

//Cell properites are added to the yoke and to the pole. The magnetic properties of the
material "Steel" are defined. This magnet is made of C1010 steel, and so the
corresponding BH data, C1010.BH (or tenten.BH), is loaded if the analysis is set to be
nonlinear. The path to the BH data may need to be updated. The analysis type, TOSCA, is
also specified for each.
```

```
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=J.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=J.00002
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POLE_DSL SIZE=#POLE_ES ELEMSHAPEPREF=HEXOPRISM
$IF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=0
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=LINEAR MUANISOTROPY=ISOTROPIC MU=2000 HC=0
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=YES CONVTOL=1.0E-08 HX=0.0 HY=0.0
HZ=0.0 RHS=ADAPTIVE POTENTIALCUT=YESMODEL CREATE
$ELIF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=1
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='C1010'
BHDATA OPTION=EDIT LABEL=C1010
BHDATA OPTION=LOAD LABEL=C1010 FILE='/home/mbasso/Opera_Models/
Physical_Magnet_Modelling/Quadrupoles/4Q14slash8/C1010.BH'
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=30
TOLERANCE=1.0E-7 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES
$END IF

//All of the following bodies are made of air. The center box is built and its cell
properites are added. This and the following air boxes are made by first drawing a box
and then rotating it 45 degrees. To ensure proper rotation, the boxes are made symmetric
in the xy-plane. Sections of the box are later cut away when making the model body.

BLOCK UNIQUENAME='Center box' X0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_TIP_LENGTH
Y1=#APERTURE_RADIUS+#POLE_TIP_LENGTH Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Center box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#CENTER_BOX_DSL SIZE=#CENTER_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//A series of concentric cylinders with spacing equal to the ES in the center box are
used to make cuts through the center box. This allows for a more regular mesh within
this region, which is desirable. The cuts are made using the following DO block.

$DO #RADIUS #CENTER_BOX_ES #APERTURE_RADIUS-#CENTER_BOX_ES #CENTER_BOX_ES
CYLINDER Name='Cut' X0=0 Y0=0 Z0=0 X1=0 Y1=0 Z1=#BACKGROUND_Z_LENGTH +TUBE
SHAPECONTROL=TUBE MAJORRADIUS=#RADIUS MINORRADIUS=#RADIUS TOPRADIUS=#RADIUS THICKNESS=0
SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='Center box'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$END DO

//The coil box is built and its cell properites are added. The z-dimension is made to be
slightly larger (1.1 times as large) than total width of the coil to ensure the coil is
well contained inside the box. This is the only body in the model that is made a region
of reduced potential; all other bodies are made regions of total potential.

BLOCK UNIQUENAME='Coil box' X0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_LENGTH
Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=1.1*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The yoke box is built and its cell properites are added. It is important to note that
Y0 and Y1 do not have the same multiplicative prefactors as X0 and X1. The resulting
body (after building the model body) does not have a triangular cross-sectional area;
instead, this cross-sectional area is a quadrilateral. For some reason, this shape
results in better surface and volume meshing over the entire model (volume meshing fails
```

```
otherwise).

BLOCK UNIQUENAME='Yoke box' X0=-1.2*#YOKE_OUTER_LENGTH/2.0 Y0=-1.1*#YOKE_OUTER_LENGTH/
2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0 Y1=1.1*#YOKE_OUTER_LENGTH/2.0
Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Yoke box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 1 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 1' X0=-1.2*#YOKE_OUTER_LENGTH/2.0
Y0=-1.1*#YOKE_OUTER_LENGTH/2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0
Y1=1.1*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 1'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_1_DSL SIZE=#BACKGROUND_1_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 2 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 2' X0=-1.0*#BACKGROUND_XY_LENGTH
Y0=-1.0*#BACKGROUND_XY_LENGTH Z0=0 X1=#BACKGROUND_XY_LENGTH Y1=#BACKGROUND_XY_LENGTH
Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_2_DSL SIZE=#BACKGROUND_2_ES ELEMSHAPEPREF=TETRAHEDRAL

//Two cuts are made through Background 2: one is along the z-direction edge of the yoke
box and the other is slightly offset from and parallel to the x-direction edge of the
yoke box (the predominant face along this side). These cuts enable the surface mesh to
be more regular in the far-field region.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH) X1=2.0*#BACKGROUND_XY_LENGTH*COSD(45)
Y1=#BACKGROUND_XY_LENGTH*COSD(45) Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.3*#YOKE_OUTER_LENGTH/2.0 Z0=0
X1=1.3*#YOKE_OUTER_LENGTH/2.0 Y1=1.3*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Cut'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The symmetry of the model is specified: xy- and zx-plane reflection symmetry and z-
axis rotational symmetry. Finally, the model body is created and the model is given a
surface mesh with a maximum ES equal to that of the largest ES of any body in the model.
The mesh shape is forced to be mosaic to ensure regular meshing.

BACKGROUND OPTION=LOAD
BACKGROUND OPTION=SET SHAPE=TRIM XYSYMMETRYPLANE=YES YZSYMMETRYPLANE=NO
ZXSYMMETRYPLANE=YES EMRXY=TANGMAGN EMRZX=NORMMAGN ROTZNUM=4 EMROTZTYPE=TANGMAGN
MODEL CREATE
MESH SIZE=#BACKGROUND_2_ES NORMALTOL=30.0 SURFACETOL=0.0 TOLERANCE=1.0E-06 TYPE=MOSAIC

//At this point, one only needs to perform volume meshing and set up an analysis
database for the model prior to starting the TOSCA analysis.
```

A.2 4Q8.5/8.5 Quadrupole

```
//4Q8.5/8.5 Quadrupole Magnet Model - Prepared by Matthew Basso in Opera 18R1/2
//Please note: this magnet has been almost entirely parameterized. One can enter
parameters for a magnet sharing a similar shape but with different dimensions as
compared to 4Q8.5/8.5 and this script should be able to build the new magnet without any
further intervention.

CLEAR |//This command may need to be commented out before initially running the macro.
YES   |//This command may need to be commented out before initially running the macro.

$CONST #MM_PER_INCH               25.4

//The analysis type is specified. If #ANALYSIS_TYPE=0, the analysis type is linear. If
#ANALYSIS_TYPE=1, the analysis type is nonlinear.

$CONST #ANALYSIS_TYPE             1

//The dimensions of the quadrupole as well as the meshing parameters are entered below.
The names have been made as descriptive as possible, but one should refer to the
provided sketches if it is unclear how a dimension is defined. Where applicable, the DWG
number associated with the drawing from which the dimension was obtained is noted.

$CONST #APERTURE_DIAMETER         4.060*#MM_PER_INCH  |//Obtained from DWG No. IMQ0003D.
$CONST #POLE_LENGTH               5.750*#MM_PER_INCH  |//Obtained from DWG No. IMQ0004C.
$CONST #POLE_BASE_WIDTH           5.000*#MM_PER_INCH  |//Obtained from DWG No. IMQ0004C.
$CONST #POLE_TIP_WIDTH            3.248*#MM_PER_INCH  |//Obtained from DWG No. IMQ0004C.
$CONST #POLE_TIP_RADIUS           2.335*#MM_PER_INCH  |//Obtained from DWG No. IMQ0004C.
$CONST #POLE_END_RADIUS           1.25*#MM_PER_INCH   |//Obtained from DWG No. IMQ0004C.
$CONST #POLE_CHAMFER_DISTANCE     0.06*#MM_PER_INCH   |//Obtained from DWG No. IMQ0004C.
$CONST #YOKE_EDGE_WIDTH           2.5*#MM_PER_INCH    |//Obtained from DWG No. IMQ0005C.
$CONST #YOKE_THICKNESS            8.500*#MM_PER_INCH  |//Obtained from DWG No. IMQ0004C.

$CONST #COIL_OFFSET               5.0                 |//This dimension was arbitrarily
selected. The coils must have some small (nonzero) offset from the poles.
$CONST #COIL_EDGE_WIDTH           1.25*#MM_PER_INCH   |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_LENGTH               3.5*#MM_PER_INCH    |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_CURRENT              310.0 A             |//In Doug Evans' field survey
(051398.1_RES) for this magnet, the current put through coils was 310 A.
$CONST #COIL_TURN_NUMBER          60.0                |//Obtained from DWG No. IMQ0002D.

$CONST #CENTER_BOX_ES             5.0                 |//"ES" refers to "element size".
The "Center box" refers to the body enclosing the good field region at the center of the
quadrupole.
$CONST #POLE_ES                   2.0*#CENTER_BOX_ES  |//The "Pole" refers the body
which makes up the poles.
$CONST #YOKE_ES                   4.0*#CENTER_BOX_ES  |//The "Yoke" refers the body
which makes up the yoke.
$CONST #COIL_BOX_ES               2.0*#CENTER_BOX_ES  |//The "Coil box" refers the body
which encloses the coils and the poles.
$CONST #YOKE_BOX_ES               5.0*#CENTER_BOX_ES  |//The "Yoke box" refers the body
which encloses the coils, the poles, and the entire yoke.
$CONST #BACKGROUND_1_ES           5.0*#CENTER_BOX_ES  |//"Background 1" refers to the
smaller background region enclosing the quadrupole.
$CONST #BACKGROUND_2_ES           6.0*#CENTER_BOX_ES  |//"Background 2" refers to the
larger background region enclosing the quadrupole.

$CONST #POLE_DSL                  6    |//"DSL" refers to "data storage level". The pole
and the yoke have the highest DSLs. Subsequent DSLs are assigned in the order in which
the air boxes are drawn.
$CONST #YOKE_DSL                  5
$CONST #CENTER_BOX_DSL            4
$CONST #COIL_BOX_DSL              3
$CONST #YOKE_BOX_DSL              2
$CONST #BACKGROUND_1_DSL          1
$CONST #BACKGROUND_2_DSL          0
```

```
$CONST #XY_SCALING_FACTOR         6.0  |//This factor defines how many times larger
Background 2 should be in terms of length relative to the side length of the yoke.
$CONST #Z_SCALING_FACTOR          8.0  |//This factor defines how many times larger
Background 2 should be in terms of thickness relative to the thickness of the yoke.

//The following dimensions are implicit from the above dimensions. The current density
in the coils may be calculated given a desired current and knowing the cross-sectional
area of the coils used and number of turns passing through that area. As the analysis
uses SI-MM, the units of current density are A/mm^2.

$CONST #YOKE_OUTER_LENGTH         #APERTURE_DIAMETER+2.0*(#POLE_LENGTH+#YOKE_EDGE_WIDTH)
$CONST #YOKE_INNER_LENGTH         #YOKE_OUTER_LENGTH-2.0*#YOKE_EDGE_WIDTH
$CONST #POLE_TIP_LENGTH           #POLE_TIP_RADIUS*(1-COS(ASIN(#POLE_TIP_WIDTH/2.0/
#POLE_TIP_RADIUS)))
$CONST #BACKGROUND_XY_LENGTH      #XY_SCALING_FACTOR*#YOKE_OUTER_LENGTH/2.0
$CONST #BACKGROUND_Z_LENGTH       #Z_SCALING_FACTOR*#YOKE_THICKNESS/2.0
$CONST #APERTURE_RADIUS           #APERTURE_DIAMETER/2.0
$CONST #COIL_CROSS_SECTIONAL_AREA #COIL_EDGE_WIDTH*#COIL_LENGTH
$CONST #COIL_CURRENT_DENSITY      #COIL_CURRENT*#COIL_TURN_NUMBER/
#COIL_CROSS_SECTIONAL_AREA

//The yoke of the quadrupole is drawn and covered.

WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=0 Z0=0 X1=0 Y1=#POLE_LENGTH
+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z0=0
X1=#YOKE_OUTER_LENGTH/2.0 Y1=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_OUTER_LENGTH/2.0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH
Z0=0 X1=#YOKE_INNER_LENGTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_INNER_LENGTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_BASE_WIDTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_BASE_WIDTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_TIP_WIDTH/2.0 Y1=#POLE_TIP_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_TIP_WIDTH/2.0 Y0=#POLE_TIP_LENGTH Z0=0 X1=0 Y1=0
Z1=0 EDGETYPE=CENTRE X2=0 Y2=#POLE_TIP_RADIUS Z2=0

//The 2D drawing of the yoke is displaced in the y-direction. The ends of the pole are
blended to create smooth corners and the entire edge of the pole tip is chamfered.
Please note, DWG No. IMQ0004C does not show the chamfer as extending along the entire
edge of the pole tip, but it is easier to model in Opera if one does it this way. The
yoke is then rotated around the z-axis, and swept in the z-direction to create a body.
The pole is made using a cut-plane.

PICK PROPERTY=UNIQUENAME LABEL='Yoke'
COVER
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=DISPLACE DU=0 DV=#APERTURE_RADIUS DW=0
PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=-1.0*#YOKE_THICKNESS/2.0
DRAFTTYPE=NONE
PICK OPTION=TOGGLE TYPE=EDGE UNIQUEBODYNAME='Yoke' IDENTIFIER=H.00006
BLEND OPTION=BLEND RADIUS=#POLE_END_RADIUS
BLOCK UNIQUENAME='Cut' X0=0 Y0=#APERTURE_RADIUS+#POLE_LENGTH Z0=0 X1=#POLE_BASE_WIDTH/
2.0 Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=#YOKE_THICKNESS/2.0
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45

//All four of the coils are built with negative rotational symmetry. A local coordinate
system is used to position the coils.

RACETRACK OPTION=NEW -KEEP XP1=#POLE_BASE_WIDTH/2.0+#COIL_OFFSET YP1=0
WIDTH=#COIL_EDGE_WIDTH THICKNESS=#COIL_LENGTH H1=#YOKE_THICKNESS/2.0+#COIL_OFFSET
R1=0.01*#POLE_BASE_WIDTH INCIRCUIT=NO CIRCUITELEMENT= CURD=#COIL_CURRENT_DENSITY
TOLERANCE=0 DRIVELABEL='Default Drive' THETA2=0 PHI2=-45 PSI2=0 XCEN2=(#POLE_LENGTH
```

```
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) YCEN2=(#POLE_LENGTH
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) ZCEN2=0 LCNAME='Global coordinate
system' RXY=0 RYZ=0 RZX=0 SYMMETRY=-4 MODELCOMPONENT=NO

//Cell properites are added to the yoke and to the pole. The magnetic properties of the
material "Steel" are defined. This magnet is made of C1010 steel, and so the
corresponding BH data, C1010.BH (or tenten.BH), is loaded if the analysis is set to be
nonlinear. The path to the BH data may need to be updated. The analysis type, TOSCA, is
also specified for each.

PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=K.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=K.00002
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POLE_DSL SIZE=#POLE_ES ELEMSHAPEPREF=HEXOPRISM
$IF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=0
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=LINEAR MUANISOTROPY=ISOTROPIC MU=2000 HC=0
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=YES CONVTOL=1.0E-08 HX=0.0 HY=0.0
HZ=0.0 RHS=ADAPTIVE POTENTIALCUT=YESMODEL CREATE
$ELIF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=1
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='C1010'
BHDATA OPTION=EDIT LABEL=C1010
BHDATA OPTION=LOAD LABEL=C1010 FILE='/home/mbasso/Opera_Models/
Physical_Magnet_Modelling/Quadrupoles/4Q8.5slash8.5/C1010.BH'
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=30
TOLERANCE=1.0E-7 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES
$END IF

//All of the following bodies are made of air. The center box is built and its cell
properites are added. This and the following air boxes are made by first drawing a box
and then rotating it 45 degrees. To ensure proper rotation, the boxes are made symmetric
in the xy-plane. Sections of the box are later cut away when making the model body.

