J. Synchrotron Rad. (1998). **5**, 196–201

The ESRF Insertion Devices

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(*Received 4 August 1997; accepted 18 September 1997*)

The European Synchrotron Radiation facility is presently operating 47 segments of insertion devices (IDs). A record brilliance of 1×10^{20} photons s^{-1} (0.1% bandwidth)$^{-1}$ mm^{-2} $mrad^{-2}$ has been reached. Almost all devices are built with permanent magnets with or without iron pole pieces. They have been mechanically and magnetically designed and field-measured in house. Multipole shimming has been applied to all devices to remove the integrated dipole and higher-order multipole fields, thereby reducing the interaction between the IDs and the stored beam. For all undulators, the field errors have been corrected further using spectrum shimming in order to achieve ideal spectral brilliance on all harmonic numbers from 1 to 15. A significant effort has been made to optimize the magnet terminations for both field-integral correction and phasing. A phasing scheme of the undulator segments has been developed which allows the independent manufacture and operation of individual segments. Several designs for undulator phasing are presented, together with a comparison between hybrid and pure-permanent-magnet technology. A new type of variable-polarization helical undulator is presented.

Keywords: insertion devices; undulators; wigglers; permanent magnets; brilliance.

1. Status

The European Synchrotron Radiation Facility (ESRF) is a third-generation synchrotron source optimized to produce hard X-rays in the 1–100 keV range. The large majority of beamlines use an insertion device (ID) as the source point which generates high flux and brilliance. At present, 47 segments of IDs (cumulated length greater than 70 m) are in operation serving 26 beamlines. Table 1 lists their magnetic periods, peak fields and technology. Except for a superconducting 4 T three-pole wiggler (Stampfer & Elleaume, 1994), all devices are permanent-magnet undulators (76%) or wigglers (24%), each 1.6 m long with magnet blocks located in the air on both sides of the vacuum chamber. Three ID segments can be placed on a single straight section, as is already the case for four beamlines. Eight beamlines operate with a minimum magnetic gap of 20 mm. All the other beamlines operate with a minimum gap of 16 mm or less. Recently, a copper-plated stainless steel chamber with 10 mm external aperture has been developed and tested on the ID11 and ID27 beamlines and does not degrade the lifetime of the stored beam (>50 h at 200 mA). This new chamber will gradually replace the existing ones. Fig. 1 presents the brilliance routinely achieved in spring 1997. The ring is operated with a 200 mA current, horizontal emittance of 4 nm and a 1% coupling. The brilliance on the ID3 beamline (equipped with two undulator segments) reaches 1×10^{20} photons s^{-1} (0.1% bandwidth)$^{-1}$ mm^{-2} $mrad^{-2}$ around 5 keV. A typical undulator beamline equipped with a single fully tuneable segment of 42 mm period installed on a high-beta straight section presents a brilliance higher than 1×10^{19} photons s^{-1} (0.1% bandwidth)$^{-1}$ mm^{-2} $mrad^{-2}$ for any photon energy between 2 and 20 keV. Recently, the vertical beta functions in all the ID straight sections have been reduced to 2.5 m in order to minimize the scraping of the electron beam by the 5 m-long narrow-aperture

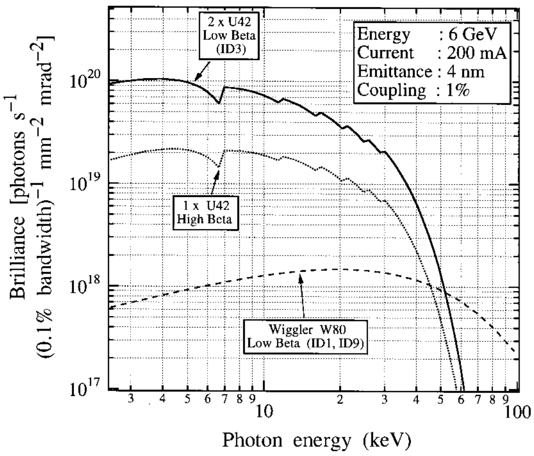

Figure 1
Comparative brilliance reached by undulators and wigglers at the ESRF. By combining electron emittances of 4 and 0.04 nm, a current of 200 mA and two undulator segments, a record brilliance of 1×10^{20} photons s^{-1} (0.1% bandwidth)$^{-1}$ mm^{-2} $mrad^{-2}$ is reached around 5 keV.

