Conceptual and technical design of a 3PW photon source for the BEATs beamline at SESAME synchrotron

Abstract

In this report we describe the magnetic design of a 3PW along with the tolerances, magnet types and other magnetic elements needed in order to be tendered.

Please note: Mechanics, motors, motor controllers and controls in general are not included in this document because they have to submit to SESAME standards, and therefore have to be prepared by SESAME responsible

Prepared by: J. Campmany	*Checked by:*	*Approved by:*
Authorship: J. Campmany		

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Draft 0.0	29/03/2019	all	Initial release
Rev. 1.0	15/06/2019	3-16	New model to reduce decapole
Rev. 2.0	16/07/2019	3-16	New model to reduce the forces

TABLE OF CONTENTS

References

[1] J. Campmany, *Photon source for the BEATS beam line at SESAME. Options to be considered*, ALBA document AAD-IDBEATS-A-001.

[2] RADIA, by O. Chubar, P. Elleaume, J. Chavanne: open code for magnetic calculations: http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia

[3] SPECTRA, by Takashi Tanaka: open code for synchrotron radiation calculations: http://spectrax.org/spectra/

1. Introduction

In a previous report we presented three possible options as photon source for BEATs at SESAME accelerator.[1] After the meeting hold on March 12^{th}-13^{th}, a decision was taken: the photon source will be an out-vacuum 3-pole wiggler, with a maximum field of 3 T.

In this report we present the conceptual magnetic design of the 3-pole wiggler to be installed at SESAME for the BEATS beamline, as well as the technical specifications for magnets and iron to be used. The main design constraints considered for the model are:

- Minimum gap: 11 mm
- Maximum field: ~3 T
- Magnetic length: < 1 m.
- Spectral range achieved with flux > 10^{11}: 20-50 keV

2. Conceptual model

Magnetic model has been generated using RADIA code, taking into account the parameters given in the introduction.[2] Model is refined to reduce the decapole multipole and the forces involved. The model is shown in Figure 1 below. New model allowed reducing B_r down to 1.28 T, thus making the magnetic material procurement easiest and cheaper. Peak field is 3.0025 T.

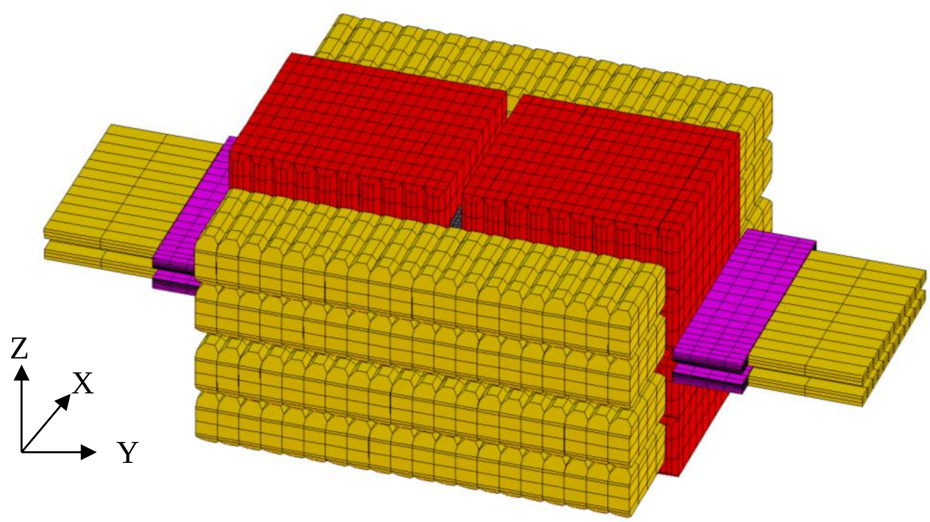

Figure 1. Axis definition and magnetic model generated by RADIA. Red and yellow parts are NdFeB magnets. Pink parts are iron poles (there is another iron pole –grey– in the center). Overall length is 0.755 m, overall width is 0. 400 m, overall height is 0.331 m and minimum gap is 11 mm.

With this new improved design, we obtain three benefits:

a) The magnetic force is compensated and decreased to a very low value (~150 kg)

b) The magnetic field is concentrated in the central part and, as a consequence, the central field is enhanced. Therefore, we can made the device using magnetic materials with lower remanence (B_r ~ 1.28 T) and higher coercitivity than those used in the first version.

c) Side blocks are no more needed.

In Figure 2 we show the field lines in the gap of the insertion device.

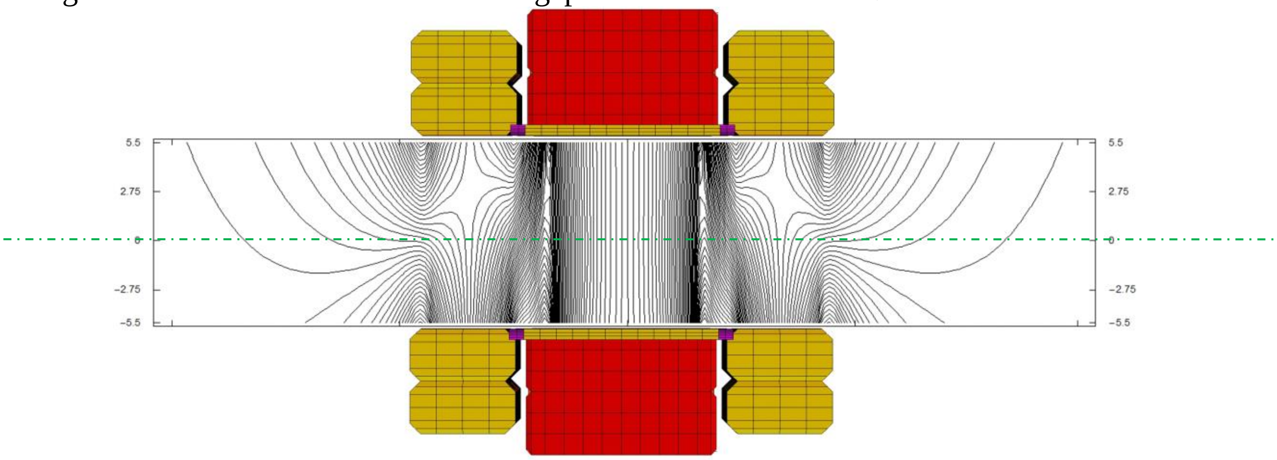

Figure 2. Magnetic field lines within the gap at longitudinal position Y=0.

