A Parallel-Transmit Halbach Magnet TRASE MRI System

Jonathan C. Sharp, Aaron Purchase, Christopher Sedlock, Boguslaw Tomanek

Department of Oncology, University of Alberta,

Edmonton, Alberta, Canada

UNIVERSITY OF ALBERTA

Summary

- MRI is based on **Nuclear Magnetic Resonance (NMR)** of protons in the body
- MRI is very effective, however also very expensive
- there is a growing interest in **accessible and portable MRI**
- Our technique “TRASE” simplifies MRI equipment by eliminating the “gradient coils”
- In this work, we have simplified the system further:
  - permanent low field magnet with built-in gradient
  - 2 radiofrequency (RF) channels powering 2 solenoid coils
  - a rotation system

- Talk:
  - Review regular MRI
  - Review TRASE spatial encoding
  - the TRASE Magnet system

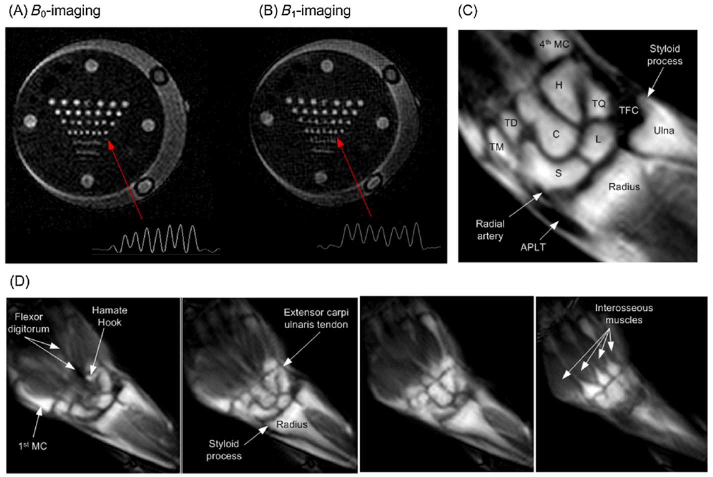
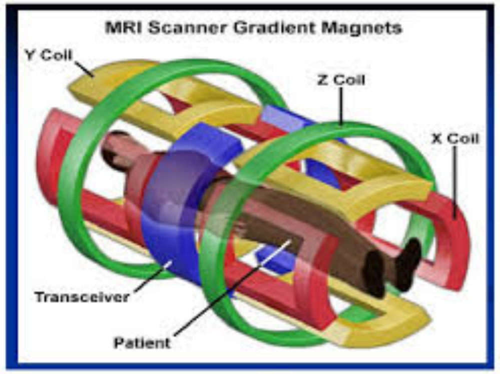


Figure 4. Experimental imaging results. (A) B_0 encoding: spin echo, TE = 14 ms, TR = 1000 ms. (B) B_1-encoded image pulse length, 500 μs; pulse–pulse gap, 200 μs; acquisition window, 80 μs; first echo at 2 ms, TR = 1000 ms, two averages. Both images are two-dimensional projections through a thin phantom and with an identical nominal pixel size of 0.86 mm (256 × 256 matrix). Also shown are profiles through the fourth row of dots. (C) 0.2-T wrist image from a three-dimensional dataset, with two dimensions (in plane) encoded by Transmit Array Spatial Encoding (TRASE) and one dimension by B_1 phase-encoding (200 echoes; pixel size, 1.1 mm; partition width, 5 mm; eight partitions; TE = 10 ms; echo spacing, 1.1 ms; TR = 500 ms; T_1 recovery time, 282 ms). Typical anatomical features of the wrist are identified: APLT, abductor pollicis longus tendon; C, capitate; H, hamate; L, lunate; MC, metacarpal; S, scaphoid; TD, trapezoid; TFC, triangular fibrocartilage; TM, trapezium; TQ, triquetrum. (D) A series of images acquired as in (C), but at a lower resolution (128 echoes; pixel size, 1.72 mm; partition width, 7.5 mm; eight partitions; echo spacing, 1.1 ms; TR = 500 ms).

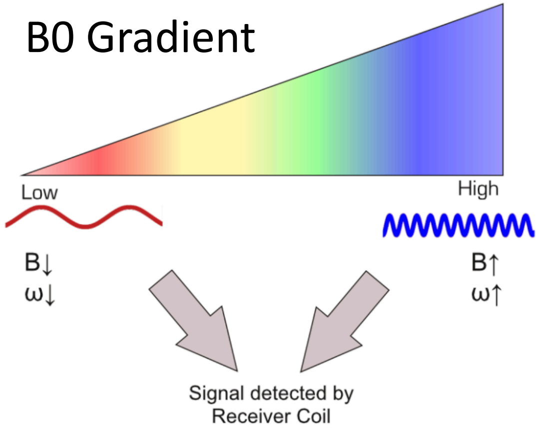
How Regular MRI Works

REVIEW

B0 = 1.5T



B0 Gradient



MRI System

In NMR, the spin frequency is proportional to the applied magnetic field: Larmor Equation: **frequency = (γ/2π) × magnetic field**

$$\omega = \gamma B$$

$\omega = 2\pi f$

γ_H (gamma) is the gyromagnetic ratio for H

B_0 = 1.5 Tesla, f_0 = 64 MHz

B_0 = 3.0 Tesla, f_0 = 128 MHz

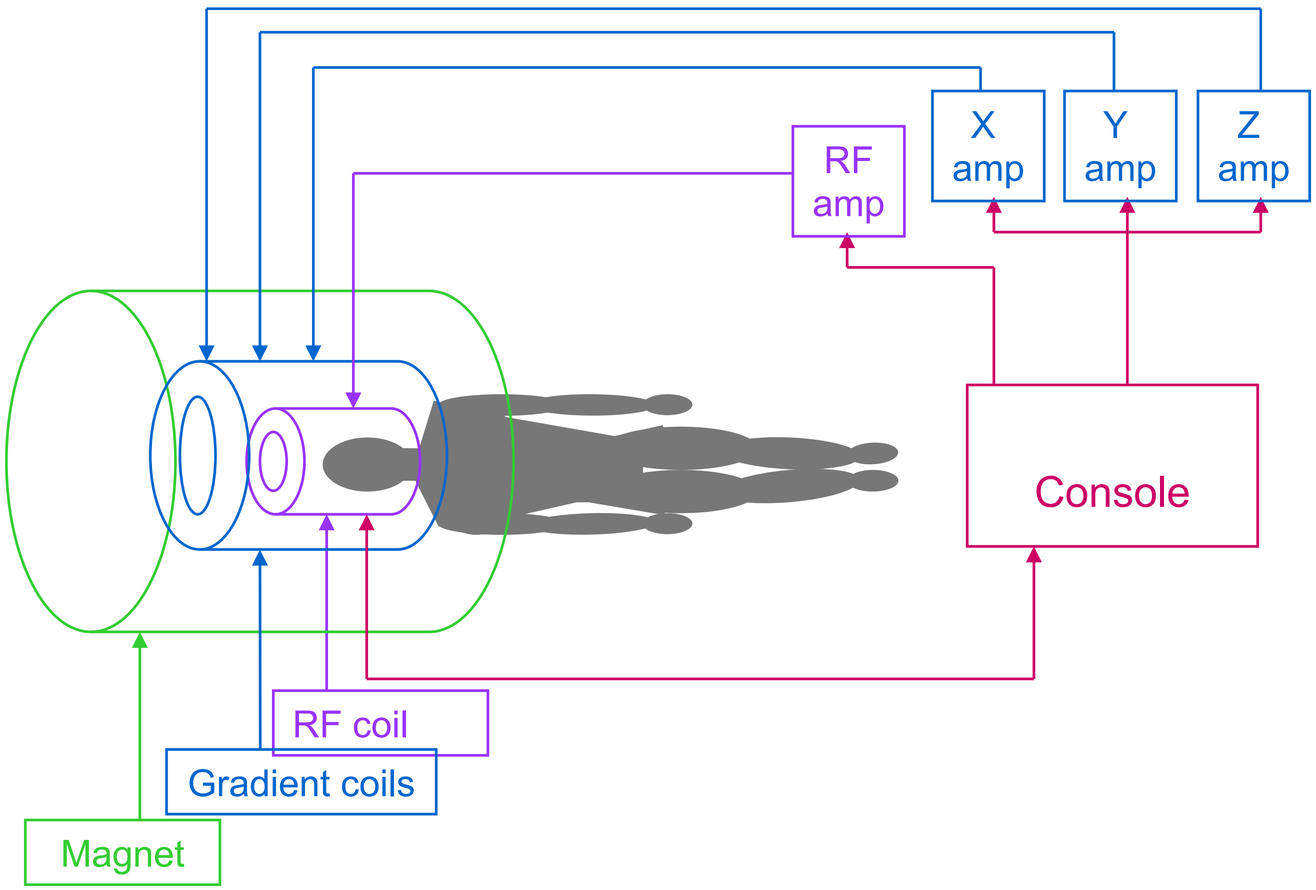
64 MHz

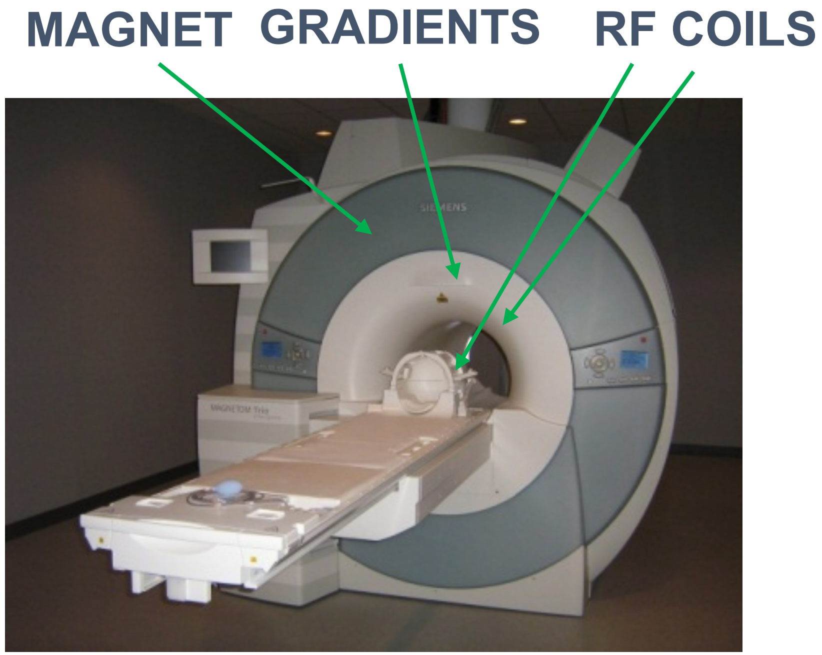
We can make the applied B_0 field vary linearly in a defined direction, to make the resonant frequency vary within the patient. This called a **field gradient, G_X**

$$\omega = \gamma(B + x\,G_x)$$

Fourier (frequency) analysis of the acquired signal is used to relate signals of specific frequencies to specific positions. By switching a full set of gradient fields (GX, GY, GZ) on and off during the pulse sequence (experiment), the **spatial origin** of each NMR signal can be pinpointed in 3D in the body. Since the **signal strength** depends upon **proton density**, **T_1** and **T_2** we have all the information to display images.

