Balancing a 500 mm central gap split gradient coil for a hybrid MRI-linac scanner.

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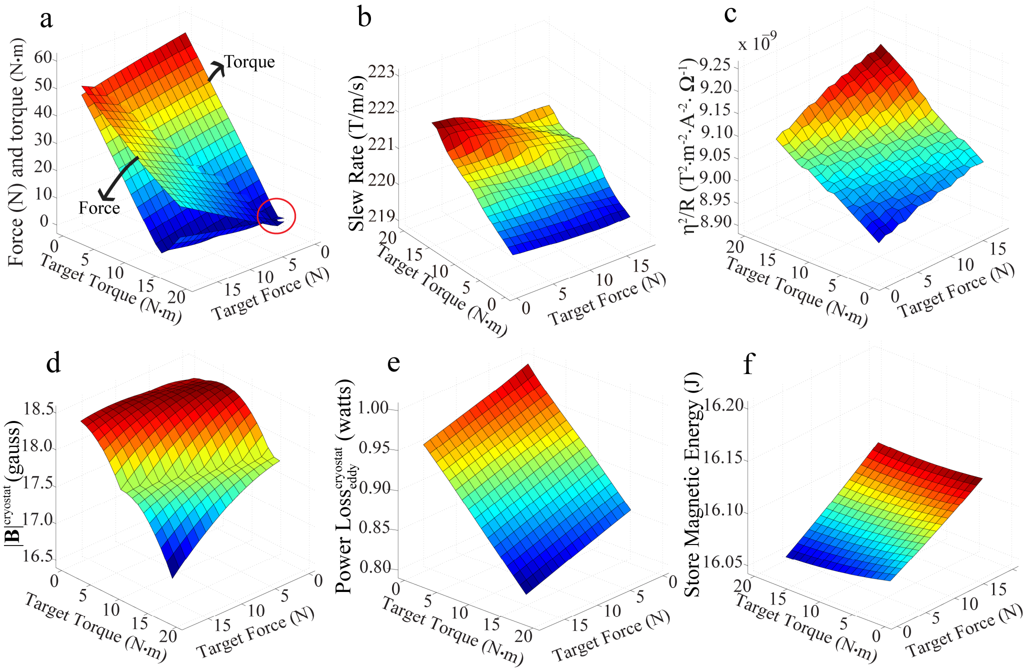
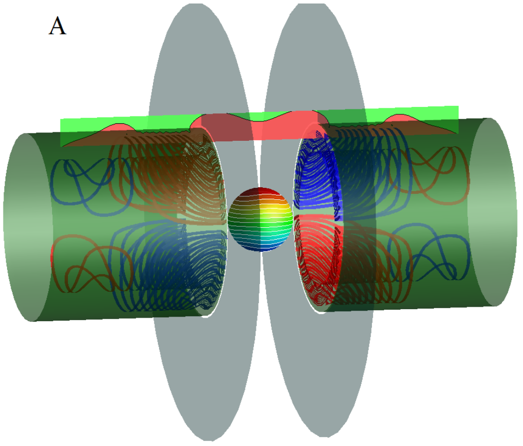
Target Audience: This work can be of interest of those engineers dedicated to the design of gradient coils for conventional and hybrid MRI scanners.

Purpose: This study aims to determine the highest coil performance possibly obtainable for a nearly zero torque/force 500 mm central gap split *x*-gradient coil. The gradient coil requirements are: a 500 mm central gap, 620 mm bore split gradient coil aimed to produce 20 mT/m using around 600 A, shielding ratio $max(B_z^{eddy}/B_z^{coil})_{DSV}$ smaller than 1% and slew rate larger than 200 T/m/s. We studied the behavior of the coil performance for different shielding strategies when the shielding ratio is varied from super-shielding (0.2%) to moderate shielding (2%) [1]. Shielding is one of the most critical parameters to control due to the openness structure of the split coils. We found that the most suitable shielding strategy to balance the coil to zero torque/force and yet to produce a high performance was the minimization of the total stored magnetic energy. Nearly equivalent to that strategy was the minimization of the total power loss in the coil and cold shield. Both strategies are very suitable to produce coils with optimal pre-emphasis and high slew rate; however minimal peak current density were registered in coils with minimal stored energy, hence our choice of balancing the coils using these shielding option.



