Predesign Study of a 4-5 T Superconducting Wiggler Magnet for the ESRF

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Abstract - **The ESRF is currently setting up a beam line for very hard photons well above 250 keV. This requires the installation of a high field three pole wavelength shifter. The nominal and target fields of the wiggler magnet are 4 and 5 tesla respectively while the nominal field integral over the central pole is 0.256 T-m at 4 T. The proposed magnet is a system of superconducting main and two side pole coils connected in series. An additional superconducting correction coil system enables to tune the field integral. The coils, made of high performing NbTi, are enclosed and prestressed in an aluminium coil housing. About 15 % field enhancement, shielding and force balancing is achieved with two iron plates sandwiching the coil housing. The cooling concept is a cryostat with a closed helium re-condensation system. Cooling is provided by a mechanical hybrid GM and JT refrigerator with a cooling capacity of about 2.5 W at 4.4 K. The paper reports on the design concepts and optimisations and a preferred solution is presented.**

I. INTRODUCTION

At the European Synchrotron Radiation Facility (ESRF) facilities are being built for fundamental and applied physics research. The synchrotron radiation is in the hard X-ray domain and will be produced by bending the circulating electron beam in undulator and wiggler type magnets. At least one beam line is intended for very hard photons with energies well above 250 keV. For this beam line the best solution is to apply a superconducting wiggler magnet. A predesign study was initiated and carried out by a collaboration of the University of Twente (magnetic system), SBT (cryogenic system) and ESRF (supervision). In the following sections the main results of the magnetic and cryogenic design studies are presented.

II MAGNETIC DESIGN

The wiggler consists of three poles, one central pole to generate the main bending field of nominally 4 T; two side poles connected in series with the main poles to shorten the axial length of the wiggler; and two correction poles to zero the field integral along the electron beam over the entire field range of 0 to 5 T. In figure 1 the overall view of the system is pictured. Three sets of dipole coils are arranged around the electron beam in the channel. The fourth set of correction coils is integrated into the side poles and not indicated. The positive field integral over the central pole has to be less than 0.256 T-m and the desired width of the central pole is about 70 mm. This field integral determines the distance between the central and the side coils and thus the overall length of the system in the direction of the beam.

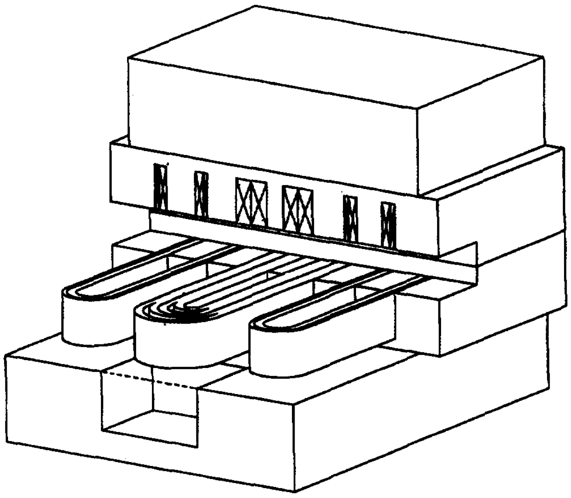

Fig. 1. Overall view of the proposed wiggler magnet showing the central coil system and both adjacent side pole coils, the Al coil housing sandwiched between iron yoke plates.

The magnet has a warm bore of 40 mm minimum, enabling a cold bore of at least 32 mm.

An important subject for analysis is *the mechanics*, i.e. the support of the windings and the containment of the forces. Many dipole magnets suffer from considerable training problems [1,2,3]. In most of the wiggler magnets the iron is shaped with pole shoes to guide the flux lines. The iron is present to counteract the Lorentz forces, to enhance the field and to shield the magnet. However, it is then difficult to obtain a sound mechanical system and any prestress of the coils is lost due to differences in thermal contraction. In this design the coils are inserted in an Al cassette providing a net prestress after cooling down. A similar technique was applied in the SRS wiggler [4].

Two iron *yoke* plates extend as far as the coils mainly to take advantage of the field enhancement. A second argument is that they provide shielding. Other advantages of this basic

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geometry are: less saturation and thus a more linear behaviour, reduced weight because iron is replaced by Al, and easier balancing of the forces. Strictly speaking the iron is not necessary. Also with air core coils a wiggler can be built. In that case the system is perfectly linear, but more superconductor is required to attain the field.

