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Superconductive in-vacuum undulators for storage rings, concept and first operational experience

Bernhard A. [1]**, Casalbuoni**[2] **S., Hagelstein M.** [2]**, Kostka B.** [2]**, Rossmanith R.** [2]**, Steffens E.** [3]**, Weisser M.** [3]**, Wollmann D.** [1]**, Baumbach T.** [1]

1 University of Karlsruhe, 2 Forschungszentrum Karlsruhe, 3 University of Erlangen-Nürnberg

rossmanith@anka.fzk.de

Abstract. Superconductive undulators with a small period length are a novel tool in generating X-ray beams with high brlliance. The concept and the first prototype for a s storage ring was developed for ANKA, a 2.5 GeV synchrotron light source in Karlsruhe, Germany.

1. Introduction

Undulators are the preferred insertion devices in light sources. Generally speaking a relativistic electron emits synchrotron radiation into a narrow cone with an opening angle of $2/\gamma$ (γ is the ratio of beam energy and rest energy). By alternating magnetic fields the undulator forces the relativistic electrons of a light source to oscillate around the otherwise unperturbed trajectory. When the maximum deflection angle of the electron is smaller than the emission angle $2/\gamma$, the photons can interfere. In this case the undulator emits single lines instead of a white X-ray spectrum. The wavelength of the undulator line is shifted by changing the field strength of the undulator [1].

Conventional undulators are generally made from permanent magnets. The maximum field strength is limited by the magnetic properties of the permanent magnets. The maximum field strength is obtained when the permanent magnet undulators are cooled to liquid nitrogen temperature [2].

2. Superconductive undulators

In order to increase the field strength beyond the limits given by permanent magnets it was proposed that the permanent magnets be replaced by superconductive wires [3]. The concept is sketched in fig. 1. The alternating field is generated by superconductive wires with alternating current directions. The wire bundles are separated by iron poles. In order to obtain high fields the wires have to be close to the beam. Therefore the wires are in vacuum. The magnetic field strength is altered by changing the current through the undulator.

The prototype undulator described in this paper has the following design parameters:

- period length 14 mm
- 100 periods
- max. field 1.5 T at 1000 A /mm^2 at a gap of 5 mm .

An example of the measured field pattern is shown in fig. 2. The measurement is performed with a Hall probe moved through the cold bore of the undulator.

The whole device is indirectly cooled in order to bring the superconductive wires as close as possible to the beam. In this paper the first experimental results are described which were obtained by

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installing such a device in a normal storage ring. The main interest concentrates on studying how the cold surface in a small gap interacts with the high current electron beam.

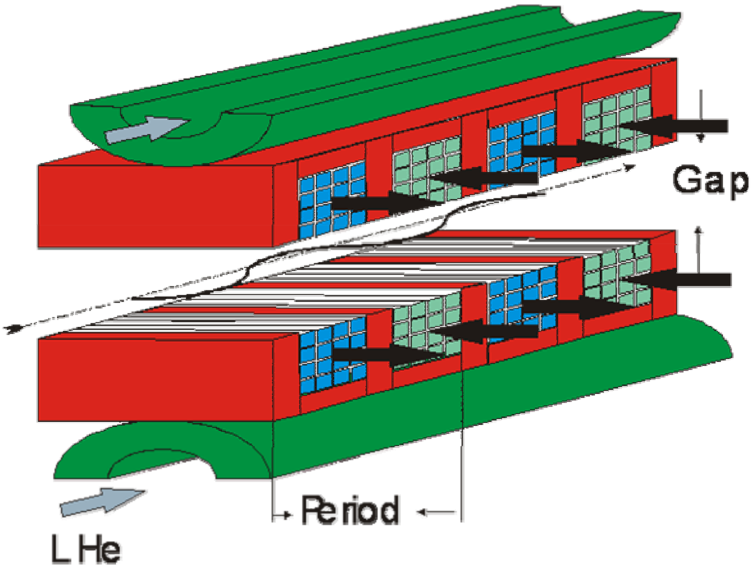

Fig. 1
Schematic layout of a superconductive in-vacuum undulator. The current direction in the wires alters. The undulator can be cooled indirectly either by liquid helium or a cryo-cooler. The arrows mark the direction of the current.

