# Control system for a variable period undulator prototype

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# Control system for a variable period undulator prototype

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**Abstract**. The magnetic structure of the proposed variable period undulator consists of cylindrical magnets. Each magnet can be rotated by a small stepper motor, in order to adjust the magnetic field and form an arbitrarily shaped magnetic field profile on-axis. Meanwhile, a short prototype exists, equipped with a scalable control system to drive a large amount of stepper motors. This paper describes details of the control system implementation, results of the tests on different rotary encoder concepts for a magnet positioning feedback, and first magnetic measurements of the variable period undulator prototype.

## 1. Introduction

The proposed variable period undulator (VPU) magnetic structure consists of motorized cylindrical magnets. Adjusting the undulator period in order to change wavelength results in a significantly larger tuning range comparing to ordinary fixed period variable gap undulators [1, 2]. It also allows to create software defined arbitrary shaped magnetic fields (figure 1).

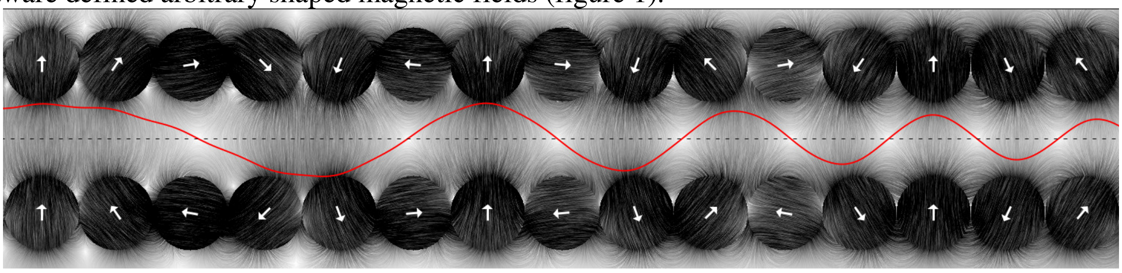


**Fig. 1.** Variable period undulator magnetic structure.

We report on tests of a short prototype (figures 2-4). It consists of 32 individually controlled motor axes, 8 in each of 4 rows around a $10x10mm^2$ aperture for the vacuum chamber. Cylindrical magnets with a diameter of 10mm and 11mm pitch are fixed at the ends of shafts, which are supported with two ball bearings and driven by NEMA 8 sized (~21mm) staggered stepper motors, that are reinforced by planetary gearboxes to get sufficient torque to overcome magnetic forces between neighboring magnets.

Since a 2.5m long full scale VPU would comprise over 900 individual magnets and axes, it was decided to develop a custom control system. Although many of the required elements would be available as standard industrial off-the-shelf components, a commercial system would be considerably complex and extensive due to the sheer number of axes. The chosen approach proves to be affordable, scalable and can be integrated thus be minimized. In addition, it can be customized in order to implement also uncommon types of rotary encoders.

