Title: A 3T Head Scanner Designing Stage: the HTS magnet and the 200mT/m Hyper-Vision Gradient Coil.
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Abstract: This work presents the design stage of a 3T MRI head scanner aimed to register temporal physiological events in the scale below 1 sec while imaging brain structures below 0.5 mm of resolution. The hyper-vision gradient coil concept is capable to produce 200 mT/m and nearly 1900 T/m/s using a high end amplifier. The 3D folded coil exhibits shoulder cut of an aperture of 250 mm and a DSV of 250mmx210mm while keeping resistance, eddy currents, force and inductive decoupling with the HTS magnet under control. Details and characteristics of the coil and magnet are presented in this work.
Target Audience: This work is of interest of engineers and neuroscientists interested in the design of MRI head scanners to investigate the complexity of clustered functional neurons at the mesoscopic scale by using a hyper-vision concept gradient coil.
Purpose: This work aims to introduce the design stage of a 3T MRI head scanner based on DI-BSCCO Type-HT wire and a high performance gradient coil (hyper-vision) capable to probe at mesoscopic scale the blending connection between micro-vessels and brain tissue while measuring temporal physiological events in the scale below 1 sec.
Introduction: The causes of neurodegenerative diseases such as Alzheimer, Parkinson and dementia reminds unknown due to the lack of imaging tools capable to probe the interaction mechanism and interface of micro vessels with the brain tissue at the mesoscopic scale (<0.5mm). How at this scale, neurons with similar functions clusters, storages information, forms dynamic micro-circuits and interacts with the brain tissue remains an unexplored area or *terra incognita*[1]. Current gradient coils performance limits the frontier of understanding of such mechanism mainly due to the lack of spatiotemporal resolution to probe physiological events in the scale below 1 sec and registering anatomical imaging with a resolution below 0.5mm. The connectome whole body gradient coil boosts 300 mT/m with high risk of PNS if the coil is used at full performance[2]. In this work an alternative head symmetric gradient coil is architected to produce 200 mT/m and nearly 1900 T/m/s to delve at the scale below 0.5mm. The coil exhibits shoulder cut and 3D folded conductors and it is plan to be part of a 3T HTS head scanner. A high end amplifier 850A and 2000V will be use to drive the hyper-vision coil.
Method: A first version of an unshielded 3T HTS magnet was designed. A pk-pk homogeneity smaller than 5 ppm was targeted in a 240 mm DSV. The characteristics of the DI-BSCCO Type-HT wire was provided by Sumitomo Electric Industries, Ltd. The number of axial turns in each coil were constrained to be even, the peak field and the Br field component were constrained; safety margin, axial force, simplified hoop stress, sensitivity of the solution and computing precision were also controlled to guarantee a reliable and practical to manufacturer design. The stability of the solution was tested by perturbing each coil within an error tolerance range (±0.5mm) and a minimal number of passive shim pockets were determined in order successfully correct unwanted field inhomogeneity while minimizing the risk of Bo drift due to shim heating. Two Hyper-Vision gradient coils were designed using different ID envelopes; two DSV sizes were also defined and a maximum non-linearity of 6.5% was specified. The secondary field was controlled in the DSV and constrained to be as linear as the primary field and the maximum residual value was set to <0.5%, considering an aluminum cryostat. The shoulder cut aperture was fixed to 250mm. Coils and shims are inductively decoupled with the magnet and a power loss <0.5 watts was constrained in the cold surface. Peak values of current densities were avoided in the coil and in the cryostat(induced); same as peak values of force. The wire length was minimized by using *l*1 (Z-gradient coil) and *l*2 (X, Y-gradient coil) norms optimization[3].
Results and Discussions: Fig 1 a, shows the magnet and the field homogeneity profile. The Br component is higher at the extreme axial planes of the coil 1(1m) thus increasing the safety margin up to 83%. Replacing some axial turns with a wire of higher critical current reduces the safety margin below 60%. Table 1, describes some characteristics of the HTS magnet. Figs b, c and d describe the result of the stability analysis and the prediction of 24 passive shims azimuthal drawers to be used to bring within 5 ppm the resultant homogeneity after construction. Fig 2 a, shows the envelope of the hyper-vision coil. The coil envelop total

