Focusing Lens PXIE-SSR1-L02 (C1896M): Magnetic Axis Position Measurement

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This note presents results of the magnetic axis position measurements for the first production lens made at Crymagnetics, Inc. (Sept. 2014) and at FNAL (Dec. 2014 – June 2015). Cryomagnetics serial number of the lens is C-1896-M; Fermilab's ID number is PXIE_SSR1_L02. The procedure of the data analysis used in this note is similar to how it was done earlier, when position of the magnetic axis of the prototype lens was measured in [1].

At Cryomagnetics, rotating Hall probe was used to locate magnetic axis; the following coordinate system was used:

- Probe rotation is around Z axis.
- Coordinate X is positive towards the angle mark "0°".
- Coordinate Y is positive towards the angle mark "90°".
- Coordinate Z = -64 mm corresponds to the flange of the lens marked as "A".
- Coordinate Z = +64 mm corresponds to the flange of the lens marked as "B".

The axis of the magnet bore was taken as a basis (X = 0, Y = 0) in this measurement. This position was inferred by using rims on the flanges of the device that were precisely machined as a part of the winding bobbin. Position of the magnetic axis (ΔX, ΔY) was calculated relative to this basis. Fig. 4 in [1] illustrates the setup.

Results of the measurements made using the first production cold mass **at Cryomagnetics** are summarized in Table 1.

Table 1. SSR1 focusing lens magnetic axis position measured by Cryomagnetics

Z [mm]	ΔX [mm]	ΔY [mm]	dX/dZ [mrad]	dY/dZ [mrad]
-64	0.039	0.067	-0.8	-0.18
+64	-0.064	0.045		
0	-0.0125	0.056		
dX/dZ, dY/dZ	-0.0008	-0.00018		

At FNAL, vibrating wire technique was used to locate magnetic axis. After position in space of the wire corresponding to zero integrated voltage was established, it was taken as a reference axis: (X = 0, Z = 0). Position of the lens relative to this axis was established using precise geodesic measurements. Following coordinate system was used here:

Y axis was directed along the wire from "**A**" flange to "**B**" flange of the lens.

Z axis was directed vertically, towards the "270°" mark on the flanges.

X axis was directed towards the "0°" mark to form a right-handed coordinate system.

The difference in the coordinate definition between what was used at Cryomagnetics and at FNAL must be taken into account when the two sets of data are compared.

Tables 2, 3, and 4 show results obtained at FNAL for three cases where position of the lens's geometric axis was calculated using the surveillance results based on the inner bore surface, the outer surface, and the rim of the flange. Two sets of data are compared in each of the tables: one is taken before the LHe vessel was added, the other was taken after it was welded to complete the assembly.

Table 2. Axis position extracted based on the inner bore survey at FNAL

	Y [mm]	ΔX [mm]	ΔZ [mm]	dX/dY [mrad]	dZ/dY [mrad]
Before welding	-82.4	-0.40	-0.20	+2.6	+1.5
	+82.4	+0.025	+0.050		
	0	-0.19	-0.075		
After welding	-82.27	-0.33	-0.13	+2.9	+1.6
	+82.677	+0.15	+0.13		
	0	-0.09	0		

Table 3. Axis position extracted based on the outer surface survey at FNAL

	Y [mm]	ΔX [mm]	ΔZ [mm]	dX/dY [mrad]	dZ/dY [mrad]
Before welding	-74.70	-0.203	-0.229	+1.8	+2.1
	+79.45	+0.076	+0.102		
	0	-0.068	-0.069		
After welding	-66.42	-0.305	+0.203	+4.9	-0.2
	+62.87	+0.330	+0.178		
	0	+0.021	+0.190		

Table 4. Axis position extracted based on the bolt flange rim surface survey

	Y [mm]	ΔX [mm]	ΔZ [mm]	dX/dY [mrad]	dZ/dY [mrad]
Before welding	-79.375	-0.279	-0.229	+2.0	+1.6
	+79.4	+0.051	+0.025		
	0	-0.114	-0.102		
After welding	-79.4	-0.203	-0.102	+2.6	+1.6
	+79.35	+0.203	+0.152		
	0	0	+0.025		

Data in all three tables taken **before welding** show satisfactory consistency. Table 5 summarized these "before welding" measurements **by averaging** corresponding data and indicating the uncertainty. The data in the tables is adjusted to the end position Y = ±80 mm by using linear interpolation.

Table 5. Axis position summary before welding - FNAL

	Y [mm]	ΔX [mm]	ΔZ [mm]	dX/dY [mrad]	dZ/dY [mrad]
Before welding	-80	-0.29 ± 0.10	-0.220 ± 0.025	**+2.0**±0.3	**+1.75**±0.25
	+80	+0.05 ± 0.04	+0.06 ± 0.04		
	0	**-0.12 ± 0.07**	**-0.08 ± 0.02**		
	dX/dY, dZ/dY	0.0020±0.0003	0.00175±0.00025		

Data in the tables 2, 3, and 4 taken **after welding** indicate that although the data taken at the inner flange and at the reference surface of the flange show satisfactory similarity, the data taken at the outer surface deviates significantly from this set and also from what was measured before welding. This difference was expected as a result of welding that was performed along the flanges on the outer surface of the LHe vessel cylinder. **One should not use the outer surface of the lens' LHe vessel as a reference surface when the lenses are installed in the beam line**.

Table 6 summarized the measurements based on the inner surface and the reference flange surface "after welding" **by averaging** corresponding data and indicating the uncertainty. The data in the tables is also adjusted to the end position Y = ±80 mm by using linear interpolation.