Table 1
Type, spatial period, peak field and technology used to build the 47 segments of IDs presently in operation (PPM denotes the pure-permanent-magnet technology).

ID No.	Type	Period	Field	Technology
1	Wiggler	70	0.85	Hybrid
	Undulator	42	0.56	PPM
2	Undulator	46	0.48	PPM
	Undulator	26	0.16	PPM
3	Undulator	42	0.56	PPM
	Undulator	42	0.56	PPM
6	Undulator	46	0.48	PPM
9	Wiggler	70	0.85	Hybrid
	Undulator	46	0.62	PPM
	Undulator	26	0.27	PPM
10	Undulator	42	0.56	PPM
	Undulator	42	0.56	PPM
	Undulator	26	0.71	PPM
11	Wiggler	125	1.20	Hybrid
	Undulator	34	0.70	PPM
12A	Helical undulator	85	0.51	PPM
12B	Helical undulator	52	0.36	PPM
13	Undulator	46	0.65	Hybrid
14	Undulator	42	0.56	PPM
	Undulator	23	0.20	Hybrid
15A	Asymmetric wiggler	220	1.8	Hybrid
15B	Three-pole wiggler	200	4	Superconducting
16	Undulator	42	0.56	PPM
	Undulator	42	0.56	PPM
	Helical undulator	52	0.36	PPM
17	Wiggler	150	1.9	Hybrid
18	Undulator	23	0.21	PPM
	Undulator	34	0.42	PPM
19	Wiggler	150	1.9	Hybrid
20	Asymmetric wiggler	210	1	PPM
	Undulator	48	0.5	Hybrid
21	Wiggler	80	0.81	Hybrid
	Wiggler	80	0.81	Hybrid
	Wiggler	80	0.81	Hybrid
22	Undulator	42	0.56	PPM
23	Undulator	48	0.65	PPM
	Undulator	46	0.62	PPM
	Undulator	44	0.59	PPM
24	Undulator	42	0.56	PPM
26	Undulator	42	0.56	PPM
	Undulator	42	0.56	PPM
27	Undulator	46	0.48	PPM
30	Undulator	40	0.52	PPM
	Undulator	40	0.52	PPM
	Wiggler	70	0.82	Hybrid
32	Undulator	48	0.50	PPM
	Undulator	40	0.40	PPM

vacuum chamber, resulting in a longer lifetime of the stored beam and less *bremsstrahlung* in the beamlines. There is nevertheless a significant difference between the low- and high-beta source points, having respectively horizontal beta functions of 0.5 and 35 m. Undulators on low-beta straight sections typically give 10–30% greater brilliance depending on the photon energy; however, the high-beta straight sections are more in demand. This is due to their low horizontal divergence and small horizontal spot size of 0.57 mm r.m.s. at a distance of 40 m, to be compared with 3.6 mm in a low-beta straight section.

Table 2
Maximum integrated multipoles (normal and skew) measured on all conventional undulators.

The multipoles are obtained by measuring the field integrals as a function of the horizontal position of the beam over a range of ±25 mm from the electron-beam axis.

Dipole	< 20 G cm
Quadrupole	< 10 G
Sextupole	< 10 G cm^{-1}
Octupole	< 10 G cm^{-2}
Decapole	< 10 G cm^{-3}

