# DEVELOPMENT OF AN IN-VACUUM UNDULATOR SYSTEM FOR U-SAXS BEAMLINE AT PLS

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*Abstract*

The design of a hybrid in-vacuum undulator with 20mm period, effective peak field of 1.05 Tesla, and 1800 mm magnetic length is being presented (Figure 1). The design requirements and mechanical difficulties for holding, positioning, and driving the magnetic arrays are explored. The structural and finite element analysis, magnetic design, and electrical considerations that influenced the design are then analyzed.

This in-vacuum undulator (IVUN) is being installed at Pohang Accelerator Laboratory (PAL) for U-SAXS (Ultra Small Angle X-ray Scattering) beamline. The IVUN will generate undulator radiation up to ~14 keV using higher harmonic (upto $9^{th}$) undulator radiation with 2.5 GeV PLS electron beam.

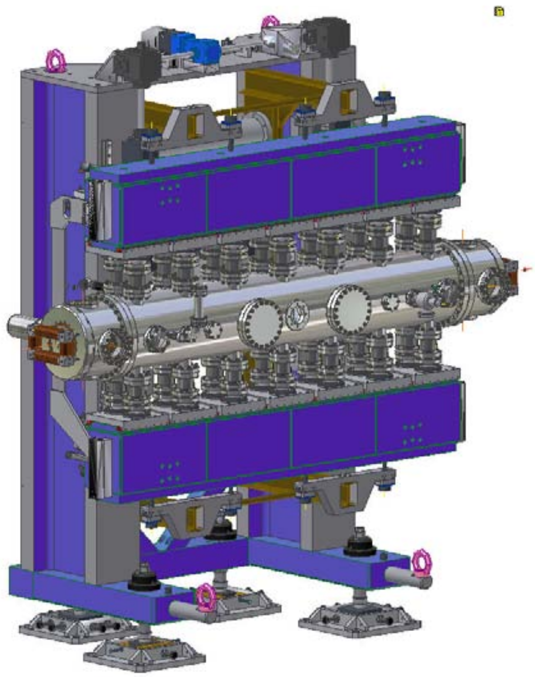

Figure 1: PLS In-Vacuum Undulator

## CONTROL ARCHITECTURE

The proposed controller is based on a single motor design for gap control with a separate motor for taper. The control architecture is presented in figure 2. The primary controller is a Siemens S7 PLC. This device is used widely at SSRF and is a very powerful PLC both in speed and programming features. The PLC controls stepper motor and driver both made by Parker-Hannifin. The gap motor is supplied with a brake that is normally on (applied with power off).

Position feedback is derived from two TR Electronics linear absolute LTS-240 encoders mounted across the gap on each end of the magnet array. The absolute encoder interface is SSI and the resolution is programmable down to .1 um per count. Since the encoder is absolute, there will be no need to home the gap axis and the taper is always known. The advantage of linear encoders is the measurement is more direct and is not subject to wind-up and deflection that a rotary encoder would see on the end of a ball screw. Four limits are provided as well as 4 kill switches.

The 4 switches (2 limits and 2 kills) at min gap are optical and the 4 outer switches (2 limits and 2 kills) are mechanical. The limits prevent further motion in the direction they protect but allow the axis to be driven in the other direction (off the switch). The Kill switches remove power to the motor, however, these are defeated by a key switch to allow motion in the other direction.

The taper motor and driver also are Parker-Hannifin but the position feedback is derived from a rotary incremental encoder. This encoder is only used to close the position loop on relative moves, actual taper is measured at the linear encoders. The taper motor drives a large gear reducer that produces a taper by effectively altering the length of the screw-jack on one side of the gap drive motor. Figure 3 shows schematic of the device.

The controller layout is shown in figure 4. The major components are mounted on a vertical plate and which mounts easily in a 19 inch rack. Emergency Motor Off switches are provided on an operator panel and at the ID unit.

