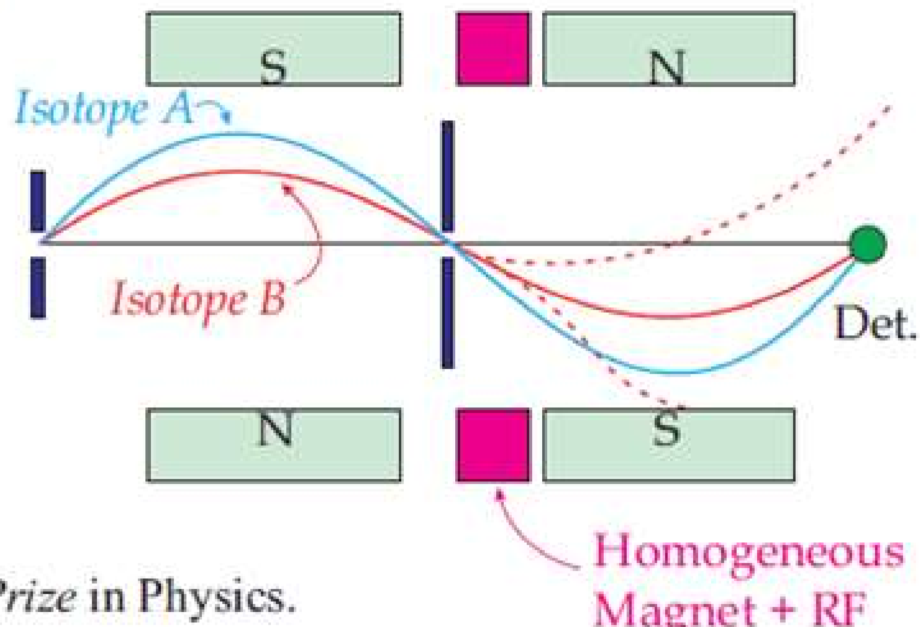
Dr. Rabi: electron's magnetic moment in homogeneous magnet!

1938 I.I. Rabi (Columbia) refines the Stern & Gerlach technique to observe the effect from the nuclear magnetic moment. Using a homogeneous magnet (with field strength B) and applying a specific radio frequency he observed that a beam of atoms split into separate paths. This showed that there were quantized energy levels separated by:

$$\Delta E = \gamma \hbar B_0$$

Highly accurate magnetic moments were obtained with this method.

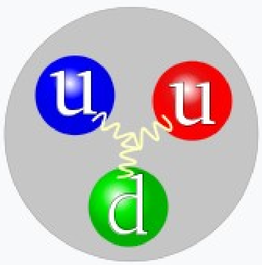


1944 Rabi wins the *Nobel Prize* in Physics.

Limitation: Only applicable to molecular beams under high vacuum.

NMR basics: properties of quarks and some nuclei!

Quark



A proton is composed of two up quarks, one down quark, and the gluons that mediate the forces "binding" them together. The color assignment of individual quarks is arbitrary, but all three colors must be present.

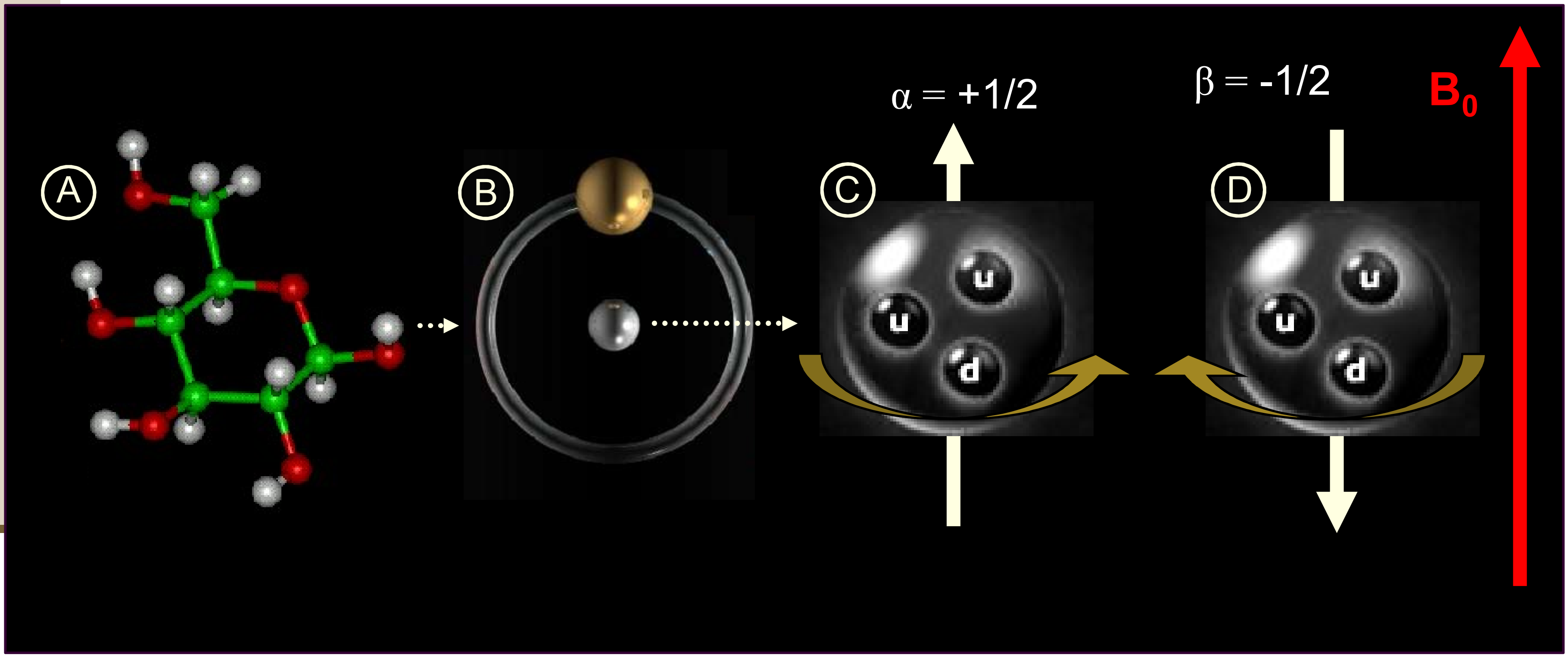
Composition	Elementary particle
Statistics	Fermionic
Generation	1st, 2nd, 3rd
Interactions	Electromagnetism, gravitation, strong, weak
Symbol	q
Antiparticle	Antiquark ($\bar{q}$)
Theorized	Murray Gell-Mann (1964) George Zweig (1964)
Discovered	SLAC (c. 1968)
Types	6 (up, down, strange, charm, bottom, and top)
Electric charge	$+\frac{2}{3}$ e, $-\frac{1}{3}$ e
Color charge	Yes
Spin	$\frac{1}{2}$
Baryon number	$\frac{1}{3}$

