NMR BASED CURRENT/VOLTAGE SOURCE*

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Abstract

A one-ampere current has been stabilized using nuclear magnetic resonance (NMR) techniques. A pair of tandem solenoids produce two uniform magnetic fields in opposite directions and these fields are not affected by external magnetic shielding. The current and background field are controlled to 0.1 ppm in three hours.

Introduction

Locking a magnetic field to an NMR frequency is a well established technique in high-resolution NMR experiments [1]. Fluctuations in the magnetic field are detected by NMR and compensated by a servo-current. Using this method, a magnetic field has been stabilized to better than 1 in 10^9 [2]. At the Electrotechnical Laboratory, ETL, Japan, a current from an electromagnet under NMR control has been stabilized to 0.2 ppm/hour [3]. The limitation to current stability at ETL was the changes in dimensions of the electromagnet caused by heating in the windings. The magnetic hysteresis of the ferrous material prevented return to the same current each time the magnet was energized. In the present experiment these limitations of the electromagnet current source have been reduced by using low thermal expansion fused silica as the solenoid former and a coil geometry that eliminates magnetic material in the magnetic circuit.

The Experiment

A set of two solenoids are used to produce two uniform magnetic fields in opposite directions and both fields are linear with the current. A constant current and a constant "background" field are produced by employing two servo systems that keep both NMR frequencies constant. Thus at the same time you make a current source, you make a sensitive vector magnetometer.

Tandem fields. Figure 1 shows the coil configuration used to produce two uniform magnetic fields pointing in opposite directions. Two solenoids wound on a fused silica form are wired so the current in each has an opposite sense. The gradient from one solenoid greatly limits the uniformity at the center of the other. A second fused silica former has two additional solenoids (outer windings) and the dimensions and turns ratio have been chosen so that the area-turns of the larger coils is the same as the area-turns of the inner coils. Therefore each

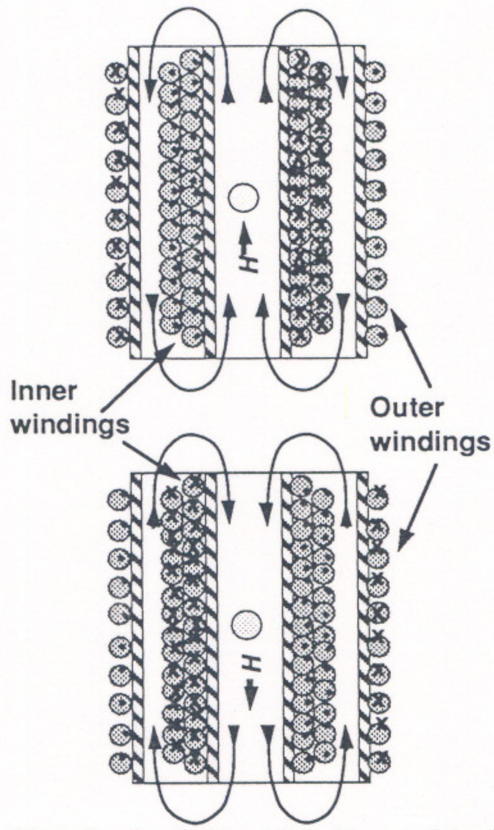

Fig. 1. Tandem fields produced by coaxial coils

set of inner and outer coils has no dipole field [4]. In fact, there is almost no field outside the pair so the gradient produced at the neighbor's center is much less, and the interaction with magnetic shields which surround the coils is small. The magnitude of the field produced is reduced by about the square of the ratio of the diameters. The two outer coils are axially offset slightly from the inner coils to cancel the small remaining gradient produced by the other coil set. Additional subcurrents are added to sections of the inside coils to compensate for higher order gradients [5]. The fields at the center of each set are uniform to 5 ppm over 3 cm diameter.

NMR measurements. The frequencies of both fields are "locked" to the same frequency, 62025 Hz, using flowing water NMR. The water is polarized in a 0.3 T field outside the magnetic shield, then pumped into a 2.5 cm diameter sphere at the center of each solenoid. Just before entering the sphere a small coil applies a cw field. The magnitude of this field is adjusted so that each proton passing through sees a $\pi/2$ pulse. A detector coil surrounding the sphere is orthogonal to both the $\pi/2$ field and the dc magnetic field. Each sample has a lock-in detector whose dispersion signal is fed-back to control either the main current or the current that controls the background field. The NMR linewidth is limited by the

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magnetic field gradient and is 1.0 Hz for the main current signal and 2.4 Hz for the background field signal. The natural line width for water is ten times narrower. This line broadening is thought to be the major limitation to the present accuracy.

