OPTIMIZED UNDULATOR TO GENERATE LOW ENERGY PHOTONS FROM MEDIUM TO HIGH ENERGY ACCELERATORS

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Abstract

While emitting low energy photons from a medium or high energy storage ring, the on-axis heat load on the beam line optics can become a critical issue. In addition, the heat load in the bending magnet chamber, especially in the vertical and circular polarization mode of operation may cause some concern. In this work, we compare the heat loads for the APPLE-II and the Knot-APPLE, both optimized to emit 10 eV photons from the 3 GeV TPS. Under this constraint the heat load analysis, synchrotron radiation performance and features in various polarization modes are presented. Additional consideration is given to beam dynamics effect.

INTRODUCTION

To pursue a high brightness hard x-ray source, it is customary to increase the electron beam energy and decrease the period length of an undulator. For maximum research flexibility broad band, high brightness synchrotron radiation (SR) from VUV to soft X-ray is desired as well in high and medium energy storage rings. To serve as a low energy photon source, an undulator must have a high strength parameter, which in turn results in a high radiation power made up of mostly undesired photons. The radiation power causes a heat load on the beam line optics while the wiggling of the electron beam increases the impact on beam dynamics. These are two critical challenges which we will address in this paper.

To solve the heat load issue one could increase the period length with a corresponding decrease of the magnetic field. The concept was implemented in the designs [1-3] with the additional advantage of a rapid change of the polarization. The other solution is to offset the peak radiation power from the axis, leading to a decrease of the heat load on the beam line optics [4]. This scheme transfers the heat load from the beam line optics to high heat load components in the front end while keeping a reasonable heat load on the ring vacuum chamber.

In addition to the requirement of low photon energy, variation of SR polarization is desired. An APPLE-II with a long period length is a feasible design choice at the expense of on-axis flux density. To be an adjustable polarization source with low on-axis radiation power and a high on-axis flux density an undulator, called Helical-8, was proposed and developed at Spring-8 [5]. The undulator requires magnetization of magnets at different angles and therefore relies on available manufacturing technology for permanent magnets. An alternative design, called Knot-APPLE [6], is based on the APPLE-II design and has been constructed for use at the SSRF [7]. The undulator consists of four Knot arrays outside and four APPLE arrays inside. Similar to the APPLE-II design, the polarization change of the Knot-APPLE also relies on mobile magnet arrays.

In this paper, we compare the performance of an optimized APPLE-II and Knot-APPLE to emit low energy photons at TPS. We organize this paper as follows. In Section 2, we discuss the heat load on the beam line optics for 10 eV photons with horizontal polarization. In Section 3, the heat load on the ring vacuum chamber will be discussed. The performance of SR with circular and vertical polarization is discussed in some detail in this section. In Section 4, the effect on beam dynamics will be discussed and a summary is given in Section 5.

HEAT LOAD ON THE BEAM LINE OPTICS

The fundamental photon energy E_p, radiated from an undulator, is for K >>1, given by

$$E_p \propto \frac{E_e^2}{\lambda_u K^2} \quad (1)$$

E_e is the electron beam energy, λ_u is the period length of an undulator, K is the undulator strength parameter. E_p is proportional to the square of E_e, which means that an increased E_e is suitable for high photon energies, E_p but requires large values for K and λ_u to deliver low energy photons. Additionally, a high photon flux density is desired which pushes the number of periods to higher and the period length λ_u, to lower values. In other words, pursuing a low energy photon beam with high flux density, the undulator should have a short period λ_u but a high strength parameter. This condition causes a heat load issue. The on-axis angular power density is given by

$$\frac{dP}{d\Omega}(0,0) \propto \frac{N \cdot E_e^2 \cdot K \cdot G(K)}{\lambda_u} \quad (2)$$

Where N is the number of periods, the function $G(K)$ is close to 1 for $K > 1$. In the case of the 3 GeV TPS, an APPLE-II with $\lambda_u = 124\ mm$ serving as a 10 eV photon source, the fractional power passing through a slit aperture of ±2sigma of photon beam divergence is up to 1.74 kW. The allowable heat load for the first optics elements in the beam line should not exceed 1 kW utilizing liquid nitrogen cooling. This means the heat load from this APPLE-II cannot be absorbed by the beam line optics.

A straightforward remedy would be to reduce N, but the angular flux density would then drop. For our example, the period number N must be reduced from 32 to 12 to reduce the power to 1 kW, but at the same time the angular flux

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density would drop by 84%. The second method is to increase the period length λ_u. Figure 1 shows that for λ_u =155 mm (APPLE155), the heat load becomes acceptable, while the angular flux density is only reduced by 16%.

