Operation of a digital flux injector coupled to a 50-MHz HTS insert magnet

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Abstract. By periodically injecting a quantified amount of flux in a “slightly” resistive magnet, a digital flux injector (DFI) enables the magnet to effectively operate in persistent mode. This paper presents the operation and performance results of DFI coupled to a 50-MHz HTS insert coil for an NMR magnet.

1. Introduction

It has been known for some time that high-temperature superconductors (HTS) are critical for the construction of NMR magnets generating 1 GHz and above. Such systems generally require an HTS insert to be placed in the inner high-field region of a low temperature superconducting (LTS) magnet. Among the problems in the HTS technology presently available are joint resistance and index dissipation, which make it essentially impossible for HTS to operate in persistent mode. Unless operated in driven mode with a very stable power supply, the HTS insert generally cannot achieve NMR-quality temporal stability. Another option, as proposed in an earlier paper [1], is by the use of a digital flux injector (DFI), a transformer type device that can inject metered quantities of flux into a “slightly” resistive load magnet to compensate the energy dissipation over time.

Previous work [2, 3] at the Francis Bitter Magnet Laboratory (FBML) showed a prototype DFI operate successfully with an LTS magnet and demonstrated the basic concepts of this alternative approach. Based on the prototype, a full-scale DFI (DFI 1) was built and tested with an Nb-Ti LTS coil [4]. Subsequently, DFI 1 was installed to a 50-MHz HTS insert (Insert 1) for an NMR magnet; selected major parameters of Insert 1 [5] and DFI 1 are listed in tables 1 and 2. In this paper, we will first remind the operation of DFI, report the present condition of Insert 1, and finally discuss the performance results of DFI 1 coupled to the insert.

Table 1. Selected Parameters of Insert 1: HTS, three-ply Bi2223/Ag tape; 50 double-pancakes (DP).

| Parameter                  | i.d. [mm] | o.d. [mm] | Length [mm] | \( L_{mg} \) [H] | \( I_{op} \) at 4.2K [A] | Center field at \( I_{op} \) [T] |
|----------------------------|-----------|-----------|-------------|-------------------|--------------------------|-----------------------------|
| Value                      | 78.2      | 120.3     | 327.6       | 1.12              | 49                       | 1.26                        |

Table 2. Selected Parameters of DFI 1: LTS, Nb,Sn tape; 4 DP for primary coil and secondary coil.

| Parameter                  | i.d. [mm] | o.d. [mm] | # Turns/DP | \( L_{ps} \) [μH] | \( M_{ps} \) [μH] | Toroid diameter [mm] |
|----------------------------|-----------|-----------|------------|-------------------|-----------------|----------------------|
| Pri. Coil                  | 65.7      | 104.8     | 110        | 5400              | 169             | 200                  |
| Sec. Coil                  | 62.0      | 64.1      | 6          | 17                |                 |                      |

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2. Digital Flux Injector

The design of DFI 1 was largely based on the prototype, which consists of primary and secondary LTS coils with their respective self inductances of $L_p$ and $L_s$, and a mutual inductance of $M_{ps}$. Each coil was wound with GE Nb$_3$Sn tape as four double-pancakes (DP) arranged 90 degrees apart in a toroid, with each secondary coil DP firmly nested inside a primary coil DP. Two thermal switches extended from the secondary coil, $S_2$ and $S_3$, are used to control current commutation with the load magnet, in this case, a HTS insert with a self inductance of $L_{mg}$. During operation, the insert is submerged in liquid helium while the switches at the bottom of DFI are kept slightly above the liquid helium level so as to use the vapor helium to maintain their thermal stability.

Figure 1 shows the basic circuit diagram of the DFI operation with a load magnet. At the beginning of each injection cycle, since there are no heater current, switches $S_2$ and $S_3$ are superconducting and closed. Primary coil current $I_p$ is turned on and induces secondary coil current $I_s$ such that $I_s > I_{op}$, where $I_{op}$ is the initial operating current of the insert. Then $S_3$ is heated and switched open by a heater current of 2 Amps, and as a result, $I_{op}$ and $I_s$ are forced to equilibrate, raising $I_{op}$ by the amount of $\Delta I_{op}$, which can be found by the following:

$$\Delta I_{op} = \frac{M_{ps}I_p - L_sI_{op}}{L_{mg} + L_s}$$

(1)

Afterwards, $S_3$ is closed and the insert is isolated from the secondary coil, which begins to discharge when $S_3$ is opened. Finally, $I_p$ is shut off and $S_3$ is closed, and the cycle—which normally lasts 5 seconds—is now complete.