BLOCK UNIQUENAME='Center box' X0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_TIP_LENGTH
Y1=#APERTURE_RADIUS+#POLE_TIP_LENGTH Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Center box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#CENTER_BOX_DSL SIZE=#CENTER_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//A series of concentric cylinders with spacing equal to the ES in the center box are
used to make cuts through the center box. This allows for a more regular mesh within
this region, which is desirable. The cuts are made using the following DO block.

$DO #RADIUS #CENTER_BOX_ES #APERTURE_RADIUS-#CENTER_BOX_ES #CENTER_BOX_ES
CYLINDER Name='Cut' X0=0 Y0=0 Z0=0 X1=0 Y1=0 Z1=#BACKGROUND_Z_LENGTH +TUBE
SHAPECONTROL=TUBE MAJORRADIUS=#RADIUS MINORRADIUS=#RADIUS TOPRADIUS=#RADIUS THICKNESS=0
SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='Center box'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$END DO

//The coil box is built and its cell properites are added. The z-dimension is made to be
slightly larger (1.1 times as large) than total width of the coil to ensure the coil is
well contained inside the box. This is the only body in the model that is made a region
of reduced potential; all other bodies are made regions of total potential.

BLOCK UNIQUENAME='Coil box' X0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_LENGTH
Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=1.1*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
```

```
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The yoke box is built and its cell properites are added. It is important to note that
Y0 and Y1 do not have the same multiplicative prefactors as X0 and X1. The resulting
body (after building the model body) does not have a triangular cross-sectional area;
instead, this cross-sectional area is a quadrilateral. For some reason, this shape
results in better surface and volume meshing over the entire model (volume meshing fails
otherwise).

BLOCK UNIQUENAME='Yoke box' X0=-1.2*#YOKE_OUTER_LENGTH/2.0 Y0=-1.1*#YOKE_OUTER_LENGTH/
2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0 Y1=1.1*#YOKE_OUTER_LENGTH/2.0
Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Yoke box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 1 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 1' X0=-1.2*#YOKE_OUTER_LENGTH/2.0
Y0=-1.1*#YOKE_OUTER_LENGTH/2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0
Y1=1.1*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 1'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_1_DSL SIZE=#BACKGROUND_1_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 2 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 2' X0=-1.0*#BACKGROUND_XY_LENGTH
Y0=-1.0*#BACKGROUND_XY_LENGTH Z0=0 X1=#BACKGROUND_XY_LENGTH Y1=#BACKGROUND_XY_LENGTH
Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_2_DSL SIZE=#BACKGROUND_2_ES ELEMSHAPEPREF=TETRAHEDRAL

//Two cuts are made through Background 2: one is along the z-direction edge of the yoke
box and the other is slightly offset from and parallel to the x-direction edge of the
yoke box (the predominant face along this side). These cuts enable the surface mesh to
be more regular in the far-field region.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH) X1=2.0*#BACKGROUND_XY_LENGTH*COSD(45)
Y1=#BACKGROUND_XY_LENGTH*COSD(45) Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.3*#YOKE_OUTER_LENGTH/2.0 Z0=0
X1=1.3*#YOKE_OUTER_LENGTH/2.0 Y1=1.3*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Cut'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The symmetry of the model is specified: xy- and zx-plane reflection symmetry and z-
axis rotational symmetry. Finally, the model body is created and the model is given a
surface mesh with a maximum ES equal to that of the largest ES of any body in the model.
The mesh shape is forced to be mosaic to ensure regular meshing.

BACKGROUND OPTION=LOAD
BACKGROUND OPTION=SET SHAPE=TRIM XYSYMMETRYPLANE=YES YZSYMMETRYPLANE=NO
ZXSYMMETRYPLANE=YES EMRXY=TANGMAGN EMRZX=NORMMAGN ROTZNUM=4 EMROTZTYPE=TANGMAGN
```

```
MODEL CREATE
MESH SIZE=#BACKGROUND_2_ES NORMALTOL=30.0 SURFACETOL=0.0 TOLERANCE=1.0E-06 TYPE=MOSAIC

//At this point, one only needs to perform volume meshing and set up an analysis
database for the model prior to starting the TOSCA analysis.
```

A.3 UoA 4Q12/6 Quadrupole

```
//UoA 4Q12/6 Quadrupole Magnet Model - Prepared by Matthew Basso in Opera 18R2
//Please note: this magnet has been almost entirely parameterized. One can enter
parameters for a magnet sharing a similar shape but with different dimensions as
compared to the UoA 4Q12/6 and this script should be able to build the new magnet
without any further intervention.

/CLEAR |//This command may need to be commented out before initially running the macro.
/YES   |//This command may need to be commented out before initially running the macro.

$CONST #MM_PER_INCH               25.4

//The analysis type is specified. If #ANALYSIS_TYPE=0, the analysis type is linear. If
#ANALYSIS_TYPE=1, the analysis type is nonlinear.

$CONST #ANALYSIS_TYPE             1

//The dimensions of the quadrupole as well as the meshing parameters are entered below.
The names have been made as descriptive as possible, but one should refer to the
provided sketches if it is unclear how a dimension is defined.

$CONST #APERTURE_DIAMETER         4.0*#MM_PER_INCH    |//Obtained from P.Q26-1 in the
TRIUMF Magnet Index.
$CONST #POLE_LENGTH               132.5               |//This was calculated given the
edge width of the yoke, the length of one side of the yoke (~490 mm), and the aperture
diameter.
$CONST #POLE_BASE_WIDTH           4.75*#MM_PER_INCH   |//This was measured using a
measuring tape. This dimension is very approximate.
$CONST #POLE_TIP_WIDTH            4.0*#MM_PER_INCH    |//The pole does not taper, so the
tip width is the same as the base width.
$CONST #POLE_TIP_RADIUS           58.4                |//This was calculated given
knowledge of the characteristic aspect ratio of the aperture diameter to the raidus of
the pole tip (~1.74) and the aperture diameter.
$CONST #YOKE_EDGE_WIDTH           70.0                |//This was measured using a
measuring tape.
$CONST #YOKE_THICKNESS            12.0*#MM_PER_INCH   |//Obtained from P.Q26-1 of
section "Quadrupole U of A Quads" in the TRIUMF Magnet Index.

$CONST #COIL_OFFSET               5.0                 |//This dimension was arbitrarily
selected. The coils must have some small (nonzero) offset from the poles.
$CONST #COIL_EDGE_WIDTH           1.5*#MM_PER_INCH    |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_LENGTH               3.25*#MM_PER_INCH   |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_CURRENT              250.0 A             |//In Doug Evans' field survey
(01010295.DAT) for this magnet, the current put through coils was 250 A.
$CONST #COIL_TURN_NUMBER          46.0                |//The turn number 46 was found to
result in simulated field data which agreed well with DE's field survey data.

$CONST #CENTER_BOX_ES             5.0                 |//"ES" refers to "element size".
The "Center box" refers to the body enclosing the good field region at the center of the
quadrupole.
$CONST #POLE_ES                   2.0*#CENTER_BOX_ES  |//The "Pole" refers the body
which makes up the poles.
$CONST #YOKE_ES                   4.0*#CENTER_BOX_ES  |//The "Yoke" refers the body
which makes up the yoke.
$CONST #COIL_BOX_ES               2.0*#CENTER_BOX_ES  |//The "Coil box" refers the body
which encloses the coils and the poles.
$CONST #YOKE_BOX_ES               5.0*#CENTER_BOX_ES  |//The "Yoke box" refers the body
which encloses the coils, the poles, and the entire yoke.
$CONST #BACKGROUND_1_ES           5.0*#CENTER_BOX_ES  |//"Background 1" refers to the
smaller background region enclosing the quadrupole.
$CONST #BACKGROUND_2_ES           6.0*#CENTER_BOX_ES  |//"Background 2" refers to the
larger background region enclosing the quadrupole.

$CONST #POLE_DSL                  6    |//"DSL" refers to "data storage level". The pole
and the yoke have the highest DSLs. Subsequent DSLs are assigned in the order in which
the air boxes are drawn.
```

```
$CONST #YOKE_DSL                  5
$CONST #CENTER_BOX_DSL            4
$CONST #COIL_BOX_DSL              3
$CONST #YOKE_BOX_DSL              2
$CONST #BACKGROUND_1_DSL          1
$CONST #BACKGROUND_2_DSL          0

$CONST #XY_SCALING_FACTOR         6.0  |//This factor defines how many times larger
Background 2 should be in terms of length relative to the side length of the yoke.
$CONST #Z_SCALING_FACTOR          9.0  |//This factor defines how many times larger
Background 2 should be in terms of thickness relative to the thickness of the yoke.

//The following dimensions are implicit from the above dimensions. The current density
in the coils may be calculated given a desired current and knowing the cross-sectional
area of the coils used and number of turns passing through that area. As the analysis
uses SI-MM, the units of current density are A/mm^2.

$CONST #YOKE_OUTER_LENGTH         #APERTURE_DIAMETER+2.0*(#POLE_LENGTH+#YOKE_EDGE_WIDTH)
$CONST #YOKE_INNER_LENGTH         #YOKE_OUTER_LENGTH-2.0*#YOKE_EDGE_WIDTH
$CONST #POLE_TIP_LENGTH           #POLE_TIP_RADIUS*(1-COS(ASIN(#POLE_TIP_WIDTH/2.0/
#POLE_TIP_RADIUS)))
$CONST #BACKGROUND_XY_LENGTH      #XY_SCALING_FACTOR*#YOKE_OUTER_LENGTH/2.0
$CONST #BACKGROUND_Z_LENGTH       #Z_SCALING_FACTOR*#YOKE_THICKNESS/2.0
$CONST #APERTURE_RADIUS           #APERTURE_DIAMETER/2.0
$CONST #COIL_CROSS_SECTIONAL_AREA #COIL_EDGE_WIDTH*#COIL_LENGTH
$CONST #COIL_CURRENT_DENSITY      #COIL_CURRENT*#COIL_TURN_NUMBER/
#COIL_CROSS_SECTIONAL_AREA

//The yoke of the quadrupole is drawn and covered.

WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=0 Z0=0 X1=0 Y1=#POLE_LENGTH
+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z0=0
X1=#YOKE_OUTER_LENGTH/2.0 Y1=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_OUTER_LENGTH/2.0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH
Z0=0 X1=#YOKE_INNER_LENGTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_INNER_LENGTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_BASE_WIDTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_BASE_WIDTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_TIP_WIDTH/2.0 Y1=#POLE_TIP_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_TIP_WIDTH/2.0 Y0=#POLE_TIP_LENGTH Z0=0 X1=0 Y1=0
Z1=0 EDGETYPE=CENTRE X2=0 Y2=#POLE_TIP_RADIUS Z2=0

//The 2D drawing of the yoke is displaced in the y-direction, rotated around the z-axis,
and swept in the z-direction to create a body. The pole is made using a cut-plane.

PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=DISPLACE DU=0 DV=#APERTURE_RADIUS DW=0
PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=-1.0*#YOKE_THICKNESS/2.0
DRAFTTYPE=NONE
BLOCK UNIQUENAME='Cut' X0=0 Y0=#APERTURE_RADIUS+#POLE_LENGTH Z0=0 X1=#POLE_BASE_WIDTH/
2.0 Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=#YOKE_THICKNESS/2.0
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45

//All four of the coils are built with negative rotational symmetry. A local coordinate
system is used to position the coils.

RACETRACK OPTION=NEW -KEEP XP1=#POLE_BASE_WIDTH/2.0+#COIL_OFFSET YP1=0
WIDTH=#COIL_EDGE_WIDTH THICKNESS=#COIL_LENGTH H1=#YOKE_THICKNESS/2.0+#COIL_OFFSET
R1=0.01*#POLE_BASE_WIDTH INCIRCUIT=NO CIRCUITELEMENT= CURD=#COIL_CURRENT_DENSITY
TOLERANCE=0 DRIVELABEL='Default Drive' THETA2=0 PHI2=-45 PSI2=0 XCEN2=(#POLE_LENGTH
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) YCEN2=(#POLE_LENGTH
```

```
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) ZCEN2=0 LCNAME='Global coordinate
system' RXY=0 RYZ=0 RZX=0 SYMMETRY=-4 MODELCOMPONENT=NO

//Cell properites are added to the yoke and to the pole. The magnetic properties of the
material "Steel" are defined. This magnet is made of C1010 steel, and so the
corresponding BH data is loaded if the analysis is set to be nonlinear. The analysis
type, TOSCA, is also specified for each.

PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=J.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=J.00002
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POLE_DSL SIZE=#POLE_ES ELEMSHAPEPREF=HEXOPRISM
$IF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=0
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=LINEAR MUANISOTROPY=ISOTROPIC MU=2000 HC=0
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=YES CONVTOL=1.0E-08 HX=0.0 HY=0.0
HZ=0.0 RHS=ADAPTIVE POTENTIALCUT=YESMODEL CREATE
$ELIF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=1
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='C1010'
BHDATA OPTION=EDIT LABEL=C1010
BHDATA OPTION=LOAD LABEL=C1010 FILE='/home/mbasso/Opera_Models/
Physical_Magnet_Modelling/Quadrupoles/UoA_4Q12slash6/C1010.BH'
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=30
TOLERANCE=1.0E-7 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES
$END IF

//All of the following bodies are made of air. The center box is built and its cell
properites are added. This and the following air boxes are made by first drawing a box
and then rotating it 45 degrees. To ensure proper rotation, the boxes are made symmetric
in the xy-plane. Sections of the box are later cut away when making the model body.

BLOCK UNIQUENAME='Center box' X0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_TIP_LENGTH
Y1=#APERTURE_RADIUS+#POLE_TIP_LENGTH Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Center box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#CENTER_BOX_DSL SIZE=#CENTER_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//A series of concentric cylinders with spacing equal to the ES in the center box are
used to make cuts through the center box. This allows for a more regular mesh within
this region, which is desirable. The cuts are made using the following DO block.

$DO #RADIUS #CENTER_BOX_ES #APERTURE_RADIUS-#CENTER_BOX_ES #CENTER_BOX_ES
CYLINDER Name='Cut' X0=0 Y0=0 Z0=0 X1=0 Y1=0 Z1=#BACKGROUND_Z_LENGTH +TUBE
SHAPECONTROL=TUBE MAJORRADIUS=#RADIUS MINORRADIUS=#RADIUS TOPRADIUS=#RADIUS THICKNESS=0
SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='Center box'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$END DO

//The coil box is built and its cell properites are added. The z-dimension is made to be
slightly larger (1.1 times as large) than total width of the coil to ensure the coil is
well contained inside the box. This is the only body in the model that is made a region
of reduced potential; all other bodies are made regions of total potential.

BLOCK UNIQUENAME='Coil box' X0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_LENGTH
Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=1.1*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
```

```
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The yoke box is built and its cell properites are added. It is important to note that
Y0 and Y1 do not have the same multiplicative prefactors as X0 and X1. The resulting
body (after building the model body) does not have a triangular cross-sectional area;
instead, this cross-sectional area is a quadrilateral. For some reason, this shape
results in better surface and volume meshing over the entire model (volume meshing fails
otherwise).

