Field Stabilization of the Iseult/Inumac magnet operating in Driven Mode

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***Abstract*—A neuroscience research centre with very high field MRI equipments was opened in November 2006 by the CEA life sciences division. Three MRI systems operating at 3, 7 and 17 T have been already installed. One of the imaging systems will require a 11.75 T magnet with a 900 mm warm bore. The large aperture and high field strength of this magnet provide a substantial engineering challenge compared to the largest MRI systems ever built. This magnet is being developed within an ambitious R&D program, Iseult, whose focus is high field MRI. Traditional MRI magnet design principles are not readily applicable and thus concepts taken from high energy physics or fusion experiments, namely the Tore Supra tokamak magnet system, will be used. The coil will be made of a niobium-titanium conductor cooled by a He II bath at 1.8 K, permanently connected to a cryoplant. Due to its design the magnet will be operated in a non-persistent mode. As the field stability needed for MRI imaging requires a field drift of less than 0.05 ppm/h, it is hardly feasible to directly transpose these requirements in the power supply specification. Two existing solutions developed for other applications have been selected: one using a semi-persistent mode, and the other using a short-circuited superconducting coil in the inner bore. In order to make a decision on experimental basis, an ambitious R&D field stability program has been set-up based on magnet prototypes, high field test facility (Seht, a 44 H and 8 T magnet with a warm bore to 600 mm). We will present development and experimental results of the two stabilization solutions. In conclusion, the stability solution selected for the Iseult magnet is given.**

***Index Terms*— Magnetic resonance imaging, Superconducting magnet, Power supplies, Current limiters, Driven-mode**

I. Introduction

By its design [1], the 11.75 T MRI magnet [2] will operate in driven mode, i.e. the Power Supply Unit (PSU) will be permanently connected to the magnet. Magnetic field drift will depend on the stability of PSU and could be at best of 1 ppm/h. The field stability required for imaging, however, is less than 0.05 ppm/h. Two potentially applicable stabilization solutions, selected from the literature [4], have been tested on a high field test facility called Seht. Prototypes for these stabilization solutions have been realized and experimental results will be presented.

TABLE I Seht and Iseult - electrical parameters

Parameters	Unit	Seht	Iseult
Magnetic field	T	8	11.75
Magnet resistance, *Rmag*	nΩ	100	~200
Inductance, *Lmag*	H	44	308
External dump resistor, R_D	Ω	2	2.7
Time constant, τ_{maq}	s	22	114
Nominal current, *Imag*	A	880	1483
Voltage discharge max, *Ud max*	V	1800	4000

For Seht, dedicated NMR probes at room temperature have been developed by Iramis[1] to achieve NMR measurements for field stability in inhomogeneous magnetic fields and have been performed at 0.965 T for both stabilization solutions (Fig. 1). Measurement methods have already been previously described for field stability measurement on a small 7 T magnet at low temperature [3].

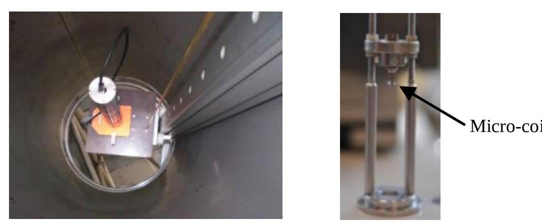

Fig. 1 NMR measurement pictures. Left, probe and shim stack mounted on the mechanical support. Right, micro-coil (Ø=1.2, 2.4 mm length) on base.

II. Stabilization solution principle

A. Coil stabilization

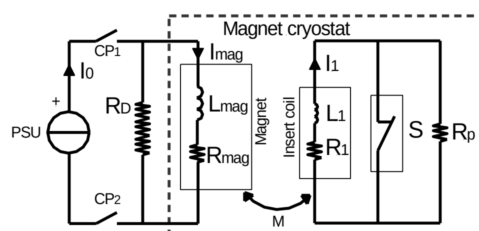

Fig. 2 Coil stabilization solution principle. Magnet resistance R_0, Insert coil resistance R_1, Insert coil protection resistance R_P.