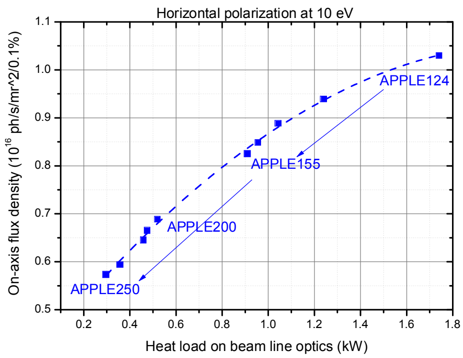

Figure 1: On-axis angular flux density versus heat load on beam line optics for different APPLE-II period lengths.

To understand the source of the heat load, Fig. 2(a) shows the on-axis flux density of APPLE124. The desired photon energies can be obtained from the first and third harmonics. As seen from Fig 2(a) most of the radiation power comes from higher harmonics and must be absorbed by beam line optics elements. In the Knot-APPLE design, a horizontal field exists even in the horizontal polarization mode. This field deflects the electron beam vertically and with it the radiation power from the mid plane. Compared to the APPLE-II, Fig. 2(b) shows that the on-axis angular flux density of the Knot-APPLE becomes significantly smaller above 1 keV, which explains why the Knot-APPLE results in a smaller heat load than a conventional APPLE-II. In the calculation, the period ratio of the Knot and APPLE arrays is 1.5. The period length of the APPLE array is still 124 mm.

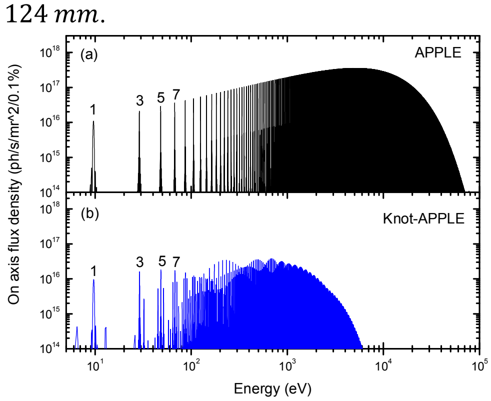

Figure 2: Comparison of the on-axis angular flux density spectra for the APPLE124 (a) and the Knot-APPLE (b), both with a period length of 124 mm. Indices show the harmonic number.

We compare the characteristics of the APPLE124 and Knot-APPLE in Fig. 3. Each of them produces a total power in excess of 10 kW, which, however, still can be handled by the front end. While the APPLE-II produces excessive power to the beam line, the power from the Knot-APPLE is reduced to 0.38 kW. The on-axis flux density of the first harmonic is also suppressed but only by 6%. Figure 4 shows the tuning curve of four different IDs serving as 10 eV photon sources. The Knot-APPLE not only produces the lowest heat load on the beam line optics, but also the highest angular flux density to the end user over the full operating range.

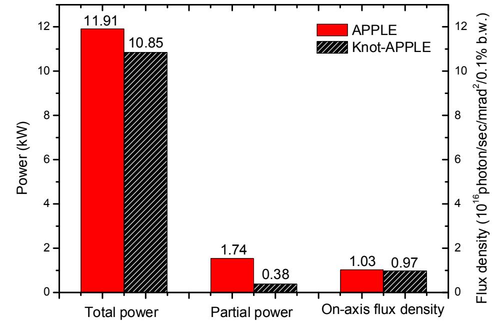

Figure 3: Comparison of APPLE124 and Knot-APPLE parameters. The bar chart shows the total power, the partial power and the on-axis flux.

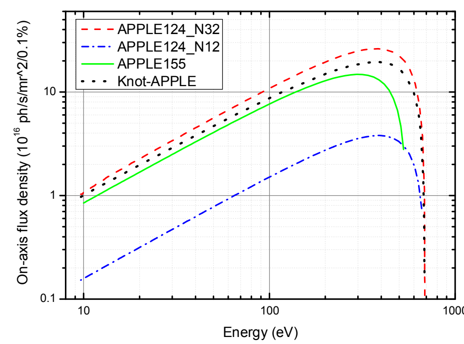

Figure 4: Tuning curve for four different IDs serving as 10 eV photon sources with horizontal polarization.

HEAT LOAD IN THE RING VACUUM CHAMBER

To decrease the partial power, the Knot-APPLE deflects the peak power from the axis due to the horizontal field generated in the magnet array. However, the limited vertical aperture in the vacuum chamber from undulator to the front end limits the horizontal deflection parameter K_x, because the radiation deflection is related to K. This limitation also applies to the APPLE-II and Knot-APPLE while operated in any non-horizontal polarization mode. In the case of TPS, a conservative value for K_x is 3.5. Under this condition, the allowable minimum photon energy at vertical and circular polarization modes for the APPLE-II and Knot-APPLE are determined. Figure 5 shows the gap-dependent of the fundamental energy and K for the Knot-APPLE and APPLE124. Both have a similar gap-dependent of K_x but the Knot-APPLE has a large effective field contribution from the Knot array leading to lower photon energies than the APPLE124. The effective undulator strength K_{eff} of APPLE124 is the same as K_x. Both sources have a nearly ideal degree of polarization at the fundamental energy. It is worth noting that the degree of polarization changes with energy except for the

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fundamental energy. If a user would like to use, for example, the third harmonic, the radiation turns out not to be purely polarized in the vertical plane. For circular polarization, the angular flux density of the Knot-APPLE at the fundamental energy is much lower than that of APPLE-II which has a longer period length 155 mm, as seen in Fig. 6. This can be understood by the magnetic field distribution as shown in the insert of Fig. 6. The magnetic field is still periodic but consists of multi-harmonics.

