Low field MgB_2 and NbTi fast ramped coils: temperature behaviors and empirical comparison

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Abstract

As it is well known, all types of superconductors are affected by AC losses.
Those losses occur when a time varying current flows in a superconductor or when it is subjected to a variable magnetic field.
The main effect of these losses on the conductor is a temperature rise due to the energy dissipation within the superconductor. The main task of superconductor manufacturers is to optimize the design of the wire in order to reduce AC losses according to the magnet requirements.
Many methods were previously studied in order to reduce the magnitude of this loss.
This poster presents the results of an empiric experiment designed to demonstrate the theoretical benefit of MgB_2, with respect to standard NbTi, in low-field/fast-ramped applications.

Introduction

During current ramps the wires of the magnet are subjected to a variation of magnetic field. Superconductors subjected to varying magnetic fields see multiple heat sources that can impact on the conductor performance and stability. All the energy loss sources can be expressed as an equivalent magnetization loss induced in the conductor[1].
Two major contributions are taken into account: hysteresis losses and coupling losses. Using the simplest model[1], the power density generated during field variation is equal to:

$$P = \underbrace{\frac{2}{3\pi} J_c d_f \lambda \dot{B}_i}_{\text{hysteresis}} + \underbrace{2\tau\lambda_f \dot{B}_i^{\,2}}_{\text{coupling}} \qquad (1)$$

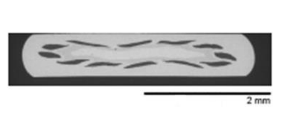
A power loss inside a superconductor leads to a temperature rise. Depending on field amplitude and ramp speed this temperature rise can be high enough to cause transition to the normal state (quenching). Two main strategies can be used in order to reduce this phenomenon:

1. Wire and strand optimization
2. Increase of the enthalpy margin

The first method consists in optimising the manufacturing parameters of wire and strands in order to reduce AC losses[2].
The second strategy is to reduce the temperature increase, not by reducing the losses, but by enlarging the enthalpy margin to transition of the conductor.

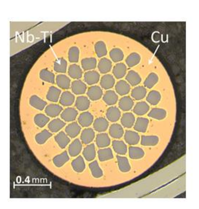
To achieve this, it is necessary to change materials and, most importantly, to operate at higher temperatures.

MgB_2 wire



Material	Area $[mm^2]$	%
Nichel	1.39	63
Copper	0.33	15
MgB_2	0.26	12
Iron	0.22	10
Total	2.20	100

NbTi wire



Material	Area $[mm^2]$	%
Copper	2.03	88
NbTi	0.29	12
Total	2.32	100

Figure 1. Detail of the composition of wires.

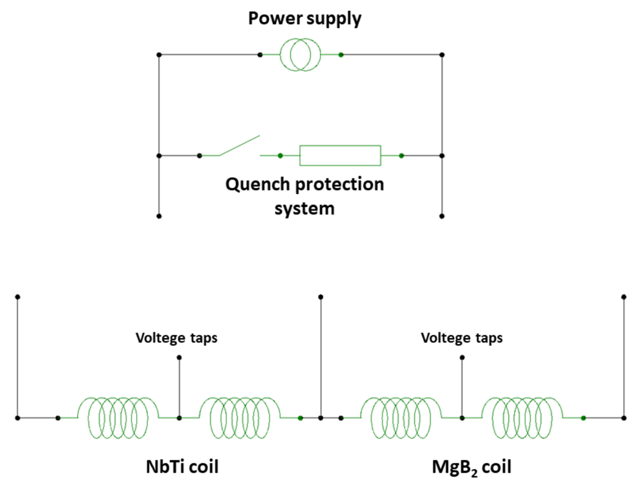
Experiment

In order to compare NbTi and MgB_2 two solenoids were designed using legacy tool by ASG[3] and Cobham Opera[4]. The design was made using two standard commercial wires, see **Figure 1**:

- NbTi commercial standard wire Ø1.8
- MgB_2 wire ASG MRO plus wire[5]

The two coils have been designed to be as similar as possible from a magnetic point of view, see **Figure 2**.

The cryogenic system used to keep the set-up cold is composed of a Sumitomo RDK 415D cryocooler and a Cryomech PT815 PulseTube. The cryocooler 2nd stage is linked to the NbTi side of the coil, while the 1st stage is used to keep the thermal shield cold. The PulseTube is used to refrigerate the current leads.



The two coils are connected in a three way system but tested one at time. The power supply is capable of providing 6V and 300A.

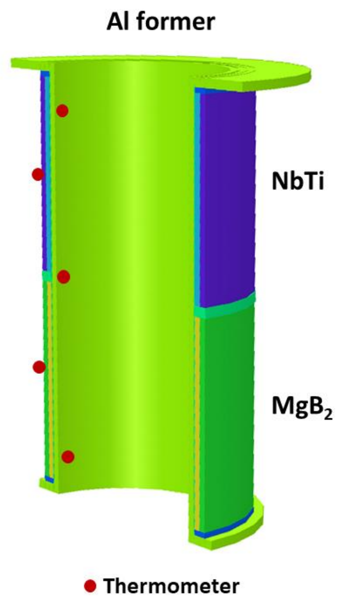


Figure 2. Sketch of the experimental set up.

