Status of the SSR1 prototype focusing lens fabrication and testing

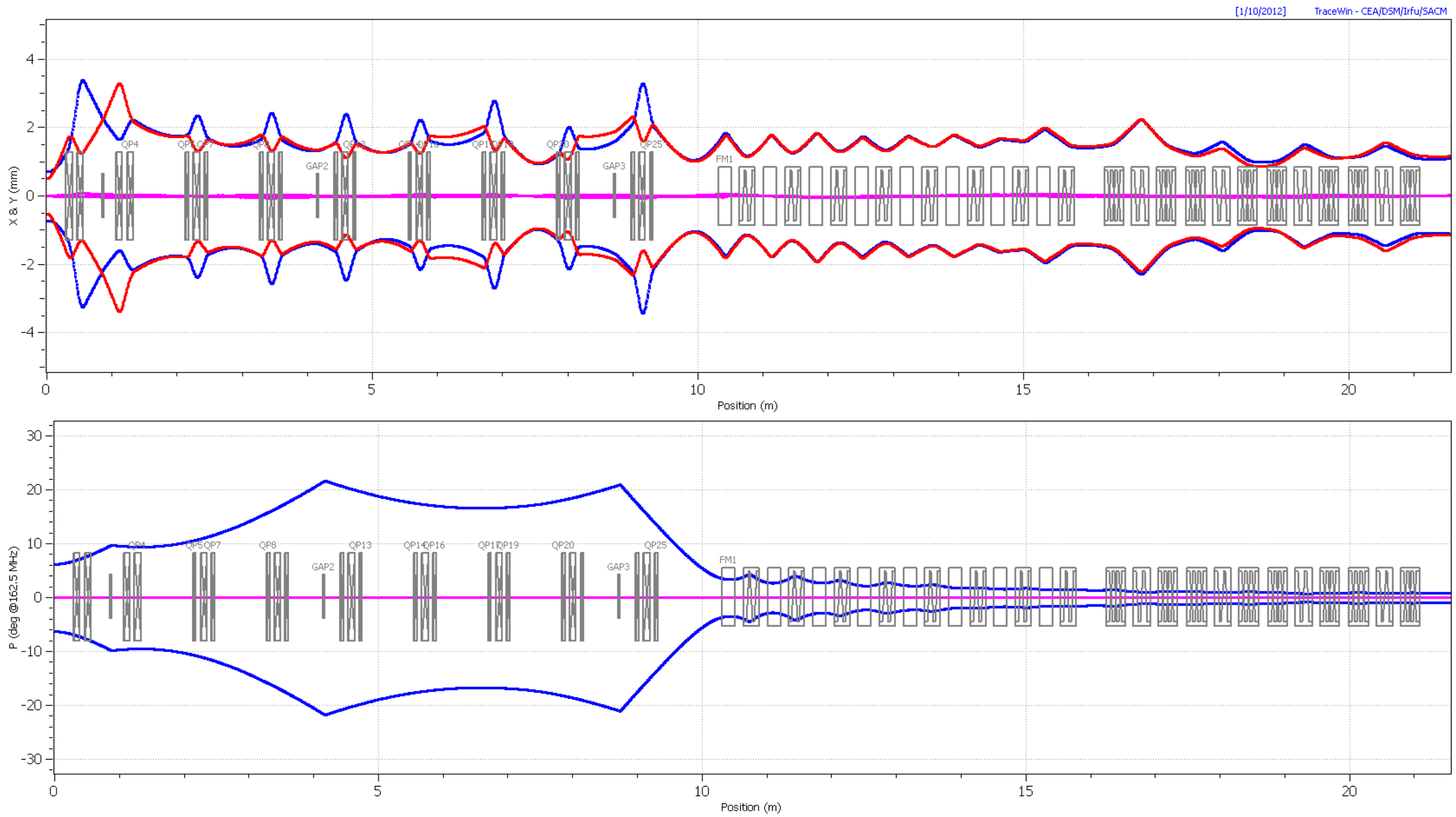
Content

- Introduction and some (challenging) requirements
- Approach to the design (no ferromagnetic materials)
- Trapped magnetic field
- Current leads
- Quench protection
- Design approach
- Fabrication and test procedure. Final assembly.
- Alignment studies
- Final performance test

Introduction

This report summarizes studies made at TD in support of design, fabrication and performance testing of a focusing lens for the PXIE SSR1 cryomodule.

In the optical scheme of PXIE accelerator front end shown below (N. Solyak, Jan. 2013), HW, SSR1, and SSR2 cryomodules of the front end use superconducting solenoid-based lenses as focusing elements.



Used Information:

- TD-12-004 (Current Leads);
- TD-12-005 (Conduction Cooling);
- TD-12-006 (Analysis of Lens Configurations);
- TD-12-007 (Quench Degradation);
- TD-12-008 (Fringe Field Requirements);
- TD-12-010 (Design Proposal);
- TD-13-011 (Quench Protection);
- TD-14-003 (Quench Protection);
- TD-14-004 (Magnetic Axis Position Measurements);
- TD-14-0XX (Lens Performance) - pending