length is 700mm and distance shoulder to DSV center is 150 mm. Fig 2 b,c and d describe the gradient coil set. Table 2, presents the main characteristics. The Z-coil with ID 400mmID produces 200 mT/m; which is predominantly used in fMRI. The forced was reduced below 20N. The shoulder cut may shift up the cylinder eigenmodes thus avoiding mechanical resonances. Reducing the coil radius limits the surface area and the space to place conductors. A brief E-field calculation (5mm Duke model) foresees that at the top of the scalp and neck area are where major density of the E-field and current density are registered.
Conclusion: The designing stage of a head scanner based on a 3T HTS magnet has been presented. The hyper-vision gradient coil producing 200 mT/m and nearly 1900 T/m/s to delve at the mesoscopic scale the connection between micro-vessels and brain tissue has been introduced. The two hyper-vision coil envelopes with standard ergonomics dimensions classifies as "connectome" gradient coils and would be the necessary boosting to bring UHF to clinical practice at its full potentiality.

Table 1. 3T HTS Magnet characteristics						
Field Homogeneity of 1.59 ppm (red circle) within 240 mm DSV. 600 mm bore.						
Coils	Z1 (mm)	Z2 (mm)	R1 (mm)	R2 (mm)	J (A/mm^2)	Safety Margin (%)
Coil 1	372.73	549.53	345	411.74	100.7	83.12
Coil 2	162.42	245.62	345	394.82	100.7	67.98
Coil 3	16.73	110.33	345	378.37	100.7	61.58
Coil 3m	-110.33	-16.73	345	378.37	100.7	61.58
Coil 2m	-245.62	-162.42	345	394.82	100.7	67.98
Coil 1m	-549.53	-372.73	345	411.74	100.7	83.12
Stored energy:2.6MJ. Peak Field:4.96T.Peak Br field:3.76T						

Table 2. Some characteristics of the Hyper-Vision gradient coils ("connectome")						
Envelope->	ID/OD-360mm/590mm			ID/OD-400mm/590mm		
Properties	X	Y	Z	X	Y	Z
η (μT/A)	258	257	250	203	204	251
Inductance (μH)	462	315	256	436	387	406
Resistance (mΩ)	97	119	84	91	118	120
Slew rate (T/m/s)@2000V	1078	1564	1893	894	1053	1245
Conduct. Thickness (mm)	2.2	2.5	2.2	2	2.5	3
Conduct. min width (mm)**	2.4	5	3.2	2.4	5	4.4
Residual Eddy (%)*	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Roll over from center (mm)	145	172	150	150	150	150
DSV	225mmX190mm			250mmX210mm		
Max Non-linearity (%)	6.5	6.2	-6.5	-6.5	-6.2	-6.5
Max Non-Uniformity (%)	-25	+28	-33	-23	+28	-27
*The linear term decays with only one time constant (one eigenmode excited). The eddy field in DSV max non-linearity is 5% respect to primary field for a long pulse of 1s.** Minimum gap between consecutive conductors 1.7 mm. Copper sheet max track width set to 12 mm. A resolution around 0.4mm is expected.						

