UNDULATOR TECHNOLOGIES FOR FUTURE FREE ELECTRON LASER FACILITIES AND STORAGE RINGS

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Abstract

Insertion devices (undulators and wigglers) are key components for high brightness third generation synchrotron sources and for the amplifying medium of free electron lasers, which appear to impose some particular constraints. Different technological developments carried out worldwide lead to improved undulator performance. In particular, the advances concerning the in vacuum permanent magnet systems, especially for short period ones with the operation at cryogenic temperature with NdFeB or PrFeB magnets or for long period ones where in vacuum wigglers is described. Secondly, progress in superconducting undulators is reported. Then, Elliptical Polarized Undulators (EPU), with in particular the DELTA undulator and fast switching of the polarization are discussed. Finally, exotic concepts including variable period, adaptative gap, bi-periodic device, transverse gradient undulator/wiggler or extremely short period systems are presented.

INTRODUCTION

Modern accelerator based light sources use extensively undulators and wigglers creating a permanent periodic (period λ_o) magnetic field B_o for the production of intense of radiation for users [1, 2, 3]. In the case of an planar undulator creating a sinusoidal field in the vertical plane, the synchrotron radiation on the axis is emitted at the resonance wavelength λ, $\lambda = \lambda_o (1+K^2/2) /2\gamma^2$, and its odd harmonics, with a linear horizontal polarization, with K the deflection parameter ($K = 0.94\ \lambda_O(\mathrm{cm})\ B_O(\mathrm{T})$), γ the normalized energy of the particles. Elliptically polarized undulators generate fields in two planes with adjustable phase and provide circular polarization. The photon energy can be scanned by a modification of the undulator magnetic field. In the "undulator" regime (rather small K value), the radiation emitted from the dfferent half periods interferes. These interferences can be constructive and the radiation is produced in a very intense spectral rays (harmonics) form. In the "wiggler" regime ($K >> 10$), the radiation of the different harmonics overlaps and is similar to the dipole one, with a higher intensity.

The third generation light sources arose on storage rings with reduced emittances and high number of installed undulators or wigglers. They provide a high average brilliance and a partial transverse coherence thanks to the low beam emittance in the storage ring and to the high number of insertion devices generating spontaneous emission. Medium energy storage rings such as SOLEIL, DIAMOND, CLS, ALBA, TPS, Australian Synchrotron, NSLS II, MAX IV... look for high field short period undulators to cover the high energy photon range, to the difference of the high energy rings such as SPring-8, ESRF, APS, PETRA-III, PEP-X mainly devoted to produce hard X-ray. Ultimate Storage Ring (USR) [4, 5, 6, 7] with reduced emittances will enable to generate high brilliance, with larger energy spread which can affect somehow the high order harmonics bandwidth of undulator radiation. Third generation light pulses are limited in terms of pulse duration to a few ps, unless particular optics [7] or slicing scheme [8, 9] are applied, but with reduced total flux.

Energy Recovered linacs [10] joins some advantages or rings and linear accelerators for X-ray production, in particular the short pulse duration and the beam recirculation.

Fourth Generation Light Sources generally use linear accelerators for short pulse duration (femtosecond range). In addition, they enable longitudinal coherence by setting in phase the emitting electrons thanks to the Free Electron Laser (FEL) process. A light wave of wavelength (spontaneous emission progressing along the undulator, stored in an optical cavity or external seed) interacts with the electron bunch in the undulator, inducing an energy modulation of the electrons; which is gradually transformed into density modulation at the wavelength and leads to a coherent radiation emission. Nowadays, two FEL on linear accelerator, LCLS (Stanford, USA) [11] and SACLA [12] (Harima, Japan), are operating in the 1 Å region with 100-10 fs pulse and GW peak power. Saturation is achieved after typically one hundred meter of undulators. FLASH [13], SCSS Test Accelerator [14] and FERMI@ELETTRA [15] operate in the soft X-ray region. It is also considered to replace the conventional linac is replaced by a Laser Wakefield Accelerator (LWFA), which provides GV/m of acceleration with very short bunches [16], such as for the LUNEX5 project in France [17].

CONSTRAINTS

The trend is to push towards more compact system, implying for undulators higher fields, small gap for permanent magnet one, operation at lower temperature (cryogenic and superconducting systems). Specific wigglers are also requested for USR.

The requirements for the insertion devices depend on the accelerator type (see table 1). Indeed, multi-turn recirculating vacuum chambers should be rather wide, especially in the horizontal dimensions for accelerators such as storage rings for synchrotron radiation because of the beam excursion during injection, leading to a flat vacuum chamber. In contrast, single or few pass accelerator such as linac, Energy recovey Linac (ERL) or Laser WakeField Accelerator enable small aperture cylindrical vacuum chamber, enabling to add magnetic material on the sides.

