Insertion device development for a broad range of radiation properties

M.E. Couprie
Synchrotron SOLEIL, L’Orme des Merisiers, Saint-Aubin, BP 48, F 91 191 Gif-sur-Yvette, France
couprie@synchrotron-soleil.fr

Abstract. On intermediate energy synchrotron radiation light sources, a broad spectral range can be covered by a wide panoply of insertion devices, from long period electromagnetic systems to short period in vacuum undulators. Furthermore, in-vacuum wigglers can be developed as an alternative to superconduting ones. The effects on the electron beam, also more critical at low electron beam energies, require specific care on the magnetic field multipolar terms and can include direct compensation of the dynamical integral. In addition, for field enhancement at short period, cryogenic undulators are now currently developed, with a recently installed PrFeB based undulator at SOLEIL. Besides, variable polarisation can be provided with APPLE-II type undulators, with possible aperiodicity. Rapid switching can be achieved with electromagnet/permanent magnet undulator using copper sheets coils.

1. Introduction
Insertion devices (undulators and wigglers) are key components of modern accelerator based light sources either for emitter of radiation to users [1] or for damping excitations to reduce the emittance [2]. Creating a periodic permanent magnetic field, they force the relativistic electron beam to underpass various trajectory oscillations, leading to emission of synchrotron radiation from the various periods. Depending on the deflection parameter value \( K = 0.94 \lambda_0 \text{cm} B_0 \text{T} \) with \( \lambda_0 \) the period and \( B_0 \) the peak magnetic field, the radiation is emitted in series of sharp spectral lines resulting from the interferences from alternative field inversions in the undulator regime or in a dipole-like broader spectrum resulting from the overlap between the different harmonics in the wiggler regime \( (K>10) \). Low emittance third generation can accommodate a high number of installed undulators leading to a brightness increase and a partial transverse coherence. 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. An example of the SOLEIL [2] covered spectral range with the panoply of insertion devices is shown in fig.1. Fourth Generation Light Sources (4GLS) enable longitudinal coherence by setting in phase the emitting electrons thanks to the FEL process. Nowadays, two FEL on linear accelerator, LCLS
(Stanford, USA) [3] and SACLA [4] (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 [5] and FERMI@ELETTRA [6] operate in the soft X-ray region. In the so-called Fifth Generation Light Source (5G) the conventional linac is replaced by a Laser Wakefield Accelerator (LWFA), which provides GV/m of acceleration with very short bunches [7], such as for the LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) project in France [8].

The requirements for the insertion devices depend on the accelerator type (see table 1). Indeed, vacuum chambers in multi-turn recirculating machines should be rather wide, especially in the horizontal dimension 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 recovery Linac (ERL) or Laser Wakefield Accelerator enable small aperture cylindrical vacuum chamber, enabling to add magnetic material on the sides. Again, because of recirculation, multipolar terms can be critical for storage rings for lifetime and beam injection efficiency. 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 [9]. Impedance restrictions result from extremely short bunches, vacuum chambers type (size, roughness, discontinuity) and number of turns.

![Figure 1. Brightness produced by the insertion devices of SOLEIL calculated with SRW [10]. The period is given in mm with HU for Helical undulator, BM for bending magnet, WSV for in-vacuum wiggler, W for wiggler, and U for undulator](image)

2. **In-vacuum undulators**

In-vacuum undulators enable to reach a higher field by placing directly the magnets inside the vacuum chamber. After a first prototype at BESSY [11], they have been extensively developed in Japan [12], with in particular a 30 m long device [13] and revolver one [14]. Specific RF tapers have been designed for preserving a proper value of the impedance [15, 16] with or without water cooling. At SOLEIL, the initial design leading to temperature increses for particular gaps have been modified to enable operation at 500 mA. Care is taken as well not to introduce bunch lengthening in presence of the closed insertion device, as confirmed both by calculations and measurements with a double sweep streak camera. The liner, a conductive (generally Ni-Cu) foil is
laid on the magnet arrays to prevent heat load from image current due to wakefields or up-stream synchrotron radiation. Liner degradation has occurred [17]. Proper calculations of the heat load on the liner, tapers due to up-stream synchrotron radiation, wakefield for the different bunch patterns is generally performed to properly design the thermal budget of the in-vacuum undulator.

