IN-VACUUM AND CRYOGENIC PERMANENT-MAGNET UNDULATORS AT THE ESRF

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Abstract

The European Synchrotron Radiation Facility (ESRF) operates a large number of in vacuum undulators (IVUs) and cryogenic permanent magnet undulators (CPMUs). Eight IVUs and nine CPMUs are currently in service, and a few more are under construction or planned. CPMU technology is employed for short-period, high-field undulators. These undulators generate intense high-order harmonics and can reach high photon energies up to about 100 keV at the ESRF. A major limitation of this approach is the heat load on the photon front-ends and on the optical elements of the beamlines. This issue can be mitigated by combining a tunable device with a short period, almost monochromatic IVU dedicated to a single photon energy. The various layouts of the ESRF IVU and CPMU straight sections are presented, together with the CPMU operating experience, construction and installation trends.

INTRODUCTION

In-Vacuum Undulators (IVUs) are now standard components of storage-ring-based lightsources and FELs. Because they generate strong magnetic fields at shorter periods than out-of-vacuum devices, they are key elements for improving the source brilliance at high energies. Cryogenic Permanent Magnets Undulators (CPMUs) have been progressively deployed at the ESRF for almost two decades for high photon flux and high-energy beamlines.

The first section focuses on IVUs and CPMUs: after a brief reminder of the main characteristics of these devices, their magnetic gaps and the technologies used at the ESRF are presented. The heat load generated by these undulators on optical components is discussed. The second section gives a brief history of IVU and CPMU installation at the ESRF, and presents the current installation and contruction plans. The third section summarise the operation experience.

IN-VACUUM UNDULATORS

Basics

The peak magnetic field of an undulator varies as

$$B \approx B_0 \exp\left(-\frac{\pi g}{\lambda_0}\right),$$

where g is its magnetic gap and λ_0 its period.

The on-axis wavelength of the emitted radiation is

$$\lambda_R = \frac{\lambda_0}{2\gamma^2 n}\left(1 + \frac{K^2}{2}\right),$$

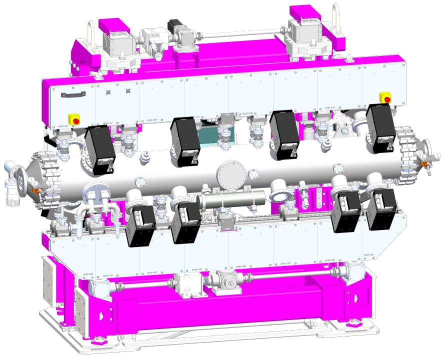

Figure 1: Design view of a cryogenic in-vacuum undulator. The permanent magnets, cooled down by liquid nitrogen, are installed in the cylindrical vacuum chamber visible in the middle.

where γ is the relativistic Lorentz factor, n the harmonic number and K the deflection parameter:

$$K = \frac{e\lambda_0 B}{2\pi mc} \propto \lambda_0 \exp\left(-\frac{\pi g}{\lambda_0}\right).$$

K decreases rapidly with the period λ_0. Short-period undulators typically have a low K value and have a reduced tuning range when the field is varied, unless a high-field technology is used. Finally, the radiated power and power density vary with

$$P \propto B^2$$
$$\frac{dP}{d\Omega} \propto B.$$

It should also be noted that undulators emit mainly first-harmonic radiation for $K < 1$ and high-harmonics for $K > 1$ (see, for instance, reference [3]).

Table 1: Minimum Gaps of Undulators at the ESRF

Out-of-vacuum	11	mm
In-vacuum (side)	6	mm
In-vacuun (middle)	5	mm
In-vacuum (middle, low chroma)	4	mm

Magnetic Gaps

The standard undulator vacuum chambers at the ESRF have a thickness of 10 mm, leading to minimum gaps of about 11 mm for out-of-vacuum undulators. These gaps can be further reduced if the magnets are installed in vacuum [1] [2]. In this case, the magnet arrays are surrounded by a large vacuum chamber (Fig. 1).

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The minimum undulator gaps (Table 1) were set assuming that the vertical apertures of the undulators scale with the vertical beam size:

$$\sigma_Y = \sqrt{\varepsilon_Y \left(\beta_0 + \frac{z^2}{\beta_0}\right)},$$

with z the longitudinal position and β_0 the value of the vertical β-function at the center of the straight section.