2. Manufacture of IDs

In view of the large number of IDs required by the ESRF, a research and development programme was initiated in 1988 in order to develop in-house expertise. As a result of this effort, the ESRF ID produced 30 segments over the past three years. There are two important sets of specifications. A small field integral along the path of the electron beam is required to ensure a small closed-orbit distortion as one varies the gap. A highly periodic magnetic field is also required to ensure a high brilliance on all useful harmonics of the spectrum. To limit the r.m.s. closed-orbit distortion below 10% of the r.m.s. beam size, one must maintain the horizontal (vertical) field-integral variations with gap below 60 G cm (20 G cm). To reach these figures, a special shimming technique (Chavanne & Elleaume, 1995*a*,*b*) has been developed which consists of placing thin pieces of iron (0.1 mm) on the surfaces of the blocks. The iron becomes magnetized under the external field produced by the magnet and, through its magnetization, modifies the surrounding field. Using multipole shimming, one removes nearly all integrated normal and skew multipoles. Table 2 presents the maximum normal and skew residual multipole components achieved on the 31 conventional undulator segments. Because of the larger magnetic fields, the wigglers present higher multipoles. The worst case was observed on the 1.8 T wiggler of ID15, which presents a maximum integrated sextupole of 90 G cm^{-1}. Note that both the vertical and horizontal field integrals (but not the higher multipoles) can simply be compensated by adding correction coils powered by a current which depends on the magnetic gap. Thanks to the multipole shimming, all conventional undulators are operated without electromagnet correction, simplifying the control and commissioning. Nevertheless, a large number of wigglers and most helical undulators are operated with such correctors. The second set of specifications is related to the constructive interference of the radiation from each period. Small fluctuations of period or field induce a phase shift of the radiation. The accumulation of small phase shifts may result in a reduction of the angular spectral flux and brilliance on the high harmonic numbers, which are the most sensitive. The correction of these errors involves a special shimming (called spectrum shimming). Spectrum shimming has been routinely applied at the ESRF for the past three years. The average r.m.s. phase error over the last 13 conventional undulators produced is 1.5° at a gap of 16 mm with 1.9° for the worst segment. Phase errors are corrected at the minimum gap around 16 mm and we observe a 30% higher value typically in the useful gap range. These errors are low and, taking a filament mono-energetic electron beam, they correspond to an angular spectral flux reaching 96% (88%) of an ideal undulator on harmonic 9 (15). We consider that this level of correction is sufficient because on those high harmonic numbers the electron energy spread (0.1% r.m.s.) is the dominant source of broadening of the harmonic peaks. There are nevertheless limitations in the use of shims. The shims essentially short-circuit some of the flux produced by the magnet blocks, resulting in a reduction of the peak field on the electron-beam axis. Also, a large number of shims induce an interaction between the shims located in the upper magnet array and those of the lower array, resulting in a field-integral correction which deviates from the simple addition of the effect from each shim. Moreover, the field integrals produced by these interactions are highly gap-dependent. For these reasons, we have recently modified the method of manufacture and insist on purchasing homogeneously magnetized blocks (manufactured by transverse die pressing), make careful pairing of blocks and perform magnetic field tuning through small vertical displacements of the magnet blocks (50–100 μm). As a consequence, the last ten undulators produced have an average of only 15 shims per undulator to be compared with an average of 50 shims four years ago (for the same field quality).

The time required for the pairing and shimming is largely dictated by the accuracy and speed of magnetic field measurements. The continuous improvement of the field-measurement benches has been considered a key issue from the very beginning. For the manufacturing of an ID, we use two types of benches: a field-integral bench and a local field bench. Data acquisition from both benches is accelerated by acquiring data on-the-fly. The field-integral bench is capable of mapping the horizontal and vertical field integrals in the middle of the magnetic gap for 41 different horizontal positions spaced every 2.5 mm in less than a minute, with an absolute accuracy of 10 G cm and a repeatability of 2 G cm (for a 1.6 m-long ID segment with 0.7 T peak field). A complete multipole shimming typically requires 20 of these scans. The local field bench usually samples 2000 points over a 2 m distance in 3 min. The three components of the field are measured with Hall probes. They are immediately processed to remove orientation errors, non-linearity in the response and most importantly the planar Hall effect. The planar Hall effect can dramatically offset the field integral deduced by numerical integration of the data. It varies from one manufacturer to another and may even vary within a batch of probes from the same manufacturer. We therefore characterize each probe in two steps. First we determine its non-linearity by comparing it with an NMR probe. Second, we fit the planar Hall coefficient by measuring the three components of the field at various positions in a known field geometry. On a short period (23 mm) vertical field undulator, a field-integral offset as large as 600 G cm has been observed which was induced by the planar Hall effect. The offset was reduced below 50 G cm after compensation for the planar Hall effect. The field measurements of helical undulators are also particularly sensitive to the planar Hall effect. Finally, the corrected field data are processed to derive the spectrum of the radiation using our program *B2E* (Elleaume & Marechal, 1991).

3. Magnetic design of extremities

Nearly all three-dimensional magnetostatic finite-element codes require significant memory and CPU time and are suitable for designing the central field while they are rather unreliable for estimating the field integrals along the electron path. This is a result of the fact that the errors of the predicted field integrals have several origins: the refinement of the mesh, the sampling of the points where the field is computed and the truncation at some finite distance to approximate infinity. This difficulty has been solved at ESRF by the development of the computer code *Radia* (Elleaume *et al.*, 1997). For the past five years, all magnetic assemblies have been designed with *Radia* or an earlier version. It computes the central field of an undulator or a 1.4 T wiggler within 10 s of CPU time on a PowerMac 4400 or Intel Pentium 133 with an absolute error smaller than 1%. Field integrals are also accurately predicted within a few minutes to a precision of 10 G cm. Typical magnet-block errors such as dimension tolerances, ‘easy-axis’ misorientation, variation of magnetization or susceptibility from block to block are easily simulated with *Radia*.