BLOCK UNIQUENAME='Yoke box' X0=-1.2*#YOKE_OUTER_LENGTH/2.0 Y0=-1.1*#YOKE_OUTER_LENGTH/
2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0 Y1=1.1*#YOKE_OUTER_LENGTH/2.0
Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Yoke box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 1 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 1' X0=-1.2*#YOKE_OUTER_LENGTH/2.0
Y0=-1.1*#YOKE_OUTER_LENGTH/2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0
Y1=1.1*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 1'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_1_DSL SIZE=#BACKGROUND_1_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 2 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 2' X0=-1.0*#BACKGROUND_XY_LENGTH
Y0=-1.0*#BACKGROUND_XY_LENGTH Z0=0 X1=#BACKGROUND_XY_LENGTH Y1=#BACKGROUND_XY_LENGTH
Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_2_DSL SIZE=#BACKGROUND_2_ES ELEMSHAPEPREF=TETRAHEDRAL

//Two cuts are made through Background 2: one is along the z-direction edge of the yoke
box and the other is slightly offset from and parallel to the x-direction edge of the
yoke box (the predominant face along this side). These cuts enable the surface mesh to
be more regular in the far-field region.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH) X1=2.0*#BACKGROUND_XY_LENGTH*COSD(45)
Y1=#BACKGROUND_XY_LENGTH*COSD(45) Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.3*#YOKE_OUTER_LENGTH/2.0 Z0=0
X1=1.3*#YOKE_OUTER_LENGTH/2.0 Y1=1.3*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Cut'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The symmetry of the model is specified: xy- and zx-plane reflection symmetry and z-
axis rotational symmetry. Finally, the model body is created and the model is given a
surface mesh with a maximum ES equal to that of the largest ES of any body in the model.
The mesh shape is forced to be mosaic to ensure regular meshing.

BACKGROUND OPTION=LOAD
BACKGROUND OPTION=SET SHAPE=TRIM XYSYMMETRYPLANE=YES YZSYMMETRYPLANE=NO
ZXSYMMETRYPLANE=YES EMRXY=TANGMAGN EMRZX=NORMMAGN ROTZNUM=4 EMROTZTYPE=TANGMAGN
MODEL CREATE
MESH SIZE=#BACKGROUND_2_ES NORMALTOL=30.0 SURFACETOL=0.0 TOLERANCE=1.0E-06 TYPE=MOSAIC
```

```
//At this point, one only needs to perform volume meshing and set up an analysis
database for the model prior to starting the TOSCA analysis.
```

A.4 Danfysik TUDA Short Quadrupole

```
//Danfysik TUDA Short Quadrupole Magnet Model - Prepared by Matthew Basso in Opera
18R1/2
//Please note: this magnet has been almost entirely parameterized. One can enter
parameters for a magnet sharing a similar shape but with different dimensions as
compared to the Danfysik TUDA Short and this script should be able to build the new
magnet without any further intervention.

CLEAR |//This command may need to be commented out before initially running the macro.
YES   |//This command may need to be commented out before initially running the macro.

$CONST #MM_PER_INCH               25.4

//The analysis type is specified. If #ANALYSIS_TYPE=0, the analysis type is linear. If
#ANALYSIS_TYPE=1, the analysis type is nonlinear.

$CONST #ANALYSIS_TYPE             1

//The dimensions of the quadrupole as well as the meshing parameters are entered below.
The names have been made as descriptive as possible, but one should refer to the
provided sketches if it is unclear how a dimension is defined. Where applicable, the DWG
number associated with the drawing from which the dimension was obtained is noted.

$CONST #APERTURE_DIAMETER         3.346*#MM_PER_INCH  |//Obtained from P.5 of section
"Other Quadrupole Magnets" in the TRIUMF Magnet Index.
$CONST #POLE_LENGTH               132.5               |//This was calculated given the
edge width of the yoke, the length of one side of the yoke (~490 mm), and the aperture
diameter.
$CONST #POLE_BASE_WIDTH           85.0                |//This was measured using a
measuring tape.
$CONST #POLE_TIP_WIDTH            85.0                |//The pole does not taper, so the
tip width is the same as the base width.
$CONST #POLE_TIP_RADIUS           49.0                |//This was calculated given
knowledge of the characteristic aspect ratio of the aperture diameter to the radius of
the pole tip (~1.74) and the aperture diameter.
$CONST #YOKE_EDGE_WIDTH           70.0                |//This was measured using a
measuring tape.
$CONST #YOKE_THICKNESS            9.875*#MM_PER_INCH  |//Obtained from P.5 of section
"Other Quadrupole Magnets" in the TRIUMF Magnet Index.

$CONST #COIL_OFFSET               5.0                 |//This dimension was arbitrarily
selected. The coils must have some small (nonzero) offset from the poles.
$CONST #COIL_EDGE_WIDTH           1.5*#MM_PER_INCH    |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_LENGTH               3.25*#MM_PER_INCH   |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_CURRENT              235.0 A             |//In Doug Evans' field surveys
(041300.1 and 041300.2) for this magnet, the current put through coils was 235 A and 120
A, respectively.
$CONST #COIL_TURN_NUMBER          44.0                |//The number of turns was counted
by looking at the coils.

$CONST #CENTER_BOX_ES             5.0                 |//"ES" refers to "element size".
The "Center box" refers to the body enclosing the good field region at the center of the
quadrupole.
$CONST #POLE_ES                   2.0*#CENTER_BOX_ES  |//The "Pole" refers the body
which makes up the poles.
$CONST #YOKE_ES                   4.0*#CENTER_BOX_ES  |//The "Yoke" refers the body
which makes up the yoke.
$CONST #COIL_BOX_ES               2.0*#CENTER_BOX_ES  |//The "Coil box" refers the body
which encloses the coils and the poles.
$CONST #YOKE_BOX_ES               5.0*#CENTER_BOX_ES  |//The "Yoke box" refers the body
which encloses the coils, the poles, and the entire yoke.
$CONST #BACKGROUND_1_ES           5.0*#CENTER_BOX_ES  |//"Background 1" refers to the
smaller background region enclosing the quadrupole.
$CONST #BACKGROUND_2_ES           6.0*#CENTER_BOX_ES  |//"Background 2" refers to the
larger background region enclosing the quadrupole.
```

```
$CONST #POLE_DSL                 6    |//"DSL" refers to "data storage level". The pole
and the yoke have the highest DSLs. Subsequent DSLs are assigned in the order in which
the air boxes are drawn.
$CONST #YOKE_DSL                 5
$CONST #CENTER_BOX_DSL           4
$CONST #COIL_BOX_DSL             3
$CONST #YOKE_BOX_DSL             2
$CONST #BACKGROUND_1_DSL         1
$CONST #BACKGROUND_2_DSL         0

$CONST #XY_SCALING_FACTOR        6.0  |//This factor defines how many times larger
Background 2 should be in terms of length relative to the side length of the yoke.
$CONST #Z_SCALING_FACTOR         6.0  |//This factor defines how many times larger
Background 2 should be in terms of thickness relative to the thickness of the yoke.

//The following dimensions are implicit from the above dimensions. The current density
in the coils may be calculated given a desired current and knowing the cross-sectional
area of the coils used and number of turns passing through that area. As the analysis
uses SI-MM, the units of current density are A/mm^2.

$CONST #YOKE_OUTER_LENGTH        #APERTURE_DIAMETER+2.0*(#POLE_LENGTH+#YOKE_EDGE_WIDTH)
$CONST #YOKE_INNER_LENGTH        #YOKE_OUTER_LENGTH-2.0*#YOKE_EDGE_WIDTH
$CONST #POLE_TIP_LENGTH          #POLE_TIP_RADIUS*(1-COS(ASIN(#POLE_TIP_WIDTH/2.0/
#POLE_TIP_RADIUS)))
$CONST #BACKGROUND_XY_LENGTH     #XY_SCALING_FACTOR*#YOKE_OUTER_LENGTH/2.0
$CONST #BACKGROUND_Z_LENGTH      #Z_SCALING_FACTOR*#YOKE_THICKNESS/2.0
$CONST #APERTURE_RADIUS          #APERTURE_DIAMETER/2.0
$CONST #COIL_CROSS_SECTIONAL_AREA #COIL_EDGE_WIDTH*#COIL_LENGTH
$CONST #COIL_CURRENT_DENSITY     #COIL_CURRENT*#COIL_TURN_NUMBER/
#COIL_CROSS_SECTIONAL_AREA

//The yoke of the quadrupole is drawn and covered.

WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=0 Z0=0 X1=0 Y1=#POLE_LENGTH
+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z0=0
X1=#YOKE_OUTER_LENGTH/2.0 Y1=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_OUTER_LENGTH/2.0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH
Z0=0 X1=#YOKE_INNER_LENGTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_INNER_LENGTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_BASE_WIDTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_BASE_WIDTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_TIP_WIDTH/2.0 Y1=#POLE_TIP_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_TIP_WIDTH/2.0 Y0=#POLE_TIP_LENGTH Z0=0 X1=0 Y1=0
Z1=0 EDGETYPE=CENTRE X2=0 Y2=#POLE_TIP_RADIUS Z2=0

//The 2D drawing of the yoke is displaced in the y-direction, rotated around the z-axis,
and swept in the z-direction to create a body. The pole is made using a cut-plane.

PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=DISPLACE DU=0 DV=#APERTURE_RADIUS DW=0
PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=-1.0*#YOKE_THICKNESS/2.0
DRAFTTYPE=NONE
BLOCK UNIQUENAME='Cut' X0=0 Y0=#APERTURE_RADIUS+#POLE_LENGTH Z0=0 X1=#POLE_BASE_WIDTH/
2.0 Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=#YOKE_THICKNESS/2.0
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45

//All four of the coils are built with negative rotational symmetry. A local coordinate
system is used to position the coils.

RACETRACK OPTION=NEW -KEEP XP1=#POLE_BASE_WIDTH/2.0+#COIL_OFFSET YP1=0
WIDTH=#COIL_EDGE_WIDTH THICKNESS=#COIL_LENGTH H1=#YOKE_THICKNESS/2.0+#COIL_OFFSET
```

```
R1=0.01*#POLE_BASE_WIDTH INCIRCUIT=NO CIRCUITELEMENT= CURD=#COIL_CURRENT_DENSITY
TOLERANCE=0 DRIVELABEL='Default Drive' THETA2=0 PHI2=-45 PSI2=0 XCEN2=(#POLE_LENGTH
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) YCEN2=(#POLE_LENGTH
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) ZCEN2=0 LCNAME='Global coordinate
system' RXY=0 RYZ=0 RZX=0 SYMMETRY=-4 MODELCOMPONENT=NO

//Cell properites are added to the yoke and to the pole. The magnetic properties of the
material "Steel" are defined. This magnet is made of C1010 steel, and so the
corresponding BH data, C1010.BH (or tenten.BH) is loaded if the analysis is set to be
nonlinear. The path to the BH data may need to be updated. The analysis type, TOSCA, is
also specified for each.

PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=J.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=J.00002
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POLE_DSL SIZE=#POLE_ES ELEMSHAPEPREF=HEXOPRISM
$IF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=0
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=LINEAR MUANISOTROPY=ISOTROPIC MU=2000 HC=0
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=YES CONVTOL=1.0E-08 HX=0.0 HY=0.0
HZ=0.0 RHS=ADAPTIVE POTENTIALCUT=YESMODEL CREATE
$ELIF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=1
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='C1010'
BHDATA OPTION=EDIT LABEL=C1010
BHDATA OPTION=LOAD LABEL=C1010 FILE='/home/mbasso/Opera_Models/
Physical_Magnet_Modelling/Quadrupoles/Danfysik_TUDA_Short/C1010.BH'
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=30
TOLERANCE=1.0E-7 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES
$END IF

//All of the following bodies are made of air. The center box is built and its cell
properites are added. This and the following air boxes are made by first drawing a box
and then rotating it 45 degrees. To ensure proper rotation, the boxes are made symmetric
in the xy-plane. Sections of the box are later cut away when making the model body.

BLOCK UNIQUENAME='Center box' X0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_TIP_LENGTH
Y1=#APERTURE_RADIUS+#POLE_TIP_LENGTH Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Center box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#CENTER_BOX_DSL SIZE=#CENTER_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//A series of concentric cylinders with spacing equal to the ES in the center box are
used to make cuts through the center box. This allows for a more regular mesh within
this region, which is desirable. The cuts are made using the following DO block.

$DO #RADIUS #CENTER_BOX_ES #APERTURE_RADIUS-#CENTER_BOX_ES #CENTER_BOX_ES
CYLINDER Name='Cut' X0=0 Y0=0 Z0=0 X1=0 Y1=0 Z1=#BACKGROUND_Z_LENGTH +TUBE
SHAPECONTROL=TUBE MAJORRADIUS=#RADIUS MINORRADIUS=#RADIUS TOPRADIUS=#RADIUS THICKNESS=0
SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='Center box'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$END DO

//The coil box is built and its cell properites are added. The z-dimension is made to be
slightly larger (1.1 times as large) than total width of the coil to ensure the coil is
well contained inside the box. This is the only body in the model that is made a region
of reduced potential; all other bodies are made regions of total potential.

BLOCK UNIQUENAME='Coil box' X0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_LENGTH
Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=1.1*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
```

```
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The yoke box is built and its cell properites are added. It is important to note that
Y0 and Y1 do not have the same multiplicative prefactors as X0 and X1. The resulting
body (after building the model body) does not have a triangular cross-sectional area;
instead, this cross-sectional area is a quadrilateral. For some reason, this shape
results in better surface and volume meshing over the entire model (volume meshing fails
otherwise).

BLOCK UNIQUENAME='Yoke box' X0=-1.2*#YOKE_OUTER_LENGTH/2.0 Y0=-1.1*#YOKE_OUTER_LENGTH/
2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0 Y1=1.1*#YOKE_OUTER_LENGTH/2.0
Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Yoke box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 1 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 1' X0=-1.2*#YOKE_OUTER_LENGTH/2.0
Y0=-1.1*#YOKE_OUTER_LENGTH/2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0
Y1=1.1*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 1'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_1_DSL SIZE=#BACKGROUND_1_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 2 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 2' X0=-1.0*#BACKGROUND_XY_LENGTH
Y0=-1.0*#BACKGROUND_XY_LENGTH Z0=0 X1=#BACKGROUND_XY_LENGTH Y1=#BACKGROUND_XY_LENGTH
Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_2_DSL SIZE=#BACKGROUND_2_ES ELEMSHAPEPREF=TETRAHEDRAL

//Two cuts are made through Background 2: one is along the z-direction edge of the yoke
box and the other is slightly offset from and parallel to the x-direction edge of the
yoke box (the predominant face along this side). These cuts enable the surface mesh to
be more regular in the far-field region.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH) X1=2.0*#BACKGROUND_XY_LENGTH*COSD(45)
Y1=#BACKGROUND_XY_LENGTH*COSD(45) Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.3*#YOKE_OUTER_LENGTH/2.0 Z0=0
X1=1.3*#YOKE_OUTER_LENGTH/2.0 Y1=1.3*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Cut'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The symmetry of the model is specified: xy- and zx-plane reflection symmetry and z-
axis rotational symmetry. Finally, the model body is created and the model is given a
surface mesh with a maximum ES equal to that of the largest ES of any body in the model.
The mesh shape is forced to be mosaic to ensure regular meshing.

BACKGROUND OPTION=LOAD
```

```
BACKGROUND OPTION=SET SHAPE=TRIM XYSYMMETRYPLANE=YES YZSYMMETRYPLANE=NO
ZXSYMMETRYPLANE=YES EMRXY=TANGMAGN EMRZX=NORMMAGN ROTZNUM=4 EMROTZTYPE=TANGMAGN
MODEL CREATE
MESH SIZE=#BACKGROUND_2_ES NORMALTOL=30.0 SURFACETOL=0.0 TOLERANCE=1.0E-06 TYPE=MOSAIC

//At this point, one only needs to perform volume meshing and set up an analysis
database for the model prior to starting the TOSCA analysis.
```

A.5 Danfysik L5 Quadrupole

```
//Danfysik L5 Quadrupole Magnet Model - Prepared by Matthew Basso in Opera 18R1/2
//Please note: this magnet has been almost entirely parameterized. One can enter
parameters for a magnet sharing a similar shape but with different dimensions as
compared to the Danfysik L5 and this script should be able to build the new magnet
without any further intervention.

