Quench Protection of Focusing Lenses for PXIE Cryomodules

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Introduction

The design of focusing lenses in the beam line of the Project X Injector Experiment (PXIE) must meet certain requirements. The most important of these requirements are:

- Focusing strength of the lenses defined by the beam optics.
- Available space for the lenses and arrangement of interfaces in the cryomodule.
- Allowed level of magnetic field on the walls of accelerating cavities.
- Accuracy and reproducibility of the lenses' magnetic axis positioning in the cryomodule.
- Accepted method of cooling and coolant temperature.

At the design stage, these requirements can contradict one another. For example, small available space causes difficulties in lens assembly and reduction of fringe field; high coolant temperature can lead to increased size of the coil, etc. Prior experience with focusing lenses for the HINS linac program [1] shows that a significant reduction of the fringe field requires the use of bucking coils and a thick steel flux return; these measures make the task of locating the magnetic axis tricky.

On the other hand, solutions like conduction cooling can simplify the way the lens is designed and placed in the cryomodule. With conduction cooling, the absence of a liquid Helium vessel allows tighter control over the relative position of the axis of the spool that the main coil is wound on and the magnetic axis of the coil. Although conduction cooling may lead to uncertainties in coil temperature, this design reduces longitudinal space occupied by the lens in the cryomodule and simplifies lens alignment. Additionally, if in the frame of conduction cooling the lenses in a cryomodule are not mechanically bound to the beam pipe, their position becomes more predictable and reproducible; a less bulky alignment fixture can be employed in this case. To further reduce the amount of needed space, lenses can be built without bucking coils, as long as a higher level of magnetic field is allowed on the cavity walls.

A goal of this study is to analyze possible configurations of a conduction-cooled focusing lens from the point of view of quench protection. This study is based on the quench analysis method described in [2]. Interpretation of the results will allow us to make a better decision on the design approach, namely to use either a one-coil or segmented design of the main coil of the lens to ensure proper protection in case of a quench.

Lens Geometry

The following input parameters for this concept study of the focusing lens were chosen based on the assumed configuration of the cryomodule:

- Lens assembly is not mechanically connected to the beam pipe.
- Inner radius of the winding in the lens R_i = 24 mm.
- Thickness of the winding $R_o - R_i$ = 25 mm.
- Focusing strength of the lenses exceeds 4 $T^2 \cdot m$.

- Length of the coil does not surpass 170 mm.

Fig. 1 shows the radial layout of the sample coils specified later in this study.

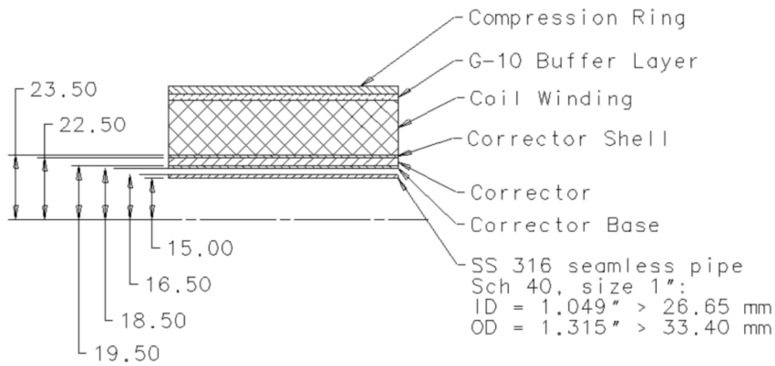

Fig. 1. Radial Position of Layers in Conduction-Cooled Coil.

In this study, we assume that round NbTi 0.5 mm diameter strand is used for coil fabrication. Table 1 compares strand parameters used during modeling with those specified by the vendor (Oxford Instruments) and with the results of sample measurements at FNAL. The parameter set used during modeling safely underestimates the critical current and is close to what is specified by the vendor.

Table 1. Critical Current Ic (A) of NbTi 0.5 mm Strand at 4.2 K.

B (T)	8	7	6	5	4	3	2	1
Specifications	94	134	173	213	252			
Sample1 0.5 mm	98	151	202	255	308	367	451	621
Sample2 0.5 mm		154	206	258	310	370	456	646
Modeling 0.5 mm		126		207				

Lens geometry and its main properties were modeled using the code described in [3], which was upgraded by introducing temperature parameterization in accordance with [4]. Table 2 provides a comparison of four coil designs in the temperature range from 4.5 K to 6 K.

Table 2. Sample Lens Designs Based on Temperature.