MRI System Components





Gradients cause dephasing

Gradient and Spins

gradient and spins

Set gradient(s) to see spin precession:

Gx: 0 mT/m

Gy: 0 mT/m

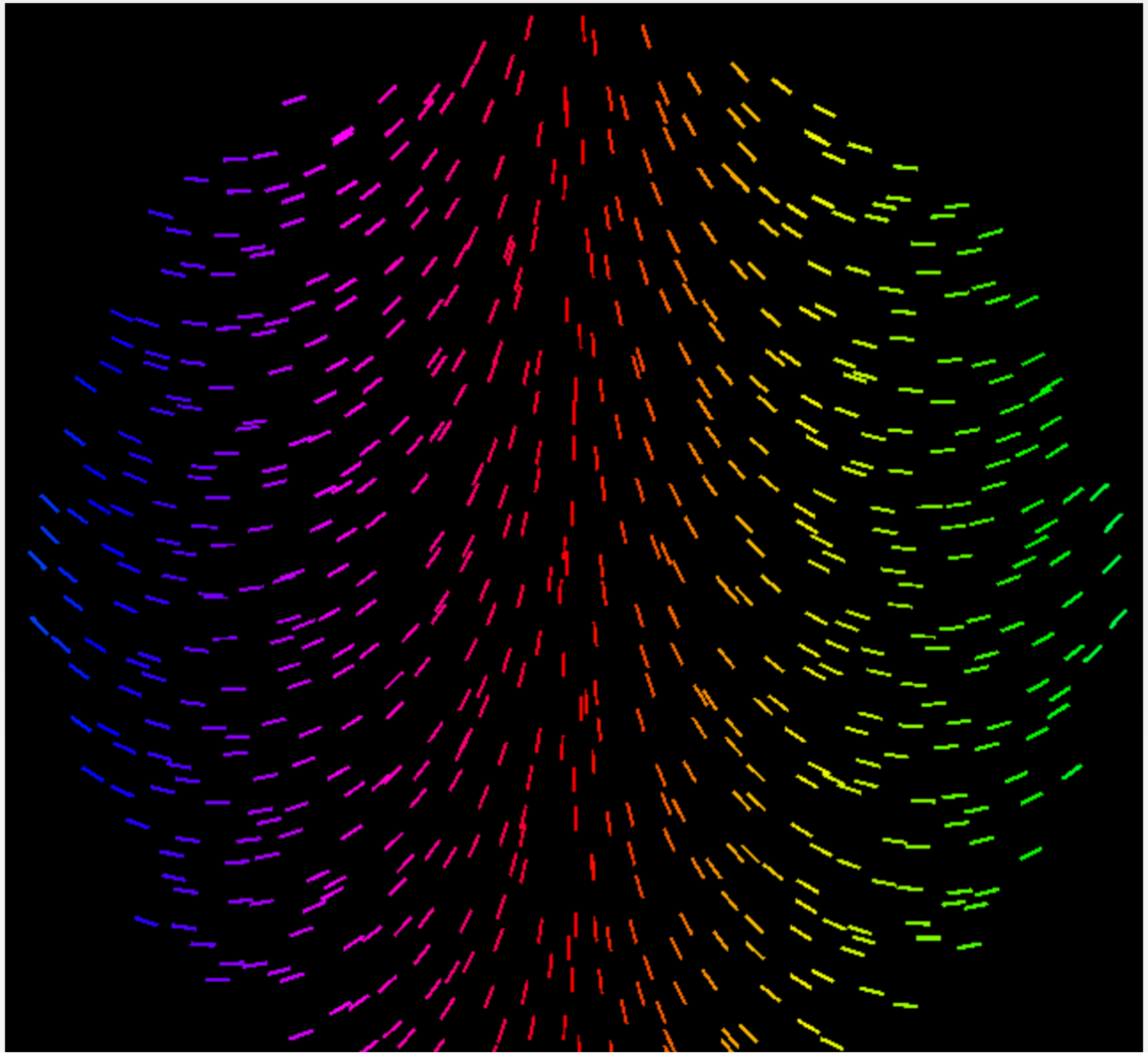
Use Restart for these:

Spin Size: 15

spins: 30

Colour: 100 %

RESTART



Exercise 1: Spin Phases

→ 1) Set: Spin Size to MAX
→ 2) Set: Spin Number to MIN
→ 3) Click RESTART button
→ 4) Set: Gx slider to 1 mT/m
→ 5) Watch a single spin as it rotates. How is the colour
d to spin orientation?
NOTE: In NMR, when spins have the same orientation
eir signals add coherently. This called being 'in phase'.

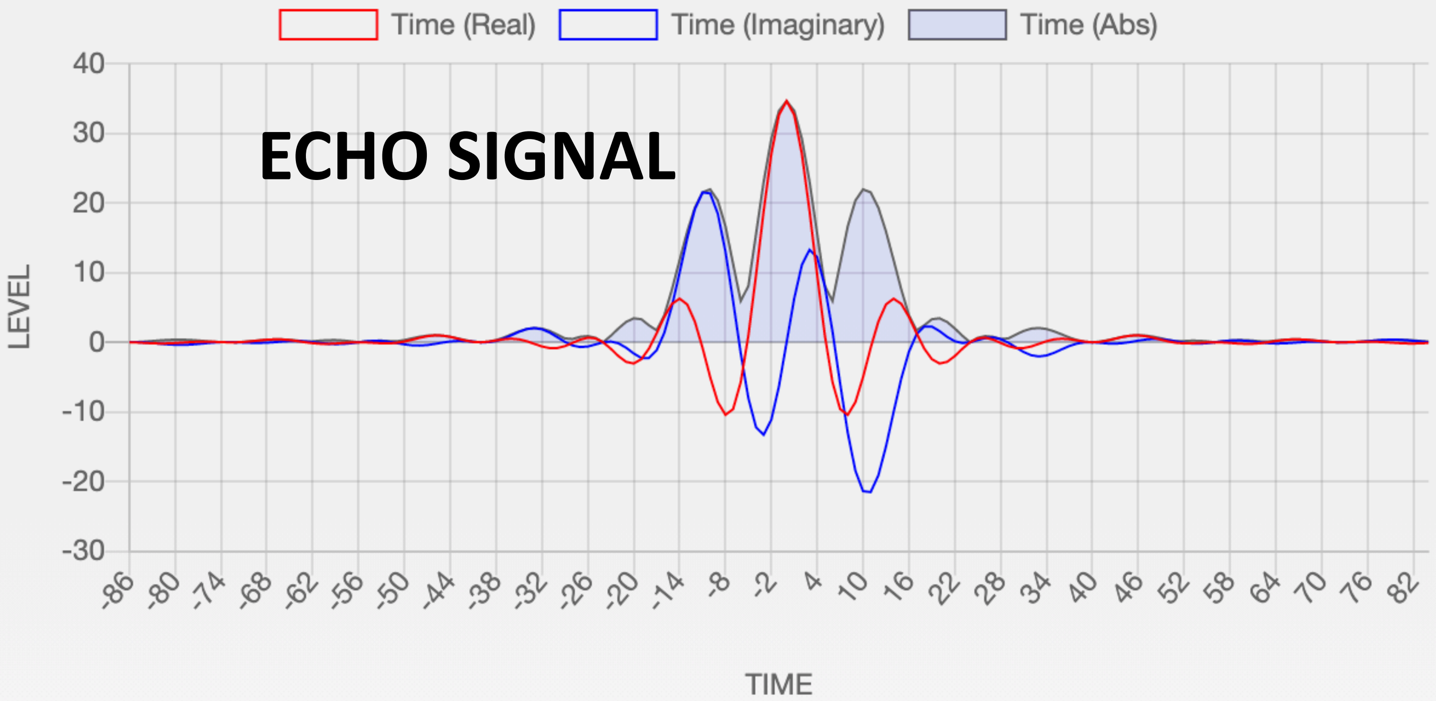
Read Gradient → 1D Image

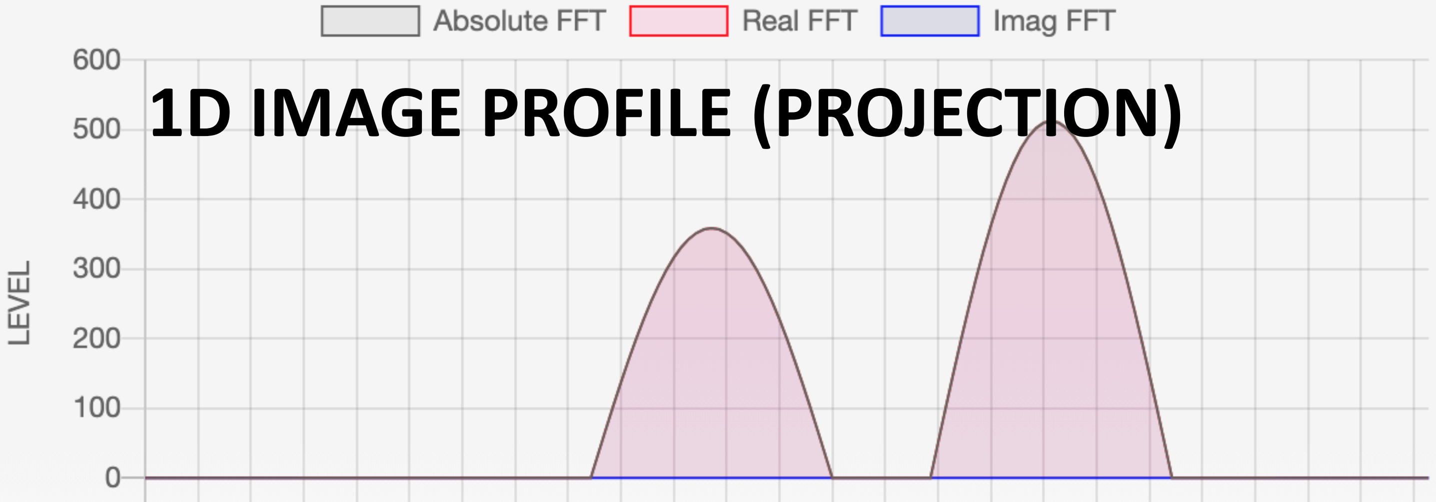
Sliders set frequency. Number in white box is amplitude. (For fine frequency control, select a slider, then use keyboard arrow keys).