Four correction coils are planned for vertical and horizontal correction These coils are mounted outside the vacuum chamber. The power supplies are Kepco BOP (bipolar) supplies. These provide up to 400 watts of power in the full 19 inch rack package. Current control and tracking is accomplished using analog input and output. The water cooling unit and vacuum pumps are also monitored and controlled via analog IO.

There are 2 Ion pumps, 2 TSP pumps, and 2 Getter pumps with NEG filters. The controller monitors vacuum pressure and controls the vacuum pumps for operation and regeneration.

## SOFTWARE

The PLC has two tasks that can run independently. The main task holds all the motion controls, error checking, and host interface. A separate high speed task updates the data to the correction coils using a 4 coil array – execution time is less than 5 ms.

Both the Main task and the high speed task are written in structured text. The programming environment is Step-7, which is a powerful tool for program development and debug. SSRF has supplied ADC with an EPICS driver for the Siemens PLC. ADC will verify EPICS communication with a Linux PC.

Communication is via Ethernet TCP/IP. The PLC acts as a server with the host the client. DHCP is not supported.

Figure 3 shows the vertical first integrals at 12.5 mm and 17.9 mm gap as functions of the transverse position. The values are within the specified range of ±100 Gcm over the full range and can be minimized on the center line by the correction magnets. The narrower pole in the modified design give rise to integrated sextupole components in the integrals, -27 G/cm at 12.5 mm gap and 29 G/cm at 17.9 mm gap, well within the modified specification of ±50 G/cm for the normal integrated sextupole. The skew integral is zero due to symmetry. The data can be found in Table 1.

Figure 2. The transverse roll off at the center of the pole for 12.5 mm gap.

Figure 3. The vertical first integral as a function of the transverse position at 12.5 and 17.9 mm gap.

Figure 3 and Table 1 show the vertical second integrals for the full size wiggler for 12.5 and 17.9 mm gaps. The horizontal second integral is zero due to symmetry.

Figure 4. The second integral for the full size wiggler.

Figure 5 shows the integrals produced by the correction magnet with a current of 200 Ampere-turns in the short vertical coils and 450 Ampere-turns in the long horizontal coils. The current density in the coils is below 1 $A/mm^2$, comfortable current densities for air cooled coils. The field distribution on the median plane is shown in Figures 6 and 7 for 200 and 450 A-turns respectively. We expect to use 10-20% of the available strength in the correction coils.

Two correction magnets, one in front and one behind the wiggler will have a correction capability of ±1000 Gcm for the first integrals and ±64000 $Gcm^2$ for the second integrals. For a 3 GeV electron beam this corresponds to an angular correction of ±100 microradians and an offset correction of ±64 microns.

Figure 5. The first integrals produced by one correction magnet.

Figure 6. The vertical field on the median plane in Gauss from the correction magnet for 200 A-turns in the short coils.

Figure 7. The horizontal field on the median plane in Gauss from the correction magnet for 450 A-turns in the long coils.

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Table 1: The vertical first and second integrals for the full size wiggler at 12.5 and 17.9 mm gaps.

| x (mm) | 12.5 mm Gap | | 17.9 mm Gap | |
|---|---|---|---|---|
| | $I_y$ (Gcm) | $J_y$ ($Gcm^2$) | $I_y$ (Gcm) | $J_y$ ($Gcm^2$) |
| -12 | -8.36 | -750 | 82.50 | 5071 |
| -10 | -8.00 | -634 | 55.51 | 3872 |
| -8 | -3.46 | -309 | 37.98 | 2633 |
| -6 | 1.82 | 68 | 26.66 | 1832 |
| -4 | 6.33 | 390 | 19.59 | 1333 |
| -2 | 9.35 | 605 | 15.71 | 1059 |
| 0 | 10.38 | 670 | 14.48 | 972 |
| 2 | 9.35 | 605 | 15.71 | 1059 |
| 4 | 6.33 | 390 | 19.59 | 1333 |
| 6 | 1.82 | 68 | 26.66 | 1832 |
| 8 | -3.46 | -309 | 37.98 | 2633 |
| 10 | -8.00 | -634 | 55.51 | 3872 |
| 12 | -8.36 | -750 | 82.50 | 5071 |

