

# Design of Electromagnetic Canting Magnets and a Hybrid Wiggler for Diamond-II Beamline Sources

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## Abstract

Diamond Light Source is the UK's national synchrotron facility providing high-brightness X-ray, ultraviolet and infrared beams for multidisciplinary scientific research. To continue delivering the world-changing science that Diamond enables, the facility is being upgraded. The ongoing Diamond-II upgrade [1] aims to enhance the facility's performance through a major upgrade of the accelerators together with the development of new beamlines and other upgrades.

This paper presents COMSOL Multiphysics® simulation studies of the canting magnets and hybrid wiggler required for the K14 and K18 beamlines. The K14 beamline requires a 116 mm period hybrid wiggler, a magnetic device used to generate a periodic static magnetic field along the electron beam, comprising permanent magnets and low-carbon steel poles, together with three canting magnets, which are used to provide the required horizontal beam offset and restore the electron beam to the nominal orbit. The K18 beamline requires three horizontal and three vertical canting magnets for beam separation and trajectory control.

The electromagnetic simulations of the canting magnets and hybrid wiggler have been carried out using the AC/DC Module of COMSOL Multiphysics®. Three-dimensional models of the magnetic devices including the yoke, poles, coils, permanent magnets and surrounding air region have been developed in COMSOL Multiphysics® to calculate the magnetic field distribution. Nonlinear magnetic properties of the iron components have been included, and coil excitations have been applied according to the magnet design requirements.

The magnetic field simulations have been used to determine the magnet design parameters required to meet the beamline specifications. The magnetic flux density distribution, peak field, and saturation behaviour have been evaluated for the proposed design configurations. The simulation results confirm that the proposed magnetic designs meet the required specifications of the K14 and K18 beamlines for the Diamond-II upgrade.

**Keywords:** COMSOL Multiphysics®, AC/DC Module, Magnetic Fields, Hybrid Wiggler, Canting Magnet, Synchrotron, Insertion Device

## Introduction

In synchrotron light sources, insertion devices and canting magnets operate under stringent requirements, where small variations in magnetic field can influence the electron beam trajectory and consequently affect the stability and quality of the generated photon beam. Three-dimensional electromagnetic simulations provide an effective approach for analyzing complex magnetic assemblies containing nonlinear magnetic materials, permanent magnets and current-carrying coils. Finite element electromagnetic modelling enables detailed evaluation of the magnetic flux distribution and saturation behaviour of magnetic components.

This work presents the electromagnetic design analysis of the K14 and K18 magnetic systems for the Diamond-II upgrade using COMSOL Multiphysics®. The simulations are used to evaluate the magnetic-field distribution and key design parameters of the proposed magnet configurations and to verify their compliance with the required

beamline specifications. The calculated magnetic fields are used to evaluate the electron-beam trajectory and radiation characteristics for both beamlines using SPECTRA [2].

## Magnetic Design Configuration

### K14 Hybrid Wiggler and Canting Magnets

The K14 beamline required photon energy range is 4-35 keV. The K14 beamline magnetic system consists of a hybrid wiggler and three electromagnetic canting magnets. Table 1 summarizes the key magnetic parameters, including the position, peak field, and deflection angles of the canting magnets and wiggler. The source must be canted by 5 mrad (1st chicane) for the beamline to fit onto the experimental hall floor. The angles required to return the beam to the nominal path in the space remaining in the mid-straight section are 18 mrad (2nd chicane) followed by 13 mrad (3rd chicane). The hybrid wiggler is designed with a magnetic period of 116 mm and contains 6.5 full periods, and a peak magnetic field of 1.3 T. The 116 mm period

was selected to reduce interference effects in the flux-energy spectrum. The number of full periods is constrained by the available space in the mid-straight after the required canting magnets have been accounted for. The overall physical length of the full magnetic assembly (wiggler + canting magnets) is 1938.5 mm. Figure 1 shows the 3D model of K14 chicane magnets and hybrid wiggler.

