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Confined-walking mode for an elliptical polarized undulator and its application

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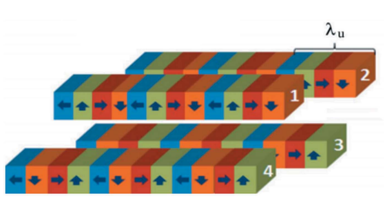
Elliptical polarized undulators (EPUs) are broadly used in the soft X-ray energy range. They have the advantage of providing photons with both varied energy and polarization through adjustments to the value of the gap and/or shift magnet arrays in an undulator. Yet these adjustments may create a disturbance on the stability of the electron beam in a storage ring. To correct such a disturbance, it is necessary to establish a feed-forward table of key nodes in the gap-shift-defined two-dimensional parameter space. Such a table can only be scanned during machine-study time. For a free-walking mode, whereby an undulator is allowed to manoeuvre in the whole gap-shift space, all the key nodes need to be scanned at the expense of a large amount of machine-study time. This will greatly delay the employment of a full-polarization capable undulator (especially circularly polarized). By analyzing data-collecting patterns of user experiments, this paper defines a reduced set of key nodes in gap-shift parameter space, with the number of key nodes to be scanned for feed-forwarding scaled down to one-third of the original; and introduces a new walking mode for EPUs: confined-walking mode, whereby the undulator is manoeuvred only within the reduced set of key nodes. Such a mode is firstly realized on the EPUs at the DREAMLINE beamline at Shanghai Synchrotron Radiation Facility (SSRF). Under confined-walking mode, the undulator movements are stable and there is no obvious disturbance to the electron beam with the feed-forward system in operation. Successful experiments have been carried out using the circularly polarized light obtained via the new walking mode. This mode is expected to be applied to future EPUs at SSRF with the increasing requirements for various polarization modes.



1. Introduction

In modern light sources, undulators have been widely used to generate synchrotron radiation, not only because its luminous intensity is at least four to five orders of magnitude higher than that of an ordinary bending magnet but also because its emitted light polarization can be tuned by changing the relative positions of its permanent magnet arrays. Such a polarization tunability is a very important feature for studying many phenomena in condensed matter physics, materials science, biology, chemistry and other fields.

Since the 1990s, different types of elliptical polarized undulator (EPUs) with a variety of phase modes have emerged, among which the APPLE-II type (Sasaki, 1994; Lidia & Carr, 1994) has been widely used. The most common description of EPU tunability in accordance with Schmidt & Zimoch (2007) is given as follows: to tune beam polarization,

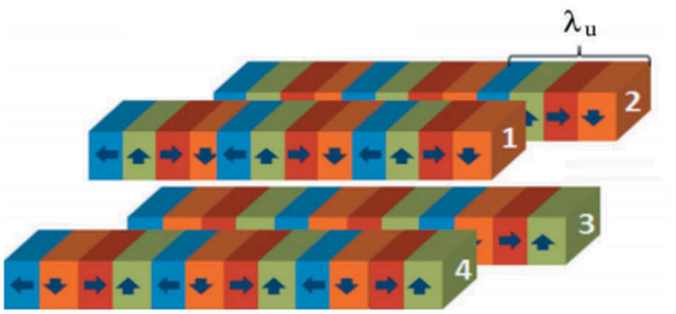


Figure 1
Magnet arrays (1–4) in the APPLE-II undulator.

two arrays of magnets across the diagonal (*e.g.* ⟨1, 3⟩ in Fig. 1) move synchronously horizontally relative to the other two arrays of magnets across the diagonal (*e.g.* ⟨2, 4⟩); the light polarization evolves from horizontal, through elliptical, circular to vertical when the movement has an offset (so-called 'shift') varied from 0 to $\lambda_u/2$ (λ_u is the length of one period in the array). To tune the photon energy, the vertical spacing (so-called 'gap') between the magnet arrays of ⟨1, 2⟩ and that of ⟨3, 4⟩ is regulated. In recent years, electromagnet-assisted undulators have been developed for polarization fast-switching (Chavanne *et al.*, 1998; Marteau *et al.*, 2012), which is beyond the scope of this article.