Magnet for in-vacuum devices are selected with sufficient coercivity, so that Sm2Co17 (remnant field B_r ≤ 1.05T; coercivity μH_c = 2.8 T) were preferred for a while to Nd2Fe14B (B_r ≤ 1.4T; μoHc = 1.4-1.6) for which an intermediate grade have been selected (B_r ≤ 1.26T; μoHc = 2.4T), in parallel to extensive demagnetization tests [18]. Regarding machine protection, setting the scraper values so that they become the preferred beam loss position in taking into account the betatron function at their and in-vacuum location prevents from loosing the beam in the permanent magnets. Cooling down RE2Fe14B Rare Earth (RE) permanent magnets enables to increase B_r by 10% and H_c by a factor of 3 [19]. Whereas Nd2Fe14B cannot be operated below 130 K because of the appearance of the Spin Reorientation Transition (SRT) phenomenon [20] requiring the cryogenic undulator to be cooled down to the liquid nitrogen temperature and heated back to the working temperature to 140 K, PrFeB based undulators can be directly cooled and operated at 77 K because of the absence of the SRT. Cryogenic Permanent Magnet Undulator (CPMU) have been proposed and tested at SPring-8 in 2004 [21] with a prototype built with Nd2Fe14B permanent magnet at cryogenic temperature. Full scale installed Nd2Fe14B cryogenic undulators have been built at ESRF [22], [23], at SLS [24] and DIAMOND [25]. PrFeB cryogenics prototypes have been built at NSLS-II [26], SOLEIL [19], BESSY [27]. A full scale PrFeB cryogenic undulator has been built and installed at SOLEIL [28] (see fig. 2). 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 in different places. Compared to an in-vacuum undulator of equivalent spectral range (i.e. same deflection parameter), the flux is enhanced thanks to the field increase and to additional periods for a given total length (a smaller period leads to the same deflection parameter).

![Figure 2. Comparison of the magnetic field of the PrFeB cryogenic undulator at room and low temperature.](image)

Table 1: Characteristics of full scale CPMU installed in 3rd generation synchrotrons and prototypes developed in different laboratories. λ_o: period, B_r: remnant magnetization, H_c: Intrinsic coercivity at room temperature, L: Length, T: working temperature, 3G for third generation light source.

| Installation   | Magnet type | B_r (T) | H_c (kA/m) | L (m) | Baking | T (K) |
|----------------|-------------|---------|------------|-------|--------|-------|
| SPring-8       | Nd2Fe14B    | 1.41    | 1114       | 0.6   | No     | 135   |
| NSLS II        | PrFe14B     | 1.37    | 0.1        | 0.1   | Yes    | 150   |
| SPring-8/SLS   | Nd2Fe14B    | 1.33    | 1670       | 2     | No     | 135   |
| ESRF n°1       | Nd2Fe14B    | 1.16    | 2600       | 2     | Yes    | 150   |
| ESRF n°2       | Nd2Fe14B    | 1.37    | 2          | 2     | No     | 150   |
| Danfysik/Diamond | Nd2Fe14B    | 1.31    | 1670       | 2     | No     | 150   |
| SOLEIL         | Nd2Fe14B    | 1.41    | 1114       | 0.1   | No     | 145   |
| SOLEIL         | PrFe14B     | 1.35    | 1355       | 0.1   | No     | 77    |
| SOLEIL         | PrFe14B     | 1.35    | 1355       | 2     | No     | 77    |
3. Quest for high field undulators

