LATEST DEVELOPMENTS ON INSERTION DEVICES*

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Abstract

A review is made of the latest developments of Insertion Devices. The construction of a number of sychrotron sources with energy around 3 GeV and with the goal of producing brilliant radiation around 1 angstroem is driving the development of short period small gap undulators. At this time in-vacuum permanent magnet undulators using the hybrid magnet structure represent the most efficient and most performant technology. This technology is now mature and adopted in various places. For NdFeB based magnetic structures, an increase in the magnetic field is expected from the cooling of such undulators around 150 deg K. Superconducting undulators have the potential of going further but still require substancial R&D. The status of the development of such undulators will be presented. Variable polarization undulator radiation is very much in demand. New Apple II have been built. The difficulties encountered with the operation of Apple II undulators will be presented. Electromagnet helical undulators have been built for low energy. Wiggler development has been focused on superconducting wigglers with smaller gaps than before. Finally, a number of facilities have started to build typical 100 m long permanent magnet undulators used for single pass free electron lasers based on self amplified spontaneous emission.

PERMANENT MAGNET UNDULATORS

In recent years, cost optimisation of the light source infrastructure along with the aim of producing sufficient high brilliance around 1 Angstroem (protein crystallography,…) has resulted in the construction of a number of medium electron energy sources of 3 GeV that make use of an aggressive undulator technology with short periods and gaps. The best magnet technology available today is the permanent magnet with magnet blocks placed in the vacuum of the storage ring. The idea of such in-vacuum undulators can be traced to the early 1980's with the installation on the NSLS [1], BESSY [2] and photon factory [3]. Then a real advance and coming of age took place with the large scale engineering development made at SPring-8 [4]. SPring-8 is presently operating more than 34 in-vacuum undulators each with a typical length of 4.5 m as well as a 20 m long in-vacuum undulator. 10 of such undulators are also in operation at the ESRF [5] and most light sources have a few of them. Such undulators are now commercially available [6]. Most recently built in-vacuum undulators have a magnetic length of 2m, a period of between 17 and 25 mm and are designed to operate at a magnetic gap around 5 mm. They are intended for use on a high harmonic number of the spectrum and require optimal phase errors below 3 deg rms (limit set by the energy spread of the electron beam). The simplest technology is a pure permanent magnet with, typically, 4 magnet blocks per period. A few devices have recently been built with the hybrid technology including pole pieces with high saturated field. Hybrid in-vacuum undulators typically give 20% higher field than pure permanent magnet undulators of same period and gap. Such a field increase is equivalent to a gap reduction of 1.2 mm for a typical 20 mm period device. The field tuning and shimming of hybrid undulators is somewhat more delicate. Special care must also be taken to provide a copper sheet on the block surface to channel the return current. The extremities must also allow an easy path for the return current in a variable gap geometry by means of special transition material made of copper or copper-beryllium. A short revolver type in-vacuum undulator has been developed at SPring8 [7] and is presently in operation at Pohang Light Source. It combines 4 magnet arrays with period lengths of 10, 15, 20 and 24 mm. Demagnetisation of magnet blocks made of NdFeB following exposure to high energy electrons has been reported by several groups [8-9]. A detailed investigation has been carried out by a SPring8 team on the linac of Pohang Light Source [10]. It is a particularly crucial issue for small emittance light sources since the majority of electrons are being lost at a high rate (consecutive to the short lifetime) inside the small aperture of the various in-vacuum undulators. The remedy is either to use Sm_2Co_{17} magnet blocks with a typical remanence of 1.05 T or specific NdFeB grades with a coercivity higher than 2000 kA/m and remanence around 1.1 T. Such NdFeB materials are commercially available [11].