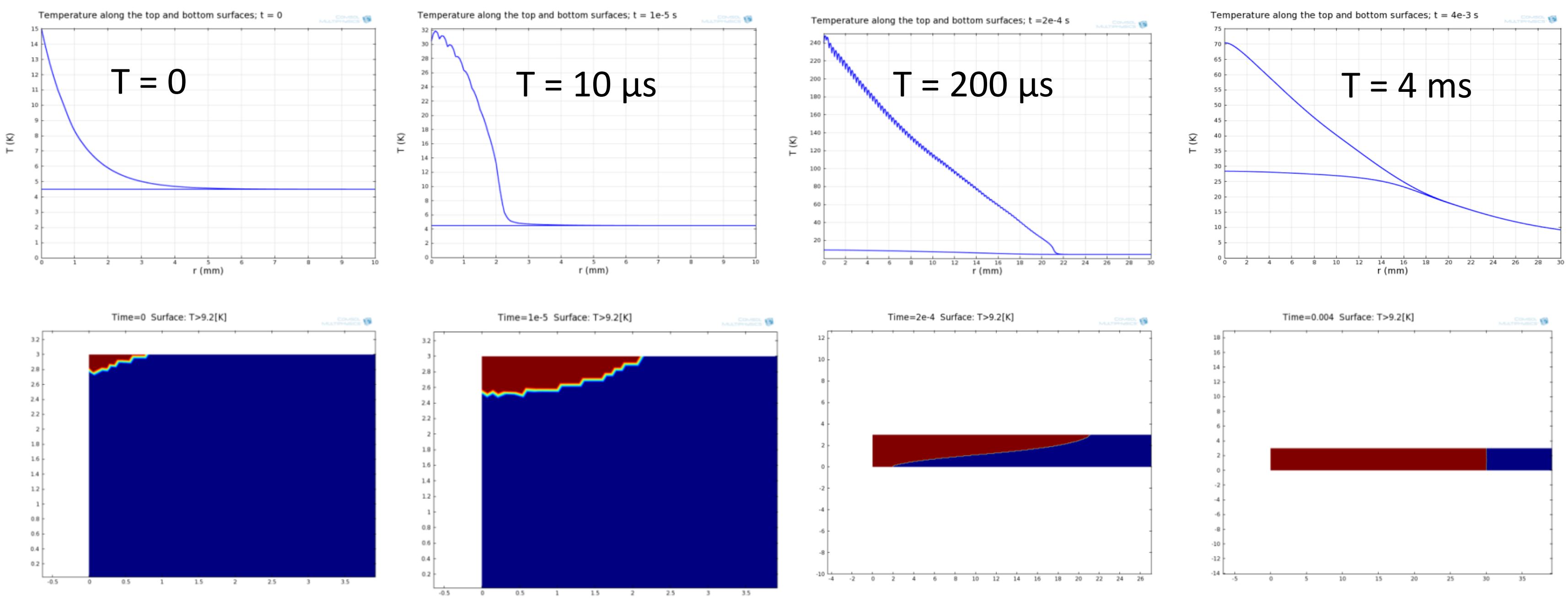
Main Requirements

Main requirements for the focusing lenses of the SSR1 section were set iteratively as beam optics study progressed. Requirements for the focusing strength, steering coil strength and alignment precision were finalized by V.L. in February 2012. Functional requirement specification was released in June 2012. Technical specification was approved in September 2012. Early in 2013, the requirement of having skew quadrupole correctors was added to the FRS. Table 1 below compares several (most challenging) requirements for the lenses built and tested for HINS with those required for the SSR1 section of PXIE.

	HINS SS1	HINS SS2	PXIE SSR1
Lens strength ($T^2 \cdot m$)	3.5	5.8	4
Steering dipole strength ($T \cdot m$)	$8 \cdot 10^{-3}$	0.01	$2.5 \cdot 10^{-3}$
Insertion length, max. (mm)	180 / 300 (Cold mass/shield)	260 / 380 (Cold mass/shield)	160 (no shield)
Magnetic field on SRF cavities, max. (μT)	10	10	$0.5 \cdot Q_0$ criterion
Transverse misalignment (mm)	±0.3 max (each end with steering)	±0.3 max (each end with steering)	0.5 RMS
Angular misalignment (mrad)	(±2.5 max)	(±2.0 max)	1 RMS

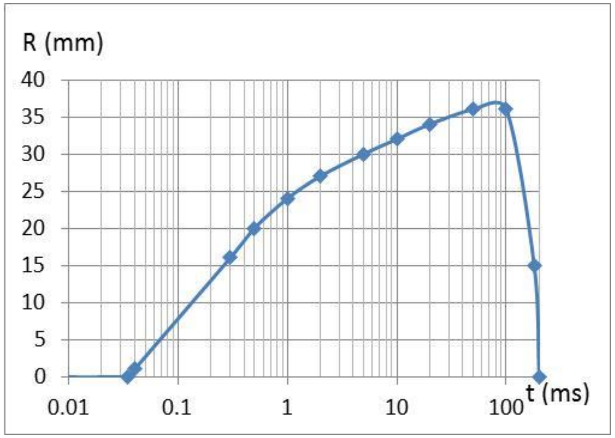
Fringe Magnetic Field Requirement

Purely active shielding of an ironless lens is less effective than the shielding made by combining it with the passive shielding, e.g. as it was done for the HINS project. On the other hand, possible impact of the higher magnetic field can only be observed when a superconducting RF cavity quenches. It has been shown that it is possible to evaluate a degree of degradation of a cavity performance during quenching, and an integrated criterion for acceptable level of fringe magnetic field was suggested. This criterion was verified by making direct measurements using cavities with different geometries and frequencies.

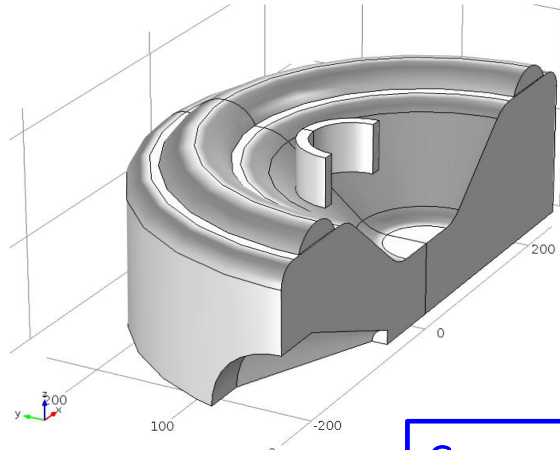


Fringe Magnetic Field Requirement

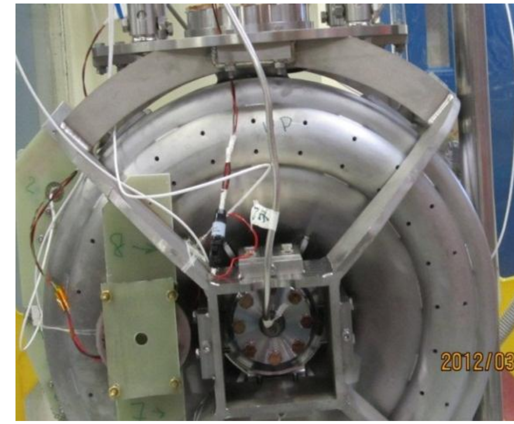
Development of normally conducting opening in the wall of a superconducting cavity during quenching