A *parametric study* is carried out to find optimal solutions for the dimensions of the various coils and the iron. A computer code has been developed that searches for minima of an optimisation function which consists of the following terms: the design field B_0; {Bmax-B(J)} per coil, where Bmax and J are the peak field and the current density in a coil respectively; the required total field integral δB.dl and the positive integral δB^+.dl. The iron is taken into account using the mirror technique and a constant mean permeability m_r (=20). The $J_c(B)$ relation of the selected NbTi superconductor and a margin of about 50 %, taking account for the winding density and safety, are also implemented. A further simplification arises if the coil cross sections are rectangular blocks. Using the code as described above, a very fast examination of various classes of optimal designs can be considered. A final selection is made by considering practical sizes for the coils. Detailed results of the parametric study are presented elsewhere [5].

After a certain geometry has been selected, a detailed check of the fields and forces have been carried out using 2d-POISSON and 3d-MAGNUS. In this way we can determine: the final shape and thickness of the iron, the minimum length in order to minimise the system volume and the required lay-out of the coil heads in order to keep the peak fields in the coil heads below those in the straight sections.

The main parameters of the wiggler as determined by the optimisation process are collected in table 1.

The Lorentz forces acting on the four coil sections are calculated using the analytical method and POISSON with infinite iron and the actual sizes. A comparison of the results are given in figure 2. The agreement is quite satisfactory.

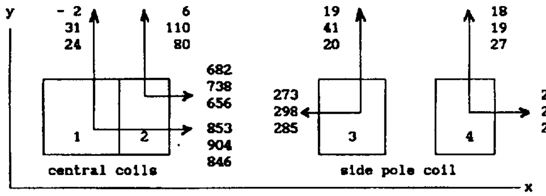

Fig. 2. Comparison of the forces on the various coil sections in kN/m. Top values=POISSON with finite iron, mid values= POISSON with infinite iron, bottom values= analytical method , infinite iron with m_r = 20.

TABLE 1.
SUMMARY MAIN PARAMETERS OF THE WIGGLER MAGNET (PREDESIGN)

Nominal/maximum operating field	4.0 / 5.0	T
Peak field inner central coils @ 5T	7.6	T
Peak field outer central coils @ 5T	5.6	T
Nominal/max. current	132 / 165	A
Assumed critical current density	3000	A/mm^2
Mean current density inner / outer central coils @ 5T	168 / 444	A/mm^2
(I/Ic) inner central coils @ 4/5 T	22/47	%
Current correction coils	0-5	A
Operating temperature	4.4	K
Overall length coils/magnet	400 / 420	mm
Width / height magnet	320 / 300	mm
Overall length / diameter cryostat	350 / 450	mm
Cold mass	270	kg
Stored magnetic energy @ 5T	60	kJ
Stored volume of Helium	20	L
Sum horizontal forces Fx @ 5T	1260	kN/m
Average vertical force Fy @ 5 T	30	kN/m

Using these forces the stress levels in the coils and the construction parts are analysed using the ANSYS FEM code.

The horizontal and vertical displacements due to excitation are quite small with a maximum value of about 10 micro meter. The maximum stress levels in the Al and the coils are about 60 and 40 MPa respectively. This demonstrates that the stiffness of the Al cassette is sufficient and that the coil clamping is safe.

An important choice to be made is the length of the magnet system. The lower limit can be found by using a 3d method that takes into account the real shape of the coil ends and the iron. The ESRF requirement for the homogeneity in axial directions is that the integral δB^+.dl. of 0.161 T-m at 5 T changes less than 0.005 T-m when going from z =0 to z= 25 mm, i.e. less than 3 %. This requirement is not severe and is satisfied if the field $B_y(x)$ itself changes less than 0.1 T over that range of 25 mm. In figure 3 the field profile along the x-axis (e-beam) of the magnet with straight sections of 240 mm is shown together with the field change DB due to 25 mm displacement in the z-direction (coils axis). From this figure it is clear that this coil system is still one order of magnitude better than the ESRF specification. Thus, a further reduction of the length is still possible.