Nuclide	Spin	Natural abundance	Gyromagnetic ratio γ [10^7 rad T^{-1} s^{-1}]	NMR Frequency (at 18.8 Tesla)	Relative receptivity
Proton (^{1}H)	½	99.985	26.7522	799.734 (1)	1.00
Carbon-12 (^{12}C)	0	98.9	-	-	-
Carbon-13 (^{13}C)	½	1.108	6.7283	201.133 (1/3.976)	6.73×10^{-7}
Nitrogen-14 (^{14}N)	1	99.63	1.9338	57.820 (1/13.831)	1.00×10^{-3}
Nitrogen-15 (^{15}N)	½	0.37	-2.7126	81.093 (1/9.861)	3.85×10^{-6}

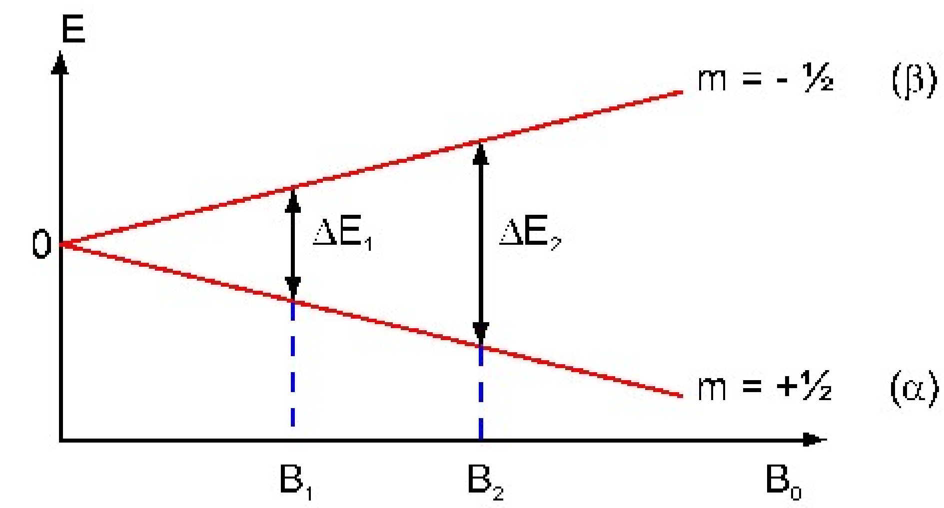
Table 1. Some nuclei properties important for NMR detection.

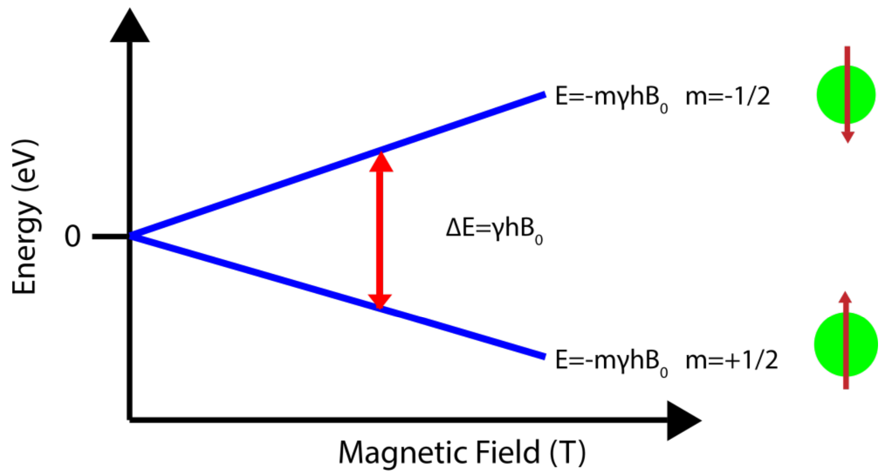
$$\Delta E = \gamma \hbar B_0$$

NMR basics: from molecule to nuclear spin ±1/2 at B_0!



NMR basics: energy levels!





The evolution of NMR magnetic fields!

