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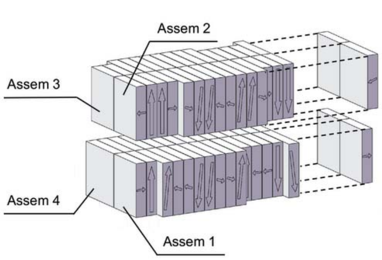

Practical design and performance of a new merged APPLE-Knot undulator

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Constructing vacuum-ultraviolet beamlines at synchrotron radiation facilities with giga-electron volt storage ring results in serious heat load on the beamlines which can reduce their performance. To solve this problem, an APPLE-Knot undulator with eight magnet rows has been built at the Shanghai Synchrotron Radiation Facility and has achieved very good performance. However, its performance in vertical polarization mode is imperfect. Here, a new configuration of a magnet-merged APPLE-Knot undulator that has achieved a better performance is reported.

1. Introduction

Vacuum-ultraviolet light and soft X-rays with controllable polarization produced by undulators are powerful for studying the electronic and atomic structures of materials. Along with an increase in storage ring energy, the heat load on beamlines has become a serious problem when excellent performance is needed, particularly for low-energy beamlines. An APPLE-2 (Sasaki, 1994) undulator can generate variably polarized radiation; however, its on-axis heat load is the same as that of a linear undulator. To suppress the on-axis power, an APPLE-Knot undulator (Sasaki *et al.*, 2013) with blank segments that mimic the electromagnetic knot undulator (Qiao *et al.*, 2009) was proposed, which can generate arbitrarily polarized photons with low on-axis heat load. However, the suppression of on-axis heat load is ineffective for vertical polarization mode due to the low vertical field generated by knot rows. To deal with this problem, two methods were proposed by Ji *et al.* (2015). The first was to change the magnetization directions of the knot rows and this new structure has been implemented at the Shanghai Synchrotron Radiation Facility (SSRF) beamline 03U with very good performance (Sun *et al.*, 2020). However, its on-axis heat load in the vertical mode is still obviously higher than that in the horizontal mode due to the insufficient strength of the vertical field generated by the knot rows due to the large gap in the horizontal direction. To solve this problem, Ji *et al.* (2015) proposed a second method, which merged the APPLE and knot rows [Figs. 1(*a*) and 1(*b*)] into one [Fig. 1(*c*)], and the structure recovered from an eight-row to a four-row APPLE-2 undulator. Recently, we found that, although its polarization in the vertical mode was good for small gaps, the polarization became low for large gaps due to the poor configuration of the magnets, especially for undulators with short period. In this paper, a new configuration that can generate photons with a high degree of polarization and low on-axis heat load in various modes is reported and its