Temperature [K]	4.5 K	5 K	5.5 K	6 K
Length [mm]	90.2	100.0	120.5	151.2
Inner radius [mm]	24	24	24	24
Outer radius [mm]	46.6	49	49	49
Turns per layer	169	188	226	284
Number of layers	42	46	46	46
Total turns	7050	8660	10400	13100
Critical Current [A]	92.1	77.3	67.3	57.4
Focusing Strength [$T^2 \cdot m$]	4.03	4.01	4.00	4.00

For temperatures exceeding ~6.5 K, there is no solution that would fit the allocated longitudinal space of 170 mm. Nevertheless, preliminary experiments made in a test cryostat show that in the 4.5 K environment (the temperature of liquid Helium in the cooling pipes) we can rely on the temperature of a conductively-cooled winding being less than 5.5 K [5]. Extrapolating this data to a 2 K environment, and including some safety factor because of the fast changing thermal conductance at this low temperature, we can use as a starting point for this quench protection study a coil temperature of 5.5 K. The coil parameters chosen for this case are provided in Table 3.

Table 3. 5.5 K Selected Lens Design.

Temperature [K]	Strand diameter [mm]	Inner radius [mm]	Outer radius [mm]	Length [mm]	Turns per layer	Layers in coil	Total turns in coil	Critical Current [A]	Focusing Strength [$T^2 \cdot m$]
5.5	0.5	24	49	125	235	46	10810	66.9	4.17

The coil's geometry differs from what is shown in Table 2. This adjustment was made to slightly increase the focusing strength of the lens to ~4.17 $T^2 \cdot m$, which is above the established minimum level of 4 $T^2 \cdot m$. Using coolant with a temperature of 2K would result in a significant safety factor. Fig. 2 shows the cross-section of the coil chosen for quench propagation analysis.

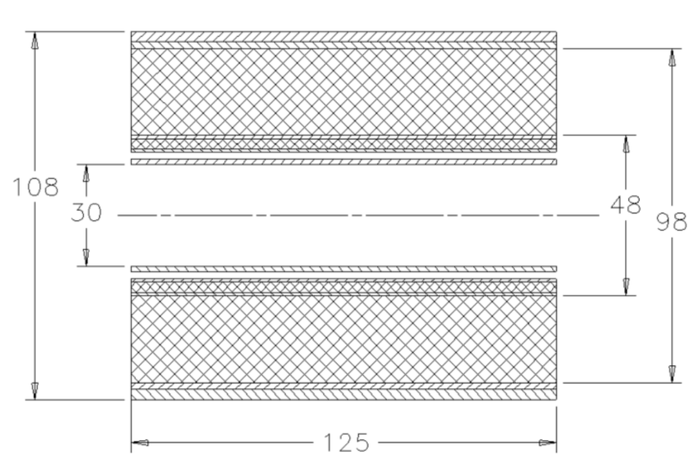

Fig. 2. Cross-Section of Winding in Chosen Coil.

The large number of turns in the coil can impose a problem in configuring a quench protection system because of the high inductive voltage generated inside the coil during quenching. To evaluate this voltage, we need to find the mutual inductances between layers in the coil and the total coil. If we know these inductances, we can readily find the voltage induced in each layer due to changing current in the lens. Superimposed with the voltage drop on the resistances of the quenching coil layers, the inductive voltage helps find the voltage distribution inside the lens' winding. Mutual inductance can be calculated using a method similar to that in [6]. To find the mutual inductance between a source coil (coil #1) and a layer in another coil (coil #2, which can be the same coil), the following formula was derived for this study:

$$M_{C1L2} = \frac{2\pi \cdot N1 \cdot W2}{J1 \cdot S1 \cdot L2} \cdot \int (R2 \cdot A2) dz \qquad /1/$$

In this expression, *N1*, *J1*, and *S1* are the total number of turns, average current density, and cross-sectional area in the source coil. *W2*, *R2*, and *L2* are the number of turns, radius, and length of a layer in the receiving coil (coil #2). *A2* is the vector potential in this layer (it has only one φ component for the axial symmetric problem), which is a function of the position *z* within the layer in the receiving coil. Integration in the expression is made over the length of the layer.

Two options were studied: the solenoid of the lens is made as one coil, and a two-coil solenoid design is used. For the two-coil scheme, thermal separation of the coils is assumed. A map of vector potentials was calculated within the lens' winding using COMSOL Multiphysics. Mutual inductances for several thin (sample) layers evenly spaced radially along the lens, found using expression /1/, are shown in Table 4. To calculate the total inductance of the coil, the sum of these sample layer inductances needs to be multiplied by the ratio of total layers over the number of samples. The data below was found at a current of 1 A (and corresponding *J0* of $3.46 \cdot 10^6$ A/m^2), with the layers positioned radially as follows: R1 = 24 mm, R2 = 29 mm, R3 = 34 mm, R4 = 39 mm, R5 = 44 mm, R6 = 49 mm.

