

Focusing Lenses for the SSR1 Cryomodule of the PXIE Test Stand

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Five focusing lenses have been fabricated and tested for use in the SSR1 cryomodule of PXIE test stand. Requirements for the lenses are specified by the Functional Requirement Specification (FRS) document [1], which was generated based on the FRS for the SSR1 cryomodule [2]. Major requirements specified by [1] are listed below:

- Requirements essential for the beam dynamics [3]:
 - Integrated focusing strength of the lens must be not less than $4 \text{ T}^2\text{m}$.
 - Each lens must contain four additional windings that can be configured in a combination of two steering dipoles (horizontal and vertical) and one skew quadrupole focusing element; bending strength of each steering dipole must be not less than $0.0025 \text{ T}\cdot\text{m}$.
 - Integrated gradient of the focusing quadrupole must be not less than 0.02 T .
 - Clear aperture in the lens must be not less than 30 mm .
 - Uncertainty of the location of the effective magnetic axis in the focusing solenoid of the lens relative to the outer surface of the device must be better than 0.1 mm RMS .
- Requirements essential for proper functioning of the Cryomodule:
 - Maximum current in the solenoid of the lens must be less than 100 A .
 - Maximum current in the dipole correctors must be less than 50 A .
 - LHe vessel must be used for cooling the windings down to 2 K .
 - The lenses must be quench-protected.
 - Maximum magnetic field generated by lenses in the Cryomodule in the area near the surface of the SSR1 superconducting cavities must not exceed the level that would result in more than two-fold reduction of the intrinsic quality factor after quench event at any point on the surface of the cavity.

Using FRS [1] as a directive, technical specifications were developed.

The problem of the magnetic axis position uncertainty was studied when HINS focusing lenses were fabricated and tested at FNAL [4]. It was shown by direct magnetic measurements that the magnetic axis of focusing solenoids fabricated for HINS experienced significant shifts, both linear and angular, after the LHe vessel was added to the cold mass assembly by welding. The shifts were comparable with the alignment accuracy required for the HINS linac focusing lenses. Two main sources of the shifts were identified:

- Insufficient level of the accuracy specified for the assembly.
- Deformation of the assembly after the final welding operation.

Based on this observation, one of the goals set for the mechanical design of the PXIE SSR1 focusing lens was to ensure satisfactory positioning precision of the coils in the lenses and to minimize deformation of the bobbin after welding.

Definitely, additional, not fully predictable shifts of the magnetic axis will take place when the cryomodule is pumped out and cooled down; these shifts must be taken into account when the alignment of all elements of the cryomodule is made.

To quantify the fringe field requirement from the requirement list above, a special R&D program was conducted with the goal to understand the scale of the effects caused by the magnetic field trapped in the superconducting walls of RF cavities. A trapped magnetic flux

criterion was introduced and a technique was developed to calculate the trapped flux in an RF structure. Specially designed tests were conducted using several resonators and a test coil to validate results obtained during this study. The allowed trapped flux for accelerating cavities in the SSR1 Cryomodule was calculated in [5].

Lens Design

Conceptual design of the SSR1 focusing lens was proposed in [6]; it was used during the Cryomodule design stage to establish required interfaces: mechanical, cryogenic, electrical, and magnetic [7]. As this integration process proved successful, an order was placed with Cryomagnetics, Inc. for building and testing a prototype of the focusing lens. Design proposed in [6] and [7] was improved by Earle Burkhardt (then with Cryomagnetics, Inc.): fringe field of the lens was made even smaller and the lens assembly process was simplified. Final design of the lens is shown schematically in Fig. 1.

