OPERATIONAL ASPECTS OF ELLIPTICAL UNDULATORS AT ELETTRA

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Abstract

Six variable polarization undulators of the APPLE-II type, are now in operation at the ELETTRA synchrotron light source. Their period length vary from 48 to 125 mm, thus providing linearly, circularly and elliptically polarized radiation in a wide spectral range from the near UV to the soft X-Rays. Two of them are arranged in a chicane so that two beamlines can make simultaneous use of the two sources. Also two identical undulators, together with a phase-modulator electromagnet, form an optical klystron which is routinely used for the storage ring Free Electron Laser. The impact of these devices on the electron beam dynamics is mainly due to their non-linear fields determining, in some cases, large tune-shifts and dynamic aperture reduction. The operational problems associated with these effects are discussed together with the results of the compensation methods which have been tested so far. The problem of the wide vertical distribution associated with the elliptical fields, and the consequent high heat load on the vacuum chamber and other components, is also briefly addressed.

1 OVERVIEW

Motivated by the increasing users' demand for adjustable polarisation radiation sources, a series of six APPLE-II type undulators [1] have been designed, constructed and installed in the ELETTRA storage ring in the last three years. They produce either linearly or circularly polarised photons in the UV and soft X-Ray region from 10 to 800 eV using the fundamental harmonic (see fig. 1), while higher harmonics extend the useful range up to about 2500 eV in the linear and elliptical polarisation modes. Table 1 below gives the main parameters of the various devices at the minimum gap of 19 mm.

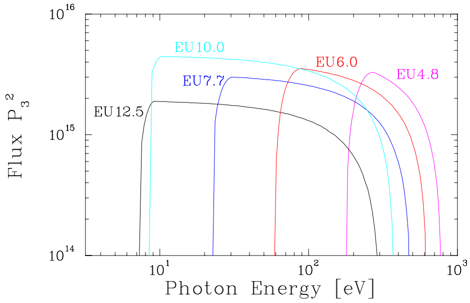

Figure 1: tuning range (fundamental harmonic). for the different devices .

period λo (cm)	Np	Horizontal Polarization		Circular Polarization		Vertical Polarization	
		B_0	ε_1	B_0	ε_1	B_0	ε_1
4.8	44	0.58	178	0.29	287	0.34	366
6.0	36	0.78	59	0.42	94	0.51	123
7.7	28	0.92	21	0.53	32	0.64	43
10.0	20+20	1.02	8	0.63	11	0.77	14
12.5	17	0.77	8	0.48	10	0.59	13

Table 1: Measured field strength (T) and corresponding fundamental photon energy (eV) for the new undulators

The construction of these undulators required significant improvements in the mechanical design of the support structures, the control of magnetic material properties and the development of adequate field error correction methods [2,3,4]. Despite a successful construction and the good magnetic field quality achieved, several problem areas are still to be fully investigated. The non-homogeneous field distribution inherent to this type of undulator affects the beam dynamics causing large tune shifts and reduction of dynamic aperture and lifetime. The wide vertical power distribution associated with the elliptical fields produces significant heat load on the vacuum chamber and other components, and special procedures must be adopted to minimise the risk of damage. Also the arrangement of the new devices in the storage ring (determined in some cases by specific design features of the beamlines) introduced new operational problem. These aspects will be described in some detail in the following sections.

2 BEAM DYNAMICS ISSUES

The significant impact of the new undulators on the dynamics of the stored electron beam became evident since the first device was put into operation. Large focusing effects have been observed in the form of polarisation dependent tune shift. This is illustrated in figure 2 where the measured tune is shown as a function of the longitudinal array shift Zs for the EU6.0 and EU12.5 undulators at the minimum gap. Model calculations [5,6], based on the ideal three-dimensional field distribution, agree well with the measurements, thus proving that the effect is intrinsic to the magnetic structure and not related to multipolar field errors. The model also shows that, keeping all other parameters constant, the focusing strength is proportional to $(\lambda o/E)^2$, and therefore larger for long-period devices and low electron beam energy.

