MGH/HST Athinoula A. Martinos Center for Biomedical Imaging

Implementation of low-cost, instructional tabletop MRI scanners

Clarissa Z Cooley[1,2], Jason P Stockmann[2,3], Cris LaPierre[2,3], Thomas Witzel[2], Azma Mareyam[2], Feng Jia[4], Maxim Zaitsev[4], Pascal Stang[5,6], Greig Scott[6], Yang Wenhui[7], Wang Zheng[7], and Lawrence L Wald[2,8]

[1] *Electrical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA*

[2] *Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Charlestown, MA, USA*

[3] *Department of Physics, Harvard University, Cambridge, MA, United States*

[4] *Department of Radiology – Medical Physics, University Medical Centre Freiburg, Freiburg, Baden-Württemberg, Germany*

[5] *Procyon Engineering, San Jose, CA, USA*

[6] *Electrical Engineering, Stanford University, Stanford, CA, USA*

[7] *Electromagnetic Detection and Imaging Technology, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China*

[8] *Harvard Medical School, Boston, MA, USA*

Challenge: Build educational MRI scanner for < $10K

- Existing commercial tabletop educational scanners cost above $25K [1-4].
- *<u>Goal:</u>* Build economical tabletop scanner with 1cm FOV
- Build the scanner in the same spirit as a recently-introduced open-source relaxometer [5], with mainly off-the-shelf components and open-source pulse sequence codes

[1] http://pure-devices.com/ [2] http://www.ebresearch.net/ [3] http://www.magritek.com/applications-teaching
[4] Wright SM, MAGMA 2002. [5] Twieg M, ISMRM 2013 #0139.

Challenge: Build educational MRI scanner for < $10K

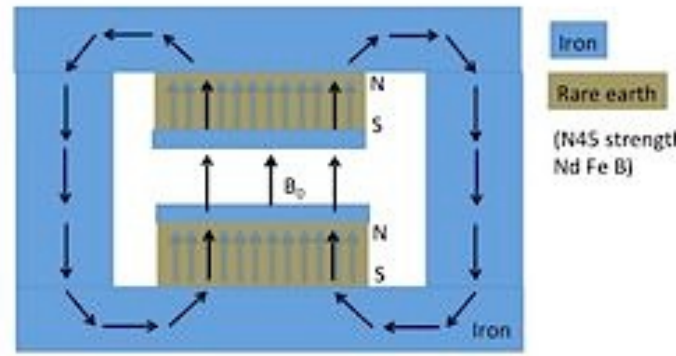
- First application: 20 scanners for MIT undergraduate class *EECS 6.S02 – Intro to EECS from a Medical Technology Perspective*
  - Teach basic concepts in data acquisition, computer control of experiments, signal processing, and Fourier analysis
  - Pulse sequences and data processing in Matlab
  - Demonstrate concepts of free induction decay, flip angle measurement, B_0 shimming, gradient echo, spin echo, 1D projection, and 2D as well as 3D imaging.