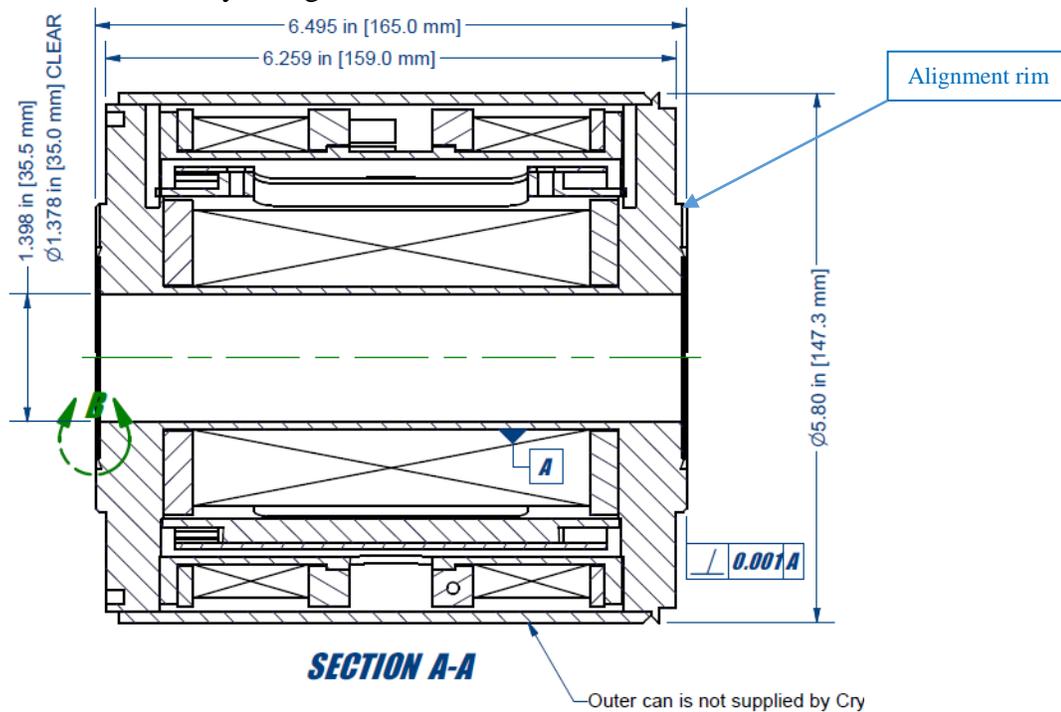


Fig. 1. PXIE SSR1 lens design suggested by Cryomagnetics, Inc.

Focusing solenoid of the lens consists of a main coil and two bucking coils. The geometry of the main and the bucking coils, the type and size of superconducting strand, and the number of turns in the windings were chosen to satisfy the required focusing strength (with some margin) and to make sure that the level of fringe magnetic field on the surface of the surrounding RF cavities meets the fringe field requirement. The bucking coils are wound concentrically with the main coil and are located at each end of the lens. The gap between the bucking coils is used to bring all current leads out of the lens.

Four steering (corrector) windings (each occupying a 90° azimuthal sector) are placed in the radial space between the main coil and the bucking coils (see Fig. 2).

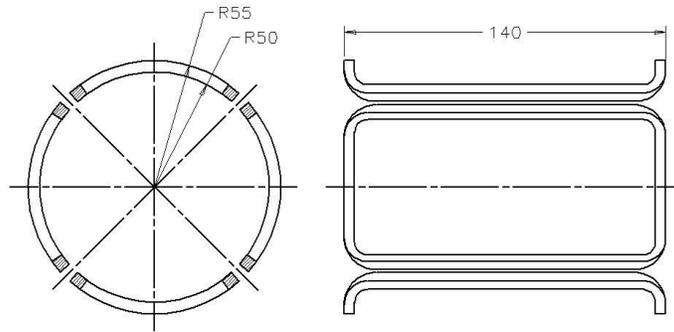


Fig. 2. Corrector assembly concept

Lens fabrication and testing was executed in several steps:

- Prototype cold mass was fabricated at Cryomagnetics, Inc.
- All the windings were quench-trained in a bath of LHe at 4.2 K.
- Magnetic field distribution of the solenoid was measured at the nominal current.
- Position of magnetic axis was measured using Hall probe method at 4.2 K at Cryomagnetics.
- The prototype cold mass was tested at 4.6 K and at 2.16 K at Fermilab.
- Position of the magnetic axis in the prototype cold mass was measured at room temperature using vibrating wire technique.
- The cold mass of the prototype was assembled with the LHe vessel.
- Position of the magnetic axis was re-measured at room temperature using vibrating wire technique for the finished lens before and after the LHe vessel was added by welding.
- The assembled prototype lens was tested at 4.6 K and at 2.16 K at Fermilab.
- Feedback was provided for the Cryomagnetics team with recommendations to modify the acceptance test procedures and certain details of the cold mass assembly.
- Four production cold masses were fabricated at Cryomagnetics.
- They were trained at 4.2 K, and position of magnetic axis of each lens was measured using Hall probe method at 4.2 K.
- The cold masses were assembled with LHe vessels at Fermilab.
- Four production lenses were tested at 2.16 K at Fermilab.
- Position of the magnetic axis in the first production magnet was measured at room temperature using vibrating wire technique before and after the final welding assembly operation.

Tables below compare winding data of the main and bucking coils of the lenses fabricated by Cryomagnetics, Inc. with that established by the magnetic design.