	Freq	Hz	Ampl	
f0		-60	1	☐
f1		-11	0.7	☑
f2		34	1	☑
f3		30	1	☐
f4		60	1	☐
f5		90	1	☐
Offset		0		
Zoom (t)		3		
Zoom (f)		3		

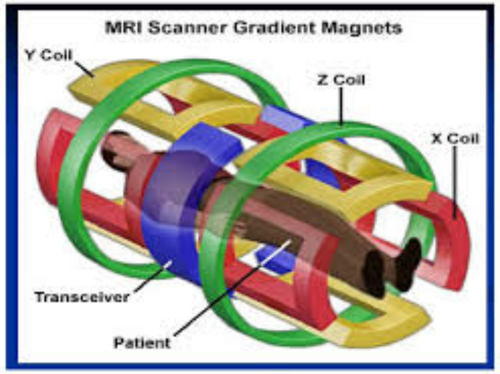
Shape: Circle Width: 32

Offset (Hz): This value is added to ALL frequencies
Zoom: zooms DISPLAY only (does not affect data)
Tick boxes: these enable / disable each frequency component.





2DFT MRI Pulse Sequence



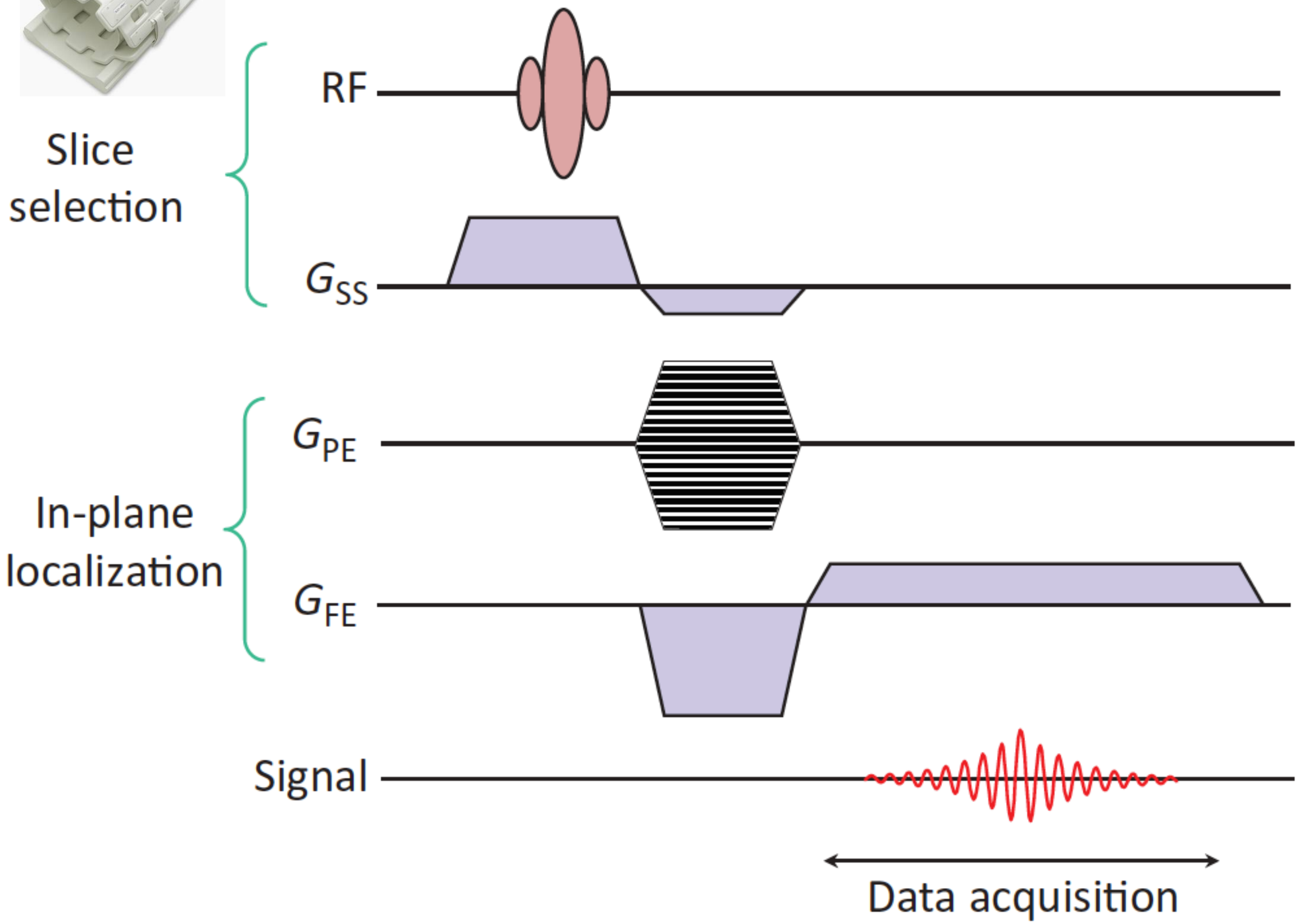


Figure 8.1 Basic gradient-echo MR imaging sequence. Amplitude is shown vertically, time horizontally. G_{SS} is the slice-selective gradient, G_{PE} the phase-encoding gradient and G_{FE} the frequency-encoding gradient.

Spatial Frequencies

- The center of k-space corresponds to low resolution information.
- The outer parts of k-space ←→ high frequency (edge) information.
- This diagram - Bushberg

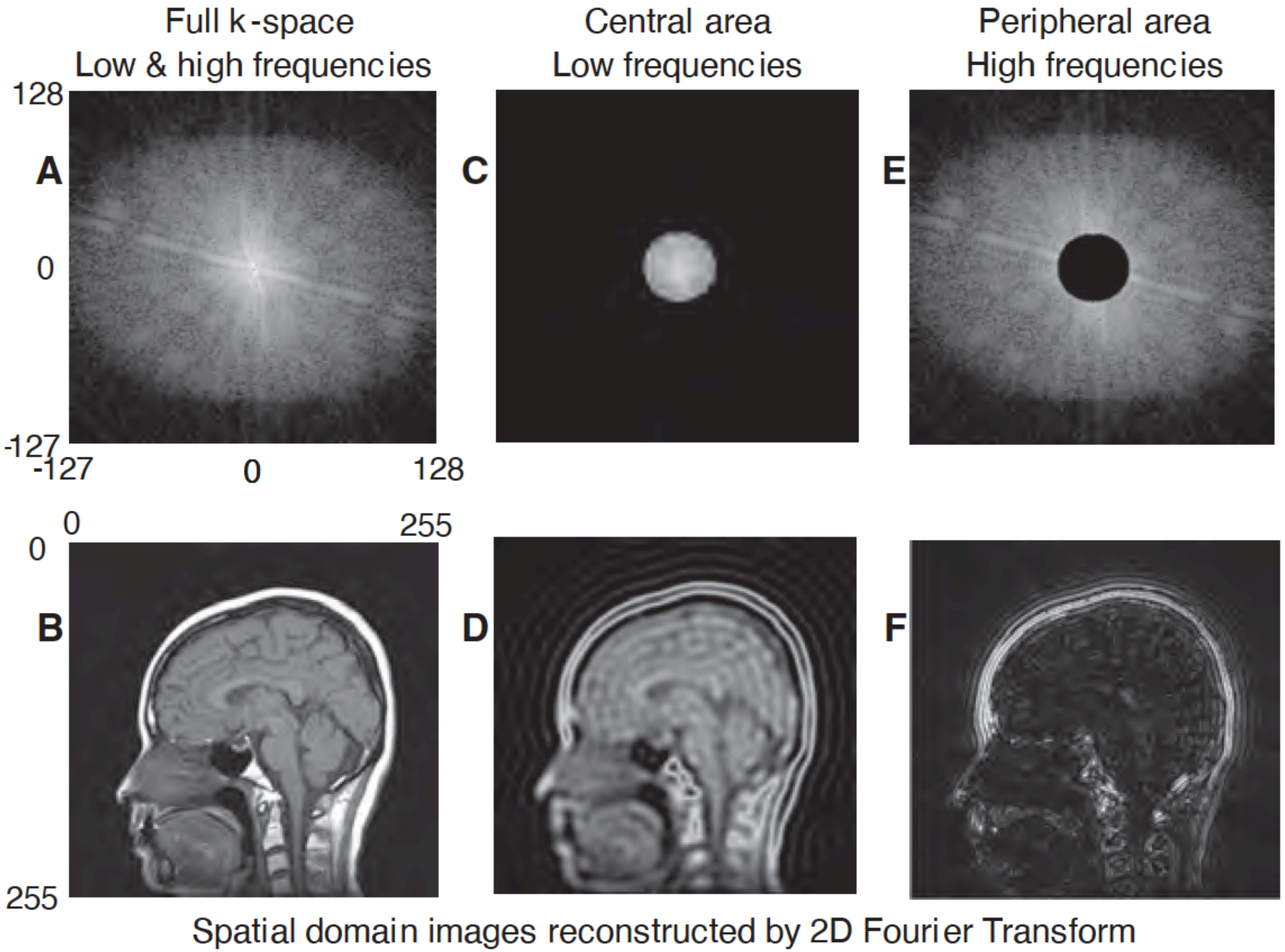
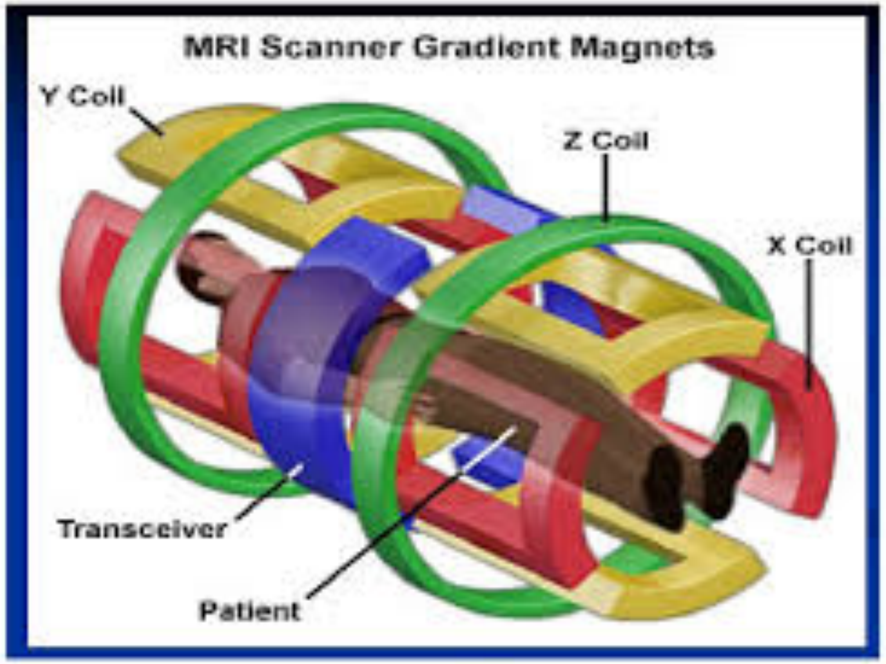


FIGURE 12-59 A. Image representations of *k-space* segmentation show a concentration of information around the origin (the k-space images are logarithmically amplified for display of the lowest amplitude signals). **B.** Inverse two-dimensional Fourier transformation converts the data into a visible image. **C.** Segmenting a radius of 25 pixels out of 128 in the central area and zeroing out the periphery extracts a majority of the low-frequency information. **D.** The corresponding image demonstrates the majority of the image content is in the center of k-space. **E.** Zeroing out the central portion and leaving the peripheral areas isolates the higher spatial frequency signals. **F.** The resulting image is chiefly comprised of high frequency detail and resolution. Ringing that is visible in the image is due to the sharp masking transition from the image data to zero.