Calculation of the magnetic flux trapped in walls of the SSR1 cavity



Configuring the test



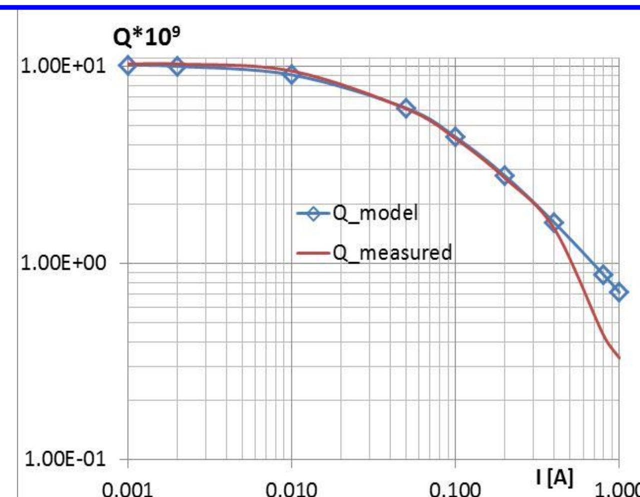
Trapped Flux Criterion

$$\eta = Q_{aq}/Q_0$$

$$\Phi_{tr} = [(2\mu_0\Phi_0)/(R_s\cdot \xi_0^2)]\cdot[(f\cdot V)/(\Lambda_H\cdot Q_0)]\cdot[(1-\eta)/\eta].$$

Φ_0 is the flux quant: $\Phi_0 = h/2e = 2\cdot 10^{-15}$ Wb,
$R_s(f, T)$ is the surface resistance of normal conducting Nb, ξ_0 is the coherent length in Nb: $\xi_0 = 3.9\cdot 10^{-8}$ m,
V is the volume of the cavity,
Λ_H is the energy density factor: $\Lambda_H = \mu_0\cdot H_t^2\cdot V / (2\cdot W_0)$,
Q_0 is the initial value of the cavity quality factor.

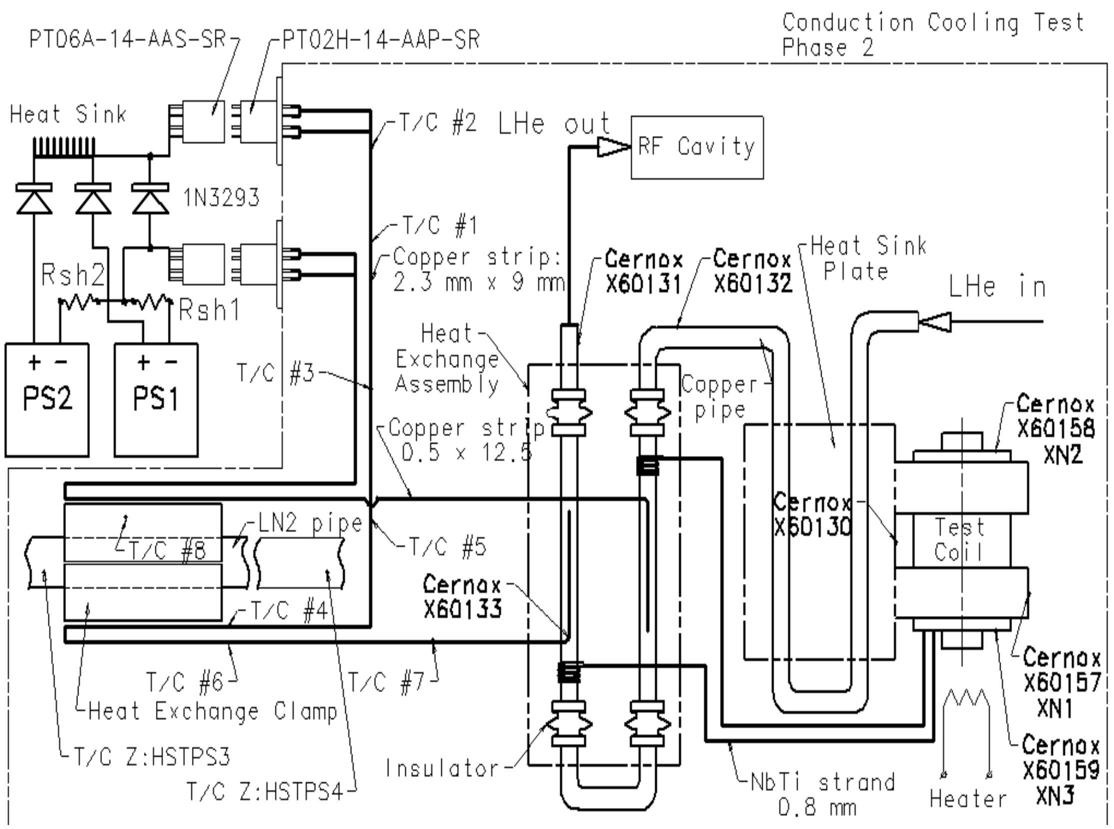
Comparing the measured performance with predictions of the modeling