III. CRYOGENIC DESIGN

The cryogenic system to be inserted in the beam line includes the following main components: the wiggler magnet's cryostat (horizontal axis) and the refrigerator turret

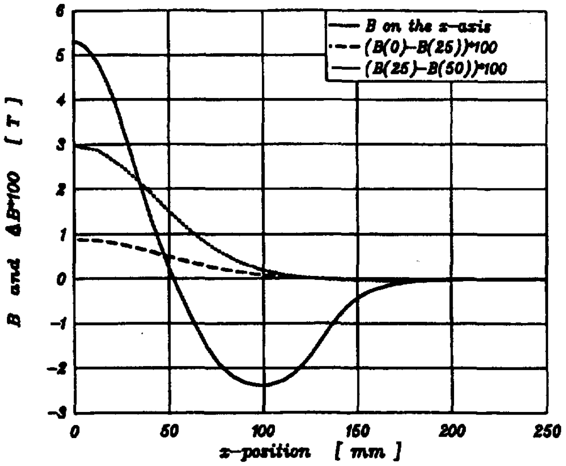

Fig. 3. Field profile B(x) of the wiggler (5.3 T) along the beam axis, and deviation DB due to a displacement in the z-direction for z intervals 0-25 and 25-50 mm.

(vertical axis). Both components are closely connected with a common vacuum, independent of the beam chamber vacuum.

The wiggler magnet's cryostat is constructed around the rectangular vacuum chamber for the e-beam. The connections to the main beam chamber are made by means of metallic seal flanges and bellows to allow for the thermal differential contraction during cool down. The helium vessel is radially mechanically anchored at both ends to the structure of the cryostat by means of four adjustable fibre glass tensile rods for alignment of the magnetic axis. Both beam pipe and helium vessel are surrounded by a copper thermal radiation shield cooled by conduction to about 80 K.

The refrigerator turret contains the cooling components and circuits. A mechanical cryo-refrigerator (G.M. + JT loop) is used for re-condensation of the helium vapour. Its operation is fully automatic. Thermal radiation shield cooling is also provided by a mechanical cryocooler (single stage G.M.). A schematic diagram of the cooling circuits and components is given in figure 4.

The radiation heat flux from the room temperature surfaces to *the thermal radiation shields* has been estimated to be about 45 watts. A rough super isolation (5 to 6 layers of aluminised mylar) is provided around the wiggler helium vessel thermal shield (~10000 cm^2) and around the refrigerator turret thermal shield (~6000 cm^2) but none around the internal warm bore (~1500 cm^2).

The helium re-condensation system consists of a closed cycle cooler using a double staged G.M. cryocooler for the precooling of a JT loop. Precooling is necessary to compensate for the inefficiency of the counter flow heat exchangers of the JT loop and to achieve a temperature level compatible with cooling by isenthalpic expansion of helium gas. The mass flow rate for the JT loop, which remains very small compared to the G.M. mass flow rate, is provided by the G.M. compressor (HP$\simeq$ 20 bar). High pressure JT helium gas is precooled in three successive counter flow heat exchangers and to exchangers on the G.M. cold head heat stations. The isenthalpic JT expansion valve is of a pneumatic type with automatic adjustment allowing for maximum mass flow rate during precooling and regulated flow at nominal conditions (temperature stability 0.03 K at 4.4 K). A pneumatic bypass valve that is automatically

