Test Solenoid Design Proposal

I. Terechkine

I. Introduction

This note describes mechanical design of a test solenoid. The main goal of building a test solenoid before prototyping solenoids for a room temperature sections (DTL and MEBT) in the Front End of the Proton Driver (PD) is to gain some confidence in the used modeling methods, verify relevant properties of material used to build solenoids, and converge of the assembling techniques.

This note is a part of the solenoid design package and must be used with supporting documents [1] and [2].

Because this solenoid is going to be the first one made in TD, it will serve as a base model to use during setup of a test stand, including solving issues of the device protection and measurement system development. The way we are planning to make this solenoid is to use compact winding using readily available round, 0.808 mm diameter (bare size) NbTi wire and interlayer insulation made of fiberglass cloth or tape. Fig. 3 in [1] shows pattern of this winding. Compaction factor of the coil winding in this case can be relatively high (k = 0.62 is accepted as a reasonable guess value; it will be corrected after several models are built), but this method of winding will result in some deviation from the axial symmetry. Ability to measure these deviations will indicate quality of the measurements and provide valuable information on defining requirements for axial symmetry of the lens' magnetic field.

Required maximal focusing strength (focusing integral $FI = \int B^2 dl$) for this type of a solenoid is 264 T^2cm. Having about 30% margin for the magnetic field, we come to the required strength of about 450 T^2cm.

Maximal length of the coil is defined by the available space between accelerating cavities in the cryomodule with distance between solenoids defined by the beam transport requirements. At the moment, we have a 180 mm gap for the solenoids. If to take into the account space needed for the solenoid's cryostat, only ~ 125 mm is left for the solenoid length. To have some reserve, we will use 100 mm test solenoid length.

Beam bore diameter of 25 mm was specified for the solenoids in the warm sections of the PD Front End. Taking into the mind that some space will be needed for radial thermal insulation in the solenoid cryostat, inner diameter $D_{in} \approx 50$ mm was chosen for the coil of the test solenoid. This value of diameter for the test coil was also chosen because this size INCONEL-625 pipe (with reduced contraction coefficient) was available. Whether this coil size will be used in the prototype solenoids will be defined later based on approach to the coil cryostat design.

Knowing the length, inner diameter, and the required strength of the lens, we can use results of [2] to find outer diameter of the coil so that the required strength can be reached: $D_{out} \approx 90$ mm. At maximal current of ~295 A, the field in the center of the solenoid will be 7.23 T, and maximal field in the coil will be 7.5 T. At 100 mm from the center of the solenoid, one still can expect magnetic field ~ 0.7T.

For this range of parameters, coefficient K that defines a ratio between the maximal magnetic field in the coil and the current K = 0.0254 (T/A).

As we now know all geometrical parameters of the coil, we also know needed amount of wire (~ 2.5 kg), wire length (~ 600 m), and number of turns in the coil (~ 2400). So, we have all the data to make stress analysis.

The method of analysis is described in [1]. In this note, we will apply this method to finalize the solenoid design that ensures satisfactory mechanical behavior of the coil during the stages of assembling at room temperature, cooling down, and excitation to get the required field. All calculations will be made using MATHCAD environment.

II. Coil design and material choice.

Coil must be wound on a coil bobbin made of a strong material (to save radial space and being able to sustain stress during winding) with relatively low contraction coefficient (to keep prestress during cooling down). Main candidates for the material are listed in the table 1 below:

Table 1. Bobbin material candidates

Property / Material	Young's modulus (GPa)	Yield strength (Mpa)	CTE (1/K)	Relative coeff. of magnetizat.
MP35N	233	400 – 2000	12.8	non-magnetic
Kawasaki Steel	195	680	10.5	1.001
Inconel 625	~ 200	460	12.8	1.001
Inconel 718	~ 200	1100	13.0	1.0006
Nitronic 50	193		16.2	non-magnetic
SS-316	200	210	16.5	1.008

Because one of main requirements for the bobbin is to keep coil prestress during cooling down, material with lower contraction coefficient is preferable. Inconel 625 pipe was chosen as the **initial choice** material because of its availability from Burns Stainless LLC. It has very low permeability, low contraction coefficient, and good mechanical properties. The pipe has the outer diameter of 2" (50.8 mm), inner diameter of 1.9" (48.4 mm); the wall thickness is 49 mils (1.2 mm) (gauge 18).

