IN-VACUUM UNDULATORS

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Following the successful operation of a prototype in-vacuum undulator on ID11, the ESRF has started the production of 4 in-vacuum undulator segments, of 2 m in length and with periods between 17 and 23 mm.

INTRODUCTION

The magnetic gap of undulators and wigglers, as for any other accelerator magnet (dipole, quadrupole,…), is a design parameter of major importance. The smaller the gap, the lower the current or the smaller the volume of magnetic material (permanent magnet or steel) needed to reach a given magnetic field. In the case of undulators, a reduction of the gap also allows a reduction of the spatial period which results in a shift of the radiation spectrum to higher energies. This is of prime interest in a number of scientific applications. In the classical and simplest approach, one uses a fixed-gap vacuum chamber and places the magnet blocks in the air outside the vacuum. At the ESRF, the smallest aperture left to the electron beam (beam stay-clear) is around 5-6 mm if one does not want to reduce the lifetime of the stored beam (see below). When taking into account the thickness of the chamber wall, the flatness and position errors, the result is a minimum gap in the range of 10-11 mm. So far the majority of ESRF beamlines are equipped with a 15 mm-thick chamber which permits a minimum gap around 16 mm. The first 10 mm chambers have met the mechanical specifications but the lack of distributed pumping has not allowed user operation for lengths exceeding 2 m. This is due to the Bremsstrahlung generated by the collision of the electrons with the residual gas. One way to avoid these difficulties is to place the permanent magnet blocks in the vacuum of the ring (in-vacuum undulator). This allows a minimum gap almost identical to the beam stay-clear. The idea of in-vacuum undulators can be traced to the early 1980's with an installation on the NSLS [1] ring and later BESSY [2]. The technology was re-examined with the installation of a 3.6 m-long device at the photon factory [3]. Then a real advance took place with the large-scale engineering development made at SPRING-8 [4]. SPRING-8 is presently operating more than 15 in-vacuum undulators each with a typical length of 4.5 m and a 30 m-long in-vacuum undulator is also under construction. Recently a short in-vacuum undulator (0.32 m) was installed at the NSLS [3]. The record minimum gap is 3.3 mm with a 10% lifetime penalty. Such a small gap is only possible due to the short length of

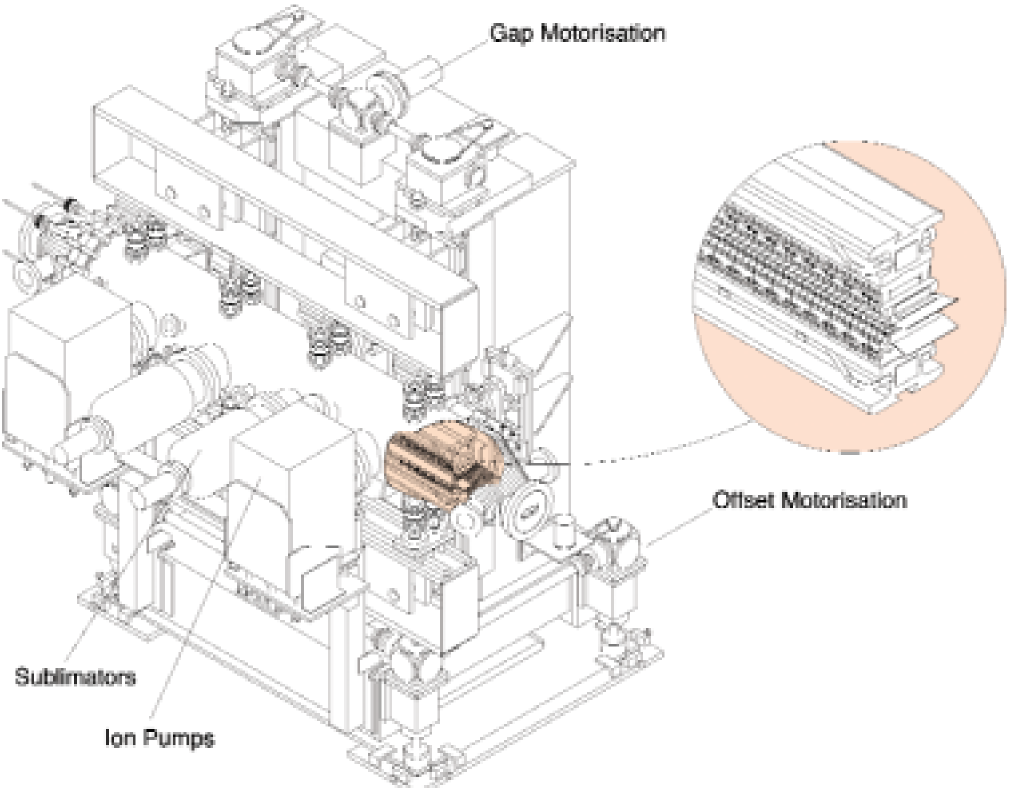

Fig. 1: Prototype in-vacuum undulator installed on the ID11 beamline.

