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NEW DESIGNS OF SHORT-PERIOD UNDULATORS FOR PRODUCING HIGH-BRIGHTNESS RADIATION IN SYNCHROTRON LIGHT SOURCES

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Abstract

We review modern state-of-the-art and new concepts of undulators planned for new generation light sources. Both superconducting and permanent-magnet-based insertion devices feature unique solutions to reach high precisely tunable fields in the period range of 10-18 mm, 2-4 meters in length and with the ID gaps of less than 5 mm. The same quest for small gaps and shortest possible period length exists also for elliptically polarizing undulators. A review of new designs in Europe, Asia and Americas will be in the focus of this presentation.

INTRODUCTION

Today's state of the art light sources, such as 3rd generation synchrotron radiation storage rings, diffraction limited storage rings, and linear accelerator free electron lasers are all using undulators for the production of high brightness synchrotron radiation.

In order to push the photon energy spectrum to higher photon energies, without increasing the energy of the accelerator electron beam, the period length should be as short as possible.

For short wavelength planar polarization, in-vacuum undulators is the main workhorse at light sources. For elliptically polarized light, small gap elliptically polarizing undulators are installed around a thin extruded aluminum vacuum chamber. The most common elliptically polarizing undulator type is the APPLE II type.

A recent development is that the new diffraction limited storage rings, as well as free electron lasers, allow the installation of round small diameter vacuum chambers, which opens up possibilities for new undulator concepts.

The intention with this presentation is to give an overview of the development of short period undulators, both planar and elliptically polarizing.

IN-VACUUM UNDULATORS

After the first proposal to build and install an in-vacuum undulator at KEK in Japan [1], there has been a tremendous evolution of the in-vacuum technology. The main initial driver of the development of in-vacuum undulators was SPring8 in Japan [2,3]. Other laboratories have followed and in-vacuum undulators have been further developed at, for example, the ESRF in France [4] and PSI in Switzerland [5]. For example, the 100 m long rows of in-vacuum undulators at the SACLA FEL is an impressive achievement [6]. The SwissFEL has a comparable installation of in-vacuum undulators at the ARAMIS beamline [5].

The in-vacuum undulator technology is fully mature and industrial partners can deliver complete undulator systems with individual undulator lengths of 5 m or more. The grade of magnet material used in the hybrid type magnet structure stands the elevated temperatures during the initial vacuum bake-out after installation and vacuum problems are rare. Mechanical problems are also rare [7]. The main problem with in-vacuum undulators is that, being close to the smallest aperture in the accelerator, they may be exposed to demagnetization, showing reduced radiation properties and changing multipole contents [8]. The maximum field strength is limited by the maximum remanence of the rare earth alloys used. Some enhancement of the field is obtained by carefully surround the poles, which are made of soft magnetic material, with permanent magnet material.

CRYOGENICALLY COOLED IN-VACUUM UNDULATORS

The shortcomings of the in-vacuum undulator, with sensitivity to radiation induced demagnetization and the limit put by rare earth materials at room temperature, were addressed by suggesting to cool the magnet rows down to cryogenic temperatures and that make use of the increased remanence and intrinsic coercivity of the magnet material at low temperatures [9].

In principle, the change from running cooling water to keep the in-vacuum undulator at room temperature, to instead run a cryogenic fluid or install cryocoolers to keep the magnet rows at cryogenic temperatures, is minor. In practice, however, it is rather complicated. Finding solutions to the problems given by the various thermal expansion rates of the mechanical supports structure, the magnet material properties that change with temperature, and the necessity of carrying out magnetic measurement in-situ under vacuum in the undulator have been challenging.

By a major effort carried out at several laboratories [10–16], the challenges have been overcome and the cryogenically cooled undulator technology is now a mature technology and it is possible to order cryogenically cooled undulators from industry. The maximum length is however limited to about 4 m.

SUPERCONDUCTING UNDULATORS

Superconducting wavelength shifters and wigglers have with success been used at synchrotron light sources for decades and the experience from these application regarding cryostats, cryocoolers, heat loads, winding techniques, and current leads was valuable for the development of superconducting undulators.

