Using The SXU-HE Midplane Encoders

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1 Introduction

Encoders are being added to the SXR-HE undulators to measure the position of the top jaw relative to the frame. Currently, the top jaw position is determined by absolute encoders on the motors, but looseness in the drivetrain limits the accuracy of determining the top jaw position. Current typical errors on the top jaw position are more than 100 $\mu$m. This error shifts the midplane during tuning, and it prevents any significant checks of the midplane in the tunnel. The midplane encoders will be used to correct these errors.

The SXU-HE midplane encoders are not envisioned to be part of the active control system which sets the undulator gap, so no changes to the control system which sets the gap need be made. Rather, the midplane encoders will be read after the gap is set. They let us determine the midplane location, and based on their readings, corrections to the midplane position can be made. They also let us check and recalibrate potentiometers that are currently used to set the gap. This note discusses the use of the newly added midplane encoders.

2 Midplane Encoders

In this section we work out in detail how to use the midplane encoders to find the midplane position. It necessarily involves many symbols indicating the undulator jaw, undulator end, encoder type, etc. In spite of the notation, the end result is simple. If the top jaw does not move by half the gap change, the centerline has shifted. We now proceed to discuss this quantitatively.

2.1 Undulator Alignment

Figure 1 shows the configuration of an SXR-HE undulator after alignment. The jaws are parallel and centered on the alignment axis. The figure shows the added midplane encoders and the gap encoders. In the figure we show the naming conventions used in this note: “u” denotes upstream end, “d” denotes downstream end, “t” denotes top, and “b” denotes bottom, “m” denotes midplane. A “0” in the subscript denotes the value after the alignment. The midplane encoders read $M_u$ and $M_d$, and their values after the alignment are $M_{u0}$ and $M_{d0}$. Since offsets are added to all raw encoder readings, we adjust the offsets so $M_{u0} = 0$ and $M_{d0} = 0$. (Note that each time the undulator is aligned, the offsets will need to be changed. This is equivalent to storing the encoder values after each alignment with a fixed offset.) The gap encoders read $G_u$ and $G_d$ and their values after alignment are $G_u = G_0$ and $G_d = G_0$. After alignment, all positions on the gap side of the top jaw read $Y_{ut} = Y_{dt} = Y_t(Z) = G_0/2$, where $Y$ is the vertical distance from the alignment axis and $Z$ is the position along the undulator. After alignment, all positions on the gap side of the bottom jaw read $Y_{ub} = Y_{db} = Y_b(Z) = -G_0/2$. After alignment, the midplane is at $Y_{um} = Y_{dm} = Y_m(Z) = 0$. All $Y$ positions are relative to the axis set during alignment.
2.2 Parallel Gap Motion

As a first example of using the midplane encoders, consider the case of parallel gap motion where the midplane stays parallel to the alignment axis. Suppose the control system instructs the undulator to open the gap until the gap encoders read $G_u = G$, $G_d = G$. This is illustrated in figure 2. The upstream end of the top jaw moves to position

$$Y_{ut} = G_0/2 + M_u$$

(1)

The downstream end of the top jaw moves to

$$Y_{dt} = G_0/2 + M_d$$

(2)

Since the gap motion is parallel,

$$Y_{ut} = Y_{dt}$$

(3)

The upstream and downstream ends of the bottom jaw move to

$$Y_{ub} = Y_{ut} - G$$

(4)

$$Y_{db} = Y_{dt} - G$$

(5)

$$Y_{ub} = Y_{db}$$

(6)

The midplane is at

$$Y_{um} = (Y_{ut} + Y_{ub})/2$$

(7)

$$Y_{dm} = (Y_{dt} + Y_{db})/2$$

(8)

Substituting the expressions for the top and bottom jaw positions, we get for the midplane position at the upstream end

$$Y_{um} = G_0/2 + M_u - G/2$$

(9)
Figure 2: Parallel opening of the gap with the undulator centerline shifted.

or

\[ Y_{um} = M_u - (G - G_0)/2 \]  \hspace{1cm} (10)

Similarly,

\[ Y_{dm} = M_d - (G - G_0)/2 \]  \hspace{1cm} (11)

### 2.3 Tapered Gap Motion

As the next example of using the midplane encoders, consider tapered gap motion where the midplane does not necessarily stay parallel to the alignment axis. In this case, the positions of the encoders along the undulator need to be taken into account. The positions of the encoders are shown in figure 3. The upstream end of the undulator is at \( Z = 0 \). The upstream midplane encoder is at \( Z_{um} \). The downstream midplane encoder is at \( Z_{dm} \). The downstream end of the undulator is at \( Z_d \).

