

Development of the Next Generation Superconductive Undulators for Synchrotron Light Sources

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Abstract—Superconducting insertion devices are very attractive for synchrotron light sources. For a given gap and period length, higher fields can be reached in respect to permanent magnet insertion devices thus permitting to reach higher photon fluxes.

A new R&D program has been recently launched at ANKA aiming for the development of the next generation superconducting insertion devices for light sources. A cold bore superconducting undulator (14 mm period length, 100 full periods long) is installed in the ANKA storage ring since three years. This will be replaced by an improved version which shows a more efficient cooling system and a high precision design aiming for reduced field errors. Under planning are two additional devices. One will allow to electrically switch the period length between 15 mm and 45 mm corresponding to an undulator and a wiggler mode, respectively. The other will be optimized for third generation light sources. It will be capable of tolerating higher beam heat loads up to 6 W while achieving very small field errors. The field error minimization will be obtained through the use of new shimming concepts which will correct inaccuracies due to manufacturing tolerances. This paper describes the technical concepts of the three projects.

Index Terms— Superconducting Magnet, Superconducting Undulator, Insertion device, NbTi, Cryogen Free.

I. INTRODUCTION

THE superconducting undulator SCU14 installed in ANKA in 2005 as a demonstrator has been in operation since that time without interruption. Based on this experience two main areas of further improvements were identified [1].

1) Since the measured beam heat load on the cold surfaces is higher than expected [2] [3], a design has been developed

aiming to reduce the beam originated heat load on the superconducting coils. The performance of the superconducting coils is extremely dependent on temperature gradients which become particularly critical for cryogen free magnets.

2) The field errors in superconducting undulators are related only to mechanical tolerances. This is a considerable difference with respect to permanent magnet undulators where field errors are related to mechanical tolerances and variation in the magnetic strength of the individual magnets. In order to reduce the field errors, the mechanical tolerances have to be improved or shimming techniques have to be developed [4].

The superconducting undulators now under construction or in a detailed planning stage will integrate step by step these concepts.

II. SCU 15: THE PROTOTYPE FOR A NEXT GENERATION SUPERCONDUCTING INSERTION DEVICES

SCU15 is a 15 mm period length, 100.5 full periods long undulator with the addition of one period at each side of the magnet, which is used to adjust the end field distribution. The specifications of the magnet are shown in Table I. In principle this is an improved version of the existing SCU14 installed in ANKA.

TABLE I SCU 15 SPECIFICATIONS

	Units	Value
Period length	mm	15
Number of full periods		100.5
Max field on axis with 5 mm gap	T	1.5
Max field in the coils	T	2.4
Minimum gap	mm	5
Operating gap	mm	8
Gap at beam injection	mm	25
K value at 5 mm gap		>2
Design beam heat load	W	4

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In order to reach the performance, as mentioned above, special attention was given to the cryogenic design and to the manufacturing process.

A. Cryogenic Design

The cryogenic design of a cryogen free magnet is, by itself, a very demanding task already for devices of simple shape such as standard solenoids. This is due to the limited amount of cooling power at 4 K furnished by commercially available cryocoolers and due to the presence of temperature gradients in the cold mass related to the thermal conduction dominated design imposed by this cooling source.

In the case of undulators, the requirements become even more stringent due to the presence of high heat loads generated by the beam. The main beam heat sources mechanisms are: synchrotron radiation, resistive wall heating, electron and/or ion bombardment and RF effects. While the complete investigation of these heating processes is part of planned experiments [5], in the case of SCU15 the heat contribution due to the beam considered during the design phase is 4 W.

In order to limit possible increases of the operating temperature of the magnet, a design based on a concept originally developed for superconducting wigglers at BINP [6] has been adopted. Figure 1 shows the basic principle of this concept consisting in the separation of the cooling circuit of the magnet with respect to the one of the beam pipe (liner).

Surrounding the beam is a 300 μm thick stainless steel non magnetic vacuum chamber (liner) with a high quality Cu coating in the vicinity of the beam (50 μm thick). The heat generated by the beam in the Cu layer is transported to high thermal conductivity Cu blocks positioned sideward's of the beam. These Cu blocks are then connected to the cooling circuit.