[3] Gradient coils geometry 3 directions: x,y,z

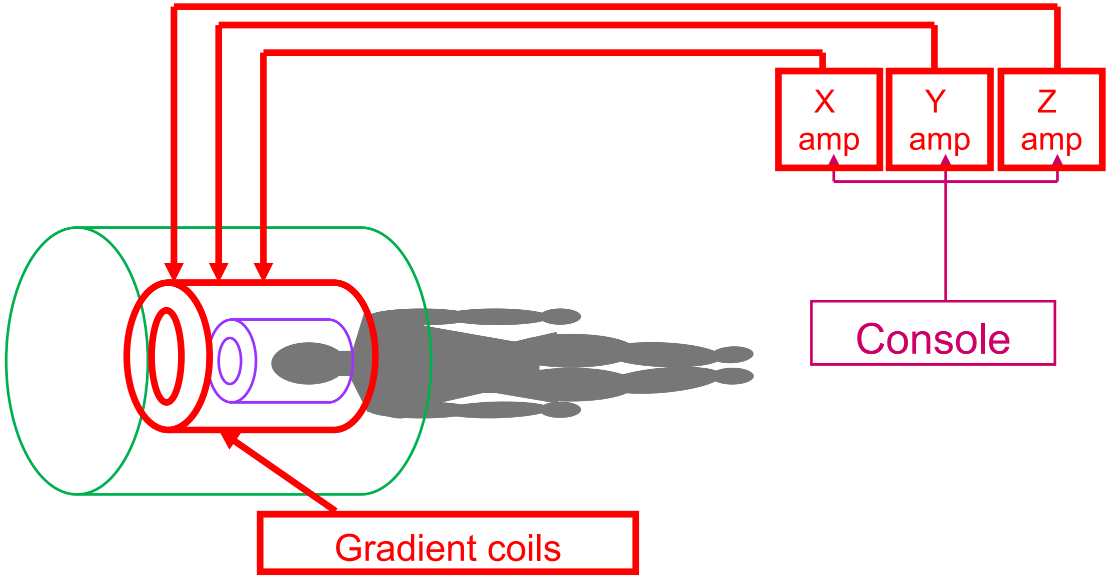


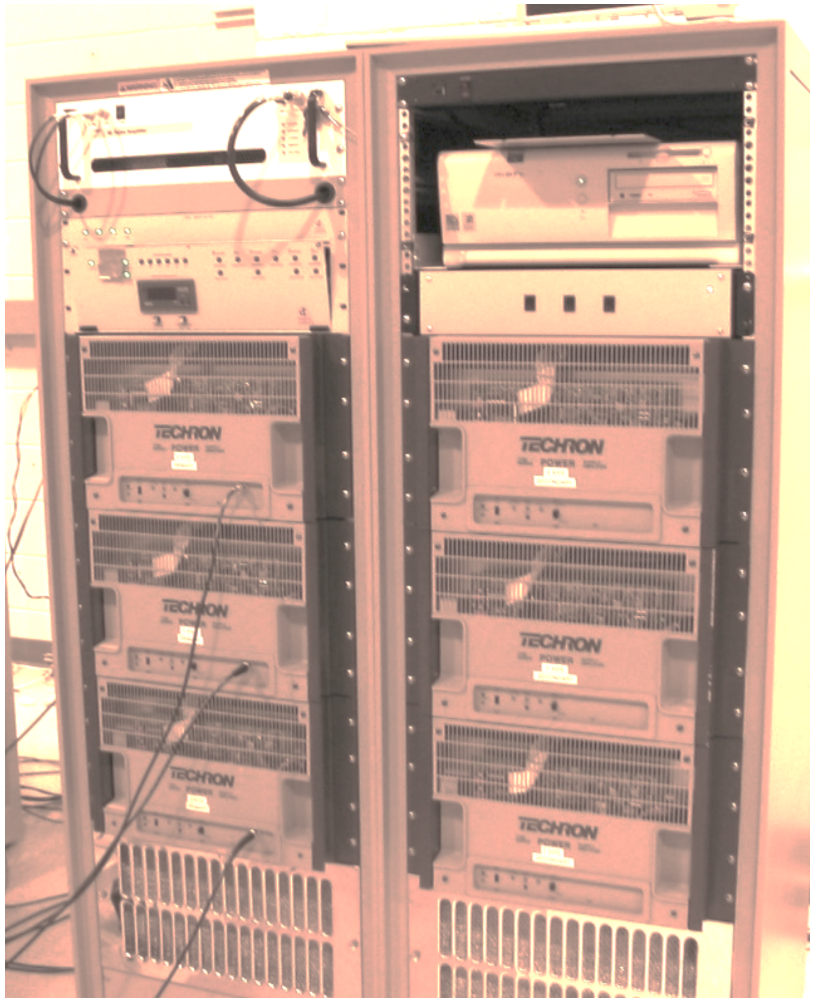
https://www.dotmed.com/listing/mri-coil/philips/gradient-coil/2234815

https://www.amberusa.com/blog/gradient-coils-inside-mri-what-you-need-to-know/

Gradient coils - amplifiers

Gradient amps: to amplify voltage from the console (from ~1V to ~500V)





An example of a set of gradient amplifiers (2 per each direction)

Gradients amplifiers - requirements:

- Power (3 phases)
- Cooling (water or air)

Also good for rock concerts

How TRASE Works

TRASE = TRANSMIT ARRAY SPATIAL ENCODING

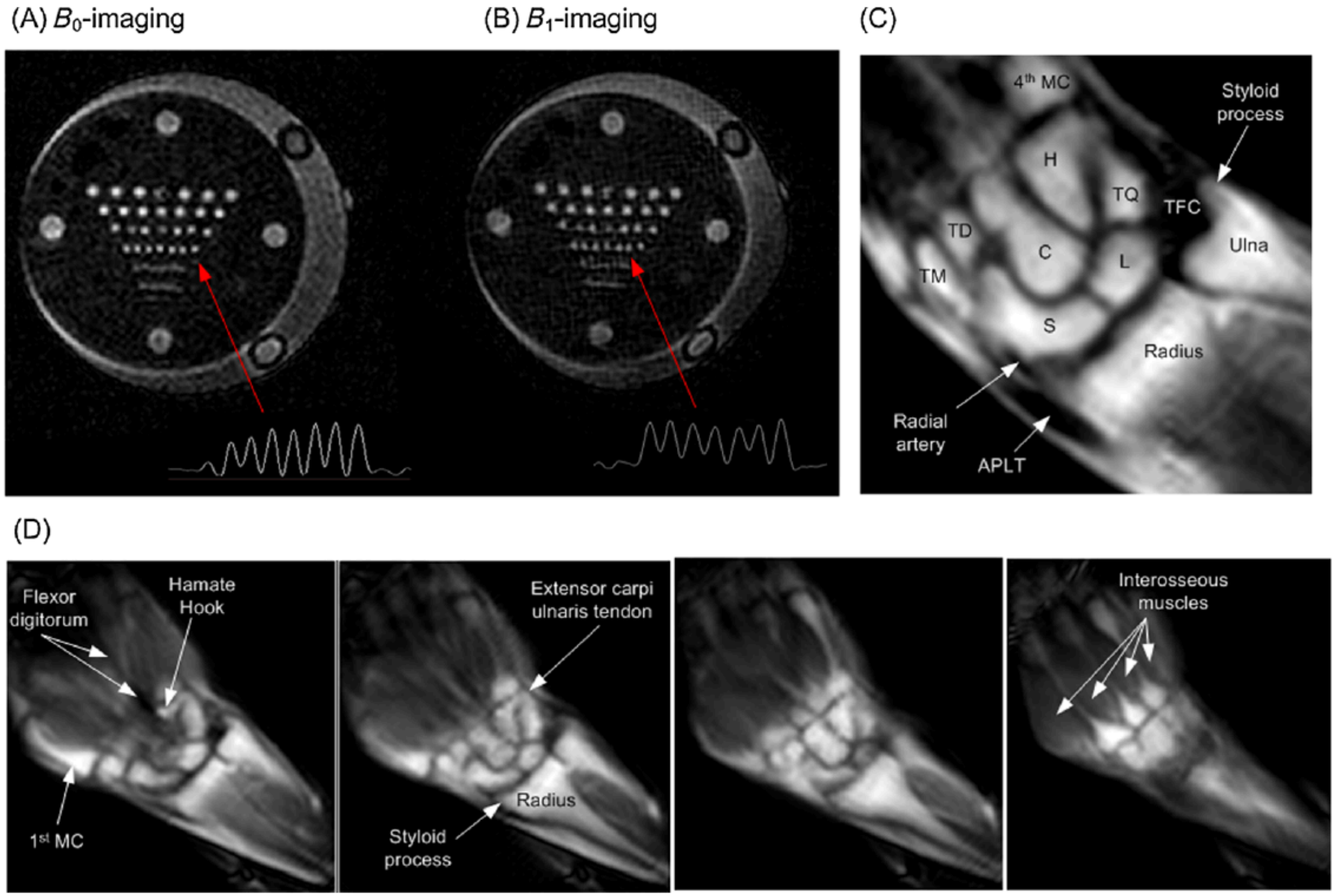


Figure 4. Experimental imaging results. (A) B_0 encoding: spin echo, TE = 14 ms, TR = 1000 ms. (B) B_1-encoded image pulse length, 500 µs; pulse–pulse gap, 200 µs; acquisition window, 80 µs; first echo at 2 ms, TR = 1000 ms, two averages. Both images are two-dimensional projections through a thin phantom and with an identical nominal pixel size of 0.86 mm (256 × 256 matrix). Also shown are profiles through the fourth row of dots. (C) 0.2-T wrist image from a three-dimensional dataset, with two dimensions (in plane) encoded by Transmit Array Spatial Encoding (TRASE) and one dimension by B_1 phase-encoding (200 echoes; pixel size, 1.1 mm; partition width, 5 mm; eight partitions; TE = 10 ms; echo spacing, 1.1 ms; TR = 500 ms; T_1 recovery time, 282 ms). Typical anatomical features of the wrist are identified: APLT, abductor pollicis longus tendon; C, capitate; H, hamate; L, lunate; MC, metacarpal; S, scaphoid; TD, trapezoid; TFC, triangular fibrocartilage; TM, trapezium; TQ, triquetrum. (D) A series of images acquired as in (C), but at a lower resolution (128 echoes; pixel size, 1.72 mm; partition width, 7.5 mm; eight partitions; echo spacing, 1.1 ms; TR = 500 ms).

