J. Synchrotron Rad. (1998). **5**, 448–450

A superconductive undulator with a period length of 3.8 mm

T. Hezel,[a]* B. Krevet,[b] H. O. Moser,[a] J. A. Rossmanith,[c] R. Rossmanith[d] and Th. Schneider[e]

[a]*Projektgruppe Errichtung ANKA, Forschungszentrum Karlsruhe, PO Box 3640, D-76021 Karlsruhe, Germany,* [b]*Institut für Mikrostrukturtechnik, Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany,* [c]*Christopher Newport University, Newport News, Virginia, USA,* [d]*DESY Hasylab, D-22605 Hamburg, Germany, and* [e]*Institut für Technische Physik, Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany. E-mail: hezel@anka.fzk.de*

(*Received 4 August 1997; accepted 6 November 1997*)

During recent years several attempts have been undertaken to decrease the period length of undulators to the millimetre range. In this paper a novel type of in-vacuum undulator is described which is built using superconductive wires. The period length of this special device is 3.8 mm. In principle, it is possible to decrease this period length even further. A 100-period-long undulator has been built and will be tested with a beam in the near future.

Keywords: undulators; superconductivity; in-vacuum.

1. Introduction

Following various publications on concepts of micro-undulators (Granatstein *et al.*, 1985; Tatchyn & Csonka, 1987), work on a superconductive micro-undulator started in Karlsruhe in the early 1990s (Moser *et al.*, 1991; Holzapfel, 1991).

Independently, a short prototype of a superconductive undulator with an 8.8 mm period was built at Brookhaven (Ben-Zvi *et al.*, 1990) following a slightly different concept. Field calculations and measurements were performed recently with a longer prototype (Ingold *et al.*, 1996). Also independently, a group at Spectra Technology Inc. (Gottschalk *et al.*, 1991) pointed out that FELs built with superconductive electromagnetic undulators might have advantages over a design with permanent magnets. Since that time the interest in reducing the period length of undulators has grown steadily (Stefan *et al.*, 1991; van Vaerenbergh, 1996; Tanabe *et al.*, 1997). In 1996, the Forschungszentrum started experimental work on a superconductive undulator with a period length of 3.8 mm. First results were presented by Hezel *et al.* (1997)

There are many reasons for building such undulators. They include (i) producing higher-energy photons with a given particle beam energy, and (ii) obtaining a given spectrum with lower energy machines with favourable consequences for the brilliance.

Millimetre-period undulators might also play an important role in the development of X-ray lasers in the future.

In principle, millimetre-period-length undulators can be built in various ways: they can be Halbach-type undulators (with permanent magnets), hybrid-type undulators or so-called electromagnetic undulators. Electromagnetic undulators generate the field by the current in a wire (Biot–Savart). Halbach-type undulators and hybrid undulators are difficult to build when the period length is in the millimetre region: mechanical problems make the design difficult (Tatchyn & Csonka, 1987; Rakowsky *et al.*, 1997). Electromagnetic undulators, on the other hand, have the disadvantage that the required currents as well as the ohmic losses are relatively high. The use of superconductors instead of normal conductors reduces the ohmic losses to a negligible degree. For this reason ANKA is pursuing their development. The principal layout of the undulator is shown in Fig. 1.

Undulators with short periods require a small gap. According to the well known formula of the field strength in the gap as a function of the gap height,

$$B_{\rm gap} = B_0/\cosh(\pi g/\lambda_u),$$

where B_0 is the field at the pole, g is the gap height and λ_u is the undulator period, the period length should not be less than $4g$ in order to prevent reduction of the maximum field by more than $\sim$20%. This poses a problem since the gap has to be in the millimetre range; therefore, the undulator must be integrated into the vacuum system. Otherwise, the thickness of the vacuum chamber will already significantly reduce the strength of the maximum obtainable field. The different superconductive materials are selected according to their suitability for integration into a vacuum system, *e.g.* NbTi conductors are integrated into a copper matrix. The metallic copper surface is almost ideal for installment into a UHV environment. Nb_3Sn technology appears less appropriate, and at the moment high-T_c wires cannot handle the required current. Nevertheless, we feel that high-T_c super-

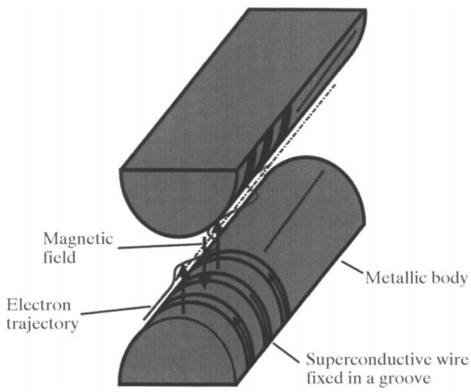


Figure 1
Layout of the superconductive undulator.