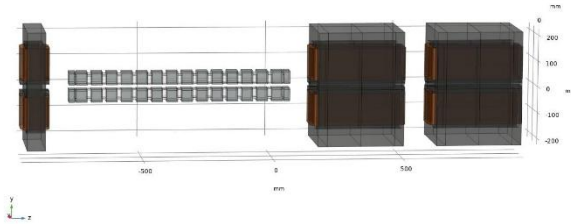


Figure 1. 3D model of K14 chicane magnet and hybrid wiggler

Table 1. Position, peak field and deflection angles for the canting magnets and wiggler

| Parameters                                         | Chicane 1 | Chicane 2 | Chicane 3 | Wiggler          |
|----------------------------------------------------|-----------|-----------|-----------|------------------|
| Longitudinal Position from centre of straight [mm] | -910      | 330       | 788.5     | -355             |
| Deflection angle [mrad]                            | 5         | 18        | 13        | N/A              |
| Peak field [T]                                     | 0.403     | 0.5408    | 0.3965    | 1.3              |
| Physical length including coils (z) [mm]           | 111       | 370       | 370       | 851              |
| Yoke length [mm]                                   | 62        | 330       | 330       | --               |
| Effective magnetic length [mm]                     | 145.1     | 392.1     | 392.55    | --               |
| Pole gap [mm]                                      | 26        | 14        | 14        | 16.7             |
| Pole material                                      | Soft iron | Soft iron | Soft iron | Low carbon steel |

### K18 3 Pole Wiggler and Canting Magnets

The K18 beamline required photon energy range is 2-35 keV. The K18 3 pole wiggler (3PW) beamline utilizes six fixed gap electromagnets. Figure 2 shows the layout of K18-3PW. There are three thicker magnets (H type) for vertical fields with a pole gap of 12 mm and three thinner magnets (V type) for horizontal fields with a pole gap of 50 mm to provide the required beam separation and trajectory control. Table 2 and Table 3 gives the positions, peak magnetic fields, and deflection angles for the H and V type magnets.

K18 will accept only photons from the radiator, that is the central pole of the 3PW, with a front-end aperture of 2.7 mrad (h) and 0.165 mrad (v). The K18 beamline will have two optical branches horizontally separated, and approximately 1 mrad of horizontal acceptance will be used to focus the beam at the sample position for each of the branches.

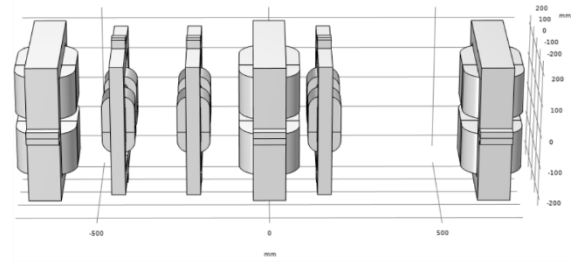


Figure 2. 3D model of K18-3PW

Table 2. Position, peak field, and deflection angle for the H magnets

| Magnet         | H magnet 1 | H Radiator | H magnet 2 |
|----------------|------------|------------|------------|
| Position [mm]  | -650       | 0          | + 650      |
| Angle [mrad]   | +4.08      | -8.16      | +4.08      |
| Peak field [T] | -0.678     | +1.4       | -0.678     |

Table 3. Position, peak field, and deflection angle for the V magnets

| Magnet         | V Chicane 1 | V Chicane 2 | V Chicane 3 |
|----------------|-------------|-------------|-------------|
| Position [mm]  | -438        | -220        | + 160       |
| Angle [mrad]   | -0.874      | 1.411       | -0.537      |
| Peak field [T] | -0.114      | +0.182      | -0.067      |

The total physical thickness including the coils for the H-magnets is 176.20 mm and for the V-magnets is 95.15 mm. The overall physical length of 3PW is 1476.2 mm.

### Numerical Model and Simulation Method

Three-dimensional finite-element simulations of the K14 and K18 magnetic assemblies were performed in COMSOL Multiphysics® using the Magnetic Fields (mf) interface of the AC/DC Module. A stationary formulation was used to obtain the magnetostatic field solution, governed by

$$\nabla \times H = J \text{ and } \nabla \cdot B = 0.$$

Nonlinear B-H characteristics were assigned to ferromagnetic components to account for their field-dependent magnetic response.