Different paths towards higher field undulators are followed. R&D is under progress on superconducting undulators [29] with achieved 0.69 T at 7 mm gap for a 15 mm period [30], or 0.81 T with 14 mm period and 4 mm gap on a small scale device, and 1.15 T on a 11.5 mm period for a 5.85 mm gap on a 1.74 m device [31]. R&D on insertion devices using high temperature superconductors is also carried out [32]. Besides, combined permanent magnet undulator with high temperature superconducting coils, as proposed and tested in SPring-8 [33] enables the field for a U15 undulator at 5.5 mm to grow by 7% with coils at 77 K and 22% with coils at 40 K. The proposed adaptive gap undulator concept [34] enables to satisfy the stay-clear and impedance constraints with segments of different periods. The flux enhancement is typically of 10%.

4. In-vacuum wiggler

Similarly to in-vacuum undulators, in-vacuum wigglers take advantage of the small gaps which enables to reach high fields. Small gap technology also enables to reduce the period length, thus to increase the number of periods and then to produce high photon energy. As the field is strong, the magnetic forces can be compensated with springs as in the SOLEIL case [35], or with additional arrays of permanent magnets (such as on SPring-8 [36] and BEPC [37]). They ensure a smooth daily operation without quench risk and cheap operation without He consumption. The strong dynamical integral occurring off axis [38] can be pre-compensated at the stage of the magnetic assembly, so that the electron beam dynamics of storage rings will not be strongly affected, as shown in fig. 3.

5. Elliptical Polarised Undulators (EPU) and fast switching of the polarisation

Electromagnetic technology with [39] or without poles [40] suits well for the fabrication of rather long period EPU, providing the possibility of any type of polarisation or aperiodicity. Analogue feedforward ensures the synchronisation of the main and corrector power supplies, enabling for the transient orbit deviations to be cancelled [41]. Different designs of permanent magnet based EPU such as crossed EPU [42], HELIOS [43], Diviacco/Walker scheme [44], APPLE-I [45], APPLE-II [46], APPLE-III [47], a 6-arrays device [48], DELTA [49] have been proposed and tested. For out-of-vacuum systems, APPLE type provide the largest horizontal and vertical fields whereas the DELTA undulator enables to reduce significantly the aperture for the electron beam. APPLE-III and DELTA are well suited for linac or Energy Recovery Linac applications. Depending on the horizontal and vertical field combinations, the radiation can exhibit different patterns, which can be retrieved from magnetic measurements data [50]. Quasi-periodic EPU can be applied to APPLE-II [51] or to the so-called Figure-8 [52], for out-of-vacuum and in-vacuum versions. The quasiperiodic scheme works properly in horizontal linear mode but it is less efficient in vertical linear mode [53]. Besides setting a chicane enabling to select the radiation from a first or a second segment, combining electromagnets and permanent magnet provides a fast switching of the polarisation from circular right to circular left and vice-versa as installed at NSLS [54] and at ESRF [55]. Real-time synchronisation is necessary to
ensure a proper compensation of the Eddy currents. For short periods, conventional coils can be replaced by Cu sheets alternated with cooling Cu ones [56]. The ElectroMagnetic Permanent magnet Helical Undulator (EMPHU) developed in such a way at SOLEIL [57] employs three series of coils for independent compensations of the field integral, the exit position and the pointing direction: after static corrections, dynamical corrections without and with the vacuum chamber are measured thanks to the analysis of the pulse response, so that tables prepared in the magnetic measurement laboratory are directly applied for the undulator commissioning, leading to typical less than 10 µm residual close orbit distortion.

6. Conclusion

The new trends in insertion device developments are either oriented to the quest of high fields or short period small gap systems, where the heat load calculation and handling can become an issue, as for cryogenic undulators and even more for superconducting ones. Such new developments push further the instrumentation and measurements limits and require benches allowing the measurements to be performed directly in vacuum and at low temperature. Besides, for providing further flexibility for the users, fast switching of the polarisation is also provided. Further evolution of the insertion devices is also foreseen with the new paradigm brought by the fourth generation light sources, based on FELs or ERLs.

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