STATUS OF THE DEVELOPMENT OF SUPERCONDUCTING UNDULATORS AT THE ESRF

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Abstract

This note describes the present status of the development of superconducting undulators at the ESRF. Magnetic models of superconducting undulators suitable for the ESRF storage ring have been developed and evaluated. The superconducting undulators studied are horizontally polarizing undulators with a flat field profile. The vertical physical aperture of the undulator is 6 mm. 2D models of the local field in a period of the undulator as well as 3D models of the complete super-conducting undulator, including the end sections and current leads, have been evaluated. The practical limit for the obtainable magnetic field was estimated from the known performance of superconducting wire available from the cabling industry. The conceptual design of the cryostat of the superconducting undulator and estimations of the expected heat load to the cryostat at different filling modes of the storage ring are also described.

INTRODUCTION

There is general interest within the synchrotron radiation community in producing undulator radiation with a short a wavelength as possible. In this respect superconducting undulators (SCU) are an attractive option for the future. The technical difficulties connected to the construction and operation of small aperture short period SCUs have so far prevented the technology from being used on a wide scale at synchrotron light sources. Recent developments in the coil manufacturing process have shown that it is possible to build small period SCUs with a magnetic field strength greater than the permanent magnet technology without severe field errors [1]. It has also been shown that it is possible to install cold bore superconducting insertion devices on storage rings with affordable heat loads to the cryogenic system [2]. The limits for the obtainable field precision and also the heat load to the cryogenic system of a cold bore device installed in a storage ring with demanding filling patterns are, however, not fully known.

This note describes calculations [3], using the software package Radia [4,5], of the expected magnetic field and field integrals in an SCU. A similar study was carried out by H. O. Moser and R. Rossmanith [6]. An SCU's performance depends on the choice of wire and the winding technique used on the coils. It is therefore difficult to give a general calculation of the peak field in a SCU without specifying both the wire and the winding technique used. It is assumed that the superconducting wire operates at 4.2 K, is made of NbTi filaments in a Cu matrix, and the ratio Cu/ NbTi in the wire is 1.35. The boundary conditions for the ESRF storage ring are a physical aperture of 6 mm, a period length of 15 mm and a K value larger than 1.5.

2D MODEL

The 2D model, shown in Figure 1, is a model of the central part of the SCU. The aim of the 2D modelling is to find the appropriate relative size of the conductor versus the iron pole width and the iron return field yoke thickness. The magnetic field is enhanced with iron poles and iron may also be used in the return yoke on top of the conductor. The magnetic modelling is carried out using the software package Radia [4].

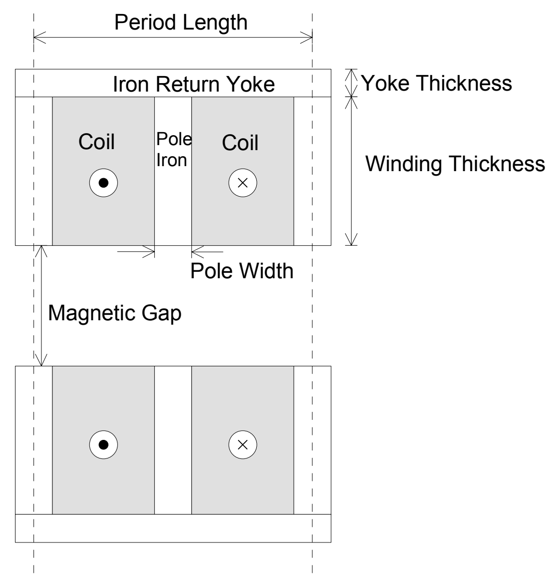

Figure 1: Geometry of 2D model.

The physical aperture is determined by the required beam stay clear aperture of the storage ring, while other parameters such as the period length, are given by the desired K-value of the SCU. 6 mm is the minimum physical aperture in the straight sections and it is assumed that the magnetic gap of the SCU is 6.5 mm, leaving space for a 0.25 mm thick vacuum chamber between the pole faces and the accelerator vacuum. The 2D model is parameterized and adjusts the maximum current density of the superconducting coils to the magnetic field present in the coils. The magnetic field in the coils is monitored by looking at the absolute magnetic field 25 µm into the coils along the side facing the iron pole. 25 µm correspond the wire insulation thickness. With the period length and the magnetic gap fixed, there are still three free geometric variables: the pole width, the winding thickness, and the yoke thickness. It should be noted that the winding thickness should be kept at reasonably low values since the coils have to be compatible with the bobbin winding technique.