## MECHANICAL DESCRIPTION

The strength of the wiggler comes from the strong back C frame. This is required to prevent the high magnetic attraction of the magnets from deforming the parallelism of the girders and to prevent any beam-line shift as the gap is changed. The strong back consists of 2 I-beams that are normally used in bridge construction. These are mounted vertically on a substantial base plate of aluminum. The I-Beams are joined at the top by a similar aluminum plate. This design is very similar to a 2 meter wiggler that was delivered and installed by ADC at AS [2].

The framework is supported on 3 points using feet that are adjustable in X,Y and Z directions. The range is +/-25 mm in X and Z and +/- 30 mm in Z. For this reason it was determined that an automatic lifting mechanism is unnecessary. The wiggler will be set to the critical beam height by hand. The feet employ a 50 mm diameter steel ball at each of the 3 points of support. This provides reduced friction but also provides a repeatable means to relocate the machine if it is ever removed from the ring. The machine is simply lifted 25 mm to clear the balls and can be rolled back on wheels.

The magnets are held in a magnet assembly with a keeper. The magnet assembly holds two main magnets, and two side magnets surrounding a pole piece. The magnets are adjusted with shims and threaded bolts. End magnets are smaller than internal magnets. Magic fingers are also provided on either end for beam angle correction.

The magnet assemblies are bolted to aluminum girders. The aluminum girders are mounted to trucks that attach to vertical bearing rail assemblies. There are 2 bearing rail guides on the top girder and 2 on the bottom.

The girders are also mounted to two left and right hand threaded ball screws. These ensure the gap motion is consistent and even during the motion. The ball nuts are preloaded and employ many circuits to ensure long life and zero backlash.

The gap ball screws are driven by a single stepper motor made by Phytron. One slip coupling is provided to protect the assembly from serious damage in the event it encounters a hard stop. The gap drive stepper motor uses a rotary encoder to detect stepper motor slip and a brake is provided integral to the motor.

A gear box is also provided that produces a controllable taper. The gear box is mounted on a shaft between the two ball screws. A small stepper motor advances the output relative to the input but the input to output ratio is always 1:1. The stepper motor also drives a small lead screw with mechanical flags for limit switches and hard stops to prevent excessive taper. Taper can be in either direction, that is, wider at the entrance vs. exit or wiser at the exit vs. the entrance. A rotary encoder is used to detect motor slip.

Gap feedback comes from two linear absolute encoders mounted across the gap at either end of the machine. These are made by TR electronics. They are programmable down to .1 um per count. They employ the Synchronous Serial Interface (SSI) used with high resolution absolute encoders.

Limit switches and hard stops are provided to limit the travel of the girders. These consist of 4 high repeatability optical switches – two on the upper and two on the lower girders - that actuate in the negative gap or vacuum chamber direction. Similarly, 4 kill switches are provided that actual in the same direction but at a gap slightly smaller than the first set of switches. The first set of switches feedback to the ICEpap controller to prevent further motion in that direction, the second set of switches feed back to the PLC which then can disable or even power off the ICEpap controller.

Another set of 4 switches are provided for the positive or maximum gap direction but these are simple snap action mechanical switches. These switches have less mechanical repeatability but high precision is not required in this direction.

## ELECTRICAL DESCRIPTION

Control portion consists of the IOC PC and software, motor driver/controller (ICEpap), correction coil power supplies, and PLC code. Communication between the IOC PC and the ICEpap, PLC, and correction coil power supplies is accomplished via Ethernet. See figure 2.

