ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM001

# FOUR-ROWS APPLE-KNOT UNDULATOR ON HEPS

X. Y. Li†, Y. W. Yang, Y. Jiao, H.H. Lu, S.K. Tian
Key Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, CAS, Beijing 100049, China

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

*Abstract*

The High Energy Photon Source (HEPS) is a 4th generation synchrotron radiation source being built in China. An APPLE-Knot undulator with a new configuration is designed for the XCMD beamline of the HEPS. It is the first time to apply four-row APPLE-Knot undulator in storage ring based light sources. The main differences between the novel design and the conventional design of the APPLE-Knot undulators are discussed. Furthermore, the influences of the APPLE-Knot undulator on storage ring optics, as well as the dynamic effects during the process of gap variation at different polarization modes, are investigated and will be introduced in this paper.

## INTRODUCTION

Among the 14 ID beamlines planned for Phase I of HEPS [1], a special beamline used to generate polarization tuneable soft X-rays is planned to be built for the XMCD experiment. It is the only soft X-ray beamline in the first phase of HEPS with the requirement of the minimum photon energy lower than 100eV. To achieve such a lower fundamental photon energy, a large deflection parameter (K) is required in the undulator. However, for linear polarization modes, a high K value can result in unwanted high harmonics, leading to on-axis heat load issues that can be particularly challenging for high-energy storage rings like HEPS. Therefore, a four-row APPLE-Knot undulator [2,3] has been designed to solve this difficulty and adopted by users in 2021. For it is the first attempt to use this type of undulator on a storage ring, the design of the configuration has gone through a major revision to become more symmetric [4] at the expense of performance. The main consideration of this revision is that the magnetization orientation distribution of two magnet arrays in the past configuration is no longer symmetric, there is a notable net kick for electrons in circular polarization mode [5]. This net kick influences the electron trajectory significantly appears like a constant field error and is required additional corrections. A relatively conservative design was chosen with the configuration more symmetric though, the defect of polarization drop in vertical mode has been made up by optimize the corresponding APPLE magnetic blocks and the rotation angle of magnetization specifically. The design of this APPLE-Knot undulator was finalized in September 2021 and manufactured in the last December. Physical design, dynamic effects progress as well as laboratory adjustment of the 4-rows APPLE-Knot undulator are briefly presented below.

## PHYSICAL DESIGN

As is mentioned above, physical design of this undulator pass through some revisions. The major revision is to change the configuration to become more symmetric and optimize the blocks dimension as well as magnetization tilt angle to ensure the polarization ratio over 95% at any polarization modes. A special end configuration consist with tilted magnetization magnets was designed to compensate the first and second integral field errors in two directions. The whole configuration including ends is shown in Fig. 1.

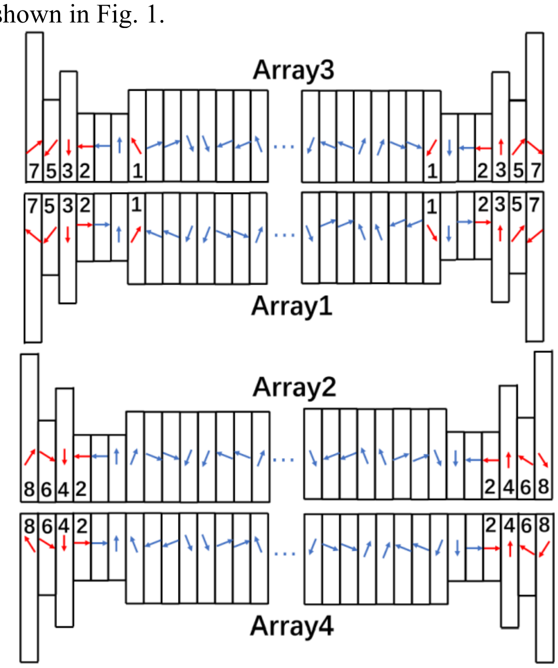


Figure 1. Configuration of 4-rows APPLE-Knot undulator. Blocks with numbers represent the end configuration.