Methods: The magnetic field profile as well as the cold shield information of the 1 T split superconductor magnet was provided by Agilent. The coil envelope was defined as a folded structure with mean primary and secondary surface radius at 310 mm and 407 mm, respectively. The inner and outer axial positions were set to 270 mm and 950 mm, respectively in order to allow a mechanical support and provide a clear central gap of 500 mm. Figure A), shows the cold shield aluminum structure. We used the EMC [2] code and invoked the option of total energy minimization for the whole system. The target net torque and force were varied from 0.5 (N) to 15 (N) and 0.5 (Nm) to 15 (Nm), respectively. An uniform gradient field of 10 mT/m was specified in a 300 mm DSV with 5 % of maximum deviation from the target field for all the designs. Each coil was discretized using 40 contours to produce more than 30 µT/mA, wire gap of 3 mm and minimal and maximal track width of 5 mm and 12 mm, respectively. Our target was to optimize the force/torque to values smaller than 5 N and 5 Nm, respectively and yet to produce a slew rate larger than 200 T/m/s. The EMC code was adapted to balance the coil. The coil pattern of the final design was spread in order to increase the coil efficiency [3].

Results: Figure a) shows the resultant net force and torque when the solution is constrained to the targets. The circle indicates the value for which torque and force reach the **minimum when the coil is balanced per half**. Figure b-e) describes the slew rate, figure of merit (FoM), field flux and average power loss in the cryostat for the target constrained net force and torque, respectively. Figure f) shows the behavior of the store magnetic energy in the whole system. Figure A) shows the coil current pattern of one of the balanced coils.



Discussions and Conclusions: The minimum net toque and force value occurs when the force is constrained to small value and the torque is under a relaxed constraint. The **slew rate tends to increase when the torque constraint is relaxed**. This result strongly depends on the field profile generated by the magnet hence that the present the methodology must be repeated for each particular case. Figure c) shows that the FoM changes in a linear fashion respect to the variation of the target torque/force. **A stringent force/torque constraint acts to the detriment of the coil FoM, the shielding performance and thus the average power loss in the cryostat** (see figures d-f). Others observed parameters such as current density and shielding ratio changes in linear fashion under the target torques and forces constraints. Zero torque/force increase the current density and compromise the shielding ratio. The red circle indicates the solution space on which the final solution was tuned and obtained. Figure A) shows the resultant coil pattern of the 500 mm split transverse gradient coil. The **resultant efficiency was 33 µT/mA**, the **inductance 278 µH,** the **slew rate 230 T/m/s, rise time 43 µs, the resistance 100 mΩ, maximum linear field deviation from the target 4%, net torque and force 1.7 Nm and 5.75 N**, respectively when the coil is driven with 302 A. The minimum track width was 5 mm. Figure A) shows contour of the magnetic field in the DSV as well as the shielding characteristic of the designed coil. We conclude that: **1-Minimzing the total energy of the coil and cryostat leads to coil solutions suitable for balancing the torque and the force. 2-Exploring the solution space of the coil most critical parameters as function of the target torque and forces provides a deep understanding of possible conflicting parameters such as shielding ratio, current density, slew rate and the coil FoM. 3- Despite of the large central gap and axial coil bore the coil still shows good quality performance typical of whole body coils.**

References [1] H. Sanchez, et al, submitted ISMRM 2014.[2] H. Sanchez, et al J Magn Reson, 199, 48-55, (2009). [3] M. S. Poole et al Magn Reson Med, vol. 68, pp. 639-648, 2012