CLEAR |//This command may need to be commented out before initially running the macro.
YES   |//This command may need to be commented out before initially running the macro.

$CONST #MM_PER_INCH               25.4

//The analysis type is specified. If #ANALYSIS_TYPE=0, the analysis type is linear. If
#ANALYSIS_TYPE=1, the analysis type is nonlinear.

$CONST #ANALYSIS_TYPE             1

//The dimensions of the quadrupole as well as the meshing parameters are entered below.
The names have been made as descriptive as possible, but one should refer to the
provided sketches if it is unclear how a dimension is defined. Where applicable, the DWG
number associated with the drawing from which the dimension was obtained is noted.

$CONST #APERTURE_DIAMETER         71.0                |//This was read off the sticker
on the side of the magnet.
$CONST #POLE_LENGTH               170.1               |//This was calculated given the
edge width of the yoke, the length of one side of the yoke (565.15 mm), and the aperture
diameter.
$CONST #POLE_BASE_WIDTH           135.0               |//This was measured using a
measuring tape.
$CONST #POLE_TIP_WIDTH            2.75*#MM_PER_INCH   |//This was measured using a
measuring tape.
$CONST #POLE_TIP_THICKNESS        169.0               |//This was measured using a
measuring tape.
$CONST #POLE_TIP_RADIUS           40.8                |//This was calculated given
knowledge of the characteristic aspect ratio of the aperture diameter to the radius of
the pole tip (~1.74) and the aperture diameter.
$CONST #YOKE_EDGE_WIDTH           3.03125*#MM_PER_INCH|//This was measured using a
measuring tape.
$CONST #YOKE_THICKNESS            200.0               |//This was measured using a
measuring tape.

$CONST #COIL_OFFSET               5.0                 |//This dimension was arbitrarily
selected. The coils must have some small (nonzero) offset from the poles.
$CONST #COIL_EDGE_WIDTH           1.25*#MM_PER_INCH   |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_LENGTH               3.5*#MM_PER_INCH    |//This dimension was arbitrarily
selected as the exact dimensions of the coils are unimportant.
$CONST #COIL_CURRENT              100.0 A             |//In Doug Evans' field survey
(20040519.DAT) for this magnet, the current put through coils was 100 A.
$CONST #COIL_TURN_NUMBER          85.0                |//The coil turn number was found
by originally running the magnet at 100 A for 50 turns and then by scaling the 50 turns
by the scaling factor between the maximum field strength of the simulation and DE's
field sruvey data.

$CONST #CENTER_BOX_ES             5.0                 |//"ES" refers to "element size".
The "Center box" refers to the body enclosing the good field region at the center of the
quadrupole.
$CONST #POLE_ES                   2.0*#CENTER_BOX_ES  |//The "Pole" refers the body
which makes up the poles.
$CONST #YOKE_ES                   4.0*#CENTER_BOX_ES  |//The "Yoke" refers the body
which makes up the yoke.
$CONST #COIL_BOX_ES               2.0*#CENTER_BOX_ES  |//The "Coil box" refers the body
which encloses the coils and the poles.
$CONST #YOKE_BOX_ES               5.0*#CENTER_BOX_ES  |//The "Yoke box" refers the body
which encloses the coils, the poles, and the entire yoke.
$CONST #BACKGROUND_1_ES           5.0*#CENTER_BOX_ES  |//"Background 1" refers to the
smaller background region enclosing the quadrupole.
$CONST #BACKGROUND_2_ES           6.0*#CENTER_BOX_ES  |//"Background 2" refers to the
```

```
larger background region enclosing the quadrupole.

$CONST #POLE_DSL                  6    |//"DSL" refers to "data storage level". The pole
and the yoke have the highest DSLs. Subsequent DSLs are assigned in the order in which
the air boxes are drawn.
$CONST #YOKE_DSL                  5
$CONST #CENTER_BOX_DSL            4
$CONST #COIL_BOX_DSL              3
$CONST #YOKE_BOX_DSL              2
$CONST #BACKGROUND_1_DSL          1
$CONST #BACKGROUND_2_DSL          0

$CONST #XY_SCALING_FACTOR         6.0  |//This factor defines how many times larger
Background 2 should be in terms of length relative to the side length of the yoke.
$CONST #Z_SCALING_FACTOR          9.0  |//This factor defines how many times larger
Background 2 should be in terms of thickness relative to the thickness of the yoke.

//The following dimensions are implicit from the above dimensions. The current density
in the coils may be calculated given a desired current and knowing the cross-sectional
area of the coils used and number of turns passing through that area. As the analysis
uses SI-MM, the units of current density are A/mm^2.

$CONST #YOKE_OUTER_LENGTH         #APERTURE_DIAMETER+2.0*(#POLE_LENGTH+#YOKE_EDGE_WIDTH)
$CONST #YOKE_INNER_LENGTH         #YOKE_OUTER_LENGTH-2.0*#YOKE_EDGE_WIDTH
$CONST #POLE_TIP_LENGTH           #POLE_TIP_RADIUS*(1-COS(ASIN(#POLE_TIP_WIDTH/2.0/
#POLE_TIP_RADIUS)))
$CONST #BACKGROUND_XY_LENGTH      #XY_SCALING_FACTOR*#YOKE_OUTER_LENGTH/2.0
$CONST #BACKGROUND_Z_LENGTH       #Z_SCALING_FACTOR*#YOKE_THICKNESS/2.0
$CONST #APERTURE_RADIUS           #APERTURE_DIAMETER/2.0
$CONST #COIL_CROSS_SECTIONAL_AREA #COIL_EDGE_WIDTH*#COIL_LENGTH
$CONST #COIL_CURRENT_DENSITY      #COIL_CURRENT*#COIL_TURN_NUMBER/
#COIL_CROSS_SECTIONAL_AREA

//The yoke of the quadrupole is drawn.

WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=0 Z0=0 X1=0 Y1=#POLE_LENGTH
+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z0=0
X1=#YOKE_OUTER_LENGTH/2.0 Y1=#POLE_LENGTH+#YOKE_EDGE_WIDTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_OUTER_LENGTH/2.0 Y0=#POLE_LENGTH+#YOKE_EDGE_WIDTH
Z0=0 X1=#YOKE_INNER_LENGTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_INNER_LENGTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_BASE_WIDTH/2.0 Y1=#POLE_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_BASE_WIDTH/2.0 Y0=#POLE_LENGTH Z0=0
X1=#POLE_TIP_WIDTH/2.0 Y1=#POLE_TIP_LENGTH Z1=0 EDGETYPE=STRAIGHT
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_TIP_WIDTH/2.0 Y0=#POLE_TIP_LENGTH Z0=0 X1=0 Y1=0
Z1=0 EDGETYPE=CENTRE X2=0 Y2=#POLE_TIP_RADIUS Z2=0

//The 2D drawing of the yoke is displaced in the y-direction. The pole is made using a
cut-plane.

PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=DISPLACE DU=0 DV=#APERTURE_RADIUS DW=0
PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=-1.0*#YOKE_THICKNESS/2.0
DRAFTTYPE=NONE
BLOCK UNIQUENAME='Cut' X0=0 Y0=#APERTURE_RADIUS+#POLE_LENGTH Z0=0 X1=#POLE_BASE_WIDTH/
2.0 Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=#YOKE_THICKNESS/2.0
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//As end of the pole along the z-axis is sloped, a cut-plane is drawn, rotated,
displaced, and subtracted from the end of the pole. The resulting cell is deleted to
create the sloping surfaces.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=0 X1=#POLE_BASE_WIDTH/2.0 Y1=SQRT((#POLE_LENGTH)^2+
```

```
((#YOKE_THICKNESS-#POLE_TIP_THICKNESS)/2.0)^2) Z1=0
PICK OPTION=TOGGLE TYPE=FACE UNIQUEBODYNAME='Cut' IDENTIFIER=A.00001
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=1 ROTV=0 ROTW=0
ANGLE=ATAND((#YOKE_THICKNESS-#POLE_TIP_THICKNESS)/2.0/#POLE_LENGTH)
TRANSFORM OPTION=APPLY KEEP=NO TYPE=DISPLACE DU=0 DV=#APERTURE_RADIUS
DW=#POLE_TIP_THICKNESS/2.0
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=N.00002
DELETE REGULARIZE=YES EXTERNAL=NO
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45

//All four of the coils are built with negative rotational symmetry. A local coordinate
system is used to position the coils.

RACETRACK OPTION=NEW -KEEP XP1=#POLE_BASE_WIDTH/2.0+#COIL_OFFSET YP1=0
WIDTH=#COIL_EDGE_WIDTH THICKNESS=#COIL_LENGTH H1=#YOKE_THICKNESS/2.0+#COIL_OFFSET
R1=0.01*#POLE_BASE_WIDTH INCIRCUIT=NO CIRCUITELEMENT= CURD=#COIL_CURRENT_DENSITY
TOLERANCE=0 DRIVELABEL='Default Drive' THETA2=0 PHI2=-45 PSI2=0 XCEN2=(#POLE_LENGTH
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) YCEN2=(#POLE_LENGTH
+#APERTURE_RADIUS-#COIL_LENGTH-#COIL_OFFSET)*COSD(45) ZCEN2=0 LCNAME='Global coordinate
system' RXY=0 RYZ=0 RZX=0 SYMMETRY=-4 MODELCOMPONENT=NO

//Cell properites are added to the yoke and to the pole. The magnetic properties of the
material "Steel" are defined. This magnet is made of C1010 steel, and so the
corresponding BH data, C1010.BH (or tenten.BH) is loaded if the analysis is set to be
nonlinear. The path to the BH data may need to be updated. The analysis type, TOSCA, is
also specified for each.

PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=J.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=N.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POLE_DSL SIZE=#POLE_ES ELEMSHAPEPREF=HEXOPRISM
$IF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=0
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=LINEAR MUANISOTROPY=ISOTROPIC MU=2000 HC=0
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=YES CONVTOL=1.0E-08 HX=0.0 HY=0.0
HZ=0.0 RHS=ADAPTIVE POTENTIALCUT=YESMODEL CREATE
$ELIF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=1
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='C1010'
BHDATA OPTION=EDIT LABEL=C1010
BHDATA OPTION=LOAD LABEL=C1010 FILE='/home/mbasso/Opera_Models/
Physical_Magnet_Modelling/Quadrupoles/4Q8.5slash8.5/C1010.BH'
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=30
TOLERANCE=1.0E-7 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES
$END IF

//All of the following bodies are made of air. The center box is built and its cell
properites are added. This and the following air boxes are made by first drawing a box
and then rotating it 45 degrees. To ensure proper rotation, the boxes are made symmetric
in the xy-plane. Sections of the box are later cut away when making the model body.

BLOCK UNIQUENAME='Center box' X0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_TIP_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_TIP_LENGTH
Y1=#APERTURE_RADIUS+#POLE_TIP_LENGTH Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Center box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#CENTER_BOX_DSL SIZE=#CENTER_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//A series of concentric cylinders with spacing equal to the ES in the center box are
used to make cuts through the center box. This allows for a more regular mesh within
```

```
this region, which is desirable. The cuts are made using the following DO block.

$DO #RADIUS #CENTER_BOX_ES #APERTURE_RADIUS-#CENTER_BOX_ES #CENTER_BOX_ES
CYLINDER Name='Cut' X0=0 Y0=0 Z0=0 X1=0 Y1=0 Z1=#BACKGROUND_Z_LENGTH +TUBE
SHAPECONTROL=TUBE MAJORRADIUS=#RADIUS MINORRADIUS=#RADIUS TOPRADIUS=#RADIUS THICKNESS=0
SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='Center box'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$END DO

//The coil box is built and its cell properites are added. The z-dimension is made to be
slightly larger (1.1 times as large) than total width of the coil to ensure the coil is
well contained inside the box. This is the only body in the model that is made a region
of reduced potential; all other bodies are made regions of total potential.

BLOCK UNIQUENAME='Coil box' X0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH)
Y0=-1.0*(#APERTURE_RADIUS+#POLE_LENGTH) Z0=0 X1=#APERTURE_RADIUS+#POLE_LENGTH
Y1=#APERTURE_RADIUS+#POLE_LENGTH Z1=1.1*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The yoke box is built and its cell properites are added. It is important to note that
Y0 and Y1 do not have the same multiplicative prefactors as X0 and X1. The resulting
body (after building the model body) does not have a triangular cross-sectional area;
instead, this cross-sectional area is a quadrilateral. For some reason, this shape
results in better surface and volume meshing over the entire model (volume meshing fails
otherwise).

BLOCK UNIQUENAME='Yoke box' X0=-1.2*#YOKE_OUTER_LENGTH/2.0 Y0=-1.1*#YOKE_OUTER_LENGTH/
2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0 Y1=1.1*#YOKE_OUTER_LENGTH/2.0
Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Yoke box'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 1 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 1' X0=-1.2*#YOKE_OUTER_LENGTH/2.0
Y0=-1.1*#YOKE_OUTER_LENGTH/2.0 Z0=0 X1=1.2*#YOKE_OUTER_LENGTH/2.0
Y1=1.1*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 1'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_1_DSL SIZE=#BACKGROUND_1_ES ELEMSHAPEPREF=TETRAHEDRAL

//Background 2 is built and its cell properites are added.

BLOCK UNIQUENAME='Background 2' X0=-1.0*#BACKGROUND_XY_LENGTH
Y0=-1.0*#BACKGROUND_XY_LENGTH Z0=0 X1=#BACKGROUND_XY_LENGTH Y1=#BACKGROUND_XY_LENGTH
Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
TRANSFORM OPTION=APPLY KEEP=YES TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=45
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_2_DSL SIZE=#BACKGROUND_2_ES ELEMSHAPEPREF=TETRAHEDRAL

//Two cuts are made through Background 2: one is along the z-direction edge of the yoke
box and the other is slightly offset from and parallel to the x-direction edge of the
yoke box (the predominant face along this side). These cuts enable the surface mesh to
be more regular in the far-field region.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH) X1=2.0*#BACKGROUND_XY_LENGTH*COSD(45)
```

```
Y1=#BACKGROUND_XY_LENGTH*COSD(45) Z1=1.2*(#YOKE_THICKNESS/2.0+#COIL_OFFSET
+#COIL_EDGE_WIDTH)
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.3*#YOKE_OUTER_LENGTH/2.0 Z0=0
X1=1.3*#YOKE_OUTER_LENGTH/2.0 Y1=1.3*#YOKE_OUTER_LENGTH/2.0 Z1=#BACKGROUND_Z_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Cut'
TRANSFORM OPTION=APPLY KEEP=NO TYPE=ROTATE ROTU=0 ROTV=0 ROTW=1 ANGLE=-45
PICK PROPERTY=UNIQUENAME LABEL='Background 2'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The symmetry of the model is specified: xy- and zx-plane reflection symmetry and z-
axis rotational symmetry. Finally, the model body is created and the model is given a
surface mesh with a maximum ES equal to that of the largest ES of any body in the model.
The mesh shape is forced to be mosaic to ensure regular meshing.

BACKGROUND OPTION=LOAD
BACKGROUND OPTION=SET SHAPE=TRIM XYSYMMETRYPLANE=YES YZSYMMETRYPLANE=NO
ZXSYMMETRYPLANE=YES EMRXY=TANGMAGN EMRZX=NORMMAGN ROTZNUM=4 EMROTZTYPE=TANGMAGN
MODEL CREATE
MESH SIZE=#BACKGROUND_2_ES NORMALTOL=30.0 SURFACETOL=0.0 TOLERANCE=1.0E-06 TYPE=MOSAIC

//At this point, one only needs to perform volume meshing and set up an analysis
database for the model prior to starting the TOSCA analysis.
```

A.6 4VB1 35° Bending C-Frame Dipole

```
//4BV1 Dipole Magnet Model - Prepared by Matthew Basso in Opera 18R1/2
//Please note: this magnet has been almost entirely parameterized. One can enter
parameters for a magnet sharing a similar shape but with different dimensions as
compared to the 4VB1 and this script should be able to build the new magnet without any
further intervention.


