Saturation Pulse Design with Explicit Sensitivity Maximization for Bloch-Siegert B_1^+ Mapping

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Purpose: B_1^+ mapping using the Bloch-Siegert (BS) shift [1] is challenging at 7 T and higher, due to SAR limitations and signal loss resulting from the high amplitude and long duration of the saturation pulse (e.g. 4 - 6 ms Fermi, or 4 ms Quad waveforms [2] with $B_1^{peak} \approx$ 20μT). Hence, it is desirable to shorten the saturation pulse while maximizing the sequence's sensitivity (i.e. the derivative of the phase shift as a function of $|B_1^+|$ (ϕ_{BS})) and negligibly exciting on-resonant spins. A previous method for BS pulse design was based on optimization of an indirect and approximate sensitivity objective [1,2]. Here we propose a novel way of designing BS pulses, which directly maximizes sensitivity subject to a constraint requiring negligible on-resonant excitation.

Methods: The ideal BS pulse maximizes the sequence's sensitivity and limits the excitation of on-resonant spins to negligible levels. Moreover, maximizing the derivative of ϕ_{BS} (i.e. sensitivity) with respect to $|B_1^+|$ and requiring the derivative to be positive across the $|B_1^+|$ range of interest guarantees a one-to-one mapping of ϕ_{BS} onto a B_1^+-ΔB_0 hyper-plane, as the positivity condition enforces monotonicity of the function $\phi_{BS}(|B_1^+|;\Delta B_0)$**.** We therefore design the BS waveform to maximize the sum of $\partial\phi_{BS}/\partial|B_1^+|$ values evaluated on a B_1^+-ΔB_0 grid. This objective function and the on-resonant excitation constraints ($|\beta| < 0.01$) were expressed explicitly in terms of spinors α and β [3]. The optimization was performed on a B_1^+-ΔB_0 grid defined by a range of 0.1-20 μT and ±600Hz in B_1^+ and ΔB_0 directions with 1μT and 60Hz steps, respectively [2]. A 2ms duration was selected and the waveform was treated as a train of 312 block sub-pulses (each 6.4μs long), each being subject to amplitude and phase modulation. To avoid convergence issues due to phase wrapping, the sub-pulses' RF amplitudes were constrained to be between ±1 and their phase was unconstrained.

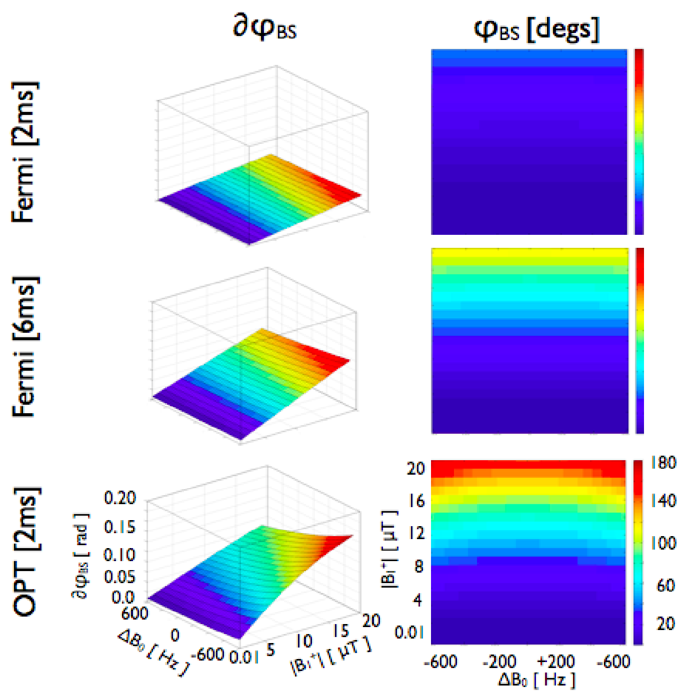

Fig.1: Sensitivity maps (on B_1^+-ΔB_0 grid) – left column (expressed in terms of derivative of ϕ_{BS} with respect to $|B_1^+|$) and phase maps ϕ_{BS} – right column for 2ms, 6ms Fermi and 2ms optimized pulse.

