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# CONCEPTUAL DESIGN OF A PERMANENT MAGNET UNDULATOR FOR FAST PULSE-TO-PULSE POLARIZATION SWITCHING IN AN FEL*

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*Abstract*

In this paper, we propose the design of an undulator to alter polarization at a fast frequency and the energy spectrum pulse-to-pulse in free-electron lasers (FELs). A fast time varying magnetic field generated in an undulator can alter characteristic light features. An electromagnetic (EM) and permanent magnet (PM) type undulator provides typically a magnetic field switching frequency below 100 Hz. Inductance and heating issues from coils limit the performance for the EM type and favor small magnetic fields and longer periods and for the PM type, strong magnetic forces between magnet arrays create undesired relative motion. In this paper, we discuss these issues and propose an undulator made of Halbach cylinders with rotating magnet arrays to switch the magnetic fields. Concept, magnet structure and performance are discussed in this note.

## INTRODUCTION

Polarization control in synchrotron light sources and FELs has many applications in the study of structural, electronic and magnetic properties of materials. Many experiments demand particularly circularly polarized light to probe electronic spin in materials. Several schemes have been implemented at X-ray FELs to fulfil these requirements. There are two important schemes. One is to convert linearly polarized lights to circular polarization based on interference effects [1-3]. The other is to control the motion of the electron beams in helical undulators [4-6].

Polarization switching is another approach to polarization control. The possibility of fast switching would benefit the signal-to-noise ratio for experiments, for instance, for X-ray magnetic circular dichroism (XMCD) [7]. A straightforward method is to switch the helicity using an EM helical undulator by a flip of excitation currents [8,9]. However, the magnetic field strength and the switching frequency of the device is significantly limited by the capacity of power supplies and heating limits generated in coils. A PM helical undulator is compact, promises a shorter period length and is usually arranged linearly according to a Halbach structure [10], as seen in Fig. 1(a). A helical undulator consists of four arrays with a narrow gap between them and can creates a helical field by relative linear motion of the arrays to switch the helicity [11,12]. Because of the narrow gap between the arrays, the motion must overpower extremely large magnetic forces, resulting typically in a low switching frequency of around 1 Hz. Some remedies, such as dedicated force compensation [13] or a driving system [14] have been used to increase the switching frequency.

Except for a superconducting linac, an FEL is normally driven in a pulsed mode by an electron beam from a room temperature linac at a repetition rate of the order of 100 Hz. An undulator with a compatible and tuneable switching frequency would allow multi-polarization and pulse-to-pulse energy changes. This study proposes an undulator consisting of PM cylinders to change the magnetic fields by rotation of magnets, as seen in Fig. 1(b). The switching frequency is tuneable and can exceed 100 Hz.

PM cylinders are useful in many applications, such as particle accelerators [15], motors [16] and for nuclear magnetic resonance (NMR) [17]. A rotatable cylinder structure has been shown to change magnetic fields of focusing quadrupole magnets in Laser Plasma acceleration [18] and the field of steering magnets for modulating the phase between two undulators in a storage ring [19]. A delicate linear configuration of rotatable rods has been developed to modulate the period length of an undulator [20]. These pioneering works inspired us to create a PM cylinder undulator with the ability to switch the polarization quickly. This paper is organized as follows. In Section 2, we discuss operations of polarization changes using a relative rotation of PM cylinders. In Section 3, we study the torque for a practical construction and discuss construction feasibilities. To increase the switching frequency, two types of PM cylinders are studied in Section 4. A discussion for an application in an FEL is given in Section 5.

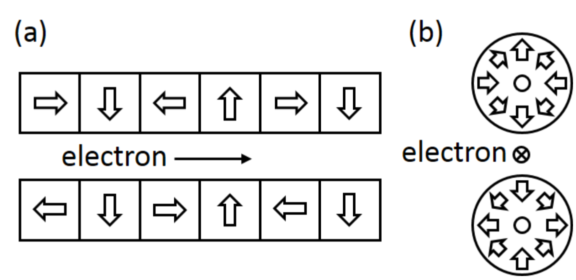


Figure 1: (a) A PM undulator consisting of Halbach arrays. (b) Rotatable Halbach cylinders. The magnetization of the PM is indicated by arrows.

## MAGNETIC FIELD CHANGES AND POLARIZATION CONTROL

The magnetic field in our proposed structure is produced by a pair of PM cylinders. Several magnetization configurations in a cylinder are feasible.