This solution allows maintaining the temperature of the superconducting coils below the critical value independently from the heat generated by the beam. In addition, being separately cooled, the beam pipe can operate at average temperatures higher than 4 K allowing taking advantage of the higher cryocooler efficiency. For example, commercially available double stage GM cryocoolers are capable of generating a cooling power of 1.5 W at 4 K which increases to 4 W at 8 K. In order to maximize the magnetic field on the axis of the undulator, the magnetic gap must be as close as possible to the beam stay clear distance.

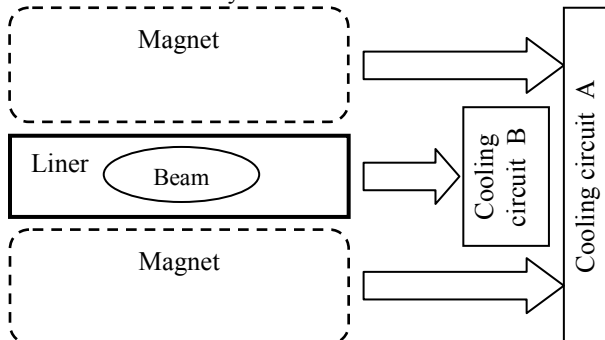


Fig. 1 Schematic of the undulator cold mass. The superconducting coils are thermally separated from the liner and are independently cooled.

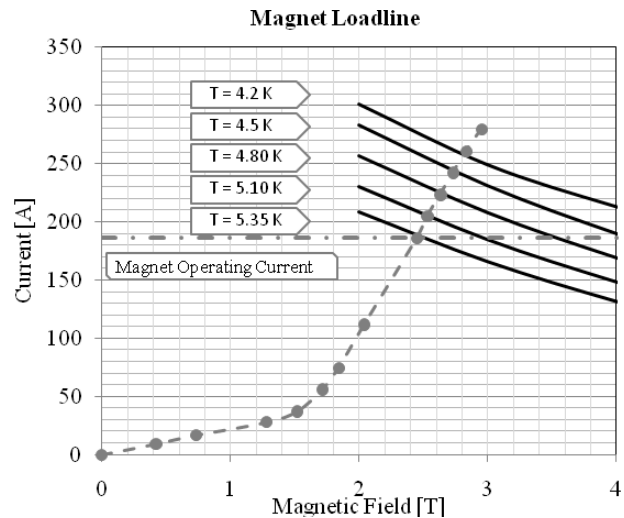


Fig. 2 Load line of the magnet. The solid lines represent the critical current characteristic at a given temperature and magnetic field of the superconductor. The dashed curve is the load line of the magnet which is iron dominated at low fields. The dot-dashed line represents the operating current of the magnet.

This requirement results in a major limitation of the space available for the liner. As a result, the design of the liner and of the copper heat collectors is the core element of the overall concept for the device. The thermal separation must be guaranteed within a space smaller than 0.4 mm.

A number of detailed studies including both numerical simulations and experiments are at the moment under way with the goal of identifying the optimal configuration.

As mentioned in Table I, the maximum expected magnetic field in the superconducting coils is below 2.4 T. For this reason a commercially available NbTi conductor was chosen. The expected load line of the magnet compared to the critical surface of the conductor is shown in Figure 2. In the same figure the critical current characteristics of the chosen conductor for different temperatures are displayed allowing identifying the temperature margin of the magnet.

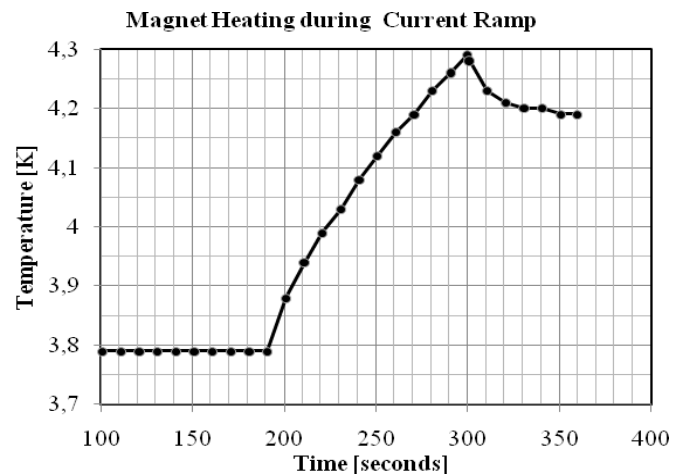


Fig. 3 Maximum temperature within the magnet during current ramping. The magnet warming is due to a heat load generated by: AC losses, magnetization and coupling losses in the conductor. The current ramping started at time 190 s for a total duration of 100 s. The starting temperature of ~ 3.7 K is calculated taking into account the overall static heat loads acting on the magnet before the ramp is started. The maximum reached temperature is below 4.3 K.

