## Lecture #5

2-D Imaging and Slice Selection

The NMR Microscope

There are many excellent descriptions of NMR instrumentation, here the focus is on the changes necessary to implement microscopy on a high resolution, high field spectrometer. Fortunately these are quite modest, since many spectrometer have the necessary gradient amplifiers and controllers, and all modern instruments are capable of performing the experiments. The fundamental difference is the NMR probe, shown schematically below.
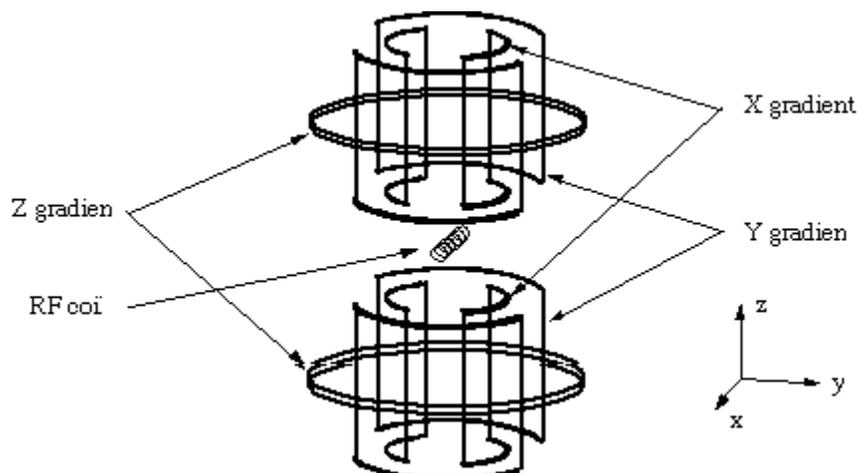
A schematic representation of the NMR microscopy probe, the magnetic field is along the vertical axis. The probe has a small RF coil wrapped tightly about the sample, the good filling of the coil is necessary to reduce resistive losses in the coil. This is surrounded by three gradient coils that are connected to audio frequency amplifiers. The z-gradient is a Maxwell pair through which currents flow in opposite directions. Moving inwards, the x and y-gradient coils are each composed of four semi-circular current paths through which currents flow in parallel.

Notice that the field of view is normally limited physically by the size of sample that can be accommodated in the RF coil. This is advantageous for sensitivity reasons, and quite necessary for reasonable experimental times. Some typical values are given in table 2.

Table 2 Some typical NMR Microscopy Probe Configurations

field of view	2.5 cm	1.0 cm	2.5 mm
resolution	100 μm	20 μm	5 μm
gradient strength	50 G/cm	100 G/cm	1,000 G/cm
magnet	9.6T/89 mm	9.6T/89 mm	14T/54 mm

2-D Imaging

Having seen that by applying a magnetic field gradient one can encode a 1-D image and collect a

projection of the spin density of the sample, one clear path to 2-D imaging is to collect a series of such projections with the gradient at various orientations and then to use Radon filtered back projection to reconstruct the image. Early NMR images were acquired in this fashion, and occasionally solid state images still are. However, most imaging is performed via Fourier Imaging where a 2 or 3-D region of reciprocal space is sampled corresponding to the desired resolution and field of view. Such data are easily measured since the gradients are under experimental control and virtually any gradient waveform can be generated. Since the various sequences can be rather complex, often a pictorial representation of reciprocal space is employed where the trajectory of the experiment is mapped out. It is then possible to focus on the manner in which 2-D k-space is sampled rather than to get caught up in the details of the NMR experiment.
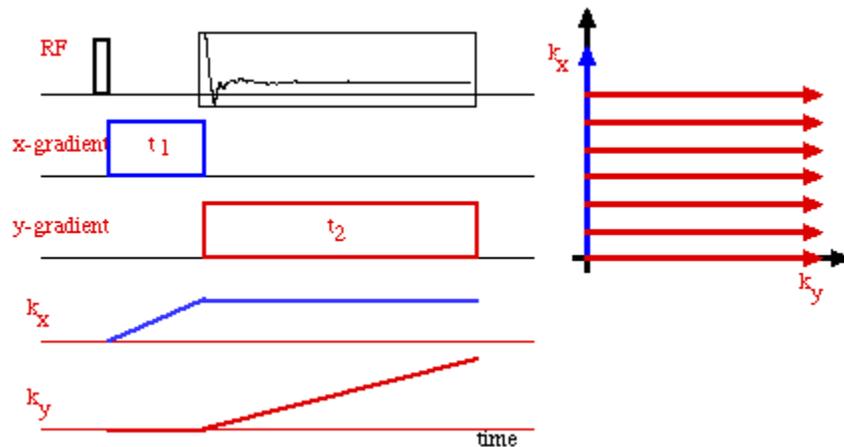
A generic 2-D Fourier imaging experiment. The data are collected on a Cartesian raster during the time period labeled t_2, and in the presence of a y-gradient. Prior to this, a brief x-gradient pulse has been applied to create a magnetization grating in the x-direction. The collection period therefore corresponds to the red rays in the reciprocal space picture at right, and reach individual ray is collected during a separate experiment. The length of t_1 is systematically varied to achieve the desired offset along the k_x axis.