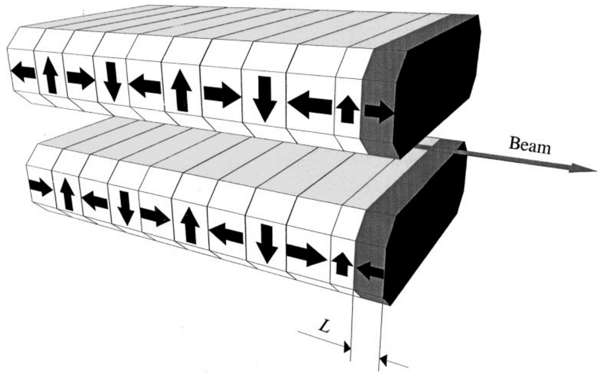

Figure 2
Termination of a pure-permanent-magnet undulator. The conventional termination is the half-thickness block shown in white. The grey magnet has been added to eliminate field-integral variations with the magnetic gap. The length L of the block is adjusted numerically with *Radia*.

3.1. *Field-integral compensation*

Assuming a zero susceptibility of the permanent magnets, one can easily show that, by design, the field integrals of a correctly terminated pure permanent-magnet (PPM) device are zero independently of the gap. In real devices, one observes some field-integral variations with gaps originating from inhomogeneous magnetization of the blocks, machining and positioning errors and residual non-zero susceptibility of the magnet material. All these errors can be corrected by multipole shimming, except for that originating from the non-zero susceptibility of the material. We have modified the extremities of the ESRF PPM undulators as shown in Fig. 2, by adding a magnet at the end. Its longitudinal dimension L is typically 15% of the period and with a magnetization oriented parallel to the electron-beam axis. For several years, all the PPM undulators produced have received such a termination and resulted in field-integral variations smaller than 10 G cm in the gap range between 15 and 200 mm. This must be compared with 60 G cm for a 42 mm-period undulator with the conventional termination (half-thickness block vertically magnetized). This termination is now being replaced by phasing termination (see below). This method of compensation for the field integral of PPM undulators has been found to be applicable over a wide range of gap/period ratios. The optimum length L varies slightly with the undulator period and the width and height of the magnet blocks. Similar work has been performed for hybrid undulators and wigglers using *Radia*. The magnetic designs for several hybrid terminations can be found in Chavanne *et al.* (1995, 1996*b*). Unfortunately, we have not found any simple universal method applicable to all hybrid structures and a completely new optimization is required for each new device.

3.2. *Phasing*

The reason for phasing the undulator sections is to ensure that a three-segment assembly produces the same spectrum as a 5 m-long single ID unit. The magnet termination should be carefully designed to minimize the field integral induced as one varies the gap of one segment while maintaining the gap of the other unchanged. The proper operation of such a termination allows the user group to vary the length of its undulator by switching between one, two or three segments at any time, thereby optimizing the heat-load conditions in the beamline to the ring current and photon energy. The first attempt to phase the undulator segments was carried out on a pure-permanent-magnet assembly in 1995 (Chavanne *et al.*, 1995). Phasing is now in use on five beamlines, each operating two undulator segments of identical periods. The magnetic assembly is presented in Fig. 3. The principle of the design is to increase the peak field in the last periods close to the junctions between the two undulators. This is performed by splitting the vertically magnetized blocks into two sub-blocks each being magnetized in a direction making an angle of 45–70° with respect to the horizontal plane. The phase advance originating from the higher peak field compensates for the phase delay induced by the lack of field in the air gap. The magnet blocks used in the phasing section have a smaller horizontal width than those from the centre of the undulator to improve the phasing compensation as a function of the gap. The vertical field integral produced at the junction between the segments is smaller than 32 G cm for any gap combination of the segments (as low as 15 mm). These phasing sections are robust and inexpensive. They also allow the proper phasing of undulators of slightly different periods or different materials. As a result, all PPM undulators produced at the ESRF over the past two years are systematically equipped with such phasing sections. We have built such phasing sections for undulator periods of 35 and 42 mm and have designed sections for 20 and 32 mm period devices. They are all very similar with small variations of block dimensions and orientation of the magnetization, which are optimized following three-dimensional field computations made with *Radia*.