Table 1. Geometry of the main coils of the SSR1 focusing lenses

Parameter	Design	Lens #1 C1856M	Lens #2 C1896M	Lens #3 C1897M	Lens #4 C1898M	Lens #5 C1899M
ID [mm]	40.0	40.26	40.310	40.183	40.157	40.411
OD [mm]	82.5	81.41	82.296	82.372	82.55	81.788
L [mm]	110.808	110.745	111.506	111.252	110.82	111.506
N	12450	12462	12441.000	12486.7	12427.9	12471
S [mm ²]	2354.67	2278.58	2340.857	2346.805	2348.996	2306.892

Table 2. Geometry of the bucking coil #1 of the SSR1 focusing lenses

Parameter	Design	Lens #1	Lens #2	Lens #3	Lens #4	Lens #5
ID [mm]	115.0	115.367	116.078	115.545	115.494	115.24
OD [mm]	133.7	133.985	134.391	133.706	133.579	133.223
L [mm]	32.4	32.639	32.563	32.512	32.563	32.512
Z_cen [mm]	39.204	39.192	39.294	39.218	39.268	39.141
N	1602	1606.1	1568.000	1584.6	1590	1603
S [mm ²]	302.94	303.84	298.168	295.225	294.451	292.332

Table 3. Geometry of the bucking coil #2 of the SSR1 focusing lenses

Parameter	Design	Lens #1	Lens #2	Lens #3	Lens #4	Lens #5
ID [mm]	115	115.443	116.078	115.545	115.494	115.24
OD [mm]	133.7	133.883	134.239	133.706	133.426	133.452
L [mm]	32.4	32.639	32.563	32.512	32.563	32.512
Z_cen [mm]	-39.204	-39.192	-39.294	-39.218	-39.268	-39.141
N	1602	1624.1	1568.000	1584.6	1590	1603
S [mm ²]	302.94	300.93	295.687	295.225	291.960	296.054

At the nominal current (that provides the required focusing strength: $I_{nom} \approx 65.5$ A) the central field in the solenoid reaches ~ 7 T. Inductance of the solenoid in the lens is ~ 2.5 H.

Corrector windings in each lens were fabricated following the next protocol:

- Inside winding radius 47.245 mm
- Outside winding radius 51.56 mm
- Inside winding length 96.165 mm
- Inside winding angle 66°
- Outside winding angle 88°
- Number of turns 100

Maximum magnetic field on the strand in the corrector windings in the dipole mode (with the required integrated bending strength) is ~ 0.3 T. Maximum magnetic field on the strand in the quadrupole mode (with the required integrated focusing strength) is ~ 0.04 T.

All the coils were wound using round, ML-insulated, 0.4 mm bare diameter strand from Oxford Wire. The order for 21 km of the strand was placed in June 2012; it was delivered in November 2012 and sent to Cryomagnetics, Inc. Critical current of the strand at 4.2 K as specified by the Oxford Wire is shown in Table 4 for the magnetic field range from 3 T to 8 T.

Table 5. Oxford 0.4 mm NbTi strand critical current at 4.2 K

B (T)	3	4	5	6	7	8
I (A)	194	167	140	113	86	60

This set of the geometry data and superconducting strand parameters allows calculation of expected critical parameters of this magnetic system. To scale critical current of the strand from nominal 4.2 K to the temperatures used during the tests (4.6 K and 2.16 K), a critical current parameterization was used in the form suggested by L. Bottura [8]. Critical current density is expressed as a function of the relative temperature $t = T/T_{c0}$ and magnetic field $b = B/B_{c2}(T)$ with $B_{c2}(T) = B_{c20} \cdot (1-t^n)$:

$$J_c(B,T) [A/m^2] = C_0/B \cdot b^\alpha \cdot (1-b)^\beta \cdot (1-t^n)^\gamma \quad /1/$$

Earlier studies of quench propagation in the winding of the lens showed that this scaling worked sufficiently well when used with the following set of parameters:

$$C_0 = 28.4 \text{ T}\cdot\text{A}/\text{m}^2; B_{c20} = 14.25 \text{ T}; T_{c0} = 9.35 \text{ K}; \alpha = 0.8; \beta = 0.89; \gamma = 1.87; n = 1.7.$$

Table 6 compares expected (calculated) quench currents calculated using the 4.2 K strand performance data in Table 5 and the scaling law /1/ at the temperatures measured during the performance tests (4.2 K during the tests at Cryomagnetics, Inc. and 2.15 K at Fermilab) with the measured quench currents of each solenoid. The last column of the table records the maximum magnetic field on the strand at the quench current.

Table 6. Expected and measured quench currents of the solenoids in the SSR1 focusing lenses.