Table 4. One-Coil.

Layer	Inductance
1	0.03459
2	0.04897
3	0.06165
4	0.07129
5	0.07648
6	0.07574
Sum(1:6)	0.36872
Sum*46/6	2.826853

Table 5a. Two-Coil (Self).

Layer	Inductance
1	0.01409
2	0.02009
3	0.02530
4	0.02915
5	0.03104
6	0.03028
Sum(1:6)	0.14995
Sum*46/6	1.149617

Table 5b. Two-Coil (Mutual).

Layer	Inductance
1	0.00366
2	0.00506
3	0.00644
4	0.00769
5	0.00873
6	0.00949
Sum(1:6)	0.04107
Sum*46/6	0.31487

In Table 4, mutual inductances between a coil and its own layers are shown for the case of one-coil winding. For the case of two-coil winding, the model was modified to introduce lens segmentation: the winding consists of two coils, each coil being half of the original one-coil winding. There is a thermal barrier between these two halves, so propagation of a quench from one coil to another can only happen through an inductive connection. Table 5a shows the mutual inductances between one half-coil and the layers of the same half. Table 5b corresponds to the mutual inductances between the layers of one half and the winding of the second half.

In the segmented design, the inductance of the entire lens is calculated as the sum of all discrete inductances ($L = M_{11}+M_{12}+M_{21}+M_{22}$). Because of symmetry, the total inductance in this case simply is $2 \cdot (M_{11}+M_{12}) = 2 \cdot (0.315+1.150) = 2.93$ H.

The inductance of the lens in the one-coil case is 2.83 H (Table 4). The two values for total inductance of the system are not identical, although they should be. This disparity may originate from the interpolation procedure used to switch from sample layers to the total number of layers in the coil, as well as small differences in the COMSOL models. Some loss of precision is also possible due to rounding. As further verification, the total inductance of the system was found through formulas available in handbooks [7]. Results (2.67 H to 2.98 H) are quite comparable with what was found by our approach.

Knowing the matrix of mutual inductances, it is straightforward to write expressions for the current and voltage change in the discharge circuit for use during the quench propagation modeling for each configuration of lens design. The next sections summarize the results of these analyses.

Quench Propagation Analysis for the One-Coil Case

After a quench is detected, the power supply must be disconnected, and the current in the circuit continues through a dump resistor that is permanently connected in parallel to the coil. So, after detection of a quench, the coil and the dump are effectively connected in series (Fig. 3). In principle, one can avoid using fast disconnect if the maximum voltage of the power supply is just above the voltage drop on the normally conducting leads. As the coil resistance increases above this level, the current in the coil stops being dangerous and can be allowed to flow permanently. Saying this, we need to add that the beam-related protection must be activated in any case to prevent radioactive contamination due to losses in the walls of the beam pipe.

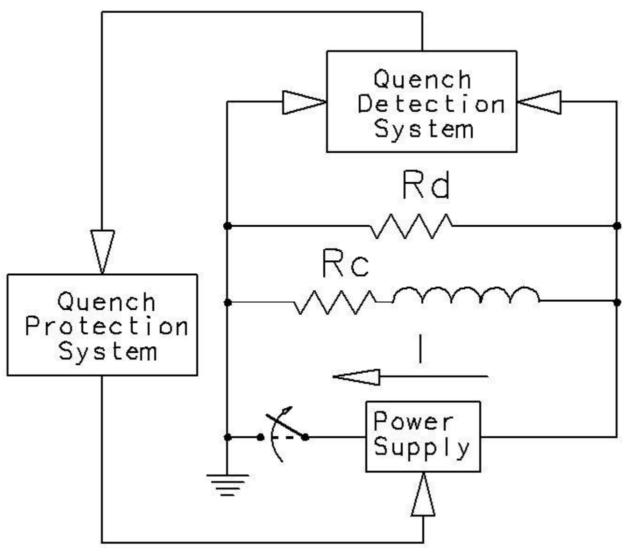

Fig. 3. Discharge Circuit for One-Coil Lens Design.

To solve the quench propagation problem in this study, the analysis software [2] was modified:

- New input data (geometry, inductances, etc.) corresponding to the coil design was used.
- Through the model generated in COMSOL, a sample matrix of magnetic field in the coil at 65 A was found. In the two-coil case, the ratio of currents in the coils is taken as another matrix dimension. The matrix is then interpolated to expand it into the complete turn-by-turn field matrix in the coil. Since the strength of the magnetic field is directly

proportional to current in the coil, the interpolated magnetic field data can be multiplied by $I/65$ to calculate magnetic field at a current of I.