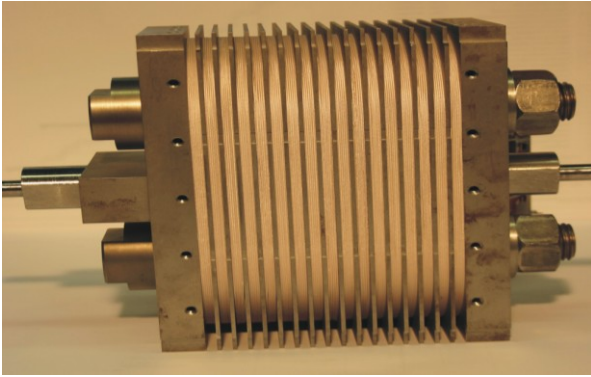


Fig. 4 Nb₃Sn Undulator mock-up before the heat treatment.

This is an extremely valuable information for a cryogen free magnet where large temperature gradients are present especially during magnet ramping.

In fact a major limitation of such magnets is the restricted ability of quickly reaching the maximum operating field due to heat generation in relation to AC losses in the conductor. Numerical simulations have been performed in order to evaluate the maximum gradients in the magnet during the magnetic field ramping and results are shown in Figure 3.

An additional chance to reduce the dependence of the undulator with respect to the heat load of the beam is to use a less temperature sensitive wire, e.g. Nb₃Sn which has a critical temperature of 18.3 K (at zero magnetic field). First tests with a mock-up (Figure 4) were performed and will be continued in the near future. The aim is to study how the heat treatment of the wire acts on the phase error of the undulator. Similar tests were performed earlier in LBNL [7] and ANL [8].

Initial tests showed that the used Nb₃Sn wire can transport currents up to 2200 A/mm² in simple test devices such as solenoids consisting of a few windings. The maximum current density in the Nb₃Sn mock-up shown in Fig. 4 was limited to about 1000 A/mm². The design will be improved in future prototypes to reduce the performance gap between short sample tests and undulator mockups. If the limitations due to the 700° C heat treatment on the allowed materials and on the final achievable tolerances will be overcome, the use of Nb₃Sn could help in increasing the available space between beam stay clear and magnetic gap. This could lead to an increase of the thermal separation between liner and magnet and at the same time of the maximum tolerable temperature in the superconducting coils.

B. Manufacturing tolerances and shimming

In order to obtain a superconducting undulator with a low field error, a detailed statistical analysis on the mechanical tolerances has been performed. The aim was to obtain, for the planned SCU15, a phase error equal or below 3.5 degrees. The phase error, Figure 5, is determined by three mechanical inaccuracies:

- a) Tolerances in the period length
- b) Tolerances in the position of the pole relative to the beam axis
- c) Tolerances of the wire position relative to the pole

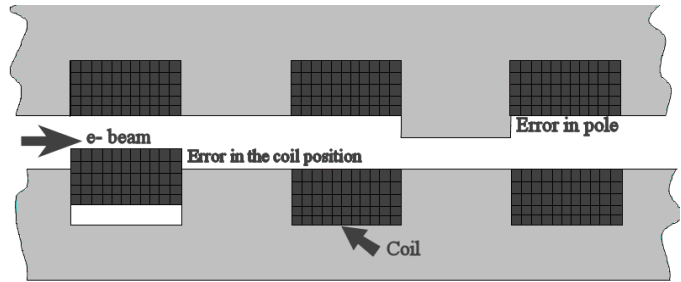


Fig. 5 Possible mechanical errors contributing to the phase error in a superconducting undulator: errors in the pole position and errors in the position of the wire relative to the pole.

A Monte Carlo simulation has been performed in order to evaluate the overall effect of the combination of the three tolerances on the phase error of the undulator. In particular it was assumed the mechanical tolerances for a), b) and c) to be 10 μm (3 sigma). The phase error for 1000 configurations was calculated under the assumption of mechanical tolerances randomly distributed. The results of the simulations are summarized in table II. The strongest contribution to the phase error is correlated to the inaccuracy in the period length (a) followed by the errors of the pole position (b).