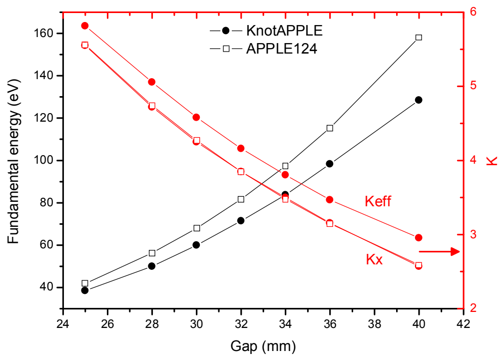

Figure 5: The gap-dependent of the fundamental energy and K. The Knot-APPLE (solid circle) and APPLE124 (open square).

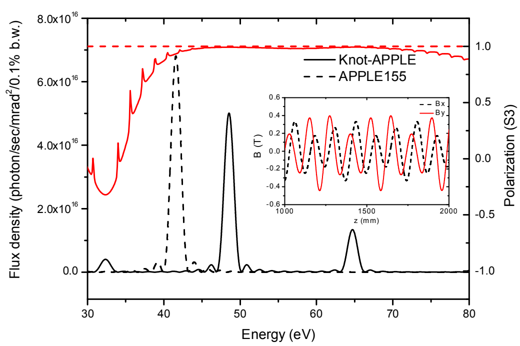

Figure 6: Angular flux density and degree of circular polarization for the Knot-APPLE (solid line) and APPLE155 (dashed line). The insert shows the magnetic field distribution in the Knot-APPLE.

BEAM DYNAMICS EFFECT

The good field region should now also include the space needed for the wiggling of the electron beam. It is known that the APPLE-II has an inherently small uniform region especially for vertical polarization, resulting in an obviously second-order kick [8]:

$$\theta_{x,y}^{2nd}(x,y) = -\frac{1}{2(B\rho)^2}\frac{\partial}{\partial x,y}\int_0^L [\left(\int_0^{\lambda_u} B_x(x,y,s')ds'\right)^2 + \left(\int_0^{\lambda_u} B_y(x,y,s')ds'\right)^2]ds \quad (3)$$

$B\rho$ is the magnetic rigidity proportional to the beam energy, L is the insertion device (ID) length. The second-order kick becomes significant for a long ID, a large magnetic field, and a small electron beam energy. Due to the partial differential in Eq. 3, a small uniform magnetic field gives rise to large higher order multipole errors, causing tune shifts and a reduction of the dynamic aperture. For the Knot-APPLE, the second-order kick was analysed using Eq. 3 as shown in Fig. 7. Compared to an APPLE-II of the same period length, the Knot-APPLE exhibits a similar magnitude for the second-order kick which contributes the most influence to the vertical polarization. To compensate the adverse effects, an active [9] or passive method [10] was demonstrated for the APPLE-II and is proposed for the Knot-APPLE as well.

Another part of the study aimed to evaluate the impact on the electron beam energy spread and emittance due to the synchrotron radiation integrals. For the TPS operating in a low emittance mode (non-achromatic mode), the Knot-APPLE decreases the energy spread by 0.4% but increases at the same time the emittance by 0.2%.

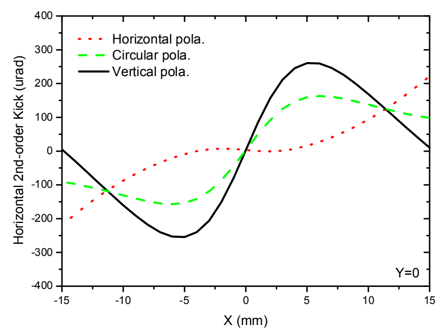

Figure 7: Horizontal second-order kick (eq.3) for the Knot-APPLE in the mid plane for horizontal (dotted), circular (dashed) and vertical (solid) polarization.

DISCUSSION

To produce low energy photons from a medium or high energy storage ring, this study addresses the major issues for an optimized undulator, including heat load on the beam line optics, on the ring vacuum chamber and beam dynamics effects. The characteristics of SR of various polarizations are compared for the APPLE-II and Knot-APPLE. The Knot-APPLE generates the highest angular flux density with the lowest heat load on beam line optics. Even so, two somewhat negative characteristics of the Knot-APPLE must be noted. The first is that poor polarization can be obtained only within a small energy range. Second, the Knot-APPLE produces a non-uniform distribution of the heat load, which increases the risk of non-uniform mechanical distortion of beam line optics.

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