TRASE uses 2 radio-frequency (RF) coils for 1D spatial encoding

the RF field direction (phase) varies linearly with position

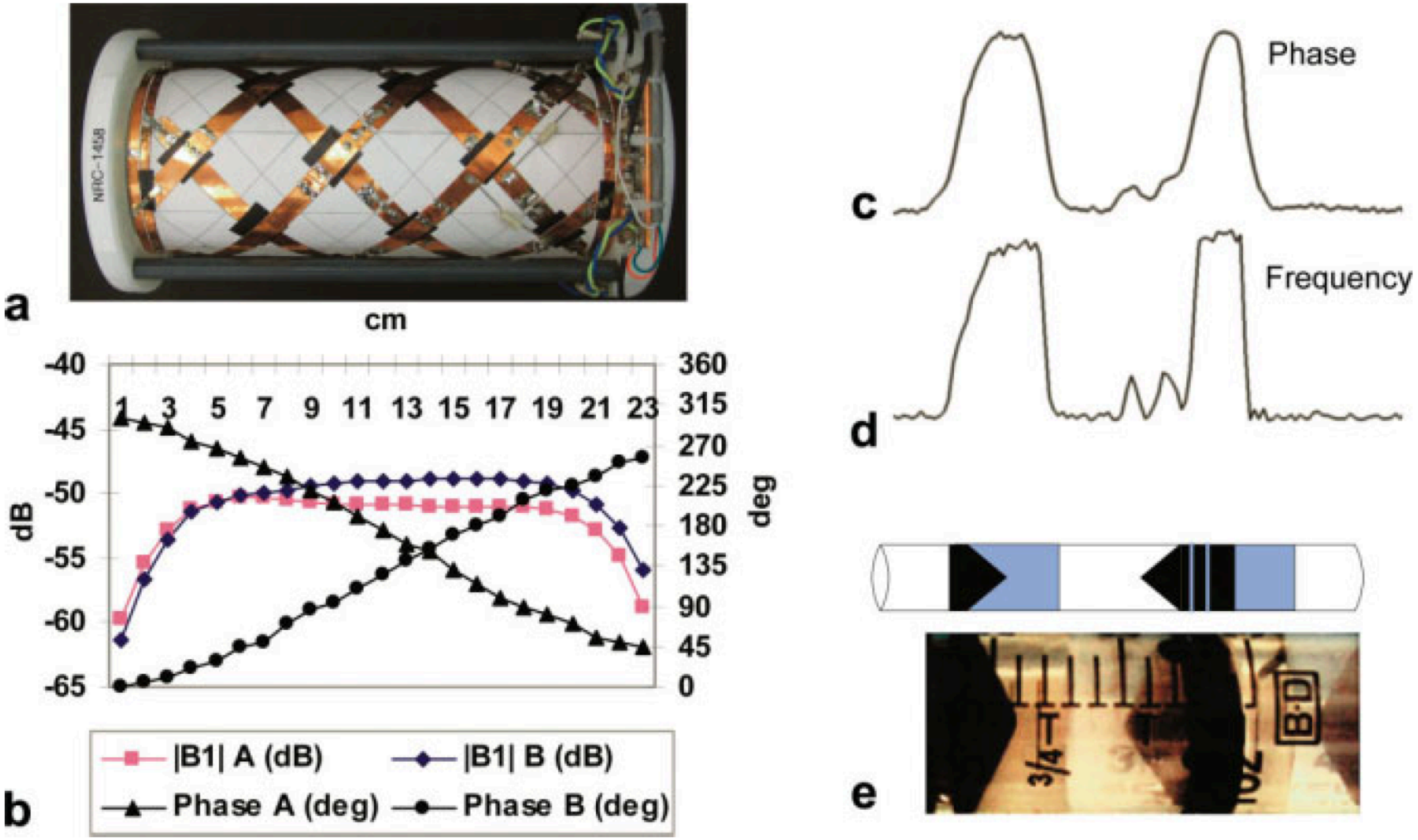
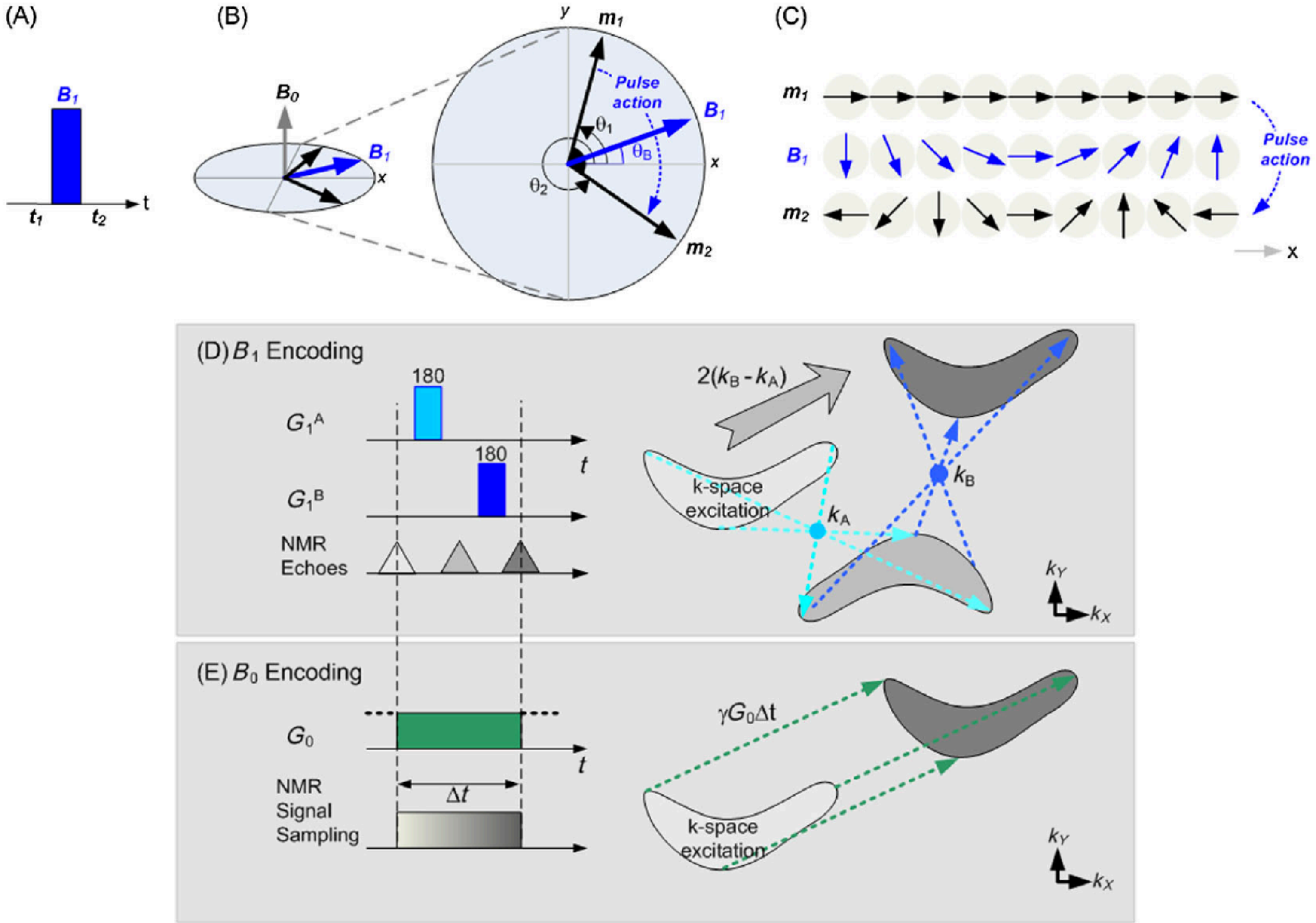


FIG. 6. The 1D RF phase gradient imaging experiment results. **a:** $\pm 1.5\pi$ Spiral birdcage coil array consisting of two coils wound with copper tape on a single 200mm-long, 90mm-diameter former. **b:** B_1 magnitude (decibels) and phase (degrees) plots for the spiral birdcage array. **c:** Experimental 1D profile obtained by reordering and Fourier transformation of acquired *k*-space data from TRASE (ETL = 64), RF pulses: 90°(0.4 ms), 180°(0.8 ms), single train, pulse spacing 5 ms; and **(d)** standard SE frequency encoding (TE = 22 ms, 128 points). **e:** The two-compartment water phantom (2.5-cm-diameter water-filled syringe) with graphic.



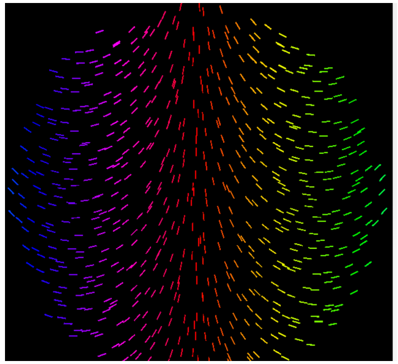


Figure 1. 180° radiofrequency (RF) pulse encoding action. (A) A 180° RF pulse (B_1) represented in the time domain. (B) Transverse magnetization m_1 is transformed into m_2 by reflection about a direction defined by the phase of the RF pulse. (C) Refocusing by a B_1 phase gradient field produces spin dephasing. (D) Two point reflections (representing refocusing by two different RF phase gradient fields) resulting in a translation of excitation (signal) in the k-space plane. For comparison, (E) shows the continuous k-space translation resulting from B_0 encoding.