Figure 2 illustrates 10 injection cycles during which, the voltage across the load magnet, $V_{mg}$, jumps up to a peak at each injection and the flux density at the center of the magnet, $B_z$, increases step by step. As described by equation 1 above, this flux increment, which is directly proportional to current increment, $\Delta I_{op}$, decreases as $I_{op}$ is increased. In other words, it will be more and more difficult to charge up the magnet. In addition, for an HTS load magnet, $I_{op}$ tends to decay due to the resistive nature of splicing and index dissipation. At some point, the self decay rate exceeds the maximum injection rate of the DFI, and it is impossible for DFI to maintain the operating current constant.
3. Insert 1

The self decay rate of the operating current in Insert 1 can be found by assuming exponential decay,

$$\frac{dI_{op}}{dt} = \frac{I_{op}}{\tau} = \frac{I_{op}}{L_{mg}/R_{cir}} \quad (2)$$

where $\tau = L_{mg}/R_{cir}$ is the exponential time constant, and $R_{cir}$ represents the overall effective resistance present in the closed loop formed by the insert and $S_2$ of the DFI, as shown in figure 1. Among several components of the overall resistance, the splice resistance, $R_{sp}$, and the effective resistance due to index, $R_n$, are inherent of the HTS insert, which comprises 50 double-pancakes with 49 Bi2223/Ag-to-Bi2223 Ag splices between them. Even a slight mishandling degrades a splice, resulting in a large splice resistance of over 50 nΩ [5]. Since the insert was completed in 2002, and it is believed that some level of mishandling might have occurred during assembly, disassembly and movement, splice resistance tests and $I_c$ check were redone to ensure knowledge of the insert's present condition.

3.1. Splice measurement at 77 K

In liquid nitrogen, Insert 1 was driven by an external power supply up to 15 A. Voltage across each individual splice was measured and plotted against current to obtain slope, or $R_{sp}$. Eight bad splices ($R_{sp} > 1 \mu\Omega$) were found and together they comprised 90% of the total resistance of 21.3 $\mu\Omega$.

3.2. Splice measurement at 4.2 K

In liquid helium, Insert 1 was driven by an external power supply up to 50 A, and resistance of each individual splice was found from the slope its V-I curve. The same eight bad splices were noticed but with substantially reduced magnitude of resistance (a total of 4.4 $\mu\Omega$). Compared to the total splice resistance of 1.5 $\mu\Omega$ found in 2002, it is evident that some damage had occurred.

3.3. Measurement of $I_c$ at 77 K

Operating current of Insert 1 was swept at a constant rate of 0.5 Amp per sec. up to 25 A, and voltage across each DP was monitored. As expected, the top two and bottom two DP coils were the only ones to quench at $I_c \geq 20 A$, similar to the values in previous work [5].

3.4. Measurement of $I_c$ at 4.2 K

Operating current was swept at a constant rate of 1 Amp per sec. up to 115 A, which is the limit of the power supply. Voltage measurement across each DP did not show any increase toward the critical voltage, therefore $I_c$ is believed to be beyond 115 A. According to previous investigation, $I_c$ at liquid helium temperature is at least six times larger of that at liquid nitrogen, which makes sense given the critical current at 77K found above.

The effective resistance due to the index dissipation can be found from the following expression,

$$R_n = \frac{V_c}{I_c} \left( \frac{I_{op}}{I_c} \right)^{n-1} \quad (3)$$

where $V_c$ is 4.5 mV for one DP and 225 mV for the entire insert; the index number, $n$, was estimated to be 12 at 77 K from previous work, but it could be lower due to degradation. Since neither $I_c$ nor $n$ is known with reasonable accuracy, the contribution of $R_n$ to the self-decay of the operating current in the insert cannot be assessed at the moment.

4. Performance results of DFI 1 coupled to Insert 1
Insert 1 was connected to Sᵢ of DFI 1 by soldering the Bi2223/Ag layer onto the outside copper layer of the GE Nb₃Sn tape. The resistance of the joint, another contribution to the overall Rᵢₛ, was tested on a separate test and turned out to be on the order of several nano-ohms; hence, it can be neglected. Throughout the test, the liquid helium level was maintained between the top of the insert and the bottom of the switches to ensure fast response of the switches.

With Sᵢ and Sᵢ open, the first step was to establish the initial operating current of 50 A by gradually increasing the output from the power supply. Next, with Sᵢ and Sᵢ closed and the power supply turned off, Iᵢₛ = 50 A flew in the closed loop formed by the insert and Sᵢ. Without turning on DFI, the self decay rate of the insert, dIᵢₛ/dt was measured; from equation 2, the overall resistance, Rᵢₛ, could be calculated. As the current level dropped, Rᵢₛ also dropped (equation 3), Rᵢᵣ was unaffected, therefore, the overall resistance and the self decay rate both decreased. On the other hand, the magnitude of the flux increment, ΔIᵢₛ became larger for lower level of operating current (equation 1). These two opposite trends gradually allowed the insert current to be compensated by DFI, as in figure 3(a-c). Eventually, Iᵢᵣ was low enough that Rᵢᵣ was no longer a factor, and Rᵢᵣ approached to Rᵢᵣ.

In summary, DFI 1 can operate successfully with Insert 1 from a current compensating standpoint up to a certain current level that is governed by the overall effective resistance of the insert.

![Figure 3. Measurement of operating current (Iᵢₛ) at 50A, 26A and 17A, with the DFI (Iᵢᵣ) on and off.](image)
The "self" decay rates at these three levels were 1 mA/sec, 0.26 mA/sec and 0.11 mA/sec respectively.

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