

Quantum Control and magnetic-field gradients

‘Quantum Control’ is TeachSpin’s name for a recently-developed tabletop apparatus that allows students to study, in exquisite detail, the dynamics of a driven transition in a quantum-mechanical two-level system. We’ve devoted Newsletters of May 2022 and May 2024 to some of the many investigations that can be performed using this system. But (as is usual with TeachSpin apparatus) there is more that can be done, and in this Newsletter we show how our system can be used to help students understand that B is not just a number, but a *field* – that is, something showing variation from point to point in space.

This works because our two-level system is formed by the spin-up vs. the spin-down states of protons’ magnetic moments in a B -field of magnitude about 2000 μT (20 gauss). Ideally that field would be perfectly uniform in magnitude over the full volume (58 cm^3) of the proton-containing sample. But the resolution of our detection technique is such that even tiny spatial variations in that field strength have

detectable consequences. Better still, this claim is readily checked via the deliberate *cancellation* of those variations-with-position (that is, those spatial gradients) using the simplest of ‘correction coils’ to achieve such a tailoring of the magnetic field.

If you’ve seen signals from a Quantum Control unit, you might have seen images like those shown in Fig. 1 below. These depict behavior captured in single ‘runs’ of the experiment, covering 500 ms in time. At the left, we ‘prepare’ the spin system; at the midpoint in time, we ‘intervene’ in the spin system; everything else is the result of the spin-system’s free evolution in time. The payoff is the ‘spin echo’ that appears toward the right side of those images. We’ve commented in previous Newsletters on how the *strength* of that spin echo is a wonderfully useful indication of the success of the intervention in driving a quantum transition. Here, we remark on the *width*-in-time of that spin-echo signal, which is something we can *not* predict for your QC unit at your location.

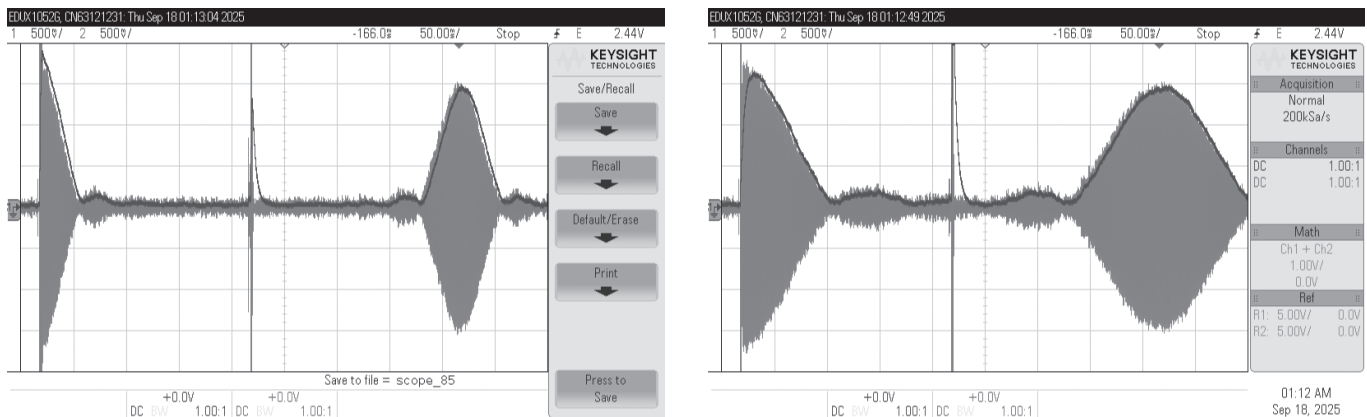


Fig. 1: At left, a spin-echo sequence obtained without any gradient correction. At right, the results obtained when an optimized dB_z/dz counter-gradient is added.

That's because that width, that 'timescale for decoherence of the signal', depends in practice on the non-uniformity of the B -field's strength over the sample volume. If the field strength differs by just 1 μT between two locations at a typical separation 0.04 m in the sample, then the precession frequency of spins will differ by 1 part in 2000 at these locations. So after 1000 such cycles, some protons' spins will have precessed half-a-turn farther than others, and that's the reason for the magnetic-moment cancellations causing the spin signals to die away prematurely. Sure enough, with precession cycles coming every 10 μs or so, this causes decoherence on a time scale of about 10 ms.