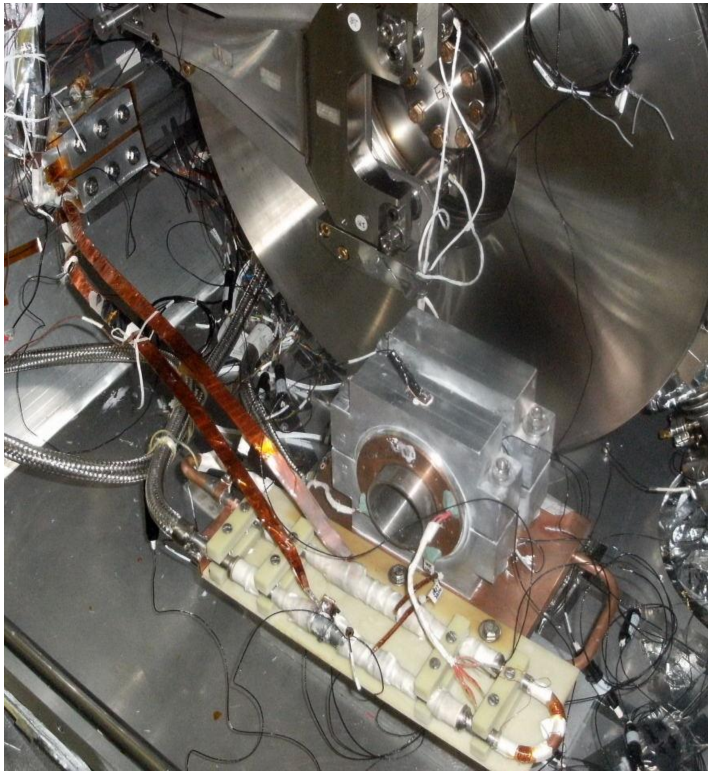


Current Leads

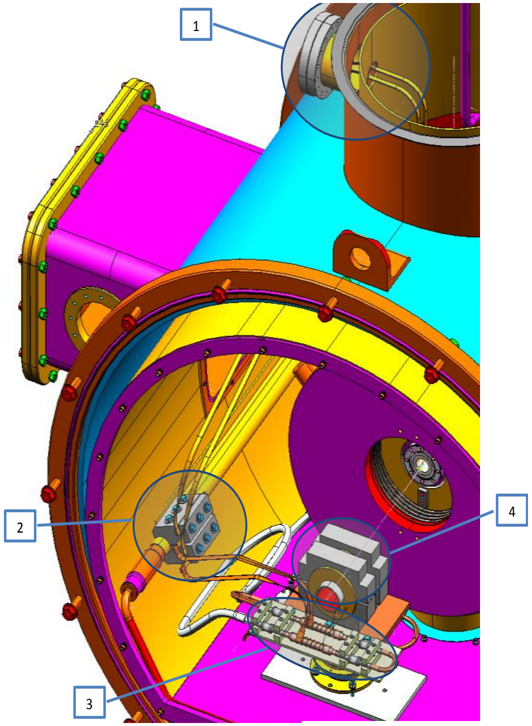
Cavities and Lenses in the SSR1 cryomodule use 2K LHe for cooling. The use of a HINS-style vapor-cooled current leads is not an option any more. Conductively-cooled current leads must be used.

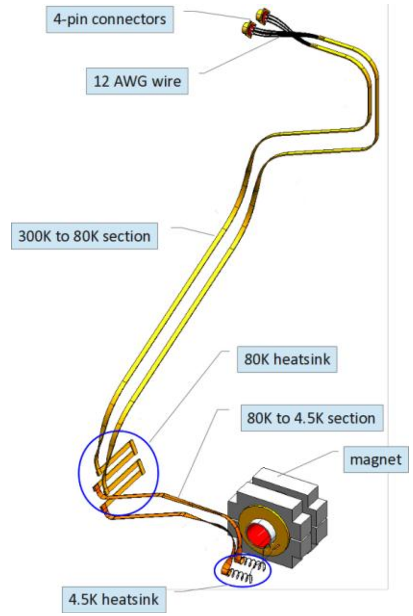
To limit heat flux into the cryomodule along the leads, a technique of anchoring the leads at different temperature levels was developed and tested. A design of simple conductively cooled current leads with heat traps at the 80 k and 4 K levels was suggested and tested.