In order to optimize the design, we have assumed that the mechanical tolerances of magnetic blocks and iron poles in longitudinal axis are ±0.020 mm. This means that the void (also referred as "air gap") left between blocks and poles to allow tolerances should be 20 microns. (Figure 3).

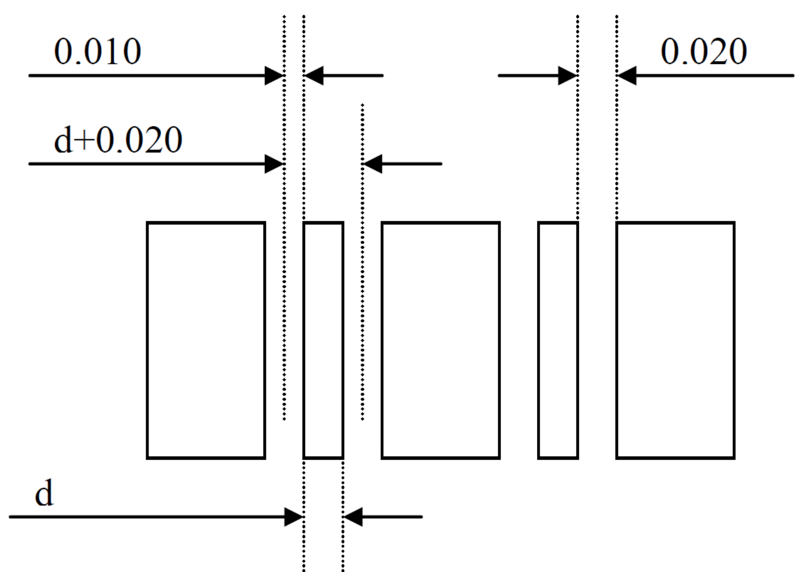

Figure 3. Schematics of pole / block arrangement and airgaps left for tolerances

All permanent magnets are made with the same material and with the remnant field B_r = 1.28 T Magnetization orientation is as shown in Figure 4 below.

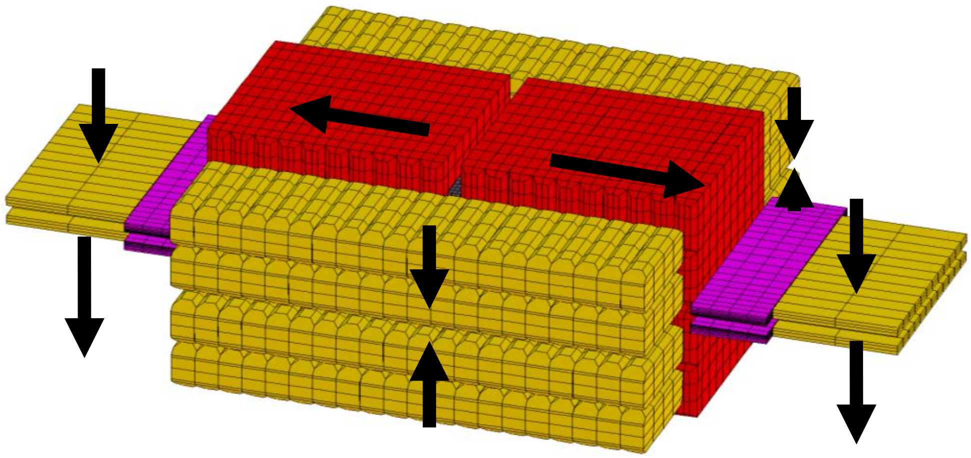

Figure 4. Magnetization directions in the assembly of 3PW.

Design has been optimized to obtain a low field first integral, low force and low decapole. Table 1 presents the longitudinal position and sizes of each block

Table 1. Description of the magnetic arrangement

Position (mm)	Magnetic structure	Length (mm)	B_r orientation
-377.5	Edge block	105	(0,0,-1) top and bottom
-272.5	Air gap	0.5	-
-272.0	Iron (permendur)	64	-
-208.0	Air gap	0.5	-
-207.5	10 magnetic blocks	200	(0,-1,0) top (0,1,0) bottom
-7.5	2 Side blocks	15	(1,0,0) and (-1,0,0)
-7.5	Iron (permendur)	15	-
7.5	10 magnetic blocks	200	(0,1,0) top (0,-1,0) bottom
207.5	Air gap	0.5	-
208.0	Iron (permendur)	64	-
272.0	Air gap	0.5	-
272.5	Edge block	105	(0,0,-1) top and bottom
377.5	End of device	-	-
-50.0	20 Lateral blocks	400	(0,0,±1) opposite top and bottom

Magnetic field is shown: along axis in Figure 5 and along transversal axis (roll-off) in Figure 6.

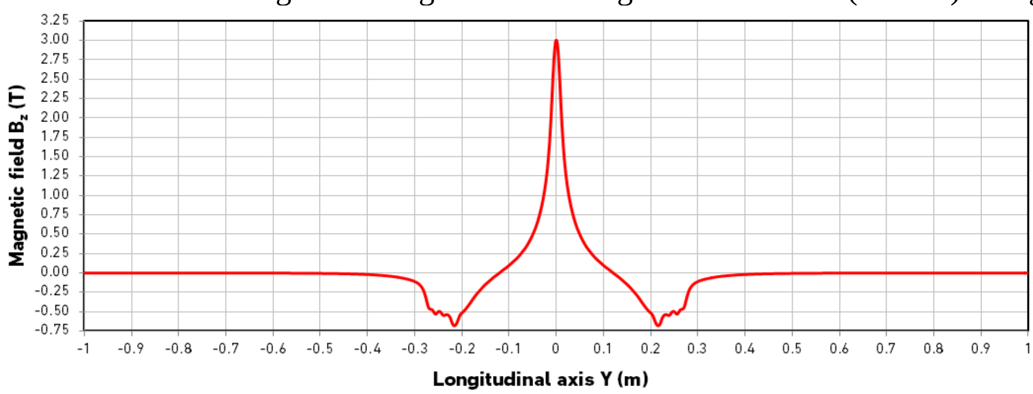

Figure 5. Magnetic field B_z on axis.

