Challenges and solutions for accurate magnetization reversal and tipping outside the RWA

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EUROMAR 2023 - *Poster 005, pp. 201-202*

Challenges and solutions for accurate magnetization reversal and tipping outside the RWA

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Introduction

In low static field, with a linear rather than circular polarized rf field, a breakdown of the rotating-wave approximation (RWA) may occur and lead to significant deviations from expected trajectories on the Bloch sphere. The effects depend strongly on several factors including detuning (via the static field or rf frequency) and pulse characteristics (phase, amplitude, shape, or transients).

Aims

Using simulations and experiments, we seek to explore the many combined effects that one must consider when using pulsed linear rf fields outside the RWA. We aim to develop practical strategies that can be employed in this regime to generate accurate tip angles.

Methods

Relaxation and diffusion were ignored in simulations. The Bloch equation was solved via numerical integration to compute the magnetization vector in the laboratory frame. Either nominal or recorded coil currents were used as inputs in the simulations. Experiments were performed in a home-made 3-mT MRI system[1] with wired rf coils[2], using laser-polarized ^{3}He gas or thermally-polarized water samples.

Results

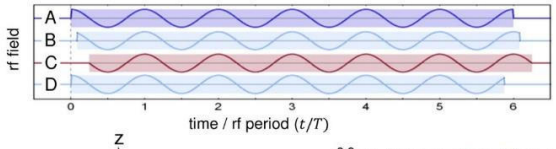
The desired terminus can be achieved through the application of a suitable phase-dependent Bloch-Siegert shift, notably different from that of cw NMR, and appropriate consideration of pulse timings[2]. The figure displays selected simulation results obtained for rectangular Π pulses: rf-driven North-South trajectories, terminus points, and Bloch-Siegert shifts needed to reach the South pole. Experimental data are in good agreement with expectations. They are very sensitive to fine details in coil currents and rf fields.

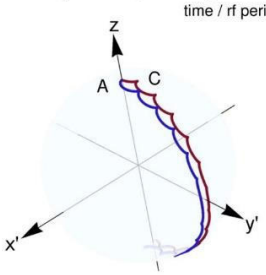
Conclusions

For any pulse duration and start phase, a shift from resonance and a small change in rf amplitude can be used to compensate for inaccuracies induced by operation outside the RWA. Practical considerations arising from this work and prospects for further investigations will be described.

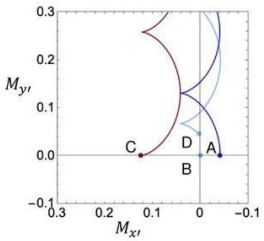
[1]Nacher et.al., J. Magn. Reson 310 (2020) 106638
[2]Bidinosti et.al., J. Magn. Reson 345 (2022) 107306

Outside the RWA: Rectangular π-pulses of equal areas ($B_1 t_\pi$) but different start phases (ϕ_s) and durations ($t_\pi = \nu_\pi T$) lead to different trajectories on the Bloch sphere and do not all produce accurate magnetization reversal.





Trajectories for pulses A and C

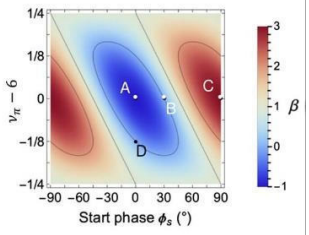


Terminus near south pole

Bloch-Siegert shift for rf pulses:

$$\delta B_{\mathrm{p}} = \beta\left(\frac{B_\omega}{16\nu_\pi^2}\right)$$

where $|\gamma|B_\omega = 2\pi/T$.



	ϕ_s	ν_π	β	rf amplitude
A	0°	6	-1	nominal B_1
B	30°	6	0	nominal B_1
C	90°	6	3	nominal B_1
D	0°	$5 + 7/8$	0	increase B_1 by 1.5%

Conditions required to achieve terminus at the south pole