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For simplicity, a dipole ring is discussed and further studies are given in Section 4. A pair of magnets are arranged at regular intervals of a half period in the electron beam direction to create sequentially horizontal or vertical magnetic fields, as shown in Fig. 2. Operation in the horizontal linear mode creates a vertical field but cancels the horizontal field. It is achievable using opposite rotations of the A and B arrays while keeping the C and D arrays fixed in opposite directions, as seen in Fig. 2(a). Figure 2(b) shows a similar operational concept for the vertical linear mode. Polarization switching between both modes is possible via simultaneous rotation of four arrays.

A preliminary design was performed to calculate the magnetic field using the 3-D RADIA code [21]. The parameters of the PM cylinder undulator are summarized in Table 1. For this design, a pair of magnets is able to produce a magnetic field of 0.5 T for a period length of 60 mm and a gap of 10 mm. To achieve circular polarization switching, one pair of magnets is fixed in the same direction and the other pair is rotated in opposite directions. Figure 3 shows how the horizontal field is produced by the fixed C and D arrays and the vertical field is changed by rotation in opposite directions of the A and B arrays. A change of the phase delay between both transverse fields is observed to show the helicity change.

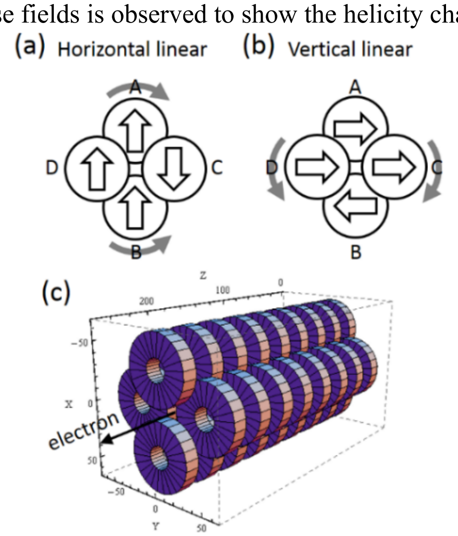


Figure 2: The configuration of four PM cylinder arrays. The rounded arrows represent the rotation direction. The operation to change the magnetic field in the (a) horizontal linear mode and (b) vertical linear mode. (c) Is a three-dimensional illustration of the PM cylinder undulator.

Table 1: Parameters of the PM Cylinder Undulator

| | | |
|---|---|---|
| Period length | mm | 60 |
| Gap | mm | 10 |
| $B_r$ | T | 1.26 |
| $R_{in}$ | mm | 5 |
| $R_{out}$ | mm | 20 |
| Thickness | mm | 9 |

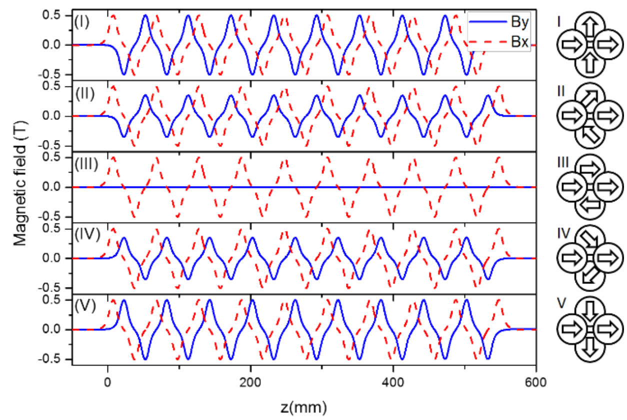


Figure 3: Change of the vertical ($B_y$) and horizontal ($B_x$) magnetic fields during helicity switching. Configurations (I) to (V) represent the orientations of the PM cylinders.

## TORQUE ANALYSIS

The torque of the PM cylinders can be calculated by the Maxwell stress tensor by performing an integration over a closed surface. An analytical expression for a two-dimensional structure gives the torque as being proportional to the radial and tangential components of the magnetic field. For a finite length cylinder, a numerical calculation is necessary to obtain the effect of flux leakage through the ends of the cylinders. A change of torque, corresponding to a rotation of the A and B arrays for helicity switching, is shown in Fig. (4). Because of the mono dipole ring, the torque has a period of $2\pi$. Similar to a commercial motor or driving system design, it can be rotated at 30-60 Hz up to a total length of about 1-2 m.

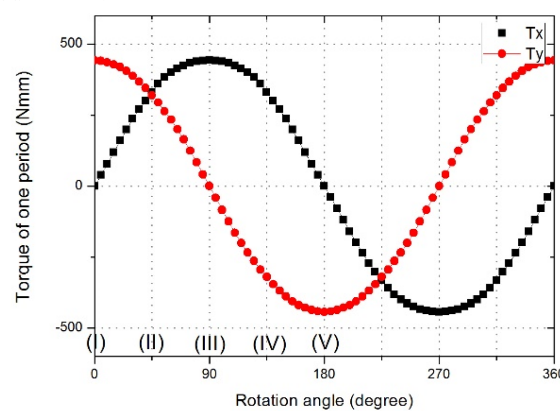


Figure 4: The torque per unit period for a PM cylinder undulator with dimensions as given in Table 1. The configurations (I) to (V) correspond to the orientations of the PM cylinders in Fig. 3.