Magnet #	Expected at 4.2 K	Measured at 4.2 K	Expected at 2.15 K	Measured at 2.15 K	B _{max} at 2.15 K
1	68 at 4.6 K	67.9 at 4.6 K	90.7	91.7	9.35 T
2	72.5	72.5	89.0	89.8	9.41 T
3	72.3	72.4	88.8	89.6	9.42 T
4	72.8	72.7	89.2	90.4	9.40 T
5	72.9	72.6	89.2	91.1	9.39 T

When trained at 4.2 K at Cryomagnetics, just several (or none) training quenches were observed in the coils of the solenoid and in the corrector windings. During repeated performance tests at FNAL at 4.6 K and at 2.15 K no training quenches were observed indicating good quality of windings and training memory.

The performance of the correcting coils was measured at Cryomagnetics with the nominal current in the solenoid (that is the current that results in the required minimum focusing strength of a lens: I = 65.5 A). As the required strength of the correctors was exceeded during the 4.2 K test at Cryomagnetics, no testing of these coils at 2 K were required at Fermilab.

Axial scan of magnetic field was made at Cryomagnetics for solenoids of each cold mass at the nominal current. Fig. 3 compares results of the measurement with the calculated projection for the prototype magnet based on the reported geometric data in tables 2 and 3.

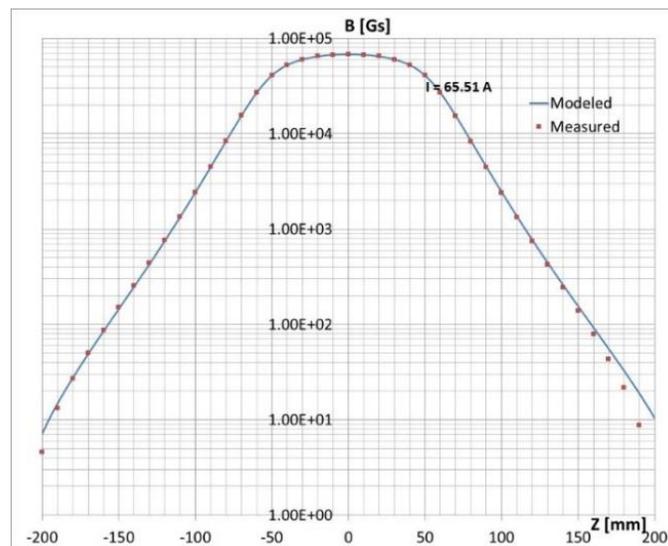


Fig. 3. Calculated (FNAL) and measured (Cryomagnetics) magnetic field of the prototype lens

Satisfactory correspondence between the measurements and the predictions is observed for all the magnets in the desired range of the distances from the center of the magnet.

To compensate for possible nonlinear effects of focusing by solenoidal lenses, the direction of the magnetic field in the neighboring lenses in the Cryomodules must alter. This change of polarization also helps to compensate for rotation of the beam cross-section happening in the lenses. To establish needed polarity of lenses after assembly in the cryomodule, one needs to use lead naming accepted by the vendor for each fabricated magnet.

Current leads naming convention:

The main coil and two bucking coils of the solenoid are connected in series. The main coil (MC) is between the leads marked as “**Main Start**” and “**Diode Tap**”; $R_{\text{Main}} \approx 570$ Ohm. Two bucking coils (BC) are between the leads “**Diode Tap**” and “**Main Finish**”; $R_{\text{BC}} \approx 290$ Ohm.

The corrector winding located at the azimuth $\varphi = 0^\circ$ (generating magnetic field directed along the line from 0° to 180°) will be referred to as **X0**. The same rule applies to other azimuths: 90° (**X90**), 180° (**X180**), and 270° (**X270**). All leads are coming out at the azimuth 270° .

Magnetic field direction in the prototype magnet (lens #1, 1856M)

For each of the four steering/correcting winding, the current coming into the lead marked as positive (+) results in the magnetic field directed towards the center of the magnet. Name of each winding is related to its position relative to the **angle mark** on the “**negative**” ($Z < 0$) flange. E.g. the winding located at the azimuth $\varphi = 0^\circ$ (that is generating magnetic field along the line directed from 0° to 180°) will be referred to as **X0**. Plus sign after this name (**X0+**) will show that the incoming current generated field directed towards the center. The second lead of this winding will be called **X0-**.

Current coming into the lead “**Main Start**” results in the field directed from the “negative” flange (with the angle marks) towards the “positive” flange (no angle marks) in the main coil and in the opposite direction in the bucking coils.

Magnetic field direction in the production magnet #1 (lens #2, 1896M)

In this lens, both flanges are marked with the angle marks (0° , 90° , 180° , and 270°). They also are marked with symbols A (-64 mm) and B (+64 mm). The serial number is placed on the flange A.