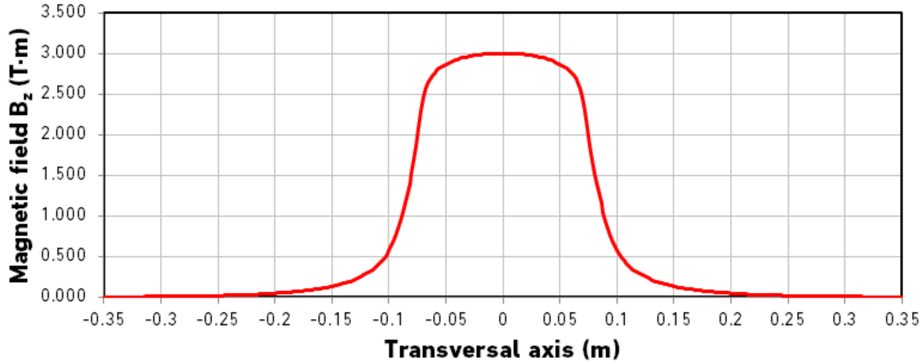

Figure 6. Magnetic field B_z along transversal axis.

The 3D field-map on symmetry plane is presented in Figure 7. Peak field is 3.0025 T

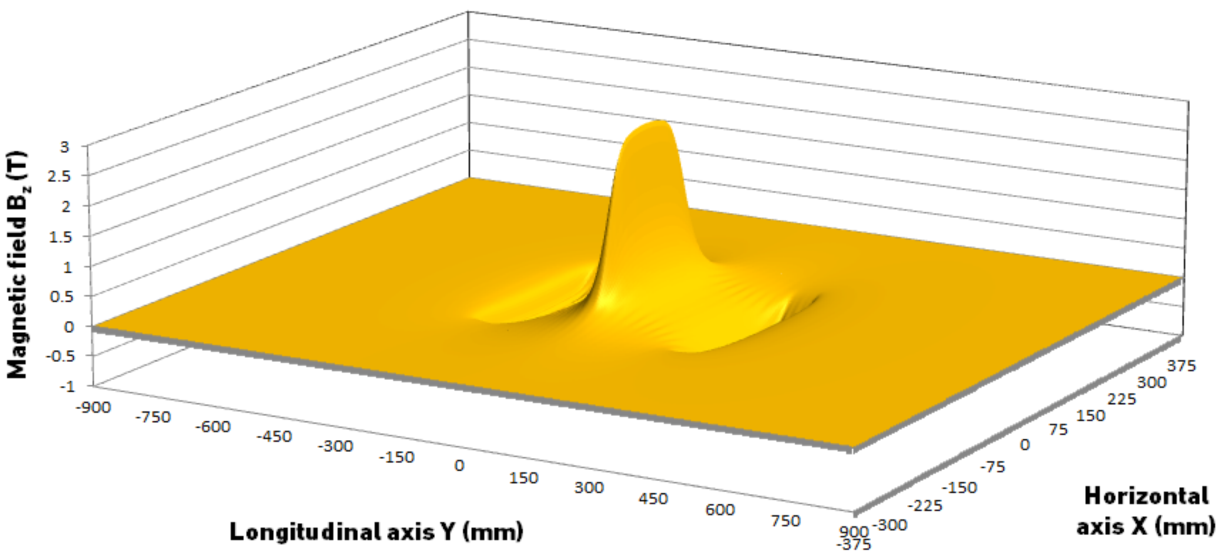

Figure 7. 3D Map of vertical field B_z in the 3-pole wiggler.

Computed velocity and electron trajectory is shown in Figures 8 and 9 below.

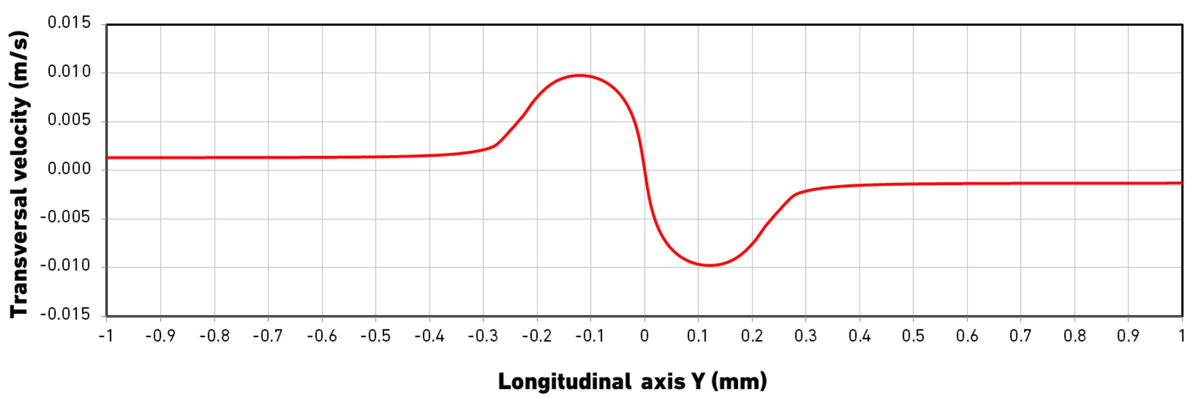

Figure 8. Map of transversal velocity of electrons along the 3-pole-wiggler.