Recently, it has been proposed to cool the NdFeB magnet array to temperatures in the 150 deg K range to benefit from both an increased remanence and coercivity. Such a device is also called a cryoundulator [12]. Figure 1 presents the results of such measurements.
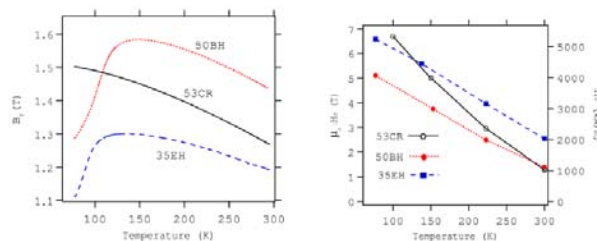

Figure 1: (Colour) Temperature dependence of the remanent fields Br and coercivity of sintered NdFeB magnets (NEOMAX 35EH and 50 BH) and a PrFeB magnet (NEOMAX 53CR).

100-150 W of cryogenic power is needed at 150 deg K. Liquid nitrogen flow or crycocoolers are suitable means to cool the magnet array. To maintain low phase errors, it is essential to minimize the mechanical and associated

magnetic gap distortion at cryogenic temperature. In this respect liquid nitrogen cooling looks more promising. Several groups have embarked upon detailed developments including SPring-8 [4], NSLS [13] and ESRF [14]. A complete magnetic field measurement measured at small gaps and cryogenic temperature is a key requirement to validate a design before putting it on a synchrotron beamline. The benefit of cryogenic cooling down to 150 K is primarily a large increase of intrinsic coercivity by at least a factor of 2 above room temperature values. In this case, NdFeB materials with remanence in excess of 1.25 T at room temperature can be used. In addition, the remanence increases by about 12% from room temperature to 150 K. When compared to Sm_2Co_{17} based device (same gap and period) a net gain of 30% can be expected for the peak field. If the highest remanence NdFeB grade compatible with the demagnetizing field at 20 deg C is used (coercivity ~ 1000 kA/m) a net increase of 45% could be reached beyond Sm_2Co_{17}. Whether such material can be used is still unclear. No baking is allowed and the required low pressure needed to minimise the Bremsstrahlung will only be achieved if enough cryogenic pumping takes place. Experience with electron beam is needed.

   When low photon energy or if a medium high photon energy is the goal (too high for undulators) or if variable polarisation is mandatory, permanent magnet undulators and wigglers with magnet blocks placed in air are still the right choice. To reduce the gap, a vacuum chamber with low aperture and thin wall thickness must be used. The preferred material is aluminium for reason of beam stability (resistive wall instability) as well as production cost. The small aperture implies a poor vacuum conductance resulting in pressure rise and significant Bremsstrahlung production under beam exposure. One successful solution consists in using an antechamber with pumping by strips covered with Non Evaporable Getter (NEG) material ribbon as developed at APS [15] .

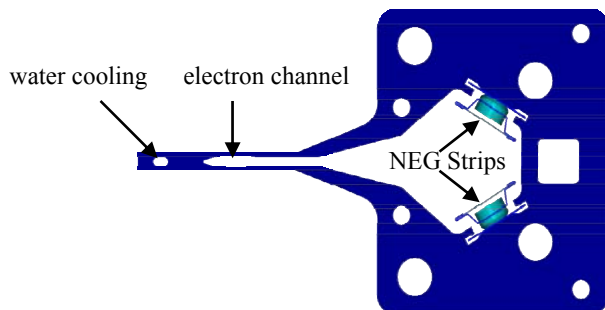water cooling   electron channel

NEG Strips

Figure 2 : APS type undulator chamber. The pumping is made by NEG strips located in the anti-chamber.

   The drawback is the transverse space occupied by the antechamber which has an effect on the undulator or wiggler design. This difficulty can be avoided by coating the chamber wall with NEG [16] which provides not only some pumping but also shows greatly reduced photon

induced desorption. Chambers with internal aperture of 8 mm, and 1 mm wall thickness and a length of 5 m are routinely used at the ESRF.

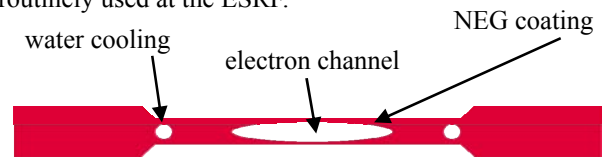water cooling   electron channel   NEG coating

Figure 3 : ESRF type undulator chamber. The pumping is obtained by coating the inner wall of the chamber with a 0.5-1 micrometer layer of an alloy of Ti, Zr, V (NEG material).