For each of the four steering/correcting winding, the current coming into the lead marked as “**Start φ** ” results in the magnetic field directed towards the **φ** mark on the flanges.

Current coming into the lead “**Start Main**” results in the field directed from the flange A towards flange B in the main coil and in the opposite direction in the bucking coils.

Magnetic field direction in the production magnet #2 (lens #3, 1897M)

Like it was for the production magnet #1, both flanges are marked with the angle marks (0° , 90° , 180° , and 270°). They also are marked with symbols A (-64 mm) and B (+64 mm). The serial number is placed on the flange A.

Like it was for the production magnet #1, for each of the four steering/correcting winding, the current coming into the lead marked as “**Start φ^0** ” results in the magnetic field directed towards the φ^0 mark on the flanges.

Current coming into the lead “Main Start” results in the main coil magnetic field directed from the flange **B** towards flange **A**. Current coming into the lead “Main Finish” results in the bucking coil magnetic field directed from the flange **B** towards flange **A**. **This is the opposite of what it was for the production magnet #1.**

Magnetic field direction in the production magnet #3 (lens #4, 1898M)

Like it was for the production magnets #1 and #2, both flanges are marked with the angle marks (0° , 90° , 180° , and 270°). They also are marked with symbols **A** (-64 mm) and **B** (+64 mm). The serial number is placed on the flange **A**.

Like it as for the production magnets #1 and #2, for each of the four steering/correcting winding, the current coming into the lead marked as “**Start φ^0** ” results in the magnetic field directed towards the φ^0 mark on the flanges.

Current coming into the lead “Main Start” (exits through the neutral) results in the field directed from the flange **B** towards flange **A**. Current coming into the lead “Main Finish” (exits through the neutral) also results in the field directed from the flange **B** towards flange **A**. This is like it was in production magnet #2 and opposite to what it was for the production magnet #1.

Magnetic field direction in the production magnet #4 (lens #5, 1899M)

Like it was for the production magnets #1, #2, and #3, both flanges are marked with the angle marks (0° , 90° , 180° , and 270°). They also are marked with symbols **A** (-64 mm) and **B** (+64 mm). The serial number is placed on the flange **A**.

Like it as for the production magnets #1, #2, and #3, for each of the four steering/correcting winding, the current coming into the lead marked as “**Start φ^0** ” results in the magnetic field directed towards the φ^0 mark on the flanges.

Current coming into the lead “Main Start” (exits through the neutral) results in the field directed from the flange **B** towards flange **A**. Current coming into the lead “Main Finish” (exits through the neutral) also results in the field directed from the flange **B** towards flange **A**.

This is like it was in production magnets #2 and #3 and opposite to what it was for the production magnet #1.

Magnet axis position summary

Results of magnetic axis position measurements at Cryomagnetics, Inc. at 4.2 K and at Fermilab at room temperature were summarized in [9] and [10]. It was shown that although position of the magnetic axis changes after welding, this change is on the level of expected uncertainty of the measurements. Taking this uncertainty into account, vendor’s data for the magnetic axis position taken at 4.2 K will be used when the lenses are installed in the beam line of the Cryomodule. At Cryomagnetics, a rotating Hall probe was used to measure the magnetic center at the axial distances -64 mm and +64 mm from the center of the magnet. As a reference surface, a precisely machined rim on the flanges of the bobbin seen in Fig. 1 was used. When using the axis position data obtained by the vendor, one needs to take into account the coordinate

system used for presenting the data: axis X in the planes of measurement is directed towards the 0° mark and axis Y is directed towards the 270° mark on the “negative” flange of the prototype or on the flange A of the production magnets. Point X = 0, Y = 0 for each flange is located on the geometric axis of the bobbin.

Having in mind this coordinate system, Table 7 summarizes the magnetic axis position measurements made by Cryomagnetics, Inc. team.

Table 7. Summary of the magnetic axis position in the SSR1 lenses

System ID	Probe position Z (mm)	ΔX (μm)	ΔY (μm)	dX/dZ (mrad)	dY/dZ (mrad)
C-1856M	-64	-93	-54	+0.54	-0.135
	+64	-24	-135		
C-1896M	-64	+39	+67	-0.8	-0.17
	+64	-64	+45		
C-1897M	-64	0	103	-0.55	-0.61
	+64	-70	25		
C-1898M	-64	75	-43	-0.09	+0.92
	+64	63	75		
C-1899M	-64	-57	-81	0.91	+0.37
	+64	59	-34		

When installing the lenses in the beamline, the data from Table 7 must be transformed to the local coordinate system used during the installation. Example of this transformation can be found in [9] and [10] where the measurements made at FNAL and Cryomagnetics were compared.