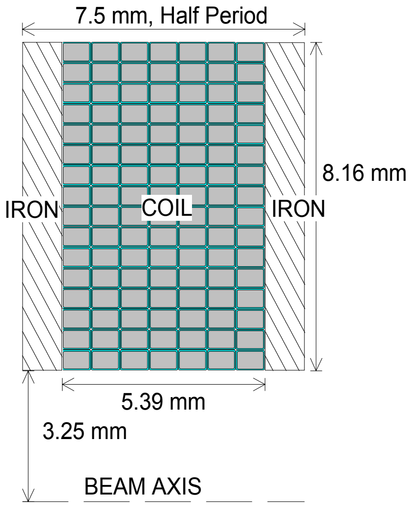

Figure 2: 2D Model showing ¼ of a period of an SCU with the dimensions given in Table 1.

Table 1: SCU at 80 % of the critical current density.

Period Length	15 mm
Magnetic Gap	6.5 mm
Iron Pole Width	2.11 mm
Winding Thickness, 16 layers	8.16 mm
Winding Width, 7 turns	5.39 mm
Maximum Magnetic Field in Coil	2.85 T
Current Density	1050 A/mm^2
Wire Current	412 A
K-Value	1.65
Peak Field	1.18 T
Field from coils	0.90 T, 76 %
Field from iron	0.28 T, 24 %

A set of iterations assuming an iron return yoke thickness of 0, 1 and 3 mm, and 100 % of the maximum critical current density, has given a number of interesting results. It is the SCU without a return field yoke that shows to have the highest peak field, which is 1.45 T. 1.45 T is found for a winding thickness of 10 mm, a pole width of 2.8 mm, and 100 % of the critical current density. The return field yoke has a positive influence on the peak field at small values of the winding thickness but, for larger values, the return field yoke may have a negative influence. The difference between the possession and non-possession of a return field yoke is, in general, small and it is therefore suggested excluding it in the design of the SCU. The dimensions of the coils in a SCU have to be adjusted to the dimensions of the actual wire used and it is also necessary to use a realistic assumption of a working point of the superconducting wire at 80 % of the critical current instead of 100 %. The coil dimensions given in Table 1 and a working point of 80 % of the critical current of the superconducting wire will fulfil the design goal of the ESRF. Figure 2 is an illustration of the coil dimensions given in Table 1. The 3D calculations in the following sections are based on the dimensions and current density given in Table 1.

3D MODEL

Matching of end sections

The matching of the end sections is carried out by using a model similar to that used for the 2D calculations. The horizontal depth of the model corresponds to the true size of the SCU's central parts. The model used for matching the end sections contains 20 standard periods plus one end section period in each end. The coils in a standard period of the model have the dimensions given in Table 1 with a total length of 80 mm centred around the beam centre, the model is therefore still partial because it relies on portions of conductors. The iron poles in a standard period of the model have the dimensions given in Table 1 with a total length of 40 mm centred around the beam centre. Figure 3 shows the end section obtained from the matching process. The first and second field integral of the 3D model are small and the matching of the end sections is hence correct at the nominal current density. The coils are, in this design, magnetically balanced for all current densities. At current densities different from the nominal current density, the magnetic balance of the iron in the end sections is changed. The first and second field integrals are, however, not severe and it would suffice to install correction coils at the entrance and exit of the 20 period model in order to correct the second field integral and first field integral errors.

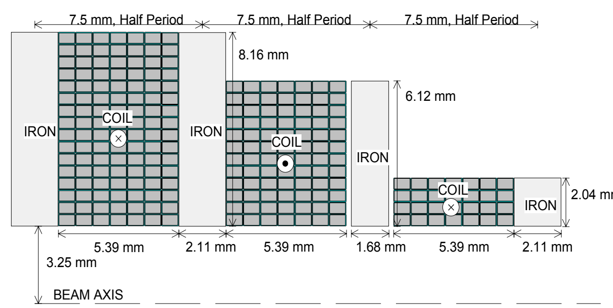

Figure 3: Illustration of the design of the SCU end section.

Full 3D model, including current leads

A 3D model containing 40 periods, the current leads, and the path of the single current carrying wire has been developed. The 40 period 3D model shows that a proper arrangement of the current leads and path of the current carrying wire is crucial for an SCU. In fact, the 40 period model, despite small field integrals at the beam axis, appears to act as a horizontally defocusing quadrupole, as was expected. In this model, the main coiling is completed with filament conductors in order to include the possible impact of return loops and current leads on the field quality. This conductor layout was expected to produce a systematic quadrupole. A precise design of the current leads and the path for the current carrying wire has not yet been found and it requires further empirical knowledge of the winding technique of the SCU.