The straight sections at the ESRF are 5 m long, and most of the undulators are 2 m long. Side undulators are installed upstream or downstream, i.e. $z = 1.25$ m, whereas the middle ones are positioned at $z = 0$ m.

A mini-beta setup, based on four additional quadrupoles installed around a CPMU, was developed and tested [4, 5]. This local modification of the lattice did not sufficiently reduce the electron beam losses on the undulator to be delivered in standard user mode. This was due to an electron beam halo larger than initially expected [6]. A low-chromaticity, halo-reduced lattice is being developed for reaching a minimum gap of 4 mm – this ultra-low gap is only available in uniform filling mode for the moment.

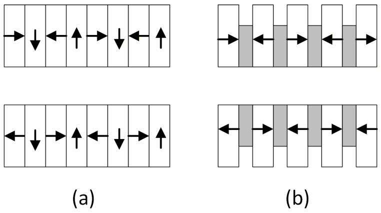
(a) (b)

Figure 2: Undulator permanent magnet assemblies. (a): pure permanent magnets Halbach arrays. (b): hybrid assembly with permanent magnets (white) and ferromagnetic poles (grey).

Technology

The simplest in-vacuum undulators are built with two Halbach arrays [7]; these devices are referred to as Pure Permanent Magnet Undulators (PPMUs, Fig. 2a). A stronger magnetic field can be obtained by replacing the vertically polarized magnet blocks by poles in ferromagnetic materials (Hybrid Permanent Magnet undulators or HPMUs, Fig. 2b). The horizontally polarized magnets have a strong demagnetizing field due to their shape and could be more affected by radiation damage. For this reason, the ESRF in-vacuum undulators installed are built with Sm_2Co_{17} material with magnetization $\mu_0 M_R \approx 1.1$ T and coercive field $H_{cJ} \approx 2$ MA/m.

When cooled to cryogenic temperature, $Nd_2Fe_{14}B$ and $Pr_2Fe_{14}B$ materials show high magnetization $\mu_0 M_R \approx 1.6$ T and coercive field $H_{cJ} \approx 5.5$ MA/m. This has driven the development of CPMUs, in which the permanent magnets are cooled down to 150 K ($Nd_2Fe_{14}B$) or 80 K ($Pr_2Fe_{14}B$) [8–10]. CPMUs are now standard hard X-ray sources in user facilities.

Figure 3 shows the main parameters of the in-vacuum undulators and CPMUs installed in the ESRF-EBS storage ring.

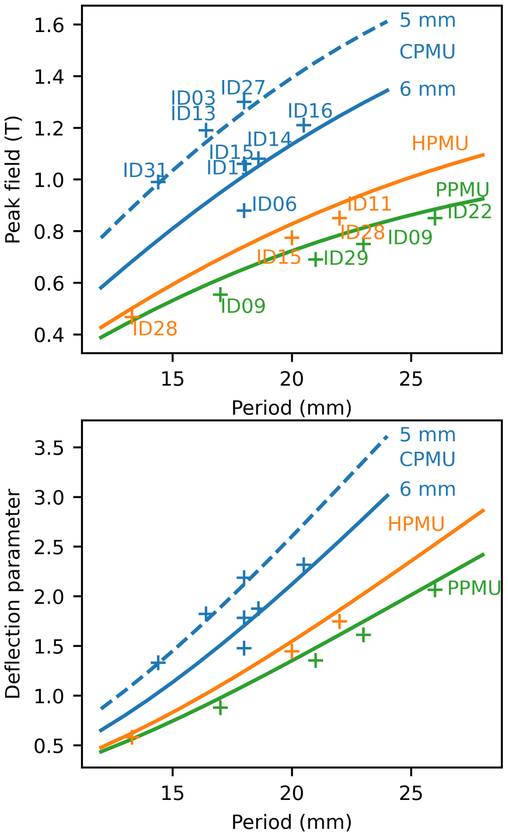

Figure 3: Peak magnetic field (top) and deflection parameter K (bottom) for the in-vacuum and cryogenic undulators currently installed in the ESRF-EBS. PPMUs and HPMUs have a 6 mm minimum gap.

Short Period Undulators and Heat Load

Hard X-rays experiments typically require:

- Short undulator periods.
- A sufficiently high K value (typ. > 1.5) to produce high harmonics and to avoid energy gaps between higher order harmonics.