SUPERCONDUCTING UNDULATORS

   Superconducting undulators have been around for years. It was used in 1975 in the first Free Electron Laser (FEL) ever operated at the HEPL in Stanford. A superconducting undulator was also installed on the ACO storage ring in 1979 at Orsay, France as a source of synchrotron radiation and for an FEL experiment. The development has been interrupted following the successful introduction of permanent magnet undulators. Several groups have continued this development but is is only in 2002 that a technical design was proposed and a short prototype built with NbTi wire, whose field was shown to exceed significantly that available from an in-vacuum permanent magnet undulator [17]. It reached 1.2 T for a period of 14 mm and a magnetic gap of 5 mm. R&D started in various groups around the world. A 1 m long undulator has been produced by ACCEL for the National University of Singapore for use in low power beam. In 2005 another prototype built by ACCEL was installed and operated on the ANKA storage ring [18-19]. It has a period of 14 mm, and a length of 1.4 m. The gap can be varied. It is a cold bore device with beam circulating in a chamber at 4.2 deg K. Radiation spectra were recorded in good agreement with expectations with ring current as high as 200 mA. Several problems were encountered during the undulator assembly. The device also suffers from quench at lower current than the design value. Because of these difficulties, the field quality and the peak field are not yet comparable to up-to-date in-vacuum permanent magnet undulators.. In the United States a collaboration has been established between APS, NSLS, LBNL and SLAC to perform the required R&D. APS has built some short sections of coils and tested the quench current and stability under heatload [20]. A magnetic measurement system designed and optimized for superconducting undulators has been built at NSLS [21]. Theoretical studies [22] and prototyping [23] work has already been started with Nb3Sn in order to benefit from the higher critical current. Compared to NbTi, a magnetic field increase by about 30-50% is expected. Efforts were not restricted to planar field undulators as several authors have also studied variable polarisation undulators [24-26]. Pole shimming to reduce phase errors is also under investigation in various institutes [27]. A study was carried out with the aim of installing such a

device in the ESRF [28] but was recently abandoned because of the large beam induced heatload. Some of the technical issues involved in the design of a superconducting undulator are:

- the requirement to insulate the ultra high electron beam vacuum from the coil through the thinnest vessel.
- The large heatload generated by the upstream bending magnet radiation as well as from the return current in the chamber wall which amounts to 5 (9) W for a 2 m long undulator on the ESRF (Diamond) operated in 2/3 filling mode at 300 mA (500 mA) and a gap of 5 mm.
- Need for magnetic field shimming operating at any current in the coil.
- High tolerance of machining and assembly of the coil and yoke

Some of these issues were discussed and reviewed in a workshop at ESRF [29]. It appears that NbTi based superconducting undulators require a few more years of development and maturity before being used in production in a third generation light source. It is highly desirable to reduce the beam induced heatload which can be done by increasing the bunch length using harmonic RF cavities and using the special end section of the dipole to reduce the upstream bending magnet radiation. The use of High Tc Superconductors in conjunction with permanent magnets at intermediate cryogenic temperature has also been proposed [30].

VARIABLE POLARIZATION UNDULATORS

The Apple II type permanent magnet undulator is the most popular source of undulator radiation of variable polarisation. Most sources have several units of such undulators. A few more devices have been produced recently [31]. The shimming is delicate but is becoming well understood by a number of groups. Industrial companies have or will soon provide such devices. Several light sources have suffered from beam perturbation induced on the stored beam. Perturbations of a different kind have been observed. Some come from the non linearities of the nominal field which are particularly severe in the mode presenting a horizontal magnetic field on axis. Such non linearities can be reduced by a special shimming [32] as experienced at BESSY [33]. Such perurbations to the beam dynamics can be predicted from the 3D field description and are efficiently implemented in tracking code using the kick map methods [34]. Some other perturbations have been reported which are generated from residual field errors either through an imperfect multipole shimming or through a skew quadrupole varying with the phase of the magnet arrays [35]. Indeed obtaining precise transparency in the operation of an APPLE II is delicate and made more complicated by the number of mechanical degrees of freedom involved. For the production of low energy photons, long period and low field are needed. It may