Performance test at 2.16 K

Prototype focusing lens was tested at Fermilab in June 2014 in the Vertical Magnet Test Facility (VMTF) located in IB1 both at 4.6 K and at 2.16 K. Schematic of the test is shown in Fig. 4. Quench protection scheme that employs cold diodes was suggested by the vendor; it was implemented and tested at FNAL when the performance test was conducted. A pair of fast switching rectifier diodes (STTH6004W) were connected in parallel to each coil of the lens. The diodes are rated 60 A at room temperature, but work well at LHe temperature in the quench protection circuits. The turn-on voltage of the diodes at 4 K is in the 5÷10 V range, but when current start flowing through the diodes, their temperature rises and the voltage drop reduces to a typical 2 V value in our quench environment.

Details of the recorded current and voltage traces were different for different quench events during this test even for the same quench currents. The observed difference in the current trace details during the prototype and production magnet tests can be explained by the fact that the differential signal was chosen to activate phasing out the power supply; this made it very sensitive to the temperature and other factors that control the timing of the protection diode opening. Voltage (or voltage difference) across the main and the bucking coils should be chosen instead when quench protection scheme is developed for the focusing lenses installed inside the SSR1 Cryomodule.

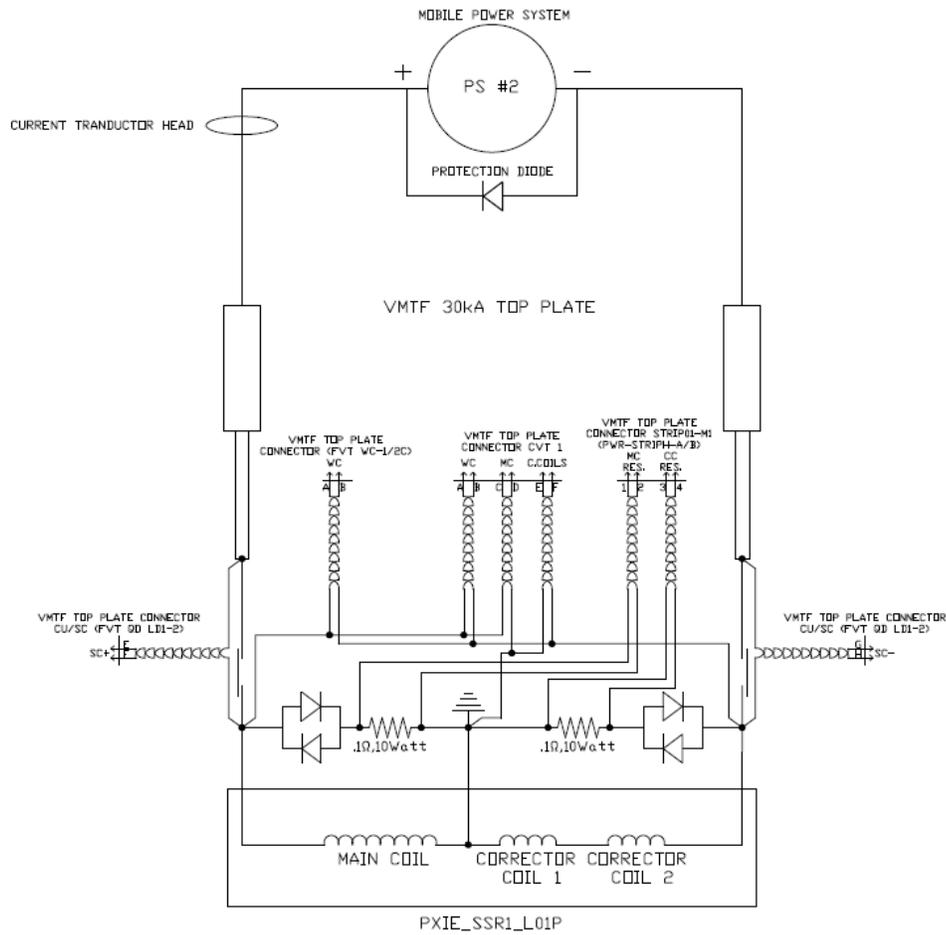


Fig. 4. Schematics of the dressed Prototype Focusing Lens test

One of recorded traces of the current discharge after the main coil of the prototype lens quenched at 91.7 A ($T = 2.16$ K) is shown in Fig. 5.