Results

As first, several voltage controlled ramps have been done in order to characterize the response of the coils to fast charges up to the faster one in a fixed current range of 100A. The presence, in the MgB_2 coil, of an higher inductance, compared to the calculated one, is believed to be due to the nickel matrix. This implies that the MgB_2 ramp speed would be slower than NbTi at the same voltage.
As shown in **Table 1**, the ramps are fast enough to be considered adiabatic and the temperature increases are low enough to allow the evaluation of the density of the released energy as follow:

$$E = \rho \cdot C_p \cdot \Delta T - E_{eddy} \qquad (2)$$

Where ρ is the winding density, C_p is the specific heat capacity and ΔT is the temperature increase during ramp up. E_{eddy} is the contribution to the temperature increase due to the eddy current induced in the aluminium former. This contribution is evaluated using the Elektra Transient module of Opera[4].

	Charge voltage [V]	Current increase [A]	Temperature increase [K]	Ramp time [s]	Ramp rate [A/s]	Estimated energy release [J/m³]
MgB_2	1.5	100	0.39	64	1.56	2431
	2	100	0.22	48	2.08	3230
	3	100	0.45	37	2.70	6594
	5	100	0.57	26	3.85	8361
	6	100	0.74	19	5.26	10831
NbTi	1.5	100	0.35	57	1.75	1357
	2	100	0.47	46	2.17	1832
	2.5	100	0.58	40	2.50	2262
	3.5	100	0.83	27	3.70	3236
	6	100	1.32	16	6.25	5147

Table 1. A selection of ramp up data of MgB_2 and NbTi windings.

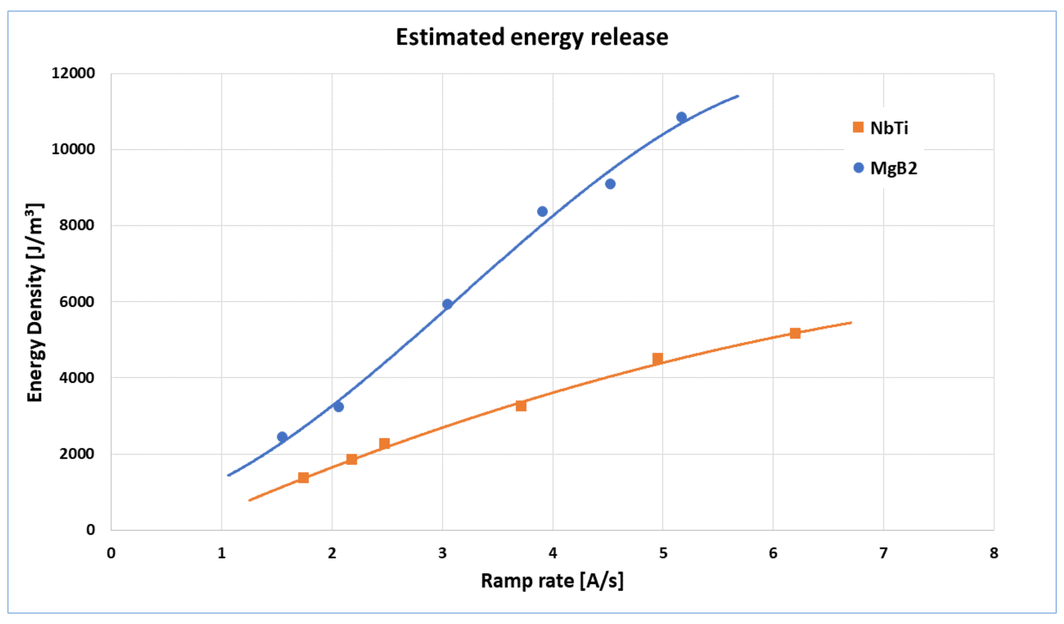


Figure 3. Energy release at different ramp rate for MgB_2 and NbTi.

Discussion

As expected, the energy released during the ramps is higher in the MgB_2 winding as shown in **Figure 3**, but the overall performance is better.
The higher energy margin compensates for the higher losses. Indeed, as shown in **Figure 4** and **Figure 5**, the MgB_2 energy needed to reach the normal state is 40 – 100 times higher than for the NbTi coil.
The energy density to transition shown in the two figures was evaluated using the relation:

$$E = \rho \cdot \int_{T_s}^{T_C(I,B)} C_p(T) \cdot dT \qquad (3)$$

Where T_s is the starting temperature of the magnet and $T_c(I,B)$ is the critical temperature of the superconductor as function of operating current and external field.