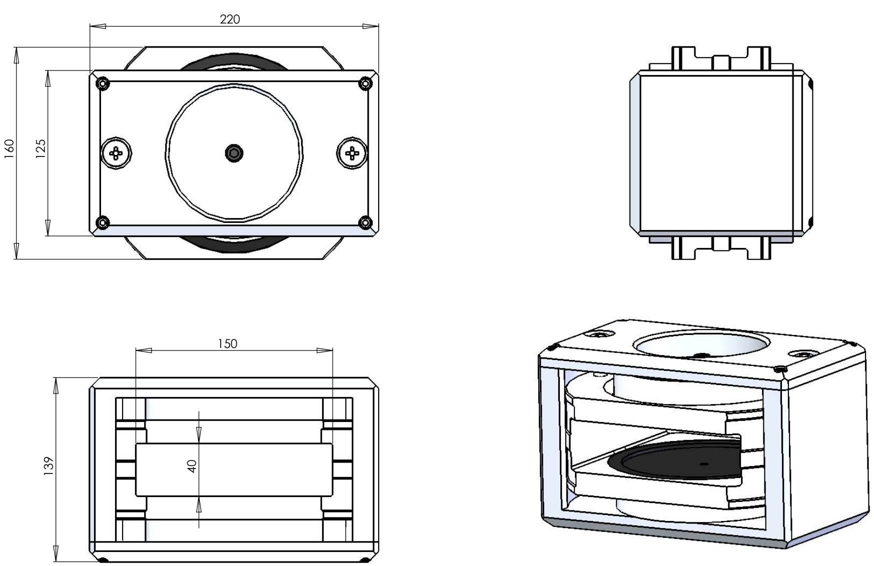
Outline

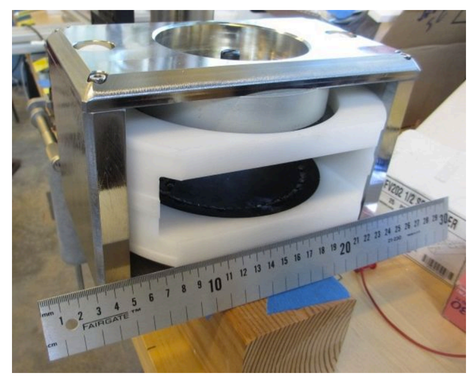
- Overview of system components
- Demonstrate scanner graphical user interface
- MIT undergraduate lab course and user Wiki
- Image gallery and conclusion

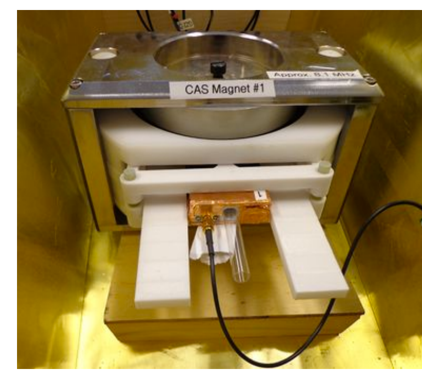
Magnet

- Built by Chinese Academy of Sciences
- Neodymium-Iron-Boron magnets mounted inside steel yoke. Iron pole pieces between magnetic pucks improves homogeneity
- B_0 field is 0.18T shimmed with small iron cylinders to less than 50 ppm over 1 cm^3 imaging volume.
- 4cm gap between pole pieces





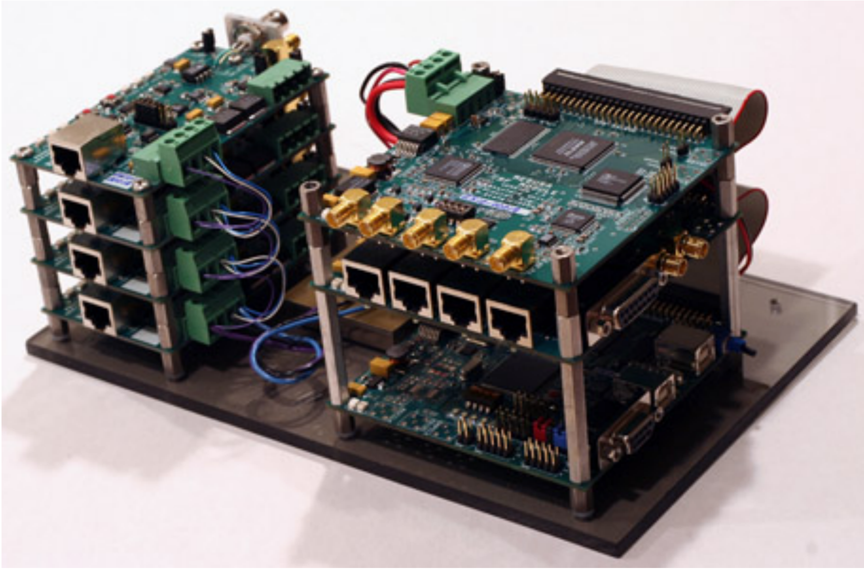




Magnet rendering (left) along with completed magnet by itself (center) and enclosed in shielded box with gradient and RF coils mounted inside