However, the introduction of an undulator in a storage ring can have some adverse effects, such as closed-orbit distortion (COD), linear optics disturbance, non-linear kicks, dynamic aperture reduction, emittance increase *etc.*, and serious damage to the beam quality may arise due to the superimposed impacts by a large number of undulators simultaneously in operation (Zhang *et al.*, 2017). For an EPU, the motion involves both gap and shift adjustment; a dedicated feed-forward table for the EPU has to be established so that the disturbance on the beam can be corrected immediately upon any undulator movement.

In practice, the tunable energy range of an EPU undulator is usually very broad. For example, a conventional working range of an udulator for soft X-rays is 200–2000 eV, which means that the range of the gap adjustment is very large, and, combined with the shift adjustment for polarization selection, this will form a huge two-dimensional parametric phase space. To ensure that the undulator navigates this parameter space with minimal or no disturbance to the beam quality of the accelerator, the feed-forward table needs to be scanned at key nodes in the parameter space. The number and location of such key nodes have to be designated for each undulator. The selection criteria for key nodes are: (i) limitation on the number of scanning points by hardware, (ii) the laws of undulators affecting beams and (iii) implementability of feed-forward interpolation. As an example, Fig. 2 shows the key nodes set in the working parameter phase space of the high-energy undulator EPU58 at the DREAMLINE beamline of Shanghai Synchrotron Radiation Facility (SSRF). The gap variation range is [15 mm, 160 mm] and that of the shift is [−29 mm, 29 mm]. Even after considering the feed-forward scanning interpolation, the number of key nodes that needed to be scanned is still as high as $N = 22 \times 21 = 462$.

Feed-forward scanning takes a large amount of time and is not allowed to be carried out during normal operation, thus can only be arranged in the machine-study time at a synchrotron radiation facility where beam time is very valuable. Machine-study time that can be arranged every week is very limited, and the maintenance, diagnosis and the new function development of the machine need to be considered together. Therefore, the amount of beam time that can be allocated to any specific undulator for feed-forward scanning

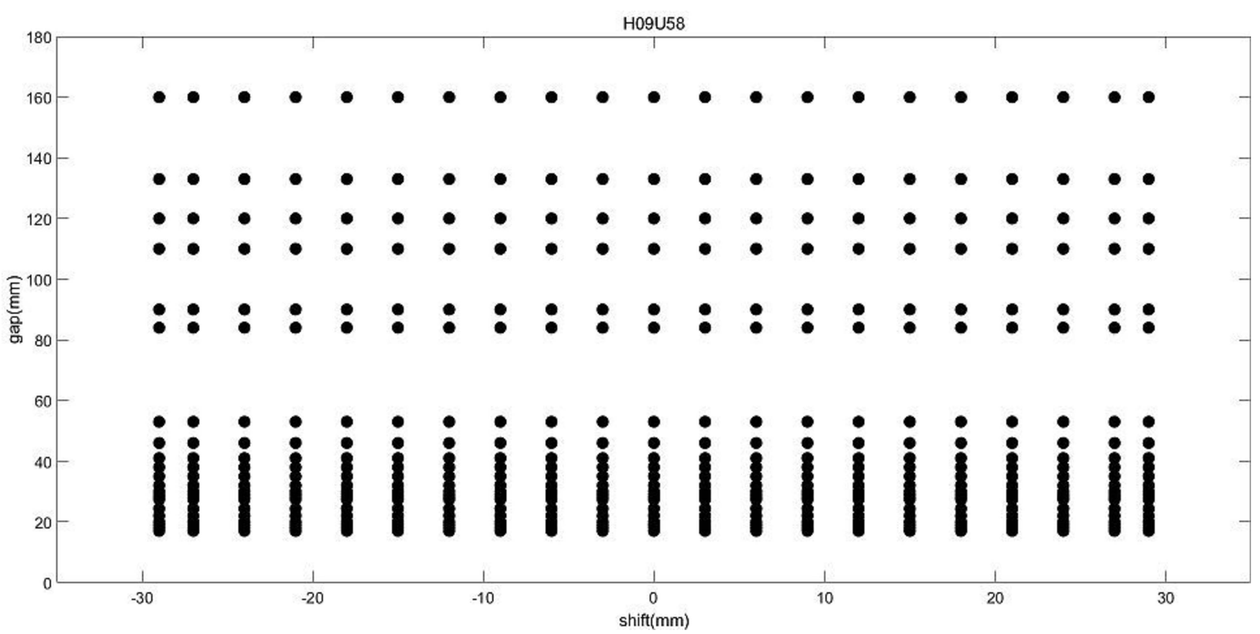


Figure 2
Key knots set in gap-shift two-dimensional phase space (marked by black-dots) of the undulator EPU58 for the DREAMLINE beamline at SSRF.