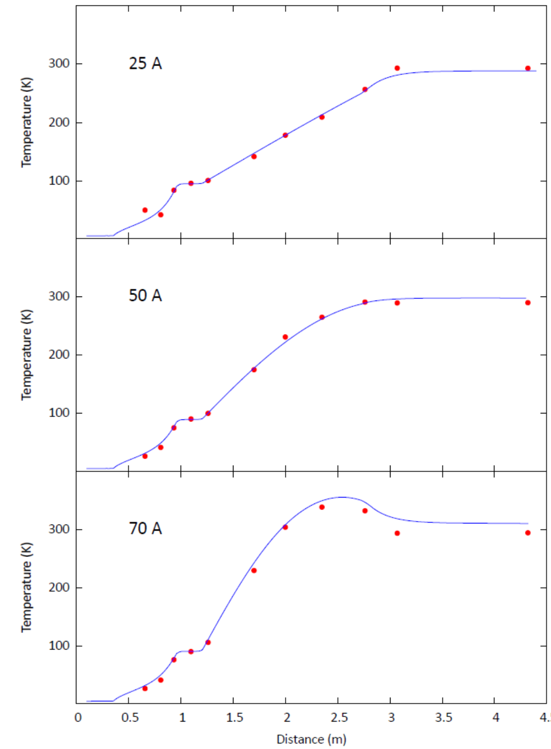


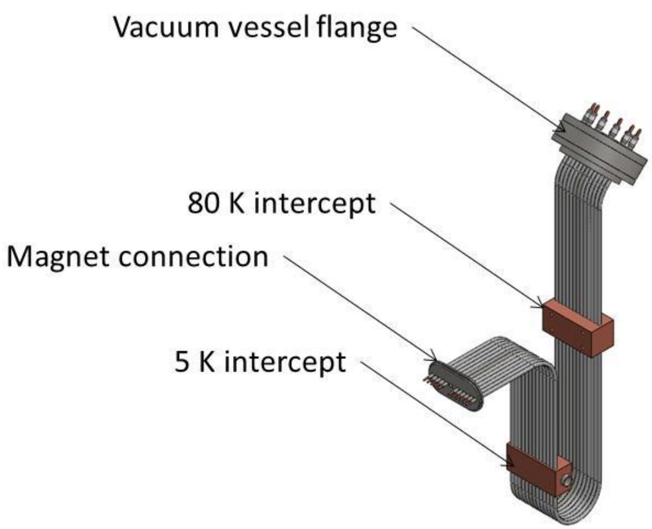


Current Leads







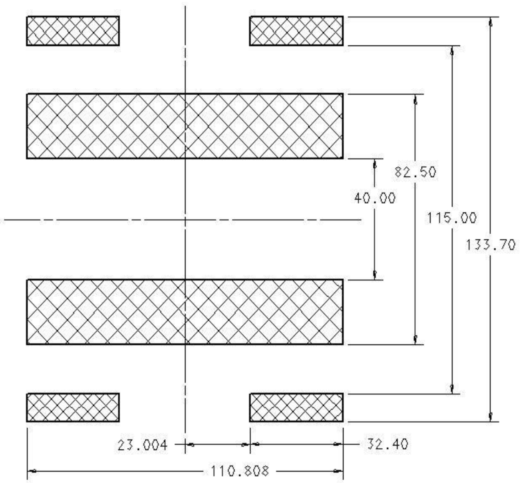


2 – 100 A solenoid leads
8 – 50 A corrector leads
1 – 50 A protection lead

All leads are in parallel in ¼" OD stainless steel tubes with epoxy impregnated fiberglass sleeve insulation