A small value of the phase error enables operation on the undulator harmonics especially on third generation storage rings of intermediate energy. It is then less critical for a Free Electron Laser application where operation takes place mainly on the fundamental wavelength and its first harmonics.

In case of short bunches, impedance should be maintained small imposing some restrictions in the vacuum chambers type (size, roughness, discontinuity) and particular designs of the RF transitions from the magnet arrays to the neighboring vacuum chamber [18, 19] and proper impedance modeling [20].

Heat load deposited by the electron beam due to the wakefields [21] (and its image current) or previous synchrotron radiation implies to install a liner [22], i.e. a conductive foil, on the magnet arrays or to protect a superconducting undulator to avoid quenching.

Multipolar terms can be critical for storage rings for lifetime and beam injection efficiency [23]. Setting the scraper for being the preferred beam loss position enables to avoid magnet degradation of in-vacuum devices.

Alignment of undulator segments for FEL is critical [24].

Table 1: ID Requirements

Type	Storage ring	Linac/ERL	LWFA
emittance	E^2	1/E	
Beam size (µm)	100 (H)-10 (V)	50-10	10-3
vacuum chamber H /V aperture	flat min gap: 5 mm	round (bore 5 mm), min. gap : 3 mm	round
charge	high	1 nC	10 pC
Pulse duration	10 ps	100 fs	10 fs
impedance	very critical	critical	critical
field integrals	very critical	very critical	very critical
double field integrals	very critical	very critical	very critical
phase error	very critical for high harmonics	critical	critical
multipoles	critical	less critical	not critical

FROM IN-VACUUM UNDULATORS TO CRYOGENIC ONES AND IN-VACUUM WIGGLERS

In-Vacuum Undulators (IVU) generate high magnetic field by placing directly the magnets inside the vacuum chamber. After a first prototype built at BESSY [25]. A first undulator (90 x 40 mm, NdFeB magnets, 10 mm gap, 0.82-0.36 T field), equipped with NEG and sputter ion pumps, has been installed on TRISTAN [26] after vacuum conditioning at 115°C for magnets stabilised at 125°C. IVU were then actively built at SPring-8, with in particular a 30 m long in vacuum undulator made of different segments (780 x32 mm, 12 mm gap, field of 0.59 T, 3.6° phase error) [27] or a revolver IVU comporting four rotating undulators (6 mm x 133, 10 mm x 100, 15 mm x 66, 20mm x 50 providing a field of 0.74, 1.07, 1.32, 1.44 T) for a minimum gap of 3.2 mm [28] installed on Pohang Light Source [29].

Magnets are chosen with sufficient coercivity, such as Sm_2Co_{17} (remnant field $B_r \leq 1.05$T; coercivity $\mu H_{cj} = 2.8$ T) or an intermediate grade of $Nd_2Fe_{14}B$ ($B_r \leq 1.26$T; $\mu_o H_c$ =. 2.4T), in parallel to extensive demagnetization tests [30]. Cooling down $RE_2Fe_{14}B$ Rare Earth (RE) permanent magnets enables to increase B_r by 10% and H_{cj} by a factor of 3 [31]. Whereas $Nd_2Fe_{14}B$ cannot be operated below 130 K because of the appearance of the Spin Reorientation Transition (SRT) [32] requiring the cryogenic undulator to be cooled down to the liquid nitrogen temperature and heated back to the working temperature to 140 K, $Pr_2Fe_{14}B$ based undulators can be directly cooled and operated at 77 K because of the absence of the SRT.

After a first prototype at SPring-8 built with $Nd_2Fe_{14}B$ permanent magnets [33], full scale cryogenic Permanent Magnet Undulator (CPMU) have been built at ESRF [34, 35], SLS [36] and DIAMOND [37]. PrFeB cryogenic prototypes have been built at NSLS-II [38], SOLEIL [31], BESSY [39]. A full scale PrFeB cryogenic undulator has been built and installed at SOLEIL [40]. Due to the operation at low temperature, the gap opening due to the contraction of the supporting rods, the period reduction due to the girder contraction and the phase error should be compensated. Particular in-vacuum magnetic measurement systems with calibration of the Hall probe at low temperature and feedback on the position have been developed. Compared to an in-vacuum undulator of equivalent spectral range (i.e. same K), the flux is enhanced thanks to the field increase and to additional periods for a given total length. Further field enhancement can be achieved with addition of high temperature superconducting coils [41].