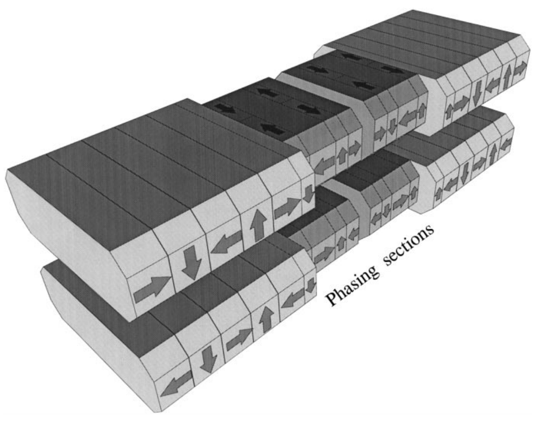

Figure 3
Phasing termination between two pure-permanent-magnet undulator segments. The dimensions and orientation of the magnetization of the blocks are adjusted numerically with *Radia*.

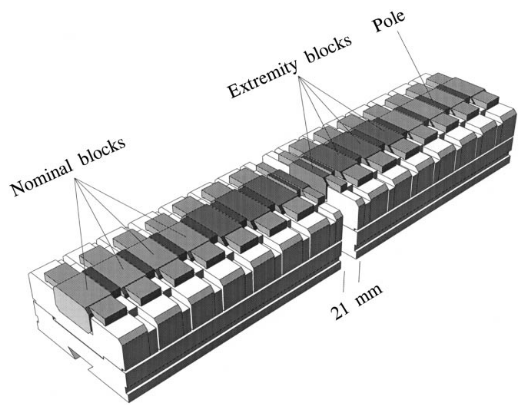

Figure 4
Phasing termination between two hybrid undulator segments. The dimensions and orientation of the magnetization of the blocks are adjusted numerically with *Radia*.

Recently, an attempt was made to phase three long-period hybrid undulators. Significant difficulty was met at the design phase in maintaining both the phase and the field integrals independent of the magnetic gap because of the large susceptibility of the iron poles. The configuration selected is shown in Fig. 3. The last magnet blocks of each section have slightly larger transverse dimensions than those in the middle of the undulator. To maintain the field-integral variations *versus* gap below 125 G cm, we had to use a large air gap of 21 mm (compared to 6 mm for a 42 mm-period PPM undulator). As a result of this large distance between the segments the phase shift varies between 0 and 20° in the useful gap range. This is sufficient to ensure constructive interference for harmonic 1 but some degradation of brilliance is expected on harmonics 3 and 5, depending on the magnetic gap.

4. Comparison of technologies

There has been a world-wide debate about the advantages and drawbacks of the pure-permanent-magnet (PPM) *versus* hybrid (HYB) technology for the manufacture of undulators and wigglers.

At the ESRF, 28% (70%) of the ID segments are of type HYB (PPM). All wigglers and a few undulators are HYBs while the large majority of undulators are PPMs. We nevertheless build and operate devices of the same period and field using both technologies. Our conclusions depend on the ratio of the period to the minimum gap. As a rule of thumb, for a ratio smaller (larger) than 4, we recommend the PPM (HYB) technology for the following reasons:

(*a*) The field and field-integral simulation of the central field and terminations of a PPM device is rather easy while that for an HYB device is much more delicate. We believe that passive (without electromagnet correction) phasing of multiple undulator segments is almost impossible with HYB technology; however, it is possible with PPM technology (see §3). In our opinion, this is the main reason why all long HYB undulators built so far have been made from single heavy and expensive mechanical structures (ALS, SRRC) while long PPM undulators have been built at other places from a number of small independent segments (ESRF, ELETTRA). Note that some laboratories (BESSY II, SPRING8) use an intermediate scheme whereby HYB or PPM undulators are assembled on short multiple support structures whose gaps are not independently controlled and therefore lack the advantage of fully variable length undulators as experienced by the beamline users of the ESRF.

(*b*) The magnetic field from an HYB device is usually greater than that of a PPM device. This is particularly sensitive for the large ratios of period over gap. We therefore recommend building the 1–2 T wigglers using hybrid technology simply because the PPM is less efficient. In the undulator regime, the difference is much reduced, typically of the order of 5%, depending on the level of optimization. Note that for an undulator, a 5% change in field is typically compensated by a 3% change of the period, which gives a maximum 3 to 6% reduction in brilliance.