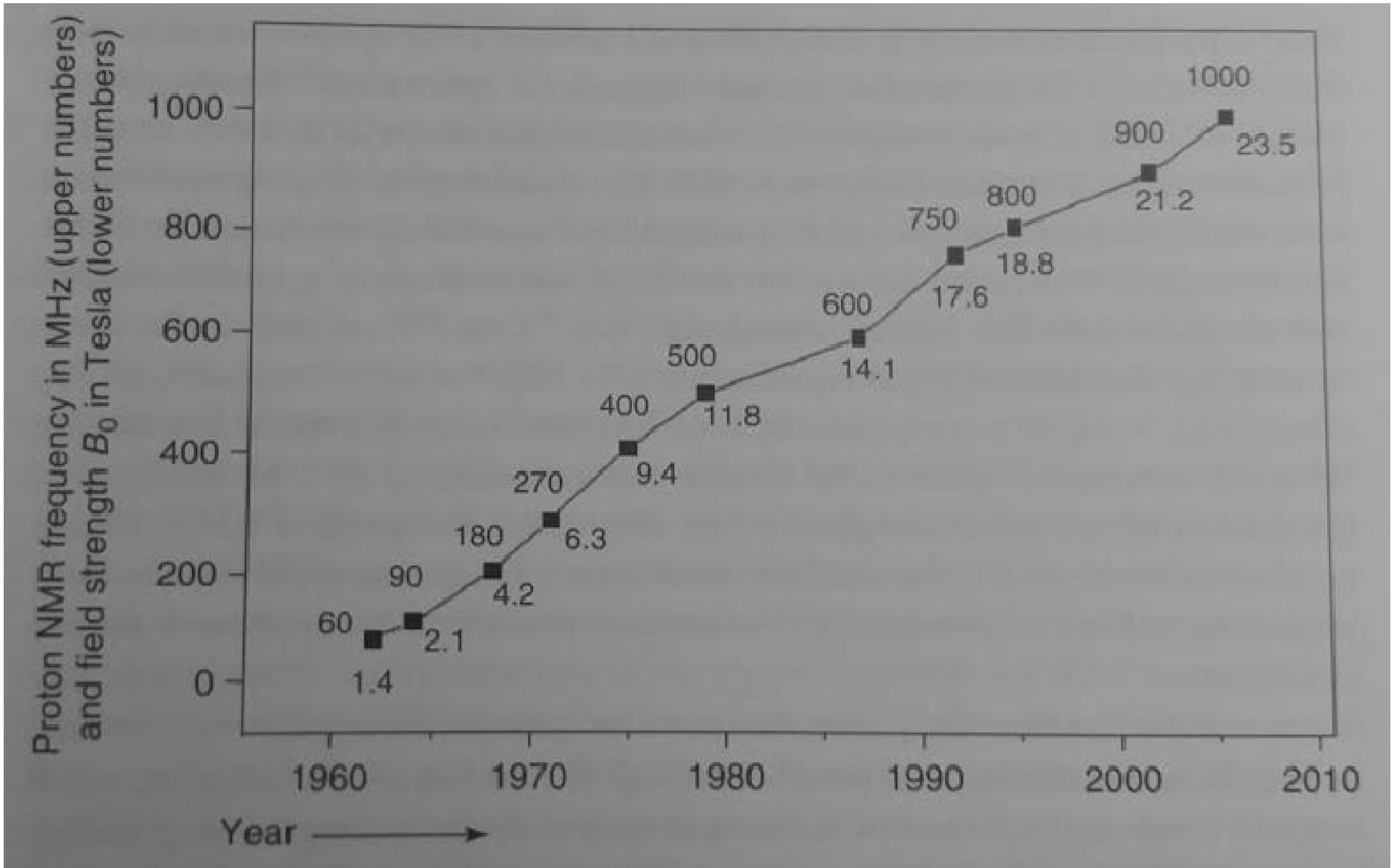
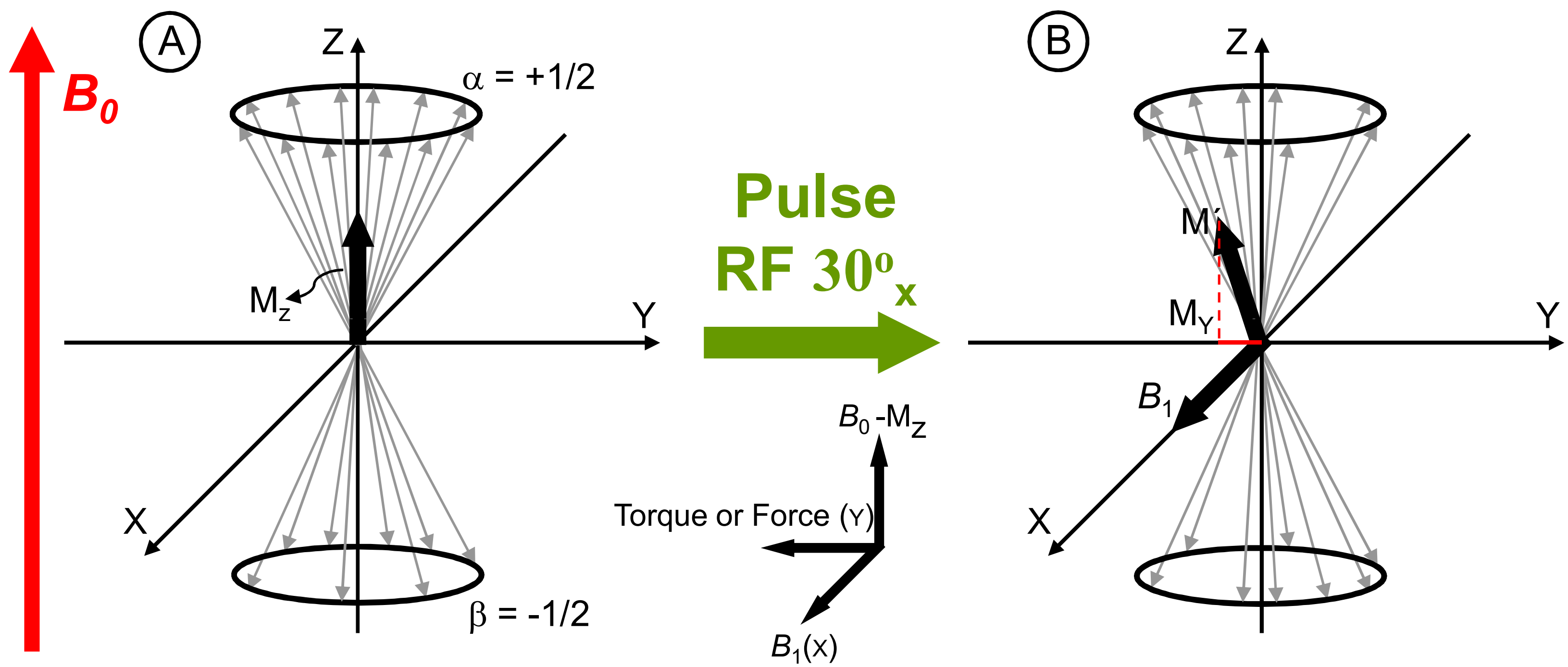
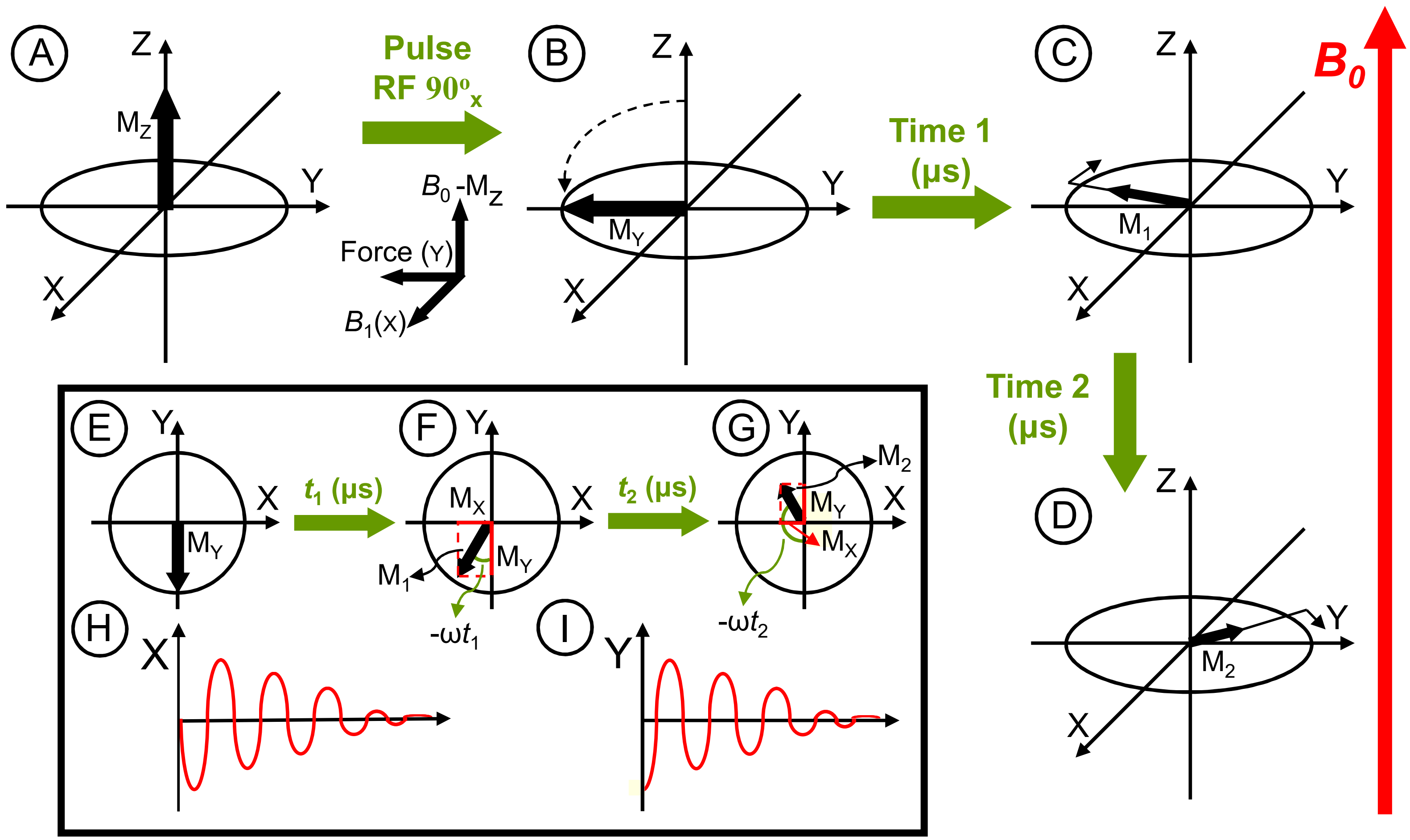