In practice, the chief spatial gradient causing this decoherence is dB_z/dz , and happily that gradient is the easiest to correct. A simple kind of 'gradient coil' is formed with two circular coils, like a Helmholtz pair -- except with a twist. We arrange for the two coils to carry currents in *opposite* directions, so at their geometrical center they jointly create zero field. But away from center, there is a non-zero field, one which is locally dominated by a linear z -gradient in $B_z(z)$. That gradient is optimally uniform for a spacing between the two coil planes of $\sqrt{3}$ times the radius of each circle, and it has magnitude

$$\frac{dB_z}{dz} = \frac{\mu_0 N i}{a^2} \cdot \frac{48\sqrt{3}}{49\sqrt{7}} \cong 0.64 \frac{\mu_0 N i}{a^2} .$$

In Fig. 2 we show two coils, each of $N = 2$ turns, wound in 'series opposition' onto a cylindrical cardboard casting-tube of radius $a = 82$ mm, and positioned so that the geometrical center of this new coil system coincides in space with the sample volume of our QC apparatus.



Fig. 2: A 'jury rig' of a dB_z/dz gradient coil, wound onto a cardboard tube, and put into place around the solenoid of a Quantum-Control apparatus.

It takes only modest currents (< 0.1 A) in such a coil system to produce a (counter-)gradient that's adequate, calculable, and under our control. And we can empirically find the sign, and the magnitude, of the current i which best succeeds in cancelling the pre-existing gradient, as revealed by the lengthening of the decoherence timescale of the spin-echo signals. That coil, and that optimization, is what made the difference between Fig. 1a and 1b on page 1.

In the example above of Fig. 1, no part of the sample had its field-strength change by more than ± 0.4 μT (1 part in 5,000!) by the application of this gradient, yet the change in the spin echo's duration is easily seen. And this is just the *beginning* of gradient control. Better results can be obtained if the axis of QC's main solenoid is tilted so as to lie parallel to the local direction of the ambient field. Still better results are available to those who work out how to deal also with the 'transverse gradients' dB_z/dx and dB_z/dy . In Fig. 3 (next page) we show what can be achieved with a tilted solenoid, and the successive optimization of 0, 1, 2, and 3 gradient corrections:

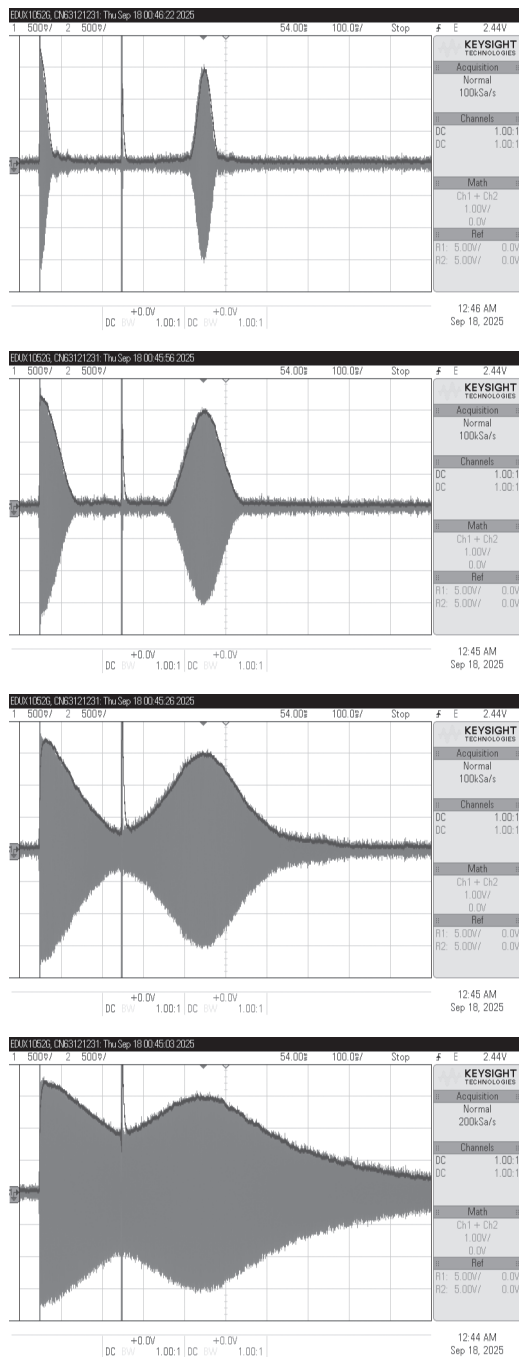


Fig. 3: Spin-echo sequences obtained with 0, 1, 2, and 3 gradients corrected. The images each show signals obtained during 1 full second of time evolution of a proton spin system.

The response of the spin system to the intervention shows that there are still some residual imperfections in the magnetic field, but we have certainly shown that three first-order gradient corrections can be independently optimized. (Note too that while these gradient corrections have changed the width of the spin echo, they didn't affect its *height* – this shows that the spin-echo signal's strength is robust against the effects of gradients.)

In the laboratory, it might be our goal to minimize gradients of a magnetic field. But in the world outside the lab, gradient coils such as these are used to create *intentional* gradients, which thereby enable the technique of MRI = magnetic-resonance imaging. It's a tailored spatial gradient in the magnitude of the field which makes possible the mapping from position-space (from place to place inside the patient) to frequency-space (where proton-NMR signals from the patient can be analyzed); such a mapping is part of what makes this form of medical imaging possible.

Alternatively, you could turn your mind to contemplate the left-hand side of Maxwell's Equations, with their $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$ operators – what are these objects, if not combinations of first-order spatial gradients of the magnetic field's components? A student project on gradient control in the context of QC will add hands-on experimental familiarity to these otherwise theoretical and mathematical entities.



Fig. 4: Silver-soldering is a technique used at TeachSpin in the fabrication of some cryogenic apparatus, one which requires more heat than a soldering iron can deliver. We accomplish this at our 'welding bench'; here Jonathan Reichert is seen passing the torch to David Van Baak.

Here's another kind of quantum transition: TeachSpin's founder Jonathan Reichert has decided to retire, after some 30 years' work, from his position as CEO of TeachSpin (though he continues to chair the Foundation which owns the company). The Board of the Foundation, at a recent meeting, chose David Van Baak to take over the role of CEO of TeachSpin. There's no *replacing* a person like Jonathan Reichert; but under its new staffing, the mission of TeachSpin remains unchanged.



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Inside:

**Using ‘Quantum Control’ to
learn about magnetic-field
gradients**

**See the ‘changing of the guard’
at TeachSpin**

Career Opportunity for Experimental Physicist

TeachSpin Inc. of Buffalo, New York, an internationally recognized designer, developer, manufacturer, and marketer of Advanced Laboratory physics instructional apparatus, is searching for an experimental physicist with experience in creating physics apparatus. An MS in physics is required, but preference will be given to those with a PhD and having experience in teaching the Advanced Laboratory.

At TeachSpin we focus on a single goal: enhancing the Advanced-Laboratory experience for undergraduate physics majors, through the creation of modern hands-on apparatus and experiments specifically aimed at this level.

If you have long-term career aspirations to make a difference in experimental physics education in the world, this might be the opportunity for you to realize that goal. Send your resume and a cover letter to dvanbaak@teachspin.com.

Buffalo is a recovering metropolitan city, located on Lake Erie, with a vibrant theater, classical-music, and arts community. A two-century tradition of immigration, one that continues today, has led to an outstanding collection of ethnic restaurants and cultural events. The city has a rich architectural heritage, dating from the era of the “Queen City”, then the sixth-wealthiest in the USA. An era of depopulation, now ending, has provided highly affordable housing. In short, Buffalo is a welcoming and friendly community -- a great place to live.

TeachSpin’s website is www.teachspin.com ; TeachSpin is an asset of the non-profit Jonathan Reichert Foundation, www.jfreichertfoundation.org .