TRASE 1D Pulse Sequence

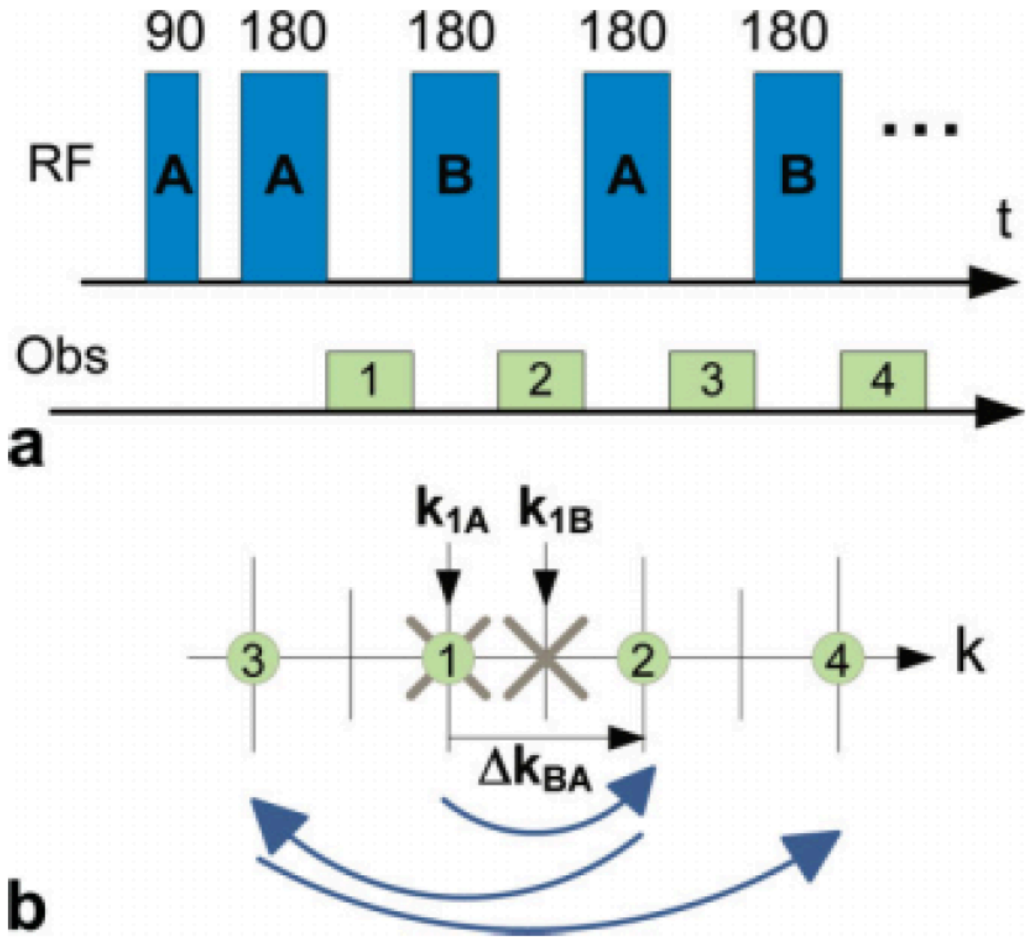


FIG. 2. A 1D phase gradient imaging experiment. **a:** The basic 1D TRASE pulse sequence consists of a 90° excitation followed by a train of 180° refocusing pulses applied alternately to the A and B transmit coils. NMR signal is observed (1-4) after each refocusing pulse. **b:** The corresponding *k*-space sampling pattern showing the *k*-space coil origins ($\mathbf{k}_{1A}$, $\mathbf{k}_{1B}$, crosses) and sampling locations (circles 1-4). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

COMPACT TRASE MRI SYSTEM

TRASE = TRANSMIT ARRAY SPATIAL ENCODING

Halbach Magnet (25 kg)

- Magnet: A 25 kg sparse dipolar Halbach magnet was built for TRASE MRI purposes (2).
- 2.84 MHz, 8-ring
- The magnets short length and small size (< 43 cm x 43 cm x 25 cm). The positions of 320 N40UH magnetic pieces (1'' x 1'' x 1/2'') was optimized using a genetic algorithm and housing constructed using 3D printed formers.
- The constructed 66.7 mT magnet is an accurate representation of the optimized design with a measured homogeneity of 11,152 ppm in a 12.7 cm diameter, 1 cm long cylindrical region of interest.
- The magnet has an inherent axial gradient for z-dimensional encoding but improvements are being made. (A. Purchase, this conference).

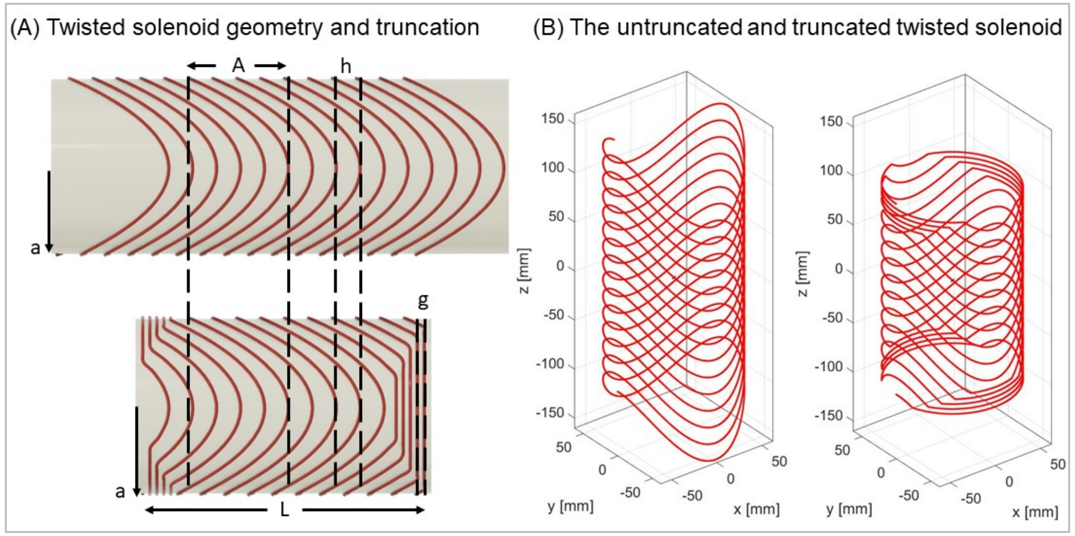
Previously fully described:

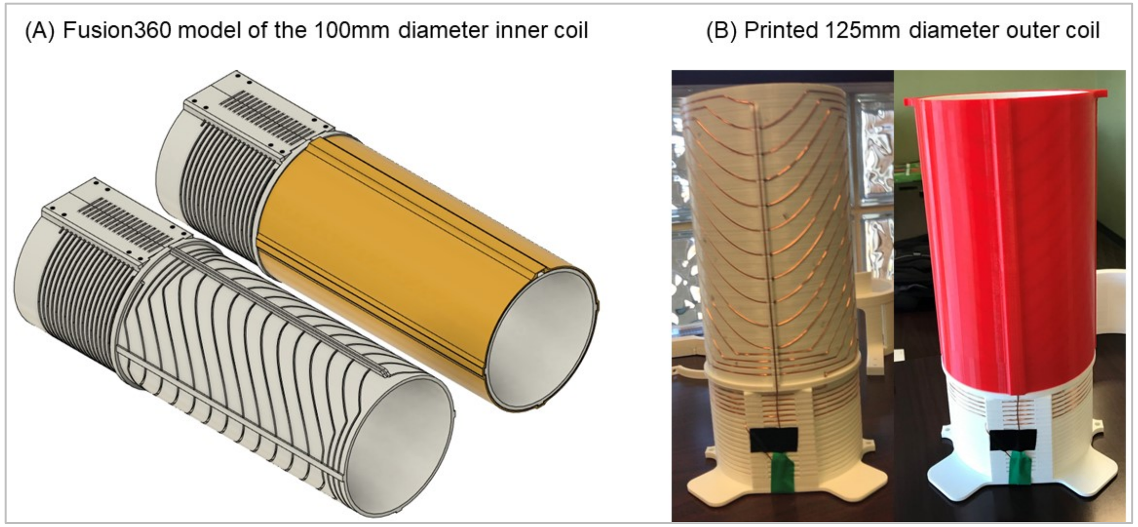
[1]**Purchase AR**, Vidarrson L, Wachowicz K, Liszkowski P, Sun H, Sarty GE, Sharp JC, Tomanek B. (2021). *A short and light, sparse dipolar Halbach magnet for MRI.* IEEE Access, Vol. 9, pp. 95294-95303.

[2]**Purchase AR**, Sarty GE, Vidarrson L, Wachowicz K, Liszkowski P, Sun H, Sharp JC, and Tomanek B.(2020). *Design of a permanent magnet for MRI of the ankle on the international space station*, Proc. Int. Soc. Mag. Reson. Med., 28: 1252.

TRASE Phase Gradient Tx Coils

- Pair of geometrically decoupled coils provide 1D encoding.
- Truncated twisted solenoid is significantly superior to previous un-truncated design.
- For 1D encoding, TRASE coils are now performing very well.
- geometrically decoupled nested twisted solenoid design (3,4).
- Two RF coil sets were built: a solenoid + saddle configuration and a pair of truncated twisted solenoids (suitable for rotation experiments). In each case coils are geometrically decoupled (i.e. no PIN diodes). In both cases, coil diameters were 100mm and 125mm with length 230mm. Imaging volume 80mm diam; 100mm length. Peak RF power for 200us pulses ~10W. Phase gradient strengths: 5.8deg/cm inner; 5.15 deg/cm outer coil.
- **Further details**: see C. Sedlock, this conference