Suppose the control system instructs the upstream gap of the undulator to be \( G_u \), and the downstream gap to be \( G_d = G_u + T \), where \( T \) is the undulator taper. The upstream midplane encoder moves to \( M_u \) relative to its zero position after alignment, and the downstream midplane encoder moves to \( M_d \). The slope of the top jaw relative to the alignment axis is given by

\[ \text{slope}_t = (M_d - M_u)/(Z_{dm} - Z_{um}) \]  \hspace{1cm} (12)

The Y-position of the top jaw at position \( Z \) is given by

\[ Y_t(Z) = G_0/2 + M_u + \text{slope}_t(Z - Z_{um}) \]  \hspace{1cm} (13)

In particular, the Y-position of the top jaw at the upstream end is given by

\[ Y_{ut} = G_0/2 + M_u + \text{slope}_t(-Z_{um}) \]  \hspace{1cm} (14)
The Y-position of the top jaw at the downstream end is given by
\[ Y_{dt} = G_0/2 + M_u + \text{slope}_t(Z_d - Z_{um}) \]  
(15)

The bottom jaw position of the undulator at the upstream end is given by
\[ Y_{ub} = Y_{ut} - G_u \]  
(16)

The bottom jaw position at the downstream end is
\[ Y_{db} = Y_{dt} - G_d \]  
(17)

The Y-position of the midplane at the upstream end is
\[ Y_{um} = (Y_{ut} + Y_{ub})/2 \]  
(18)

Substituting the expressions for \( Y_{ut} \) and \( Y_{ub} \), we get
\[ Y_{um} = G_0/2 + M_u + \text{slope}_t(-Z_{um}) - G_u/2 \]  
(19)

Rearranging terms, we have
\[ Y_{um} = M_u - (G_u - G_0)/2 + \text{slope}_t(-Z_{um}) \]  
(20)

This expression is similar to the no-taper expression, but a correction is added to account for the fact that the upstream midplane encoders are not located at the upstream end of the undulator.

At the downstream end of the undulator, the midplane position is given by a similar expression.
\[ Y_{dm} = (Y_{dt} + Y_{db})/2 \]  
(21)

Substituting the expressions for \( Y_{dt} \) and \( Y_{db} \), we get
\[ Y_{dm} = M_u - (G_d - G_0)/2 + \text{slope}_t(Z_d - Z_{um}) \]  
(22)
2.4 Offset, Pitched, And Tapered Gap Motion

The most general case where the midplane encoders are used is for offset, pitched, and tapered gap motion. In the tunnel, the entire beam line can be pointed in arbitrary directions. The undulators can not be moved horizontally, but because the good field region is wide, the K tolerance is met over a wide range of X-positions. Vertically, the range of Y-positions where the K tolerance is met is limited. To account for this, the undulators are vertically offset and pitched to follow the beam axis. The undulators can also be tapered while vertically offset and pitched. This situation is shown in figure 4.

![Figure 4: The undulator midplane is desired to follow the pitched beam axis.](image)

In this case, the equations derived above for a tapered undulator are still valid. The slope of the top jaw relative to the alignment axis is

$$slope_t = (M_d - M_u)/(Z_{dm} - Z_{um})$$  \hspace{1cm} (23)

The midplane positions relative to the alignment axis at the ends of the undulator are given by

$$Y_{um} = M_u - (G_u - G_0)/2 + slope_t (-Z_{um})$$  \hspace{1cm} (24)

$$Y_{dm} = M_u - (G_d - G_0)/2 + slope_t (Z_d - Z_{um})$$  \hspace{1cm} (25)

The control system uses potentiometers to make the top jaw follow the beam pipe as it is moved. After the move, the midplane positions calculated from the midplane encoders and gap encoders, $Y_{um}$ and $Y_{dm}$, can be compared to specified values. The control system can make corrections, if required. This will be discussed in more detail below.