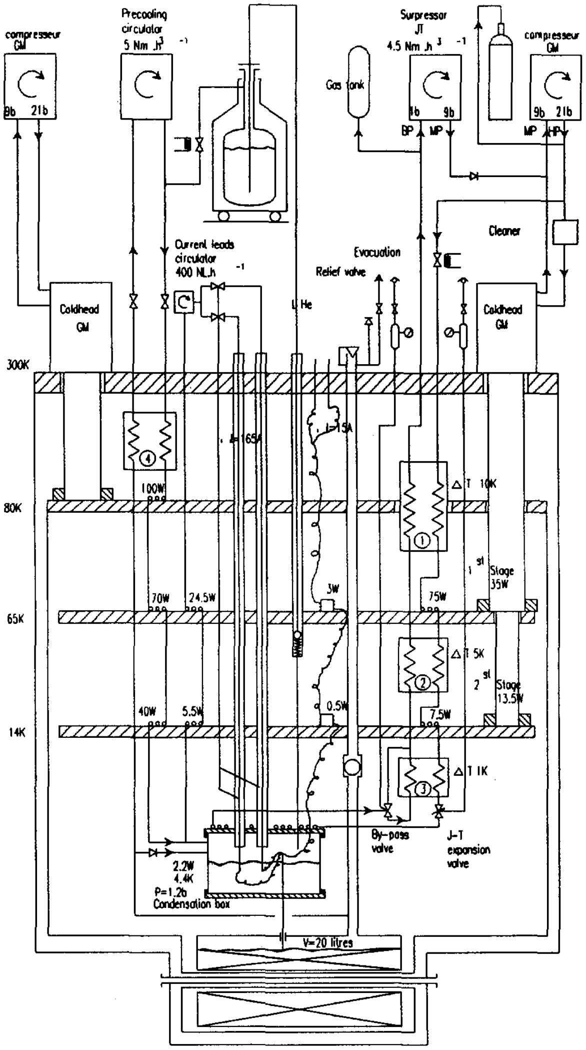

Fig. 4. Schematic diagram of the cooling circuits and components and their connection to the magnet system.

closed at 20 K, is also used to minimise the cooling down time. At room temperature the low pressure helium gas (LP˜1 bar) is compressed by a specific JT surpressor to the G.M. compressor suction pressure (MP˜9 bar).

Purification of helium gas is provided by appropriate means to avoid any plugging of the JT loop and to ensure continuous trouble free operation for more than 8000 hours. Maintenance is foreseen once a year during the technical shut down of the ESRF facility.

The cooling power of the helium re-condensing system is determined to compensate both the thermal loads on the wiggler magnet's vessel and the heat input through the current leads. This cooling power is transmitted by means of a heat exchanger to the condensation plate of a condensing box that provides both cold gas for the current leads and liquid helium to the magnet's vessel.

The current leads for the coils are cooled by gas circulation (central and side coils 165 A) or thermally anchored to the G.M. cold stations (correcting side coils 0-10 A). A circulator at room temperature forces the gas flow, the mass flow rate being regulated by a pneumatic valve driven by a condensation bulb thermally anchored to the low temperature end of the current leads to minimise the heat load. The warm gas coming out of the current leads is recirculated and cooled by means of heat exchangers on the G.M. heat stations and re-injected in the condensation box.

The thermal load at 4.4 K has been calculated as follow:

- conduction heat input (mechanical anchoring)	150 mW
- radiation heat flux from 80 K	350 mW
- correction side coils (2 x 15 A)	200 mW
- central and side coils (2 x 165 A)	1500 mW

- Total heat input at 4.4 K	2200 mW

During field ramping (4 T in 5 min.) dissipation of about 850 mW occurs in the helium bath, leading to an acceptable pressure increase of about 50 mbar (100 cm^3 vaporisation).

The JT loop has been sized assuming a 20 bar high pressure, a 1.2 bar low pressure, a single JT expansion and G.M. cold head heat station's temperatures of 14 K and 65 K, leading to a JT helium flow rate of 0.22 g/sec (4.5 Nm^3/h). For the technology of counter-flow heat exchangers developed in our laboratory, the pressure drop in the low pressure circuit is estimated to be less than 40 mbar. The cooling power required for the double staged GM has also been calculated . The results are presented in table 2.

TABLE 2.
SPECIFICATION OF THE REQUIRED COOLING POWER .

		1st stage	2nd stage
G.M. heat station temperature	[K]	65	14
JT loop precooling	[W]	7.5	7.5
Correction coils lead cooling	[W]	3.0	0.5
Central and side coils gas cooling	[W]	24.5	5.5
Total heat load	[W]	35	13.5

A specific circuit is devoted to *the initial cooling*. Precooling of the wiggler down to about 20 K is achieved by forced flow of helium gas cooled on the G.M. refrigerators heat stations. Remaining cooling down to 4 K and filling of the helium vessel (20 litres) are achieved by liquid transfer from a storage vessel. Cooling time from room temperature down to 4.4 K is estimated to be 2,5 ± 0,5 days.

IV. CONCLUSIONS

A predesign has been completed of a three pole superconducting 4-5 tesla wiggler magnet and its cryogenic system. The proposed system meets all the specifications. The design optimisation was carried out using an analytical approach implemented in a software code. A check with 2d and 3d FEM codes was made and a good agreement was found. Near linear operation of the magnet is obtained by putting the iron yoke distant from the coils. At the same time this solution enabled an Al coil housing which provides rigidity and the required prestress on the coils.

Based on the study presented here a few manufacturers made proposals to build the wiggler magnet. A particular design, which is in a few aspects quite different from the predesign presented here, has been selected. A delivery to ESRF is expected in summer 1994.

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