is very limited. It is possible, ideally, to navigate through the complete parameter space as shown in Fig. 2 within a few hours for an APPLE device. However, in reality, it is not always straightforward for feed-forward scanning to converge to a solution satisfying COD < 2 μm; quite often, multiple trials have been performed. Aside from this, slow drifting in long-lasting feed-forward scanning causes a change in the reference orbit, enforcing an orbit refreshment, which also reduces the efficiency. These two major factors can easily increase the total amount of time for commissioning by three to five times, up to 20 h, not to mention other factors such as hardware failures; this can result in a great delay for a deployment of a full polarization functional EPU.

2. Motion mode for EPU

2.1. Gap, shift and photon energy correspondence

After considering the specific needs of users, we found that the setting up of the gap and shift values of an EPU follows certain rules during the process of data acquisition in an experiment. Take the aforementioned EPU58 undulator as an example. (1) Under either horizontal polarization mode (LH mode) or vertical polarization mode (LV mode), the shift value remains constant: '0' for LH mode, '$\pm\lambda_u$' for LV mode; the photon energy is tuned by just adjusting the gap value. More complicated is (2) the circular polarization mode (LC+/LC− mode, clockwise/anticlockwise). In this mode, tuning the photon energy requires simultaneous changing of the gap and shift values. However, there is a strict one-to-one correspondence following the high-order polynomial relationship between gap value, shift value and photon energy, as shown in Fig. 3. For example, to obtain a circular polarized photon energy of 1621 eV, the undulator gap needs to be 40 mm, and its shift must be 21.2 mm; all the other values will not work.

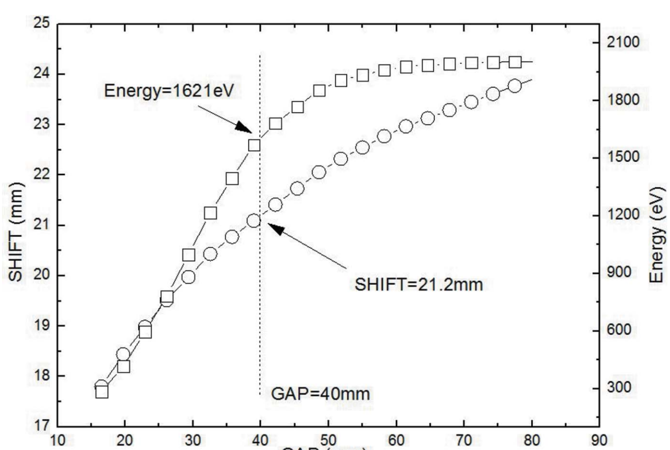


Figure 3
Correspondence between gap, shift and circular polarized photon energy of the undulator EPU58. The squares show a monotonic relationship between the gap and the corresponding circular polarized photon energy of the undulator; the circles show a monotonic relationship between the gap and the shift of the undulator.

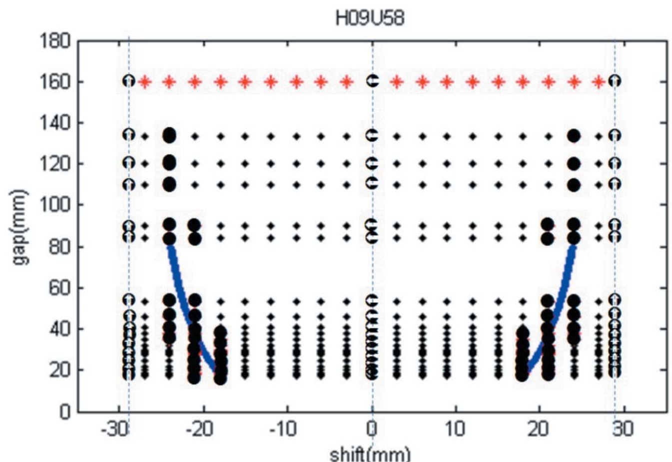


Figure 4
Reduced key nodes set in gap-shift two-dimensional parameter space of the undulator EPU58.