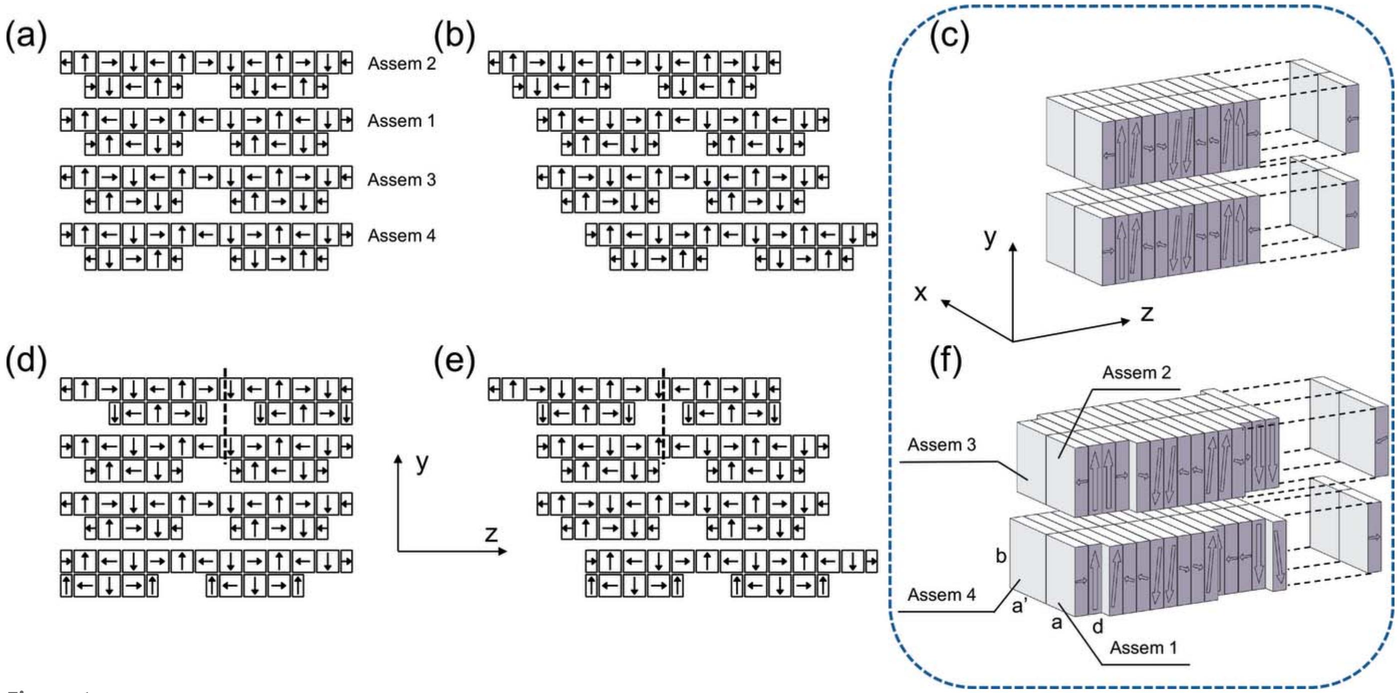

Figure 1
Different APPLE-Knot structures. (*a*), (*b*) [(*d*), (*e*)] Disassembled structures of Ji *et al.*'s (2015) work [this work] for horizontal and vertical modes. The upper and lower rows represent the APPLE and the knot rows, respectively, in each assembly. (*c*) [(*f*)] Magnet-merged structure of Ji *et al.*'s (2015) work [this work].

performance at Diamond Light Source Beamline I05 discussed.

2. Magnet-merged APPLE-Knot undulator with shifted knot rows

In the following discussions, the parameters of Diamond Light Source will be used. The storage ring energy is 3.0 GeV, the ring current is 300 mA, and the fundamental photon energy is chosen as 18.0–240.0 eV. Given the spatial coherence, the r.m.s. size σ and divergence angle σ' of the fundamental photons generated by undulators are (Onuki & Elleaume, 2003)

$$\sigma = \left[\left(1/2\pi^2\right)\lambda L\right]^{1/2}, \qquad \sigma' = (\lambda/2L)^{1/2}, \tag{1}$$

where λ and L are the photon wavelength and total length of the undulator, respectively. In the following, an acceptance angle of $4\sigma'$, in which 95% photons are included, is selected for each fundamental photon energy $h\nu$ to calculate the photon characters. For a 5.0 m undulator, the acceptance angle of 18.00 eV photons is about 0.374 mrad. All the magnetic fields and photon characters were calculated using the *RADIA* (Chubar *et al.*, 1998) and *SPECTRA* (Tanaka & Kitamura, 2001) programs. The structures of the merged APPLE-Knot undulator proposed in this work and its ancestor suggested by Ji *et al.* (2015) are shown in Figs. 1(*d*, *e*, *f*) and Figs. 1(*a*, *b*, *c*), respectively. The geometry parameters at Fig. 1(*f*) are $a' = b =$ 70.00 mm, a = 56.00 mm, d = 14.30 mm, where a is the width of the narrower magnets, and all the clearances between adjacent magnets are 0.50 mm in the x and z directions. The overall length of the undulator is 4972.30 mm. In the normal APPLE-Knot structure, the oversized APPLE magnets will result in a too small magnetic field generated by knot magnets near the undulator axis and high on-axis heat load. The merged structure removed this obstacle and the dimensions of the magnets in the x and y directions were chosen as 70.00 mm which is large enough to obtain a saturated magnetic field near the undulator axis. The dimension of the narrower magnets in the x direction showed a strong relation with vertical polarization and was adjusted to 56.00 mm to maximize the polarization. The dimension z was chosen as short as 14.30 mm to keep the fundamental photon energy lower than 18.00 eV. The magnetization of the merged magnet is obtained by vector addition of magnetizations of the APPLE and knot magnets and normalized to the remanent magnetization of the magnetic material, which is 1.33 T for NdFeB. For merged magnets, the ratios of the magnitudes of magnetization between the APPLE and knot components were chosen as 2.15 and 1.96 which correspond to rotation angles of 25° and 27° from the magnetization of the APPLE magnet for structures in Fig. 1(*c*) and Fig. 1(*f*), respectively. The ratios were chosen to obtain a balance between the suppression of on-axis heat load and photon flux.