Power supply noise can be reduced with a superconducting

Manuscript received 13 october 2009.
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coil insert positioned in the innermost radius of the main coil and short-circuited through a superconducting switch *S* (Fig. 2). A previous experimental use of this stabilization principle can be found in [5] and a theoretical background in [6]. Equation (1) gives the field variation [7] in the centre of the magnet due to a variation of the main current, δI_{mag}.

$$\delta B = B_{mag}\frac{\delta I_{mag}}{I_{mag}}\left(1-\frac{M}{L_1}\frac{B_1/I_1}{B_{mag}/I_{mag}}\right) = B_0\frac{\delta I_{mag}}{I_{mag}}\alpha \qquad (1)$$

$$\alpha = \left(1-\frac{M}{L_1}\frac{B_1/I_1}{B_{mag}/I_{mag}}\right)$$

L_{mag}, I_{mag} and B_{mag} are the inductance, the nominal current and the field produced by the magnet at its centre, respectively. L_1, I_1 and B_1 are the inductance, the nominal current and the field produced by the insert at its centre, respectively. The mutual inductance, M, between magnet and coil stabilization inductance are chosen such like δI_{mag} induces a magnetic field equal to the main magnet field drift. The insert is designed such that for any magnet current variation, δI_{mag} the field variation produced by the magnet is cancelled by the field induced inside the insert. It means screening coefficient α is equal to zero.

For this solution, the achievable stability is driven by the α parameter. Although it can be designed to be null, its real value is limited by manufacturing tolerances. It means this solution is not limited by magnet parameter, but by the insert coil manufacturing process.

B. Filtering by a resistor

For MRI magnets that cannot operate in persistent mode due to a high resistance *Rmag*, a technique of stabilization has been previously developed [8] and improved [10]. Its principle is shown in Fig. 3.

The PSU is always connected to the magnet when circuit breakers CP_1 and CP_2 are closed. A dump resistor, R_D, is permanently connected to the magnet which is short-circuited by mean of a switch *S1* in series with a resistor R_f mounted in the cryogenic area.

Power supply noise and drift are reduced by using the large inductance value as a low pass filter. Such that, PSU current variation goes directly through R_f.

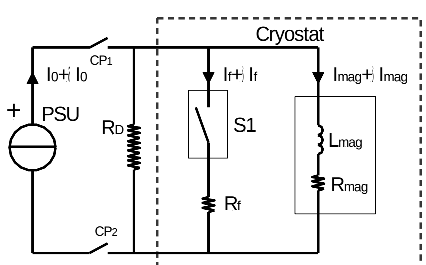

Fig. 3 Filtering stabilization solution principle

Assuming the magnet is energized at its nominal current I_{mag} and *S1* is closed, the current I_f is determined by using (2). Let us call I_0 the current supplied by the PSU ($I_0 = I_{mag}+I_f$).

$$I_f = I_{mag}.\left(R_{mag}/R_f\right) \qquad (2)$$

Current variation balance will depend on the low pass filter elements and ideally: $\delta I_{mag} = 0$ with $\delta I_{mag} = \delta I_0 - \delta I_f$.

The answer to a 1 ppm current step δI_0, allows us to see current balance and fix the problem for solving elements values of low pass filter (case studied $I_{mag} >> I_f$). The system time constant τ for current balance is given by (3).

$$\tau = L_{mag}/\left(R_{mag}+R_f\right) \qquad (3)$$

In transient mode, assuming $R_{mag} << R_f$, the slope for δI_{mag} at the origin is giving by (4) and the slope is the fastest variation in the system. This equation shows that the achievable stability of this solution is driven by the magnet inductance and resistance, not by the switch or filtering resistor.

$$\left.\frac{\delta I_{mag}}{I_0.\delta t}\right|_{t=0} \approx \frac{\delta I_0.R_f}{I_0.L_{mag}} \qquad (4)$$

In permanent mode, I_f value is given by (2).

A numerical calculation with Iseult magnet parameters has been done. Fig. 4 shows the efficiency of this stabilization solution. A field drift of one ppb/h is predicted to be possible with a highly stabilized PSU specified for one ppm/h.