Figure 4.10 Increase of the [1]H NMR frequency and of the magnetic field strength through the development of superconducting magnets.

NMR basics: spin ½ oriented at magnetic field!

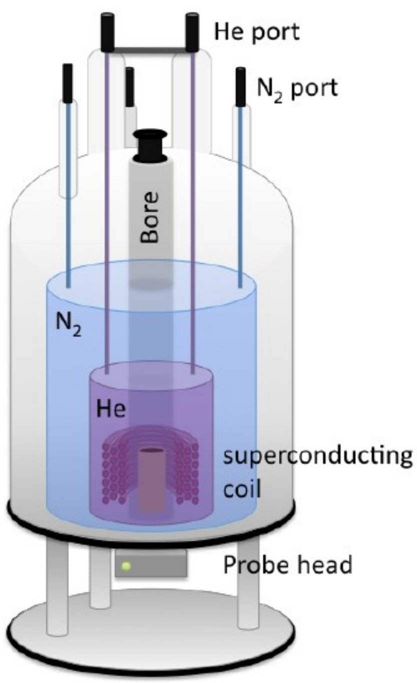


Direction of magnetization changes with pulses!



The NMR instrument

Superconducting Magnet systems



24.0 T (1020 MHz) magnet system (NIMS, Japan)

From the outside:

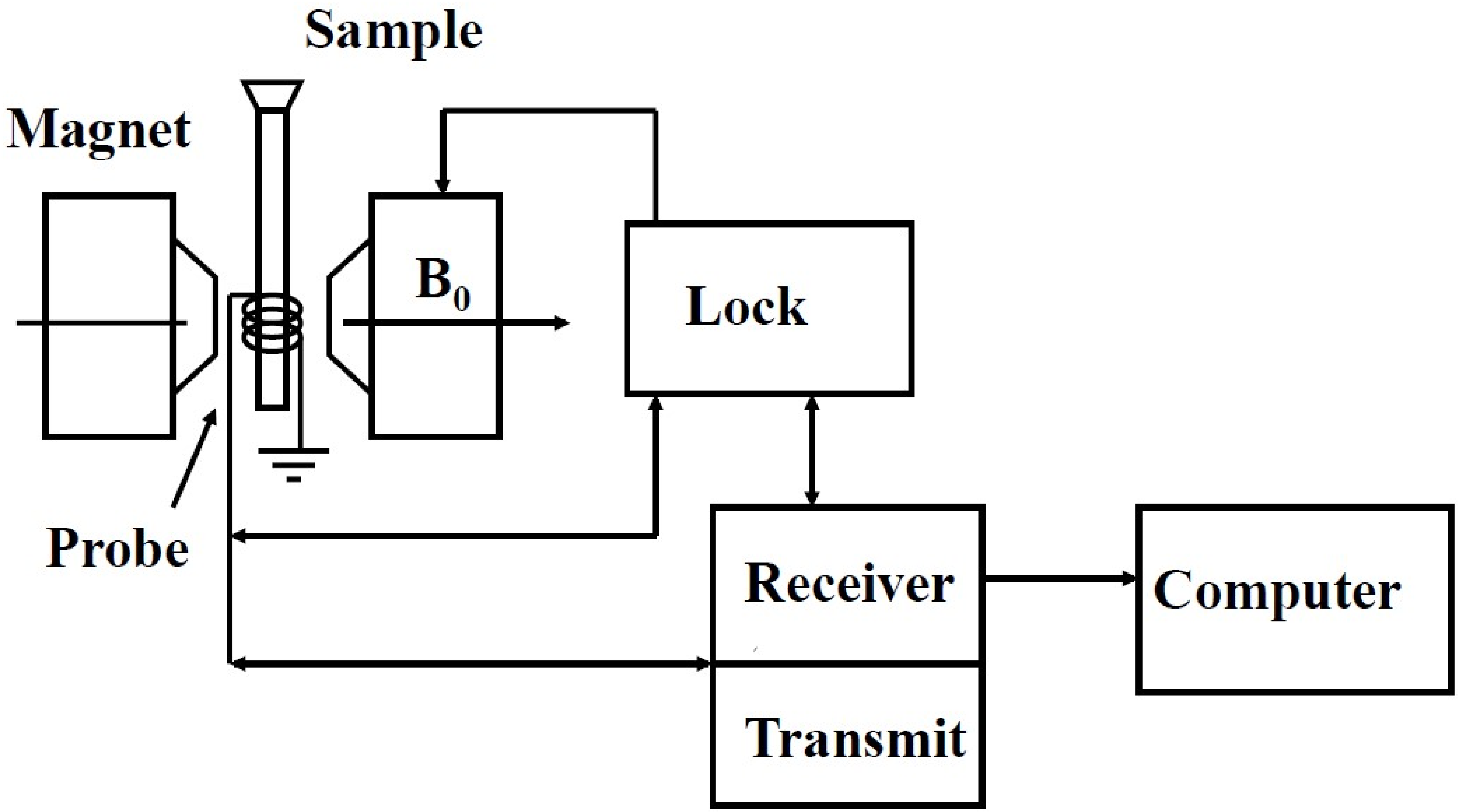
1. **Red** (outer shell)
2. Mylar insulation
3. **Yellow**, liquid N_2 Dewar
4. Mylar insulation
5. **Green**, heat shield
6. **Blue**, liquid He Dewar
7. Superconducting coil (wrapped in silver tape)
8. Copper bore tube (through center of magnet