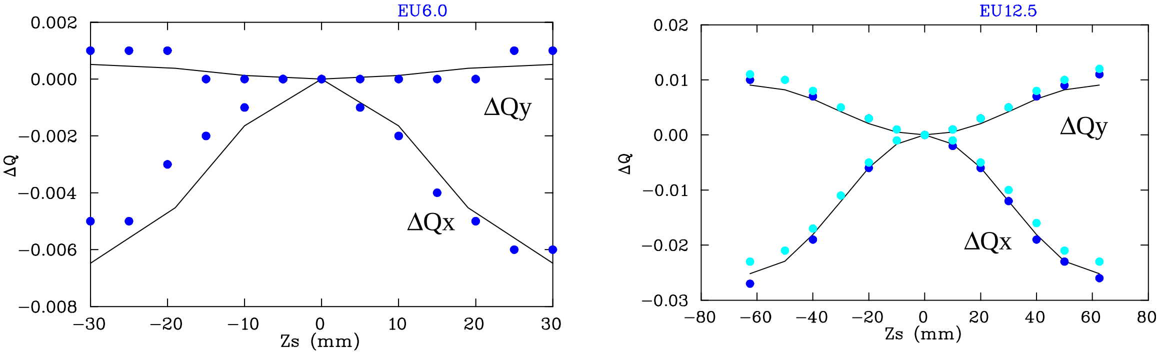

Figure 2: Measured (dots) and computed (lines) horizontal and vertical tune variation as a function of array shift for two representative devices at the minimum gap at 2 GeV.

The overall horizontal/vertical tune shifts induced by all the new devices when closed to minimum gap at 2.0 GeV range from 0.008/0.022 in horizontal polarisation, to -0.047/0.037 in circular polarisation, to -0.09/0.043 in vertical polarisation modes. Due to the rather large tune shifts, a high level software program has been written to compensate dynamically the tunes with the gap and phase variations of the devices by acting on the quadrupoles in the dispersion free straights. Whereas the program can be used during the phase of preparation of the machine for the users in which the devices are closed to their working gaps, it is not presently used for subsequent movements of the gaps or phases due to the quadrupoles being misaligned. This has the consequence that the closed orbit is severely affected by the changing currents in the quadrupoles. It is however regularly used during FEL dedicated operation, when the machine is operated at a lower energy (0.9-1 GeV). Following the realignment of the main magnets planned for the next shutdown period, the program will be tested again.

Associated with the tune shifts, the devices introduce a breaking of the symmetry of the optics which may be as large as 27% and 4% in the horizontal and vertical planes respectively when all devices are operating in the circularly polarised mode at minimum gap. The consequent destruction of the sextupole optimisation together with the intrinsic non-linearities of the devices have been noticed to influence the dynamic aperture. Previous simulations [7] predicted a dynamic aperture reduction from 16 to 12 mm horizontally and from 5 to 4 mm vertically. Recent measurements performed using the horizontal and vertical scrapers confirmed these results. Figure 3 shows the horizontal phase space over 50 turns for different initial amplitudes. It can be seen that at the limit of the dynamic aperture there is a loss of particles at the unstable fixed points of a fourth order resonance.

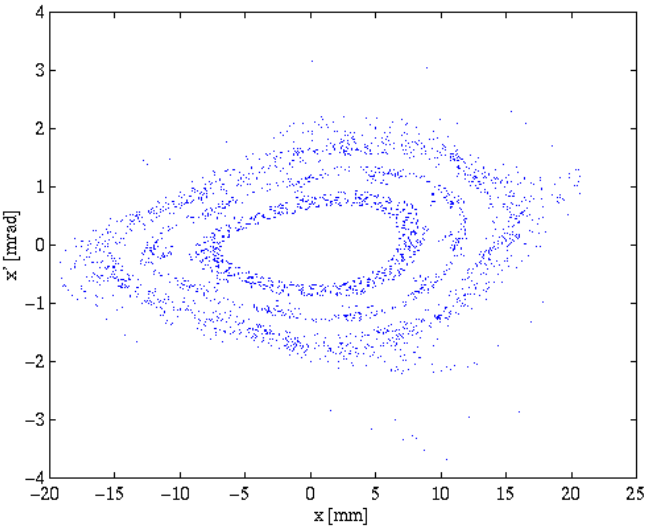

Figure 3. Horizontal phase space over 50 turns with the devices at minimum gap and in circularly polarized mode.

