Energy Storage Inductor for the Low Energy Booster Resonant Power Supply System

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Abstract

The Energy Storage Inductor (ESI) is an important part of the Low Energy Booster (LEB) Resonant Power Supply System. The ESI is a 40 mH, 3400 A, two-legged, picture frame, ONAN-cooled, linear inductor. The ESI is currently under construction at the UETM plant in Ekaterinburg (Russia) as a part of an inter-laboratory collaborative agreement between BINP (Russia) and SSCL (USA). This paper gives an overview of the ESI requirements and describes the design approach and testing methods.

Introduction

The LEB is a conventional magnet booster that accelerates the proton beam from the Linac (momentum 1.2 GeV/c) to an extraction momentum of 12 GeV/c for beam injection into the Medium Energy Booster of the Superconducting Super Collider. The LEB main magnet system contains 96 dipole and 108 quadrupole (F+D) magnets supplied in series from a Power Supply (PS) system (see Figure 1). The main operating cycle of the booster requires a magnetic field variation from 0.12 T to 1.3 T (in dipole magnets) with 10 Hz frequency. The operating cycle PS system must produce a DC current of 2.2 kA, and AC current very close to sine form with the same frequency and a 10 Hz sinewave AC current with an amplitude of 1.8 kA.

The LEB PS system [1] will contain power supplies connected in series with 12 resonant cells, each having a 10 Hz resonance frequency (Figure 1). Each cell consists of several dipole and quadrupole magnets, and a capacitor shunted by the ESI to provide a path for the DC current. Dividing the resonant system into 12 resonant cells permits a notable decrease in the system voltage to ground. The ESIs are equipped with auxiliary windings connected in parallel with each other. This equalizes the resonant cell parameters and, therefore, the voltage-to-ground distribution. An off-resonance condition in any resonant cell can be detected by monitoring current in the auxiliary windings.

ESI in the Resonant Cell

The principal parameters of the PS system determine the essential ESI characteristics. ESI current is determined from the expression:

$$I(t)=2200+1200\sin(2\pi*10t), \text{ (Amp)} \quad (1)$$

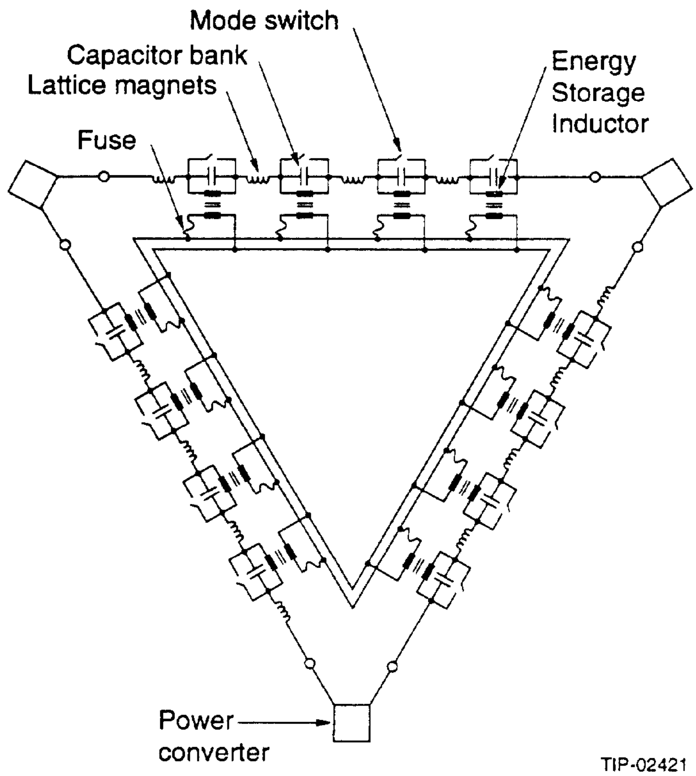

Figure 1. LEB Magnet Power Supply Network

The more significant ESI performance characteristics are presented in Table I. Very rigid mechanical vibration requirements also were specified.

ESI Design

The ESI consists of a core and coils inside an oil-filled tank (see Figure 2). Radiators on the tank provide a passive system of oil cooling. After comparing different designs [2,3], we found that only an ESI with a closed magnetic circuit containing distributed nonmagnetic gaps and with coils placed around the core of the magnetic circuit can satisfy these difficult requirements.

The ESI core is made of Type 3408 anisotropic, 0.3 mm-thickness, transformer steel according to Russian GOST 21427.1-83. The steel characteristics are presented in Figures 3A and 3B. The total length of nonmagnetic gaps is 475 mm; an average cross-section of the core is about 0.3 square meter.