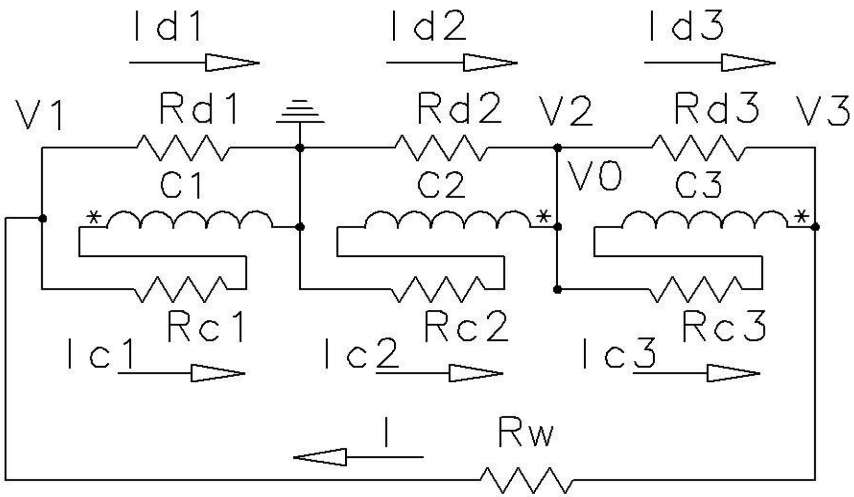
Quench Protection

Conceptual Magnetic Design

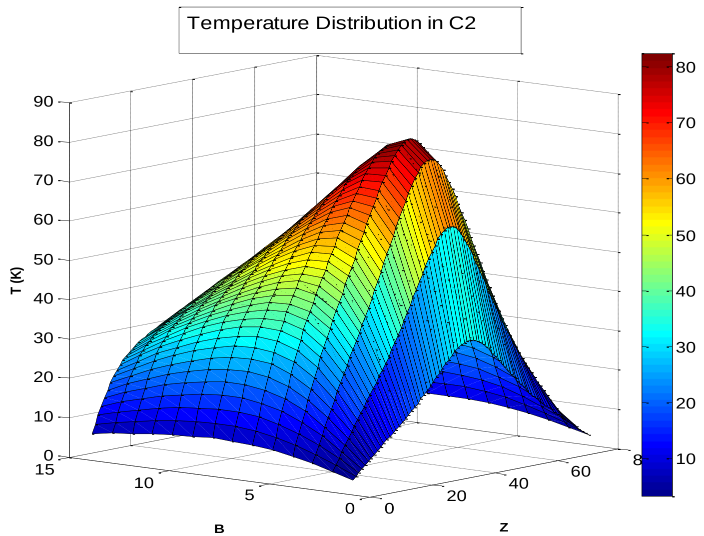


I0 = 100 A
Rd1 = 10 Ω
Rd2 = Rd3 = 1 Ω
Rw = 3 Ω

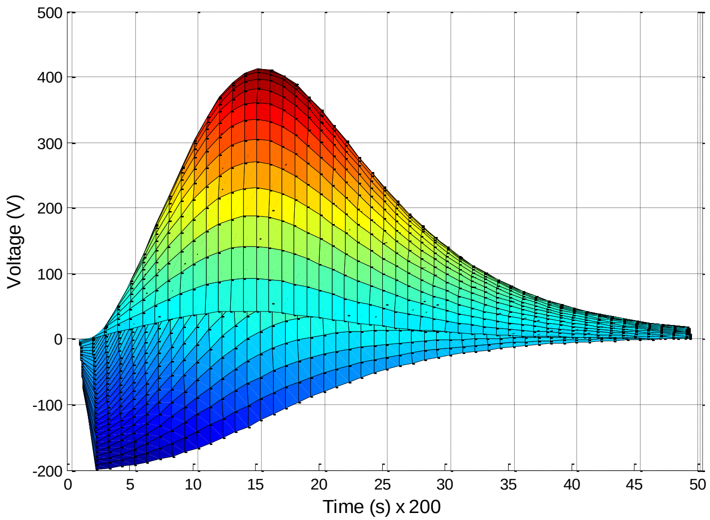
Quench Protection Circuit



Temperature in the quenching Bucking Coil



Voltage to the ground in the Main Coil

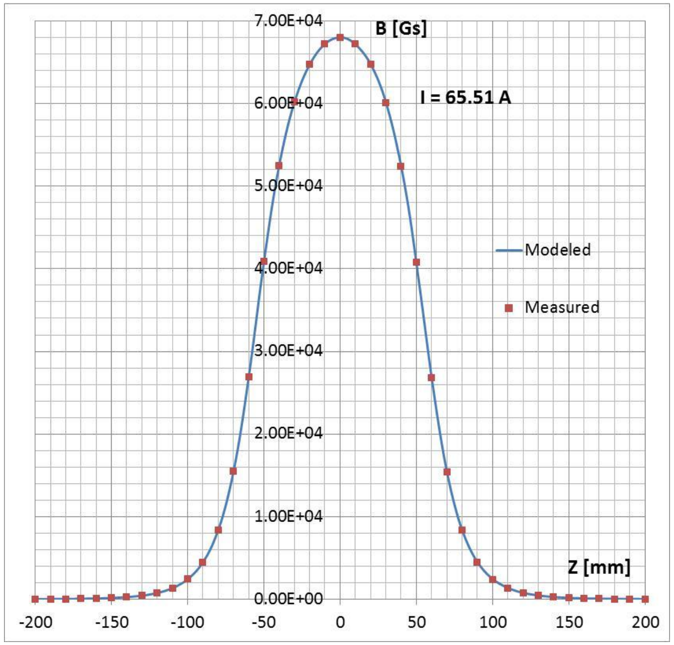


Cold Mass Performance

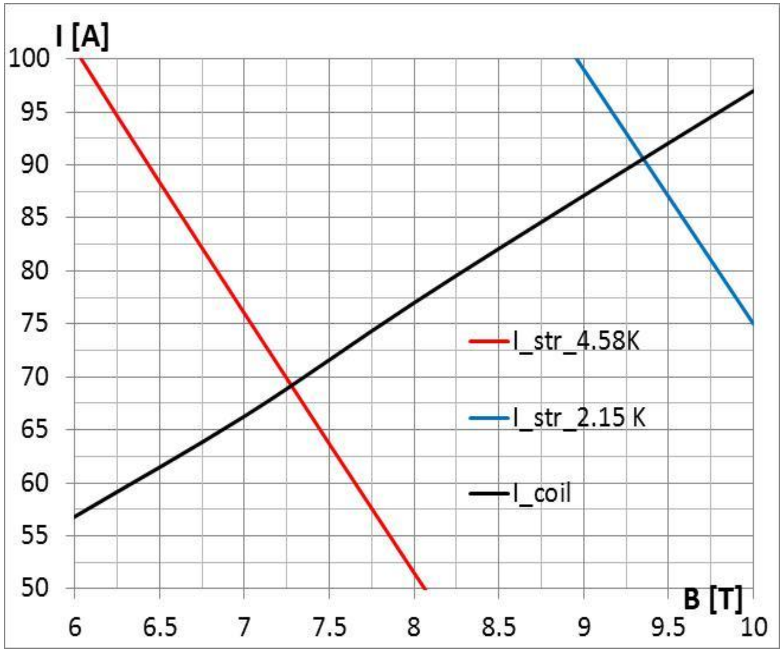
The prototype SSR1 focusing lens cold mass was tested at a production site at Cryomagnetis at 4.2 K. Focusing lens was charged to 66 A without any quenches.

The coils of correctors were tested with the present of the current (66 A) in the focusing solenoid. One training quench was observed while the current was brought to the maximum required 50 A level.

Magnetic Field on the axis: measured at Cryomagnetic vs predicted by modeling at FNAL

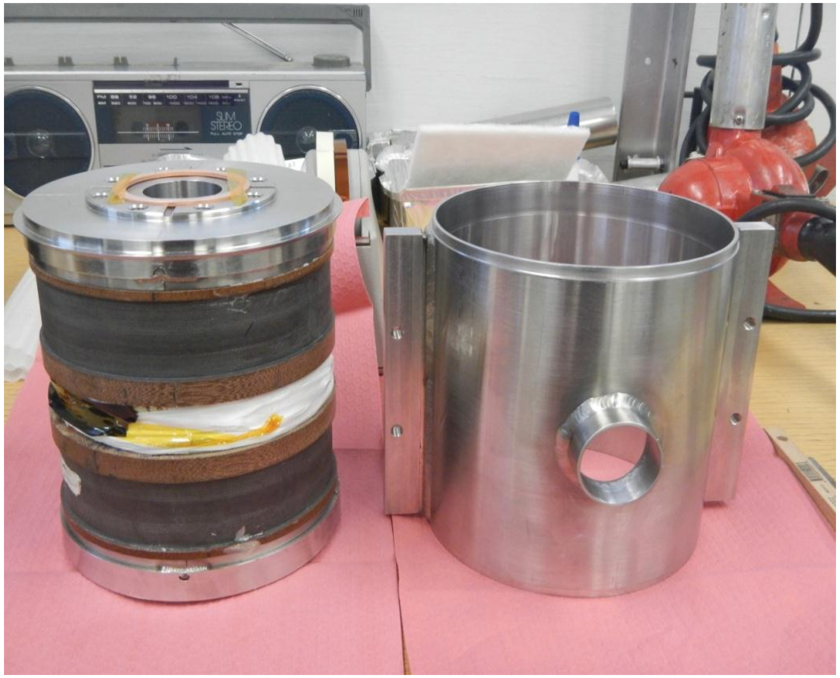


Predicted performance of the main coil at 4.58 K and 2.15 K



The magnet performed as predicted.