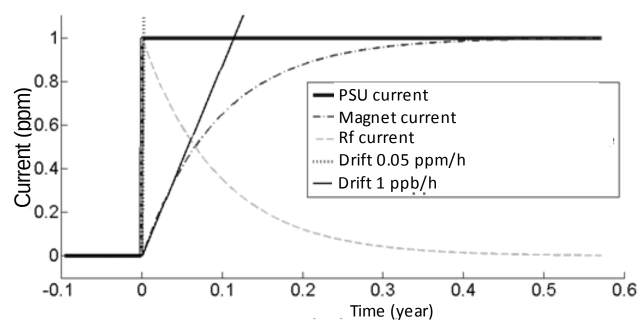

Fig. 4 Results of filtering stabilization. Answer for one ppm current step variation of PSU . Numerical application for Iseult magnet (L_{mag} =300 H, I_{mag}=1500 A, R_f=100 μΩ, R_f/R_{mag}=500, L_{mag}/R_f=800 h).

III. Experimentation

In order to make a decision on stabilization approach, an ambitious R&D field stability program has been set-up based on magnet prototypes, a high field test facility (Seht, consisting of a 44 H and 8 T magnet with a warm bore to 600 mm). Both stabilization solutions have been installed on Seht test facility whose design is similar to the Iseult magnet, put aside that magnetic energy is 20 more highest and a homogeneous magnet. Table I summarizes Seht and Iseult electrical parameters.

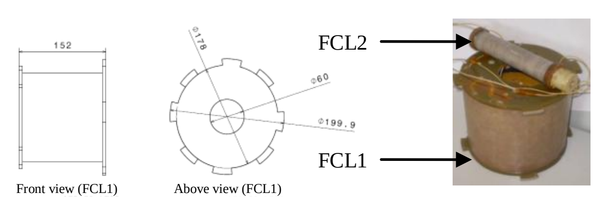

Fig. 5 Fault Current limiter prototype. FCL1, 2 kV and low current prototype. FCL2, 200 V and low current prototype.

Superconducting switches have been replaced by fault current limiters (*FCL1* and *FCL2*, see Fig. 5).

A. Coil stabilization design and realization

Insertion in the innermost radius of Seht magnet coil stabilization gives coil diameter and the location available is narrow. By using (1) a solution exists to minimize α and Table II summarizes coil stabilization features.

A numerical calculation predicts a field stability of about 1.6 ppb/h.

This insert (see Fig. 6) was operated near 4.2 K and was cooled by thermal conduction in the vacuum vessel of the magnet cryostat. A switch *S* and protection resistor for the insert coil were also installed in the vacuum vessel.

TABLE II COIL STABILIZATION – DESIGN

Description	Unit	Value
Number of layer		2
Diameter	mm	673.8
Length	mm	574.5
Isolated wire diameter	mm	0.86
Number of turn		1336
Inductance	H	0.9
Mutual with Seht	H	4.3
α (Equation 1)		2.10^{-4}

In case a quench is detected, the magnet is disconnected from PSU by the opening main circuit breakers, so that magnetic energy is discharged into the external dump resistors R_D. Due to a high coupling with Seht magnet, a maximum of 220 V is induced across stabilization coil. In order to keep insert coil in its superconducting state and hot-spot temperatures lower than 300 K, a 10 Ω resistor, *Rp*, has been designed and manufactured. Furthermore, superconducting switch has been replaced by a fault current limiter *FCL2* (low voltage FCL prototype [9], see Fig. 5).

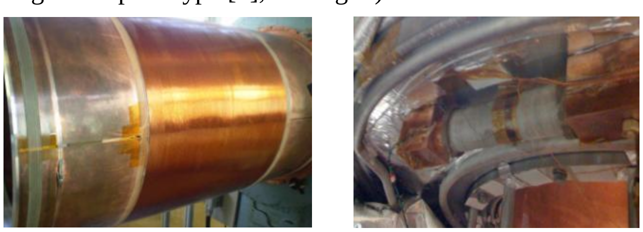

Fig. 6 Coil stabilization realization. Insert picture (left), FCL2 picture (right)

B. Filtering solution design

The filtering stabilization technique is inserted in the magnet electrical circuit and has to sustain high voltage in case of magnet discharge. The maximum voltage across the magnet is 1.8 kV. For Iseult, magnet protection will be based on Seht. So, switch *S1* (see Fig. 3) has to sustain 1.8 kV.

