A PULSED SOLENOID FOR INTENSE ION BEAM TRANSPORT*

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Abstract

A design for a pulsed solenoid magnet is presented. Some simple design formulas are given that are useful for initial design scoping. Design features to simplify fabrication and improve reliability are presented. Fabrication, assembly, and test results are presented.

DESCRIPTION

Requirements

Proposed heavy ion accelerators (drivers) for inertial confinement fusion and present experiments for the study of High Energy Density Physics (HEDP) [5], citendcx-pac05, require the transport of space charge dominated high current ion beams during acceleration and final focusing on the target. These space charge dominated beams require much higher beam focussing in both field strength and frequency (high lattice occupancy). Both quadrupole[1] and solenoidal beam transport schemes [2] are feasible, and experiments are underway to determine optimum parameters for both. For current fusion driver parameter spaces, solenoidal transport is favored for large beam sizes while quadrupole transport is favored for smaller beam sizes. Historically we have pursued quadrupole transport schemes with large numbers of small beams transported in side-by-side quadrupole arrays [8], however solenoidal transport with fewer, larger ion beams shows promise to be more cost-effective. A solenoidal transport experiment (NDCX-1b)[5] to demonstrate beam transport through four solenoids, with varying field free regions between them is now in progress. In addition, solenoidal focussing will be required for a helix pulseline acceleration experiment [3], [4]. The magnet described here is for NDCX-1b and the requirements are: a solenoidal field of 3 T of 5 cm radius over an effective length of 0.4 m, with the field time variation of less than 0.2% over a beam passage period of 4 μsec.

Optimization

For a long, thin solenoid (of field strength B, length l, radius r, current I, number of turns N, conductor cross sectional area A_c, and resistivity ρ) that is energized using a simple capacitor (C) discharge circuit (half sine only), some useful design scoping equations for inductive voltage V, and resistive energy loss Q can be derived [6].

$$V = \frac{\pi^{0.5} B r l^{0.5}}{\mu_0^{0.5} C^{0.5}} \quad (1)$$

and

$$Q = \frac{\rho \pi^{2.5} r^2 B^2 l^{1.5} C^{0.5}}{\mu_0^{1.5} A_c} \quad (2)$$

Note that the number of turns (thus the inductance) drops out and the relevant remaining free parameter for minimizing inductive voltage is C. For minimizing power dissipation, the free parameters are C and conductor cross-sectional area, A_c. Note also that current density is not a relevant design parameter. Thus the capacitance range is determined by a maximum safe working voltage, as would be best determined by risk analysis (here $\sim$4kV), and the maximum tolerable magnet temperature rise (here $\sim$50C). Of course, the minimum pulse duration is determined by the required field uniformity during beam passage but this period tends to be much shorter than tolerable, due to inductive voltage limitations. One can design for high voltage with smaller conductor cross sections, but eddy currents become troublesome, not only in the conductors, but also in the separate stainless steel beamtube, which fits through the magnet bore.

Therefore, the magnet is wound from largest Litz cable readily available, a compacted 1/0 rectangular cross section flat cable of dimension 0.4 cm x 2 cm, having 12 strands of a # 10 NEMA-35C film insulated round conductor was used. Eddy currents are negligible at the operating frequency. Table 1 shows the final physical and system parameters.

Table 1: NDCX-1b Pulsed Solenoid Parameters

Parameter		Units
Winding radius, r_w	5.08	cm
Conductor dimensions	2 x 0.4	cm
Number of conductor layers	4	
Number of turns	90	
Pulser capacitance, C	8.0	mF
Current, I	12.4	kA
Voltage, V	2.0	kV
Stored Energy, U	15.8	kJ
Resistance, DC, R	9.2	mΩ
Pulse duration (half sine), t_p	4.1	msec
Repetition rate, t_r	5	sec
Energy loss/pulse, Q_r	3.8	kJ
Temp rise (radially) acrosscoil pack, ΔT	11.5	C

In order to maximize the effective bore, the magnet is cooled only through its external diameter. A simple formula for maximum temperature [6] is (q = heat/unit vol.; k = thermal conductivity in radial direction):

$$\Delta T = \frac{q}{4k}\left(r_o^2 - r_i^2 + 2r_i^2 \ln\left(\frac{r_i}{r_o}\right)\right) \quad (3)$$

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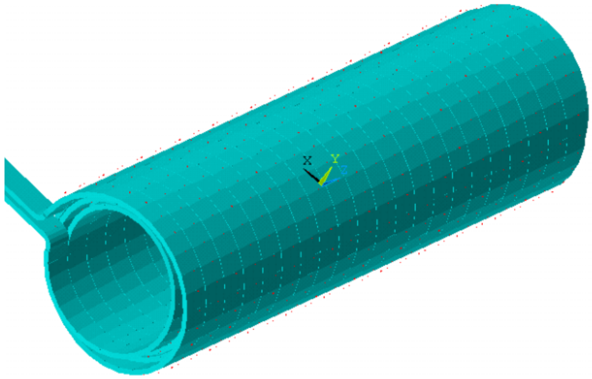