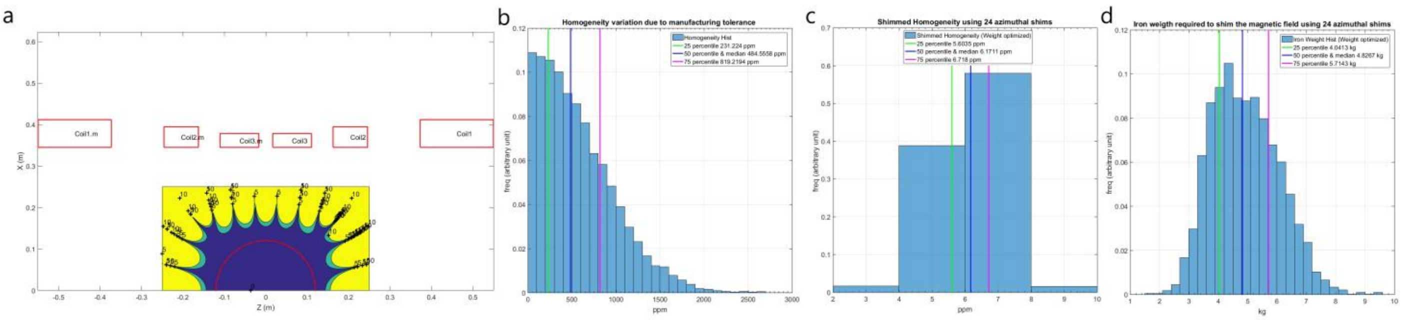

Figure 1. The 3T HTS magnet and the design stability analysis under manufacturing tolerance errors. a) the magnet profile and field homogeneity. b) 10000 designs were shimmed (c, d). An optimal number of passive shims pockets and azimuthal drawers were determined. Convex and integer optimization were used to minimize the number of passive shims assuming that within the range of 25 and 75percentile the after

manufacturing homogeneity most be shimmed. The robust shimming method no only minimizes the total number of pockets but also prioritizes thicker pieces over thinner shim pieces to facilitate handling. Maximal pocket thickness was constrained to 3mm.

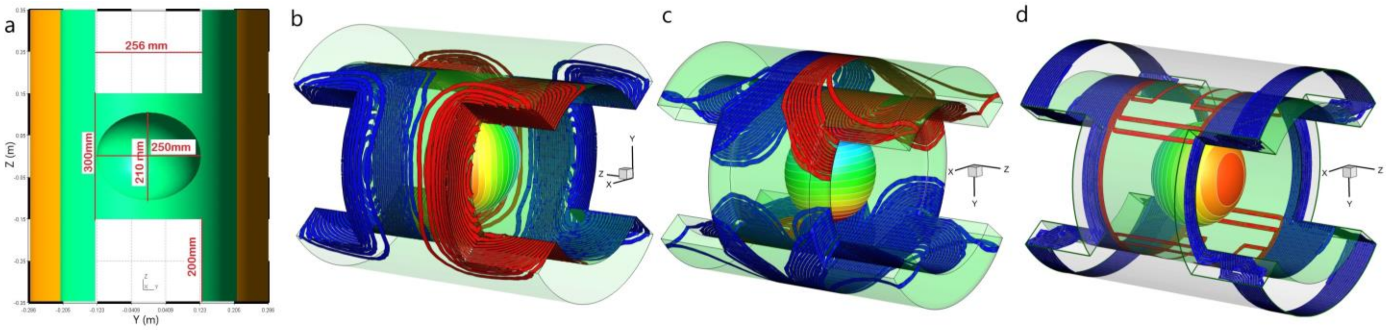

Figure 2. Hyper-vision gradient coil envelope and concept. The service side contains all connections properly arranged to avoid extra Bo term. a) The envelope. *l*1-(d) and *l*2 (b,c) norms minimization of the conductor length must be used to cluster the current density and avoid wires spread all around the coil surface (typical resistance minimization)[3]. *l*1-norm was used to design the z coil. Undesired eigenmodes were also minimized to guarantee a single decay constant. Colors do not necessarily indicate current direction.

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2- Winkler SA, Schmitt F, Landes H, DeBever J, Wade T, Alejski A, Rutt BK. 2016 Gradient and Shim Technologies for Ultra High Field MRI. NeuroImage.
3-Sanchez-Lopez H. 2016 The forgotten planar gradient coil. 24th Annual Meeting of the International Society for Magnetic Resonance in Medicine (ISMRM).