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Table I. ESI Characteristics

Characteristic	Dim	Coil #1	Coil #2
Current, peak	A	100	3400
Current, average	A	-	2200
Current, rms	A	70	2400
Fault current surge, peak	A	800	4000
Voltage across terminals, RMS	V	2300	2350
Voltage to ground, RMS	V	1200	1300
Coil #2 inductances spread at 3400 A current for all ESIs	mH	-	40-41
Inductance nonlinearity (*)	-	<0.01	
Turns ratio coil #1/coil #2		1:1	
Coupling coefficient	-	>0.95	
Hottest spot coil temperature rise above ambient	Cels. deg.	<60	<60

(*) The inductance nonlinearity is:

$$N=[L_{3400A} - L_{1700A}]/L_{3400A} \qquad (2)$$

The stored energy distribution through the ESI active part is as follows:

a. In non-magnetic gaps, approx. 84%,

b. In the magnetic core, less than 1%

c. Elsewhere, approx. 15%

This distribution of the stored energy depends upon the physical design, as well as upon the characteristics of the steel used. The steel has high relative magnetic permeability (up to 70,000) in rolling direction, and high value of saturation induction [B(sat) approximately equal to 2 Tesla]. With a 3400 A current in the main coils, the average B field in the core is 1.6 T. Since the relative magnetic permeability for this field is 40,000, the core is not saturated.

The energy distribution and the required value of coupling coefficient between the coils (>0.95) also influences the coil design. The high current coil (#2) was developed as two pairs of concentric windings on each core leg. The low current coil (#l) is divided into two windings, with one placed on each core leg in the space between concentric windings of the high current coil. The windings are epoxy-impregnated. The weight of the coils is approx. 6,000 kg. The total ESI weight (with oil) is approx. 55,000 kg.

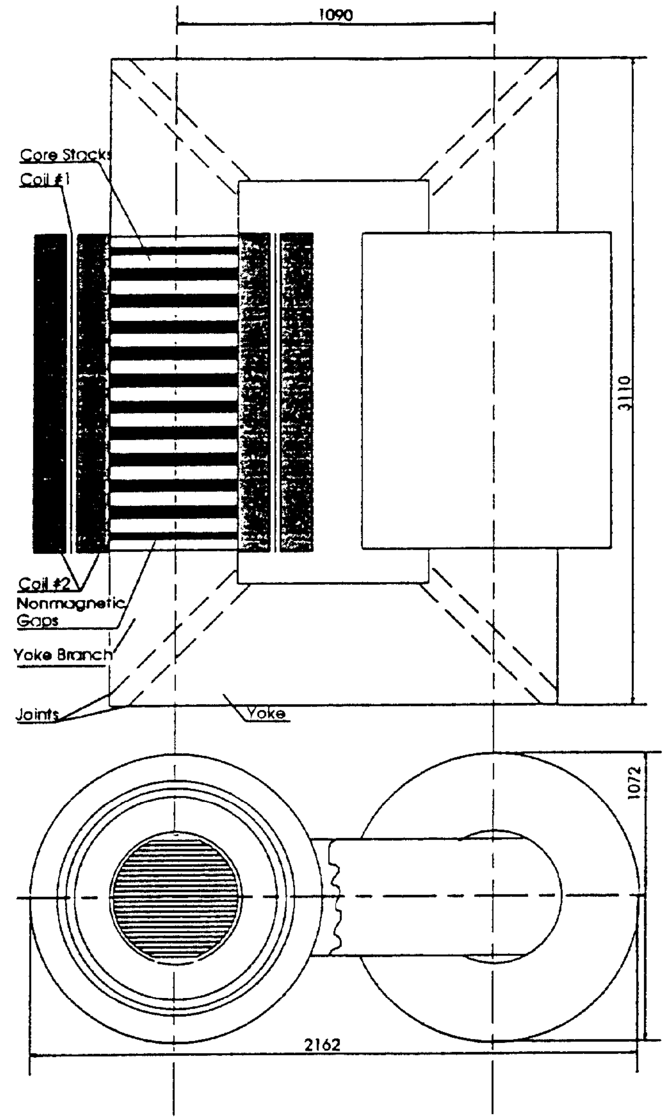

Figure 2. ESI Construction

ESI Inductance Nonlinearity

The inductance was calculated with the help of the "MAG-3D" program developed by scientists from BINP [4] for three-dimensional DC magnetic field calculations. The simulations showed the most saturated areas to be the joints between the top and bottom yoke and columns. Of the calculated -0.4% nonlinearity, -0.35% was attributed to the joints.