A dedicated R&D program has developed a fault current limiter with more favorable electrical properties in order to replace a superconducting switch [10]. In brief, the FCL must not disrupt magnet discharge, do not avoid magnet charge (see Fig. 7), no heaters are necessary for opening. The FCL is self-protected.

TABLE III FCL DESIGN FOR SEHT

Parameters	Units	Values
Electrical insulation	kV	2
Wire length	m	500
Winding layer		4
Inductance	mH	1.3
Critical current	A	50 @ 1.8K

Since of the original FCL prototype results [9], a new FCL has been designed with electrical insulation up to 2 kV (Table III). Preliminary tests (electrical insulation, opening by over critical current and high voltage test) have been done before its installing in the cryostat, called satellite, which provides He II at 1.8 K. Fig. 7 shows FCL was completely transparent for Seht magnet discharge.

The FCL is a key component for the filtering stabilization technique. Prototype, *FCL1* for Seht is shown in Fig. 5.

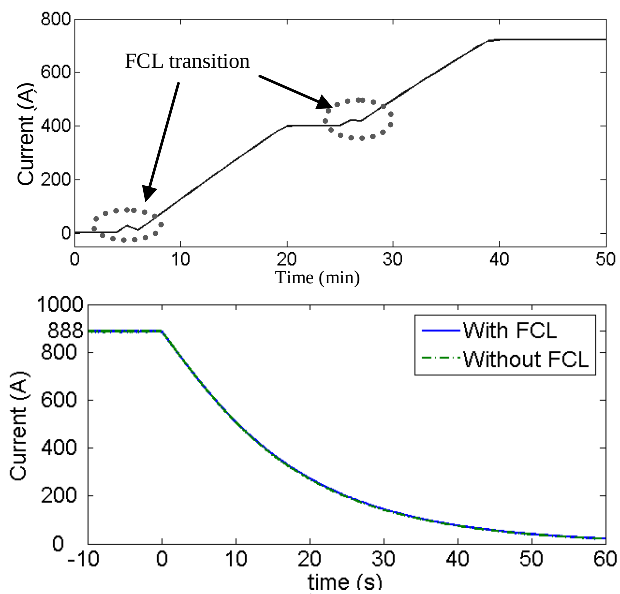

Fig. 7 Energizing and discharge of Seht magnet. Top, magnet energizing (current I_{DCCT} recording, Seht magnet has been energized in 2 steps until 666 A). Bottom, fast discharge from 888 A (both curves are stacked).

By using equations (2), (3) and (4), resistor R_f has been chosen as 100 μΩ in order to have current $I_f < 15$ A and field stability less than 0.05 ppm/h (theoretical maximum drift is 0.015 ppm/h with 2 ppm/h current drift of PSU).

IV. RESULTS

A. Coil stabilization

Two measurements have been performed with and without insert coil stabilization (Fig. 8).

After 8 hours of measurements, a drift of 1 ppm/h in driven mode was measured. With coil stabilization in operation, less 0.1 ppm/h is found. Field stability is twice more than the Iseult MRI specifications (0.05 ppm/h). This drift was not linked with the measurement system.

A measurement of the α term yielded a value of -97.10^{-4} instead of -8.10^{-4} (after winding). This difference can be explained by positioning error sensitivity and also 2% error of the magnetic field at the centre of the magnet. But it cannot be the cause of a higher field drift (0.1 ppm/h versus the expected 0.01 ppm/h). Tests have been performed and demonstrated external field variation and loss of superconducting state of insert coil were not the cause. An explanation was found at the time of study of the second stabilization solution (see part B).