For Ji *et al.*'s (2015) merged structure the performance is perfect for the horizontal mode while it is deficient for the vertical mode. Switching from horizontal to vertical mode is achieved by shifts of assemblies 2 and 4 along the z direction by $-\lambda_u/2$ and $\lambda_u/2$, respectively, where λ_u is the period of the APPLE rows. For the vertical mode, corresponding to the eight-row structure shown in Fig. 1(*b*), the heat load is higher than that of the horizontal mode and the polarization of

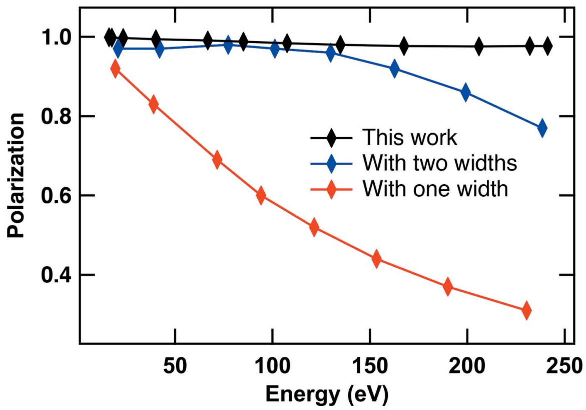

Figure 2
Comparison of photon polarization from APPLE-Knot undulators of Ji *et al.*'s merged (red), merged with two different widths (blue) and merged with knot-row shift in advance (black).

fundamental photons decreases dramatically as the gap increases (red line in Fig. 2). Two defects with this design lead to these problems. The first one is neglecting the existence of knot vacancies and setting all magnets to the same size; in fact, the rotation of magnetization of the merged magnet with knot component results in a decrease of the APPLE field and an enlarged size can compensate this change. Although this treatment increases the polarization effectively, the polarization is not high enough at large gaps (blue line in Fig. 2). The second defect is from its ancestor, the eight-row APPLE-Knot undulator. There is an imbalance between the horizontal and vertical modes due to the knot rows configuration. The configuration of knot rows is good in the horizontal mode [Fig. 1(*a*)] such that they occupy the same *z* range, while the *z* position difference between assembly 2 and 4 is as large as λ_u after switching from horizontal to vertical mode [Fig. 1(*b*)]. The switching results in unpaired knot magnets which generate a horizontal (in the *x* direction) component of the magnetic field as shown in Fig. 3, and therefore destroys the performance of the APPLE-Knot undulator, because for an ideal APPLE-Knot undulator the APPLE (Knot) rows should generate only horizontal (vertical) magnetic field in vertical mode. Shifting knot assemblies 2 and 4 by $\lambda_u/4$ and $-\lambda_u/4$, respectively [Fig. 1(*d*)], before merging the magnets is a way to deal with this problem. As a result, the maximum *z* position differences between these two knot rows are $\lambda_u/2$ for both horizontal and vertical modes. To see the effect of this shifting, a comparison of the magnetic fields taken by the *RADIA* program with the knot rows only for these two configurations in vertical mode is shown in Fig. 3; the magnetization and the gap were set to 0.60 T and 25.00 mm, respectively, during the calculation. The *x* component of the magnetic field is suppressed and the *y* component of the magnetic field is improved effectively, and a balance between vertical and horizontal modes is achieved. As a result, the polarization is increased (black line in Fig. 2) and the on-axis heat load of the vertical mode is decreased (see Fig. 8).

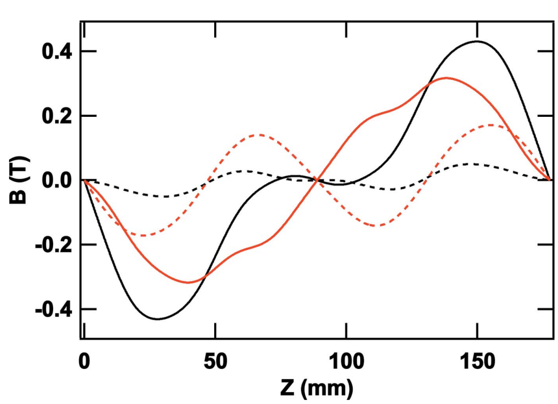

Figure 3
Comparison of vertical (solid lines) and horizontal (dashed lines) magnetic fields taken by *RADIA* with knot rows only for structures of Fig. 1(*c*) (red) and Fig. 1(*f*) (black) in vertical mode.

