Passive Shimming of MRI Magnets with B0 >= 3T at Reduced Field

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Introduction: To achieve high B0 homogeneity adequate for the required IQ, passively shimmed superconducting MRI magnets employ extensive amount of shim steel to compensate individual variations in each magnet due to manufacturing tolerances and site environmental magnetic field. The shim pieces are usually mounted on the shim trays, which are then inserted into the magnet bore. Most shim steel is placed during coarse shimming at the factory, to compensate variations in coil positions, material properties, or misalignment during assembly. The coarse factory shimming is followed by fine shimming (at factory or at site), where either the dedicated fine shim trays, or the same coarse shim trays are used.

Although the required shim capacity varies between different designs, technologies and processes, it inevitably increases substantially for scanners with B_0 = 3T and above, as the larger absolute values of the field inhomogeneities needs to be compensated with the shim pieces of the same saturation magnetic moment $\boldsymbol{M}$. Large forces and torques are present during tray insertion or extraction; they increase with field gradients at 3T and above, requiring use of special insertion tools. As a result, coarse shimming becomes a lengthy, costly and complicated process.

We've developed technique that allows shimming with drastically reduced forces and torques on individual shim trays, by implementing coarse iterations on the partially ramped down magnet. The procedure also accommodates other standard steps in the magnet test process, including the need to overramp the magnet above the operating field B_0 for training purposes.

Results: The process flow with reduced field coarse shimming is illustrated in Figure below. Initially, the magnet is ramped up to the field $B_{max}=B_0+\Delta B_{over}$, where ΔB_{over} is the overramp field level. The overramp provides sufficient margin for magnet training and eliminates potential quenches at subsequent ramps to B_0 during installation. While at B_0, the virgin map is taken and steel distribution for the first coarse shim iteration is defined.

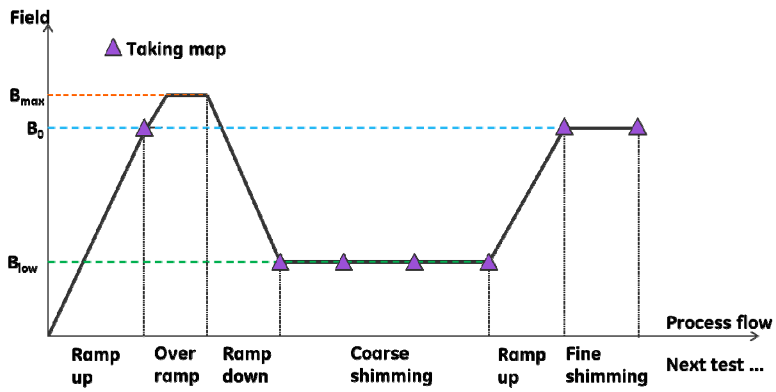

Figure. Process flow of proposed shimming scheme

As a next step, the magnet is ramped down to the prescribed low field B_{low} (e.g. 0.7T or 0.5T), and the map is taken at B_{low}. Harmonics in this map differ from those obtained at B_0, due to a) shift in coil positions under different Lorenz loads; b) different contribution from ferromagnetic components that may be present in the cryostat and in the room, such as motor shield, mounting components or room structural steel. Difference between maps at B_0 and B_{low} is used as transfer function for coarse iterations performed at B_{low}. After several coarse iterations are done (see Table), the magnet is ramped to the full field B_0 for remaining tests. Due to the fact that transfer function between maps at B_0 and B_{low} is not perfect, a few fine shimming iterations at B_0 are needed to achieve homogeneity requirement. The proposed method has been tested on multiple magnets; the sample information characterizing the process is summarized in the Table below. In these examples, 4 coarse iterations are performed; the shim mass used for every iteration has been demonstrated in terms of percentage of the final shim mass.

Table. Shimming history and performance in terms of total shim mass percentage

Magnet	Coarse shimming				Fine shimming
	1st iteration	2nd iteration	3rd iteration	4th iteration	
#1	73.9%	90.0%	93.1%	93.8%	6.2%
#2	79.5%	92.9%	96.2%	96.3%	3.7%
#3	66.7%	88.1%	95.4%	95.4%	4.6%

As one can see, 67% to 80% of the total required shim mass is applied during the first coarse iteration at B_{low}. It is also possible, by using a single low-field iteration, to avoid altogether the need for mechanical assistance during the fine shimming, if the coarse / fine tray division is employed (albeit at the expense of lower coarse shimming accuracy). The magnet would be first ramped to full (or partial) field to enable reliable measurement of the virgin homogeneity. After the mapping, the magnet would be de-energized to B_{low} (or to B = 0), to allow safe installation of the coarse shims which could cover 60 to 80% of the shimming material. This percentage after the 1st coarse iteration depends on the magnet field level B_0 and on the accuracy of prediction of coarse shims' contribution (including possible non-linear effects). Thereafter the magnet would be re-energized to B_0 and subsequent fine shimming iterations could be performed with the fine shimming trays only. Those would be safely inserted whilst the magnet is at full field due to the small shim mass mounted on the dedicated fine trays.

Summary: Novel technique of passive shimming for high field MRI magnets has been proposed. The test results have proved that the coarse-shimming the magnet at B_{low} will allow to successfully shim MRI magnet after the subsequent fine shimming stage, while drastically reducing insertion forces and torque, and minimize the need in specialized insertion tools.