Integrated thermal expansion coefficient *k* of Inconel 625 was measured from 363°K (90 °C) to 77.3°K (liquid nitrogen at normal pressure) and adjusted to the range 300°K–4°K. We will use $k = 0.0028$ in this note (for 304 stainless steel $k = 0.003$).

Kawasaki steel has additional advantage of even better thermal contraction properties. For Kawasaki steel CTE = 10.5 comparing with 12.8 for Inconel 625 or Mp35N.

After several initial attempts, it was found that it is possible to build sound mechanical system of the solenoid if stainless steel 304 or 316 is used as a material for the solenoid bobbin. So here we will use stainless steel bobbin.

Wet winding or vacuum impregnation can be used as the coil fabrication method, and we will rely on CTD-101 epoxy (with possible filling with Al_2O_3), that shows good mechanical behavior at cryogenic temperatures.

There are two aspects of the coil winding to pay attention to. The first one is prestress applied during winding due to wire tension. To find stress in the coil and corresponding deformation, one must use mechanical properties of NbTi wire (wire elongation modulus E_w = 100 GPa) and coil compaction factor as input parameters. Compaction factor depends on the wire cross-section, insulation thickness, and winding pattern. For the test coil we will use winding pattern #2 (Fig. 3 in [1]). With insulation thickness of 0.125 mm, effective insulation gap (d in Fig. 4 in [1]) is 0.055 mm and compaction factor k = 0.62. After curing the epoxy, as shown in [1], new composite structure will have mechanical properties depending on the compaction factor and thermal contraction coefficient depending on wire tension force. In this case, following [1], we will accept elongation module as average between properties on the transverse (E_t = 47 GPa) and azimuthal (E_{azim} = 67 GPa) direction, that gives us E_{coil} ~ 57 GPa.

Cured coil contraction coefficient will depend on wire tension. As was shown in [1], effective integrated shrinkage coefficient of impregnated and cured coil will change from $2.5\cdot10^{-3}$ to $3.5\cdot10^{-3}$ if wire tension changes from 0 to 50 N. We will accept here 20 N of tension force to start with and $3.0\cdot10^{-3}$ integrated shrinkage in the range 300K – 4K. With the 10 N force, the shrinkage is $2.8\cdot10^{-3}$.

The coil will have ~110 turns in one layer and ~ 25 layers that results in ~ 2600 turns. During stress evaluation, the coil will be modeled as four concentric layers with ~ 5 mm thickness each. As it was found during a preliminary stage, this number of layers gives quite sufficient accuracy with relatively low number of equation to solve.

G-10 bandage is formed by wet winding of fiberglass tape above the coil. The purpose of this winding is to provide some interface between the coil and the aluminum collar. We will assume that no fiberglass tension is used during winding, so properties of this layer will be similar to mechanical properties of G-10. Thermal and mechanical properties of G-10 depend strongly on direction. We will assume isotropic properties with E = 14 GPa and integrated thermal expansion k = 0.007. Thickness of this G-10 layer is about 5 mm. After winding and curing (simultaneously with the solenoid coil) the layer is machined so that aluminum collar will be placed above the G-10 layer with certain overlap.

Aluminum alloy A-6061 collar is used to apply pre-stress to the coil to prevent it's separation from the bobbin when powered. It has Young's modulus of ~ 70 GPa, about 250 MPa of Yield stress, and integrated thermal contraction coefficient (300 K – 4 K) of about 4.2.

For our purpose, we will use standard, schedule 80, 4" Al alloy 6061 round pipe. Outer diameter is 4.5" (114.30 mm), inner diameter is 3.826" (97.18 mm), and wall thickness is 0.337" (8.56 mm).

III. Stress modeling results

Using material properties from the previous section and preliminary coil geometry, we will try to converge on the design that shows satisfactory mechanical behavior during cooling down and powering. First, let's try to find a solution with nominal characteristics of the coil:

R_i = 25 mm
R_o = 45 mm
k = 0.62

The outer radius of the protective hood (G-10) was chosen 51 mm.
The outer radius of the Al collar was taken 56 mm.

Table 2 summarizes relevant mechanical properties of the materials used for the solenoid fabrication. Indexes (p, b, w, c, h, and y) correspond to those in the MathCad sheet used to make calculations.