3. Results and discussions

The following results are calculated based on the new structure shown in Fig. 1(*f*). For horizontal mode, ideally, all assemblies should stay at the positions corresponding to the structure shown in Fig. 1(*d*). In this case, however, the linear polarization in the 45° direction in the *x*–*y* plane (P_{l45}) is larger than 10.0% due to the improper field generated by the knot rows. To solve this problem, a small relative shift in the *z* direction between assemblies 2 and 4 is needed. In practice, P_{l45} is decreased to less than 1.0%, and meanwhile the linear polarization is maximized when assemblies 2 and 4 are shifted by 4.44 mm and −4.44 mm ($0.075\lambda_u/2$), respectively; this value is determined after multiple attempts. The magnetic field, electron beam orbit, electron beam velocity and related photon flux and polarization for horizontal mode are shown in Figs. 4(*a*), 4(*c*), 4(*f*) and 4(*b*), respectively. Polarization of 99.9% is achieved at the 17.89 eV peak intensity position. The electron beam velocity always deviated from the undulator axis by greater than 0.2 mrad and the heat load inside the 0.374 mrad × 0.374 mrad acceptance solid angle is 95.0 W; this power is the maximum in the horizontal mode, and the power is less than 70.0 W within the $4\sigma'$ acceptance solid angle when the fundamental photon energy is higher than 40.00 eV (Fig. 8). Polarization can remain above 99.0% at all photon energies.

Ideally, assemblies 2 and 4 need to be shifted by $-\lambda_u/2$ and $\lambda_u/2$ to achieve vertical mode, corresponding to the structure shown in Fig. 1(*e*). For the same reasons as in the horizontal mode, assemblies 2 and 4 need to be shifted by −68.82 mm and 68.82 mm ($1.17\lambda_u/2$) to maximize the linear polarization and minimize P_{l45}. The corresponding magnetic field, electron beam orbit, electron beam velocity, photon flux and vertical linear polarization are shown in Figs. 4(*a*), 4(*d*), 4(*g*) and 4(*b*), respectively. Polarization of 99.9% is achieved at the 18.26 eV peak intensity position. The velocity always deviated from the undulator axis by greater than 0.2 mrad and the heat load is 9.0 W inside the 0.374 mrad × 0.374 mrad acceptance solid angle. Polarization can remain above 99.0% at all photon energies. P_{l45} can be minimized to less than 1.0% at 18.26 eV and rises up to 9.0% at 212.91 eV photon energy.

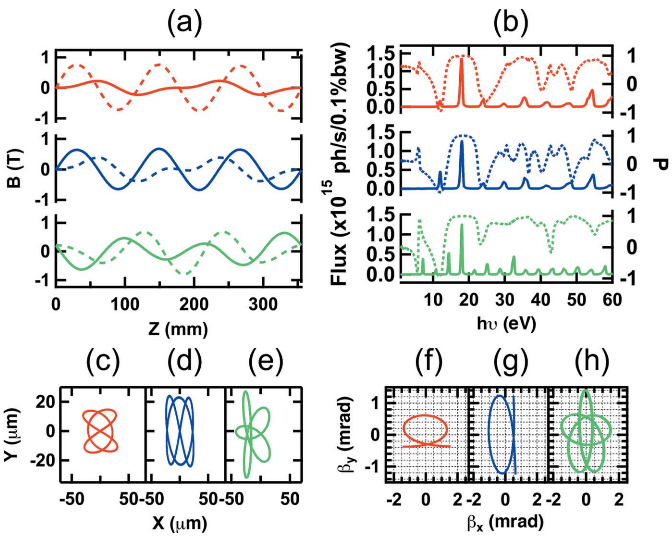

Figure 4
Performance of the APPLE-Knot undulator with structure shown in Fig. 1(*f*) in horizontal (red), vertical (blue) and circular (green) modes. (*a*) Vertical (dashed lines) and horizontal (solid lines) magnetic fields. (*b*) Fluxes (left axis, solid lines) and linear or circular polarization (right axis, dashed lines) at different photon energy. Electron orbitals [(*c*), (*d*), (*e*)] and velocities [(*f*), (*g*), (*h*)] in horizontal, vertical and circular modes.