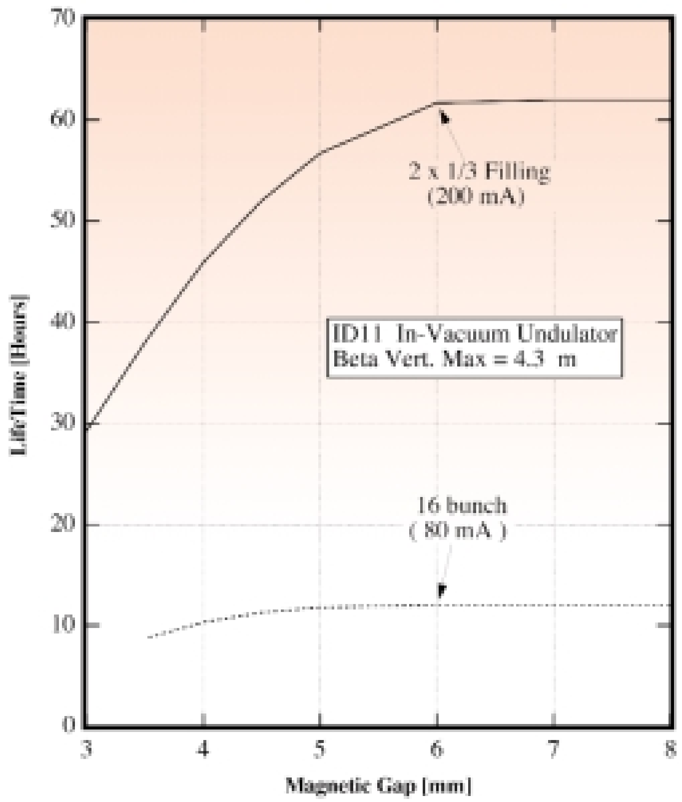

Fig. 2: Measured lifetime as a function of the magnetic gap of the prototype in-vacuum undulator.

undulator which allows the use of a small vertical beta function. Assuming an optimised beta function, the smallest gap achievable scales with the square root of the length of the undulator. For reasons of cost and resources, the development at the ESRF of this technology only started four years ago with the testing of a prototype Spring-8 undulator [6] followed by the construction of a prototype device [7]. We are now embarking on a large-scale programme of construction of such in-vacuum undulators. One should also mention that several new facilities of medium energy (Swiss Light Source, Canadian Light Source, Advanced Light Source ..) have chosen to build such in-vacuum undulators. Although they used to be considered a specialised and risky technology, in-vacuum undulators are now becoming much more common.

EXPERIENCE WITH THE ESRF PROTOTYPE

The prototype in-vacuum undulator in operation on ID11 is 1.6 m long with a period of 23 mm, and with a peak field higher than 1.1 T at the minimum operation gap of 5 mm. Figure 1 presents a 3-D view of the undulator, the support, the tank and pumping system. This undulator was designed to operate with the smallest gap that would be compatible with an acceptable reduction of the lifetime. Consequently, a significant number of the electrons lost in the ring are likely to hit the permanent magnet material. In view of the partial demagnetisation that was observed in 1993 on two conventional undulator segments (following a mis-steering of the booster beam), it was decided to use Sm_2Co_{17} material for the magnet blocks. The reduction of the field as a consequence of the use of Sm_2Co_{17} instead of NdFeB is equivalent to a 1 mm gap difference. A large pumping capacity was made available to the tank (860 l/s ion pump & 2000 l/s of titanium sublimation). As a result no measurable Bremsstrahlung could be observed on the beamline for any gap larger than 4.5 mm. Figure 2 presents the measured reduction of lifetime as a function of the magnetic gap in the 2 x 1/3 filling mode (200 mA) and 16 bunch mode (80 mA). No measurable lifetime reduction can be observed above 6 mm, however, a 5% lifetime reduction is recorded at 5 mm. Before the installation of this undulator, ID11 was operating a 1.2 T wiggler with a 125 mm period of the same length. The field was not shimmed due to a lack of time. Despite this, the new undulator produced more flux per unit surface at the primary slit for all energies below 70 keV, which has made the wiggler almost completely obsolete.

ENGINEERING DIFFICULTIES

Several engineering difficulties (vacuum, mechanical and magnetic) were encountered in the production of in-vacuum undulators. As all magnets must be coated to limit the degassing in UHV, nickel plating was used which resulted in a $9x10^{-11}$ static vacuum after bake-out at 120°C. Additionally, the magnets must be covered with a continuous conducting sheet (copper) to let the return current flow freely without heating the magnets. Continuity at the exits of the undulator must also be ensured. These exit transitions (called RF-Fingers) need to be flexible to allow a gap change in the range of 5-30 mm. Their perturbation on the beam is quantified in terms of an impedance which produces local heating (real part of the impedance) and is responsible for beam instabilities (imaginary part of the impedance). The highest temperature recorded on the prototype was 120°C at the junction between the RF-finger and the magnets. The connections between the upper and lower rigid girders (open air) and the magnet assemblies (in-vacuum) are made by 8 columns surrounded by bellows that must operate for a large number of cycles without leaking. Finally, the procedure for magnetic measurement and shimming had to be significantly modified because of the lack of lateral access for a Hall probe when the magnets are "in-vacuum".