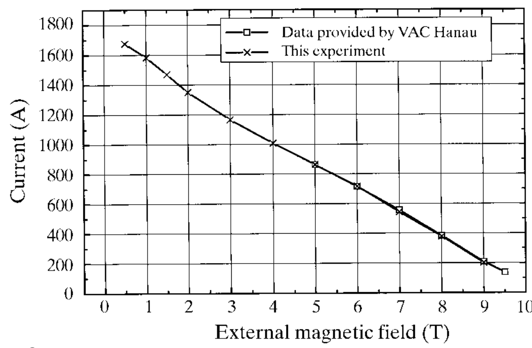


Figure 2
Measurement of the quench current as a function of an external magnetic field.

© 1998 International Union of Crystallography
Printed in Great Britain – all rights reserved

conductors may play an important role in the future, especially if period lengths are reduced further.

In the following the technical layout, magnetic field calculations and experimental results are presented.

Accelerator physics issues, such as the relationship between the gap height and the lifetime, the influence of the impedance on instabilities, as well as the question of magnetic field measurements within a small cryogenic gap, would exceed the scope of this paper and are not considered here. Various investigations have shown that these problems can be solved, in particular for third-generation synchrotron radiation sources (Stefan *et al.*, 1991; Tatchyn, 1989; Bane & Krinsky, 1993).

2. Technical layout of the undulator

For the undulator prototype a commercially available NbTi superconductor with a cross section of 1.25×0.80 mm (including insulation) has been chosen (Vakuumschmelze Hanau, 1996). Since superconductors are usually used in a high magnetic field environment, the quench behaviour in the low field region (where the undulator operates) is not well documented. Therefore, the quench current was measured as a function of an external field (Fig. 2).

From these experimental results we calculate the maximum field that can be obtained in the gap. Fig. 3 shows an optimized geometry and gives the maximum current through the wire limited by the magnetic field, the period length and the vertical field in the gap; the shaded areas represent non-magnetic material.

Only layers close to the beam contribute to the magnetic field in the gap. Therefore, the undulator winding is limited to four layers. More layers would not significantly increase the field.

The maximum current of 1470 A as calculated using *MAFIA* (1996) is in good agreement with the measured value of 1400 A.

When iron is used instead of a non-magnetic material, the maximum field in the iron is 3 T and the field in a 1 mm gap is 1 T.

The undulator is built in the following way. The body is produced first (Fig. 4). It consists of a copper core through which liquid helium flows. Attached to this copper cylinder are four aluminium half-cylinders and one iron half-cylinder with grooves. In the test undulator presently under consideration a cylindrical geometry was chosen in order to make it easier and cheaper to construct.

In the next step, the superconductive wire is wound from the original drum to a second drum. This procedure is stopped when half of the required wire is on the second drum. The middle of the wire is the starting point in the coiling procedure and is fixed in a groove on one of the aluminium half-cylinders. The groove is the shape of a half-circle. From this point the wires are wound in a bifilar way as shown in Fig. 5.

The completely coiled 100-period-long half-undulator is shown in Fig. 6. The active length of the undulator is 38 cm. The copper blocks on the left end are used for the quench test and will be

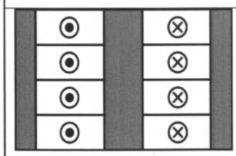
Geometry	Period length (mm)	Electric current (A)	Gap (mm)	Field in gap (T)
	3.8	1470	0.5	0.82
			1.0	0.56

Figure 3
Parameters of the undulator coil. The geometry is shown for one period only. The shaded areas represent non-magnetic material. The calculations were performed using *MAFIA* (1996).

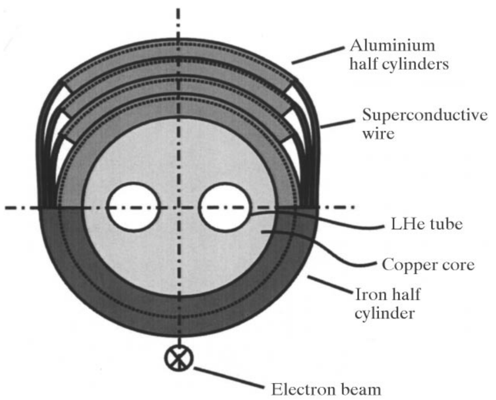


Figure 4
Cross section of the assembled undulator. A copper core cooled by liquid helium is located in the centre. The iron half-cylinder is placed next to the electron beam and the aluminium half-cylinders are placed opposite the beam.