3 Using The Midplane Encoders In The MMF

The SXR undulators did not have midplane encoders. It was found that the centerline changed with gap. This necessitated measuring the centerline as a function of gap and applying corrections at each gap so that
the measurement probes measured on the magnetic axis. This effort to map the centerline as a function of gap costs about one day per undulator during calibration.

The SXR-HE undulators will have midplane encoders which will allow the centerline to be corrected immediately after the gap is set. The procedure is as follows. First, the control system sets the top jaw position to half the desired gap value. This is done using the absolute encoders on the top jaw motors. The bottom jaw is set by the gap encoders to give the correct gap. After the gap is set, the upstream and downstream midplane positions are determined from the midplane encoders and the gap encoders using equations 12, 20 and 22. For the correction, the top jaw motors are moved to make $Y_{um}$ and $Y_{dm}$ both zero as follows. From equations 12, 20 and 22, we know the midplane positions at the ends of the undulator, $Y_{um}$ and $Y_{dm}$. The midplane position at any $Z$ location is given by

$$Y_m(Z) = Y_{um} + \left(\frac{Y_{dm} - Y_{um}}{Z_d}\right)Z$$

Let the motor positions be $Z_{umot}$ and $Z_{dmot}$ for the upstream and downstream motors, respectively. The midplane position at the upstream motor is

$$Y_{umot} = Y_{um} + \left(\frac{Y_{dm} - Y_{um}}{Z_d}\right)Z_{umot}$$

The midplane position at the downstream motor is

$$Y_{dmot} = Y_{um} + \left(\frac{Y_{dm} - Y_{um}}{Z_d}\right)Z_{dmot}$$

In order to move the midplane back to the zero position given after alignment, the upstream top jaw motor needs to move by $-Y_{umot}$, and the downstream top jaw motor needs to move by $-Y_{dmot}$. The bottom jaw motors are controlled by the gap encoders and will keep the gap constant during the top jaw motor moves. This procedure can be iterated if needed.

### 4 Using The Midplane Encoders In The Tunnel

The midplane encoders can be used in the tunnel to check that each undulator is aligned to the beam axis. Quadrupoles on either side of each undulator determine the beam axis which goes from the center of one quadrupole to the next. This is illustrated below in figure 6. When the quadrupoles are moved, the control system uses potentiometers at each end of the undulator to make the undulator follow the beam pipe. The beam pipe is attached to the quadrupole supports, so when the quadrupoles move, the beam pipe moves. The control system reads the potentiometer output before the move and keeps the potentiometer readings constant during the move by using a feedback loop. This offsets and pitches the undulator so that it follows the beam pipe and therefore follows the beam axis.

In addition, the potentiometers are used as the undulator gap is changed at fixed quadrupole positions. The potentiometer measurements are compared to the gap changes in a manner similar to equations 20 and 22 for the midplane encoders, but with the potentiometers at the undulator ends. If $P_u$ and $P_d$ are the upstream and downstream potentiometer measurements of the upper jaw position relative to the beam pipe, and their offsets are set to make $P_u = P_d = 0$ after alignment, then the midplane positions relative to the beam axis given by the potentiometers are

$$Y_{ump} = P_u - \frac{(G_u - G_0)}{2}$$

$$Y_{dmp} = P_d - \frac{(G_d - G_0)}{2}$$

These expressions are true when the beam pipe is held fixed after alignment since the situation is similar to using the midplane encoders. These expressions are also true for any beam pipe offset and pitch as seen by mentally shifting and rotating the undulator and beam pipe together; none of the quantities in these expressions change. The potentiometer midplane positions are relative to the beam axis defined by the beam.
pipe since the potentiometers measure the top jaw position relative to the beam pipe. This is in contrast to the midplane position from the midplane encoders which measure the top jaw position relative to the alignment axis which is fixed. Since we want the undulator midplane on the beam axis, the potentiometers provide a direct determination of the midplane position relative to the beam axis. If a correction is needed, the correction is done using the top jaw motors and the lower jaw follows in order to keep the gap constant. Note that the beam pipe thickness does not enter because it is included in the offset values.