2.2. Reduced set of key nodes

After summing all the photon energy tuning requirements under various polarizations, a 'road map' for those purposeful motions of an undulator in gap-shift two-dimensional parameter space can be drawn. As shown in Fig. 4, taking the undulator EPU58 as an example, the path marked by the left-facing arrowhead dots (×1), upward-facing arrowhead dots (×2) and solid lines (×2) outlines the undulator navigation routes for LH, LV and LC polarization, respectively. The stars mark the switch-over route among different polarization modes.

Thus, it is only necessary to scan the key nodes covered by the above routes and those adjacent. The number of these key nodes (so-called 'reduced set of key nodes') is far less than that of all the key nodes in Fig. 2: for the horizontal polarization (LH) it contains 22 nodes, for the vertical polarization (LV) it contains 2 × 22 = 44 nodes and for the circular polarization (LC) plus the switching-over path it comes to a total of 2 × 51 = 102 nodes. Therefore the total number of the reduced set of key nodes is 168.

2.3. Confined-walking mode *versus* free-walking mode

So far, the currently deployed EPUs at SSRF move in a so-called 'free-walking mode', that is, the gap or the shift of an undulator can be freely modified by users within the entire parameter space. This provides the advantage of a rather simple motion control code, but requires a large amount of feed-forward scanning time: in this mode, the undulator must work with a feed-forward table of all the key nodes in the parameter space. As a consequence, users may have to work with an undulator for years with only a horizontal polarization available before the feed-forward scanning for all the other polarizations is completed.

Based on the analysis above, we propose a new motion mode for an EPU, *i.e.* confined-walking mode. In this mode an undulator may only move along certain pre-defined routes which cover only the reduced key nodes set. Because the number of key nodes in the reduced set is much lower, then taking the EPU58 as an example, the number of key nodes decreases from 462 to 168; thus the workload of feed-forward scanning is reduced by nearly two-thirds, so that the timeline for users to obtain access to beam full polarization is greatly advanced. Moreover, under confined-walking mode, the functionality of various polarizations can be granted to users in a rolling-out way: whenever the feed-forward scanning for a particular polarization has been completed at its dedicated key nodes in the reduced set, that polarization is made available for users. This has great value in practice, especially for 'growing' synchrotron radiation facilities similar to SSRF, with numerous undulators queued joining the storage ring: in confined-walking mode, not only can user waiting time for a full polarization functional undulator be shortened but users also have the option to set up their priority on any earliest-needed polarization. Both modes have the same linear encoders and, as a result, the same walking precision; however, the average speed of confined-walking mode is 20% lower than that of free-walking mode due to extra step motion. The fundamental advantage of confined-walking mode is to break up the tune compensation task for the entire parameter space, which as a whole is very time-consuming, into a few sub-tasks which can be fulfilled in order of priority.

To facilitate orbit debugging, the free-walking mode is retained with access only for the machine-study personnel and is not open to routine experimental users.

3. Implementation of confined-walking mode

Under confined-walking mode, it is vital to make each undulator motion for beamline users easy and secure. A user should only worry about the polarization and gap value of an undulator that their experiment requires. The actual motion procedure of the undulator should proceed automatically by its control code. The control code should account for the integrity that the motion route of the undulator is within the authorized reduced key nodes set for which a feed-forward table has been established. The latter is essential to guarantee that the motion of the undulator presents marginal disturbance to the electron beam in the storage ring. To follow, we will take the EPU undulator of the DREAMLINE at SSRF as an example to describe how confined-walking mode is implemented.

3.1. Control logic

As mentioned previously, experimental users are granted only confined-walking mode, and free-walking mode is reserved for machine-study personnel. For confined-walking mode, depending on the targeted polarization (LH horizontal, LV+ vertical positive, LV− vertical negative, C+ circular clockwise, C− circular anticlockwise), the corresponding sub-program is called, and with the gap value input by the user the targeted shift value can be looked up in a table (or calculated). Both gap and shift targeted values are compared with the current position of the undulator (gap_pv, shift_pv) to decide whether to continue moving along the current route or switch to another route.