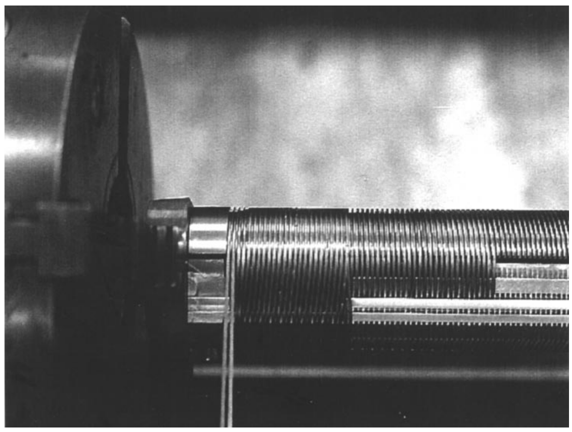


Figure 5
Photograph of the undulator prototype during coiling. The picture shows the bifilar coiling technique and the aluminium half-cylinders.

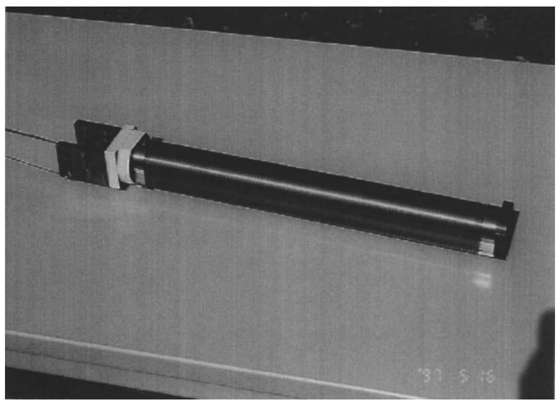


Figure 6
One completely coiled undulator plate ready for quench test in a vertical cryostat.

removed before the undulator is installed in a transportable cryostat (Fig. 7).

The undulator shown in Fig. 6 was tested in a vertical cryostat. The maximum current through the undulator was, as already mentioned, 1400 A.

3. Cryostat for beam test

A dewar, which provides helium for the undulator and at the same time serves as a radiation shield, is placed inside the vacuum chamber (Fig. 7). The current flows to the undulator *via* copper wires. These wires are cooled first by gaseous helium and later by liquid helium in order to minimize the heat transfer from outside and to minimize the ohmic losses. When the undulator is not in use, the beam can bypass the undulator in the opening to the right of the undulator body. The gap height can be adjusted by bolts (at the moment only manually).

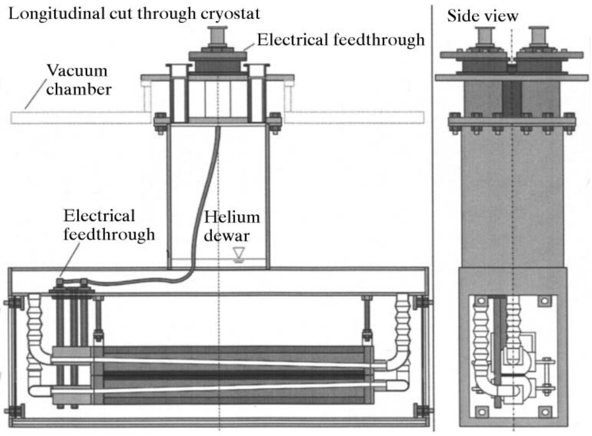


Figure 7
The transportable cryostat.

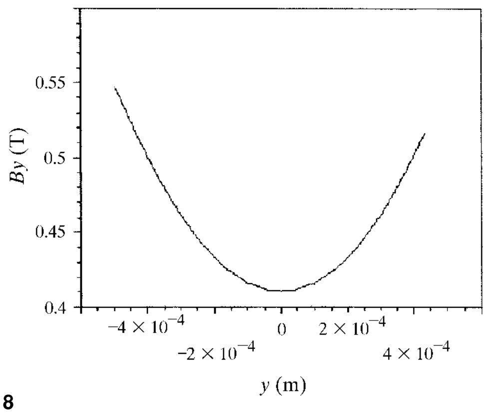


Figure 8
Field in the gap *versus* distance to the pole surface (undulator with non-magnetic casing). The minimum is in the centre of the gap. The field increases towards the coils. The sextupole component is 4.96×10^5 T m^{-2}.