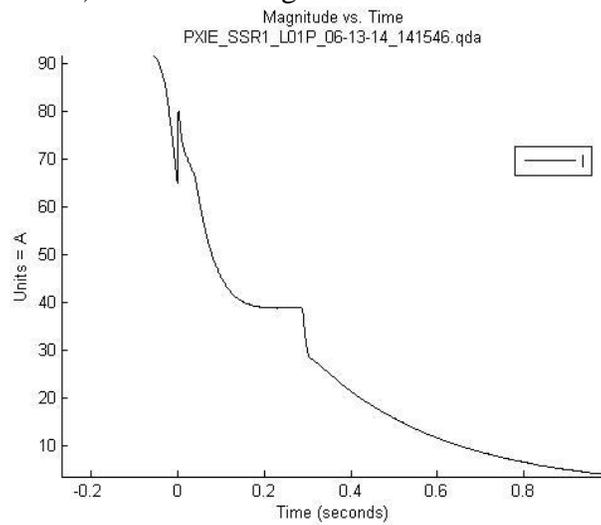


Fig. 5. Current discharge trace; main coil quench of the prototype lens at 2.16 K; $I_q = 91.7$ A.

In Fig. 6, a record of the voltage taps data (per Fig. 4 connection scheme) is shown.

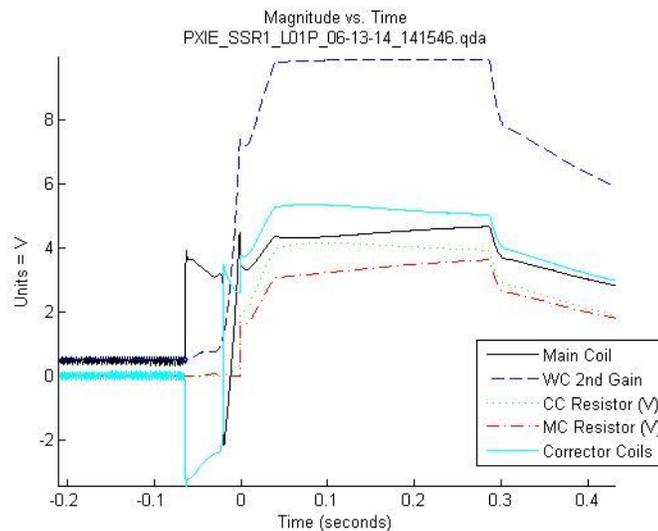


Fig. 6. Main coil quench of the production lens #2 at 2.16 K: voltage traces.

It is necessary to say that the current was measured by a current transducer located near the power supply, as shown in Fig. 4. The current decay it shows does not necessarily reflect the current in the coil – it reflects the current in the global circuit. The loop for the currents in the coils can be closed through the protection diodes. During the quench event shown in figures 5 and 6, phasing out the power supply was executed based on the whole coil (WC) signal; corresponding threshold for quench detection was set to 3 V. The quench started in the Main Coil as the voltage in this coil rises sharply at the time mark $t = -0.06$ s (Fig. 6). This rise is compensated by corresponding (negative) inductive reaction in the bucking coil, and the whole coil voltage stays close to zero. At some point, the rise of the resistance in the main (quenching) coil is so great that corresponding voltage cannot be fully compensated by the inductive circuits. When the whole coil voltage reaches 3 V, the quench detection system is triggered, and the power supply is phased out; by definition this happens at the time mark $t = 0$. We see a spike in the current curve at this moment due to the change of the current route, which now goes through a diode connected in parallel to the power supply. Eventually the current, flowing only through the main coil and the bucking coils before quench, starts circulating through the protection diode circuits connected in parallel to the coils. This happens when the voltage across the coils exceeds the opening threshold, which is greater than 5 V at 2 K. This current is witnessed by traces in Fig. 6 corresponding to the voltages across the main coil, the main coil resistor, the bucking coil, and the bucking coil resistor. As we see in Fig. 5, the global loop current completely decayed at the 0.8 s mark; the voltage across the protection diodes in the main coil and the bucking coil circuits lasts much longer. Time constants of corresponding discharge circuits are ~ 60 seconds for the main coil and ~ 10 seconds for the bucking coil circuit.

Stored magnetic energy in the lens at the 90 A current is ~ 10 kJ. In [11] it was shown that the lenses can withstand this energy without significant overheating. The discharge time constant of several seconds is sufficient to keep the maximum voltage inside the coil below the acceptable level of 500 V.