The static inductance and its nonlinearity are measured indirectly. It is useful here to recall the definitions of static and dynamic inductances, as:

$$L_{st} = \frac{\psi}{I} = \frac{1}{I}\,[aI+bI^3+cI^5+dI^7+eI^9] \qquad (3)$$

$$L_{dyn} = \frac{d\psi}{dI} = a+3bI^2+5cI^4+7dI^6+9eI^8 \qquad (4)$$

where: L_{st}, L_{dyn} are static and dynamic inductances

Ψ is magnetic flux

I is dc current in the ESI

a, b, c, d, and e, are polynomial coefficients.

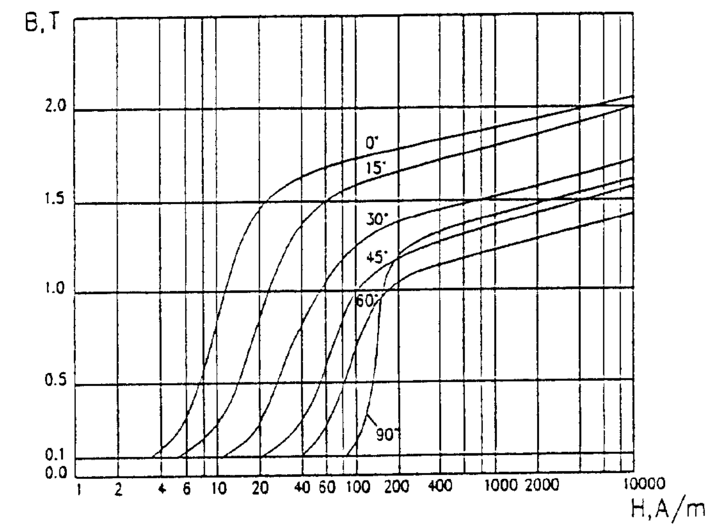

Figure 3A. B/H Curves for 3408-Type Steel in Measuring Under Different Angles in Steel Rolling Direction

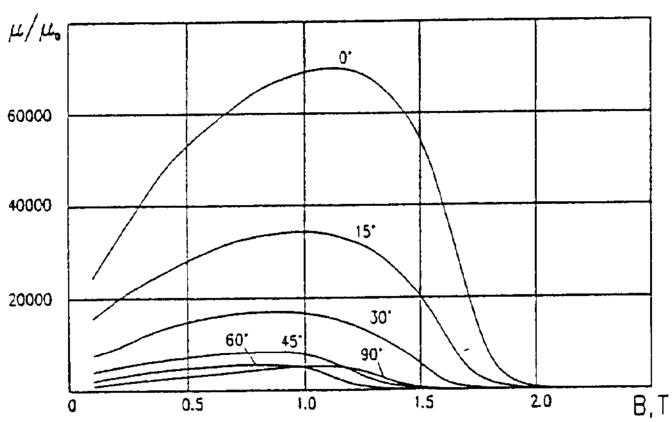

Figure 3B. Induction Dependence of Relative Magnetic Permeability for 3408-Type Steel in Measuring Under Different Angles in Steel Rolling Direction

Dynamic inductance measurements are performed at several DC current levels with superimposed small AC excitation. The computer program calculates polynomial coefficients of dynamic inductance using a curve-fitting routine and calculates values of static inductance and its nonlinearity for DC currents ranging from 1700 A to 3400 A.

Mechanical Vibration

The level of ESI vibroactivity is dependent on the active part vibration, and is produced by electromagnetic forces and magnetostriction forces associated with the presence of magnetic fields excited by the AC and DC currents of the ESI coils. Mathematical models of ESI vibroactivity were developed. The ESI active part model consisted of 28 finite elements, ESI tank with radiators of 305 elements. Oil was considered as additional mass, and the foundation as the tank base attachment. The calculations show that the maximum amplitude of the oscillations will be 70 micrometers for the active part, and 25 micrometers for the tank.

Test Results

The ESI prototype was manufactured at the UETM plant (Ekaterinburg, Russia) and was tested in February, 1993. This unit satisfied all specified requirements. Results of some of the tests are:

a. Static inductance - 40.667 mH
b. Static inductance nonlinearity - 0.0092
c. Coupling coefficient - 0.97
d. Vibration Level - 40 micrometers at the nominal current excitation

Manufacturing Plan

All ESIs will be manufactured during 1993 and delivered to the SSCL site no later than January 1994.

References

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