Confirmation of the influence of the fourth order resonance was noticed when one of the devices was closed in circularly polarised mode in the vicinity of 4·Qx = 57, where a drastic reduction in lifetime occurred. In general, it also has been noticed a great sensitivity of the lifetime on the tunes of the machine at which the devices were closed. However, restoration of the nominal working point led always to the recovery of the lifetime. However, at 1 GeV much larger effects have been seen that are in course of studying.

Motivated by the above mentioned difficulties with the tune compensation using external quadrupoles, a special magnetic shimming technique was recently tested on EU10.0. The method was originally proposed at ESRF [6] and consists in creating inside the undulator a phase dependent quadrupole in order to (partially) cancel the intrinsic undulator focusing. This was achieved with the installation of 1-2 mm wide, L-shaped iron shims near the horizontal gap between the magnets. However, attempts to install such shims in our case failed because of the positional instability generated by the magnetic forces acting on them. A modified geometry was therefore studied, using bigger shims placed at a larger distance from the beam axis (see fig. 4). This magnetically stable configuration allows easy installation and removal of the shims on the already operational undulator, with no modification to the magnetic block holders.

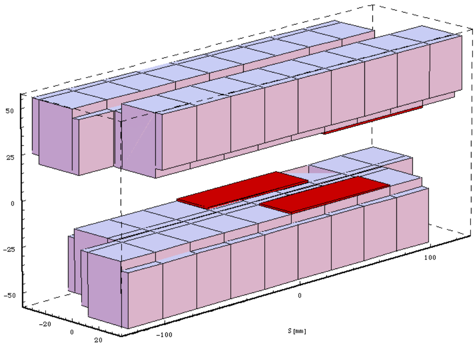

Figure 4: shim positioning on the magnetic arrays

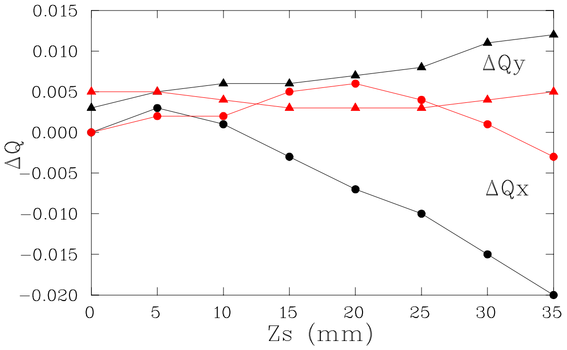

Figure 5: measured horizontal and vertical tune shift at 2 GeV before (black) and after (red) shimming.

The shims parameters were optimised in order to reduce as much as possible the total tune variation at 2 GeV. This required 8 shims of 0.5 mm thickness. Experimental results (fig. 5) confirmed the predicted reduction of the maximum tune shift by nearly a factor of four over the whole operational range. Despite these positive results, it must be considered that since compensation is achieved by correcting a second order effect ($\sim 1/E^2$) with a "real" quadrupole (focusing/defocusing at first order in 1/E), this technique only works for a particular electron energy. Since ELETTRA is operated at energies ranging from 0.9-1 GeV (FEL experiments) to 2 and 2.4 GeV (users' dedicated operation), this method cannot be conveniently applied. It could however find application in other fixed energy machines.

3 HEAT LOAD

Compared to a standard device, the angular power distribution from elliptical field undulators is widened vertically due to the helical motion of the electron beam. Therefore, increased heat load is generated on the narrow gap vacuum chamber and other front-end and beamline components. For this reason, new water-cooled Aluminium vacuum chambers have replaced the standard stainless steel chambers in the insertion device straight sections and in the downstream bending magnet where the radiation exit slots are located. This makes the operation of the new insertion devices possible even for horizontal fields exceeding the so called "Kx limit". This limit, determined by the condition that the vertical deflection of the trajectory be less than the acceptance of the radiation slot (±0.8 mrad), would require the vertical deflection parameter $Kx=0.934 \cdot Bxo \cdot (T) \cdot \lambda o(cm)$ to be less than about 3.2 for 2 GeV electron energy. In fact, due to the good thermal conductivity of Aluminium, the temperature increase of the vacuum chamber and the cooling water can be maintained below safe limits even for much higher Kx values. As an example, the case of the APE beamline is illustrated below. Two different undulators (EU12.5 and EU6.0) are placed on the same straight section of the ring, whose emission axes are angularly separated by a chicane-like steering of the electron beam (see fig. 6). This configuration allows simultaneous use of the two sources by two independent beamlines and experimental stations.