Radiation power distribution is another crucial consideration during the physical design. Since the radiation heat load generated by the undulator will be deposited on the vacuum chamber downstream and on the optical elements within the photon acceptance aperture, the radiation power distribution has to be allocated carefully during the physical design. After several iterations, parameters and specifications of the undulator are determined and list in Table1.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM001

Table.1 Parameters of 4-Rows APPLE-Knot Undulator

| | |
|---|---|
| Period length 3λu(mm) | 256.8 |
| APPLE rows period length λu(mm) | 85.6 |
| Knot rows period length 1.5λu(mm) | 128.4 |
| Effective main field (T) (HM/VM/CM) | 0.88/0.69/0.68 |
| Effective Knot field (T) (HM/VM/CM) | 0.2;0.12/0.16;0.12/0.57 |
| Number of periods | 18 |
| Gap range (mm) | 14.7-67.5 |
| Dimensions of tiltd magnetization magnets | 55×55×10.7 |
| Dimensions of parallel magnetization magnets | 55×30×10.7 |
| Magnetization tilted angle | $tg^{-1}(0.4)$ |
| Clearance between two adjacent rows(mm) | 1 |

The polarization ratio is above 95% while the minimum value occurs at the maximum gap in the helical mode and the maximum radiation power integrated within the acceptance angle is less than 220W for any polarization mode. Details of performances are shown in Fig.2.

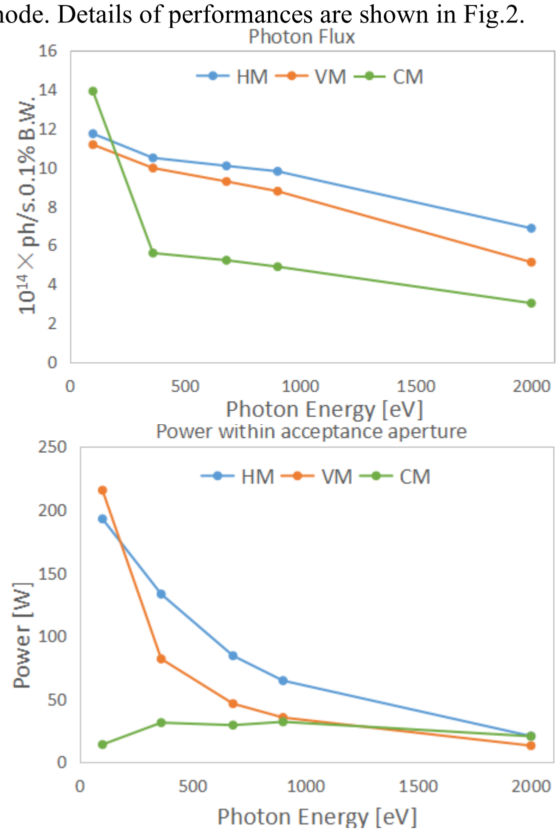


Figure 2. Radiation flux (up) and power (down) within the acceptance aperture.

## DYNAMIC EFFECTS AND

After the modification of the physical design, dynamic effects due to the APPLE-Knot undulator with the new configuration are also evaluated as same as before [6,7]. The linear optics have been matched by seven pairs of quadrupoles before the dynamic analysis. There is no significant change in the dynamic aperture compared to the previous results. The beam life-time remains above 1.6h for the high-bunch-charge mode.

In addition to the linear optics matching by quadrupoles, 12 pairs of current strips adhere on the upper and lower surface of vacuum chamber are prepared for the dynamic multipoles compensation [8]. Cross section of current strips layout and the relevant dimensions are shown in figure 3. It is indicated that the maximum current for each strip can reach 4.5A when the current density is restricted less than 1.5A/mm$^2$.

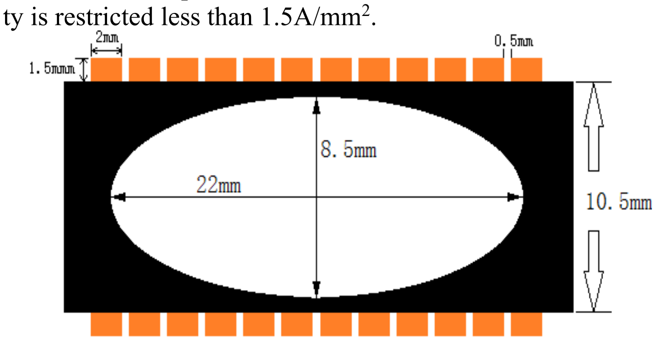


Figure.3 Layout and specifications of current scrips.

Several different correction methods are rested to compensation the dynamic multipoles due to the undulator. We first optimize the on-axis value of dynamic multipoles in horizontal and vertical directions as shown in figure 4 and found that although the tune shifts in two directions could be corrected efficiently, the dynamic aperture reduced obviously compare with the case that linear optics matching by quadrupoles. The main problem of this method is that the horizontal dynamic kick distributed along the vertical axis cannot be compensated at all.