MEDUSA console

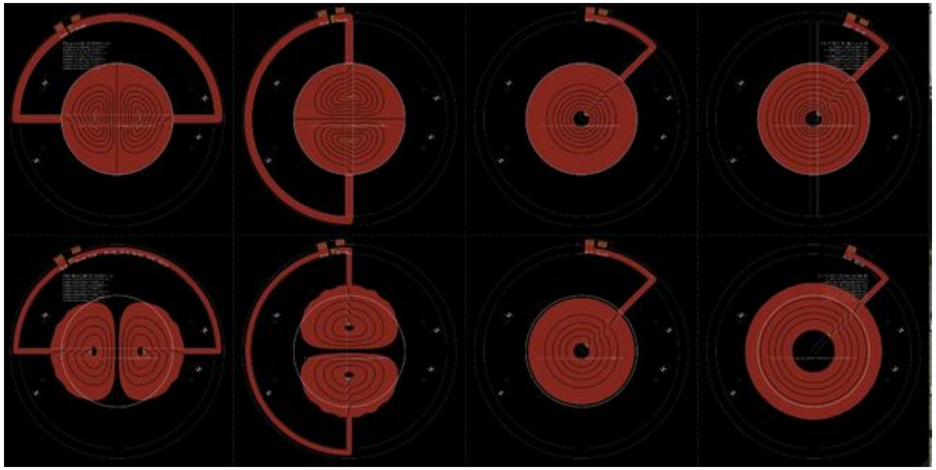
- Designed and fabricated by Pascal Stang, Stanford/ Procyon Engineering [1]
- Direct digital TX and RX up to 100 MHz
- 60 MHz 32-bit ARM processor with 2MB SRAM
- Four arbitrary waveform gradient outputs
- 16-bit low-noise optically-isolated digital-to-analog converter
- Two gating outputs
- Sequences are programmable in Matlab for seamless interface between acquisition and data processing

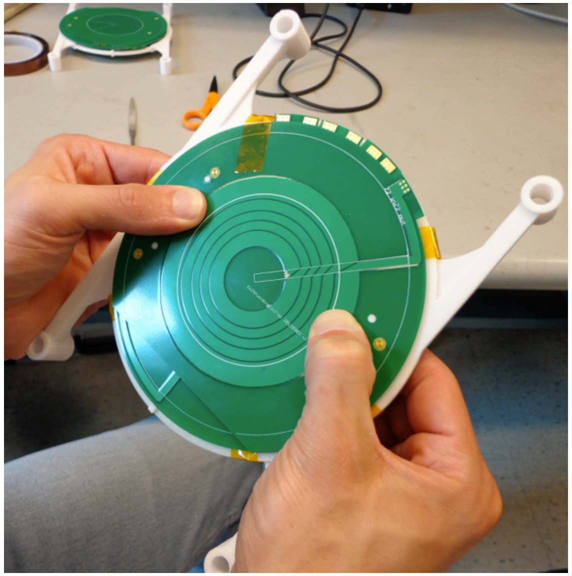


[1] Stang P, IEEE TMI 2011.