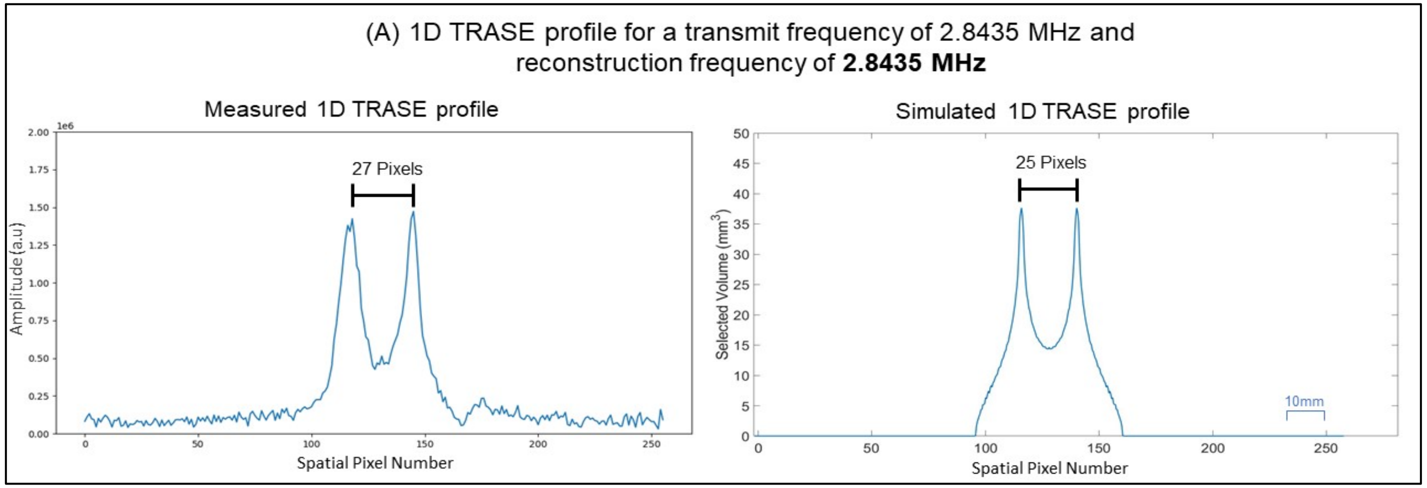


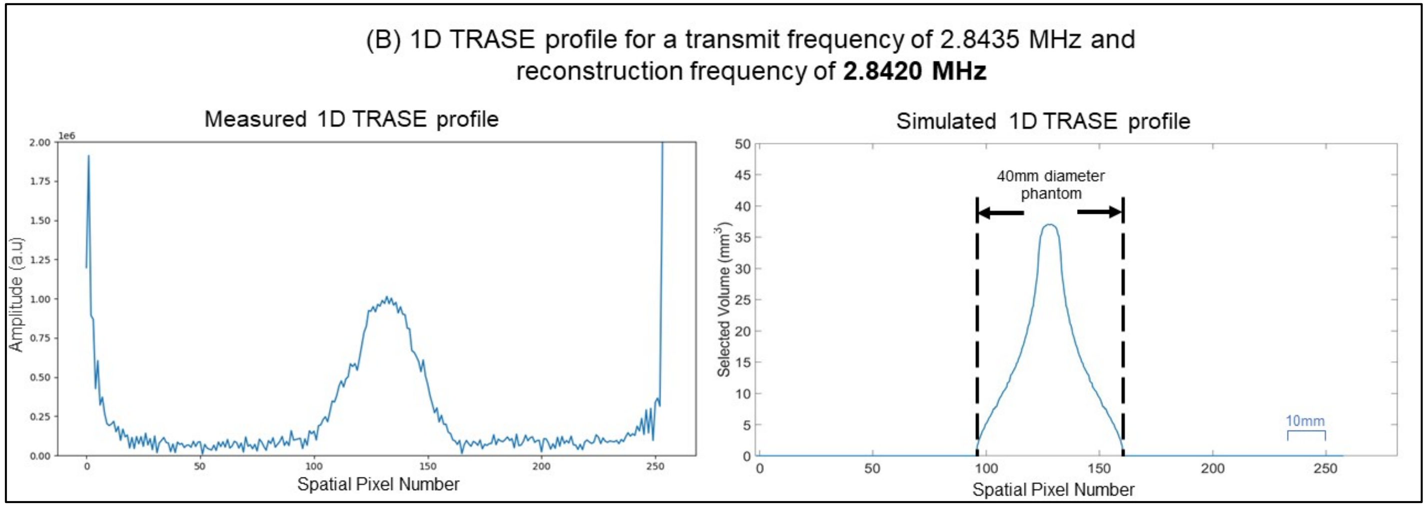


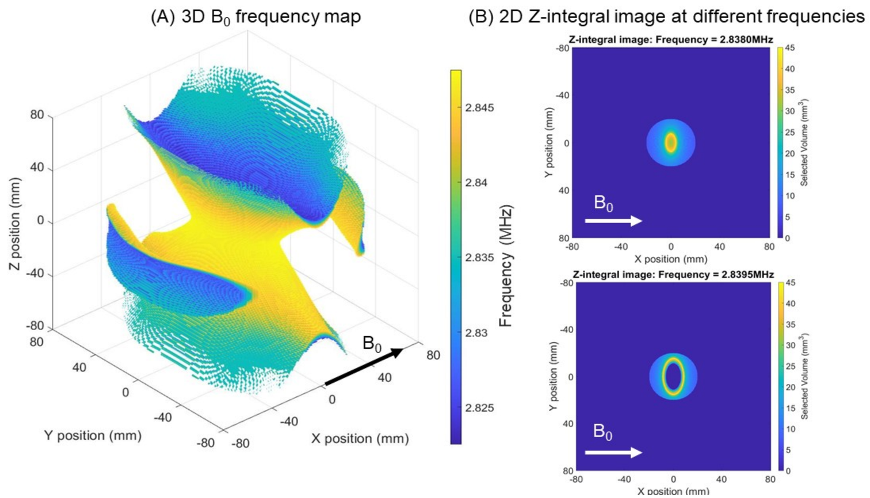
Credit: Christopher Sedlock

Results: TRASE 1D profiles

- Profiles (bottle phantom) show that **TRASE encoding is successsful**
- profiles match expected, due to the known magnet inhomogenity (i.e. effective slice shape & width is highly variable)
- Next: *higher homogeneity needed*





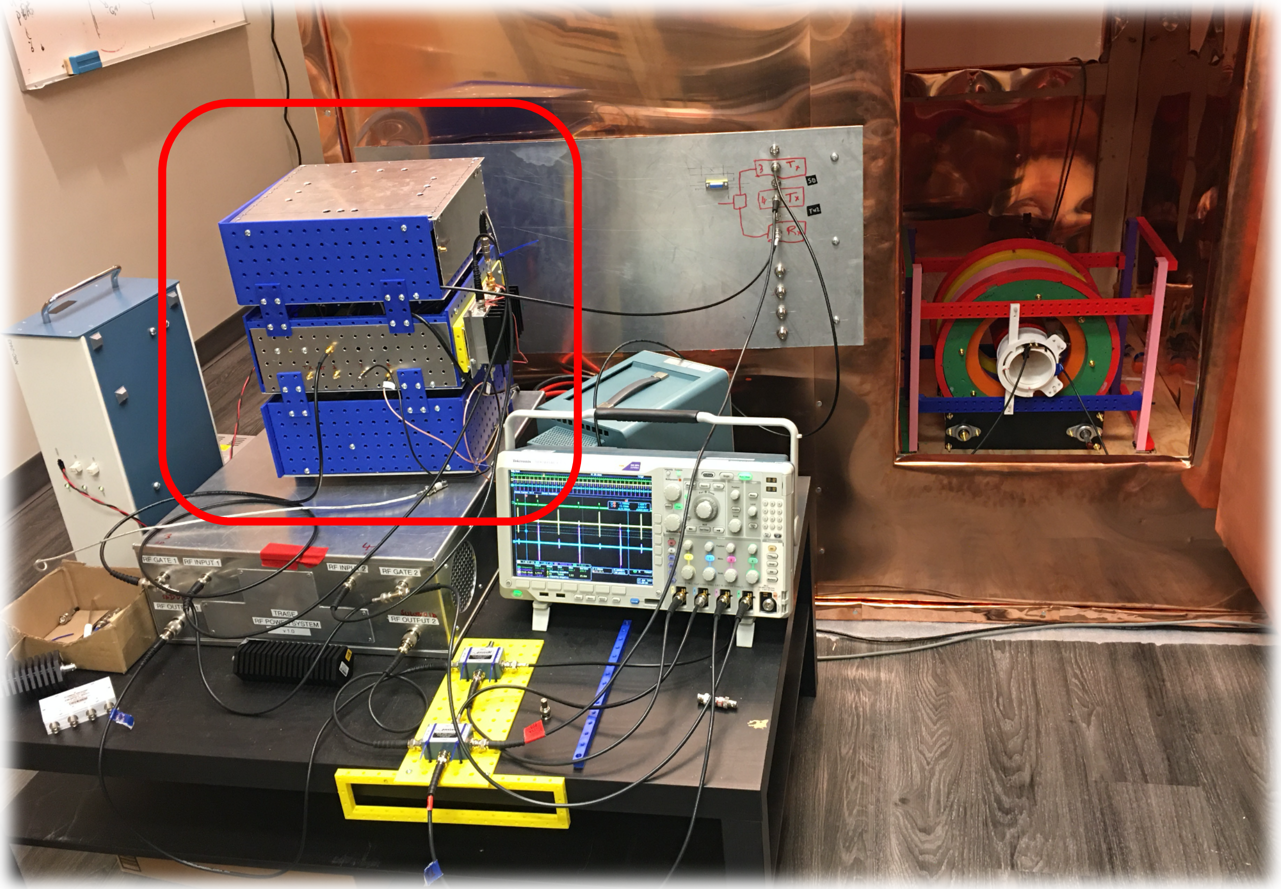


11,152 ppm in a 12.7 cm diameter, 1 cm long cylindrical region of interest.

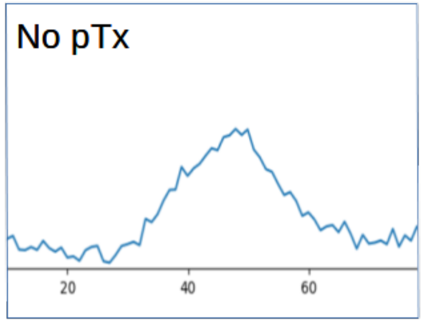
Parallel Tx Console

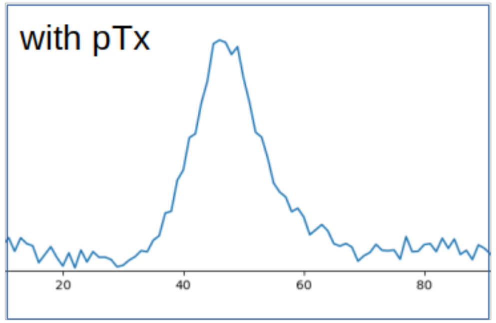
Parallel Transmit (pTx):

- console has 4 Tx channels (only 2 used)
- no high power splitter or combiners needed
- **allows compensation for residual coil coupling, by simultaneously driving both coils** (where necessary)