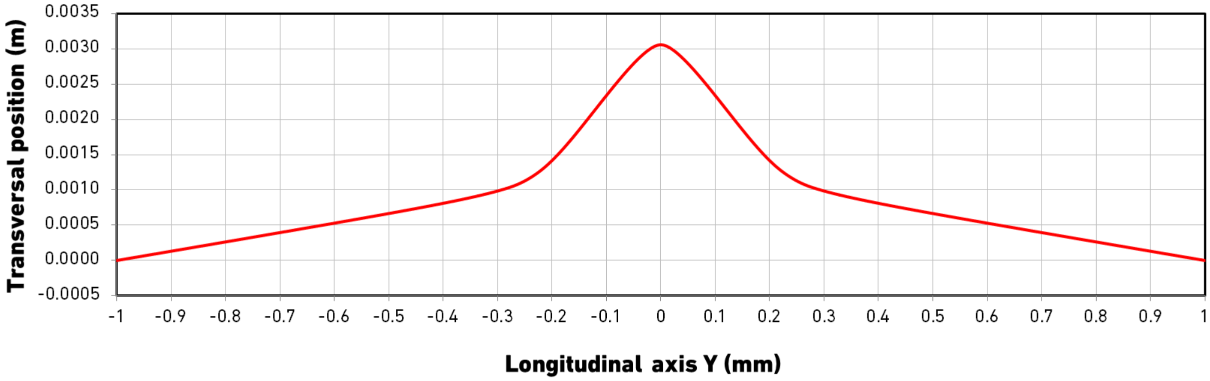

Figure 9. Map of transversal excursion of electrons along the 3-pole-wiggler.

Maximum excursion of electrons is 3.0 mm off axis, so the beamline should be aligned according to the transversal position of the photon source, and not with respect the straight section axis.

3. Effect on machine dynamics

Such a device placed in a straight section has two type of effects:

- At first order, the effect on the electron orbit is given by 1st and 2nd integrals. This effect has been minimized in our design and, if necessary, can be corrected afterwards with correction coils or magic fingers. This last option is recommended only in the case of fixed-gap operation. Correction coils will be needed if the operation of the device is at different gaps. Details are given in section 4 below

- A second order effect coming from electrons that does not follow the nominal trajectory. Given the fact that the electron beam has a size, and therefore an extension in transveral directions, these effect should be evaluated. This is done through the so-called kickmaps, that represent in a 2D matrix the kicks received by electrons placed out of nominal trajectory. This is computed in section 5 below.

4. First order effects: multipoles

The multipolar content of the 3-pole-wiggler has been computed from fieldmap. Field integral along transversal axis is shown in Figure 10 below and the fitting to find high order multipolar components is shown in Figure 11.