### K14 Magnetic Model

The K14 hybrid wiggler comprises soft-iron yokes and poles in the canting magnets, low-carbon-steel poles in the wiggler, and NdFeB permanent magnets. The permanent magnets were modelled using the

Permanent Magnet feature, with the magnetization vector specified according to the required magnetic configuration. The excitation windings were modelled using the Homogenized Multi-Turn Coil feature with Numeric excitation. The coil current  $I$  was calculated from the current density  $J$  and coil cross-sectional area  $A$ . The magnetic structure was enclosed by air domains, with magnetic insulation applied at the external boundaries. Ampère's Law in Solids was used for the solid magnetic regions. A geometry-dependent mesh was employed, using Swept and Free Quad elements in suitable regions and tetrahedral elements elsewhere, with local refinement in the beam gap, pole regions, and regions with strong magnetic-field gradients.

### K18 Magnetic Model

The K18 three-pole wiggler consists of iron yokes and poles, except for the H2 radiator, which uses a cobalt–steel–vanadium pole to achieve the required bending angle and magnetic-field strength. The excitation windings were modelled using the Homogenized Multi-Turn Coil feature with Numeric excitation. The coil current  $I$  was calculated from the current density  $J$  and coil cross-sectional area  $A$ . Ampère's Law in Solids was used for the solid magnetic regions, and the model was enclosed by air domains with magnetic insulation at the external boundaries.

A mirror symmetry was exploited to reduce the K18 computational domain, with a Perfect Magnetic Conductor boundary condition applied on the corresponding symmetry plane. The K18 model was discretized using tetrahedral elements, with local mesh refinement in the beam gap, pole regions, and other regions with strong magnetic-field gradients.

## Simulation Results and Discussion

### K14 Hybrid wiggler and Canting Magnets Magnetic Field Distribution

The geometry parameters, longitudinal positions of the magnets and wiggler, pole gap, and excitation current were varied iteratively in COMSOL to optimize the magnetic-field distribution. The resulting magnetic field profile and electron beam trajectory were evaluated for each configuration, and the final design was selected based on the required magnetic field strength, field profile, and electron-beam bending angle. The nonlinear magnetic response of the iron components was included in the simulation to identify regions approaching saturation. Magnetic flux density distribution calculated from COMSOL is shown in the Figure 3. The calculated on-axis field profile for the complete K14 magnetic assembly is shown in Figure 4. The corresponding electron beam angle and electron

beam position are shown in Figure 5 and Figure 6, respectively, demonstrating the required beam deflection and recovery to the nominal trajectory. The resulting magnetic-field profile was subsequently used to calculate the power density and partial photon flux shown in Figure 7 and Figure 8. Table 4 shows the required electrical and cooling parameters for the K14 second (18mrad) and third (13 mrad) chicane magnets.