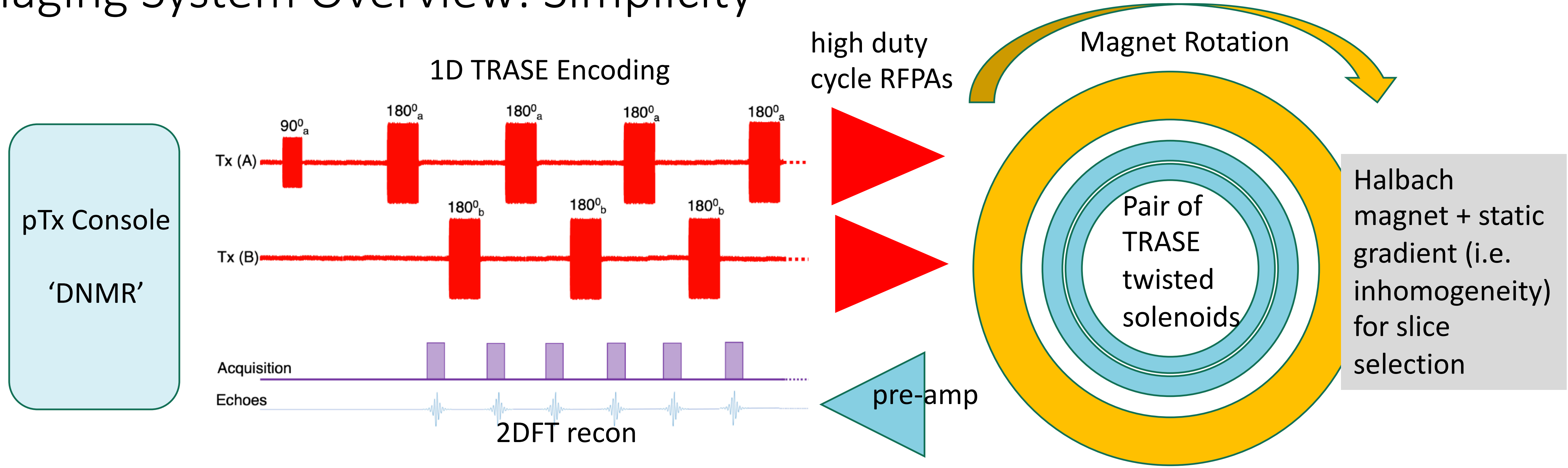


TRASE profiles without pTx vs. with pTx





Imaging System Overview: Simplicity



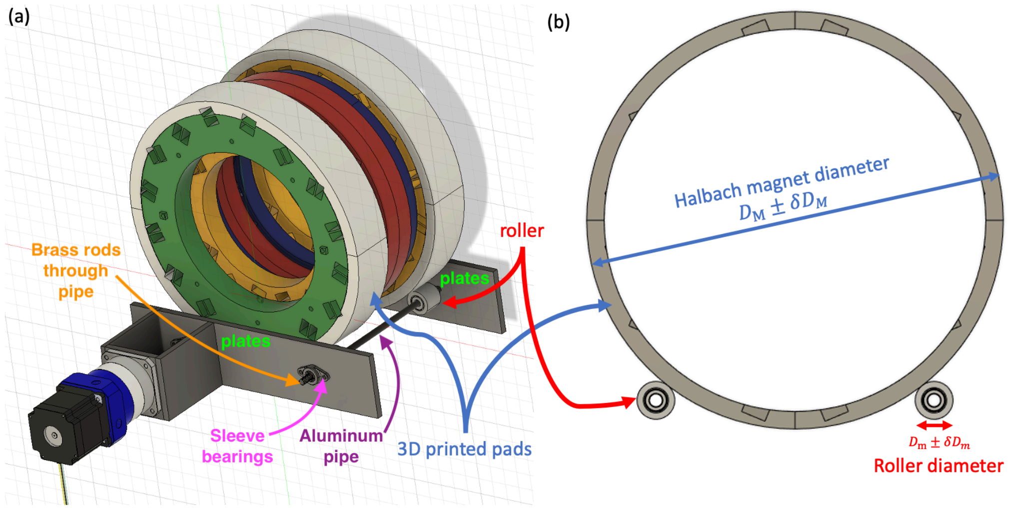
DoF	data dimensions	implementation
1	TRASE spatial dimension (1D)	pair of Tx **phase gradient** coils; echo = k-space point
2a	Frequency dimension (Fourier slice partitions)	**FT** the echo: 1) encoding; 2) artifact rejection
2b	Multi-frequency (multi-slice)	relies on **built-in inhomogeneity** for slice-selection
3	projections from rotation angle	**rotate** magnet (or coils - tbd); Radon transform.

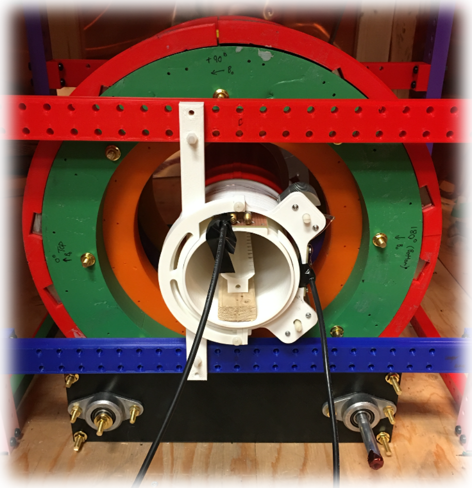
Credit: Aaron Purchase, JCS

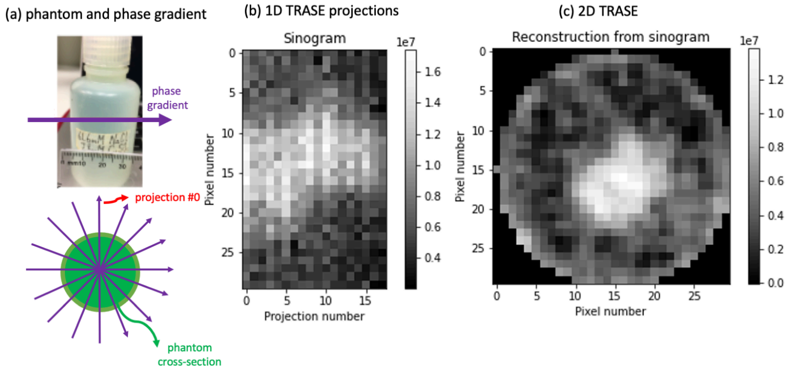
Magnet & Rotation System

- 2.84 MHz, 8 ring, 25 kg Halbach
- Rotation system under pulse sequence control
- provides projections for 2D imaging

1. Rotating machines are a mature technology
2. **Coil rotation** may be a better option for TRASE (…)







preliminary results

Credit: Aaron Purchase

Performance check list

Potential problem checklist:	Solutions:
Flip angle (B1) effects ?	XY4 phase cycle down echo train (Bohidar et al.)
Off-resonance effects ?	reject by FT of echo (under static B_0)
Eddy currents ?	none (no switched B_0)
RF power (SAR) ?	low field; 180 deg pulses only
NMR issues?	single, simple echo train; only RF pulses (2 types)
Tx coil decoupling ?	1. two Tx coils only (1D TRASE: single encoding axis) 2. geometric decoupling 3. parallel Tx
Hardware complexity?	Design is very simple: 2 RF channels, 2 Tx coils; magnet; rotation system.

Conclusions: the cheapest and most robust MRI system?

A design for a **very simple imaging system** has been presented:

1. A permanent magnet
2. Two radio-frequency amplifiers attached to two resonant tuned wire coils
3. A mechanical rotation system

Results:

- TRASE demonstrated under conditions of high inhomogeneity, **without encoding artifacts**

QUESTIONS?

QUESTIONS?

Conclusions

- We have designed and constructed a low-field TRASE RF imaging **system**.
- In TRASE k-space encoding is achieved by refocusing with **RF phase gradients**.
- The magnet is a 2.85 MHz 8-ring Halbach design. All components are custom made.
- An inherent axial gradient of the inhomogeneous magnet function as slice selection.
- The unique feature of this imaging configuration is the **simplicity**. Two RF channels and magnet rotation provide multi-slice projection reconstruction imaging.

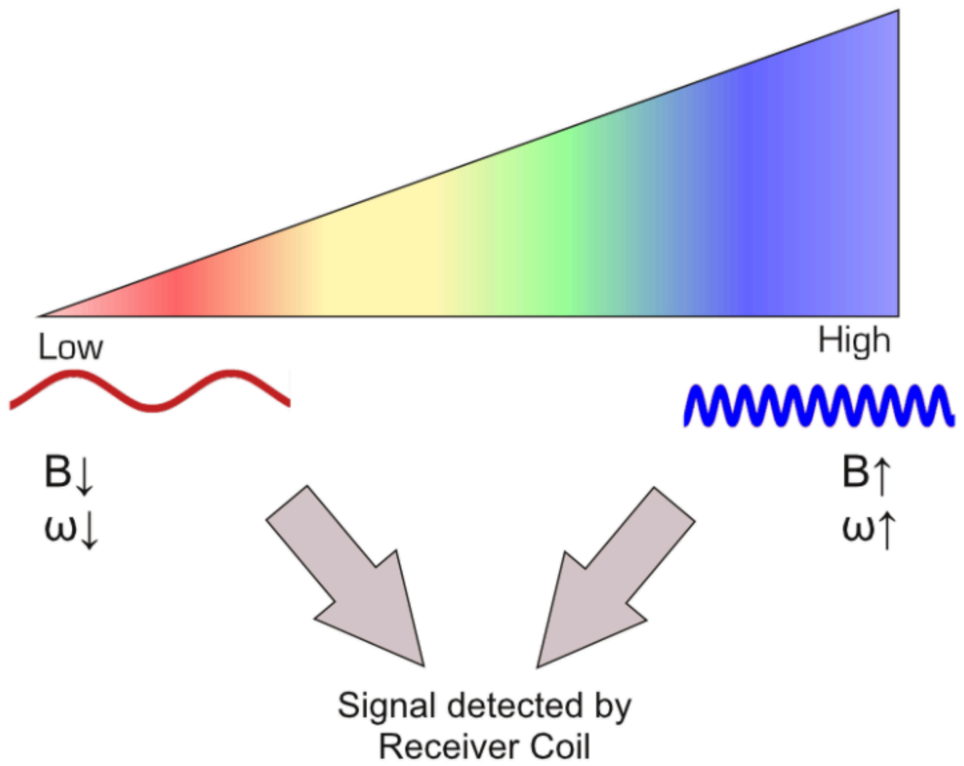
EXTRA

Conclusions:

- no gradient coils in the magnet; no gradient pulses in the sequence; no grad amps in the rack
- this study is “magnet-limited”, see Aaron Purchase (this meeting)

Idea of a Read Gradient

- “Frequency Encoding”
- “Read Gradient”
- ”Readout Gradient”
- The readout gradient is ON during data acquisition, so FFT of the NMR signal gives a us a 1D projection through the object.
- See example of circular 1D profile in OpenPhys



Data Dimensions / Degrees of Freedom

TRASE spatial dimension (1D)	each echo is a different point in k-space	FOV set by coil geometry
frequency dimension (Fourier slice partitions)	FT each echo	favoured when acquisition window > pulse length
Multi-frequency (multi-slice)	multi-freq is essentially mult-slice	
Magnet Rotation dimension	rotate magnet (180 deg range)	
Coil rotation (not implemented yet)	rotate coils (90 deg range)	

The Frequency Dimension

- no readout gradient
- FT echo to obtain partitions (Fourier encoding within “slab”)

RF Power System

Custom – built RFPA

- low frequency (3 MHz)
- 2 channels (allows pTx)
- **high duty cycle** (needed for echo train)
- 1 kW peak/channel @ 50% duty cycle
- (**10 – 35 W used in expts reported here**)
- based on a radio amateur design, with blanking added.

Previously fully described:
Purchase AR, Palasz T, Sun H, Sharp JC, and Tomanek B. (2019).
A high duty-cycle, multichannel, power amplifier for high resolution radiofrequency encoded magnetic resonance imaging.
Magn Reson Mater Phy. 32, 679-692.

(a)

(b)

Credit: Aaron Purchase

pTx Console Design

Board: **Terasic ADC-SoC Board**
Chip: **Altera Cyclone V**
Chip description: Cyclone is a SoC with an **FPGA** part and a HPS part on the same silicon. HPS is Hard Processor System dual ARM dual CPUs + memory etc. The HPS runs **C** code under **Linux.**
FPGA: Verilog (**Intel Quartus Prime Lite)**

Rx: dual 14-bit, 150 MSPS ADC

180 MHz clock →

trigger →

LTC 2x7 Header

↔ SPI Interface

Board: **4 - channel waveform generator**
Chip: **AD9106**
Chip description: Quad, Low Power, 12-Bit, 180 MSPS, Digital-to- Analog Converter and Waveform Generator

Software: load registers using SPI interface (on trigger signal)

↕ Ethernet

Quad RF Outputs

… to RF power amplifiers