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Superconducting undulators can reach even higher fields that cryogenically cooled in-vacuum undulators. Superconducting undulator are radiation hard and can stand lost electron beams and hard x-rays without degrading. The superconducting coils will quench at the radiation incident but recover after the coils have cooled down again.

The development of superconducting undulators using NbTi to the level of commercialization has been driven by the Karlsruhe Institute of Technology [17] and APS at Argonne [18]. The performance can be further enhanced by using Nb3Sn wires that, however, requires an elaborate heat treatment after winding, which leads to further technical complications [19].

The superconducting coils are wound with a bobbin winding around a core of iron with grooves for the wire. The winding is without interruption and the wire length needed is on the order of 5 km. The end sections consist of a gradual decrease of the number of turns in the last few slots. Due to the non-linearity of the iron in the magnet structure and mechanical imperfections, small superconducting correction coils are installed in the beginning and end of the undulator. The achievable phase error of the undulator depends greatly on the mechanical precision obtained during machining and winding. The RMS phase error can be brought down by using adjustable spacers between upper and lower coils [18]. Cryocoolers are used in combination with a liquid He bath [17] or conduction cooling [18].

ELLIPTICALLY POLARIZING UNDULATORS

Elliptically polarizing undulators (EPU) give control of the polarization of the emitted light. With four rows of magnets, arbitrary polarization, both elliptical and inclined planar polarization, can be achieved.

In the same way as for undulators with planar polarization, there is a quest for the shortest possible period length for elliptically polarizing undulators (EPU), which means that the magnetic gap should be as small as possible.

EPUs are normally mounted at the straight sections using an extruded aluminum vacuum chamber that allows the magnet rows operate down to a gap of about 10 mm. Recently, the first in-vacuum EPU was installed at a storage ring [20]. The In-vacuum APPLE-II EPU is featuring force compensating magnets, interlaced support points for the magnet rows, and a staggered arrangement of the support columns through the vacuum tank.

The recent development of diffraction limited storage rings and free electron lasers has made it possible to use a round vacuum chamber and bring the permanent magnets closer to the beam compared to standard EPUs, which has enabled a new development trend beyond the APPLE-II type EPUs.

An X-type undulator has been developed at the PSI [21–24]. The PSI X-type undulator is featuring a cast iron frame, a round vacuum chamber, adjustable magnet holders for robot tuning, and a moveable wedge system to adjust the radial position of the magnet rows.

A similar, but longer, X-type undulator is being developed at Lawrence Berkeley National Laboratory (LBL). Figure 1 shows the 4 m long LBL X-type undulator. The LBL X-type undulator is built using a modular approach where smaller parts are mounted on a flat granite table. Crossed bearings for the radial and phase motion is used in order to get a compact construction. Hydraulic actuators are used for both the radial and phase motion. The full length of the LBL X-type undulator is 4 m. The present status of the development is that a 1.2 m long demonstrator unit, 1/3 of full size undulator, is being assembled, commissioned, and tested.

NOVEL CONCEPTS FOR UNDULATORS

High temperature superconductors (HTS) are very tempting to use for undulators since they can operate at temperatures above liquid helium temperatures, which make the use of cryocoolers more efficient since they can absorb larger heat loads at higher temperatures.

A very promising test has been carried out using REBCO HTS tape to wind a similar coil [25] to the coils used for the APS superconducting undulators [18]. A current density above 2 kA/mm^2 was reached at the test.

Staggered superconducting undulators, where bulk blocks of HTS are arranged in a row in a solenoidal field, have the potential to reach high field strengths for short period undulators [26–30].

The HTS tapes can also be structured by making cuts in the wire and stack multiple layers of them into an arrangement that gives a short period undulator [31, 32].

SUMMARY AND CONCLUSIONS

Since its introduction 30 years ago, the in-vacuum undulator technology has gone through a tremendous evolution and is now a fully mature technology. In-vacuum undulators populate 3rd and 4th generation light sources all around the world.

