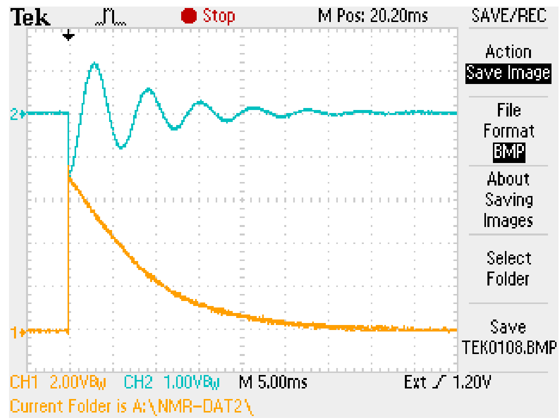
An Introduction to One-Dimensional Imaging with the TeachSpin Pulsed/CW NMR

When two sounds close in frequency are played simultaneously, two distinct sounds do not occur. Instead, our ear hears one sound that waxes and wanes with a frequency equal to the frequency difference between the two sounds. This phenomenon, common to all wave interference, is exploited when using FFT to create a one-dimensional image for the TeachSpin PS2.

The beat phenomenon is first used to find the resonant frequency for a free induction decay(FID) from a single layer sample. Electronics built into the PS2 multiply the rf frequency being used to tip the spins with the actual precession frequency the spins exhibit after the pulse.

This 'heterodyned' signal is available at both the I and Q outputs of the Receiver Module. It shows a beat frequency equal to the difference between the rf input and actual precession frequency of the protons. When working with the FID, the oscillator frequency is adjusted to achieve **zero beat** – a match of frequencies – so that the system is 'on resonance'.

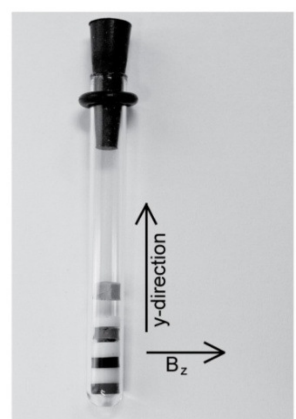
The upper trace in our screen capture is from the Q output. (The phase of the I output would differ by 90 degrees.) The beat signal indicates that when this measurement was made, the system was not exactly 'on resonance', but it is very close and requires only a little tweaking.



Upper Trace: Beat or Difference Signal
Lower Trace: FID Envelope

For 1-d imaging the process is quite different. Now we want the oscillator frequency far enough 'off resonance' to create an observable beat signal, but still close enough that the spins will 'tip'. For instance, if we adjust the rf of the oscillator to 200 kHz off resonance, a Fast Fourier Transform, FFT, of the I or Q output signal would show a single peak at 200 kHz, the 'beat signal', the ΔF .

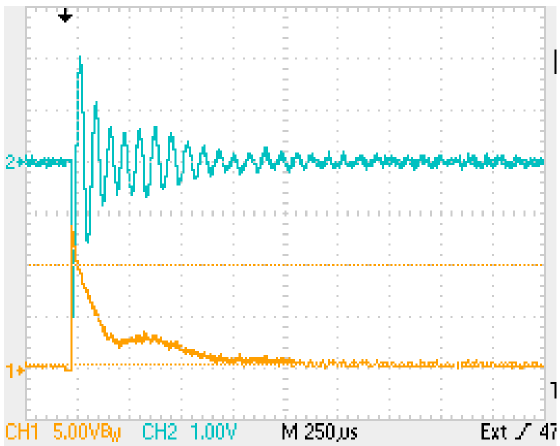
The layered samples we use for our 1-dimensional-image alternate thin discs of soft solids containing lots of protons with spacer discs that have almost none. When we create a field gradient along the axis of the sample coil, each of the discs containing protons will be in a distinctly different magnetic field. The protons of each disc will, therefore, have a significantly different precession frequency. Now, when we multiply the output signal from the precessing protons with the rf of the oscillator, multiple beat frequencies are created, one for each proton filled layer.