https://www.chemie.uni-hamburg.de/nmr/insensitive/tutorial/en.lproj/spectrometer.html

https://nmr.science.oregonstate.edu/index.php/Cross-section

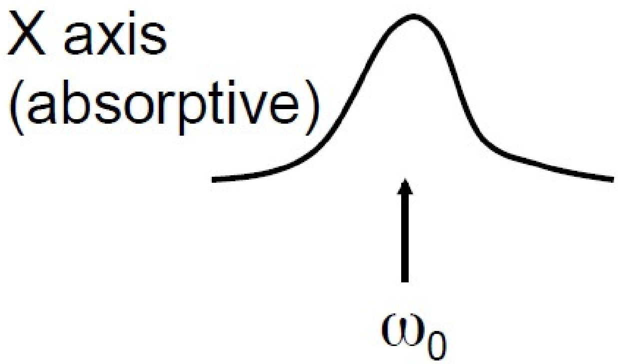
https://www.sciencedaily.com/releases/2015/07/150702184036.htm

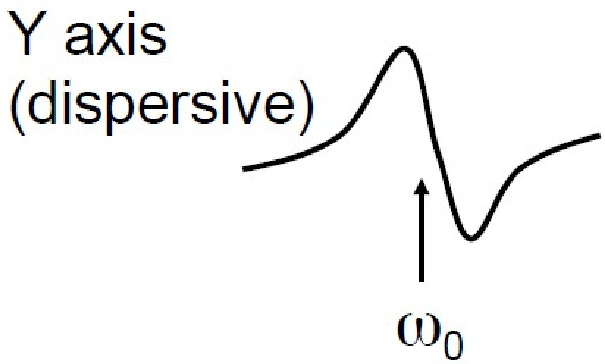
Instrumental Considerations – Block Diagram of an NMR Spectrometer



A Deuterium Lock Stabilizes the Field

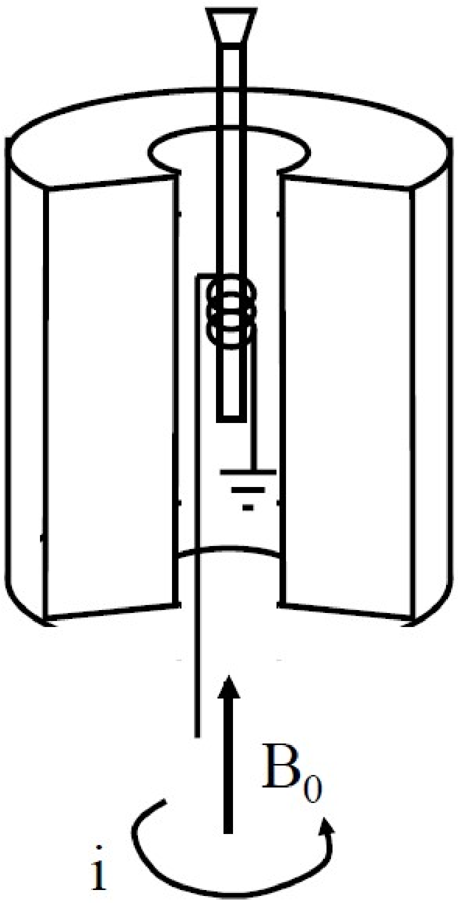
- The field strength of a typical high field NMR magnet will change, or "drift", by a few Hz per hour
- The "lock", or *field-frequency locking system* adjusts the magnetic field to compensate for this drift





Drift of field will produce positive and negative signals
Depending on direction when dispersive signal is observed

Modern NMR Magnets are Superconducting Solenoids



- Advantages:
  - -high field
  - -stability
  - -homogeneity > 1 : 10^9

- Materials: NbTi < 10T, NbSn > 10T
- Max Field (2015): 24.0 T (1020 MHz)
- Hybrid magnets: 45T **

**https://nationalmaglab.org/about/around-the-lab/meet-the-magnets/meet-the-45-tesla-hybrid-magnet

The Hybrid Magnet 45 Tesla!

Meet the 45 Tesla Hybrid Magnet

font size | Print

The world-record 45 tesla hybrid magnet.

This magnet combines a superconducting magnet of 11.5 tesla with a resistive magnet of 33.5 tesla.

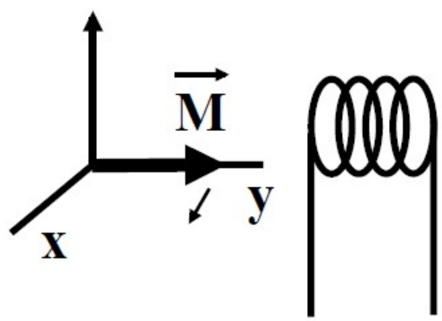
It is in wide demand among scientists across the globe. Although we operate several world-record magnets, this is the only one featured in the *Guinness Book of World Records*.