Notice that the imaging experiment contains two fundamentally different times, a phase encoding interval (t_1 during which no data are acquired) and a frequency encoding interval (during data acquisition). These two times permit the separate encoding of the two interactions - the gradients in the two orthogonal directions - and thus allow all of k-space to be sampled. The image is the 2-D Fourier transform of the collected data.

The gradient evolution during the phase encoding interval can be carried out in two fashions, the gradient strength can be kept constant and the time incremented, or the time can be kept constant and the gradient strength incremented. The second, called spin-warp imaging, has advantages since the extent of the evolution due to chemical shift or other non-gradient interactions is kept constant and these then appear solely as a signal attenuation factor. The resultant point spread function for a constant encoding time is an attenuated delta function (neglecting the contribution from sampling).

There are a wide range of imaging sequences and we will not attempt to review these here, they all include the general features shown above. The two dimensional experiments can be extended to three dimensions by encoding the third direction as a second phase encoded axis.
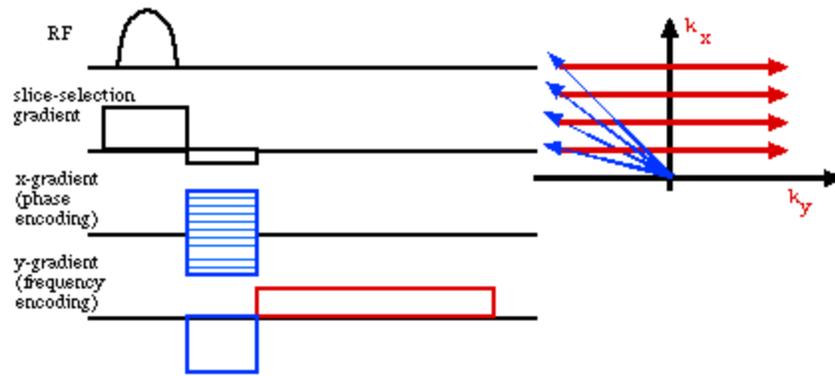
Slice Selection

Recording a full three dimensional image is often not the most economical approach to imaging and slice selection can be achieved by taking advantage of the frequency offset dependence of RF excitation. Looking back at the Bloch equations, Eq. [9], for an on resonance RF pulse ($\Delta\omega$=0) the RF field is along the x-axis and hence the evolution of the spins is a simple rotation about the x-axis. However as $\Delta\omega$ increases, then the dynamics become more complex and are most easily visualized by considering an "effective" field that is the vector sum of the RF field along the x-axis and the off-resonance field along the z-axis. The dynamics are still a simple rotation about this effective field, but the motion of the magnetization vector now describes a cone rather than a plane. The result is that as the frequency offset is increased the angle of the effective field to the z-axis decreases and eventually the RF pulse has very little influence. The key to slice selection then is to apply a relatively weak RF pulse in the presence of a strong gradient, so that the frequency offset is spatially dependent.
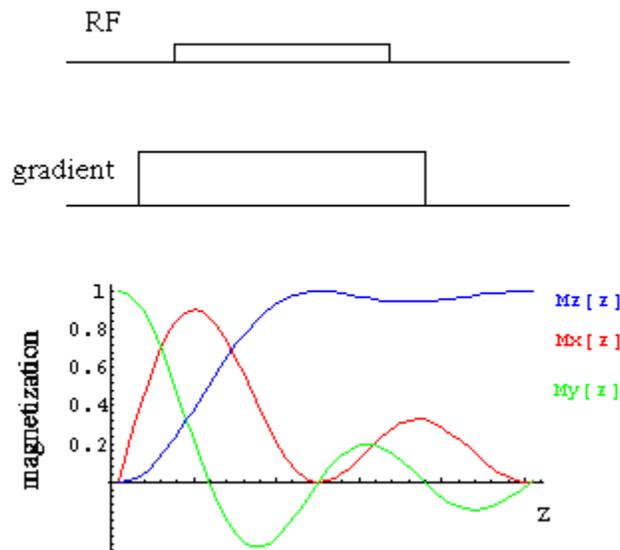
Calculated selective excitation profiles for a weak RF pulse in the presence of a magnetic field gradient. The pulse length is set to rotate the on-resonance spins (at the origin) by 90°, and notice that as the resonance offset increases (with increasing z) the effective rotation angle becomes smaller and most of the magnetization remains along the z-axis. For most images, a shaped RF pulse is employed that creates creates a square magnetization profile.

There is not a simple linear picture of the dynamics, but various shaped (amplitude modulated) RF pulses have been developed that give well defined square slice selection profiles.

So the overall slice selected 2-D imaging experiment might look like,

A slice selected 2-D spin warp, gradient echo sequence. Notice that during the phase encoding time the ky vector is offset so that both positive and negative values can be sampled. Since NMR is a coherent spectroscopy, this has the advantage of measuring the phase. The gradient echo in the slice selection direction refocuses evolution of the spins during the selective RF pulse.