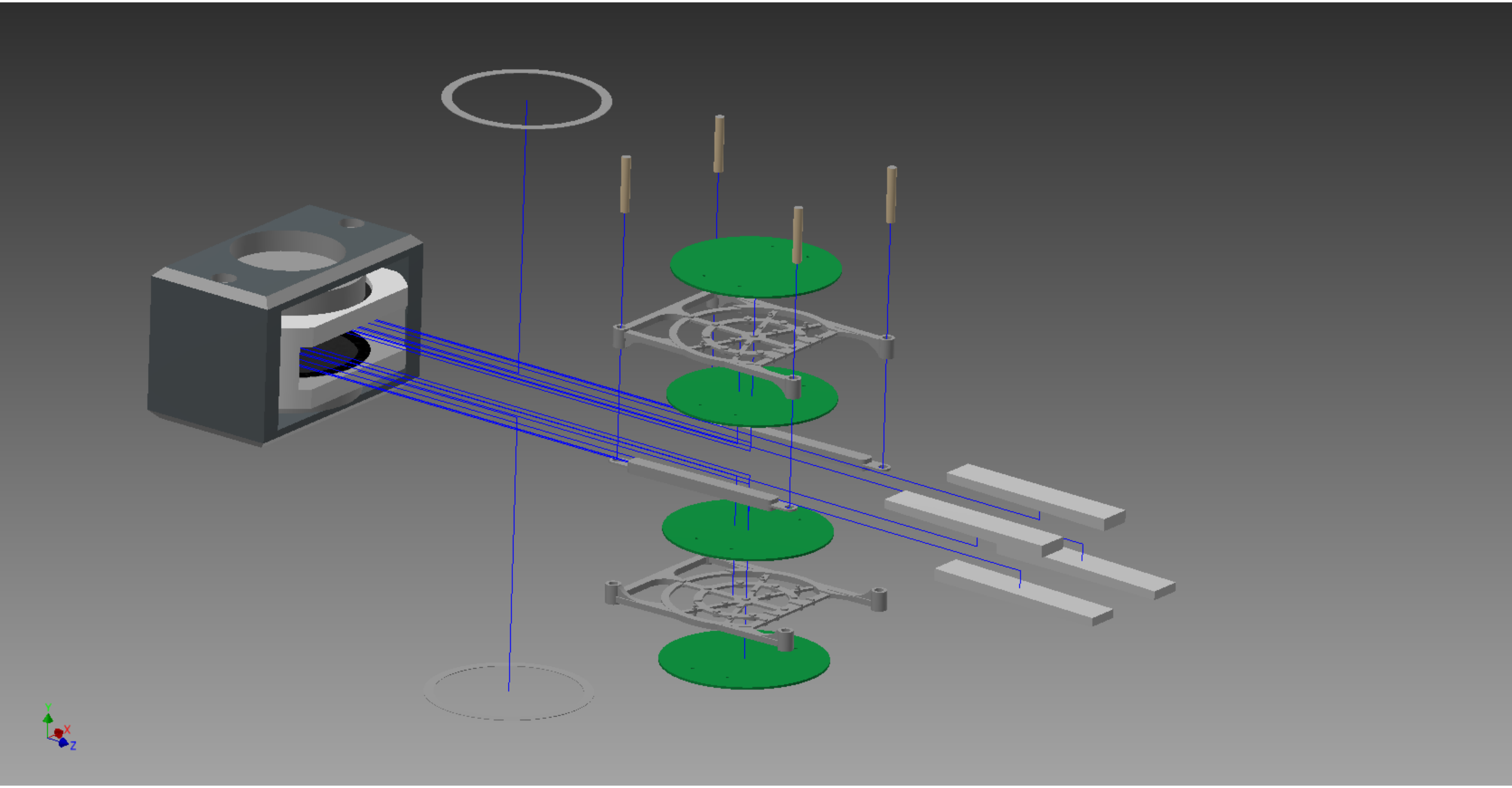
Gradient traces and board design

- Coils designed by Medical Physics group at Uni–Freiburg and fabricated at MGH
- Air-cooled gradients implemented as shielded planar coils (two primary, two shielding) for X, Y, Z, and Z2 terms
  - Gradients placed ±1cm from isocenter
  - Shield coils placed ±2cm from isocenter against magnet poles
  - 8-layer board with buried vias and 4 oz/ft^2 copper traces (140 µm) provide ~40 µT inductance
- Realized field strength is 35 mT/m/A