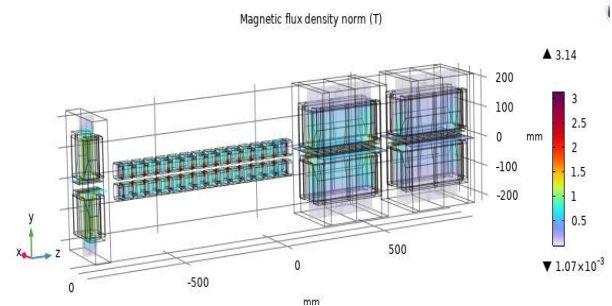


Figure 3. Magnetic flux density for K14

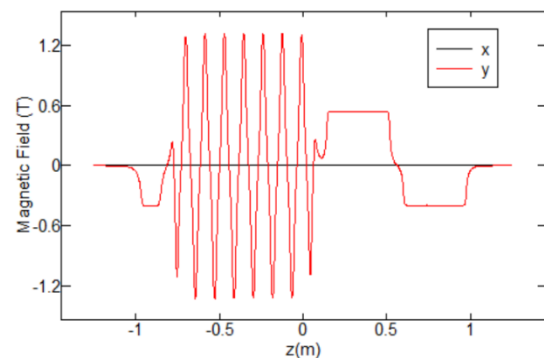


Figure 4. Full field profile for the wiggler and chicane magnets for K14

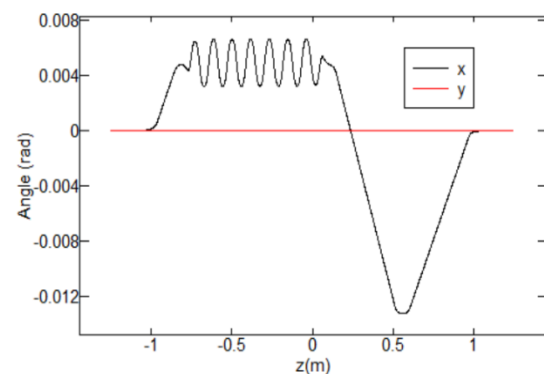


Figure 5. Electron beam angle through the wiggler and canting magnets for K14

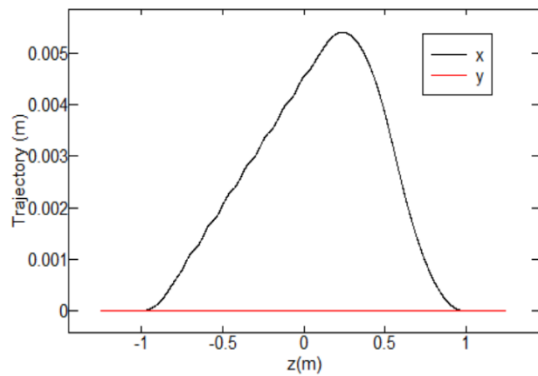


Figure 6. Electron beam position through the wiggler and chicane magnets

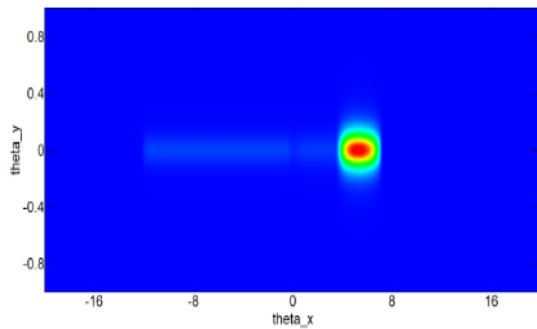


Figure 7. Power density calculated using SPECTRA for the wiggler and canting magnets for K14

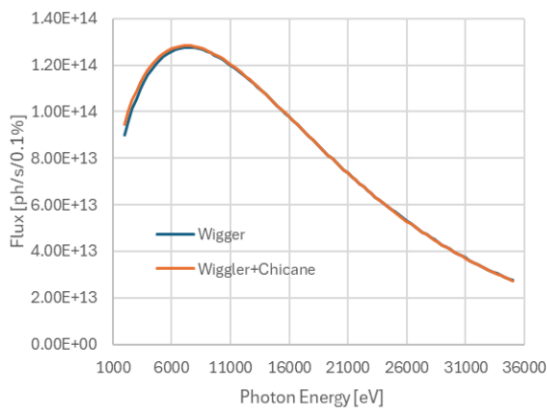


Figure 8. Partial flux calculated from SPECTRA, aperture 1 mrad x 0.126 mrad, distance 10m.

Table 4. Electrical and cooling parameters for K14 canting magnets\*

| Parameters [unit]                    | Chicane 2 | Chicane 3 |
|--------------------------------------|-----------|-----------|
| Current density [A/mm <sup>2</sup> ] | 3.81      | 2.81      |
| Nominal current [A]                  | 39.1      | 28.8      |
| Temperature change max [°C]          | 10        | 10        |
| Pressure drop <sub>max</sub> [bar]   | 6         | 6         |
| Total flow rate [L/min]              | 0.56      | 0.55      |
| Water speed [m/s]                    | 0.95      | 0.95      |
| Copper conductor size [mm x mm]      | 4 x 4     | 4 x 4     |
| Hollow diameter [mm]                 | 2.5       | 2.5       |
| Round edge [mm]                      | 1         | 1         |
| Voltage [V]                          | 10.3      | 7.6       |
| Number of turns per coil             | 79        | 79        |
| Total heat load per magnet [Watt]    | 401.1     | 217.1     |

\* First chicane magnets will be used from Diamond existing stock, so there are no design parameters shown here for the first chicane magnet.