As discussed in [1], properties of NbTi wire are important during winding and help find overlap due to wire stretching. During cooling down, cured coil properties must be used. For integrated contraction coefficient of the coil, wire tension is important as was shown in [1]. Data in Table 2 are for 10 N and 20 N tension.

Table 2

Material Property	Bobbin (index b)	NbTi wire (index w)	Coil (index c)	Hood (index h)	Yoke (index y)
Young' module (GPa)	200	68	72	14	70
Posson's factor	0.3	0	0.2	0.33	0.3
Integrated contraction	0.003	0.003	0.003 @ 20 N 0.028 @ 10 N	0.005	0.0042

Overlap during coil winding is defined by wire tensioning.

For the first iteration, 20 N wire tension was taken. Overlap between the last layer of the coil and the hood was 20 µm. Overlap between the hood and the Al collar was also chosen 20 µm.

As described in [1], room temperature stress distribution and corresponding "free state" dimensions of all components of the solenoid must be found first. Based on this data, contraction is applied to all the parts and then volumetric force is added to find stresses and deformations at maximal current. Stress distribution and deformations are shown below in the sequence: "300 K, 0 A" --- "4 K, 0 A" --- "4 K, 300 A".

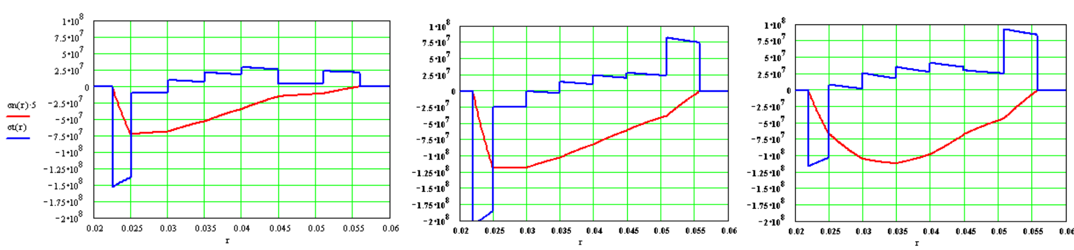

Fig. 1. Cooling – excitation cycle: F = 20 N, δch = δhy = -20 µm, Ryo = 55 mm

It is possible to see from Fig. 1 that stress developed in the bobbin during winding with tension is quite high and increases during cooling down due to thermal contraction of the Al collar (at 20 µm of overlap, thermal contraction of the coil is similar to that of the bobbin). Because stress in the Al collar does not change much during excitation, we can conclude that the overlap value between the collar and the coil does not play a major role in restricting radial movement. Results of modeling with different overlaps support this statement.

Stress in the bobbin can be reduced by reducing wire tensioning. It is necessary to remember though that changing the tension must be followed by adjustment of the integrated contraction coefficient. Stress diagrams with F = 10 N are shown in Fig. 2.

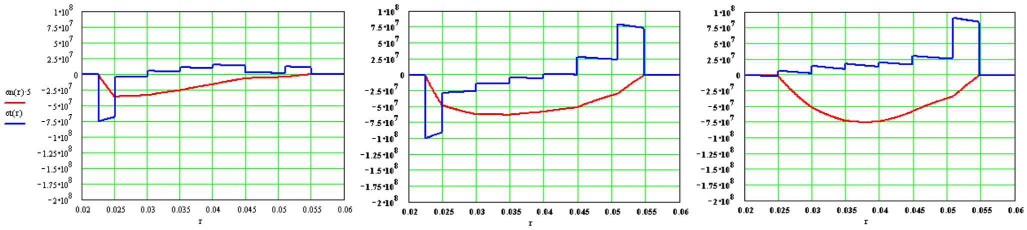

Fig. 2: F = 10 N, Ryo = 55 mm, δch = δhy = -10 µm.

After winding at room temperature, stress in the bobbin is quite modest; cooling down to 4 K results in the significant increase of tangential stress in the collar, but only slight stress increase in the bobbin occurs. After excitation, the bobbin is fully unloaded, which is an indication that coil starts to separate from the bobbin, but no significant increase in the collar stress can be found. So, at 10 N of force, we must use collar with some (10 – 20 µm) overlap to prevent coil separation from the bobbin. With increased wire tension, the collar can be eliminated from the design. The result is higher stress in the bobbin, that must be made thicker or using stronger material. Load diagrams in Fig. 3 illustrate this.