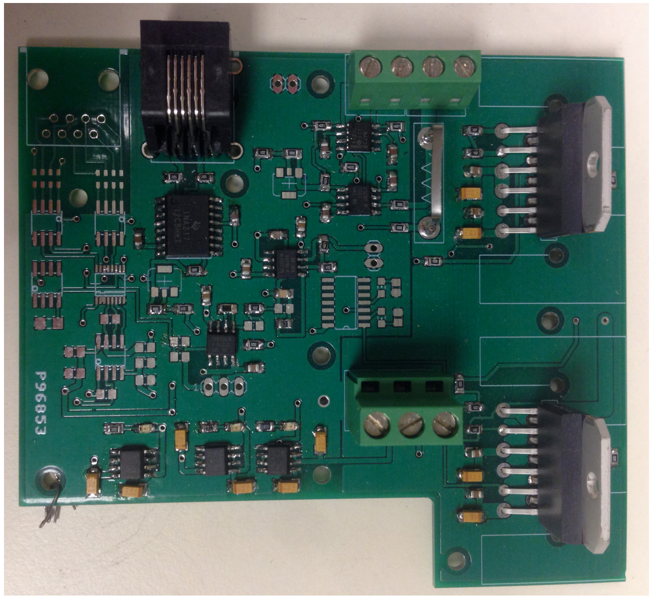


Gradient board assembly



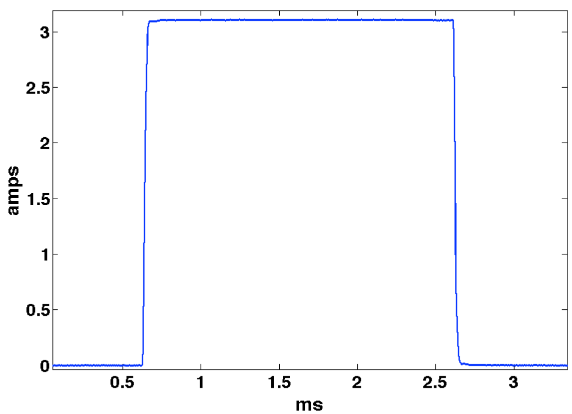
Gradient power amplifiers

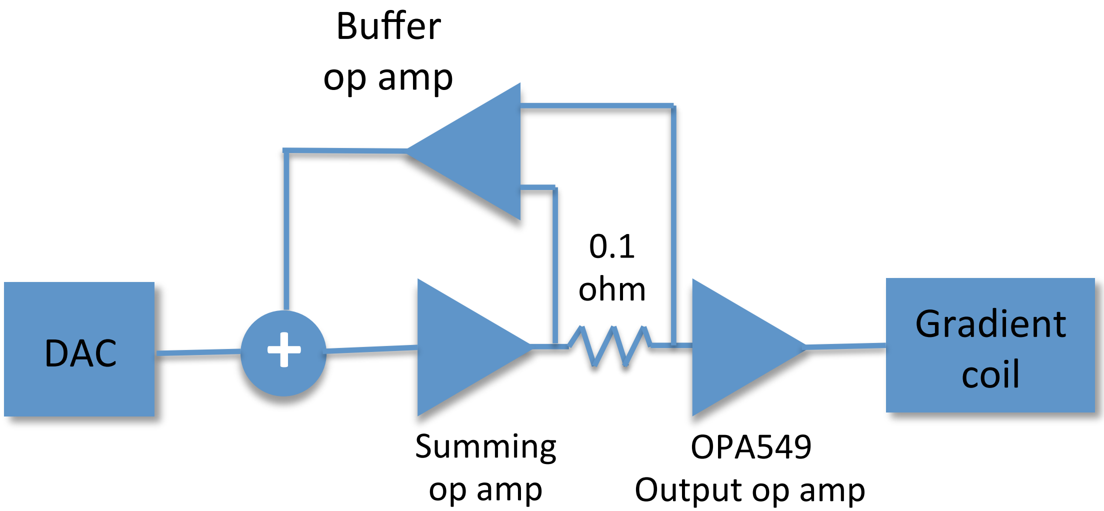
- Low-cost, in-house GPA board design
  - Output stage uses OPA549 high current op amps in master-slave configuration running on ±15V rails
  - Uses feedback via 0.1 ohm current sense resistor on output
- $100 per channel
- Ramps to 3A in only 20 μs