The most complicated motion is moving along the route for circular polarization in confined-walking mode. As illustrated in Fig. 3, for this type of polarization the gap and shift correspondence follows a high-order polynomial, which signifies a non-linear relationship. Since the current controller does not allow a simultaneous gap and shift coordinated motion, the undulator is moved stepwise by gap or shift alternately to reach the end targeted position. The size of the step is chosen cautiously to ensure that the motion of the undulator does not overshoot outside the reduced key nodes set area. It is noteworthy that, with more advanced motion controllers, a continuous motion with both motors driving in a non-linear dependency is possible, which can spare a large amount of time by avoiding gap or shift alternate motions.

3.2. Algorithm implementation

The motion control system of the DREAMLINE undulator is implemented through a Siemens SIMOTION controller (Zhang *et al.*, 2010), which controls 13 servo motors distributed all over the undulator, and a closed-loop control (shown in Fig. 5) is achieved with the assistance of 13 peripheral Heidenhain linear absolute encoders. The control system also contains 26 'limit and kill' protection switches, and uses external interlocking signals to increase protection for the undulator. PROFIBUS is used for bus connection. The local control is equipped with a human–machine interface and SIEMENS PLC, providing an EPICS IOC interface to dock with the control from the beamline. The programming of the controller can be written in a structured text that is an inter-

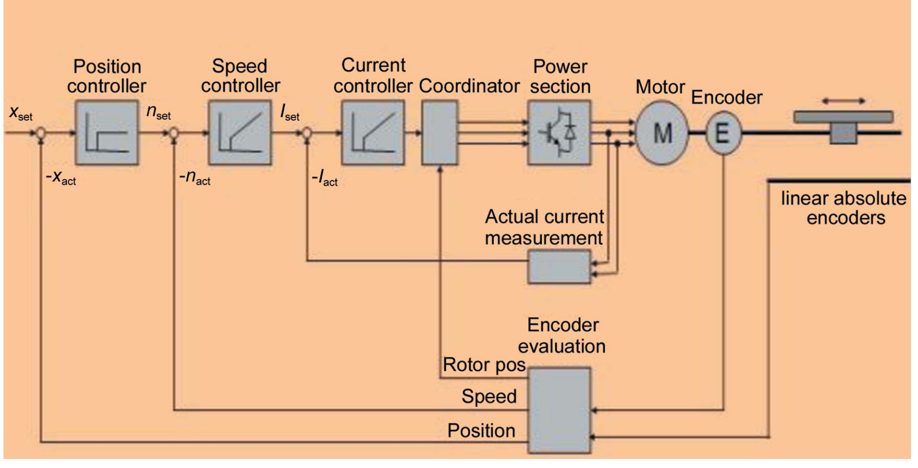


Figure 5
Closed-loop control diagram for the DREAMLINE beamline undulator.

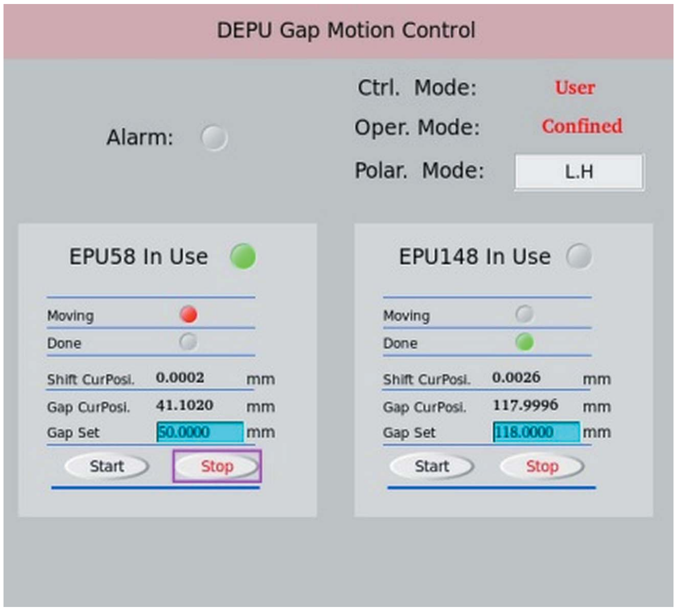


Figure 6
Control interface for the users of the DREAMLINE beamline undulators.