### K18 3 pole wiggler

The geometry parameters, longitudinal positions of the magnets, pole gap, and excitation current were varied iteratively in COMSOL to optimize the magnetic-field distribution. The resulting magnetic field profile and electron beam trajectory were evaluated for each configuration, and the final design was selected based on the required magnetic field strength, field profile, and electron-beam bending angle. The nonlinear magnetic response of the iron components was included in the simulation to identify regions approaching saturation.

Magnetic flux density distribution for H-type magnets calculated from COMSOL is shown in the Figure 9. The calculated on-axis magnetic-field profile for the K18 3PW is shown in Figure 10. The corresponding electron beam angle and electron beam position are shown in Figure 11 and Figure 12. The calculated magnetic field profile was used to obtain power density and partial flux distributions shown in Figure 13 and Figure 14. The electrical and cooling parameters for the strongest magnets of each type are listed in Table 5.

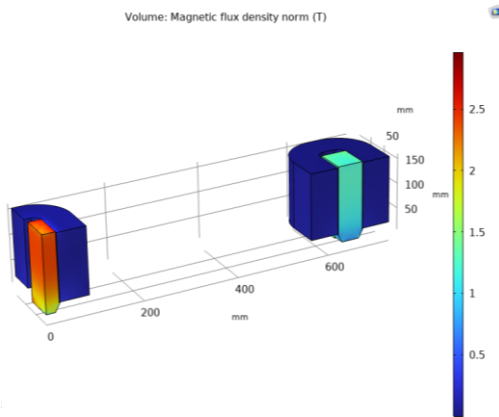


Figure 9 Magnetic flux density for K18 H-type magnets (1/8<sup>th</sup>) geometry