FUTURE

The ESRF is presently embarking on the manufacture of four new in-vacuum undulator segments, each 2 metres-long with periods of between 17 and 23 mm. In view of the extra space required for the RF-fingers, the segment length has been increased from 1.6 m to 2 m in order to accommodate a maximum number of two segments. In the longer term, the manufacture of more in-vacuum undulators will be linked to the availability of 10 mm fixed gap chambers with a proper dynamic vacuum. There are two main reasons for the use of in-vacuum undulators at the ESRF: Firstly, for a given K value (imposed by the tunability), an in-vacuum undulator can be built with a smaller period and a correspondingly higher photon energy of the fundamental and harmonics. This is of importance for beamlines where high brilliance at high photon energy is required. This is illustrated in Figure 3 which compares the ultimate brilliance of two fully tunable undulators with K=2.2, a 4 m long U28 in-vacuum operated with a minimum gap of 6 mm and a 5 m long U42 undulator with a minimum gap of 16 mm. The gain in brilliance is not significant at low energies, however, it grows very rapidly above 20 keV. Secondly, full tunability is not essential for a few ESRF beamlines, and in preference they are optimised for maximum flux on the fundamental around 12-14 keV. In-vacuum undulators are also well suited for such applications, this is illustrated by Figure 4.

As discussed earlier, in-vacuum undulators can compete with wigglers (ID11) due to their high field. Indeed, not all wiggler beamlines can benefit from such undulators since they have a very small divergence and are nevertheless limited in field and therefore in critical energy. Very high field wavelength shifters are far from being obsolete. The question has been raised of whether it is possible to build hard X-ray rings at 4-5 GeV more cheaply than the present 6-8 GeV rings by making extensive use of in-vacuum undulators instead of open-air undulators. This is partly true, but one should not forget that reducing the electron energy of a low emittance ring has a serious impact on the lifetime and the stability of the beam. ■

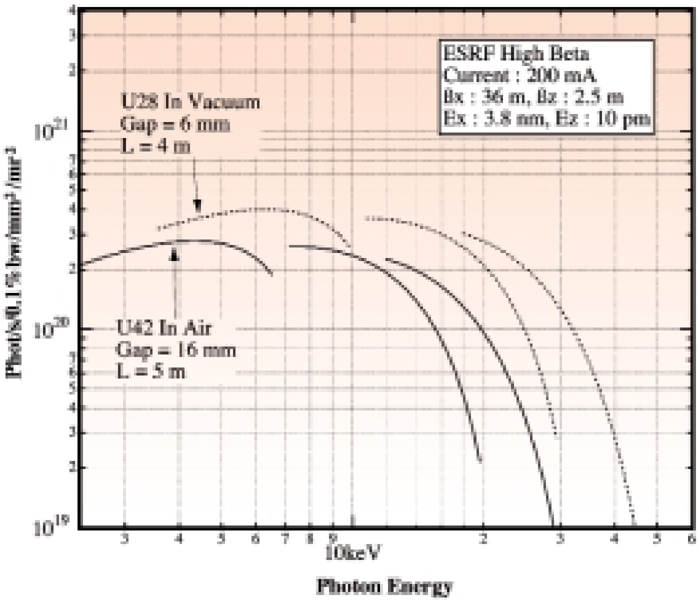

Fig. 3: Brilliance comparison between two fully tuneable undulators (K = 2.2) at a gap of 16 mm and 6 mm.

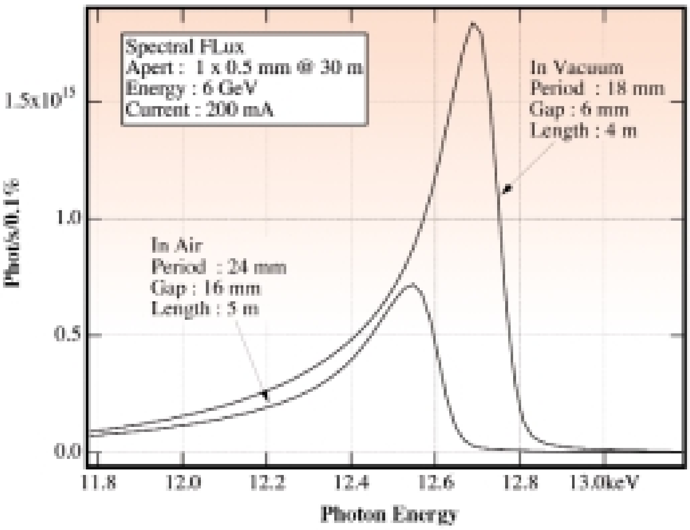

Fig. 4: Comparison of spectral flux in the fundamental for a 16 mm gap and 6 mm gap undultor. These undulators have a limited range of tunability and the period is optimised for a maximum flux around 1 Angstrom.

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