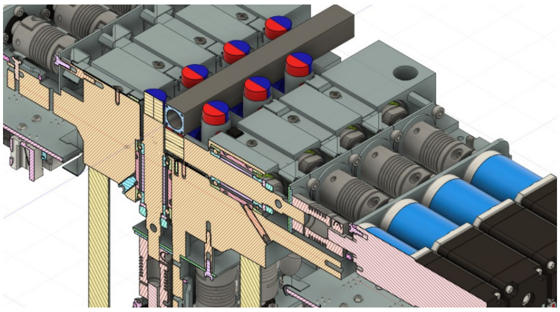


**Fig. 2.** CAD model of VPU, bottom half.

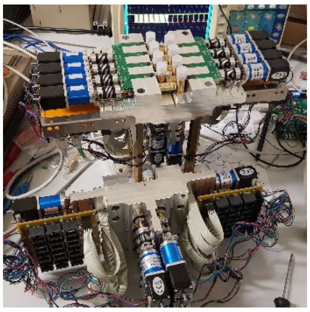


**Fig. 3.** VPU prototype.

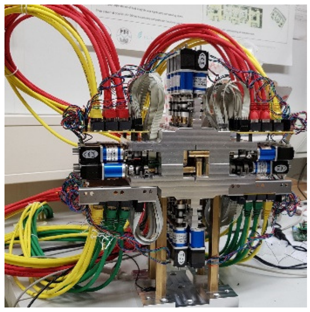


**Fig. 4.** Fully assembled.

Several encoder systems are implemented in this prototype for angular position control of the magnets, also including sensors for direct magnetic measurements of the individual magnets. Similar and complementary encoder concepts, which will also be sensitive to imperfections in mechanics and motion, as well as to cross-talk effects induced by adjacent magnets, are compared and validated for a robust control.

## 2. Control System

The control system (figure 5) uses Beckhoff TwinCAT to control an XMC4800 MCU board [3] over EtherCAT. The XMC4800 board implements an EtherCAT slave and a “CAN in Automation 402” (CiA402) device profile for TwinCAT. It bridges to a local RS485 or SPI bus to communicate with MSP430 microcontrollers of the individual axes, their enumeration on the bus, and also supports a remote firmware update [4]. Each MSP430I2041 microcontroller generates Step & Direction control pulses for a A4988 stepper motor driver and also contains a high-resolution simultaneous sampling sigma-delta ADCs for processing sin/cos signals from rotary encoder of different types.

At the level of the local RS485/SPI bus the system is easily scalable to up to about 100 axes, and at the EtherCAT level, the number of devices is limited only by 100Mbit/s ethernet bandwidth divided by a few bytes (number of steps to make and encoder readings) per axis per ~10ms of TwinCAT cycle, which results in scalability to thousands of axes.

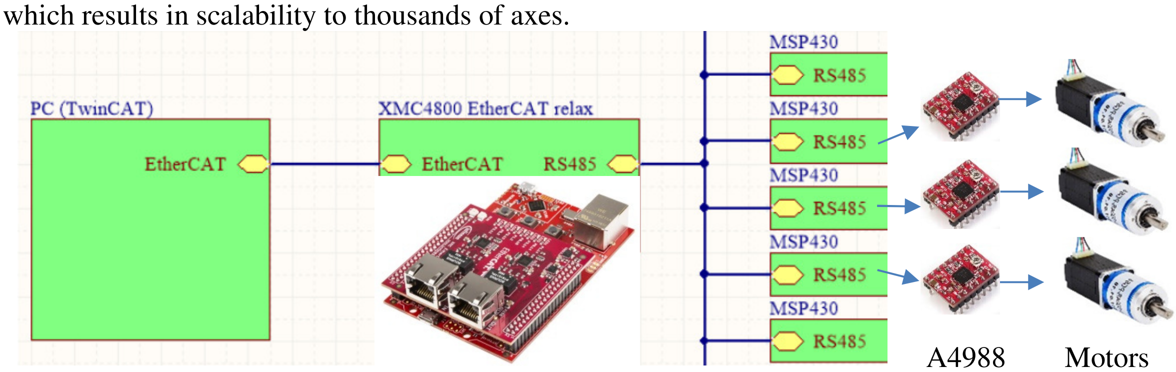


**Fig. 5.** Undulator control system.

## 3. Rotary encoders

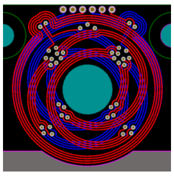
Each axis requires a rotary encoder in order to control the absolute angle, and thus magnetic field created by each magnet on the electron beam axis. Several different types of rotary encoders have been tested on a single axis test stand with an additional high precision absolute encoder on the same axis. Magnetoresistive sensors are also embedded in the short prototype for each axis, as it is required to measure all the magnetic fields from neighboring magnets in order to implement crosstalk compensation. Optical and variable rotary transformer encoders could reach the accuracy of 0.1 degree that is necessary for undulator operation, but require further reliability tests with actual EMI and radiation in accelerator tunnel before a final decision on which combination of encoder types to use.