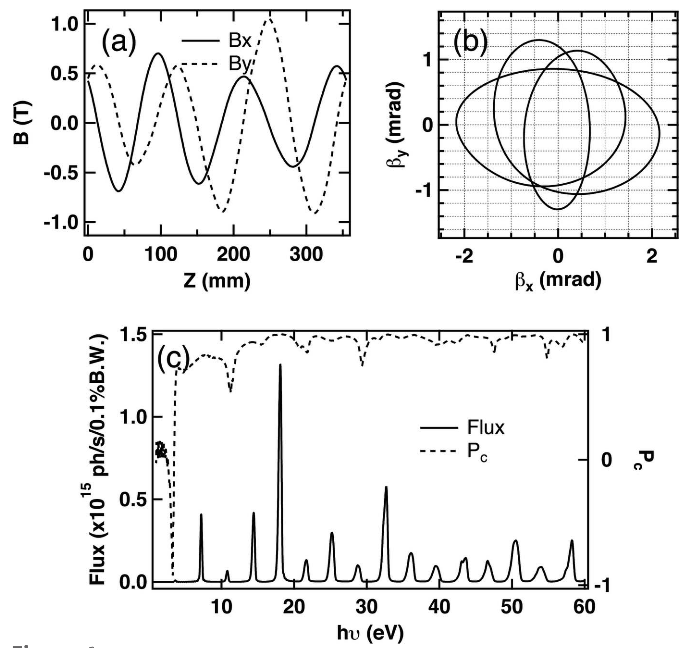

Figure 6
Magnetic field (*a*), electron velocity (*b*), photon flux (left axis, solid line) and circular polarization (right axis, dashed line) (*c*) of the undulator with the Fig. 5(*b*) structure obtained by shifting assemblies 2 and 4 by $-3\lambda_u/4$.

There are two methods to generate circularly polarized photons. The first one is to shift assemblies 2 and 4 by 39.22 mm and 28.86 mm, respectively, corresponding to Fig. 5(*a*). The corresponding magnetic field, electron beam orbit, electron beam velocity and related photon flux and polarization are shown in Figs. 4(*a*), 4(*e*), 4(*h*) and 4(*b*), respectively. Polarization of 99.9% is achieved at the 18.18 eV peak intensity position. The electron beam velocity always deviated from the undulator axis by greater than 0.2 mrad and the heat load inside the 0.374 mrad × 0.374 mrad acceptance solid angle is 40.4 W. Polarization can remain above 99.0% at all photon energies. If lower heat load is hoped, another configuration can be used. In this configuration, assemblies 2 and 4 are shifted by another $-\lambda_u$, −84.36 mm and −93.24 mm, respectively, corresponding to Fig. 5(*b*), such that the phase difference between APPLE rows is the same and meanwhile the knot rows are more separate. The magnetic field, electron beam velocity and related photon flux and polarization are shown in Fig. 6. Polarization of 99.9% is achieved at the 18.10 eV peak intensity position. This configuration results in a very low heat load of only 1.6 W inside the 0.374 mrad × 0.374 mrad acceptance solid angle. The defect of this configuration is the high P_{145} and it is as large as 11.0% at 244.70 eV photon energy due to the negative influence from the knot magnets.

As a new type of merged APPLE-Knot undulator, its realization is achievable. There are two methods to obtain a merged magnet. The first method is to sinter the magnet with the magnetic field exerted in the desired direction. The second method is to cut the desired magnet off a larger one. As for shimming, the blocks without the knot component, *i.e.* those without rotation of magnetization, can be used, and selecting different groups of blocks can adjust the magnetic field component in different directions. As an example, the blocks marked by dashed lines in Figs. 1(*d*) and 1(*e*) are selected with