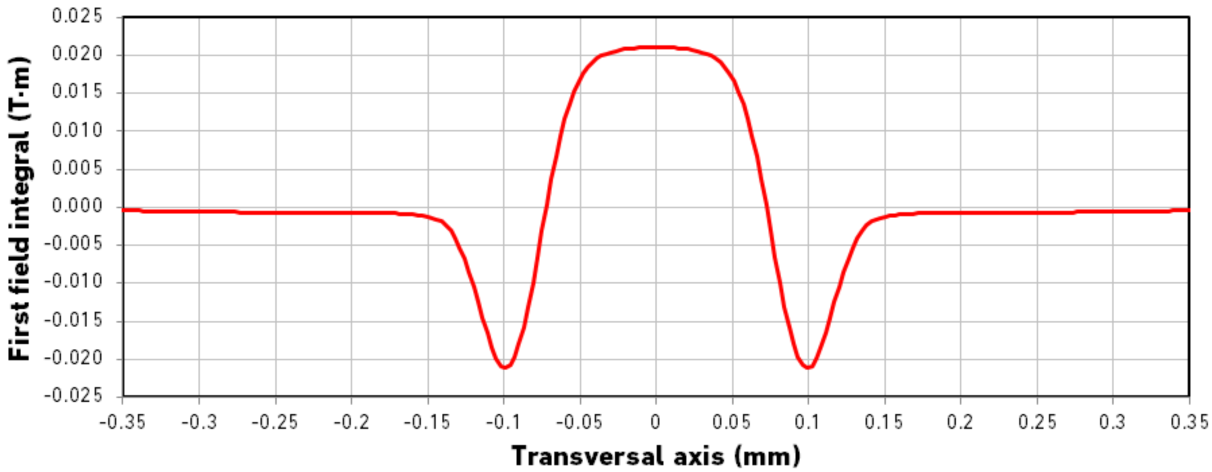

Figure 10. Field integral of the proposed 3-pole-wiggler along transversal axis

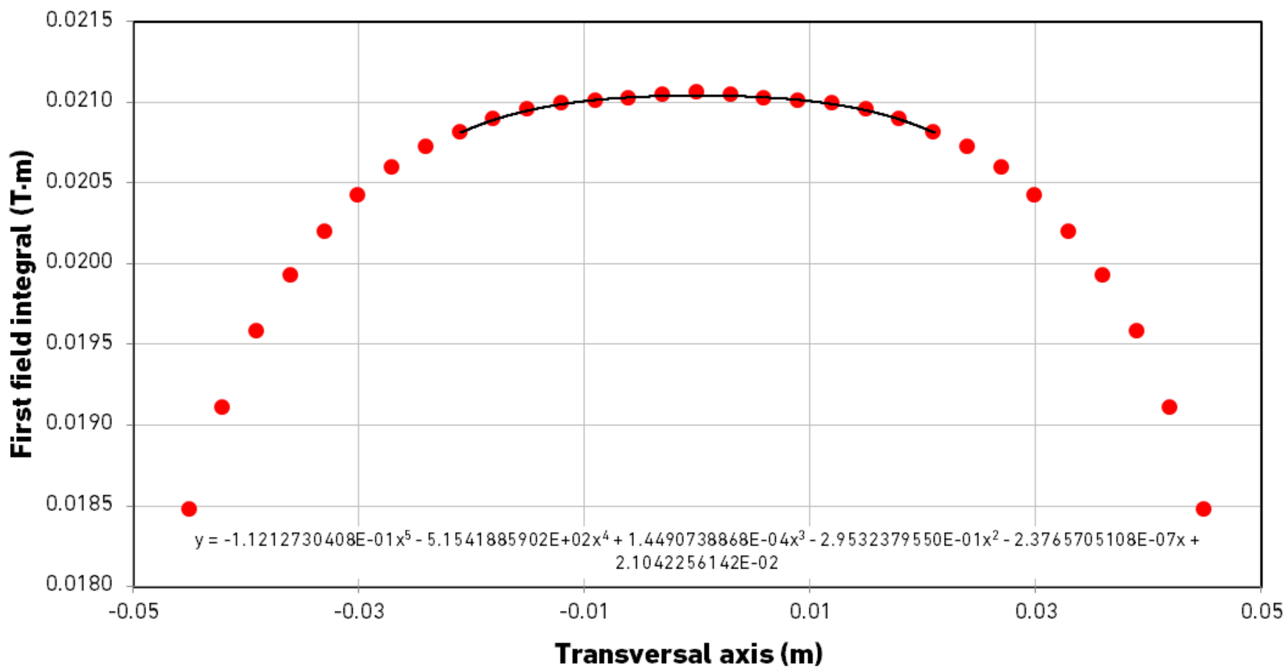

Figure 11. Field integral of the proposed 3-pole-wiggler along transversal axis in the range ±50 mm and multipole fitting in the range ±20 mm

Table 2. Multipolar component of field generated by 3-pole-wiggler

Multipole	Value
Dipole	$+2.1042 \cdot 10^{-02}$ T·m
Quadrupole	$-2.3765 \cdot 10^{-07}$ T
Sextupole	$-2.9532 \cdot 10^{-01}$ T/m
Octupole	$+1.4491 \cdot 10^{-04}$ T/m^2
Decapole	$-5.1542 \cdot 10^{+02}$ T/m^3
Dodecapole	$- 1.1213 \cdot 10^{-01}$ T/m^4

5. Second order effects: Kickmaps

We have computed the kick maps using RADIA code. Results are shown in figures 12 & 13.

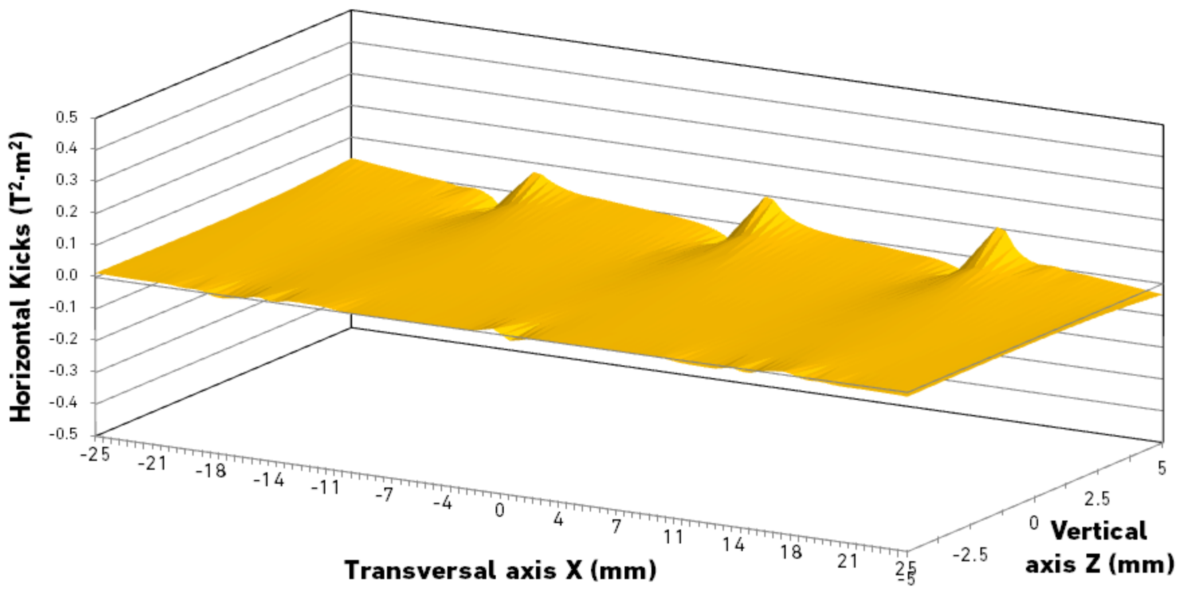

Figure 12. Horizontal kickmap.

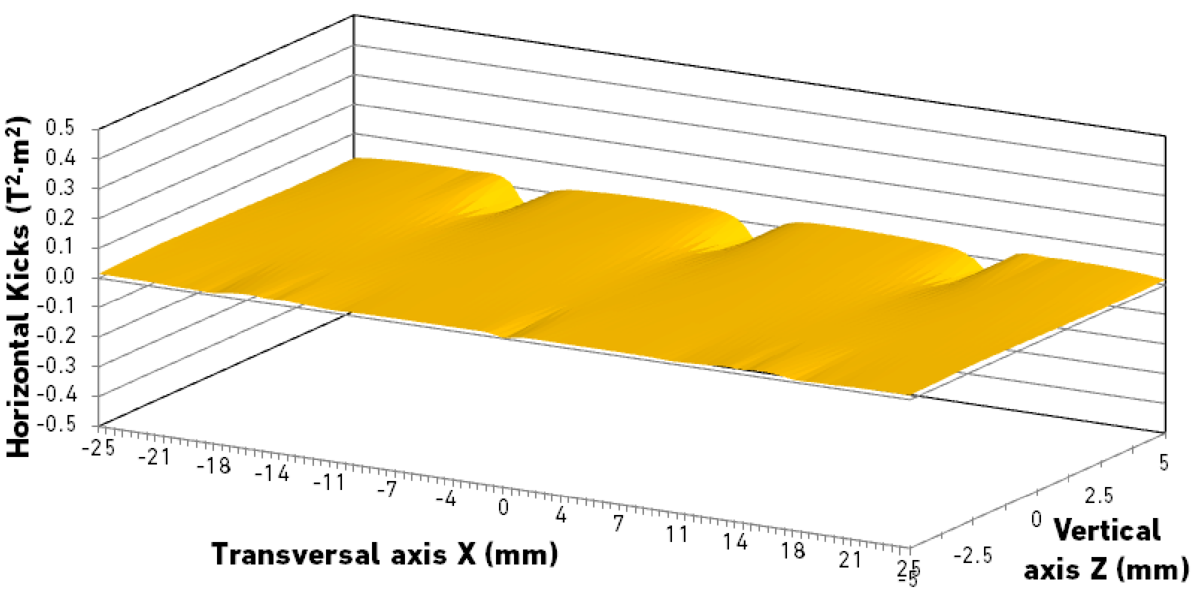

Figure 13. Vertical kickmap.