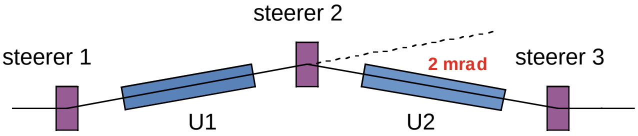

Figure 6: Layout of the APE undulators

The computed power density distribution is shown in figure 7 below for the three main polarisation modes. The 2 mrad horizontal separation between the two sources is clearly visible.

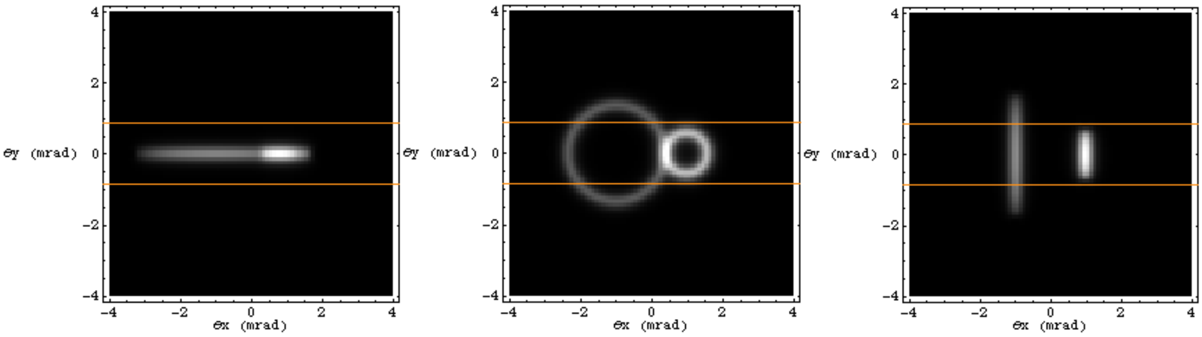

Figure 7: Power density patterns from the two undulators at minimum gap for horizontal (Kx =0) circular (Kx=5.4/2.4) and vertical (Kx=6.9/2.9) polarisation. The yellow lines represent the boundaries of the exit slot, showing the part of the radiation cone hitting the vacuum chamber.

Finite Element Analysis was performed for each case in order to verify that the temperature remains within acceptable limits in any possible situation. An example is shown in figure 8 showing the temperature distribution on the inner surface of the vacuum chamber under maximum heat load. Other sensitive components such as the photon beam shutters (see fig. 9) and radiation masks were also studied with similar results.

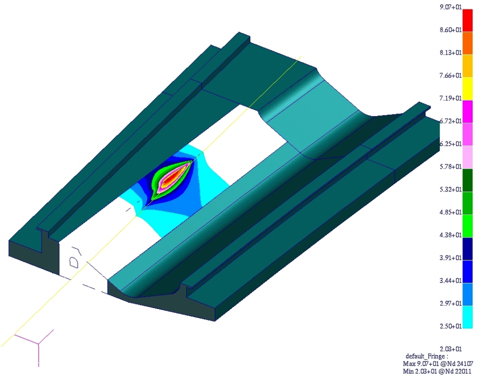

Figure 8: Thermal analysis result for the vacuum chamber (bottom half shown) with both undulators in the vertical polarization mode. Maximum chamber temperature is 91 °C in this case.