CLEAR |//This command may need to be commented out before initially running the macro.
YES   |//This command may need to be commented out before initially running the macro.

//"Length", "height", and "width" refer to x-, y-, and z-directions dimensions,
respectively.

$CONST #MM_PER_INCH                25.4

//The analysis type is specified. If #ANALYSIS_TYPE=0, the analysis type is linear. If
#ANALYSIS_TYPE=1, the analysis type is nonlinear.

$CONST #ANALYSIS_TYPE              1

//The dimensions of the dipole as well as the meshing parameters are entered below. The
names have been made as descriptive as possible, but one should refer to the provided
sketches if it is unclear how a dimension is defined. "Length", "height", and "width"
refer to dimensions in the x-, y-, and z-directions, respectively. Where applicable, the
DWG number associated with the drawing from which the dimension was obtained is noted.

$CONST #YOKE_LENGTH                57.0*#MM_PER_INCH        |//Obtained from DWG No.
E12100.
$CONST #YOKE_UPPER_HEIGHT          19.75*#MM_PER_INCH       |//Obtained from DWG No.
E12102.
$CONST #YOKE_CONNECTOR_HEIGHT      15.625*#MM_PER_INCH      |//Obtained from DWG No.
D12100.
$CONST #YOKE_WIDTH                 43.5*#MM_PER_INCH        |//Obtained from DWG No.
E12100.
$CONST #YOKE_CONNECTOR_WIDTH       20.0*#MM_PER_INCH        |//Obtained from DWG No.
D12100.
$CONST #YOKE_CORNER_CHAMFER_LENGTH 3.0*#MM_PER_INCH         |//Obtained from DWG No.
E12102.
$CONST #POLE_BASE_WIDTH            17.0*#MM_PER_INCH        |//Obtained from DWG No.
D12101.
$CONST #POLE_TIP_WIDTH             15.0*#MM_PER_INCH        |//Obtained from DWG No.
D12101.
$CONST #POLE_HEIGHT                6.273*#MM_PER_INCH       |//Obtained from DWG No.
D12101.

$CONST #COIL_EDGELESS_LENGTH       (60+13/16)*#MM_PER_INCH  |//Obtained from DWG No.
E12101.
$CONST #COIL_EDGE_HEIGHT           5.380*#MM_PER_INCH       |//Obtained from DWG No.
E12101.
$CONST #COIL_EDGE_WIDTH            5.336*#MM_PER_INCH       |//Obtained from DWG No.
E12101.
$CONST #COIL_EDGELESS_WIDTH        (20+1/16)*#MM_PER_INCH   |//Obtained from DWG No.
E12101.
$CONST #COIL_CORNER_RADIUS         2.0*#MM_PER_INCH         |//Obtained from DWG No.
E12101.
$CONST #COIL_Y_OFFSET              15.0                     |//This value was
arbitrarily selected. A positive value moves the coil in negative y-direction from the
upper edge along the connector side of the interior of the yoke.
$CONST #COIL_Z_OFFSET              25.0                     |//This value was
arbitrarily selected. A positive value moves the coil in positive z-direction from the
upper edge along the connector side of the interior of the yoke.
$CONST #COIL_CURRENT               392.290 A                |//This value was selected
to match the current used in obtaining the the survey data.
$CONST #COIL_TURN_NUMBER           64.0                     |//Obtained from DWG No.
E12101.

$CONST #CENTER_BOX_ES              10.0                     |//"ES" refers to "element
```

```
size". The "Center box" refers to the body enclosing the good field region between the
poles of the dipole.
$CONST #POLE_ES                    2.0*#CENTER_BOX_ES       |//The "Pole" refers the
body which makes up the poles.
$CONST #YOKE_ES                    5.0*#CENTER_BOX_ES       |//The "Yoke" refers the
body which makes up the yoke.
$CONST #COIL_BOX_ES                3.0*#CENTER_BOX_ES       |//The "Coil box" refers the
body which encloses the coils and the poles.
$CONST #BUFFER_BOX_1_ES            3.0*#CENTER_BOX_ES       |//"Buffer box 1" refers the
body drawn alongside the center box through the the interior of the yoke.
$CONST #BUFFER_BOX_2_ES            3.0*#CENTER_BOX_ES       |//"Buffer box 2" refers the
body buffering the ends of buffer box 1 and the center box along the x-direction.
$CONST #YOKE_BOX_ES                10.0*#CENTER_BOX_ES      |//The "Yoke box" refers the
body which encloses the coils, the poles, and the entire yoke.
$CONST #BACKGROUND_ES              20.0*#CENTER_BOX_ES      |//"Background" refers to
the background region enclosing the dipole.

$CONST #POLE_DSL                   7    |//"DSL" refers to "data storage level". The
pole and the yoke have the highest DSLs. Subsequent DSLs are assigned in the order in
which the air boxes are drawn.
$CONST #YOKE_DSL                   6
$CONST #CENTER_BOX_DSL             5
$CONST #COIL_BOX_DSL               4
$CONST #BUFFER_BOX_1_DSL           3
$CONST #BUFFER_BOX_2_DSL           2
$CONST #YOKE_BOX_DSL               1
$CONST #BACKGROUND_DSL             0

$CONST #BACKGROUND_LENGTH_SF       4.0  |//"SF" refers to "scaling factor". This factor
defines how many times larger Background should be in terms of length relative to the
length of the yoke.
$CONST #BACKGROUND_HEIGHT_SF       2.0  |//This factor defines how many times larger the
background should be in terms of height relative to the height of the yoke.
$CONST #BACKGROUND_WIDTH_SF        3.0  |//This factor defines how many times larger the
background should be in terms of width relative to the width of the yoke.
$CONST #CENTER_LENGTH_SF           10.0 |//This factor defines how many times the gap
height the center box should extend outside of the yoke in the x-direction.

//The following dimensions are implicit from the above dimensions. The current density
in the coils may be calculated given a desired current and knowing the cross-sectional
area of the coils used and number of turns passing through that area. As the analysis
uses SI-MM, the units of current density are A/mm^2.

$CONST #YOKE_HEIGHT                2.0*#YOKE_UPPER_HEIGHT+#YOKE_CONNECTOR_HEIGHT
$CONST #POLE_TIP_HEIGHT            #POLE_BASE_WIDTH-#POLE_TIP_WIDTH
$CONST #POLE_BASE_HEIGHT           #POLE_HEIGHT-#POLE_TIP_HEIGHT
$CONST #GAP_HEIGHT                 #YOKE_CONNECTOR_HEIGHT-2.0*#POLE_HEIGHT
$CONST #COIL_LENGTH                #COIL_EDGELESS_LENGTH+2.0*#COIL_EDGE_WIDTH
$CONST #COIL_WIDTH                 #COIL_EDGELESS_WIDTH+2.0*#COIL_EDGE_WIDTH
$CONST #YOKE_TO_COIL_END_WIDTH     #YOKE_CONNECTOR_WIDTH+#COIL_Z_OFFSET+#COIL_WIDTH
$CONST #BACKGROUND_LENGTH          #BACKGROUND_LENGTH_SF*#COIL_LENGTH/2.0
$CONST #BACKGROUND_HEIGHT          #BACKGROUND_HEIGHT_SF*#YOKE_HEIGHT/2.0
$CONST #BACKGROUND_Z_EDGE_1
-1.0*(#BACKGROUND_WIDTH_SF-1.0)*#YOKE_TO_COIL_END_WIDTH/2.0
$CONST #BACKGROUND_Z_EDGE_2        (#BACKGROUND_WIDTH_SF+1.0)*#YOKE_TO_COIL_END_WIDTH/
2.0
$CONST #COIL_CROSS_SECTIONAL_AREA  #COIL_EDGE_HEIGHT*#COIL_EDGE_WIDTH
$CONST #COIL_CURRENT_DENSITY       #COIL_CURRENT*#COIL_TURN_NUMBER/
#COIL_CROSS_SECTIONAL_AREA

//The yoke of the dipole is drawn and covered.

WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=0 Z0=0 X1=0 Y1=#YOKE_HEIGHT/2.0-
#YOKE_CORNER_CHAMFER_LENGTH Z1=0
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_HEIGHT/2.0-#YOKE_CORNER_CHAMFER_LENGTH Z0=0
X1=0 Y1=#YOKE_HEIGHT/2.0 Z1=#YOKE_CORNER_CHAMFER_LENGTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_HEIGHT/2.0 Z0=#YOKE_CORNER_CHAMFER_LENGTH X1=0
```

```
Y1=#YOKE_HEIGHT/2.0 Z1=#YOKE_WIDTH-#YOKE_CORNER_CHAMFER_LENGTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_HEIGHT/2.0 Z0=#YOKE_WIDTH-
#YOKE_CORNER_CHAMFER_LENGTH X1=0 Y1=#YOKE_HEIGHT/2.0-#YOKE_CORNER_CHAMFER_LENGTH
Z1=#YOKE_WIDTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_HEIGHT/2.0-#YOKE_CORNER_CHAMFER_LENGTH
Z0=#YOKE_WIDTH X1=0 Y1=#YOKE_CONNECTOR_HEIGHT/2.0-#POLE_HEIGHT Z1=#YOKE_WIDTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_CONNECTOR_HEIGHT/2.0-#POLE_HEIGHT
Z0=#YOKE_WIDTH X1=0 Y1=#YOKE_CONNECTOR_HEIGHT/2.0-#POLE_HEIGHT Z1=#YOKE_WIDTH-
#POLE_TIP_WIDTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_CONNECTOR_HEIGHT/2.0-#POLE_HEIGHT
Z0=#YOKE_WIDTH-#POLE_TIP_WIDTH X1=0 Y1=#YOKE_CONNECTOR_HEIGHT/2.0-#POLE_BASE_HEIGHT
Z1=#YOKE_WIDTH-#POLE_BASE_WIDTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_CONNECTOR_HEIGHT/2.0-#POLE_BASE_HEIGHT
Z0=#YOKE_WIDTH-#POLE_BASE_WIDTH X1=0 Y1=#YOKE_CONNECTOR_HEIGHT/2.0 Z1=#YOKE_WIDTH-
#POLE_BASE_WIDTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_CONNECTOR_HEIGHT/2.0 Z0=#YOKE_WIDTH-
#POLE_BASE_WIDTH X1=0 Y1=#YOKE_CONNECTOR_HEIGHT/2.0 Z1=#YOKE_CONNECTOR_WIDTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_CONNECTOR_HEIGHT/2.0 Z0=#YOKE_CONNECTOR_WIDTH
X1=0 Y1=0 Z1=#YOKE_CONNECTOR_WIDTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=0 Z0=#YOKE_CONNECTOR_WIDTH X1=0 Y1=0 Z1=0

//The yoke is swept in the x-direction to create a body. The pole is made using a cut-
plane.

PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=#YOKE_LENGTH/2.0 DRAFTTYPE=NONE

//The two coils are built with negative zx-plane reflection symmetry. A local coordinate
system is used to position the coils.

RACETRACK OPTION=NEW -KEEP XP1=#COIL_EDGELESS_LENGTH/2.0 YP1=0 WIDTH=#COIL_EDGE_WIDTH
THICKNESS=#COIL_EDGE_HEIGHT H1=#COIL_EDGELESS_WIDTH/2.0-#COIL_CORNER_RADIUS
R1=#COIL_CORNER_RADIUS INCIRCUIT=NO CIRCUITELEMENT= CURD=-1.0*#COIL_CURRENT_DENSITY
TOLERANCE=0 DRIVELABEL='Default Drive' THETA2=0 PHI2=0 PSI2=0 XCEN2=0
YCEN2=#YOKE_CONNECTOR_HEIGHT/2.0-#COIL_EDGE_HEIGHT-#COIL_Y_OFFSET ZCEN2=#YOKE_WIDTH-
#POLE_BASE_WIDTH/2.0+#COIL_Z_OFFSET LCNAME='Global coordinate system' RXY=0 RYZ=0 RZX=-1
SYMMETRY=1 MODELCOMPONENT=NO

PICK PROPERTY=UNIQUENAME LABEL='Yoke'
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_CONNECTOR_HEIGHT/2.0 Z0=#YOKE_WIDTH-
#POLE_BASE_WIDTH X1=#YOKE_LENGTH/2.0 Y1=#YOKE_CONNECTOR_HEIGHT/2.0 Z1=#YOKE_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//Cell properites are added to the yoke and to the pole. The magnetic properties of the
material "Steel" are defined. This magnet is made of C1010 steel, and so the
corresponding BH data, C1010.BH (or tenten.BH), is loaded if the analysis is set to be
nonlinear. The path to the BH data may need to be updated. The analysis type, TOSCA, is
also specified for each.

PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=O.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=O.00002
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POLE_DSL SIZE=#POLE_ES ELEMSHAPEPREF=HEXOPRISM
$IF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=0
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=LINEAR MUANISOTROPY=ISOTROPIC MU=2000 HC=0
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=YES CONVTOL=1.0E-08 HX=0.0 HY=0.0
HZ=0.0 RHS=ADAPTIVE POTENTIALCUT=YESMODEL CREATE
$ELIF VLU1=#ANALYSIS_TYPE LOP=EQ VLU2=1
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='C1010'
BHDATA OPTION=EDIT LABEL=C1010
BHDATA OPTION=LOAD LABEL=C1010 FILE='/home/mbasso/Opera_Models/Dipoles/4VB1/C1010.BH'
```

```
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=30
TOLERANCE=1.0E-7 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES
$END IF

//All of the following bodies are made of air. The center box is built and its cell
properites are added.

BLOCK UNIQUENAME='Center box' X0=0 Y0=0 Z0=#YOKE_WIDTH-#POLE_TIP_WIDTH X1=#YOKE_LENGTH/
2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT Y1=#GAP_HEIGHT/2.0 Z1=#YOKE_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Center box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#CENTER_BOX_DSL SIZE=#CENTER_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The coil box is built and its cell properites are added. The x- and z-dimensions are
made to be slightly larger (1.05 times as large) than total length and width of the
coil, respectively, to ensure the coil is well contained inside the box. This is the
only body in the model that is made a region of reduced potential; all other bodies are
made regions of total potential.

BLOCK UNIQUENAME='Coil box' X0=0 Y0=#GAP_HEIGHT/2.0 Z0=#YOKE_CONNECTOR_WIDTH
X1=1.05*#COIL_LENGTH/2.0 Y1=#YOKE_CONNECTOR_HEIGHT/2.0 Z1=1.05*#YOKE_TO_COIL_END_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=TETRAHEDRAL

//Buffer box 1 is built and its cell properites are added.

BLOCK UNIQUENAME='Buffer box 1' X0=0 Y0=0 Z0=#YOKE_CONNECTOR_WIDTH X1=#YOKE_LENGTH/
2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT Y1=#GAP_HEIGHT/2.0 Z1=1.1*#YOKE_TO_COIL_END_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Buffer box 1'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BUFFER_BOX_1_DSL SIZE=#BUFFER_BOX_1_ES ELEMSHAPEPREF=TETRAHEDRAL

//Buffer box 2 is built and its cell properites are added.