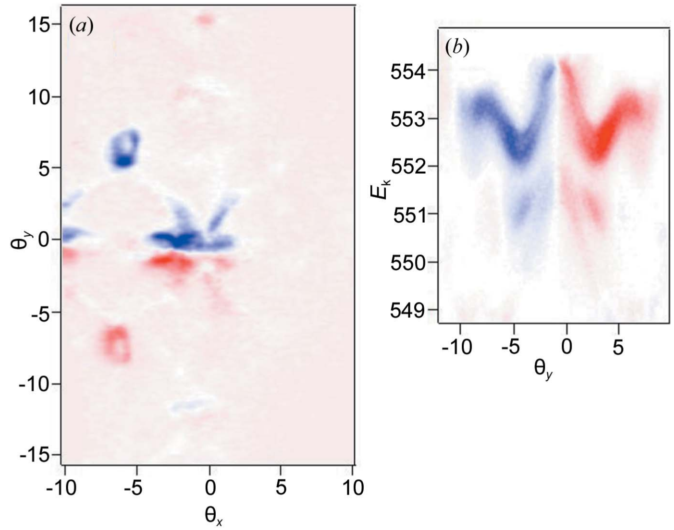


Figure 7
(*a*) Fermi surface intensity plot and (*b*) band structure of WC recorded with $h\nu = 560$ eV. The data are acquired by the difference between C+ and C− polarized beams at the DREAMLINE beamline.

national standard programming language similar to C language.

The beamline user controls the undulator through the control interface shown in Fig. 6. The control interface uses the PV variables provided by the EPICS IOC to communicate with the undulator. The status of the undulator ('Ctrl. Mode') turns into 'User' when the user obtains authorization to move the undulator. The motion mode ('Oper. Mode') of the undulator is automatically switched to 'Confined'. It can be seen from the interface that the light source of the DREAMLINE beamline is actually made up of two undulators, EPU148 and EPU58. Switching between these undulators is controlled by the central control room. Each undulator can be individually put into confined-walking mode (the 'In Use' wireless button lights up green). In the interface under 'Polar. Mode', a drop-down menu can be used to select polarization mode; for example, in Fig. 6 the chosen option 'L.H' stands for horizontal polarization. After the targeted gap value is input in the dialogue box ('Gap Set'), upon clicking the 'Start' button the undulator moves to the targeted position following a safe route within the reduced key node set. During the (step) motion, the targeted shift value of the undulator is automatically computed and displayed in the interface.

4. Results and discussion

With the introduction of confined-walking mode at SSRF, the workload for feed-forward scanning has been greatly reduced. The DREAMLINE beamline with a full polarization capability will be open to the public within one year of the start of its pilot operation. It is not currently possible to measure the polarity of the undulator beam exactly, which requires a special polarimeter (Wang *et al.*, 2012); we have adopted a standard sample [a piece of a single crystal of tungsten carbide (WC)], which has a well known photo-electron angular emission response to clockwise or anticlockwise circularly polarized light, in order to demonstrate the reliability of the undulator motion under confined-walking mode. Fig. 7 shows the Fermi structure of the WC single crystal measured at the angular-resolved photoelectron spectroscopy station (ARPES station) of the beamline. The left panel (*a*) shows the Fermi surface and the right panel (*b*) shows the ΓK direction band structure. The band structure data are the difference between those data collected by clockwise (C+) and anticlockwise (C−) circularly polarized lights under the same measuring conditions. The switching of light polarization is carried out under confined-walking mode. Red areas are positive and blue negative; both are symmetric to the centre of the Brillouin zone as shown in panel (*b*). The result is consistent with a sample showing an inverse-symmetrical Fermi edge structure, as demonstrated by Sánchez-Barriga *et al.* (2014) and Wang & Gedik (2013). Such symmetry is evidence to support that, under confined-walking mode, the undulator has delivered both correct handnesses.

5. Conclusions

According to the experimental data-collecting patterns, the number of key nodes of the two-dimensional gap-shift parameter space for real experimental needs are reduced, and confined-walking mode for an EPU is introduced. This greatly compresses the workload of the feed-forward scanning needed to maintain the beam stability of the storage ring, so that the EPU can be deployed in its full polarization function status much earlier. This, in turn, greatly improves the operation efficiency of a beamline with an EPU source. The confined-walking mode is also expected to be applied to other EPUs in the facility in the future, especially for those EPUs with various requirements for polarization modes.

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