NATIONAL HIGH MAGNETIC FIELD LABORATORY

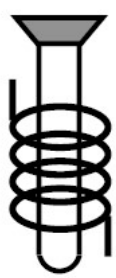
Vital Statistics	
Strength	45 tesla
Type	Hybrid
Bore size	32 mm (~1.25 inches)
Online since	December 1999
Cost	$14.4 million
Weight	31,752 kg (35 tons)
Height	6.7 meters (22 feet)
Operating temperature	-271 ° C (-456 ° F)
Water used per minute	15,142 liters (4,000 gallons)
Power required	30 MW

The probe coils

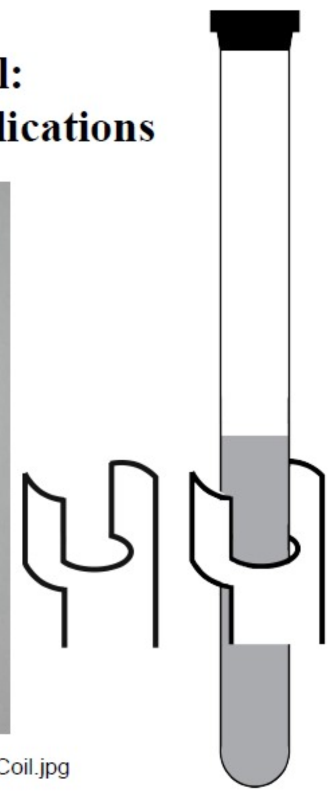
- The probe coil serves a dual role:
  - -to deliver the B_1 field pulse to the sample
  - -and to detect the oscillating bulk magnetization (dM_y/dt)
- The coil is orientated *perpendicular* to B_0



solenoid coil:
-specialized applications



Helmoltz coil:
-normal applications



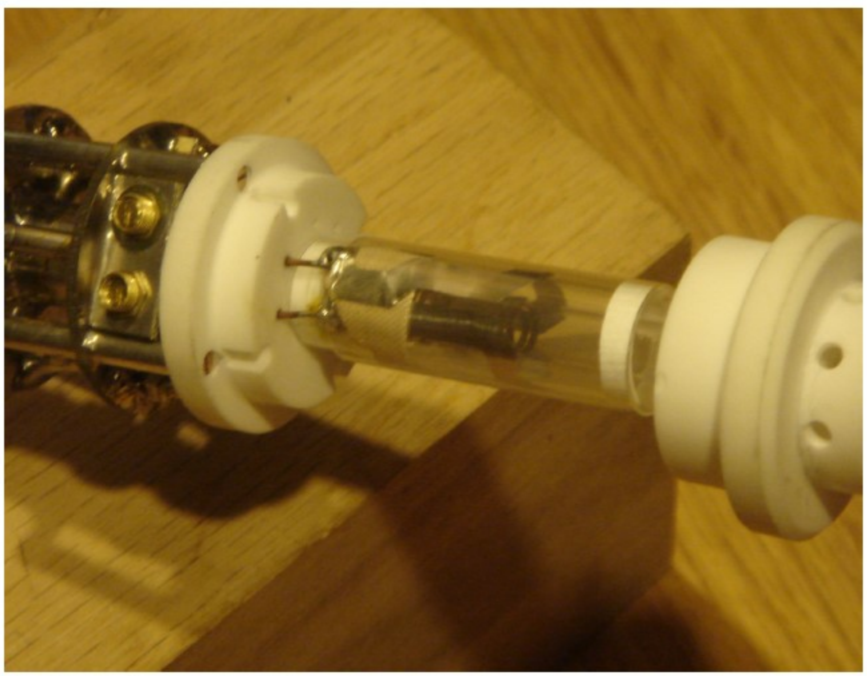
https://nmr.science.oregonstate.edu/index.php/File:Coil.jpg

The NMR probe

This is for a 7T magnet – ^{13}C observe at 75 MHz

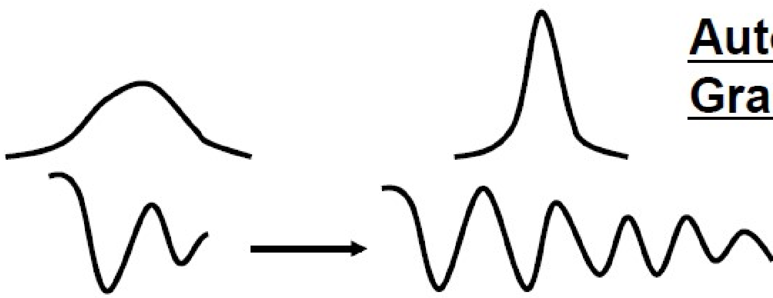
The NMR probe

Probes are delicate – glass, teflon, ceramic, electronics



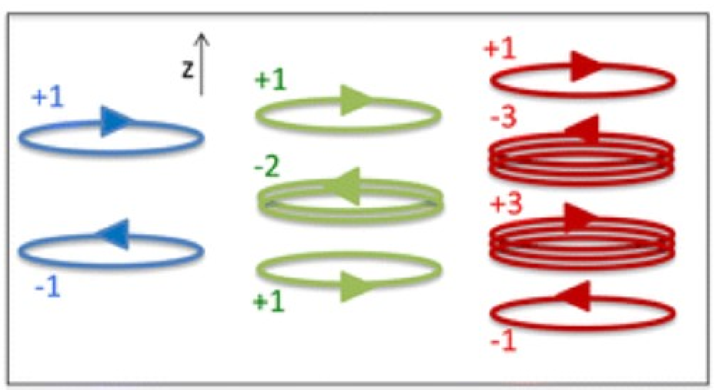
Shimming

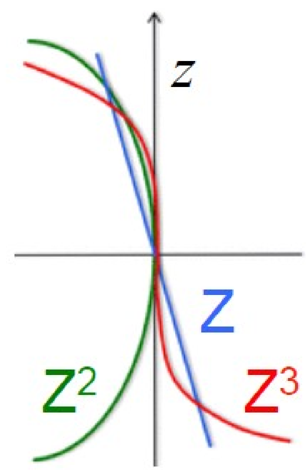
- Shimming improves peak width and S/N (increase homogeneity decrease T_2^* relaxation) and improves peak shape



<u>Auto shim</u>: based on lock signal amplitude

<u>Gradient shim</u>: observe effect of imposed field gradient – deconvolute field inhomogeniety