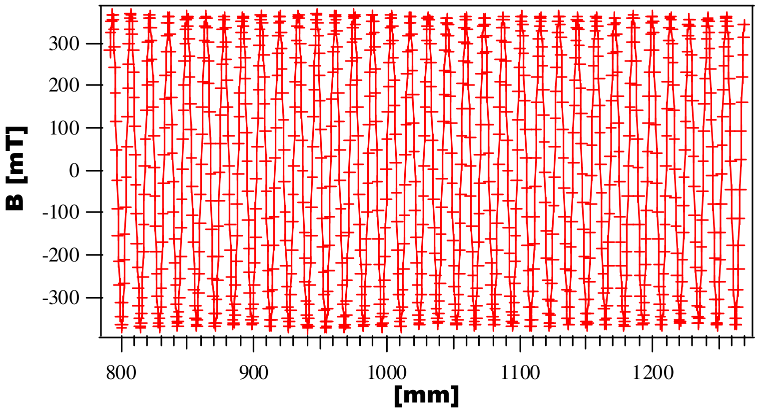

Fig. 2 Example of the measured field (several periods are selected out of 100). Gap width 8 mm, current density 500 A/mm^2. The dots mark the measured points. The length of one sinusoidal period is 14 mm.

3. The cryostat for the beam test

For a beam test in ANKA, a synchrotron light source in Karlsruhe, Germany [4], a cryostat was built which is shown in fig. 3 in a schematic drawing. The cryostat consists of two separated vacuum systems: a UHV system for the beam and an insulation vacuum system for the cold mass. The whole system was built by ACCEL Instr. GmbH in Bergisch Gladbach, Germany. The coils (green) are cooled by three Sumitomo cryo-coolers. The whole system is cryogen-free.

A taper system connects the normal beam pipe with the cold mass system and has two functions: first of all to guide the electromagnetic fields produced by the beam and secondly to make the thermal transition between the cold bore and the room temperature beam pipe. Temperature sensors are distributed inside the undulator. Three of them are shown in fig 3 (at the coils and at the taper).

In order to prevent synchrotron radiation from the upstream bending magnet hitting the cold bore, a collimator system was installed in front of the undulator (not shown in the drawings).

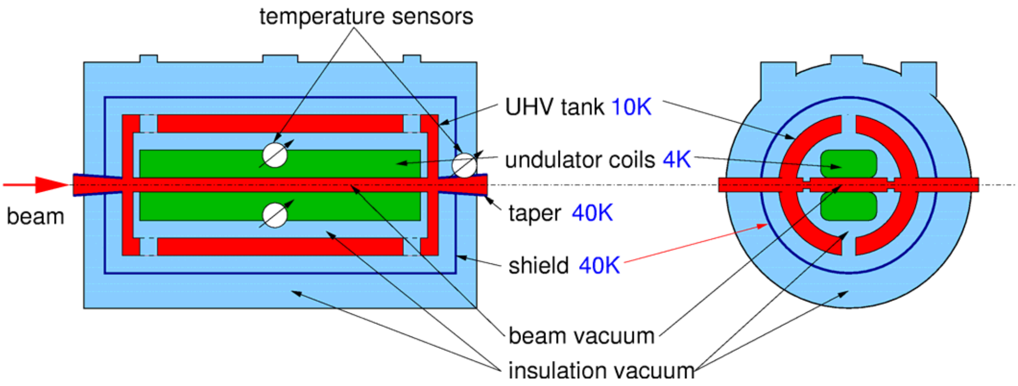

Fig. 3 Schematic drawing of the undulator. The coils (green) are cooled indirectly by three cryocoolers (not shown in this picture). The two vacuum systems (UHV beam vacuum and insulation vacuum) are completely separated. The position of three of several temperature sensors is shown.

4. Operation of the cold bore magnet in the synchrotron light source ANKA

The undulator shown in fig. 4 is the first cold-bore insertion device ever installed in a synchrotron light source. Therefore the effect of the beam on the cold bore (with a small gap) has been studied for the first time. The thermal interaction between beam and cold bore is due to one or more of the following effects:

1. The cold bore is heated by the image current. The theory describing this effect, the anamalous skin effect, has not been well investigated and therefore the predictions based on this theory are somewhat vague [5].
2. Synchrotron radiation produced by the undulator hits the cold surface and causes a temperature rise in the coils.
3. Synchrotron radiation from the upstream bending magnets hits the cold bore and heats it up. In order to minimize this effect a collimator was installed in front of the undulator (not shown in the drawings).