Magnet assembly

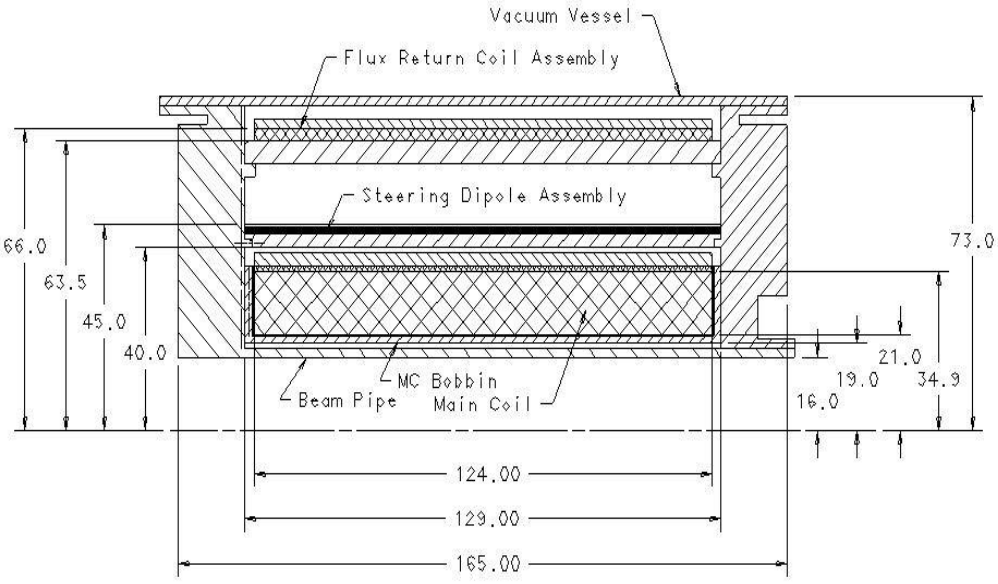


Welding LHe vessel on the cold mass results in a noticeable deformation. This deformation can become a problem if high precision installation is required.

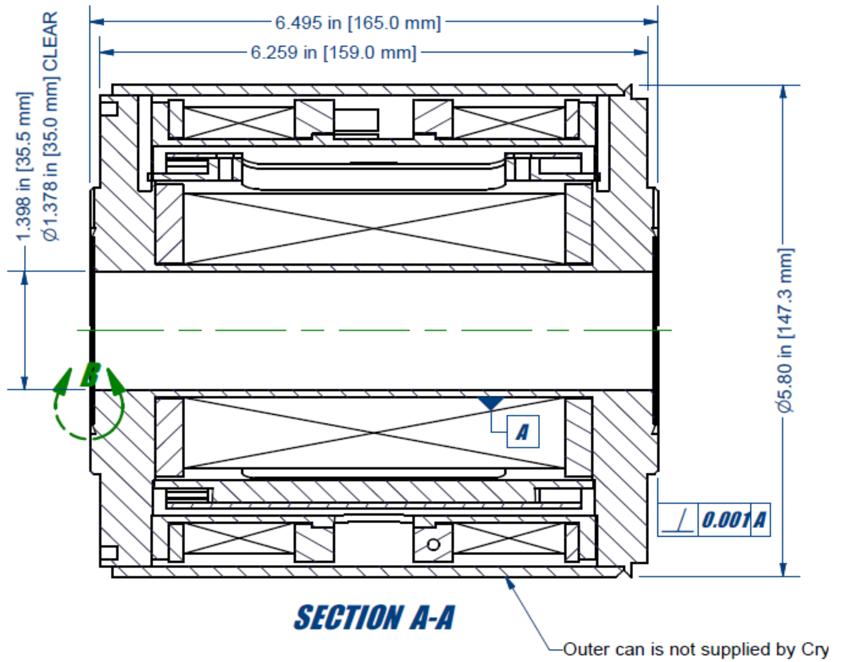
→ Study of the relative position of the magnetic and geometric axes was made

Attempts to Minimize Deformation

FNAL Proposal



Implementation by Cryomagnetics



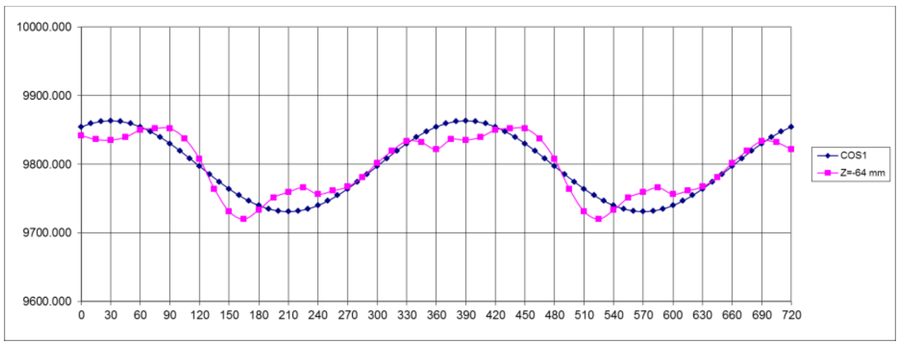
Magnetic Axis Position Measurement

At Cryomagnetis:

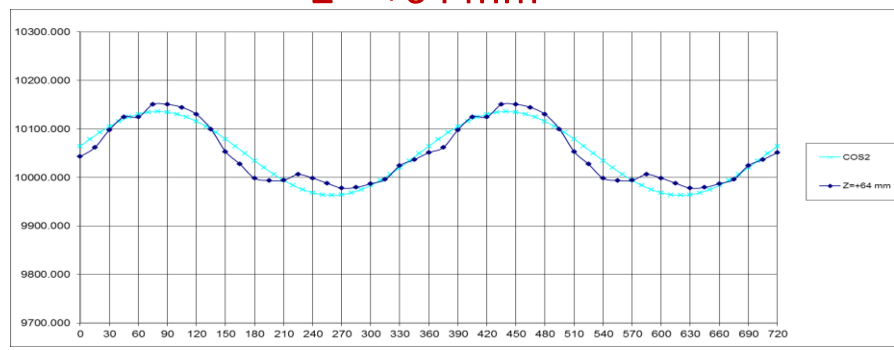
The measurements were made at two ends of the lens. Location of a point where the magnetic axis crosses the perpendicular plane Z = const was measured at 4.2 K by using a Hall probe rotated around the mechanical axis of the lens.