Voltage measurement. The 1 A current is passed through a 1 Ω resistor which has very low drift and a small power coefficient. A nanovolt meter is used to compare the voltage with a zener reference voltage standard.

The Results

Short term noise. Figure 2 shows the short term stability of the system. A three hour trace of the NMR source versus a zener reference is plotted with a calibration made by increasing or decreasing the frequency by 0.1 Hz. The lower trace is when the NMR source is replaced by another zener. Presently the noise of the current source is similar to that of the zener. With an improved line width in the NMR signal this noise will be reduced further.

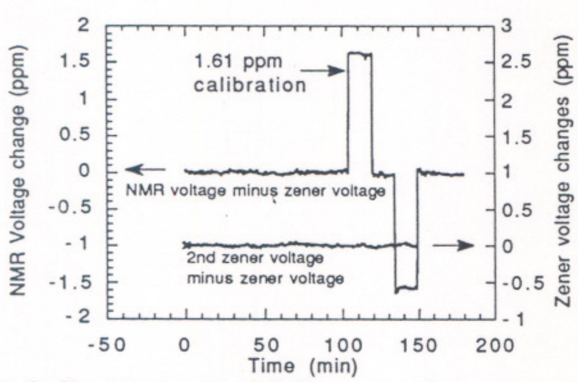

Fig.2. Short term noise. NMR vs zener & zener vs zener.

On-off noise. Figure 3 demonstrates how well the system works when turned off, then on again one minute later. The current and magnetic field were turned off four different times as indicated by the arrows. From this data it is clear there is no problem at the 0.05 ppm level with magnetic hysteresis from the shields or other problems in locking the servo system.

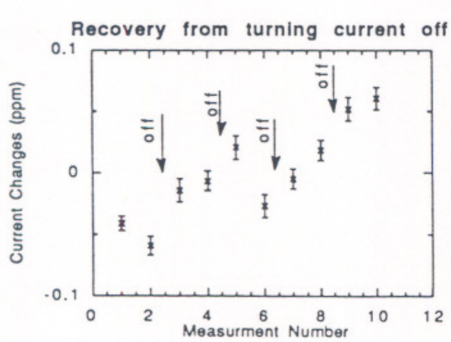

Fig. 3. Recovery from turning off current and magnetic field.

Hourly noise. Figure 4 is our best record to date of the hourly drift rate. Note that the temperature of the solenoid still is a major source of drift. The temperature coefficient is not too big, about 1 ppm / °C, but the time rate of change of the temperature is an unexplained source of noise. Better temperature control should improve the results.

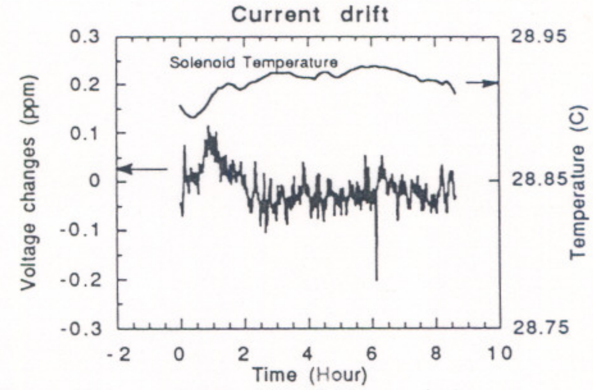

Fig. 4. Voltage changes over 9 hour period.

Summary. A current /voltage source is operated at a level better than 0.1 ppm and shows promise of outperforming zener diodes in applications requiring rugged voltage references. Such a standard will still need to be calibrated against a Joshephson array; but if some improvements are made, the time between calibration can be long. The ability to recover from being turned off shows its potential as a transport standard. Improvements in the NMR are required to realize this goal fully but techniques such as Ramsey oscillatory field techniques [6] should allow this improvement. In the meantime, this is still the best room temperature current source we have ever made.

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