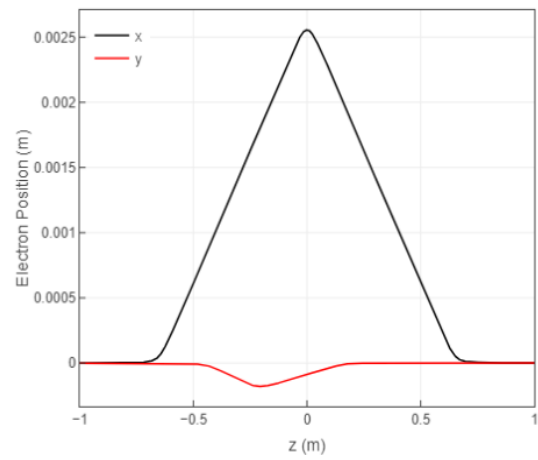


Figure 12. Electron beam position for the K18 3PW

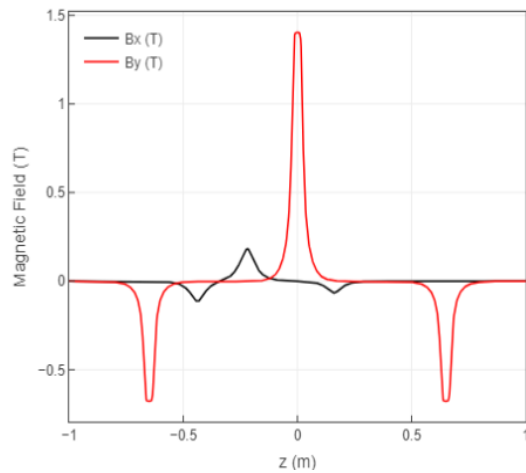


Figure 10. Full field profile for the K18 3PW

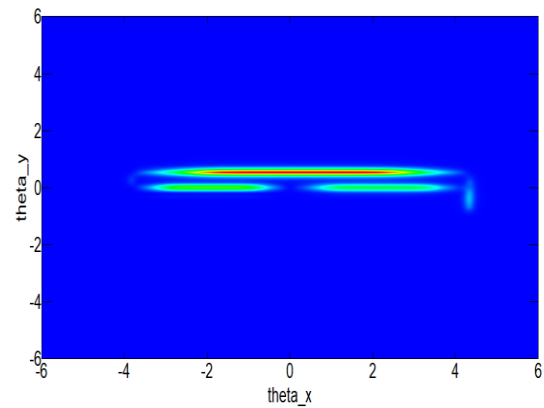


Figure 13. Power density profile for K18 3PW

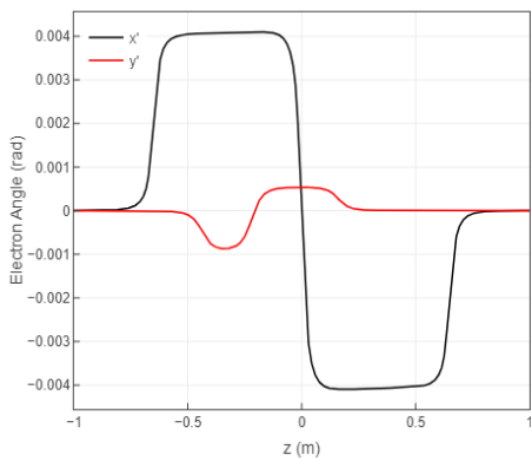


Figure 11. Electron beam angle for the K18 3PW

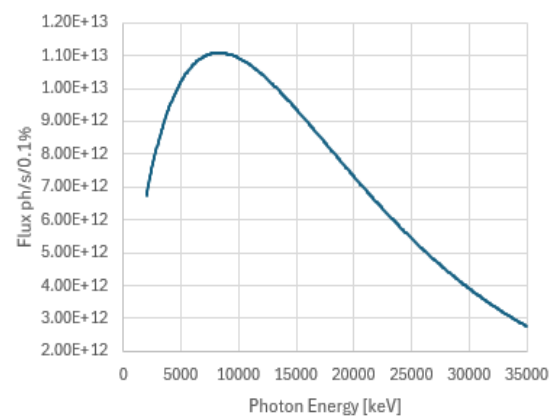


Figure 14. Partial flux after 1 mrad (H) x 0.165 mrad (V) aperture located at -0.7 mrad horizontal offset and 0.537 mrad vertical offset, distance 10m.

*Table 5. Electrical and cooling parameters for strongest magnets of each type for K18 3PW.*

| Parameters [unit]                    | Strongest H<br>-magnet<br>(radiator) | Strongest V<br>-magnet<br>(Chicane 2) |
|--------------------------------------|--------------------------------------|---------------------------------------|
| Current density [A/mm <sup>2</sup> ] | 2.99                                 | 3.11                                  |
| Nominal current [A]                  | 67.6                                 | 59.8                                  |
| Temperature change max [°C]          | 10                                   | 10                                    |
| Pressure drop max [bar]              | 6                                    | 6                                     |
| Water speed [m/s]                    | 1                                    | 1.56                                  |
| Copper conductor size [m<br>m x mm]  | 6 x 6                                | 5 x 5                                 |
| Hollow diameter [mm]                 | 4                                    | 2.5                                   |
| Round edge [mm]                      | 1                                    | 1                                     |
| Voltage [V]                          | 12.7                                 | 3.3                                   |
| Number of turns                      | 198                                  | 75                                    |

## Conclusions

The simulation results confirm the suitability of the proposed K14 and K18 magnetic design for the Diamond-II upgrade. The calculated magnetic fields and corresponding electron trajectories satisfy the beamline requirements for the specified deflection angles and peak fields. The resulting fields were also used to evaluate the photon power density and partial flux. The COMSOL results were found to be consistent with the results obtained using OPERA [3] and RADIA [4] for the Diamond existing magnets. This provided confidence in the model, which was subsequently used for the development and optimisation of the final magnetic design for K14 and K18.

## References

- [1] Diamond-II Technical Design Report, 2022.
- [2] T Tanaka, H Kitamura, "SPECTRA: a synchrotron radiation calculation code", Journal of Synchrotron Radiation, pp. 1221-1228, 2001.
- [3] <https://www.3ds.com/products/simulia/opera>
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