Figure 1: Pulsed Solenoid Finite Element Model

A finite element model (fully parametric) of the solenoid was formulated to capture the nonuniformities from both the leads and the helical windings, with their layer to layer crossovers. The model (current source elements only) is shown in fig.1. The formulation is linear magnetostatic scalar potential, and the code used was ANSYS-Emag. The source elements assume uniform current density over the cross-sectional area. A 3D map of the resulting field components was used directly for particle tracking analysis used

An effective thermal conductance in the radial direction for the coil pack is estimated here to be ∼1.5 W/m-deg. K. This is based on assuming a fill factor for the compacted cable. Compaction increases the available "thin section" heat flow area between conductor strands. The potting epoxy for the coil pack is an unfilled epoxy resin, in order to avoid filtering (with subsequent flow obstruction) of any particulate filler material by the Litz cable.

Fabrication

The conductor is wound onto a G-10 tube, 3mm thk. using approx . 100 lbf. tension. Crossover spacers and conductor ramps (to move the conductor radially outward for the next layer) were fabricated from PVC pipe and are cast into the coil pack. A creped NOMEX paper strip , .007" thk. (uncreped) is co-wrapped under the conductor to provide extra layer to layer insulation. For four layers total, the maximum layer to layer voltage is half the lead voltage difference. In hi-pot tests of crossed conductor short samples (no Nomex interlayer insulation) potted in unfilled epoxy, 5-15 kV was the range of breakdown voltages. The epoxy used is a 3 part elevated cure epoxy , CTD-105, typically used for SC magnet impregnation applications; it was chosen for its cure control and low viscosity, which enables complete impregnation. Fig. 2 shows the solenoid magnet ready for potting with the unfilled epoxy.

An acrylic tube is used here for a potting mold, on subsequent magnets a multisection aluminum mold is used. After the first potting stage, another layer of Nomex and a copper water cooling tube is wound over the coil pack.

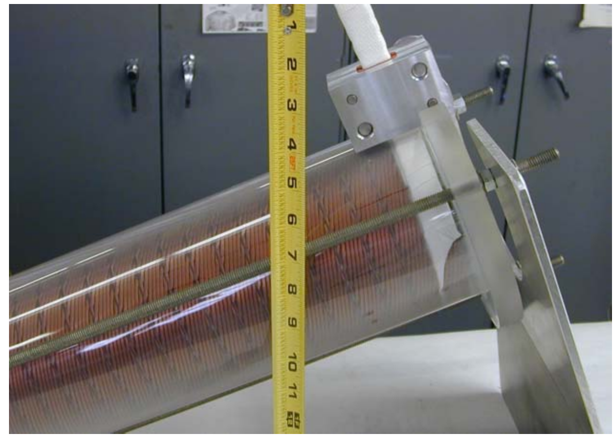

Figure 2: Pulsed solenoid ready for first potting

This assembly is then potted with heat conducting epoxy. Fig. 3 shows the magnet ready for final potting. Cooling tubes on subsequent magnets are doubled into a long narrow loopbefore winding onto the coil pack, to place both water inlet and outlets together. This cancels any net induction across the water connections. A 1/16" thk G-10 barrier plate is added between the leads for strength and improved electrical insulation.

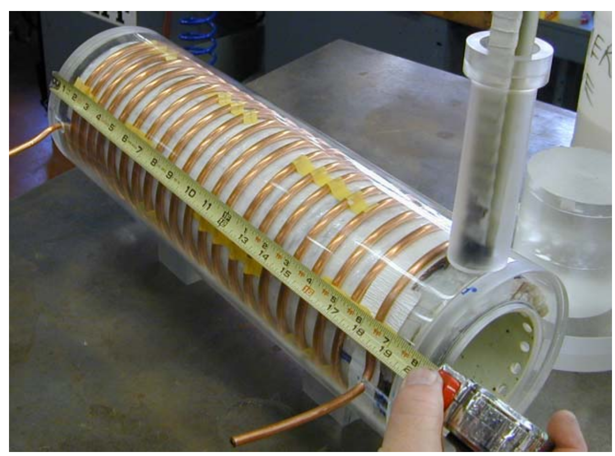

Figure 3: Pulsed solenoid ready for final potting

After final potting, the magnet is painted with a conducting paint to form a ground "plane", then painted with a non conductive topcoat (fig.4. Note the radius of the casting where the leads exit; this is to minimize electric field gradient between the leads and ground plane. Only the radius is painted with conducting paint; the remaining surfaces where the leads emanate is left unpainted with the ground layer; thus the ground layer sharp edge faces away from the leads, shielded by the radiussed section. This lead design was used on the NTX pulsed quadupoles [7]which have now operated reliably since July 2002 [9].

Figure 4: Finished solenoid

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