

## Gradient Coil Induced Joule Heating in a MRI magnet

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**Introduction** In superconducting magnets, of various field strengths, the helium pressure may rapidly increase and start to boil off with certain gradient coil activity. This pressure rise will disturb the center frequency and thus adversely affect image quality - in addition to increasing system-operating costs due to helium loss. When a MRI scanner is operating, the current pulses in the gradient coil will induce eddy currents in the metal support structures of the magnet, which in turn vibrate due to the Lorentz force supplied by the large static background field. This motion will further generate an EMF and hence additional, so called motional, eddy currents. Several authors have calculated<sup>[1]</sup> and discussed<sup>[2]</sup> this magneto-mechanical coupled interaction between gradient coil and magnet. In a conductively cooled magnet, excessive Joule heating in the 4K region is extremely critical due to the limited cold head capability. In this article, we calculate the Joule heating in the cryostat, AC losses in superconductive wires, and dielectric loss in coil epoxy, for different gradient coils designs in a 1.5T MRI magnet. The 2D model incorporates the metal vacuum vessel, thermal shield and coil former. The result is a z-gradient coil optimized for heat minimization. The physical phenomenon is further discussed by comparison to pure EM analysis and pure ME analysis.

**Theory and Methods** The basic governing EM and ME equations are  $\nabla \times \vec{H} = \vec{j}$  and  $m\ddot{w} + c\dot{w} + kw = \vec{f}$ , respectively. After some manipulation, one obtains  $\nabla \times (\frac{1}{\mu} \vec{B}_{ac}) = \sigma (-\frac{\partial \vec{B}_{ac}}{\partial t} + \frac{\partial \vec{w}}{\partial t} \times \vec{B}_{ac})$  and  $m \frac{\partial^2 \vec{w}}{\partial t^2} + c \frac{\partial \vec{w}}{\partial t} + k\vec{w} = \vec{f}_{me} - \sigma \frac{\partial \vec{B}_{ac}}{\partial t} \times \vec{B}_{ac}$ , where  $m$  is the local mass,  $\sigma$  is the electric conductivity,  $\vec{j} = \sigma(\vec{E} + \vec{v} \times \vec{B}) + \vec{j}_{ext}$ , which includes the induced and motional eddy currents and the external current source,  $\vec{j}_{ext} = \vec{j}_{ext,dc} + \vec{j}_{ext,ac}$ , the DC(main coil) and AC(gradient coil) external current,  $\vec{f} = \vec{f}_{me} + \vec{f}_e$ , denoting the ME and EM force,  $\vec{f}_e = \vec{j} \times \vec{B}(\vec{B}_{dc} \gg \vec{B}_{ac}$  in MRI), and  $\vec{w}$  is the displacement of the local mass. The coupled equations are solved with the FE method. Then joule heating  $P = \int \frac{1}{\sigma} j^2 dv$  in the metal structures, AC losses with known  $\vec{B}_{dc}$ ,  $\vec{B}_{ac}$  and frequency in the main coil<sup>[3]</sup>, and dielectric losses in the main coil epoxy due to the loss tangent<sup>[4]</sup> are calculated.

**Results and Conclusions** Figs.1(a)-(b) show the joule heating in different parts of a 1.5T magnet vs. frequency, for two different gradient coil designs, and with 200A sine wave current. The vibration peaks of the thermal shield (Curve A) are mainly responsible for the Joule heating peaks in the coil former. The peaks are much reduced after gradient coil optimization, and the heating level is suitable for conductive cooling (Curve B). (c) is the AC loss in superconductive wires, and (d) is the dielectric loss. Due to the shielding effect of the surrounding metal structure, the AC losses in the superconductive coil are small and dielectric losses in the coil epoxy are even smaller - which is different from magnet designs with a composite support structure<sup>[4]</sup>. If motion is prevented, by assuming that the support structure has infinite stiffness (pure EM analysis, no mechanical vibration), the joule heating curve is smooth (Curve C in (a) and (b)). On the other hand, if only the eddy currents from the external source  $\vec{j}_e = \sigma \vec{E}$  are allowed, with the motional eddy currents  $\vec{j}_v = \vec{v} \times \vec{B}$  eliminated (and hence no magnetic stiffness or magnetic damping<sup>[2]</sup>), the system will be converted to a pure mechanical problem with Lorentz force (by  $\vec{j}_e$ ) excitation, resulting in many peaks at different frequencies compared with the fully coupled model (e).