The maximization problem was solved using Matlab's fmincon function (The Mathworks, Natick, USA). This highly non-convex optimization problem was initialized with a 2ms Fermi pulse with constant off-resonance term set to ±4kHz. The optimized 2ms waveform was compared to 2ms and 6ms Fermi pulses with a constant off-resonance shift of ±4kHz. In order to make a comparison with previous work possible [2] we show values of BS phase as a function of B_1^+-ΔB_0 within the range defined above. Additionally we show values of $|\partial\angle\alpha|$ and the amount of excitation ($|\beta|$) on the grid of B_1^+ and ΔB_0 (defined above).

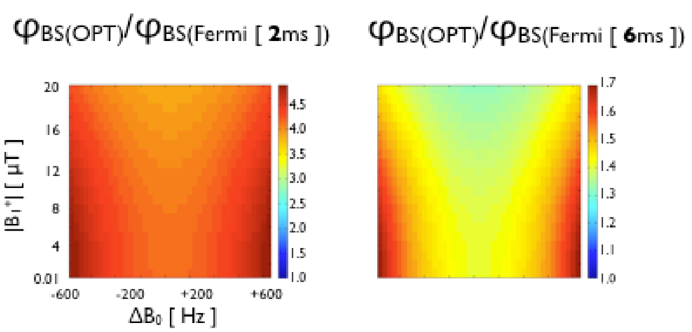

Fig.2: BS phase gain (ϕ_{BS}) for 2ms optimized pulse over 2ms and 6ms Fermi pulses. 4-5 fold gain over 2ms Fermi and 40-70% gain over 6ms Fermi pulses clearly show the advantage of the proposed pulse design.

Results: Values of $|\partial\angle\alpha|$ (left column) together with ϕ_{BS} values (right column) are shown in Fig. 1 for all of the pulses considered here**.** The maximum $|\beta|$ values on the B_1^+-ΔB_0 grid for the 2ms, 6ms Fermi and 2ms optimized waveform are 0.025/0.028/0.010, respectively. Figure 2 shows the BS phase gain of the optimized waveform compared to 2ms (left) and 6ms (right) Fermi pulses with a constant 4kHz offset. Finally, the 2ms waveform had a constant block amplitude modulation and the phase modulation function shown in Figure 3 (red) along with the phase modulation of the 2ms Fermi pulse (blue).

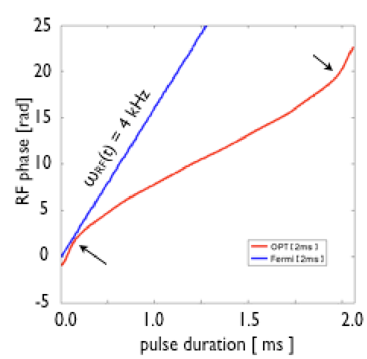

Fig.3: RF phase modulation of 2ms Fermi with a constant 4kHz offset (blue) and 2ms optimized waveform (red). Arrows point to non-linear behavior of the phase at the beginning and the end of the waveform.

Discussion: What distinguishes our approach from previous work [2] is the setup of optimization problem, in that we maximize the sequence's sensitivity directly, and use a non-convex optimization algorithm to seek the global maximum of the sensitivity objective. We do not make any approximations regarding the functional dependence of BS phase on $|B_1^+|$ or $\omega_{RF}(t)$. The optimized waveform achieves the same sensitivity and excites as little on-resonant magnetization as a much longer Fermi pulse. This will improve the robustness of this B_1^+ mapping method and opens doors to new applications. The interesting analytic shape of this waveform (constant amplitude modulation and smooth non-linear phase modulation (arrows in Figure 3)) will be a subject of further investigation.

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References: [1] Sacolick et al., MRM 63: 1315, (2010); **[2]** M.M. Khalighi, et al., Proc. Intl. Soc.Mag. Reson. Med. 19 4431 (2011). [3] J. Pauly et al., IEEE Trans. on Med. Imag., 10 53 (1991)