*3.1. Magnetoresistive sensor AA747 under each magnet*

- \+ Direct measurement of magnetic field direction
- – Crosstalk from neighbor magnets
- – Potential degradation from radiation damage
- – Uncertainty of ±180 degrees, requires additional referencing

Magnetoresistive encoders provide the most direct feedback by measuring the magnetic field of each magnet. The implemented decoupling algorithm could suppress the cross-talk from the neighboring axis, but not better than 0.5 degree of absolute accuracy. It is required to improve the precision and reach errors <0.1 deg. Thus, a more complicated mathematical model, which is aware of permeability and magnetization errors of individual magnets has to be used in the decoupling algorithm. Eventually, the magnetic encoders could also be used for characterizing the magnetization errors of each magnet.

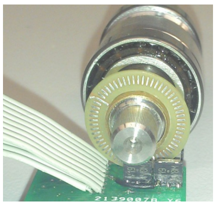
*3.2. Inductive rotary variable transformer*



- \+ "Passive" components (PCB) insensitive to radiation
- \+ Absolute encoder
- – Weak signal for small 20mm planar PCB transformer, potential EMI problems with long cables

The inductive rotary differential transformer encoder has a systematic error caused by eccentricity and different sensitivity of sin/cos coils that are partly printed on different PCB layers. With a simple calibration and correction of these errors it could achieve the requested precision of 0.1 degree. The systematic errors will probably not be much different for the individual encoders. In the worst case it would require individual calibration of each encoder. Then there still is the problem of the small signal strength resulting in a low signal to noise ratio. For the final device installed in an accelerator the control system would be placed at some distance from the undulator, e.g. outside the tunnel to avoid radiation, which results in long cable length. The signal strength can probably be increased by some electrical tuning, like tuning the capacitive load such that it hits a resonance with the transformer coils or shifting the signal phase such that the ADC always samples at a voltage peak.

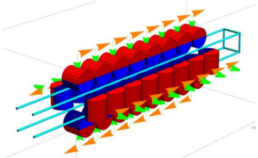
*3.3. Optical encoder using TCUT1300X01 photointerrupter*



- \+ High resolution.
- \+ Cost effective printed circuit disk, thin PCB material is transparent enough for infrared light.
- – Incremental encoder, requires additional referencing
- – Potential degradation from radiation damage

The optical encoder PCB disk with light blocking copper traces having ~60 signal periods per revolution provides the best resolution but is more sensitive to accurate mounting and alignment of the encoder disk and sensor. In its current state, it requires individual calibration of each encoder, in order to reach <0.1 degree accuracy. Also, it is unclear, what would be the lifetime of the infrared LEDs and the photo-transistors of the photointerrupter due to radiation near the accelerator beam.

*3.4. Magnetic referencing with long coil*



- • Stretched wires along vacuum chamber form long coils
- • Rotating a single magnet induces voltages up to ~14µV*s
- • Low noise ADS1263 ADC ~10nV*s @ 10s integration
- – Long measurement time of magnets one-by-one

Even without additional encoders it is possible to track axis position by counting steps of stepper motors. Including all the mechanical errors like backlash of gearboxes, this would result in >1 degree of magnet positioning error, which could cause an increased undulator phase error of about 10 degrees [1]. This could still be acceptable for some applications. Anyway, this requires an initial referencing of the magnet angle positions. Also, incremental encoders or some types of magnetic encoders with 180 degrees range require a referencing procedure. Wires along the vacuum chamber connected together on one side can form 4 long single turn coils covering all the magnets for each row. As shown in figures 6 and 7, rotating only one single magnet changes the magnetic flux through the coil by

14Tmm$^2$ and thus induces a voltage of 14μV*s. All other non-rotating magnets do not induce any voltage. Using a low noise voltmeter like an ADS1263 [5] with ~10nV*s noise level at 10s integration time, it is possible to make an initial referencing of each magnet with errors of <0.1 degree.