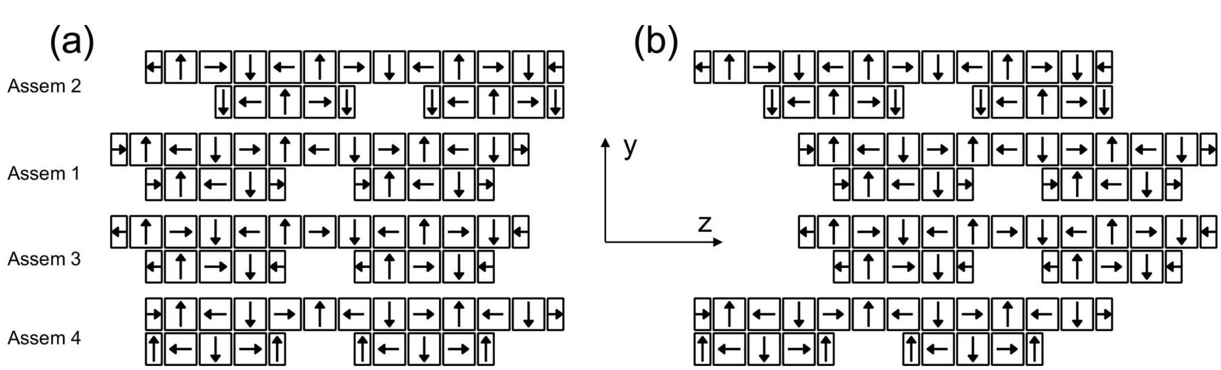

Figure 5
(*a*) [(*b*)] Configuration in circular mode obtained by shifting assemblies 2 and 4 by $\lambda/4$ [$-3\lambda/4$].

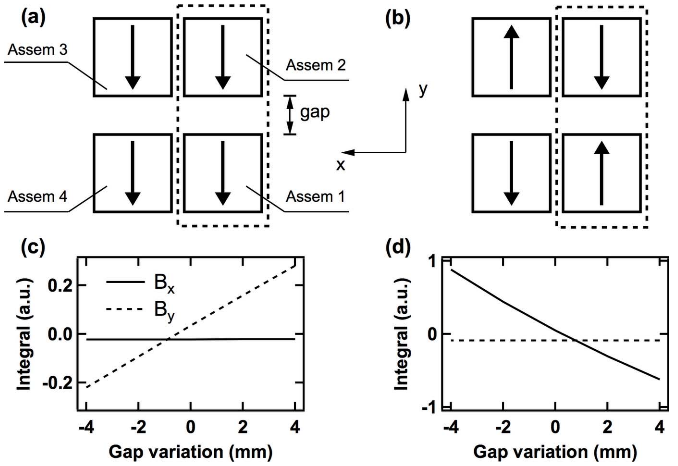

Figure 7
(*a*) [(*b*)] Cross section of the blocks marked by dashed line in Fig. 1(*d*) [Fig. 1(*e*)]. (*c*) [(*d*)] The integral of x [solid line] and y [dashed line] components of the magnetic field for different variations of gap between the blocks shown in (*a*) [(*b*)].

their cross sections shown in Figs. 7(*a*) and 7(*b*), respectively. For an initial gap of 50.00 mm, varying the gap between the blocks specified by the dashed boxes in Fig. 7(*a*) [Fig. 7(*b*)] can change the local y [x] component of the magnetic field. The integral of the x and y components of the magnetic field over the full undulator along its axis is shown in Figs. 7(*c*) and 7(*d*); the integrals of the x and y components of the magnetic field can be tuned independently. The integrals remain unchanged for different undulator phases.

A comparison of the on-axis heat load between this work and the APPLE-2 undulator used now in Diamond beamline I05 is shown in Fig. 8, showing that the on-axis heat load problem is resolved thoroughly.

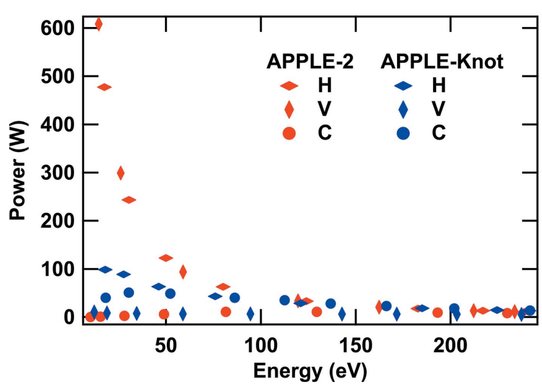

Figure 8
Comparison of on-axis heat load between the APPLE-2 undulator used now at Diamond beamline I05 (red) and this work (blue) in various modes.

4. Conclusion

In conclusion, a new magnet-merged APPLE-Knot undulator which can generate arbitrarily polarized photons with low on-axis heat load and high polarization has been designed. Our discoveries give the possibility to construct beamlines with a performance that was previously unavailable.

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