Layered Sample

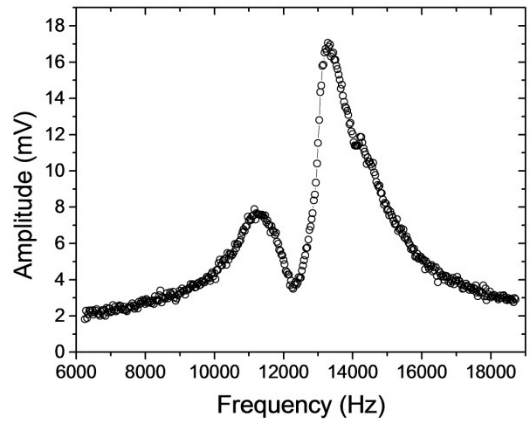
The range of beat frequencies will depend on the size of the gradient and the thickness of the spacers. On an oscilloscope, all of these signals merge into one sinusoidal like pattern. The FFT of this signal will have as many peaks as there are layers, each peak showing the difference between the oscillator frequency and the precession frequency of that particular set of protons. If the spacers in the sample tube all have the same thickness, then the proton filled layers will be equally separated within the sample tube. Because the applied gradient will be linear, the beat signals will then have equal differences in frequency space. Given the magnitude of the gradient and some relatively simple math, we can turn the frequency spacing into physical spacing within the sample tube. And now we have an 'image' of where the proton filled discs are located. The width of a particular peak indicates the height or thickness of the reacting disc. The thicker the disc, the greater the change in the magnetic field due to the gradient along the disc axis, and thus in the difference between the precession frequencies of the protons.

The FFT can even tell us something about the material in the each of the layers. The sharpness of the peaks is related to both the length of the sample along the gradient and T_2, the rate at which the spins dephase due to differences in internal magnetic fields. Changing the repetition time, the time between rf pulses gives some interesting information. If we significantly shorten the rep time, the amplitude of some of peaks will decrease significantly. The materials in those discs are not able to return to thermal equilibrium between pulses. The T_1 for the material in those layers is long compared to the rep time being used.



FID signals on a digital oscilloscope.

Lower trace is from the envelope detector and the upper trace is the signal from the Q output.



FID signal from Q, phase detector examined on the SR770 spectrum analyzer.

Using a multilayered sample in which the proton filled layers are not evenly spaced, the location of the large gap in the FFT will clearly show the direction of the applied gradient.

While the FFT of a standard 'scope shows general patterns, a true spectrum analyzer, such as the Stanford Research Systems SR770, allows you to make far more precise measurements. Although the FFT function on an oscilloscope does have a zoom function, the higher resolution of a spectrum analyzer makes the spacing of the peaks easier to see and the frequency measurements more accurate. In addition, the amplitudes of the peaks in oscilloscope FFT patterns are not calibrated so the magnitudes cannot be compared in any detail and results are often not reproducible. On a good spectrum analyzer, the change in amplitudes, as repetition times are varied, can be used to find the T_1 of the various layers.

Thinking about why we use beat signals rather than the actual frequency values to identify layers in a field gradient: The actual precession frequencies of the protons will be in the area of 21 MHz and the variation between the frequencies at the 'top' and 'bottom' of the gradient will be on the order of 10 to 20 kHz. To see these differences using the actual frequencies would require resolution on the order of a part in ten thousand. That is a major 'zoom', even for a very precise instrument. Working with the output from the I or Q connections, the 'beats', the signals are only in the tens of kHz range. The differences between these 'beat' frequencies are in the one to ten kHz range. And, of course, the difference of the differences is just the difference itself!

$$(F_{\text{synthesizer}} - F_{\text{protons at location A}}) - (F_{\text{synthesizer}} - F_{\text{protons at location B}}) = F_{\text{protons at location B}} - F_{\text{protons at location A}}$$