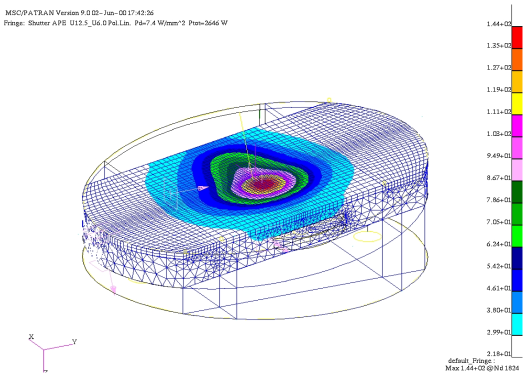

Figure 9: Thermal analysis result for the photon beam shutter with both undulators in horizontal polarization mode. Maximum surface temperature is 144 °C.

Calculations were also performed for the other undulator sources. As a result of this study, we found that the only component that cannot withstand the full power of the two simultaneously closed insertion devices is the photon beam shutter which (together with a vacuum valve) separates the storage ring from the beamlines. In this case, similarly to the case of other conventional high power devices, a suitable interlock has been implemented to protect this component from accidental exposure to excessive heat load.

During the commissioning period each undulator has been operated at increasingly smaller gaps, and in all cases the minimum design value was reached with no sign of excessive heating of any component.

4 PHASING THE TWO-SEGMENT UNDULATOR

On the Nanospectroscopy beamline, two identical 20-period undulator segments (EU10.0) and a phase-modulation electromagnet are arranged in an optical klystron configuration. This allows great operational flexibility, since this source is also used for the ELETTRA storage ring FEL [6]. In this case, the modulator is operated at relatively high field levels in order to enhance the laser gain, while during normal operation, the modulator is powered at the minimum current needed to properly phase the two undulators. This setup has been recently tested, and some results are illustrated below. Figure 10 shows the first harmonic spectrum (circular polarisation mode) measured for different modulator currents. At the optimum setting maximum intensity is obtained and the lineshape is almost identical to that of a single 40-period long undulator.

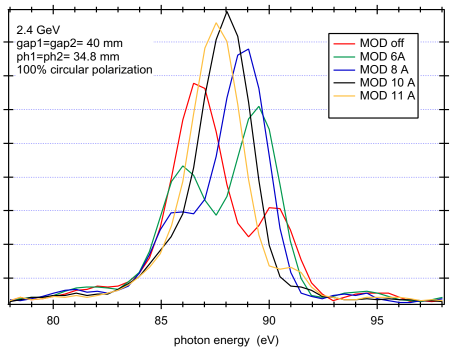

Figure 10: First harmonic spectrum for different modulator currents (optimum phasing shown in black).

The corresponding spectrum over a larger photon energy interval (fig.11, left) shows the low harmonic contribution that can be expected from purely circular polarisation. The relatively large intensity of the second harmonic is due to the large acceptance angle of 300 x 100 mrad. The same phasing exercise has been performed in the linear polarisation mode with similar results (fig. 11, right). At present the modulator is regularly operated under user's control in order to optimise the spectral intensity for any desired polarisation mode.

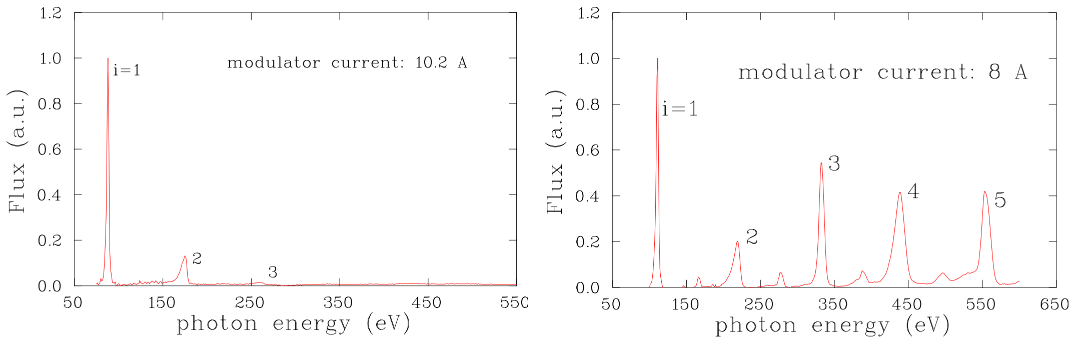

Figure 11: Extended range spectra with optimized phasing for circular (left) and linear (right) polarization.

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