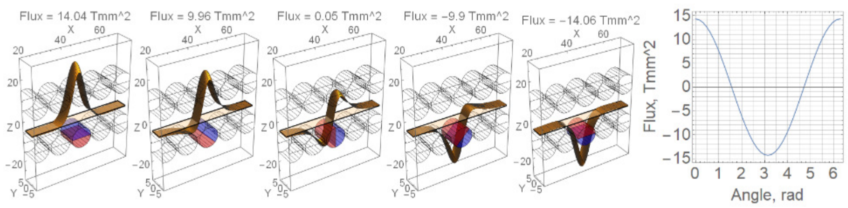



**Fig. 6.** Distribution of magnetic field in the long coil from a single rotating magnet and total magnetic flux change versus angle.

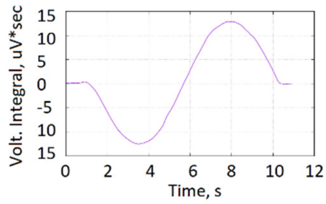



**Fig. 7.** Measured integral of induced voltage.

## 4. Magnetic measurements

Figures 8 and 9 show first magnetic measurements of the assembled variable period undulator. A single row of variable period undulator, operated with magnetoresistive encoder feedback and referenced with a coil, was measured magnetically using a Hall probe for different configurations of variable period and shift. The shift could be used for polarization control in helical mode by shifting the field of vertical rows with respect to horizontal ones. The rotation angle of each magnet could be expressed as α*n+β, where n is the magnet number. When α=90 deg, it is a normal linear Halbach array [6] with 44mm period. Varying α (angle between two adjacent magnets) changes the undulator period. Rotating all the magnets by the same angle β shifts the phase of the sinusoidal field for the whole structure.

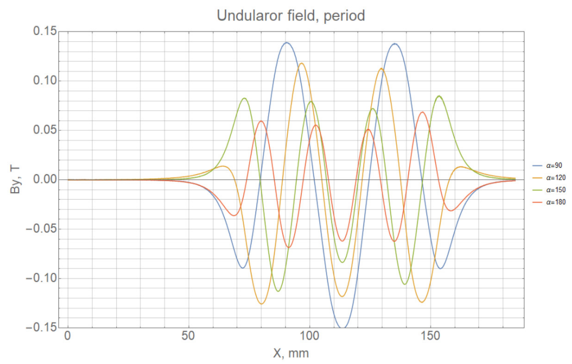



**Fig. 8.** Variable period, adjusting angle α between two adjacent magnets from 90 to 180 degrees changes period from 44 to 22mm.

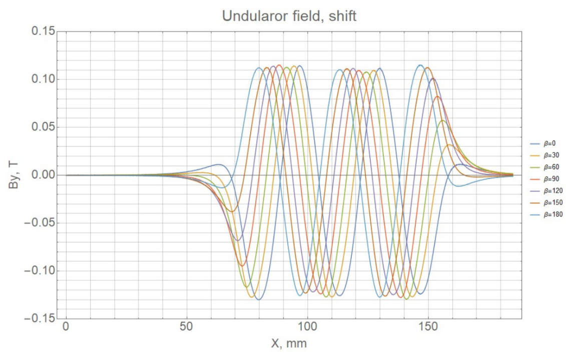



**Fig. 9.** Variable shift, rotating all the magnets by the same angle β shifts the phase of the sinusoidal field longitudinally.

After characterization of the magnetic errors of all individual magnets in order to predict and control their actual magnetic field on-axis for a given rotation angle, and after magnetic measurements of the whole device, this prototype should be ready for test installation in the accelerator tunnel.

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