Position of the magnetic axis was found by fitting the results of the measurement to a sinusoidal function.

Z = -64 mm



Z = +64 mm



Summary:

	ΔX [mm]	ΔY [mm]
Z = -64 mm	-0.093	-0.054
Z = +64 mm	-0.024	-0.135

The data corresponds to the next angles of the magnetic axis relative to the geometric axis:

dX/dZ = 0.55 mrad; dY/dZ = 0.6 mrad

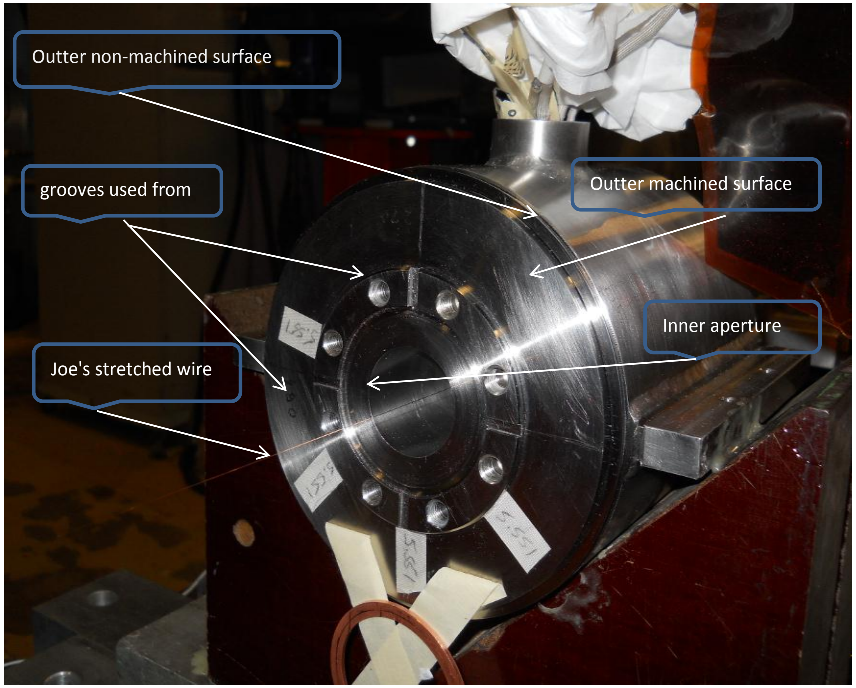
Magnetic Axis Position Measurement

At Fermilab:

The measurements were made at room temperature using vibrating wire technique. The goals of these measurements were as following:

- Compare results obtained by Cryomagnetics at 4 K with results at FNAL at RT;
- Compare position of the magnetic axis before and after the LHe vessel is added to the assembly by welding.

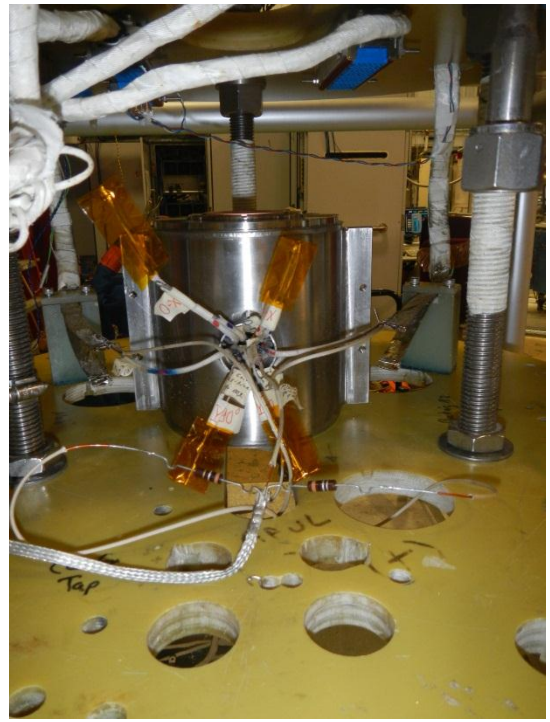
	Z [mm]	ΔX [mm]	ΔY [mm]	dX/dZ [mrad]	dY/dZ [mrad]
Before	-82.4	0.0	+ 0.15	-0.3	-0.6
	+82.4	-0.05	+0.05		
	0	-0.025	+0.1		
After	-78.1	-0.127	+0.025	-0.3	-0.15
	78.3	-0.178	+0		
	0	-0.150	+0.012		



The data show ~100 μm shift of the axis position in the center of the lens in the X and Y directions after welding.
With assumed precision of the measurements of ~50 μm RMS, using the measurement base of ~165 mm results in the uncertainty of the angular position of ~0.6 mrad RMS.

Conclusion

Final performance test has been prepared and scheduled at the VMTS in IB-1 of TD.



Four remaining (production) lenses are in the production stage at Cryomagnetics. Materials have been procured. Winding of the 1-st lens starts in the end of May. Production output – 1 lens a month. Schedule for the final assembly (Magnet Department) and testing (Test Department) to be agreed at TD.