In equations 29 and 30, it is assumed that the potentiometers accurately give the distance the top jaw has moved relative to the beam pipe. This requires a calibration of the potentiometers. At present, the calibration is done by finding the output voltage as a function of potentiometer extension by using gauge blocks in the tunnel. This is illustrated by the red circles in figure 5. After alignment, the output voltage $V_0$ is recorded when the potentiometer arm is touching the beam pipe with extension $D_0$. Gauge blocks are then placed on the beam pipe changing the arm extension and giving a set of potentiometer extensions indicated by the red circles. At each extension, the output voltage is recorded. A linear fit gives the slope $S$ indicating how output voltage changes with arm extension.

$$V - V_0 = S(D - D_0)$$

(In the previous paragraph we used $P = D - D_0$ for the potentiometer extension relative to its value after alignment.) This calibration procedure does not account for any nonlinearities in the potentiometer transfer function.

The midplane encoders let us perform a calibration check, and also a more extensive calibration. Many points can be measured in an automated fashion. Without moving the beam pipe after alignment, the potentiometer extensions relative to their values after alignment are given from the midplane encoders by

$$P_u = M_u + [(M_d - M_u)/(Z_{dm} - Z_{um})](Z_{um} - Zum)$$

$$P_d = M_u + [(M_d - M_u)/(Z_{dm} - Z_{um})](Z_d - Z_{um})$$

for the upstream and downstream potentiometers, respectively. At each gap setting, the voltage $V$ is measured, and the difference $V - V_0$ is determined. The set of measurements gives a dense set of points on the
red curve in figure 5. The measurements can be fit by a polynomial or a spline for each potentiometer. In this way, an extensive calibration, or at least a check of the gauge block calibration, can be performed in an automated way.

In principle, using the potentiometers has worked well. However, any calibration error or modest malfunction of a potentiometer has not been detectable. Because of the importance of keeping the undulator midplane on the beam axis, we wish to use the midplane encoders as a check that the positioning using the potentiometers is correct.

In figure 6, the pitch of the beam axis is given by the vertical slope of the line between the centers of the quadrupoles.

$$\text{slope}_q = (Y_{dq} - Y_{uq})/(Z_{dq} - Z_{uq})$$

(34)

where $Y_{uq}$ and $Y_{dq}$ are the Y-positions of the upstream and downstream quadrupoles relative to the alignment axis. $Z_{uq}$ and $Z_{dq}$ are the Z-positions of the upstream and downstream quadrupoles. The Y-position of the beam axis relative to the alignment axis at any Z-position is given by

$$Y_{beam}(Z) = Y_{uq} + \text{slope}_q(Z - Z_{uq})$$

(35)

In particular, the Y-position of the beam axis at the upstream and downstream ends of the undulator are

$$Y_{beam}(Z_{um}) = Y_{uq} + \text{slope}_q(Z_{um} - Z_{uq})$$

(36)

$$Y_{beam}(Z_{dm}) = Y_{uq} + \text{slope}_q(Z_{dm} - Z_{uq})$$

(37)

The error in the midplane position is given by the difference between the beam axis position and the midplane position calculated from equations 23, 24, and 25.

$$E_{um} = Y_{beam}(Z_{um}) - Y_{um}$$

(38)

$$E_{dm} = Y_{beam}(Z_{dm}) - Y_{dm}$$

(39)

Figure 6: The beam axis is determined by the quadrupole positions on either side of the undulator.
The motors need to move the top jaw so that its upstream and downstream end positions change by $E_{um}$ and $E_{dm}$, respectively. In particular, the upstream and downstream motors need to change the Y-position of the top jaw at their locations by

$$\Delta Y_{umot} = E_{um} + [(E_{dm} - E_{um})/(Z_{dm} - Z_{um})](Z_{umot} - Z_{um}) \tag{40}$$

$$\Delta Y_{dmot} = E_{um} + [(E_{dm} - E_{um})/(Z_{dm} - Z_{um})](Z_{dmot} - Z_{um}) \tag{41}$$

5 Conclusion

Midplane encoders are being added to the SXR-HE undulators. These encoders will be valuable in the MMF for keeping the measurement probes on the undulator centerline. The midplane encoders provide valuable checks that the undulator axis coincides with the beam axis in the tunnel.

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