- Circuit equations were updated to account for the new connection scheme.

Besides these adjustments, the structure of the MATLAB quench propagation modeling program used in [2] remained mostly the same. Once again, a single quench is initialized in the area of maximum magnetic field (at the central, innermost turn), as this scenario is the most likely and yet the most dangerous.

Listed below are the results of quench propagation modeling of a single coil connected in series to a dump resistor. The value of the dump resistance was taken as the independent variable of this analysis.

Table 6. One-Coil Quench Propagation Results.

Dump Resistance (Ohm)	Max. Coil Resistance (Ohm)	Max. Temperature (K)	Max. Layer Voltage (V)	Max. Layer Voltage to Ground (V)	Max. Voltage between Layers (V)	Energy Dissipation in Coil / Dump Resistor (kJ)
0	22.78	64.35	16.88	166.51	33.47	6.32 / 0
1	21.52	62.81	17.81	131.31	34.30	5.74 / 0.59
3	19.27	59.92	18.19	195	36.29	4.69 / 1.63
5	17.39	57.23	18.83	325	37.66	3.81 / 2.51
10	13.84	51.40	19.84	650	39.67	2.21 / 4.11

The results are quite encouraging:

- Maximum internal voltage to ground due to the appearance of the normal zone is just ~167 V, even without a dump resistor.
- Maximum overall voltage to ground increases only when the outer dump resistance is raised to improve the energy extraction efficiency. At a resistance of 5 Ohms, this voltage is 325 Volts, which is quite acceptable.
- Maximum temperature in the coil is at safe levels in all cases.
- Energy extraction efficiency with the 5-Ohm dump is ~40%.

So, the one-coil design does not generate many problems for protecting the coil in the case of a quench event. The only (minor) complication for the SSR1 system will be quench detection, which may require a bridge-type arrangement to increase signal-to-noise ratio. If a stronger lens is specified for the SSR2 section of the PX linac, this conclusion will need a reassessment. In that case, higher voltages can be expected inside the coil, which can make it difficult to design a one-coil lens while ensuring safe conditions during quenching.

Without any significant impact on the fabrication process, the two-coil system can provide a convenient environment for better quench detection configuration. It has the advantage of allowing direct comparison of voltages generated in the two halves during quenching to simplify quench detection and make it more reliable. Moreover, this arrangement will allow the placement of the circuit ground in the middle of the winding, thus significantly diminishing the voltage to ground problem.

It is worth noting that for both cases in the proposed quench protection approach, no switchers are required to disconnect the power supply if it is used in the current source mode with the maximum voltage defined by the voltage drop on the current leads.

Quench Propagation Analysis for the Two-Coil Case

The same coil geometry is used in this part of the study, except that the winding of the lens is made of two parts. Although separated thermally by a barrier, the sections are electrically connected to each other conductively and inductively. Each of the two halves of the winding also is permanently connected in parallel to a dump resistor. When a quench develops in one of the coils, both dumps participate in the process of energy removal. Because this case is symmetrical, the dumps must have the same resistance, since the location of the quench cannot be predicted.

Two ways of configuring the discharge circuit are possible. The first option involves disconnection of the power supply, which leaves two conductively connected and inductively coupled discharge loops. The second configuration does not require disconnection of the power supply, and uses a diode connected in parallel to the power supply to keep the current circulating in the discharge loop. This option has the advantage of better protection reliability, but both schemes should provide needed protection. Fig. 4 shows the discharge circuit used in this study.

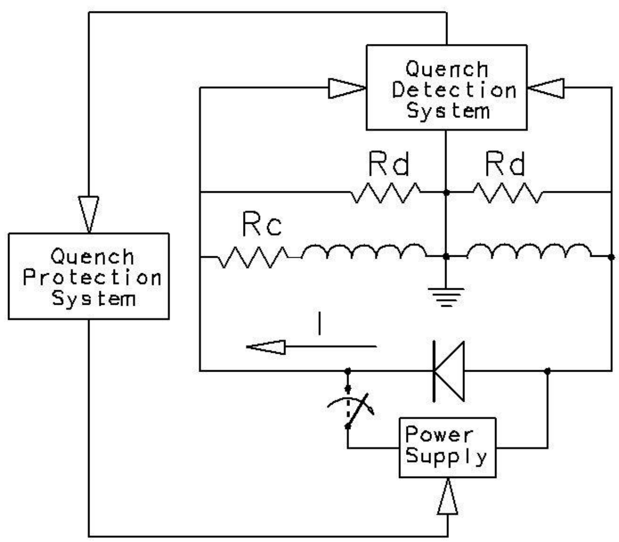

Fig. 4. Discharge Circuit for Two-Coil Lens Design.