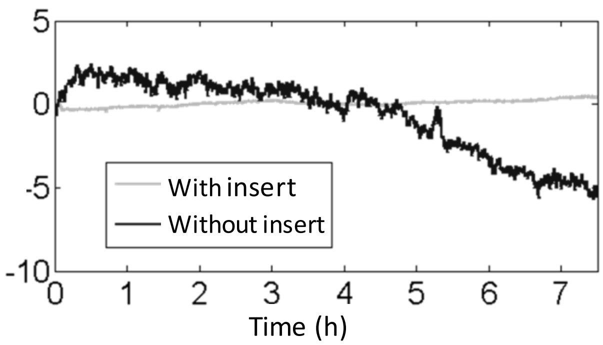

Fig. 8 Field stability measurements – coil stabilization (ppm of 0.965 T).

B. Filtering by a resistor

An NMR probe employing a micro-coil allowed us to obtain a relatively narrow (~1 ppm) signal from ^{1}H of H_2O to improve sensitivity of measurements. During several days, field stability was measured continuously. We had previously noticed that field stability was correlated with the hall day-night temperature variations, thus the NMR signal and magnet temperature were recorded simultaneously. Despite of a thermalization of the warm bore of Seht magnet, field stability was above of 0.05 ppm/h.

We could explain this temperature dependence on measured field by a dilatation of the long mechanical aluminium support of NMR probe (photo Fig. 1) combined with a greater inhomogeneity than expected of the Seht magnet. Measurements give a homogeneity of the magnet of 50 ppm over 2 mm and aluminium dilatation coefficient is 24 ppm/°C. A quick calculation gives us a magnetic field variation around 1.25 ppm/°C. In that case, all our long term field stability measurements will be dominated by the hall temperature variation. Idem, for coil stabilization measurements were done previously.

Taking into account the temperature variation effects into our measurements (see Fig. 9), we find magnetic field drift of less than 0.07 ppm/h. But, it could be lower, by adjusting current, I_F, of few mA.

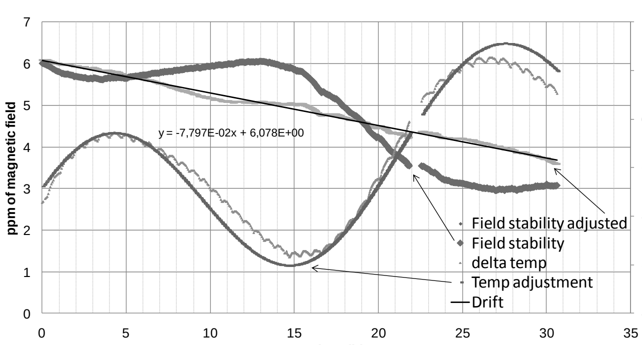

Fig. 9 Field stability measurements – filtering with resistor and FCL.

V. Conclusion

Although the field stability required for MRI imaging system was not readily reached (0.07 versus the required 0.05 ppm/h), both field stabilization solutions have demonstrated their feasibility for the Iseult magnet.

Nevertheless, drawbacks for coil stabilization are its realization and integration in the innermost radius of the magnet and protection will be tricky.

Therefore filtering by resistor and a fault current limiter is the solution for field stabilization for the Iseult magnet. This solution is better for production, integration and protection. Due to its installation within the satellite, maintenance is still possible. A key component is the fault current limiter and we should pay attention to high voltage insulation.

This technique of stabilization was applied to the reduced scale prototype homogeneous magnet [11], named H0, based on double pancakes winding. Magnetic field drift close to the 0.05 ppm/h specification was reached and this magnet is 50 times less efficient (L_{mag}/R_{mag} factor) than Iseult magnet in terms of field stability.

Therefore, field stability better than 0.05 ppm/h using a filtering resistor, a fault current limiter and a classical high stability PSU have been chosen as the reference solution for the Iseult magnet. This design is a passive, self-protected and it is transparent for magnet safety.

Acknowledgment

We thank M'hamed Lakrimi (Siemens Magnet Technology) for realization of superconducting joints between insert coil stabilization and Fault Current Limiter and for expertise on stability methods operation. We want underlying too the work of René Leboeuf, Jean-Jacques Goc and Vadim Stepanov (CEA) which have wound stabilization coil and also Gérard Barthélémy (CNRS) who has wound FCL.

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