The superconducting coils of the SCU will suffer from a hysteresis effect from persistent currents within the filaments of the superconducting wire when changing the magnetic field of the SCU. It is suggested that the persistent currents are compensated for by using a feed forward arrangement where a known ramping cycle is used when changing field strength. An alternative method could be an installation of a high resolution magnetic field sensor, which gives feed back to the SCU's power supply and regulates the excitation current in relation to the decay of the persistent currents.

CRYOSTAT

The cryostat for the SCU will be a dry cryostat cooled by local cooling machines, i.e. cryocoolers, similar or identical to the cryocoolers used for the superbend project [7]. The SCU has to be compatible with existing in-vacuum undulators installed at the ESRF, which means that the total length of the SCU cryostat should be 2.278 m. The cold length of the cryostat should be as long as possible. The physical dimensions of the accelerator vacuum tube, especially the vertical aperture, should preferably be constant over the whole cryostat. The accelerator vacuum tube surface will be coated with high purity copper with an assumed RRR value of 50. The design of the cryostat is not yet finished and it is not clear whether the undulator will have a fixed gap or a variable gap. In this note it is assumed that the SCU contains 100 periods plus one end section period in each end, giving a cold mass length of 1530 mm. The internal aperture of the accelerator vacuum tube is assumed to be 6×80 mm2.

THERMAL LOAD

The heat loads to the cold mass at about 4 K in the SCU have been estimated to be in the range 3.4 - 5.8 W depending on the filling mode of the ESRF storage ring, see Table 2. The heat load 5.8 W is for a possible future filling mode with 300 mA in 1/3 fill. The model for heating due to the resistive wall effect is found in [2]. In Table 2 the column "Cond." is the conducted heat along the acclerator vacuum tube, "Curr." the heating from current leads and "Misc." contains in addition to the foreseen static heat load of 60 mW to the cold mass, an additional 0.5 W, which is assumed to correspond to imperfections of the cryostat. With four 1.5 W cooling machines installed, there would be enough cooling capacity for all the foreseen filling modes of the ESRF storage ring.

Table 2: Thermal load to the cold mass of the SCU for different filling patterns of the ESRF ring.

Curr. [mA]	Filling Mode	Bunch L. [mm]	Res. W. [W]	S. R. [W]	Cond. [W]	Curr. [W]	Misc. [W]	Total [W]
120	16 bunch	14.4	3.01	0.44	0.18	0.31	0.56	4.50
250	1/3	6.0	2.57	0.92	0.17	0.31	0.56	4.53
300	1/3	6.0	3.73	1.10	0.06	0.31	0.56	5.76
250	Uniform	4.5	1.37	0.92	0.26	0.31	0.56	3.42
300	Uniform	4.5	1.96	1.10	0.20	0.31	0.56	4.13

COMPARISON WITH CPMU

Currently the Cryogenic Permanent Magnet Undulator (CPMU) is under development [8]. The CPMU works at temperatures far below ambient temperature and in that way an increased magnetic field performance is obtained.

An optimisation procedure for two different hybrid undulators, one at room temperature and one at cryogenic temperature, has been carried out in order to make a comparison with the performance of the SCU in this note. The period length is assumed to be 15 mm and the magnetic gap 6.2 mm, which leaves space for a 0.1 mm thick screen on the pole faces.

The peak field is found to be 0.57 T in a hybrid undulator at ambient temperature using the permanent magnet material Sm_2Co_{17} (Br = 1.05 T) and iron as the pole material. The peak field in a hybrid type undulator operating at cryogenic temperatures is found to be 0.72 T, assuming the temperature of the magnetic material to be 140 K, the magnetic material to be NdFeB (Br = 1.35 T at 140 K, Br = 1.18 T at 293 K [8]) and iron as the pole material. The results are shown in Table 3 below, where the peak field of the SCU is also given for three different magnetic apertures. It may be that 0.25 mm wall thickness between the accelerator vacuum and the pole faces is unrealistic and this is the reason for including also values for a wall thickness of 0.35 and 0.50 mm. The coil dimensions and current density of the SCU are given in Table 1.

Table 3: Comparison with CPMU, the period length is 15 mm and the physical aperture 6.0 mm.

Undulator	Magnetic Gap	Peak Field	K-Value
Sm_2Co_{17} Hybrid Type @ 300 K	6.2 mm	0.57 T	0.80
NdFeB Hybrid Type @ 140 K	6.2 mm	0.72 T	1.00
SCU, 80 % of Critical Current	6.5 mm	1.18 T	1.65
SCU, 80 % of Critical Current	6.7 mm	1.13 T	1.58
SCU, 80 % of Critical Current	7.0 mm	1.06 T	1.49

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