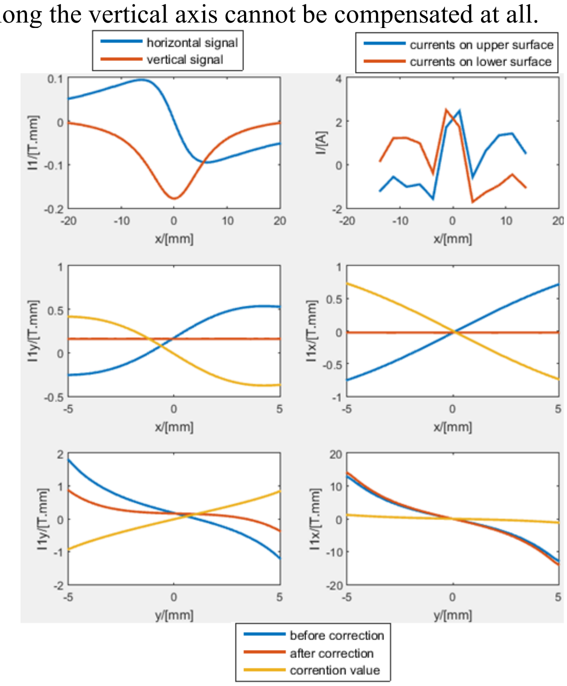


Figure 4 Results of on-axis dynamic multipoles compensation by current strips.

The comparison of dynamic apertures between the current strip compensation method and quadrupole matching method are shown in Figure 5.

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM001

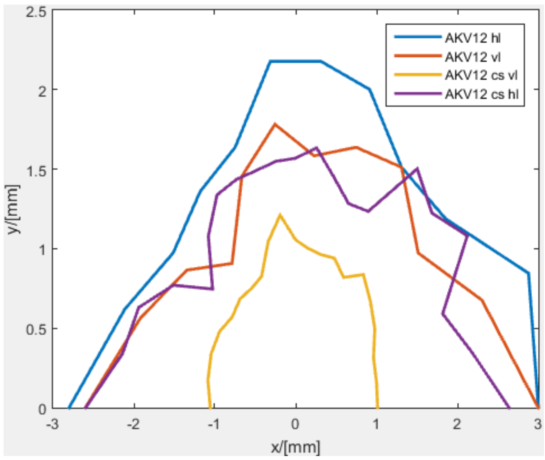


Figure.5 Comparison of dynamic aperture which 'cs' represent to the result compensated by current strips.

## LABORATORY MEASUREMENT AND ADJUSTMENT

The adjustment of this 4-rows APPLE-Knot undulator began in January this year. As a permanent undulator, most of shimming methods applied on the normal elliptical polarization undulator (EPU) can be used on this type of undulator. However, the main difference between the 4-row APPLE-Knot undulator and EPU should be considered in the shimming process is that the on-axis magnetic fields remain non-zero in both horizontal and vertical directions at any polarization modes for APPLE-Knot undulator while only horizontal or vertical on-axis magnetic field is non-vanished in the relevant polarization modes in the case of normal EPU. Therefore, each of the magnetic array is designed to consist of several independently detachable modules [9]. There are two modules with the opposite magnetization direction within one period as shown in Fig.6.

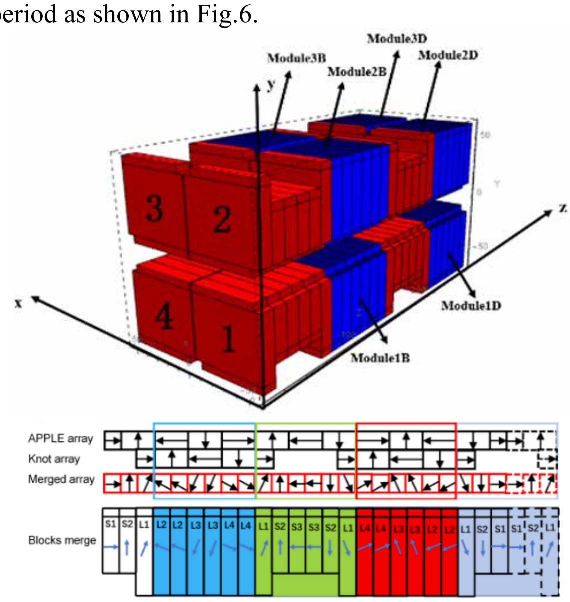


Figure 6 Module configuration (upper) and its magnetization arrangement (lower) for one period.