At constant K, shortening the period requires a higher magnetic field. This impacts the radiated power $P \propto \lambda_0^{-2}$ and on the power density $\mathrm{d}P/\mathrm{d}\Omega \propto \lambda_0^{-1}$, provided a sufficiently high magnetic field can be generated.

The power radiated by some of the existing (CPMU 18) and planned (IVU 16 and CPMU 20.5) devices is given in Table 2. Two twin CPMUs with a period of 20.5 mm are currently under construction and will be installed in the same straight section. These devices are fully tunable at the cost of a huge power which will be mostly dissipated in the front-end. Conversely, a lower K value HPMU 16 is also under construction for another beamline. It was designed to be operated only on the first harmonic and generates a significantly lower heat load.

The high power and power density generated by high-field short-period undulators may imply the front-ends be replaced and could have a detrimental impact on the beamline optical elements such as mirrors and monochromators

Table 2: Heat load from CPMUs

Type	Gap [mm]	Period [mm]	Length [m]	K	Power [kW]
HPMU	6	16	2	1.0	3.90
CPMU	6	18	2	1.6	8.81
CPMU	5	18	2	2.0	13.7
CPMU	6	20.5	2	2.3	13.8
CPMU	6	20.5	2 × 2	2.3	26.7

– their deformation under high heat load may significantly degrade the brilliance of CPMUs. The experience at the ESRF-EBS has shown that the heat load on the optical components must be validated by finite-element analysis at an early stage of the beamline design.

IVU AND CPMU STRAIGHT SECTIONS

The first IVUs installed at the ESRF were dedicated to the production of hard X-rays, with energies of a few tens of keV. These 2 m long PPMUs were typically positioned upstream or downstream of 5 m long straight sections and had a gap of 6 mm.

CPMUs were deployed in the 2010s after the successful installation of a prototype in 2008. The first 5 mm gap device, with a period of 14.4 mm, was installed in the middle of ID31's straight section in 2015. It was designed for photon energies up to 100 keV. Four CPMUs with 5 mm gaps are now installed and a fifth one is being manufactured.

The current trend is to replace IVUs by shorter period CPMUs. Most of the CPMUs recently installed are mainly used on harmonics 1 – 5 and the twin CPMUs planned for ID20 will be operated up to 25 keV on the first and third harmonics.

An HPMU with an ultra short period of 13.3 mm was recently installed on ID28. Its maximum deflection parameter is $K = 0.58$. The tuning range is limited to 21.5 – 24 keV and the energy radiated in the higher order harmonics is negligible. This monochromatic device is installed in tandem with a 22 mm period in-vacuum undulator which covers the energy range of the beamline, from 12 to 24 keV.

A similar layout is planned for ID14. A CPMU 18.6 with a wide energy range, from 9 to 90 keV, was installed in 2024. It will be completed by an HPMU with a 16 mm period dedicated to the production of 14.4 keV energy photons, which is the most-used energy on this beamline.

A phase shifter [11, 12] installed between the CPMU 18.6 and the HPMU 16 of ID14 will allow to optimize the radiation phase between the two undulators and to increase the brilliance. It should be noted that the tuning of the phase shifter depends on the radiation wavelength, on the distance between the devices and on their fringe field, but is independent of their period and deflection parameter. This was demonstrated with the present CPMU 18.6 and a 1.6 m long out-of-vacuum PPMU 20 both tuned at 14.4 keV: in this configuration, the on-axis photon flux was modulated by 30%. A phase shifter will also be installed between the twin CPMU 20.5 of ID20.

OPERATION OF CPMUS AND IVUS

After installation, the vertical offset and pitch angle of the IVUs are aligned with the electron beam by monitoring the losses observed on Beam Loss Detectors [13]. The closed orbit distortions are corrected by the feedback system. The CPMUs typically have a better vacuum than the room-temperature IVUs due to the cryogenic pumping on the magnet girders.

In the case of a failure of a CPMU cryocooler, its gap is opened immediately. The warming up of the magnet girders generates a high pressure burst a few hours after the cooling is stopped; this peak of pressure may trigger an interlock which kills the beam. It is still possible to re-inject the beam and to operate the storage ring with one or more CPMUs at room temperature, but the associated beamline front-end must remain closed due to the high pressure and bremsstrahlung radiation. A complete electrical black-out occurred on the ESRF site in 2024. The cooling of five CPMUs was recovered within half a day, while the three remaining CPMUs needed a complete warm-up and cool-down cycle (i.e. two days) which did not prevent the restart of the machine. An on-call duty was put in place due to the increasing number of cryocoolers installed.

