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TECHNICAL NOTE

MICE Spectrometer Solenoid: Magnet Quench Protection

1. Introduction

Here we review the design of the (passive) magnet protection and consider various operational regimes. According to the MICE Final Engineering Design (report by Wang NMR), the electrical insulation system for the coil is designed to withstand fairly high voltages, and was tested to 5kV. This is an important characteristic, as the high inductance and passive approach used for protection results in large internal voltages during a quench.

2. Case Studies

The following conditions have been analyzed:

1) Operation in series (e.g. during training/commissioning at vendor site)
    - The total stored energy of the system is used in the analysis.
    - Each coil has a 20 mOhm protection resistor in series with diodes, as well as a ~200 mOhm lead resistance (coils are put in series via room-temperature lead jumpers).
2) Individual coil operation
    - Each coil must absorb its stored energy, but different quenching coils can decay at different rates. Here we neglect energy transfer between coils.
    - A fully coupled investigation, taking into account mutual inductances and all possible quench initiation scenarios, is beyond the scope of this report.
    - Here we consider the case of the central solenoid and the M1 solenoid, since those coils have the most stored energy.
3) Coil connections under normal operating conditions
    - Here we consider the case of a quench in the central solenoid, when the central solenoid and E1 and E2 coils are connected in series.

3. Coil Calculations

The inductance matrix for the system is provided in Table I and is based on the dimensions and turn-numbers shown in Table II. For all simulation cases, we assume a transport current of 265A.

Table I: Mutual inductance calculations [H] (fair agreement with CDR)

Coil	M1	M2	E1	C	E2
M1	15.68				
M2	1.14	6.84			
E1	0.31	1.01	10.48		
C	0.28	0.57	3.50	43.77	
E2	0.02	0.02	0.05	3.79	12.01

The total system inductance is ~109H, resulting in a stored energy of 3.8MJ when operated in series at 265A.

To estimate the hot-spot temperature and the peak internal voltage during a quench, simulations were performed using the code "quench." Input parameters include:

- Cu:SC=3.9
- Fractional areas: Copper: 69%; SC: 17.7%; insulation: 13%
- Area of unit cell (1 turn): 0.0178 cm^2
- Relative transverse propagation velocities: 1%

The code named "quench" estimates the longitudinal propagation velocity of the normal zone and considers transverse propagation via a scaling of the longitudinal velocity.

For these calculations, the transverse propagation velocity was determined by matching the computed current decay with the decay time based on actual quench data (reference to be determined; see Kashikhin).

Table II. Basic location and turn information used for quench modeling

	R1	**R2**	**Z1**	**Z2**	**Turns**	**I [A]**	**Je[A/mm^2]**
M1	0.258	0.3027	3.5104	3.7116	5040	269.6	151.11
M2	0.258	0.2878	3.9513	4.1508	3332	245.3	137.5
E1	0.258	0.3176	4.3957	4.5063	3696	227.2	127.37
C	0.258	0.2793	4.5439	5.8582	15680	268.1	150.15
E2	0.258	0.324	5.8957	6.0063	3960	253.4	137.48

4. Case Study Result Discussion

Case 1: Placing all coils in series can result in the total system energy being deposited in a single coil during a coil, leading to a maximum hot-spot temperature. Furthermore, as the quench propagates, internal voltages rise as the system inductance compensates the resistance of the growing normal zone. Note that the lead voltage remains low.

Based on these calculations, the current decay is only weakly affected by the amplitude of the protection resistor, since the vast majority of the energy is dumped in the coil itself. The hotspot temperature is ~160K, which is reasonable for a magnet of this size. The peak internal voltage is slightly more than 6kV, which is quite high and in fact exceeds the design voltage standoff criteria. It is highly likely that the insulation scheme used for the coils is capable of withstanding these, and higher, voltages, but they do exceed the hi-pot test requirement.

Case 2: Here we consider the individual operation of each coil, in particular the central solenoid and the M1 solenoid. Since the full in series scenario described in Case 1 envisioned a quench of the central solenoid, the analysis for the central solenoid alone can be expected to result in lower hot-spot temperatures and lower internal voltages; this is quantified in Figures 1-3. The hot-spot temperature is reduced from ~160K to ~110K, and the peak internal voltage reduced from ~6000V to ~4000V.