(*c*) For an HYB device, the closed-orbit distortion induced during a gap motion may significantly differ from that predicted by the measured field integrals if the residual background field (from the earth, power cables, ion pumps *etc.*) differs between the tunnel and the laboratory where the field measurement is performed. The background field magnetizes the iron poles, which in turn creates an additional field integral which depends on the gap. At the ESRF we have observed horizontal field-integral variations as large as 200 G cm per segment per Gauss of background field. PPM devices are insensitive to such perturbations because of the small relative susceptibility of the magnets.

(*d*) We somewhat disagree with the common statement that HYB undulators present lower field errors than PPM undulators. Our findings indicate that, before any shimming, they are similar once highly uniformly magnetized blocks are used, such as those produced by the transverse die pressing technique. For both technologies, we do not see any difference after shimming.

(*e*) Finally, for the same period, the cost of the raw material and machining of HYB assemblies (permanent magnets, poles and assembly pieces) is typically between 30 and 100% higher than that of a PPM, largely depending on the quality of the iron alloy used for the poles.

5. Circular polarization

The production of circularly polarized radiation from insertion devices has always been a major priority at the ESRF. At present, the hard X-ray range between 20 and 500 keV is covered by three asymmetric wigglers located

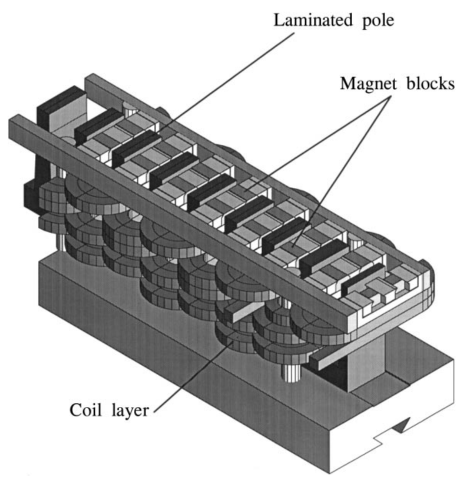

Figure 5
Helical undulator design. The vertical field is produced by a current of 300 A flowing in the coils, while the horizontal field is created by pairs of permanent magnets placed on both sides of the electron beam. The vertical (horizontal) field is tuned by varying the current (gap).

on beamlines ID15A, ID15B and ID20 (Chavanne & Elleaume, 1995*b*). The low energy range between 0.5 and 10 keV is covered by three variable-polarization helical undulators installed on the beamlines ID12A, ID12B and ID16, which are in high demand by the user community. The helical undulators are unique in the world because of their flexibility. They produce an elliptical magnetic field with independent control by the user of the amplitude and phase of the vertical and horizontal field components (Elleaume, 1994). During the three years of user operation of these devices, the most frequent field adjustment was a phase inversion which flips the circular polarization from left-handed to right-handed. Such a flip takes a few seconds which is sufficient for a number of experiments, but too slow when aiming at dichroism signals as low as 10^{-4}. To overcome this limitation, a novel-design variable-polarization helical undulator is under construction (see Fig. 5). The magnetic period is 80 mm and it is designed to be operated with a magnetic gap as low as 15 mm. The vertical magnetic field is produced by a set of coils built from a large-section hollow conductor (7.5 $\times$ 7.5 mm), six layers of which are wound around a laminated yoke with 0.35 mm thickness of lamination. The horizontal magnetic field is produced by an array of Sm_2CO_{17} permanent magnets located between the pole pieces. Both horizontal and vertical fields are variable between 0 and 0.21 T resulting in a maximum deflection parameter K of 1.6. It covers the 1–15 keV range using harmonics 1–5. The horizontal (vertical) fields are tuned by changing the magnetic gap (coil current). Fast flipping of the polarization is achieved by inverting the current in the coils. A special power supply is being built which produces a square-shaped current output between +300 and -300 A with a transition time of a few milliseconds at a repetition rate between d.c. and 20 Hz.

6. Future

Future developments include the completion and installation of additional segments to increase the brilliance of the undulator beamlines. It is estimated that 60 ID segments will be operational by the middle of 1999. The magnetic gap will be reduced by replacing the 15 mm chamber with 10 mm (external aperture) chambers. In addition to the manufacture of the electromagnet/permanent-magnet helical undulator, a prototype short period in-vacuum undulator is being built that should allow operation at a magnetic gap of around 6–8 mm. Finally, a 3 T permanent-magnet multipole wiggler is under manufacture.

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