BLOCK UNIQUENAME='Buffer box 2' X0=0 Y0=0 Z0=#YOKE_CONNECTOR_WIDTH X1=1.1*(#YOKE_LENGTH/
2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT) Y1=#YOKE_CONNECTOR_HEIGHT/2.0
Z1=1.1*#YOKE_TO_COIL_END_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Buffer box 2'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BUFFER_BOX_2_DSL SIZE=#BUFFER_BOX_2_ES ELEMSHAPEPREF=TETRAHEDRAL

//The yoke box is built and its cell properites are added.

BLOCK UNIQUENAME='Yoke box' X0=0 Y0=0 Z0=-0.2*#YOKE_TO_COIL_END_WIDTH
X1=1.2*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT) Y1=1.2*#YOKE_HEIGHT/2.0
Z1=1.2*#YOKE_TO_COIL_END_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Yoke box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=TETRAHEDRAL

//The background is built and its cell properites are added.

BLOCK UNIQUENAME='Background' X0=0 Y0=0 Z0=#BACKGROUND_Z_EDGE_1 X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_DSL SIZE=#BACKGROUND_ES ELEMSHAPEPREF=TETRAHEDRAL

//Cut planes are added along every surface of the magnet as well as along every
interface of every air box. These cuts are made to extend through the entire model and
allow for regular meshing over the enitre model. This is desirable in terms of analysis
speed and the quality of the results. The cut planes perpendicular to the x-axis are
made first and subtracted from the background.

BLOCK UNIQUENAME='Cut' X0=#YOKE_LENGTH/2.0 Y0=0 Z0=#BACKGROUND_Z_EDGE_1 X1=#YOKE_LENGTH/
2.0 Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_Z_EDGE_2
```

```
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=1.05*#COIL_LENGTH/2.0 Y0=0 Z0=#BACKGROUND_Z_EDGE_1
X1=1.05*#COIL_LENGTH/2.0 Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT Y0=0
Z0=#BACKGROUND_Z_EDGE_1 X1=#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=1.1*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT) Y0=0
Z0=#BACKGROUND_Z_EDGE_1 X1=1.1*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=1.2*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT) Y0=0
Z0=#BACKGROUND_Z_EDGE_1 X1=1.2*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The cut planes perpendicular to the y-axis are made and subtracted from the
background.

BLOCK UNIQUENAME='Cut' X0=0 Y0=#GAP_HEIGHT/2.0 Z0=#BACKGROUND_Z_EDGE_1
X1=#BACKGROUND_LENGTH Y1=#GAP_HEIGHT/2.0 Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#GAP_HEIGHT/2.0+#POLE_TIP_HEIGHT Z0=#BACKGROUND_Z_EDGE_1
X1=#BACKGROUND_LENGTH Y1=#GAP_HEIGHT/2.0+#POLE_TIP_HEIGHT Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_CONNECTOR_HEIGHT/2.0 Z0=#BACKGROUND_Z_EDGE_1
X1=#BACKGROUND_LENGTH Y1=#YOKE_CONNECTOR_HEIGHT/2.0 Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_HEIGHT/2.0-#YOKE_CORNER_CHAMFER_LENGTH
Z0=#BACKGROUND_Z_EDGE_1 X1=#BACKGROUND_LENGTH Y1=#YOKE_HEIGHT/2.0-
#YOKE_CORNER_CHAMFER_LENGTH Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_HEIGHT/2.0 Z0=#BACKGROUND_Z_EDGE_1
X1=#BACKGROUND_LENGTH Y1=#YOKE_HEIGHT/2.0 Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.2*#YOKE_HEIGHT/2.0 Z0=#BACKGROUND_Z_EDGE_1
X1=#BACKGROUND_LENGTH Y1=1.2*#YOKE_HEIGHT/2.0 Z1=#BACKGROUND_Z_EDGE_2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The cut planes perpendicular to the z-axis are made and subtracted from the
background.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=-0.2*#YOKE_TO_COIL_END_WIDTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=-0.2*#YOKE_TO_COIL_END_WIDTH
```

```
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=0 X1=#BACKGROUND_LENGTH Y1=#BACKGROUND_HEIGHT Z1=0
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_CORNER_CHAMFER_LENGTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=#YOKE_CORNER_CHAMFER_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_CONNECTOR_WIDTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=#YOKE_CONNECTOR_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_WIDTH-#POLE_BASE_WIDTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=#YOKE_WIDTH-#POLE_BASE_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_WIDTH-#POLE_TIP_WIDTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=#YOKE_WIDTH-#POLE_TIP_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_WIDTH-#YOKE_CORNER_CHAMFER_LENGTH
X1=#BACKGROUND_LENGTH Y1=#BACKGROUND_HEIGHT Z1=#YOKE_WIDTH-#YOKE_CORNER_CHAMFER_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_WIDTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=#YOKE_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.05*#YOKE_TO_COIL_END_WIDTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=1.05*#YOKE_TO_COIL_END_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.1*#YOKE_TO_COIL_END_WIDTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=1.1*#YOKE_TO_COIL_END_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.2*#YOKE_TO_COIL_END_WIDTH X1=#BACKGROUND_LENGTH
Y1=#BACKGROUND_HEIGHT Z1=1.2*#YOKE_TO_COIL_END_WIDTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The symmetry of the model is specified: yz- and zx-plane reflection symmetry. Finally,
the model body is created and the model is given a surface mesh with a maximum ES equal
to that of the largest ES of any body in the model. The mesh shape is forced to be
mosaic to ensure regular meshing.

BACKGROUND OPTION=LOAD
BACKGROUND OPTION=SET SHAPE=TRIM XYSYMMETRYPLANE=NO YZSYMMETRYPLANE=YES ROTZNUM=1
ZXSYMMETRYPLANE=YES EMRYZ=TANMAGN EMRZX=NORMMAGN
MODEL CREATE
MESH SIZE=#BACKGROUND_ES NORMALTOL=30.0 SURFACETOL=0.0 TOLERANCE=1.0E-06 TYPE=MOSAIC

//At this point, one only needs to perform volume meshing and set up an analysis
database for the model prior to starting the TOSCA analysis.
```

A.7 45° Bending H-Frame Dipole

```
//45-Degree H-Dipole Magnet Model - Prepared by Matthew Basso in Opera 18R1/2
//Please note: this magnet has been almost entirely parameterized. One can enter
parameters for a magnet sharing a similar shape but with different dimensions as
compared to this H-dipole and this script should be able to build the new magnet without
any further intervention.

CLEAR |//This command may need to be commented out before initially running the macro.
YES   |//This command may need to be commented out before initially running the macro.

//"Width", "height", and "length" refer to x-, y-, and z-directions dimensions,
respectively.

$CONST #MM_PER_INCH                25.4

//The analysis type is specified. If #NONLINEAR_ANALYSIS=0, the analysis type is linear.
If #NONLINEAR_ANALYSIS=1, the analysis type is nonlinear.

$CONST #NONLINEAR_ANALYSIS         1

//A coil clamp may be included. If #CLAMP=0, a clamp is excluded. If #CLAMP=1, a clamp
is included.

$CONST #CLAMP                      0

//A yoke chamfer along the exterior edges of the yoke (in the beam direction) may be
included. If #YOKE_CHAMFER=0, a chamfer is excluded. If #YOKE_CHAMFER=1, a chamfer is
included.

$CONST #YOKE_CHAMFER               0

//The dimensions of the dipole as well as the meshing parameters are entered below. The
names have been made as descriptive as possible, but one should refer to the provided
sketches if it is unclear how a dimension is defined.

$CONST #YOKE_LENGTH                65.0*#MM_PER_INCH
$CONST #YOKE_EDGELESS_WIDTH        34.0*#MM_PER_INCH
$CONST #YOKE_EDGELESS_HEIGHT       15.0*#MM_PER_INCH
$CONST #YOKE_EDGE_WIDTH            12.0*#MM_PER_INCH
$CONST #YOKE_EDGE_HEIGHT           13.0*#MM_PER_INCH

$CONST #POLE_BASE_WIDTH            21.0*#MM_PER_INCH
$CONST #POLE_TIP_WIDTH             19.0*#MM_PER_INCH
$CONST #POLE_HEIGHT                6.0*#MM_PER_INCH

$CONST #CLAMP_EDGELESS_LENGTH      6.5*#MM_PER_INCH
$CONST #CLAMP_LOWER_THICKNESS      1.0*#MM_PER_INCH
$CONST #CLAMP_UPPER_THICKNESS      1.0*#MM_PER_INCH

$CONST #YOKE_CHAMFER_LENGTH        2.0*#MM_PER_INCH

$CONST #COIL_EDGELESS_LENGTH       66.0*#MM_PER_INCH
$CONST #COIL_EDGELESS_WIDTH        22.0*#MM_PER_INCH
$CONST #COIL_EDGE_WIDTH            5.3*#MM_PER_INCH    |//To make the model realistic,
the coil edge width is equal to that of the 4VB1 dipole.
$CONST #COIL_EDGE_HEIGHT           5.3*#MM_PER_INCH    |//To make the model realistic,
the coil edge height is equal to that of the 4VB1 dipole.
$CONST #COIL_CORNER_RADIUS         1.0*#MM_PER_INCH
$CONST #COIL_CURRENT               850.0
$CONST #COIL_TURN_NUMBER           64.0                |//To make the model realistic,
the coil turn number per unit area is equal to that of the 4VB1 dipole.

$CONST #CENTER_BOX_ES              10.0                |//"ES" refers to "element size".
The "Center box" refers to the body enclosing the good field region between the poles of
the dipole.
$CONST #POLE_ES                    3.0*#CENTER_BOX_ES  |//The "Pole" refers the body
which makes up the poles.
$CONST #YOKE_ES                    5.0*#CENTER_BOX_ES  |//The "Yoke" refers the body
```

```
which makes up the yoke.
$CONST #COIL_BOX_ES                2.0*#CENTER_BOX_ES  |//The "Coil box" refers the body
which encloses the coils and the poles.
$CONST #BUFFER_BOX_1_ES            3.0*#CENTER_BOX_ES  |//"Buffer box 1" refers the body
drawn alongside the center box through the the interior of the yoke.
$CONST #BUFFER_BOX_2_ES            2.0*#CENTER_BOX_ES  |//"Buffer box 2" refers the body
buffering the ends of buffer box 1 and the center box along the z-direction.
$CONST #YOKE_BOX_ES                10.0*#CENTER_BOX_ES |//The "Yoke box" refers the body
which encloses the coils, the poles, and the entire yoke.
$CONST #BACKGROUND_ES              20.0*#CENTER_BOX_ES |//"Background" refers to the
background region enclosing the dipole.

$CONST #POLE_DSL                   7    |//"DSL" refers to "data storage level". The
pole and the yoke have the highest DSLs. Subsequent DSLs are assigned in the order in
which the air boxes are drawn.
$CONST #YOKE_DSL                   6
$CONST #CENTER_BOX_DSL             5
$CONST #COIL_BOX_DSL               4
$CONST #BUFFER_BOX_1_DSL           3
$CONST #BUFFER_BOX_2_DSL           2
$CONST #YOKE_BOX_DSL               1
$CONST #BACKGROUND_DSL             0

$CONST #BACKGROUND_LENGTH_SF       5.0  |//"SF" refers to "scaling factor". This factor
defines how many times larger Background should be in terms of length relative to the
length of the yoke.
$CONST #BACKGROUND_WIDTH_SF        3.0  |//This factor defines how many times larger the
background should be in terms of width relative to the height of the yoke.
$CONST #BACKGROUND_HEIGHT_SF       3.0  |//This factor defines how many times larger the
background should be in terms of height relative to the height of the yoke.
$CONST #CENTER_LENGTH_SF           8.0  |//This factor defines how many times the gap
height the center box should extend outside of the yoke in the z-direction.

//The following dimensions are implicit from the above dimensions. The current density
in the coils may be calculated given a desired current and knowing the cross-sectional
area of the coils used and number of turns passing through that area. As the analysis
uses SI-MM, the units of current density are A/mm^2.

$CONST #YOKE_WIDTH                 #YOKE_EDGELESS_WIDTH+2.0*#YOKE_EDGE_WIDTH
$CONST #YOKE_HEIGHT                #YOKE_EDGELESS_HEIGHT+2.0*#YOKE_EDGE_HEIGHT
$CONST #GAP_HEIGHT                 #YOKE_EDGELESS_HEIGHT-2.0*#POLE_HEIGHT
$CONST #POLE_TIP_CHAMFER_LENGTH    (#POLE_BASE_WIDTH-#POLE_TIP_WIDTH)/2.0
$CONST #COIL_LENGTH                #COIL_EDGELESS_LENGTH+2.0*#COIL_EDGE_WIDTH
$CONST #COIL_WIDTH                 #COIL_EDGELESS_WIDTH+2.0*#COIL_EDGE_WIDTH
$CONST #COIL_Y_POSITION            1.1*#GAP_HEIGHT/2.0
$CONST #COIL_CROSS_SECTIONAL_AREA  #COIL_EDGE_WIDTH*#COIL_EDGE_HEIGHT
$CONST #COIL_CURRENT_DENSITY       #COIL_CURRENT*#COIL_TURN_NUMBER/
#COIL_CROSS_SECTIONAL_AREA
$CONST #BACKGROUND_LENGTH          #BACKGROUND_LENGTH_SF*#YOKE_LENGTH/2.0
$CONST #BACKGROUND_WIDTH           #BACKGROUND_WIDTH_SF*#YOKE_WIDTH/2.0
$CONST #BACKGROUND_HEIGHT          #BACKGROUND_HEIGHT_SF*#YOKE_HEIGHT/2.0

//The yoke of the dipole is drawn and covered.

WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=#GAP_HEIGHT/2.0 Z0=0
X1=#POLE_TIP_WIDTH/2.0 Y1=#GAP_HEIGHT/2.0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_TIP_WIDTH/2.0 Y0=#GAP_HEIGHT/2.0 Z0=0
X1=#POLE_BASE_WIDTH/2.0 Y1=#GAP_HEIGHT/2.0+#POLE_TIP_CHAMFER_LENGTH Z1=0
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_BASE_WIDTH/2.0 Y0=#GAP_HEIGHT/
2.0+#POLE_TIP_CHAMFER_LENGTH Z0=0 X1=#POLE_BASE_WIDTH/2.0 Y1=#YOKE_EDGELESS_HEIGHT/2.0
Z1=0
WIREEDGE CONTINUE=AUTOCOVER X0=#POLE_BASE_WIDTH/2.0 Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0
X1=#YOKE_EDGELESS_WIDTH/2.0 Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_EDGELESS_WIDTH/2.0 Y0=#YOKE_EDGELESS_HEIGHT/2.0
Z0=0 X1=#YOKE_EDGELESS_WIDTH/2.0 Y1=0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_EDGELESS_WIDTH/2.0 Y0=0 Z0=0 X1=#YOKE_WIDTH/2.0
Y1=0 Z1=0
```

```
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_WIDTH/2.0 Y0=0 Z0=0 X1=#YOKE_WIDTH/2.0
Y1=#YOKE_HEIGHT/2.0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER X0=#YOKE_WIDTH/2.0 Y0=#YOKE_HEIGHT/2.0 Z0=0 X1=0
Y1=#YOKE_HEIGHT/2.0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_HEIGHT/2.0 Z0=0 X1=0 Y1=#GAP_HEIGHT/2.0 Z1=0

//The yoke is swept in the x-direction to create a body. The pole is made using a cut-
plane.

PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=#YOKE_LENGTH/2.0 DRAFTTYPE=NONE
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0 X1=#POLE_BASE_WIDTH/2.0
Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=#YOKE_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The two coils are built with negative zx-plane reflection symmetry. A local coordinate
system is used to position the coils.