Test Infrastructure

The test was conducted in the Fermilab's Vertical Magnet Test Facility (VMTF). At the time when the production lenses were ready for testing, the 30 kA test header used for the prototype magnet test was disassembled for modifications needed for testing magnets with larger bores in the superfluid LHe (below 2 K) environment. If the production lenses were tested similar to how the prototype lens was tested, the time to test all four lenses in one cycle would be prohibitively long taking into account other magnets tests scheduled for this facility in 2015. As a result, the test and the header were re-configured to test all four production magnets simultaneously, during one thermal cycle. This solution became possible because of the availability of two 150 A vapor cooled current lead clusters (6-lead) procured by the Test & Instrumentation department to equip one of the tests planned several years ago. Components remaining from the original 30 kA test header (where the test temperature was greater than 2.2 K) were used to assemble a 150 A, 2.2 K header. To complete the header assembly, a new instrumentation tree needed to be fabricated as well as two adapter flanges for mounting the current lead clusters. The test header assembly was reworked, wired and readied for the test in the beginning of October 2015.

Two lenses were wired to each of the two current lead clusters. As the lengths of the leads in the two clusters were different, during testing the helium liquid level was set first for one of the clusters. After testing the two lenses attached to that cluster, the liquid level was adjusted for the second lead cluster and the remaining two lenses were tested. Fig. 6 shows the 150A header with two six-lead clusters and new instrumentation tree. In Fig. 7, the four production magnets are shown installed and wired for the test.

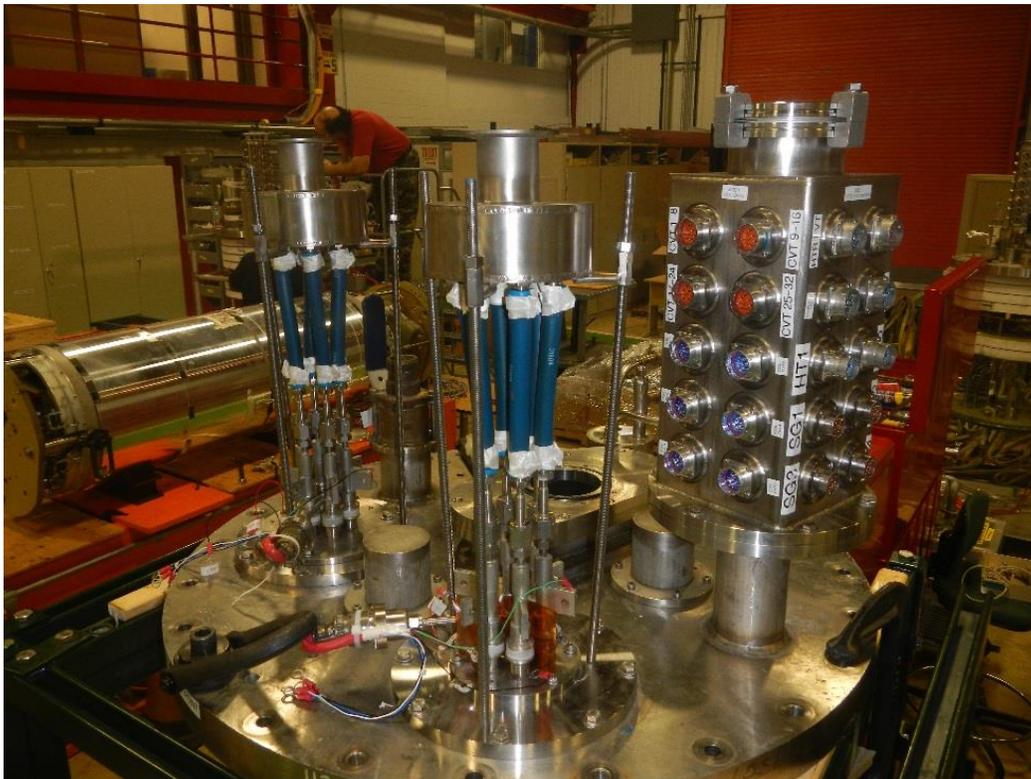


Fig. 6. Top head of the re-worked test header.



Fig. 7. SSR1 production lenses installed for testing.

Summary.

Four lenses for use in the SSR1 prototype Cryomodule have been fabricated at Cryomagnetics, Inc., tested at Cryomagnetics at 4.2 K, assembled with LHe vessels at FNAL, and tested for performance in the Vertical Magnet Test Facility in IB1.

This report summarized:

- Geometry of the lenses as fabricated.
- Winding data for each lens.
- Lead naming convention.
- Expected and measured performance at 2.15 K.
- Position of the magnetic axis.

Besides, description of the modified test infrastructure is presented and performance of cold diode-based quench protection circuit is analyzed.

Conclusion.

The lenses meet all requirements of the FRS [2] and are ready for installation in the SSR1 Cryomodule.

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