The switch signal card shown in figure 8 is designed to solve the problem of combining many limit switches for a particular axis into a single signal for input to a motion controller while providing a customizable interface to multiple switch types. The card ADC designed provides 12 NPN, or PNP, or dry contact type inputs optically coupled to a set of 12 NPN outputs and 6 NO/NC relay contacts. Each active input is indicated with a red LED. Power In and Power Out can be different levels from 5 to 24 volts. Active power is indicated with a green LED. Each input drives an NPN output capable of 5 amps at 60 volts. The relays are SPST, NONC, 10/3 amp, 277vac/30vdc. Each relay can be programmed with jumpers to be driven by any input or combination of inputs in a dot-or configuration. Relay activation is indicated by a red LED. The card can be mounted in any orientation, and requires no cooling. Connection is screw terminal. Test points are provided for input signals. Multiple cards can be ganged for more inputs. The schematics have been provided in PDF format.

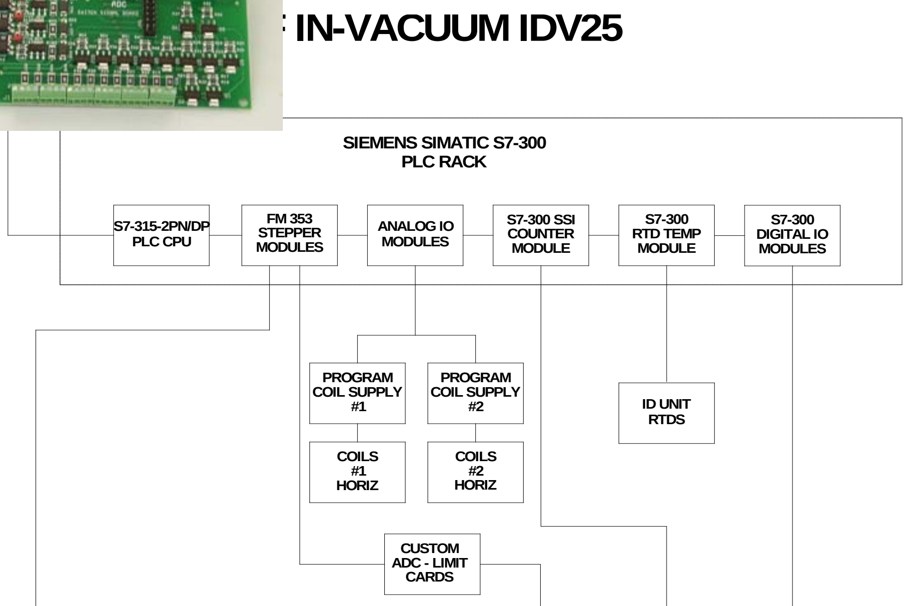


Figure 8: Support Layout

## SPECIFICATION SUMMARY

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|---|---|
| Wiggler Type | Hybrid |
| Wiggler Symmetry | Symmetric |
| Period Length | 80 mm |
| Minimum Gap | 12.5 mm |
| Maximum Gap | 300 mm |
| Number of Full Size Poles | 25 |
| Total Number of Poles | 27 |
| Magnet Assemblies and Correction Magnet | 1100 mm |
| Total Length | 1375 mm |
| Pole Material | Vanadium Permendur |
| Permanent Magnet Material: | |
| Minimum $H_{cj}$ | 24 kOe |
| Minimum Remanence $B_r$ | 1.22 T |
| At Minimum Gap ($B_r$ = 1.22 T): | |
| Peak Field | 1.782 T |
| k-value | 13.32 |
| Transverse Roll Off at x = 10 mm | 0.2% |
| Vertical First Integral | 10 Gcm |
| Vertical Second Integral | 680 $Gcm^2$ |
| Magnetic Force | 30.1 kN |

Figure 2: Control Architecture

## REFERENCES


[1]http://www.esrf.fr/machine/groups/insertion_devices/codes/Radia/Radia.html

[2] Joe Kulesza, Eric Johnson, dave Waterman, Alex Deyhim, 2007 Particle Accelerator Conference USA.