TABLE II PHASE ERROR DUE TO MECHANICAL INACCURACIES DURING THE PRODUCTION OF THE MAGNET

Phase error in degrees	
Peak of distribution	0.7
75% level	1.6
97% level	4.5

In addition to the random combination of these three geometrical tolerances, when taken singularly, even each of the three types of geometrical errors, for particular distributions, can lead to phase errors above specification.

In general the phase error can be reduced when the influence of one or two inaccuracies on the phase error can be eliminated. In order to do so the manufacturing process of the yoke must be carefully analyzed and possible sequences capable of reducing the tolerances implemented. For example the pole height can be measured on a coordinate measuring machine before winding the wire and adjusted if necessary.

The mechanical tolerances of the SCU15 are specified for a phase error equal or less than 3.5 degrees. If this goal is not reached, a shimming system can be applied [4]. A shimming concept has been tested on a short mockup with the same geometrical characteristics of SCU15. A thin superconducting wire has been wound coaxially to the main coils of the undulator in the area closer to the beam allowing for a field correction at maximum current of 1%. The same result was obtained with racetrack coils wound around the poles and on top of the main coils. The first results of the data analysis show that these two types of shimming can be used to compensate for different local inaccuracies.

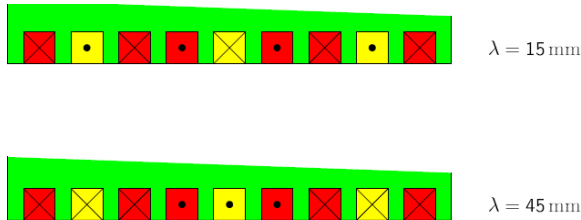


Fig. 6 The Undulator / Wiggler SCUW with an electrically switchable period length from 15 mm to 45 mm. The period length is switched by reversing the current in one of the windings.

III. SCUW

SCUW is a device which allows switching between a 15 mm period length undulator and a 45 mm wiggler. A detailed description of this concept can be found in [9]. The basic concept is described in Figure 6. The SCUW has two separate windings. By reversing the current in one of the windings the period length is changed from 15 mm to 45 mm. A practical solution for the manufacturing of the winding package has already been finalized.

At the moment first studies are under way to find an acceptable solution for the matching end periods for both operational modes. When this step will be completed a short mockup will be fabricated and tested at ANKA.

IV. SCU2

SCU2 is an advanced superconducting undulator for third generation light sources.

ANKA is filled with beam at 500 MeV and afterwards the beam energy is ramped to 2.5 GeV. Injection and acceleration is at the moment only possible when the beam stay clear is larger than 12 mm. The gap width during undulator operation is 7 mm or even less. This means that the gap has to be opened during injection and acceleration. This is, from a mechanical point of view, very demanding and makes the devices for ANKA rather complicated. The present solution for SCU15 consists in the use of two motors that move the two half magnets while precisely controlling their position and taking into account shrinking due to thermal contractions. Synchrotrons with a full energy injector do not need the possibility to change the gap.

The bunch length at ANKA is about 10 mm and in comparison with 3rd generation synchrotrons relatively long. For shorter bunch lengths and higher currents the heating due to image currents increases dramatically and causes higher beam heat load. Therefore the SCU2 will be designed to tolerate beam heat loads up to 6 W. This goal will be achieved possibly without increasing the number of cryocoolers installed in the machine.

The SCU2 will also have a small phase error. This means that shimming concepts will play a more central role in the design. As already mentioned active shimming techniques with additional superconducting wires are under consideration which will allow reducing the phase error significantly [4].

V. CONCLUSION

A strong R&D program has been recently launched at ANKA in collaboration with Babcock Noell GmbH with the aim of designing and manufacturing a new generation of superconducting insertion devices. The first stage, already at the manufacturing phase, consists in the realization of a 15 mm period length 100.5 full period long device reaching 1.5 T on its axis with a magnetic gap of 5 mm. this device is designed for a beam heat load of 4 W.

A second short prototype, in its design phase, is a device capable of switching between a 15 mm period length undulator and a 45 mm wiggler.

The third planned device aims to tolerate higher heat loads generated by the electron beam of third generation light sources and a phase error less than 1.

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