## TOWARD A HIGH-FREQUENCY DESIGN

Increasing the number of pole-pairs in a PM cylinder allows a higher switching rate. Two practically available designs, Halbach cylinders or dipole rings, are illustrated in Fig. 5. The number of pole-pairs is indicated by $n$. A Halbach cylinder can produce a field which is directed into or outward of the cylinder bore. The outward design

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for the PM cylinder undulator is given in Fig. 5(a). A Halbach cylinder consists of segments with radial and tangential magnetization. A large number of segments increases the magnetic field but requires a complex technology for construction. Comparing to a delicate Halbach cylinder, dipole rings consists of only radial segments. It can be made by assembly or a superior magnetizing process, e.g. by radial anisotropy or multi-pole anisotropy, which are both used in motor application. To further understand the magnetic field of Halbach cylinders and dipole rings, simulations with changes of the inside ($R_{in}$) and outside ($R_{out}$) radii are shown in Fig. 6. With an increase of the cylinder volume the magnetic field increases after optimization of dimensions. A design with a large *n* allows a high switching rate but produces a small magnetic field. Compared to a dipole ring, a Halbach cylinder has the advantage of a higher magnetic field but strongly relies on difficult assembly technologies.

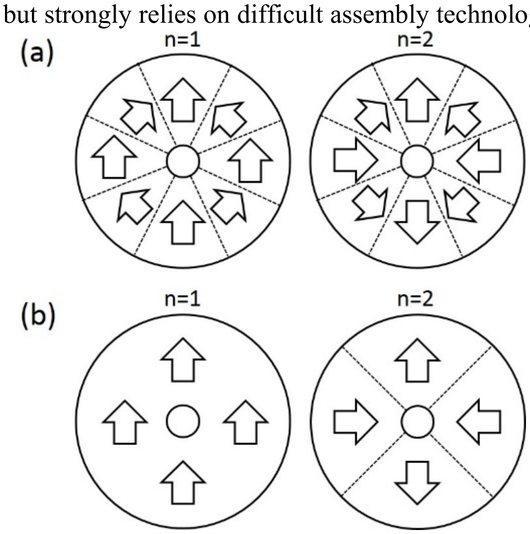


Figure 5: Two practically available designs of the PM cylinder, (a) Halbach cylinders, (b) dipole rings. The index *n* represents the number of pole-pairs.

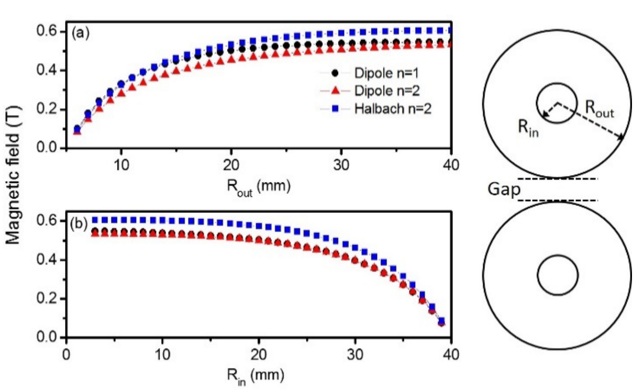


Figure 6: Simulating magnetic fields for the PM cylinder undulator versus dimensions of (a) outside radius and fixed $R_{in}$= 5mm and (b) versus inside radius at a fixed $R_{out}$= 40mm. Other parameters are from Table 1.

## DISCUSSIONS

In a PM cylinder undulator the magnetic field is changed by rotation instead of linear motion like in a typical undulator. In addition to a change in the magnetic field by rotation, the polarization can be switched quickly. With delicate matching of the rotating frequency and the beam pulse repetition rate, the device gives a new experience for polarization- or energy-dependent pulse-to-pulse changes. It has potential for applications in a helical afterburner [22] and time-interleaved schemes, which is applicable multi beam lines [23].

Comparing to an EM type undulator, the PM cylinder undulator has better performances for short periods, larger magnetic fields and fast switching rates. It seems to exhibit several technical challenges, though, like demagnetizing effects or torque induced from end fields, which should be discussed to pursue a short period undulator with high magnetic field and desired switching rates for FELs.

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