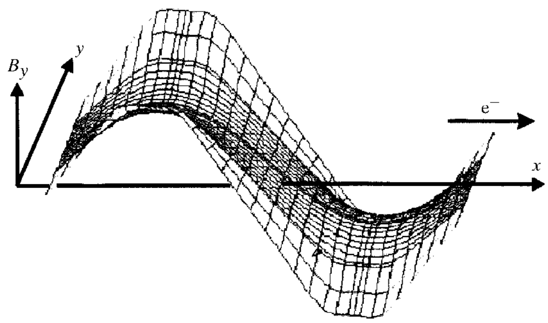


Figure 9
Plot of the field in the undulator gap for one period along the trajectory. The undulator material is non-magnetic. *y* is the coordinate across the gap.

4. Magnetic field and particle trajectories

Field calculations were performed with the help of *MAFIA* (1996).

The vertical field component of an undulator with a non-magnetic material is shown in Fig. 8. This field has a strong sextupole component of about 4.96×10^5 T m^{-2}.

Fig. 9 shows the two-dimensional field plot for one period. The field in the centre is sinusoidal; the sextupole field changes sign together with the field.

Theoretical studies on the influence of field errors and the end fields on the particle trajectory (Rossmanith, 1997) show that the displacement of the trajectory can be minimized with a matching section at the beginning and end of the undulator. This matching section is visible on the left-hand side of Fig. 5. In the matching section the depth of the grooves is different compared with the rest of the undulator.

5. Conclusions

In the near future, the undulator is planned to be installed and tested in one of the beamlines of the 850 MeV microtron MAMI in Mainz. Depending on the success of these tests, a modified superconductive undulator suitable for use in storage rings will be designed and built later.

References

Bane, K. & Krinsky, S. (1993). BNL-48792. Brookhaven National Laboratory, Upton, New York, USA.

Ben-Zvi, I., Jiang, Z. Y., Ingold, G., Yu, L. H. & Sampson, W. B. (1990). *Nucl. Instrum. Methods*, A**297**, 301–305.

Gottschalk, S. C., Pindroh, A. L., Quimby, D. C., Robinson, K. E. & Slater, J. M. (1991). *Nucl. Instrum. Methods*, A**304**, 732–737.

Granatstein, V. L., Destler, W. W. & Mayergoyz, I. D. (1985). *Appl. Phys. Lett.* **47**(6), 643–645.

Hezel, T., Rossmanith, R., Krevet, B. & Moser, H. O. (1997). *Proc. PAC97*, Vancouver, Canada.

Holzapfel, H. (1991). Diploma thesis, Universität Karlsruhe, Germany.

Ingold, G., Ben-Zvi, I., Solomon, L. & Woodle, M. (1996). *Nucl. Instrum. Methods*, A**375**, 451–455.

MAFIA (1996). CST Gesellschaft für Simulationstechnik mbH, Darmstadt, Germany.

Moser, H. O., Krevet, B. & Holzapfel, H. (1991). Patent DE 4101094 C1, Kernforschungszentrum Karlsruhe GmbH, Germany.

Rakowsky, G., Aspenleiter, J. J., Graves, W. S., Solomon, L. & Stefan, P. M. (1997). *Proc. PAC97*, Vancouver, Canada.

Rossmanith, J. A. (1997). ANKA Technical Note BES-06/97. ANKA, Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany.

Stefan, P. M., Solomon, L., Krinsky, S. & Rakowsky, G. (1991). *Proc. IEEE Part. Accel. Conf.*, San Francisco, USA, pp. 1096–1098.

Tanabe, T., Kitamura, H. & Stefan, P. M. (1997). *Proc. PAC97*, Vancouver, Canada.

Tatchyn, R. (1989). *Nucl. Instrum. Methods*, A**279**, 655–664.

Tatchyn, R. & Csonka, P. (1987). *Appl. Phys. Lett.* **50**(7), 377–379.

Vaerenbergh, P. van (1996). *Tenth ICFA Beam Dynamics Panel Workshop*, ESRF, Grenoble, France.

Vakuumschmelze Hanau (1996). Private communication.