**Reference** [1] Rausch. M, et al. IEEE T Magnetics, (2005), 41, 72-81 [2] Jiang. L, et al. Proc. ISMRM (2008) [3] Carr. AC Loss and Macroscopic Theory of Superconductors [4] Hua. Y, et al. Proc. ISMRM (2011)

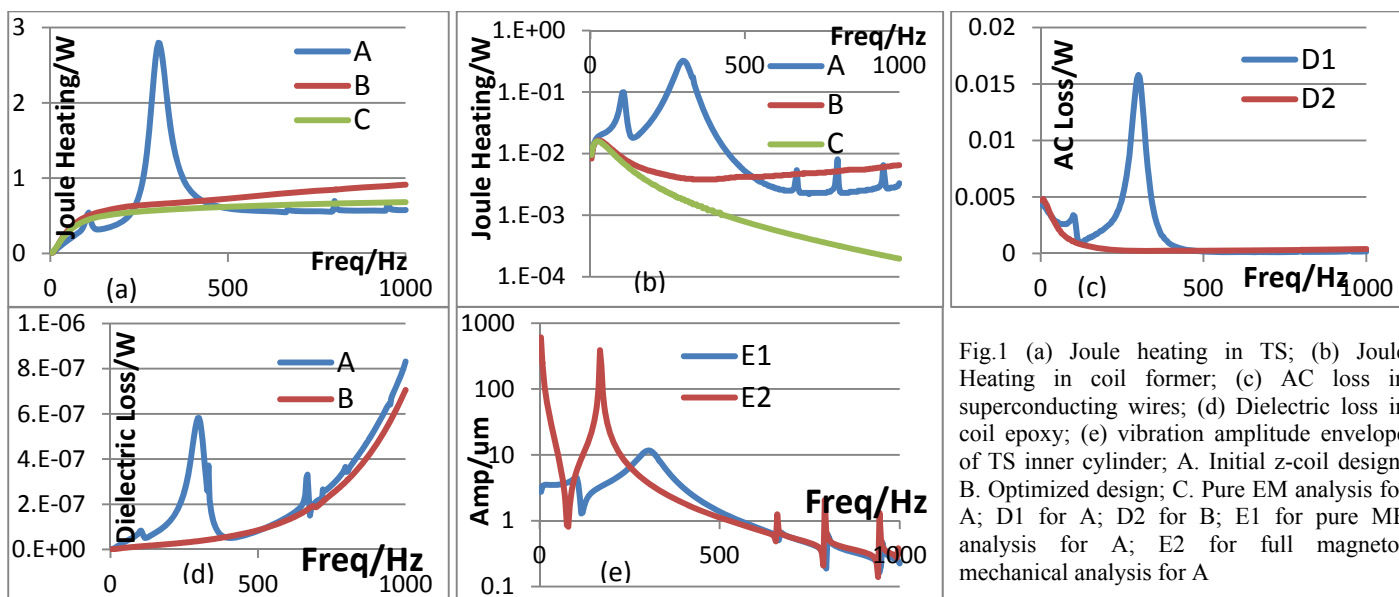


Fig.1 (a) Joule heating in TS; (b) Joule Heating in coil former; (c) AC loss in superconducting wires; (d) Dielectric loss in coil epoxy; (e) vibration amplitude envelope of TS inner cylinder; A. Initial z-coil design; B. Optimized design; C. Pure EM analysis for A; D1 for A; D2 for B; E1 for pure ME analysis for A; E2 for full magneto-mechanical analysis for A