The height and horizontal offset of each module can be shimmed simultaneously which is able to adjust the on-axis magnetic field independently in horizontal and vertical directions.

Steel gaskets is used to shim the phase dependence field errors and gap dependence field errors as shown in Figure 7. 4 pairs of integral field compensation coil are installed at both ends of the undulator as shown in figure 8. Different from feedforward coils which are installed on the storage ring, the correction strength of these coils are only calibrated in laboratory.

Figure 7 Shims on the magnets.

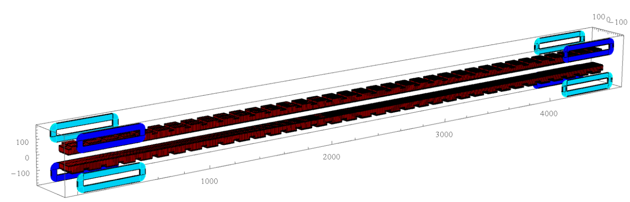

Figure 8 mode of APPLE-Knot configuration with end coils.

Because there is no requirement for the phase error of APPLE-Knot undulator, the remain objects of shimming are field integral errors and the fluctuation of electron trajectory. The on-axis integral field errors without coil correction after shimming are present in Fig.9.

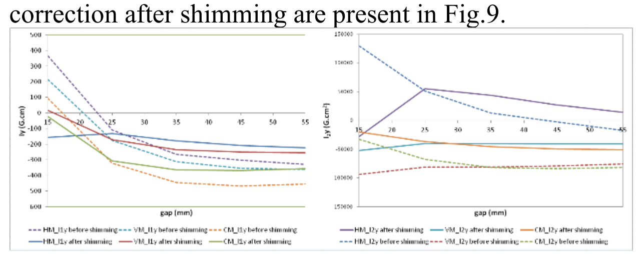


Figure 9 comparison of integral fields before and after shimming.

## SUMMARY

A 4-row APPLE-Knot undulator has been designed and manufactured for HEPS. Up to now, the undulator shimming without current strips has completed. The rest work will be concentrated on the current strips correction methods including offset measurement and calibration, linear optics correction and dynamic aperture restoration.

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM001

# REFERENCES

[1] Yi Jiao *et al*., "The HEPS project", *J. Synchrotron Radiation.*, vol. 25, no. 6. p. 1611-1618, Sep. 26, 2018. doi: 10.1107/s1600577518012110

[2] F. Xi, *et al.*, "A preliminary design of a knot undulator", *J. Synchrotron Radiat*. Vol. 20, no. 1, p. 145–152, 2013.

[3] F. Ji *et al*., "Design and performance of the APPLE-Knot undulator", *J. Synchrotron Radiat*. vol 22, no. 4, p. 901–907, 2015.

[4] Y. Yang, X. Li, H. Lu, "A new practical design of a merged APPLE-Knot undulator for High Energy Photon Source", *Nucl. Instrum. Methods Phys. Res. Section A*., vol 1034. p. 166816, Jul. 2022. doi: 10.1016/j.nima.2022.166816.

[5] Y. Yang, X. Li, H. Lu, "A practical design and field errors analysis of a merged APPLE–Knot undulator for High Energy Photon Source", *Nucl. Instrum. Methods Phys. Res. A.,* vol. 1011 p. 165579. 2021.

[6] X.Y. Li *et al*., "Status of HEPS Insertion Devices Design", *in Proc. IPAC'21*, Campinas Brazil, May 2021, pp. 339-341. doi: 10.18429/JACoW-IPAC2021-MOPAB090

[7] X.Y. Li *et al*., "Effects of Insertion Devices on Stored Electron Beam of high Energy Photon Source", *in Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 991-913. doi: 10.18429/JACoW-IPAC2017-MOPVA026

[8] J. Bahrdt *et al*., "Active \shimming of the Dynamic Multipoles of the BESSY UE112 Apple Undulator", in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper WEPC097, pp. 2222-2224.

[9] Y.S. Huang *et a*l., "Four-row APPLE-Knot undulator mechanical design and test piece studies for High Energy Photon Source", *JINST*, vol. 17, no. 08. p. T08012, Aug. 01, 2022. doi: 10.1088/1748-0221/17/08/t08012

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.