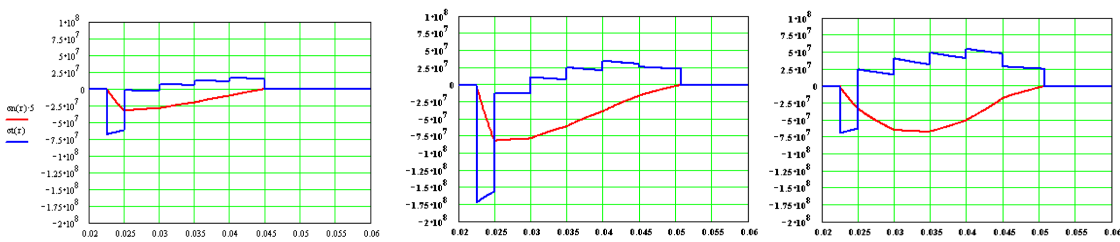

Fig. 3: F = 20 N, Ryo = 55 mm, δch = 0; no Al collar

To reduce stress in the bobbin, tension of about 15 N should be used.
Stainless steel 316 or 314 can be used for the test solenoid's bobbin. For example, cold finished, annealed and pickled tubing, e.g. 2", gauge 11 (or lower) SS 304 seamless tubing can be used.
The sketch of the solenoid in Fig. 4 shows suggested configuration of the test solenoid. Al collar is included in this design as a feature that would provide better interface with elements that support the solenoid in a cryostat.

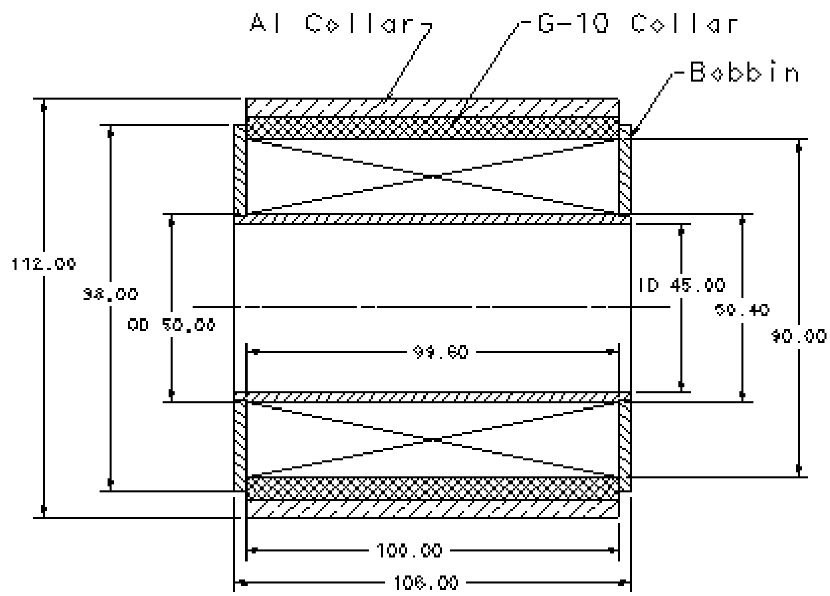

Fig. 6: Test Solenoid

IV. Summary and Remarks

Using developed earlier in [1] and [2] methods and tools for stress evaluation in multilayer solenoid structures, a design proposal of a test solenoid has been finalized. Because the developed tools use only one-dimensional approach, further modeling using ANSYS or similar program can reveal features left unnoticed during this study.

The test solenoid, although having focusing strength of solenoids for the room temperature section of the Front End, can differ from what is needed there by inner diameter, length, type of wire used, and the presence of a magnetic screen. To start designing a prototype, more information is needed about how the solenoids are positioned in accelerating modules, what is the procedure to assemble the solenoids inside the modules, what alignment technique will be used, and what heat leak is allowed for the solenoid's cryostat. These questions will be answered during the stage of the modules' design.

Other questions, like what type of current leads will be used and what quench protection technique to use must also be resolved.

References:

[1] I. Terechkine, Analysis of Stress in PD Front End Solenoids, Note # TD-05-039.
[2] I. Terechkine, Proton Driver Front End. Warm Section Focusing Solenoid, Note # TD-05-037.