then be of interest to produce the field using electromagnets as it was done recently on two devices at SOLEIL [35]. One 640 mm period, 10 m long device without any iron yoke and a field of 0.1 T has been produced and is installed on the ring. It uses three power supplies to generate any elliptical polarization. A 256 mm period 3m long with iron yoke and field of 0.4 T and two power supplies are also installed and have achieved linear or helical polarization.

WIGGLERS

The trend worldwide is to replace permanent magnet wigglers by short period in-vacuum undulators. Nevertheless, there are limits. Some applications require a large angle fan which can only be produced by wigglers or need very high photon energies which are not reachable by in-vacuum undulators due to the reduced brilliance on the very high harmonic numbers of the spectrum. Indeed most recent facilities will accommodate one or a few wigglers. Those wigglers can be built with permanent magnets or superconducting technology. Table 1 presents the characteristics of recently built superconducting wigglers.

Table 1: Characteristics of Recently Built Superconducting Wigglers

Light Source	Year	Field [T]	Period [mm]	N.of Poles	Beam Aperture [mm]
BESSY-HMI	2002	7	148	17	19
ELETTRA	2002	3.7	64	49	16.5
MaxLab	2002	3.5	61	48	12.2
CLS [37]	2005	2.2	34	63	13.5
SRRC [38]	2006	3.2	61	16	11
Diamond	2006	3.5	64	49	10

The trend is to reduce the gap as well as shrink the period in order to maximize the spectral flux over a given length of straight section. Most of those wigglers are cooled by several two stage Gifford Mac Mahon type cryocoolers. All use a shielding screen to insulate the electron beam UHV from the cold mass and intercept the beam induced heatload, with the exception of the Maxlab wiggler. Most of them were built by the Budker Institute [6] except the MaxLab (build by MaxLab) and the SRRC wigglers, (built by Wang NMR Inc. [6]).

SASE FEL UNDULATORS

A 6 x 4.5m long SASE undulator has been built, installed and operated at DESY on the TTF-II facility. It uses the same magnetic structure as the TTF-1 undulator with the FODO quadrupoles removed from the magnet array and placed in the diagnostic sections between the undulator segments. It is a hybrid structure with a fixed gap of 11 mm. A 120 m long undulator is being manufactured for the LCLS project at SLAC [39]. It is made of 33 segments each 3.4 m long with a magnetic hybrid type operated at a fixed gap of 6.8 mm and a

period of 30 mm. A lateral gradient will allow some tuning over a limited range. An undulator has been built for the SCSS project at Spring8 which consists of a number of 4.5 m long segments of in-vacuum undulators with periods of 15 mm, with a variable gap (as low as 2 mm). It is a planar structure made of a pure permanent magnet assembly with magnetization inclined at 45 degrees with respect to the horizontal [40]. A similar type of undulator structure is envisaged for the Pohang Light Source XFEL [41]. The XFEL Project in DESY has the most impressive project of undulators whose characteristics [42] are summarized in Table 2:

Table 2: Undulator Foreseen for the XFEL Project in DESY

Name	Period [mm]	Gap [mm]	Peak Field [T]	Length [m]
SASE1	35.6	10	1.0	201
SASE2	48	10-19	1.37-0.63	256
SASE3	80	10-23	0.91-0.44	128
U1,U2	20.0	6-22	0.98-0.1	122

The undulators are built from 5 m long sections of hybrid types with variable gap frames. The SASE undulators, currently under construction, are planar. A higher amplification rate per unit length can be provided by helical undulators resulting in a more compact undulator system. An Apple III design has been proposed by BESSY [43] to increase the helical field by 40% beyond that achieved by the Apple II undulator.

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