RACETRACK OPTION=NEW -KEEP XP1=#COIL_EDGELESS_WIDTH/2.0 YP1=#COIL_Y_POSITION
WIDTH=#COIL_EDGE_WIDTH THICKNESS=#COIL_EDGE_HEIGHT H1=#COIL_EDGELESS_LENGTH/2.0-
#COIL_CORNER_RADIUS R1=#COIL_CORNER_RADIUS INCIRCUIT=NO CIRCUITELEMENT=
CURD=#COIL_CURRENT_DENSITY TOLERANCE=0 DRIVELABEL='Default Drive' THETA2=0 PHI2=0 PSI2=0
XCEN2=0 YCEN2=0 ZCEN2=0 LCNAME='Global coordinate system' RXY=0 RYZ=0 RZX=-1 SYMMETRY=1
MODELCOMPONENT=NO

//All of the following bodies are made of air. The center box is built and its cell
properites are added.

BLOCK UNIQUENAME='Center box' X0=0 Y0=0 Z0=0 X1=#POLE_TIP_WIDTH/2.0 Y1=#GAP_HEIGHT/2.0
Z1=#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT
PICK PROPERTY=UNIQUENAME LABEL='Center box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#CENTER_BOX_DSL SIZE=#CENTER_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//Buffer box 1 is built and its cell properites are added.

BLOCK UNIQUENAME='Buffer box 1' X0=#POLE_TIP_WIDTH/2.0 Y0=0 Z0=0
X1=#YOKE_EDGELESS_WIDTH/2.0 Y1=#GAP_HEIGHT/2.0 Z1=#YOKE_LENGTH/
2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT
PICK PROPERTY=UNIQUENAME LABEL='Buffer box 1'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BUFFER_BOX_1_DSL SIZE=#BUFFER_BOX_1_ES ELEMSHAPEPREF=HEXOPRISM

//Buffer box 2 is built and its cell properites are added.

BLOCK UNIQUENAME='Buffer box 2' X0=0 Y0=0 Z0=#YOKE_LENGTH/2.0 X1=#YOKE_EDGELESS_WIDTH/
2.0 Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=1.1*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
PICK PROPERTY=UNIQUENAME LABEL='Buffer box 2'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BUFFER_BOX_2_DSL SIZE=#BUFFER_BOX_2_ES ELEMSHAPEPREF=HEXOPRISM

//The yoke box is built and its cell properites are added.

BLOCK UNIQUENAME='Yoke box' X0=0 Y0=0 Z0=0 X1=1.2*#YOKE_WIDTH/2.0 Y1=1.2*#YOKE_HEIGHT/
2.0 Z1=1.2*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
PICK PROPERTY=UNIQUENAME LABEL='Yoke box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The background is built and its cell properites are added.

BLOCK UNIQUENAME='Background' X0=0 Y0=0 Z0=0 X1=#BACKGROUND_WIDTH Y1=#BACKGROUND_HEIGHT
Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
```

```
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#BACKGROUND_DSL SIZE=#BACKGROUND_ES ELEMSHAPEPREF=HEXOPRISM

//Cell properites are added to the yoke and to the pole. The coil box is built and its
cell properites are added. Only a single cut plane is made perpendicular to the z-axis
if no coil clamp is specified. If a yoke chamfer was specified, the clamp and the
accompanying cut planes are made. The coil box is also built differently.

$IF VLU1=#CLAMP LOP=EQ VLU2=0
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=M.00002
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=M.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POLE_DSL SIZE=#POLE_ES ELEMSHAPEPREF=HEXOPRISM
BLOCK UNIQUENAME='Coil box' X0=0 Y0=#GAP_HEIGHT/2.0 Z0=0 X1=#YOKE_EDGELESS_WIDTH/2.0
Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=1.05*#COIL_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.05*#COIL_LENGTH/2.0 X1=#BACKGROUND_WIDTH
Y1=#BACKGROUND_HEIGHT Z1=1.05*#COIL_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$ELIF VLU1=#CLAMP LOP=EQ VLU2=1
WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Clamp' X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0
Z0=#YOKE_LENGTH/2.0 X1=0 Y1=#YOKE_EDGELESS_HEIGHT/2.0+#CLAMP_UPPER_THICKNESS
Z1=#YOKE_LENGTH/2.0
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0+#CLAMP_UPPER_THICKNESS
Z0=#YOKE_LENGTH/2.0 X1=0 Y1=#YOKE_EDGELESS_HEIGHT/2.0+#CLAMP_UPPER_THICKNESS
Z1=#YOKE_LENGTH/2.0+#CLAMP_EDGELESS_LENGTH+#CLAMP_LOWER_THICKNESS
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0+#CLAMP_UPPER_THICKNESS
Z0=#YOKE_LENGTH/2.0+#CLAMP_EDGELESS_LENGTH+#CLAMP_LOWER_THICKNESS X1=0 Y1=#GAP_HEIGHT/
2.0 Z1=#YOKE_LENGTH/2.0+#CLAMP_EDGELESS_LENGTH+#CLAMP_LOWER_THICKNESS
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#GAP_HEIGHT/2.0 Z0=#YOKE_LENGTH/
2.0+#CLAMP_EDGELESS_LENGTH+#CLAMP_LOWER_THICKNESS X1=0 Y1=#GAP_HEIGHT/2.0
Z1=#YOKE_LENGTH/2.0+#CLAMP_EDGELESS_LENGTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#GAP_HEIGHT/2.0 Z0=#YOKE_LENGTH/
2.0+#CLAMP_EDGELESS_LENGTH X1=0 Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=#YOKE_LENGTH/
2.0+#CLAMP_EDGELESS_LENGTH
WIREEDGE CONTINUE=AUTOCOVER X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=#YOKE_LENGTH/
2.0+#CLAMP_EDGELESS_LENGTH X1=0 Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=#YOKE_LENGTH/2.0
PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=#YOKE_EDGELESS_WIDTH/2.0
DRAFTTYPE=NONE
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK PROPERTY=UNIQUENAME LABEL='Clamp'
COMBINE OPERATION=UNION +REGULAR
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=M.00002
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM
PICK OPTION=TOGGLE TYPE=CELL UNIQUEBODYNAME='Yoke' IDENTIFIER=M.00001
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POLE_DSL SIZE=#POLE_ES ELEMSHAPEPREF=HEXOPRISM
BLOCK UNIQUENAME='Coil box' X0=0 Y0=#GAP_HEIGHT/2.0 Z0=0 X1=#YOKE_EDGELESS_WIDTH/2.0
Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=#YOKE_LENGTH/2.0+#CLAMP_EDGELESS_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0+#CLAMP_UPPER_THICKNESS Z0=0
X1=#BACKGROUND_WIDTH Y1=#YOKE_EDGELESS_HEIGHT/2.0+#CLAMP_UPPER_THICKNESS
Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_LENGTH/2.0+#CLAMP_EDGELESS_LENGTH
```

```
X1=#BACKGROUND_WIDTH Y1=#BACKGROUND_HEIGHT Z1=#YOKE_LENGTH/2.0+#CLAMP_EDGELESS_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_LENGTH/2.0+#CLAMP_EDGELESS_LENGTH
+#CLAMP_LOWER_THICKNESS X1=#BACKGROUND_WIDTH Y1=#BACKGROUND_HEIGHT Z1=#YOKE_LENGTH/
2.0+#CLAMP_EDGELESS_LENGTH+#CLAMP_LOWER_THICKNESS
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$END IF

//If a yoke chamfer was specified, the chamfer and the accompanying cut planes are made.

$IF VLU1=#YOKE_CHAMFER LOP=EQ VLU2=1
PICK OPTION=TOGGLE TYPE=EDGE UNIQUEBODYNAME='Yoke' IDENTIFIER=K.00017
BLEND OPTION=CHAMFER LEFTCHAMFER=#YOKE_CHAMFER_LENGTH RIGHTCHAMFER=#YOKE_CHAMFER_LENGTH
BLOCK UNIQUENAME='Cut' X0=#YOKE_WIDTH/2.0-#YOKE_CHAMFER_LENGTH Y0=0 Z0=0 X1=#YOKE_WIDTH/
2.0-#YOKE_CHAMFER_LENGTH Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_HEIGHT/2.0-#YOKE_CHAMFER_LENGTH Z0=0
X1=#BACKGROUND_WIDTH Y1=#YOKE_HEIGHT/2.0-#YOKE_CHAMFER_LENGTH Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$END IF

//The remaining cut planes perpendicular to the x-axis are made and subtracted from the
background.

BLOCK UNIQUENAME='Cut' X0=#POLE_TIP_WIDTH/2.0 Y0=0 Z0=0 X1=#POLE_TIP_WIDTH/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=#POLE_BASE_WIDTH/2.0 Y0=0 Z0=0 X1=#POLE_BASE_WIDTH/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=#YOKE_EDGELESS_WIDTH/2.0 Y0=0 Z0=0 X1=#YOKE_EDGELESS_WIDTH/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=#YOKE_WIDTH/2.0 Y0=0 Z0=0 X1=#YOKE_WIDTH/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=1.2*#YOKE_WIDTH/2.0 Y0=0 Z0=0 X1=1.2*#YOKE_WIDTH/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The remaining cut planes perpendicular to the y-axis are made and subtracted from the
background.

BLOCK UNIQUENAME='Cut' X0=0 Y0=#GAP_HEIGHT/2.0 Z0=0 X1=#BACKGROUND_WIDTH Y1=#GAP_HEIGHT/
2.0 Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#GAP_HEIGHT/2.0+#POLE_TIP_CHAMFER_LENGTH Z0=0
```

```
X1=#BACKGROUND_WIDTH Y1=#GAP_HEIGHT/2.0+#POLE_TIP_CHAMFER_LENGTH Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0 X1=#BACKGROUND_WIDTH
Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_HEIGHT/2.0 Z0=0 X1=#BACKGROUND_WIDTH
Y1=#YOKE_HEIGHT/2.0 Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.2*#YOKE_HEIGHT/2.0 Z0=0 X1=#BACKGROUND_WIDTH
Y1=1.2*#YOKE_HEIGHT/2.0 Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The remaining cut planes perpendicular to the z-axis are made and subtracted from the
background.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_LENGTH/2.0 X1=#BACKGROUND_WIDTH
Y1=#BACKGROUND_HEIGHT Z1=#YOKE_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
X1=#BACKGROUND_WIDTH Y1=#BACKGROUND_HEIGHT Z1=(#YOKE_LENGTH/
2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.1*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
X1=#BACKGROUND_WIDTH Y1=#BACKGROUND_HEIGHT Z1=1.1*(#YOKE_LENGTH/
2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.2*(#YOKE_LENGTH/2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
X1=#BACKGROUND_WIDTH Y1=#BACKGROUND_HEIGHT Z1=1.2*(#YOKE_LENGTH/
2.0+#CENTER_LENGTH_SF*#GAP_HEIGHT)
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The magnetic properties of the material "Steel" are defined. This magnet is made of
C1010 steel, and so the corresponding BH data, C1010.BH (or tenten.BH), is loaded if the
analysis is set to be nonlinear. The path to the BH data may need to be updated. The
analysis type, TOSCA, is also specified.

$IF VLU1=#NONLINEAR_ANALYSIS LOP=EQ VLU2=0
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=LINEAR MUANISOTROPY=ISOTROPIC MU=2000 HC=0
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=YES CONVTOL=1.0E-08 HX=0.0 HY=0.0
HZ=0.0 RHS=ADAPTIVE POTENTIALCUT=YESMODEL CREATE
$ELIF VLU1=#NONLINEAR_ANALYSIS LOP=EQ VLU2=1
MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='C1010'
BHDATA OPTION=EDIT LABEL=C1010
BHDATA OPTION=LOAD LABEL=C1010 FILE='/home/mbasso/Opera_Models/
Physical_Magnet_Modelling/Dipoles/4VB1/C1010.BH'
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=30
TOLERANCE=1.0E-7 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES
$END IF
```

```
//The symmetry of the model is specified: xy-, yz-, and zx-plane reflection symmetry.
Finally, the model body is created and the model is given a surface mesh with a maximum
ES equal to that of the largest ES of any body in the model. The mesh shape is forced to
be mosaic to ensure regular meshing.

BACKGROUND OPTION=LOAD
BACKGROUND OPTION=SET SHAPE=TRIM XYSYMMETRYPLANE=YES YZSYMMETRYPLANE=YES ROTZNUM=1
ZXSYMMETRYPLANE=YES EMRXY=TANGMAGN EMRYZ=TANGMAGN EMRZX=NORMMAGN
MODEL CREATE
MESH SIZE=#BACKGROUND_ES NORMALTOL=30.0 SURFACETOL=0.0 TOLERANCE=1.0E-06 TYPE=MOSAIC

//At this point, one only needs to perform volume meshing and set up an analysis
database for the model prior to starting the TOSCA analysis.
```

A.8 Bonnie H-Frame Dipole

```
//Bonnie H-Dipole Magnet Model - Prepared by Matthew Basso in Opera 18R1/2
//Please note: this magnet has been almost entirely parameterized. One can enter
parameters for a magnet sharing a similar shape but with different dimensions as
compared to Bonnie and this script should be able to build the new magnet without any
further intervention.

CLEAR |//This command may need to be commented out before initially running the macro.
YES   |//This command may need to be commented out before initially running the macro.

//"Width", "height", and "length" refer to x-, y-, and z-directions dimensions,
respectively.

$CONSTANT #MM_PER_INCH                25.4

//We set the maximum number of additional field points used in calculating Int(Hs*dl)
over the boundary between regions of total and reduced potential to 128 to reduce
potential nodal jump errors.

$CONSTANT #MAXEDGEHDLPTS              128

//The dimensions of the dipole as well as the meshing parameters are entered below. The
names have been made as descriptive as possible, but one should refer to the provided
sketches if it is unclear how a dimension is defined.

$CONSTANT #YOKE_LENGTH                32.0*#MM_PER_INCH    |//This was measured using a
measuring tape.
$CONSTANT #YOKE_EDGELESS_WIDTH        49.5*#MM_PER_INCH    |//This was calculated given
knowledge of the total width of the magnet (87.25 in.) and the yoke edge width.
$CONSTANT #YOKE_EDGE_WIDTH            18.875*#MM_PER_INCH  |//This was measured using a
measuring tape.
$CONSTANT #YOKE_EDGELESS_HEIGHT       19.0*#MM_PER_INCH    |//This dimension is actually
16.75 in., measured using a measuring tape, but was made 19 in. for the purposes of
field matching.
$CONSTANT #YOKE_EDGE_HEIGHT           17.4375*#MM_PER_INCH |//This was measured using a
measuring tape.

$CONSTANT #HOLE_DIAMETER              7.0*#MM_PER_INCH     |//This specifies the
diameter of the hole cut about the vertical axis.

$CONSTANT #COIL_EDGELESS_LENGTH       35.0*#MM_PER_INCH    |//This dimension is actually
closer to 34 in. by measuring tape, but was altered for the purposes of modelling. The
coil dimensions are relatively unimportant.
$CONSTANT #COIL_EDGELESS_WIDTH        27.5*#MM_PER_INCH    |//This dimension is actually
closer to 27.25 in. by measuring tape, but was altered for the purposes of modelling.
$CONSTANT #COIL_EDGE_WIDTH            10.25*#MM_PER_INCH   |//This was measured using a
measuring tape.
$CONSTANT #COIL_EDGE_HEIGHT           8.375*#MM_PER_INCH   |//This was measured using a
measuring tape.
$CONSTANT #COIL_CORNER_RADIUS         2.0*#MM_PER_INCH     |//This value was arbitraily
selected.
$CONSTANT #COIL_CURRENT               625.0                |//The current is chosen for
the purposes of field matching.
$CONSTANT #COIL_TURN_NUMBER           94.0                 |//The coil turn number was
chosen such that a 1.7 T field could be achieved by Bonnie for a current of 1000 A with
a pole gap of 5.5 in.; please refer to P.5 of section "Dipole magnets for Experimenters"
in the TRIUMF Magnet Index.