In-vacuum wigglers can take advantage of the small gaps which enables to reach high fields, to reduce the period length, thus to produce high photon energy. The large magnetic forces can be compensated with springs as in the SOLEIL case [42], or with additional arrays of permanent magnets [43, 44]. They ensure a smooth daily operation without quench risk and cheap operation without He consumption. The strong dynamic integral occurring off axis [45] can be pre-compensated at the stage of the magnetic assembly, so that the electron beam dynamics of storage rings is not be strongly affected.

SUPERCONDUCTING UNDULATORS

The idea of using superconducting coils for creating an undulator emerged in the seventies, with an application to the first Free Electron Laser demonstration in the infra-red [46], to synchrotron radiation [47] and to storage ring FEL [48] with periods of a few cm and field up to 0.5 T. Present use of NbTi coils enables to achieve 0.69 T at 7 mm gap for a 15 mm period [49], or 0.81 T with 14 mm

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period and 4 mm gap on a small scale device, 1.15 T on a 11.5 mm period for a 5.85 mm gap on a 1.74 m device [50], 1.4 T at 10 mm gap with 16 mm period [51], which is providing presently safe operation at APS. High temperature superconductors tape undulators are also under development [52, 53]. Particular instrumentation and diagnostics such as COLDIAG for magnetic measurements at low temperature [54] or CASPERI form electron beam heat load measurement [55] have been developed.

ELLIPTICALLY POLARIZED UNDULATORS (EPU) AND FAST POLARIZATION SWITCHING

Electromagnetic technology with [56] or without poles [57] suits well for the fabrication of rather long period EPU, providing the possibility of any type of polarisation or aperiodicity. Among the Permanent Magnet based EPU such as crossed EPU [58], HELIOS [59], Diviacco/Walker scheme [60], APPLE-I [61], APPLE-II [62], APPLE-III [63], a 6-arrays device [64], DELTA [65], the APPLE type provides the largest horizontal and vertical fields whereas the DELTA undulator enables to reduce significantly the aperture for the electron beam. For out-of-vacuum systems, APPLE-III and DELTA are well suited for linac or Energy Recovery Linac applications. The DELTA undulator prototype was successfully tested in ATF [66]. DELTA undulators have been built for SPARC [67] and LCLS-II [68]. Magnetic forces can be an issue, requiring in some case specific carriages [69] or modules and magnet holders [70].

Fast switching of the polarisation from circular right to circular left and vice-versa can be achieved in setting a chicane enabling to select the radiation from a first or a second segment, or in combining electromagnets and permanent magnet provides as installed at NSLS [71], ESRF [72], SOLEIL [73] where coils are replaced by Cu current sheets [74]. In such cases, after performing static corrections, dynamic corrections considering the vacuum chamber influence are implemented.

Quasi-periodic EPU can be applied to APPLE-II [75] or to the so-called Figure-8 [76], for out-of-vacuum and in-vacuum versions. The quasi-periodic scheme works properly in horizontal linear mode but it is less efficient in vertical linear mode [77].

EXOTIC CONCEPTS

Changing the period have been considered on the split pole undulator [78] where an undulator in being built for the THz FEL in Korea [79] or on a composite period undulator [80] enabling to enlarge the wavelength tuneability of a FEL. The superconducting technology is well suited for bi-period undulator / wiggler [81].

The proposed adaptive gap undulator concept [82] enables to satisfy the stay-clear and impedance constraints with segments of different periods. The flux enhancement is typically of 10 %.

Transverse gradient undulators or wigglers can be used to control the partition number [83] as demonstrated on DCI [84]. It is of interest either for emittance reduction on inverse Compton scattering source [85] or on third generation light sources [86] as an alternative to damping wigglers or for handling the large energy spread [87] of laser wakefield accelerator for FEL amplification [88].

Finally, dramatic reduction of undulator period is actively investigated using various techniques and concepts such as microstructure driven laser undulator [89], surface micro-machined undulator under test at UCLA [90], micro-machined magnet undulator [91], RF undulator [92] tested on NLCTA and even optical undulator [93]. Issues concern in particular the wavefields with these extremely low gaps, magnetic measurements. In addition, the low value of the deflection parameter limits the emission intensity and the harmonics operation. However, they can lead in the future to compact sources, in particular when coupled to low-size accelerator, such as laser wakefield accelerators.

CONCLUSION

Clear advances is reported for permanent magnet based systems, superconducting undulators, EPU, and the different technoligies are sometimes combined. New concepts have been proposed, for enhanced flexibility or perfomances of the light properties, but even also for a manipulation of the electron beam itself besides the compensation of the induced effects. New technologies are developing toward ultra-short period undulators. Aimgin at compact light sources. Undulator and wigglers are crucial devices for future light source for radiation production and even for electron beam properties manipulations for enhanced coherence, compactness, law size of the radiation on the sample, more flexibility for photon users.

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