Case 3: The case of a quench under nominal operating conditions… [to be completed]

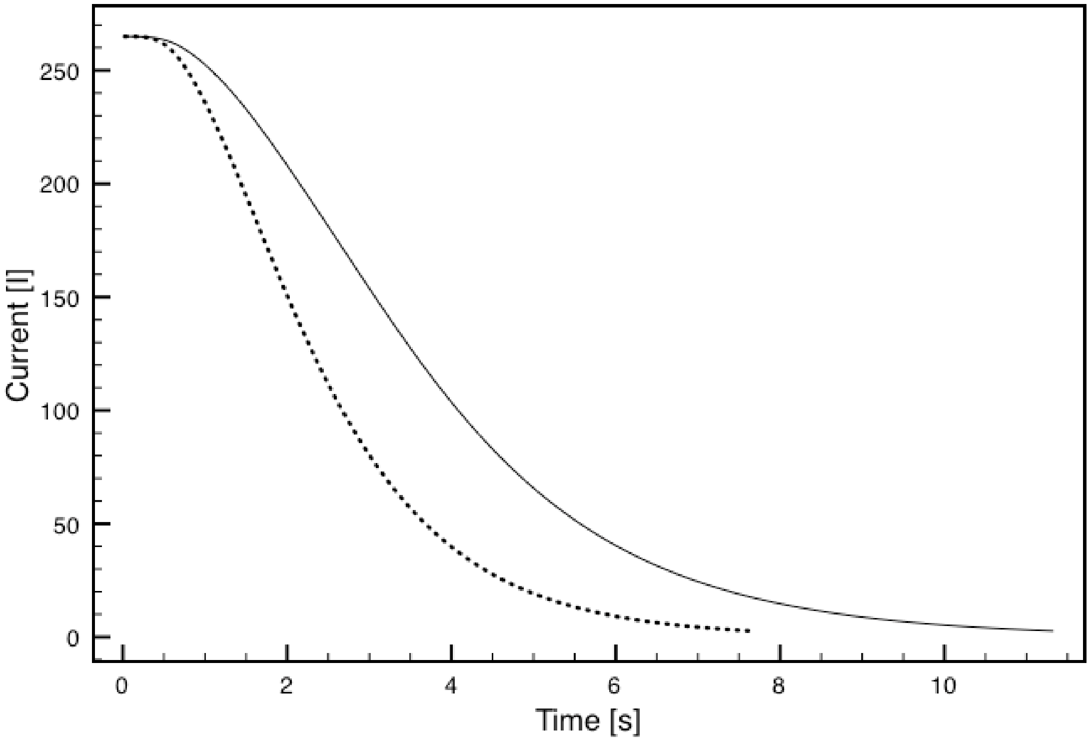

Figure 1. Current decay in the case of a) series connected system (solid line) and b) central solenoid only (dotted line). Case a) assumes that only the central solenoid has quenched.