Similar to what was done earlier, the initial quench location was chosen in the area of maximum magnetic field, which is in the middle of the inner layer of the total winding. For the quenching half-coil, this location corresponds to the innermost turn of the inner layer. The following tables describe the effects of quench propagation in both coils for different values of dump resistance.

Table 7a. Two-Coil Quench Propagation Results in Coil 1.

Dump Resistance (Ohm)	Max. Coil Resistance (Ohm)	Max. Temperature (K)	Max. Layer Voltage (V)	Max. Layer Voltage to Ground (V)	Max. Voltage between Layers (V)	Max. Voltage across Dump Resistor (V)	Energy Dissipation in Coil / Dump Resistor (kJ)
1	10.39	60.76	7.56	80.39	14.75	33.29	2.73 / 0.45
3	11.68	63.53	7.30	84.95	14.56	77.31	3.41 / 1.46
5	12.62	65.85	6.89	106.80	13.75	106.80	3.84 / 1.25
10	14.06	69.20	6.61	152.19	13.18	152.19	4.48 / 0.93

Table 7b. Two-Coil Quench Propagation Results in Coil 2.

Dump Resistance (Ohm)	Max. Coil Resistance (Ohm)	Max. Temperature (K)	Max. Layer Voltage (V)	Max. Layer Voltage to Ground (V)	Max. Voltage between Layers (V)	Max. Voltage across Dump Resistor (V)	Energy Dissipation in Coil / Dump Resistor (kJ)
1	10.28	71.46	3.85	38.20	7.55	33.29	2.63 / 0.45
3	0	5.5	2.07	77.31	4.14	77.31	0 / 1.46
5	0	5.5	2.86	106.80	5.71	106.80	0 / 1.25
10	0	5.5	4.07	152.19	8.13	152.19	0 / 0.93

Because the dump resistors are connected in parallel to each half of the lens rather than in series (as in the one-coil configuration), the resistance and temperature of the quenching coil increase as the dumps become more resistant. With a resistance of 1 Ohm, a secondary quench is observed in the second half of the coil. This quench occurs due to the increase of the current in this half above the critical level due to the inductive connection between the two coils and the decaying current in the quenching coil (dI/dt effect). The resistance of the second half then begins to increase, resulting in higher power loss in the coils. For this reason, energy extraction efficiency in the dumps is relatively low as compared to the cases with higher resistances, because the coils dissipate most of the energy. Nevertheless, the ratio of energy dissipation between the coils is almost 1:1, so dangerous conditions never develop in any section of the lens.

Conclusion

The results of this study show that both the one-coil and two-coil designs can lead to suitable quench protection configurations.

For the one-coil case, the dump resistance needs to be chosen below ~5 Ohms in order to avoid dangerously high voltages. Indeed, the data shows that zero resistance, corresponding to no dump resistor (i.e. no protection), allows the coil to remain under safe conditions. Therefore, for lenses similar to the one analyzed in this study, the one-coil configuration appears attractive.

For the two-coil case, any resistance value of 10 Ohms or less ensures adequate quench protection. In general, the conditions in the lens for this design are less extreme that those developed in the one-coil case. It is interesting to note that with low dump resistances, secondary quenching can occur, which has an impact on energy dissipation and the effects of quench propagation in the system. The two-coil configuration (or a different segmented design) may be the only option for lenses with greater focusing strength or higher number of turns, which will encounter more adverse conditions in the event of a quench.

References

1. M. Tartaglia et al., “Solenoid-Based Focusing Lenses for the R&D Proton Linac at FNAL,” PAC-09.
2. E. Khabiboulline, I. Terechkine, “Quench Protection of SSR-2 Focusing Lens,” FNAL, TD-11-018, Sept. 2011.
3. I. Terechkine, “Proton Driver Front End. Warm Section Focusing Solenoid,” TD-05-037, Aug. 2005.
4. K.-H. Mess, P. Schmuser, S. Wolff, *Superconducting Accelerator Magnets*, World Scientific, 1996, p. 195.
5. I. Terechkine, private communication, March 12, 2012.
6. I. Terechkine, “SS2 Focusing Solenoid Quench Protection Study,” FNAL, TD-09-016, June 2009.
7. H. Meinke, F.W. Gundlach, “Taschenbuch der Hochfrequeztechnik,” 1956.