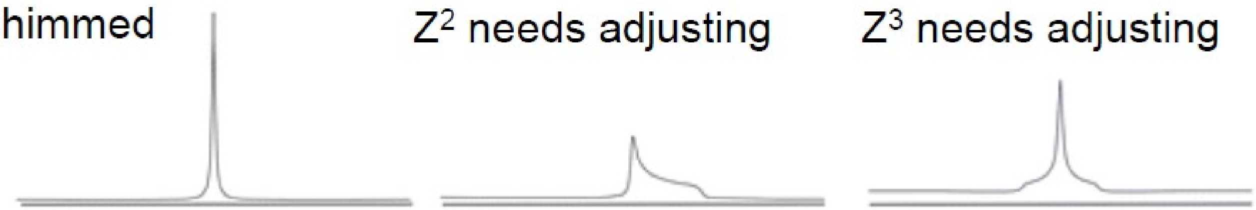




well shimmed

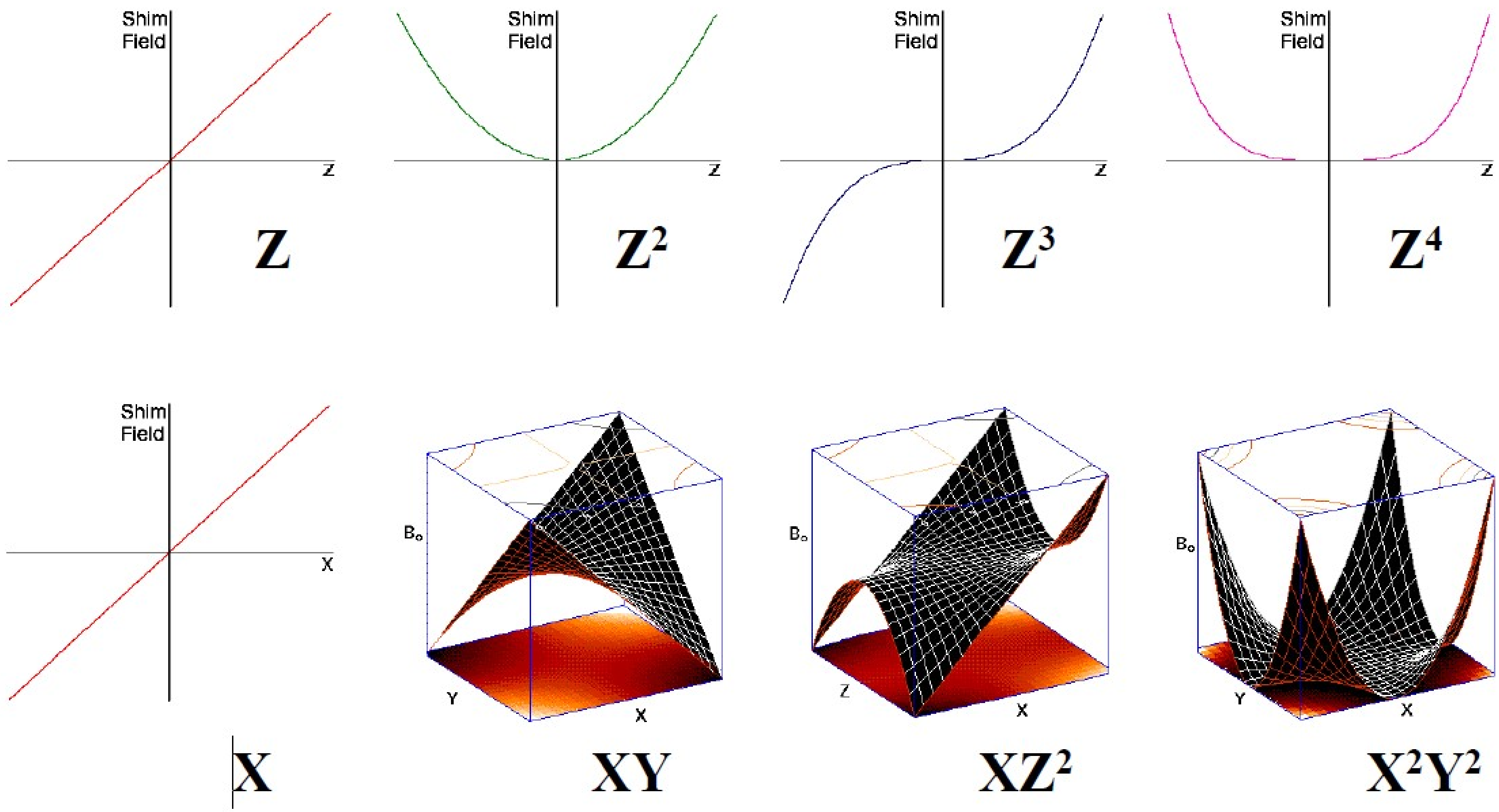
Z^2 needs adjusting

Z^3 needs adjusting

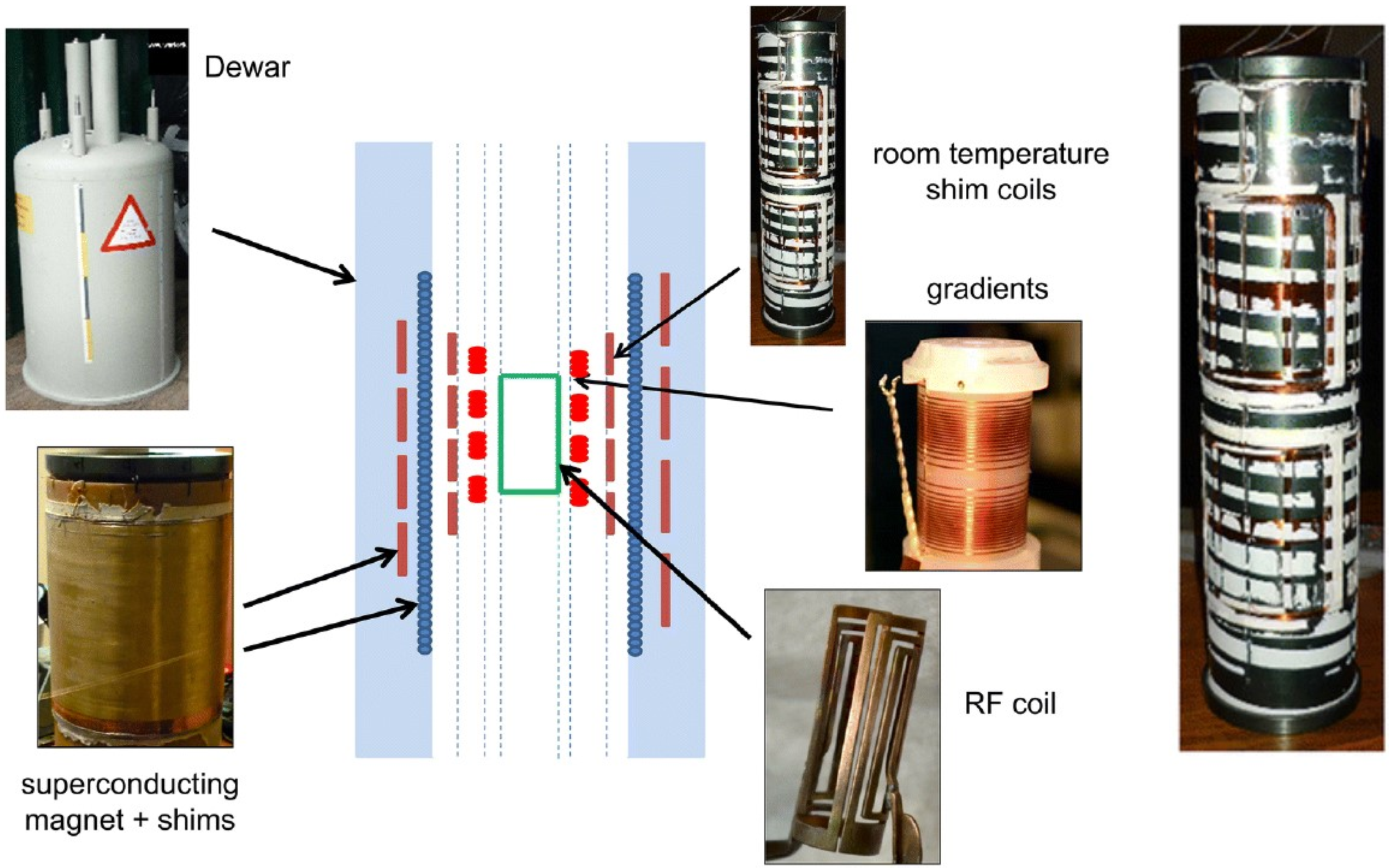


Shimming functions

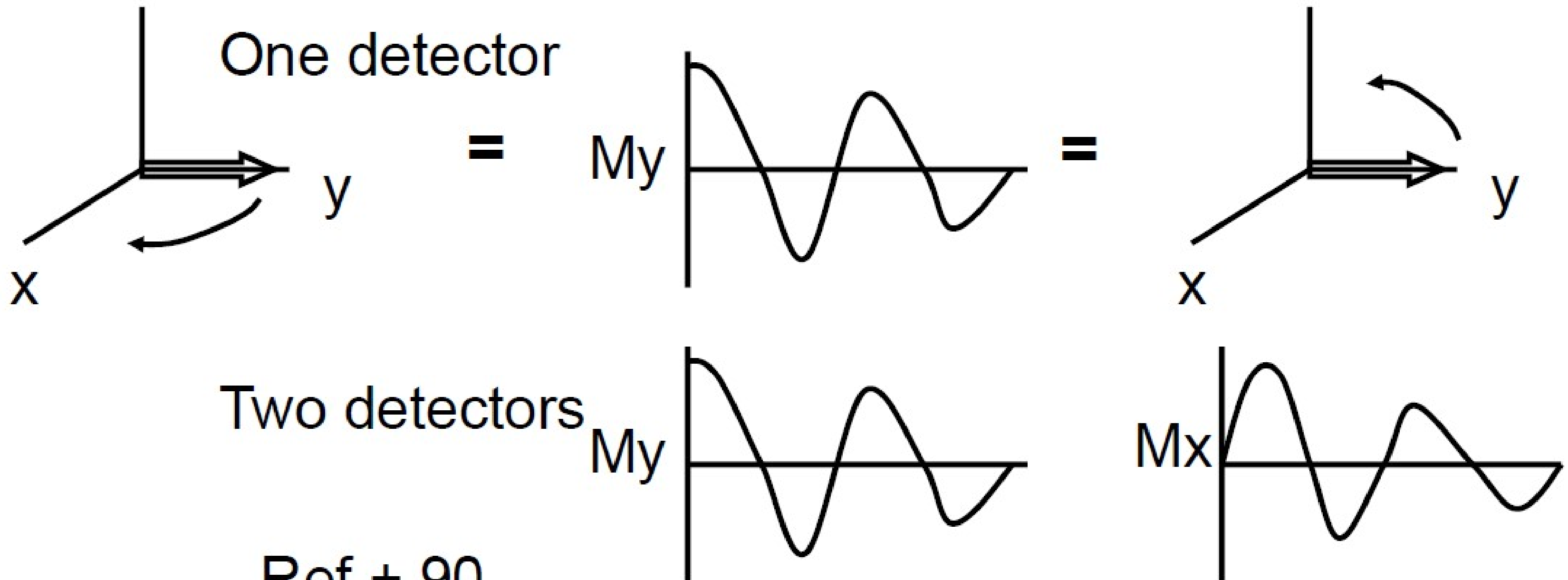
A set of 40 shim coils then provides a mechanism to make very delicate and precise