6. Force

Maximum force is produced at minimum gap. In this case, the overall force between both magnetic arrays is 1245.22 N, this is **126.934 kg**.

7. Demagnetizing fields

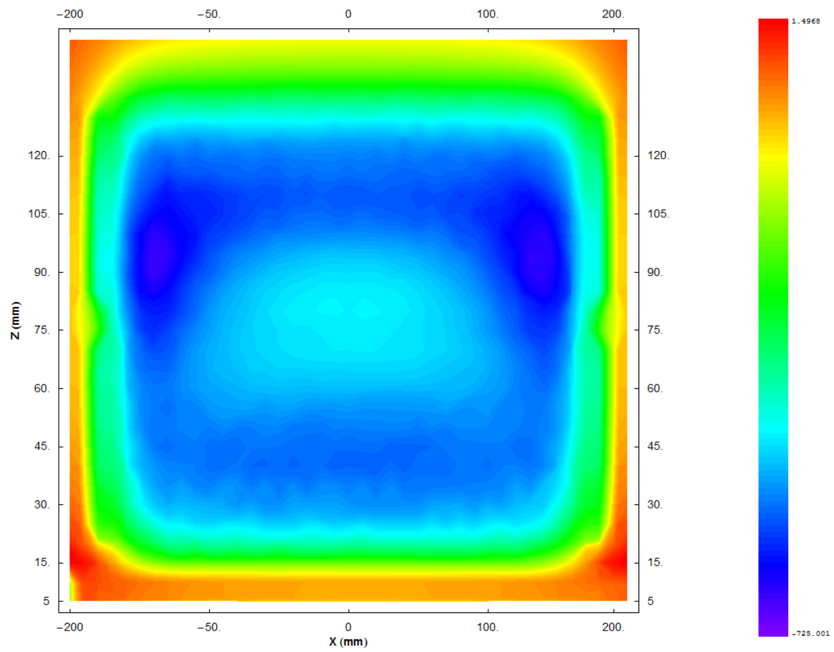

Figure 14. Demanetizing field at Central block. Maximum demagnetizing is -725 kA/m

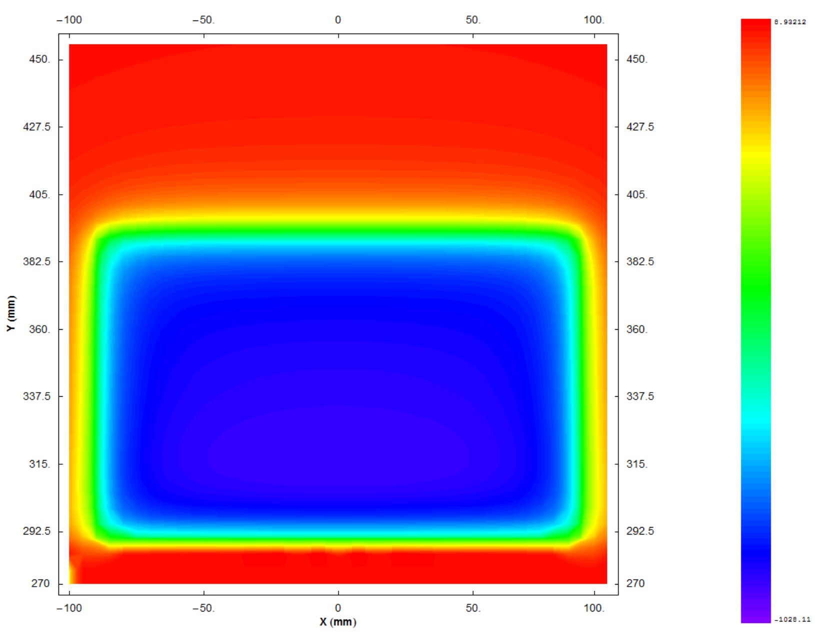

Figure 16. Demanetizing field at Edge block. Maximum demagnetizing is -1028 kA/m

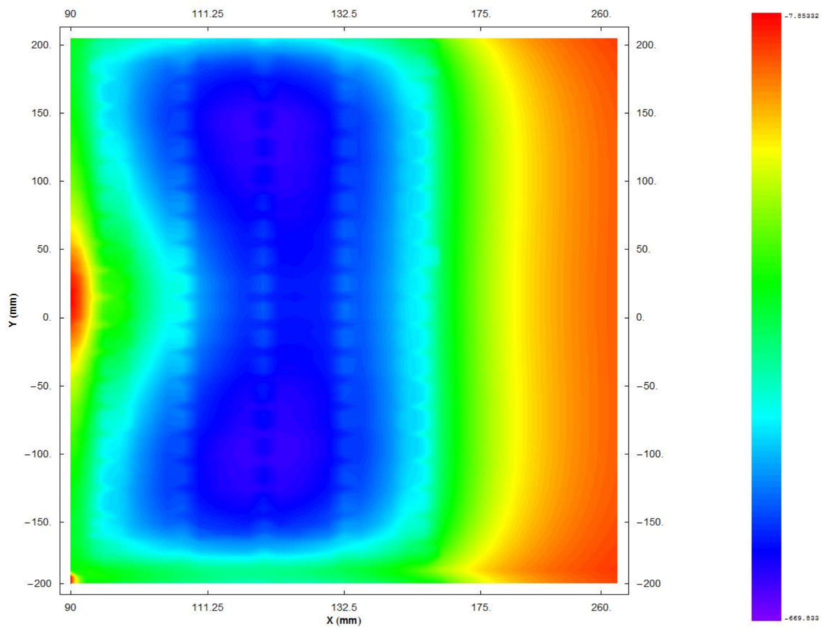

Figure 17. Demanetizing field at Edge block. Maximum demagnetizing is - 669.8 kA/m

8. Tolerances

Errors in the magnetic field related to errors in the magnetization of the magnet elements (hereinafter referred to as magnet blocks) act to perturb the uniformity of the electron orbit. A non-periodic orbit degrades the quality of the emission spectrum and disturbs the SR closed orbit.