Table 6. Axis position summary after welding - FNAL

	Y [mm]	ΔX [mm]	ΔZ [mm]	dX/dY [mrad]	dZ/dY [mrad]
After welding	-80	-0.260 ± 0.060	-0.115 ± 0.015	**+2.7**±0.5	**+1.6**±0.16
	+80	+0.175 ± 0.030	+0.140 ± 0.012		
	0	**-0.045 ± 0.045**	**+0.012 ± 0.012**		
	dX/dY, dZ/dY	0.00275±0.0005	0.00160±0.00016		

Based on the measurements made based on the inner bore and the reference surface of the flange, we can expect the uncertainty of our knowledge of the center position of ~0.1 mm in X and in Z directions and the uncertainty of the angles of ~0.5 mrad.

Although the main goal of this study was to understand to which extent welding operation during lens assembly can distort the positon of the magnetic axis relative to the mechanical features of the lens, it was tempting to compare the data obtained at Cryomagnetics and Fermilab, where different approaches to the measurements were used (as was already mentioned, at Cryomagnetics, the measurements were made using a Hall probe at LHe temperature and at FNAL the measurements were made at room temperature using the vibration wire technique). To make the comparison, the measurement data from both sources must be transferred to one coordinate system. **The system used by Cryomagnetics was chosen as the base and FNAL data were transformed correspondingly**. Following [1], the process of the translation is as following:

1. For the axis directed along the beam pipe, the name **Y** (FNAL format) was changed to **Z** (as used by Cryomagnetics);
2. The name of the axis **Z** (FNAL format) was changed to **Y** (Cryomagnetics format); directions of this axis was adjusted **by changing the sign** in the data set (in the coordinate system chosen by Cryomagnetics, the Y axis goes through the 90° azimuth to form the right coordinate system, but in the FNAL case, it goes through the 270° azimuth).
3. The data by obtained by Cryomagnetics and by FNAL were adjusted to the position of the end flanges **Z** = ±80 mm by using linear interpolation.
4. In Cryomagnetics, the axis position was measured relative to the magnet; at FNAL, the opposite took place – the magnet position was measured relative to the axis. To properly compare the data, the signs of the ΔX and ΔY displacements in the FNAL's data set were changed to the opposite.

Only measurements made before welding (Table 5) were used for the comparison as "after welding" measurements were made only at FNAL. Results are summarized in Table 7.

Table 7. Axis position before welding measured by FNAL and Cryomagnetics

	Z [mm]	ΔX [mm]	ΔY [mm]	dX/dZ [mrad]	dY/dZ [mrad]
FNAL	-80	+0.29 ± 0.1	+0.22 ±0.025	-2.0 ± 0.5	-1.75 ± 0.16
	+80	-0.05 ± 0.04	-0.06 ± 0.04		
	0	+0.12 ± 0.07	+0.08 ± 0.02		
Cryomagnetics	-80	+0.052	+0.070	-0.8	-0.18
	+80	-0.077	+0.042		
	0	-0.0125	+0.056		

- X-positions of the magnetic axis in the center plane of the lens (Z = 0) differ by ~130 μm.
- Y-positions of the magnetic axis in the center plane of the lens (Z = 0) differ by ~25 μm.
- Angles of the magnetic relative to the geometric axis in the XZ plane differ by ~1.2 mrad.
- Angles of the magnetic relative to the geometric axis in the YZ plane differ by ~1.5 mrad.

If to assume that the relative position of the magnetic and the geometric axis does not change during cooling down, the differences in linear positions measured at Cryomagnetics and at FNAL can be explained if to assume accumulated error of the measurements of approximately ±100 µm, which agrees with the spread in the data in Table 5. As the angular position of the magnetic axis is calculated based on the linear measurements made on both sides of the lens, expected error for the angles $\Delta\theta = 2\cdot(\pm 100\ \mu m) / 160\ mm = \pm 1.25$ mrad, which also agrees with the spread in the angles in Table 7.

Summary:

Magnetic axis position measurements were made on the cold mass of the SSR1 first production focusing lens at Cryomagnetics and at FNAL. At FNAL the measurements were also made after the lens was fully assembled by welding.

Comparison of the measurements made before and after welding shows that the inner pipe and the rim of the flange can be used as a reliable base for lens alignment when it is installed in the cryomodule. The outer surface of the LHe vessel cannot be used as a reference.

Comparison of the measurements made on the cold mass at FNAL and at Cryomagnetics shows that these two set of the measurements, made at different temperatures and using different techniques, are correlated within assumed accuracy of the linear measurements of ±100 µm. Having in mind the required accuracy of lens positioning in the SSR1 cryomodule (0.5 mm RMS), the set of the measurements made at Cryomagnetics (where the measurements were made at the working temperature 4.2 K) can be used to install the lenses in the beam line.

Comparison of the measurements made on the prototype lens [1] and on the production #1 lens shows that both the radial position of the magnetic axis at Z = 0 and the direction of the magnetic axis can change from lens to lens.

The conclusion made in [1] must be repeated with some modification: to reduce uncertainty of alignment, a systematic study must be set that would use statistically significant number of the measurement using different methods at the working temperature. Certification of the measurement environment, including obtaining reliable information about the resolution of the measurement systems, must not be overlooked.

References:

1. J. DiMarco, I. Terechkine and V. Bocean, “PXIE SSR1 Prototype Focusing Lens: Position of the Magnetic Axis”, FNAL TD note TD-14-004, May 2014