A few issues occurred on the RF tapered transitions installed at the extremities of these devices. This was corrected by modifying their design. The magnets and poles of IVUs are covered by a thin Cu/Ni foil which is needed to keep the impedance low enough. Bumps were observed on the foil of a CPMU at low temperature due to an insufficient tensioning of the foil. This issue, restricting the vertical aperture of the undulator, was solved by increasing the tension.

One of the HPMUs was magnetically measured after 10 years of operation at the ESRF. No sign of demagnetization was observed.

CONCLUSION

IVUs and CPMUs are operated at the ESRF for more than two decades. New devices are being built for beamline upgrades. CPMUs provide a wide energy range and energies up to 100 keV, however the heat load they generate on the optics must be assessed. Lower K value devices are also used and can be combined with fully tunable high-field undulators. A phase shifter can be installed between two IVUs to improve their brilliance, even if their periods are different.

REFERENCES

[1] S. Yamamoto *et al.*, "Construction of an in-vacuum type undulator for production of undulator x rays in the 5-25 keV region", *Rev. Sci. Instrum.* vol. 63, pp. 400–403, 1992, doi:10.1063/1.1142768

[2] T. Tanaka *et al.*, "In-vacuum undulators", in *Proc. 27th International Free Electron Laser Conference*, Stanford, CA, USA, pp. 370–377, 2005

[3] R. P. Walker, "Insertion devices: undulators and wigglers", in *Proc. CERN Accelerator School on Synchrotron Radiation and Free Electron Lasers*, Grenoble, France, pp. 129–190, 1998, doi:10.5170/CERN-1998-004.129

[4] S. White *et al.*, "Mini-beta optics for the European Synchrotron Radiation Facility", in *Proc. IPAC'23*,Venice, Italy, pp. 3177–3180, 2023, doi:10.18429/JACoW-IPAC2023-WEPL029

[5] S. White *et al.*, "Mini-beta optics commissioning at the European Synchrotron Radiation Facility extremely brilliant source", in *Proc. IPAC'24*, Nashville, TN, USA, pp. 3007–3010, 2024, doi:doi:10.18429/JACoW-IPAC2024-THPC17

[6] N. Carmignani *et al.*, "Vertical beam halo characterisation at the ESRF EBS for operation with reduced in vacuum undulator gap", in *Proc. IPAC'24*, Nashville, TN, USA, pp. 973–976, 2024, doi:10.18429/JACoW-IPAC2024-TUCN1

[7] K. Halbach, "Physical and optical properties of rare earth cobalt magnets", *Nuclear Instrum. Meth.* vol. 187, pp. 109–117, 1981, doi:10.1016/0029-554X(81)90477-8

[8] T. Hara *et al.*, "Cryogenic permanent magnet undulators", *Phys. Rev. ST Accel. Beams* vol. 7, no. 5, p. 050702, 2004, doi:10.1103/PhysRevSTAB.7.050702

[9] J. Chavanne, G. Le Bec, and C. Penel, "Cryogenic permanent magnet undulators", *Synchrotron Radiation News* vol. 24, no. 3, pp. 10–13, 2011, doi:10.1080/08940886.2011.583884

[10] C. Benabderrahmane *et al.*, "Nd2Fe14B and Pr2Fe14B magnets characterisation and modelling for cryogenic permanent magnet undulator applications" *Nucl. Instr. Meth. Phys. Res. A* vol. 669, pp. 1–6, 2012, doi:10.1016/j.nima.2011.12.015

[11] Y. Miyahara, "Phase shift and radiation spectrum of a straight series of undulators", *J. Synchrotron Rad.* vol. 3, pp. 207–212, 1996, doi:10.1107/S0909049596006875

[12] H.H. Lu, Y. Li and J. Pflueger, "The permanent magnet phase shifter for the European X-ray free electron laser", *Nucl. Instr. Meth. Phys. Res. A* vol. 605, pp. 399–408, 2009, doi:10.1016/j.nima.2009.03.217

[13] L. Torino and K. B. Scheidt, "New beam loss detector system for EBS-ESRF", in *Proc. IBIC'18*, Shanghai, China, pp. 346–352, 2018, doi:10.18429/JACoW-IBIC2018-WEOB01