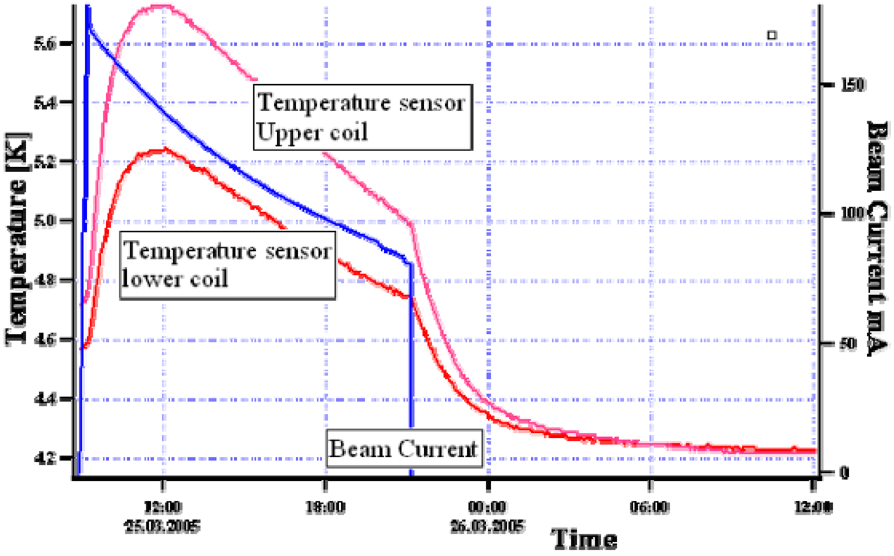

Fig. 4 Measured temperature change in the undulator device by the current (170 mA maximum beam current, beam energy 2.5 GeV). The gap width is 12 mm

4. The room temperature vacuum chamber outside the undulator (or elements of it) is warmed up by the beam and the heat is transported towards the cold bore.

Fig. 4 shows the measured temperature at the temperature sensors at the coils. The temperature rise caused by the stored beam (170 mA) is about 0.6 K. The delay between current and temperature rise of several hours is an indication that the effect is small and caused by the heating mechanism as described by point 3 or point 4.

5. The X-ray spectra obtained with the ANKA undulator

The proof that the installed undulator acts as an undulator is shown in fig. 5. This is the first measured spectrum and demonstrates that the undulator can be used during normal accelerator operation. The current through the undulator wires is 600 A, the nominal gap is 12 mm.

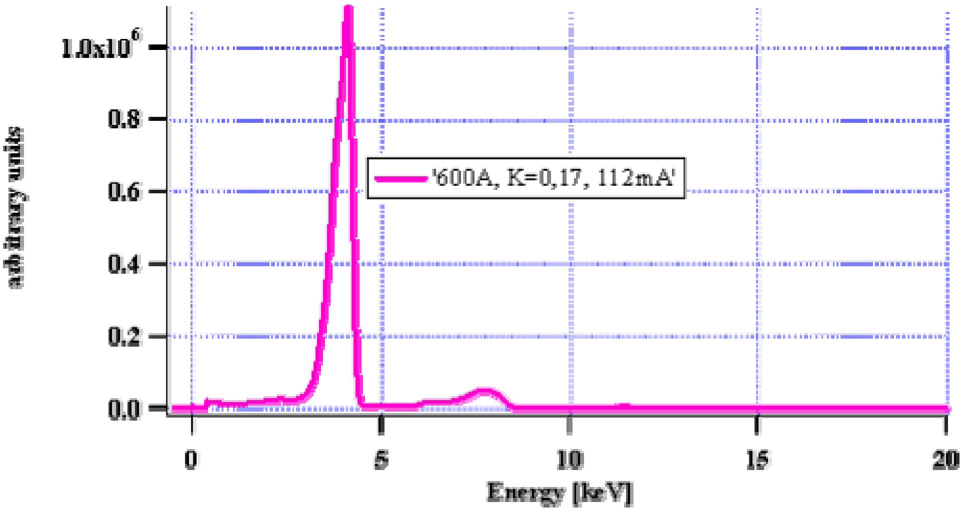

Fig. 5 The first obtained spectrum measured at the storage ring ANKA. The beam current is 112 mA, the current through the undulator is 600 A. The picture shows the first harmonic, the second and the third harmonics (very small). The vertical axis (number of photons) is arbitrary. The X-ray beam is observed through a 50 µm pinhole.

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