$CONSTANT #GFR_ES                     7.0                  |//"ES" refers to "element
size". The "GFR" or "Good Field Region" refers to the cylindrical region within the
interior of the magnet with a diameter equal to that of the cut and about the y-axis.
$CONSTANT #YOKE_ES                    5.0*#GFR_ES          |//The "Yoke" refers to the
body which makes up the yoke.
$CONSTANT #HOLE_ES                    3.0*#GFR_ES          |//The "Hole" refers to the
body which fills cylindrical holes on the top and the bottom of the yoke about the y-
axis.
$CONSTANT #PRECOIL_BOX_ES             2.0*#GFR_ES          |//The "Precoil Box" refers
to the body in the interior of the yoke and containing the GFR, surrounded by the coils.
```

```
$CONSTANT #COIL_BOX_ES                2.0*#GFR_ES          |//The "Coil Box" refers to
the body which contains the coils.
$CONSTANT #POSTCOIL_BOX_ES            2.0*#GFR_ES          |//The "Postcoil Box" refers
to the body which contains the Coil Box and the Precoil Box in the interior of the yoke.
$CONSTANT #YOKE_BOX_ES                10.0*#GFR_ES         |//The "Yoke box" refers the
body which encloses the coils, the poles, and the entire yoke.
$CONSTANT #BACKGROUND_ES              20.0*#GFR_ES         |//The "Background" refers to
the larger body containing the entire dipole.

$CONSTANT #YOKE_DSL                   7    |//"DSL" refers to "data storage level". The
pole and the yoke have the highest DSLs. Subsequent DSLs are assigned in the order in
which the air boxes are drawn.
$CONSTANT #GFR_DSL                    6
$CONSTANT #HOLE_DSL                   5
$CONSTANT #PRECOIL_BOX_DSL            4
$CONSTANT #COIL_BOX_DSL               3
$CONSTANT #POSTCOIL_BOX_DSL           2
$CONSTANT #YOKE_BOX_DSL               1
$CONSTANT #BACKGROUND_DSL             0

$CONSTANT #BACKGROUND_LENGTH_SF       5.0  |//"SF" refers to "scaling factor". This
factor defines how many times larger Background should be in terms of length relative to
the length of the yoke.
$CONST #BACKGROUND_WIDTH_SF           2.0  |//This factor defines how many times larger
the background should be in terms of width relative to the height of the yoke.
$CONST #BACKGROUND_HEIGHT_SF          2.0  |//This factor defines how many times larger
the background should be in terms of height relative to the height of the yoke.

//The following dimensions are implicit from the above dimensions. The current density
in the coils may be calculated given a desired current and knowing the cross-sectional
area of the coils used and number of turns passing through that area. As the analysis
uses SI-MM, the units of current density are A/mm^2.

$CONSTANT #YOKE_WIDTH                 #YOKE_EDGELESS_WIDTH+2.0*#YOKE_EDGE_WIDTH
$CONSTANT #YOKE_HEIGHT                #YOKE_EDGELESS_HEIGHT+2.0*#YOKE_EDGE_HEIGHT
$CONSTANT #COIL_Y_POSITION            0.95*#YOKE_EDGELESS_HEIGHT/2.0-#COIL_EDGE_HEIGHT
$CONSTANT #COIL_LENGTH                #COIL_EDGELESS_LENGTH+2.0*#COIL_EDGE_WIDTH
$CONSTANT #COIL_WIDTH                 #COIL_EDGELESS_WIDTH+2.0*#COIL_EDGE_WIDTH
$CONSTANT #COIL_CROSS_SECTIONAL_AREA  #COIL_EDGE_WIDTH*#COIL_EDGE_HEIGHT
$CONSTANT #COIL_CURRENT_DENSITY       #COIL_CURRENT*#COIL_TURN_NUMBER/
#COIL_CROSS_SECTIONAL_AREA
$CONSTANT #BACKGROUND_LENGTH          #BACKGROUND_LENGTH_SF*#YOKE_LENGTH/2.0
$CONSTANT #BACKGROUND_WIDTH           #BACKGROUND_WIDTH_SF*#YOKE_WIDTH/2.0
$CONSTANT #BACKGROUND_HEIGHT          #BACKGROUND_HEIGHT_SF*#YOKE_HEIGHT/2.0

//The yoke of the dipole is drawn and covered.

WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=#YOKE_EDGELESS_WIDTH/2.0 Y0=0 Z0=0
X1=#YOKE_WIDTH/2.0 Y1=0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=#YOKE_WIDTH/2.0 Y0=0 Z0=0
X1=#YOKE_WIDTH/2.0 Y1=#YOKE_HEIGHT/2.0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=#YOKE_WIDTH/2.0 Y0=#YOKE_HEIGHT/2.0
Z0=0 X1=0 Y1=#YOKE_HEIGHT/2.0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=#YOKE_HEIGHT/2.0 Z0=0 X1=0
Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0
X1=#YOKE_EDGELESS_WIDTH/2.0 Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=0
WIREEDGE CONTINUE=AUTOCOVER UNIQUENAME='Yoke' X0=#YOKE_EDGELESS_WIDTH/2.0
Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0 X1=#YOKE_EDGELESS_WIDTH/2.0 Y1=0 Z1=0

//The yoke is swept in the x-direction to create a body.

PICK PROPERTY=SYSTEM LABEL='Sheet face'
SWEEP KEEP=NO TYPE=DISTANCE REGULAR=NO RIGID=NO DISTANCE=#YOKE_LENGTH/2.0 DRAFTTYPE=NONE

//A cylindrical hole of a specified diameter is cut through the dipole about the y-axis.
```

```
CYLINDER Name='Cut' X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0 X1=0 Y1=#YOKE_HEIGHT/2.0 Z1=0
-TUBE SHAPECONTROL=SIMPLE MAJORRADIUS=#HOLE_DIAMETER/2.0 MINORRADIUS=#HOLE_DIAMETER/2.0
TOPRADIUS=#HOLE_DIAMETER/2.0 SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='Yoke'
PICK OPTION=TOGGLE PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The two coils are built with negative zx-plane reflection symmetry. A local coordinate
system is used to position the coils.

RACETRACK OPTION=NEW -KEEP XP1=#COIL_EDGELESS_WIDTH/2.0 YP1=#COIL_Y_POSITION
WIDTH=#COIL_EDGE_WIDTH THICKNESS=#COIL_EDGE_HEIGHT H1=#COIL_EDGELESS_LENGTH/2.0-
#COIL_CORNER_RADIUS R1=#COIL_CORNER_RADIUS INCIRCUIT=NO CIRCUITELEMENT=
CURD=-1.0*#COIL_CURRENT_DENSITY TOLERANCE=0 DRIVELABEL='Default Drive' THETA2=0 PHI2=0
PSI2=0 XCEN2=0 YCEN2=0 ZCEN2=0 LCNAME='Global coordinate system' RXY=0 RYZ=0 RZX=-1
SYMMETRY=1 MODELCOMPONENT=NO

//Cell properties are added to the Yoke.

PICK PROPERTY=UNIQUENAME LABEL='Yoke'
CELLDATA OPTION=MODIFY MATERIALLABEL='Steel' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_DSL SIZE=#YOKE_ES ELEMSHAPEPREF=HEXOPRISM

//All of the following bodies are made of air. The GFR is built and its cell properites
are added.

CYLINDER Name='GFR' X0=0 Y0=0 Z0=0 X1=0 Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=0 -TUBE
SHAPECONTROL=SIMPLE MAJORRADIUS=#HOLE_DIAMETER/2.0 MINORRADIUS=#HOLE_DIAMETER/2.0
TOPRADIUS=#HOLE_DIAMETER/2.0 SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='GFR'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#GFR_DSL SIZE=#GFR_ES ELEMSHAPEPREF=HEXOPRISM

//The Hole air box is built and its cell properties are added.

CYLINDER Name='Hole' X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0 X1=0 Y1=#YOKE_HEIGHT/2.0
Z1=0 -TUBE SHAPECONTROL=SIMPLE MAJORRADIUS=#HOLE_DIAMETER/2.0
MINORRADIUS=#HOLE_DIAMETER/2.0 TOPRADIUS=#HOLE_DIAMETER/2.0 SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='Hole'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#HOLE_DSL SIZE=#HOLE_ES ELEMSHAPEPREF=HEXOPRISM

//The Precoil Box is built and its cell properites are added.

BLOCK UNIQUENAME='Precoil box' X0=0 Y0=0 Z0=0 X1=0.95*#COIL_EDGELESS_WIDTH/2.0
Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=#YOKE_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Precoil box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#PRECOIL_BOX_DSL SIZE=#PRECOIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The Coil Box is built and its cell properites are added.

BLOCK UNIQUENAME='Coil box' X0=0 Y0=0.9*#COIL_Y_POSITION Z0=0 X1=#YOKE_EDGELESS_WIDTH/
2.0 Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=1.05*#COIL_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Coil box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=REDUCED ELEMENTTYPE=QUADRATIC
LEVEL=#COIL_BOX_DSL SIZE=#COIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The Postcoil Box is built and its cell properites are added.

BLOCK UNIQUENAME='Postcoil box' X0=0 Y0=0 Z0=0 X1=1.1*#YOKE_EDGELESS_WIDTH/2.0
Y1=1.1*#YOKE_EDGELESS_HEIGHT/2.0 Z1=1.1*#COIL_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Postcoil box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#POSTCOIL_BOX_DSL SIZE=#POSTCOIL_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The Yoke Box is built and its cell properites are added.
```

```
BLOCK UNIQUENAME='Yoke box' X0=0 Y0=0 Z0=0 X1=1.2*#YOKE_WIDTH/2.0 Y1=1.2*#YOKE_HEIGHT/
2.0 Z1=1.2*#COIL_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Yoke box'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The Background is built and its cell properites are added.

BLOCK UNIQUENAME='Background' X0=0 Y0=0 Z0=0 X1=#BACKGROUND_WIDTH Y1=#BACKGROUND_HEIGHT
Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=TOTAL ELEMENTTYPE=QUADRATIC
LEVEL=#YOKE_BOX_DSL SIZE=#YOKE_BOX_ES ELEMSHAPEPREF=HEXOPRISM

//The cut planes perpendicular to the x-axis are made and subtracted from the
background.

BLOCK UNIQUENAME='Cut' X0=#HOLE_DIAMETER/2.0 Y0=0 Z0=0 X1=#HOLE_DIAMETER/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0.95*#COIL_EDGELESS_WIDTH/2.0 Y0=0 Z0=0
X1=0.95*#COIL_EDGELESS_WIDTH/2.0 Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=#YOKE_EDGELESS_WIDTH/2.0 Y0=0 Z0=0 X1=#YOKE_EDGELESS_WIDTH/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=1.1*#YOKE_EDGELESS_WIDTH/2.0 Y0=0 Z0=0
X1=1.1*#YOKE_EDGELESS_WIDTH/2.0 Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=#YOKE_WIDTH/2.0 Y0=0 Z0=0 X1=#YOKE_WIDTH/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=1.2*#YOKE_WIDTH/2.0 Y0=0 Z0=0 X1=1.2*#YOKE_WIDTH/2.0
Y1=#BACKGROUND_HEIGHT Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The cut planes perpendicular to the y-axis are made and subtracted from the
background.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0.9*#COIL_Y_POSITION Z0=0 X1=#BACKGROUND_WIDTH
Y1=0.9*#COIL_Y_POSITION Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_EDGELESS_HEIGHT/2.0 Z0=0 X1=#BACKGROUND_WIDTH
Y1=#YOKE_EDGELESS_HEIGHT/2.0 Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.1*#YOKE_EDGELESS_HEIGHT/2.0 Z0=0 X1=#BACKGROUND_WIDTH
Y1=1.1*#YOKE_EDGELESS_HEIGHT/2.0 Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
```

```
BLOCK UNIQUENAME='Cut' X0=0 Y0=#YOKE_HEIGHT/2.0 Z0=0 X1=#BACKGROUND_WIDTH
Y1=#YOKE_HEIGHT/2.0 Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=1.2*#YOKE_HEIGHT/2.0 Z0=0 X1=#BACKGROUND_WIDTH
Y1=1.2*#YOKE_HEIGHT/2.0 Z1=#BACKGROUND_LENGTH
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//The cut planes perpendicular to the z-axis are made and subtracted from the
background.

BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#HOLE_DIAMETER/2.0 X1=#BACKGROUND_WIDTH
Y1=#BACKGROUND_HEIGHT Z1=#HOLE_DIAMETER/2.0
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=#YOKE_LENGTH/2.0 X1=#BACKGROUND_WIDTH
Y1=#BACKGROUND_HEIGHT Z1=#YOKE_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.05*#COIL_LENGTH/2.0 X1=#BACKGROUND_WIDTH
Y1=#BACKGROUND_HEIGHT Z1=1.05*#COIL_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.1*#COIL_LENGTH/2.0 X1=#BACKGROUND_WIDTH
Y1=#BACKGROUND_HEIGHT Z1=1.1*#COIL_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
BLOCK UNIQUENAME='Cut' X0=0 Y0=0 Z0=1.2*#COIL_LENGTH/2.0 X1=#BACKGROUND_WIDTH
Y1=#BACKGROUND_HEIGHT Z1=1.2*#COIL_LENGTH/2.0
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR

//A series of cylindrical cuts with radii increasing in units of the GFR's ES are made
through the GFR to promote uniform cylindrical meshing in this region.

$DO #RADIUS #GFR_ES #HOLE_DIAMETER/2.0-#GFR_ES #GFR_ES
CYLINDER Name='Cut' X0=0 Y0=0 Z0=0 X1=0 Y1=#BACKGROUND_HEIGHT Z1=0 +TUBE
SHAPECONTROL=TUBE MAJORRADIUS=#RADIUS MINORRADIUS=#RADIUS TOPRADIUS=#RADIUS THICKNESS=0
SIDES=2
PICK PROPERTY=UNIQUENAME LABEL='Background'
PICK PROPERTY=UNIQUENAME LABEL='Cut'
COMBINE OPERATION=SUBTRACT +REGULAR
$END DO

//The magnetic properties of the material "Steel" are defined. This magnet is made of
C1010 steel, and so the corresponding BH data, C1010.BH (or tenten.BH), is loaded. The
path to the BH data may need to be updated. The analysis type, TOSCA, is also specified.

MATERIALS PICK 'Steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='C1010'
BHDATA OPTION=EDIT LABEL=C1010
BHDATA OPTION=LOAD LABEL=C1010 FILE='/home/mbasso/Opera_Models/
Physical_Magnet_Modelling/Dipoles/4VB1/C1010.BH'
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=30
TOLERANCE=1.0E-7 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES

//The symmetry of the model is specified: xy-, yz-, and zx-plane reflection symmetry.
Finally, the model body is created and the model is given a surface mesh with a maximum
ES equal to that of the largest ES of any body in the model. The mesh shape is forced to
```

```
be mosaic to ensure regular meshing.

BACKGROUND OPTION=LOAD
BACKGROUND OPTION=SET SHAPE=TRIM XYSYMMETRYPLANE=YES YZSYMMETRYPLANE=YES ROTZNUM=1
ZXSYMMETRYPLANE=YES EMRXY=TANGMAGN EMRYZ=TANGMAGN EMRZX=NORMMAGN
MODEL CREATE
MESH SIZE=#BACKGROUND_ES NORMALTOL=30.0 SURFACETOL=0.0 TOLERANCE=1.0E-06 TYPE=MOSAIC

//At this point, one only needs to perform volume meshing and set up an analysis
database for the model prior to starting the TOSCA analysis.
```