8.1. Block Quantities

The 3-pole-wiggler will have 88 magnets and 6 iron poles. An additional quantity increase of 20 percent with respect to the quantity needed to perform tests and and to reduce errors due to homogeneity by block sorting is advised. Table 3 summarizes the total quantities of each magnet type.

8.2. Magnet Geometry and Dimensioning Tolerances

Type	Quantity	Length (mm)	Width (mm)	Height (mm)	Tolerance (mm)
Central pole	2+2	15	150	80	0-0.020
Side blocks	4-2	15	150	120	0-0.020
Central Block	80+16	20	180	60	0-0.020
Edge Block	4+2	64	180	10	0-0.020
Edge Pole	4+2	105	180	10	0-0.020
Lateral Block	160+32	20	100	50	0-0.020

8.3. Block and pole shapes

The specification includes magnet blocks of different shapes. The geometry and magnetization of each type of magnet block is given in the next Figures 18 to 23.

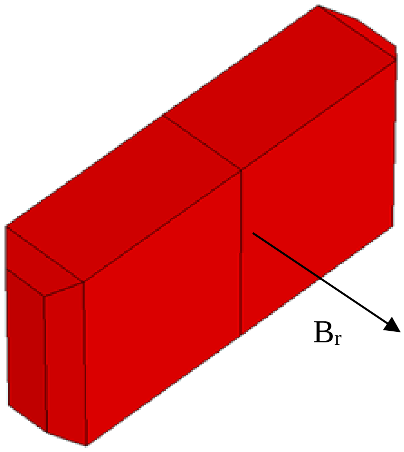

Figure 18. Main block. 180 mm wide, 60 mm high, 20 mm thick. Easy axis is oriented perpendicularly to width-height plane, as shown in the drawing. Edge cuts are 3 mm and 45°

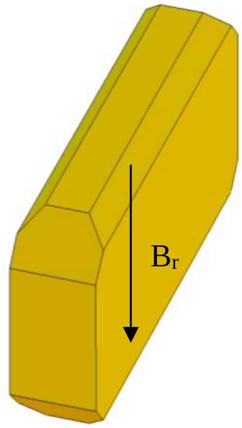

Figure 19. Lateral block, 100 mm wide, 50 mm high, 20 mm thick. Easy axis is perpendicular to thin upper side.

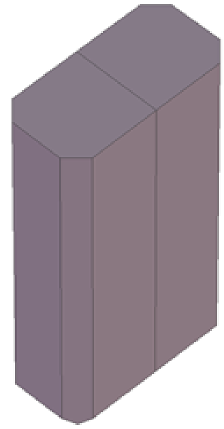

Figure 20. Central pole. 150 mm wide, 80 mm high, 15 mm long. Edge cuts are 3 mm and 45°

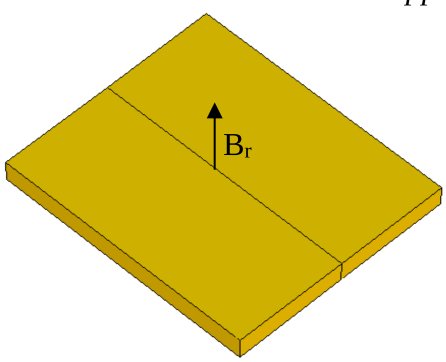

Figure 22. Edge block. 105 mm long, 180 mm wide and 10 mm thick. Easy axis perpendicular to length-width plane. Field should point towards opposite direction of the main structure field.

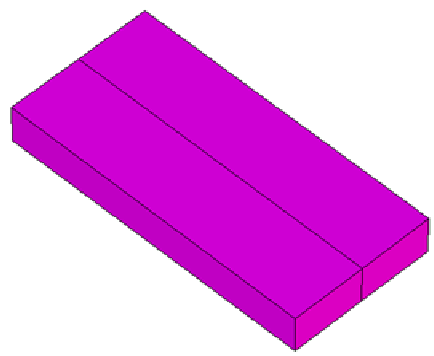

Figure 23. Edge pole. 64 mm long, 180 mm wide and 10 mm high

8.4. Taper Angle

From the point of view of light production, taper is not an issue, because the main emission is concentrated in central pole. However, regarding mechanics and machine dynamics, a taper could damage the vacuum chamber of the Storage Ring and/or introduce unexpected effects in beam dynamics. To this end, we recommend to fix a tolerance for taper angle of 0.5 mrad. Given that the force changes with gap, the tolerance should apply at miminum gap.

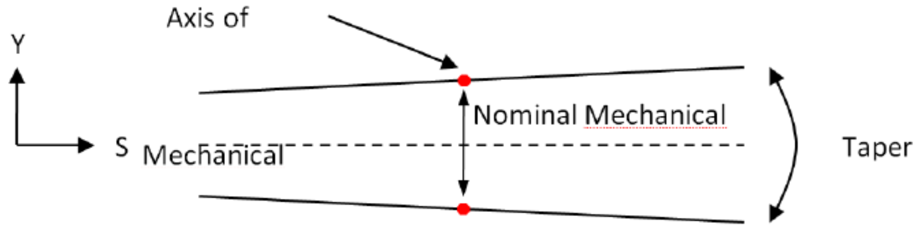

Figure 24. Schematic representation of taper. S vector points in the beam direction.

8.5. Roll Angle of the Gap

It is assumed that the rotation of the individual beams about the S-axis is equal in magnitude but opposite in direction, as shown in Figure 21. The roll angle of the beams shall better than 0.050 mrad in order to avoid additional multipolar components perturbing the electron beam dynamics.