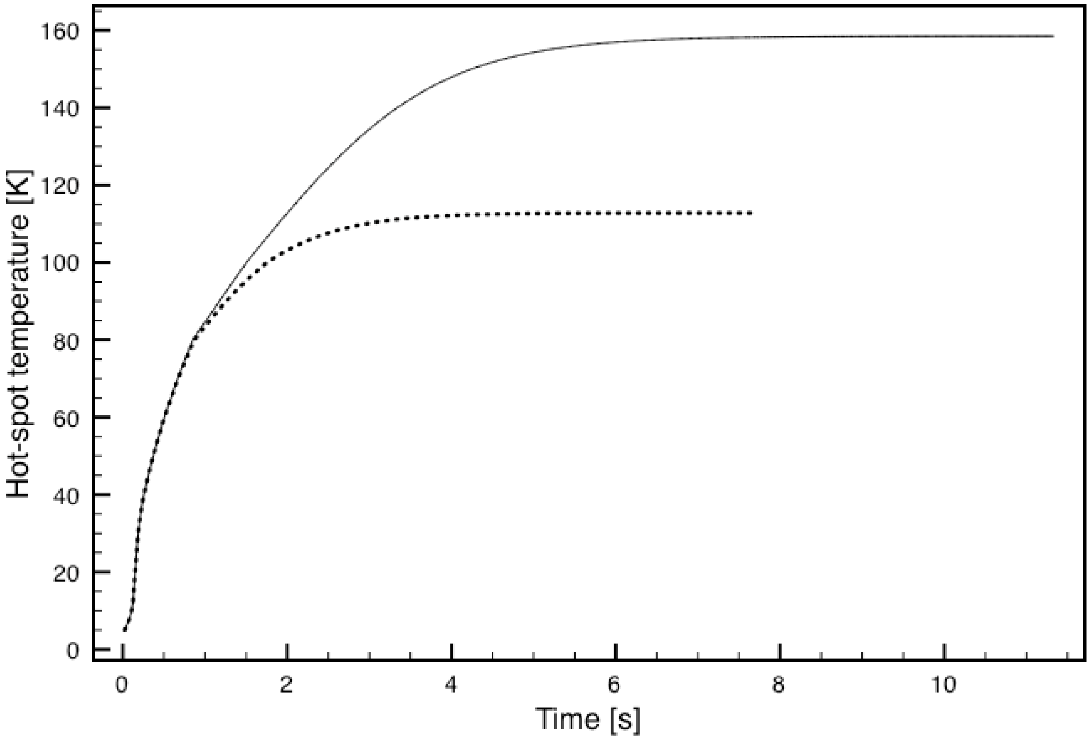

Figure 2. Hot-spot temperature in the two scenarios, as described in Fig.1.

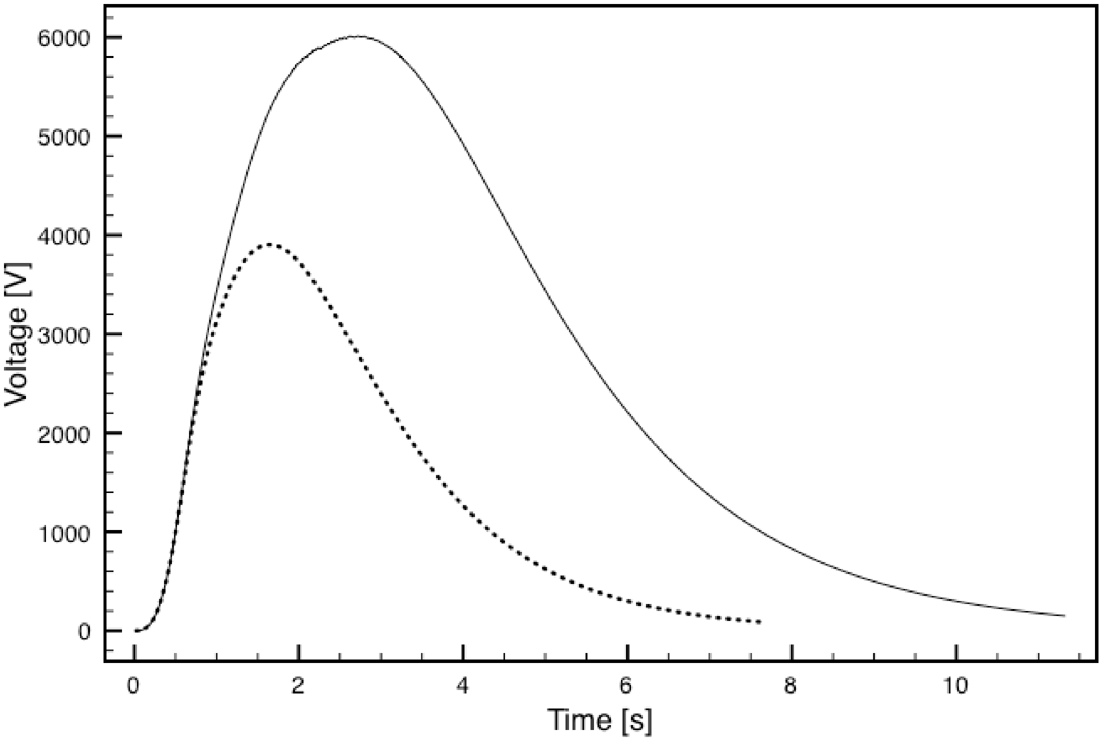

Figure 3. Internal voltage vs time for the cases described in Fig. 1. Note that the insulation scheme is designed for, and tested to, >5000V.