adjustments to the magnetic field shape, and thus the homogeneity

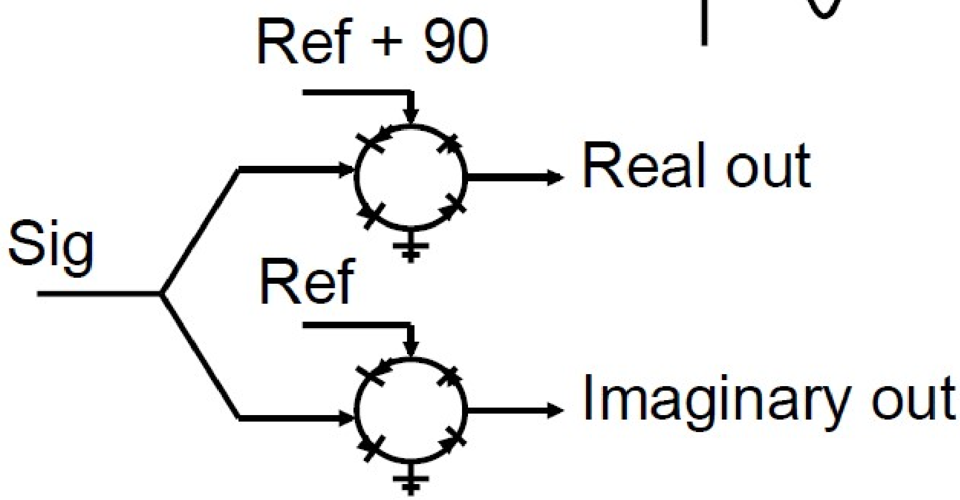


Shim coils


Dewar
room temperature
shim coils
gradients
RF coil
superconducting
magnet + shims

Quadrature detection allows distinction between +/- frequencies





Actually split signal
And use two reference
Frequency phases