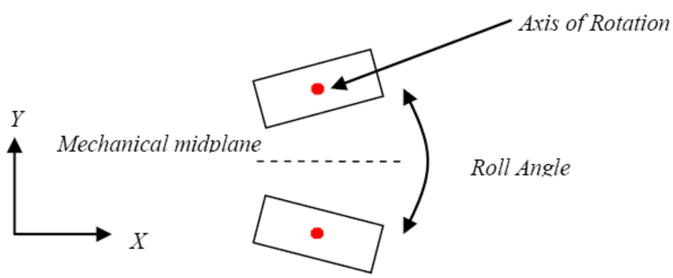

Figure 25: Schematic illustration of roll angle. X is horizontal transversal axis

9. Magnetic block characteristics

9.1. Manufacturing Process

At present, the method of transverse die pressing, application of the polarizing field in a direction perpendicular to the pressing direction produces blocks with the highest homogeneity and minimum error in the geometric alignment of the average dipole moment. The method of transverse die pressing shall be applied to all blocks such that the blocks achieve the highest remanence possible for the material specification whilst maintaining the specified material coercivity, minimum alignment error of the average dipole moment, and a maximum uniformity of the magnetic material.

9.2. Magnetic material

Magnetic structure is hybrid. Magnetic material is high grade NdFeB alloy with a remanent field of 1.28 T and coercivity no less than 1250 kA/m. These values are given, for instance, by VACODYM 633 TP from Vacuumschmelze, or 40 UH from Kyma. Iron poles should be made of Permendur.

9.3. Magnet Identification

Each magnet shall be inscribed with a magnet identifier, followed by a serial number. **<u>The magnetization orientation will be inscribed on each magnet and must be clearly visible</u>**.

9.4. Remanent Strength of Magnet Blocks

The material used for the magnet blocks will be NdFeB. The magnetic remanence shall be precisely parallel to their respective nominal easy axis for all types of blocks and not be less than 1.28 T.

9.5. Average Magnetization of Magnet Blocks

An open circuit model of the specified magnet block geometry on a B-H curve places the block not at H=0 but slightly off axis along the demagnetization curve. Therefore, the average dipole moment is expected to be less than the value of the remanence specified in 9.4. The supplier shall confirm the theoretical average magnetization of each block. The theoretical average block magnetizations shall be the average minimum magnetization for each block. Based on a recoil permeability of 1.05, dB/dH and a magnetic remanence of 1.28 T, all blocks shall have an average magnetization no less than 1050 kA/m ($\mu_0 \cdot M > 1.28$ T)

9.6. Tolerance in Error of Magnetization Strength

From a set of manufactured magnet blocks the absolute difference in magnetization from block to block of a particular type shall be less than 1.5 % for the average of the set.

9.7. Tolerance in Error of Magnetisation Direction

Each block shall have a magnetization vector that is parallel to the direction defined in their respective drawing. The maximum tolerable deviation angle is 1.5 degrees.

9.8. Intrinsic Coercivity

For this device the maximum coercive field has been calculated to be ~1028 $kA \cdot m^{-1}$ therefore we require the intrinsic coercivity of each magnet block shall not be less than 1050 kA/m at 20ºC. We therefore require the magnetic material to be in its linear region of the demagnetization curve and will not experience any irreversible losses during assembly and operation.

9.9. Segmentation of Permanent Magnet Blocks

3-pole-wiggler should not be built by gluing individual magnet blocks. Mechanical clamps attaching the blocks and poles to holder are required.

9.10. Magnet Block Coating

All the magnet blocks should be coated with an material protecting them from scratches and erosion. Aluminium layer by vapor deposition, or other similar materials should be used. In any case, the coating thickness shall be less than or equal to but no greater than 0.010-0.015 mm. The coating thickness should be clearly mentioned in the offer. No observable surface defects will be tolerated (e.g. bubbles, holes, cracks, chips, loose particles, dog bones).

9.11. Magnet Block Cleaning

Considering the magnet production, the following steps will be respected:

- Before the coating, all the blocks will be carefully degreased by using a cleaner and/or slightly etched by an acid (+ drying). The detailed process must be described by the manufacturer.
- For the magnetization process, the necessary tools will be cleaned with a solvent, or the magnets will be kept in their polyethelene bags

After the magnet coating is applied, it must never come in contact with oil or grease. They must be handled with latex gloves to avoid touching with barehands and leaving finger prints.

9.12. Radiation Resistance

The permanent magnets shall be radiation resistant.

10. Spectrum produced by 3-pole-wiggler

Emission spectrum has been computed using SPECTRA code.[3] We assumed an aperture of 4 mrad H x 1 mrad V, so the flux in Figure 26.

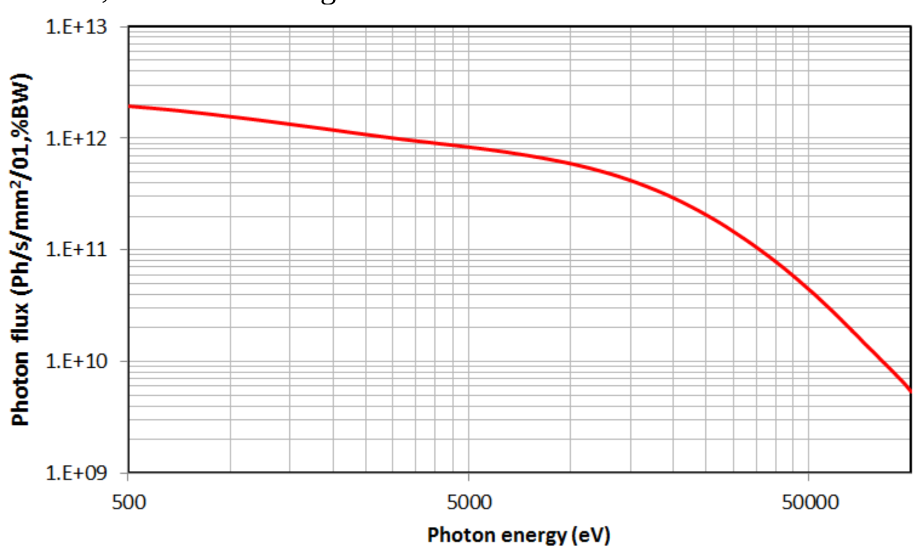

Figure 26. Emission spectrum of 3-pole-wiggler at minimum gap through an aperture of 1 mrad.