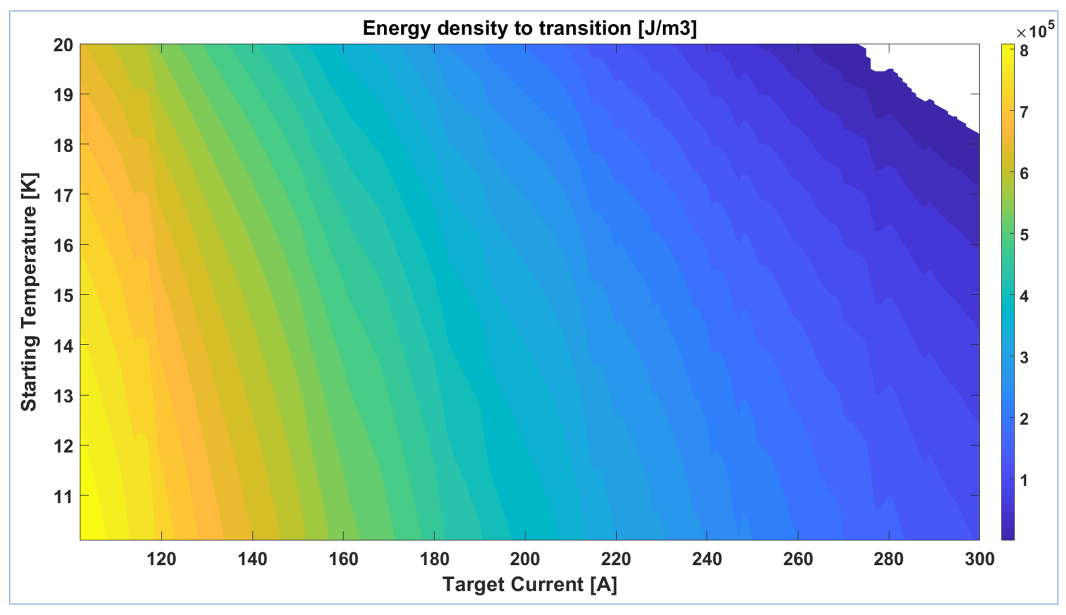


Figure 4. Energy density to transition for MgB_2 winding as function of starting temperature and target current.

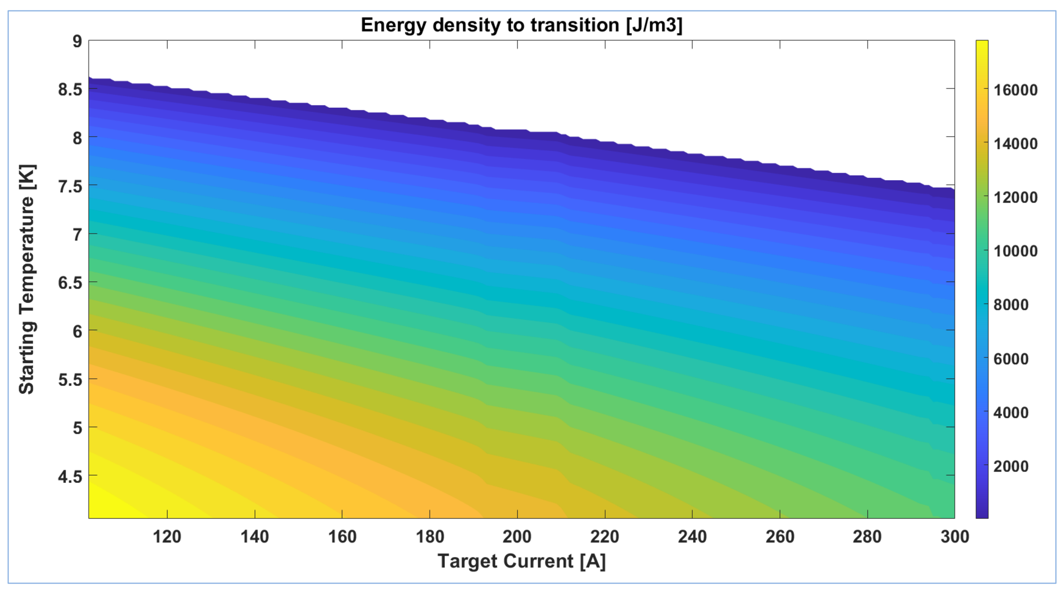


Figure 5. Energy density to transition for NbTi winding as function of starting temperature and target current.

Conclusions

As empirically demonstrated by the previous data, operating at higher temperatures naturally means a wire more resilient to field variations. Indeed the enthalpy benefits are negligible at low temperatures because of the temperature dependence ($H \propto T^4$). As can be deduced from **Figure 4** and **Figure 5**, reducing the operating temperature of the MgB_2 coil from 15K to 14K increases the energy margin by 35 times more than in the case of the same temperature decrease of 1K at 5.2K for the NbTi coil.

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