The cryogenically cooled in-vacuum undulators have over the past decade evolved to a mature technology. Compared to in-vacuum undulators, they have even higher magnetic fields and radiation hardness.

Superconducting undulators have over the past few years matured into mature technology. Superconducting undulators have even higher fields than cryogenically cooled in-vacuum undulators.

The established technology with APPLE II type EPUs can be operated at small gaps at straight sections having small cross section vacuum chambers, and in that way reach short period lengths.

The above mentioned workhorses for synchrotron radiation production will likely dominate the field of undulators for light sources over the foreseeable future.

The 4th generation light sources with diffraction limited storage rings have opened up the possibility to have small

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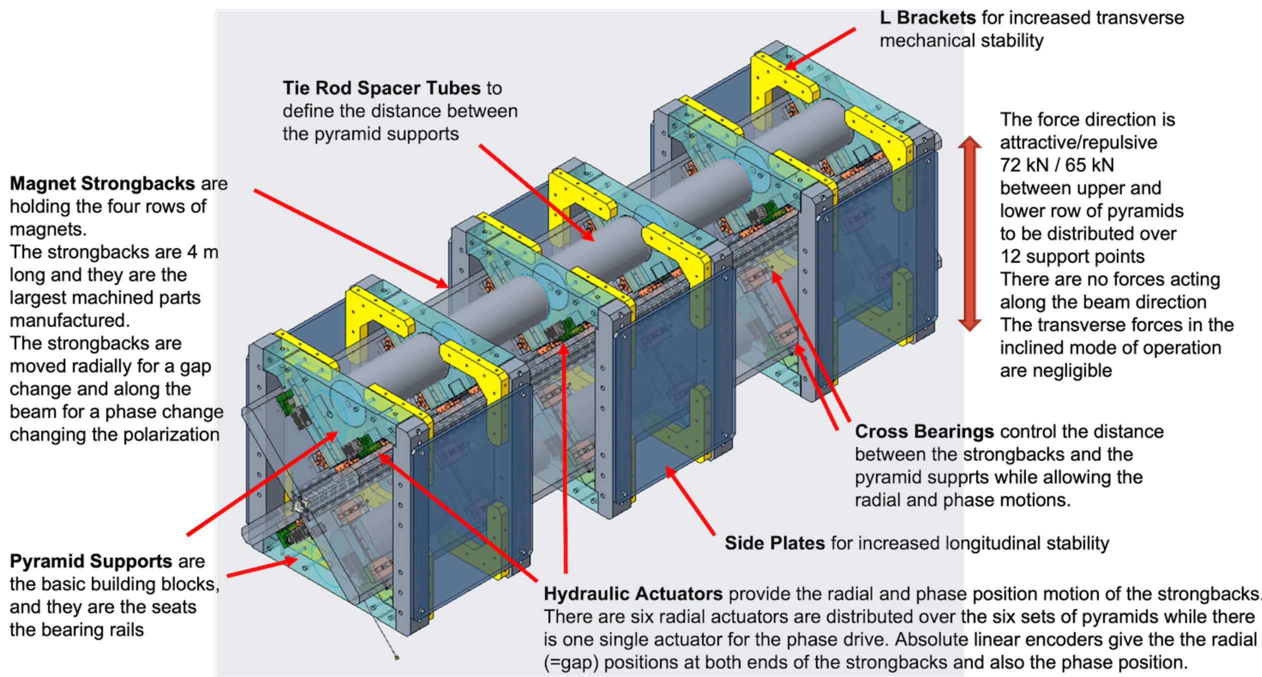

Figure 1: Overview of the mechanical system of the 4 m long LBL X-type undulator.

circular vacuum chambers in the straight sections of storage rings in addition to linac based FELs, which has led to a development of X-type undulators.

A possible breakthrough in the application of high temperature superconductors may lead to a new direction for the development of short period undulators with planar polarization.

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