Thomas Witzel, MGH

Oscilloscope trace

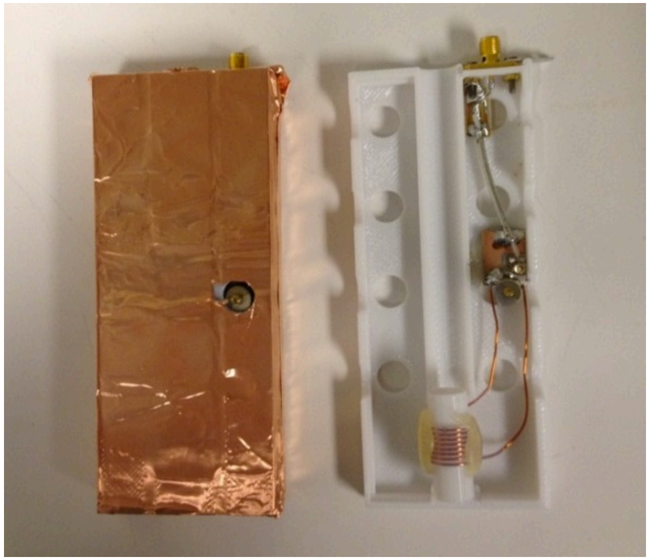


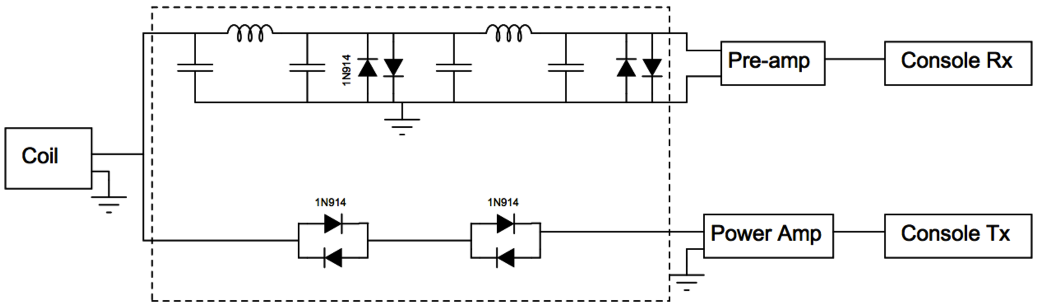


RF transmit and receive

- RF coil uses solenoid wrapped around 10mm sample tube that holds imaging phantoms
  - Copper foil shield improves SNR
- Two low-cost GALI-74 preamp stages used
  - ~25 dB provided by each preamp stage
  - 2.7 dB noise figure
- Passive T/R switch used to protect pre-amps during RF transmission
- 1W Transmit amp: Mini-Circuits ZHL-3A
  - Blanking circuit to prevent signal leakage through T/R switch

RF transmit-receive coil





Complete assembly

Magnet with gradients and RF coil nested inside

Plywood box shielded with brass foil

Low-pass filters on gradient cables

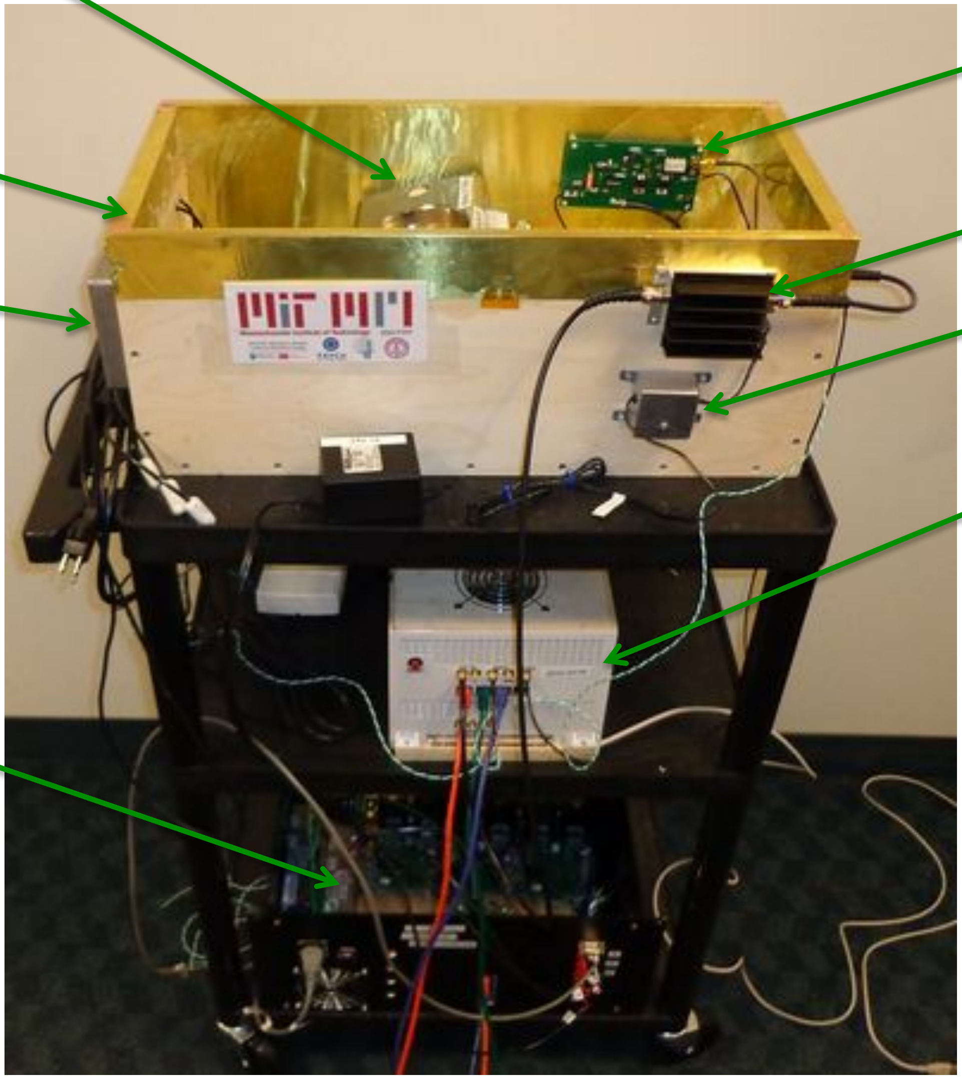
Gradient power amplifiers and power supplies in chassis

T/R switch with on-board pre-amps

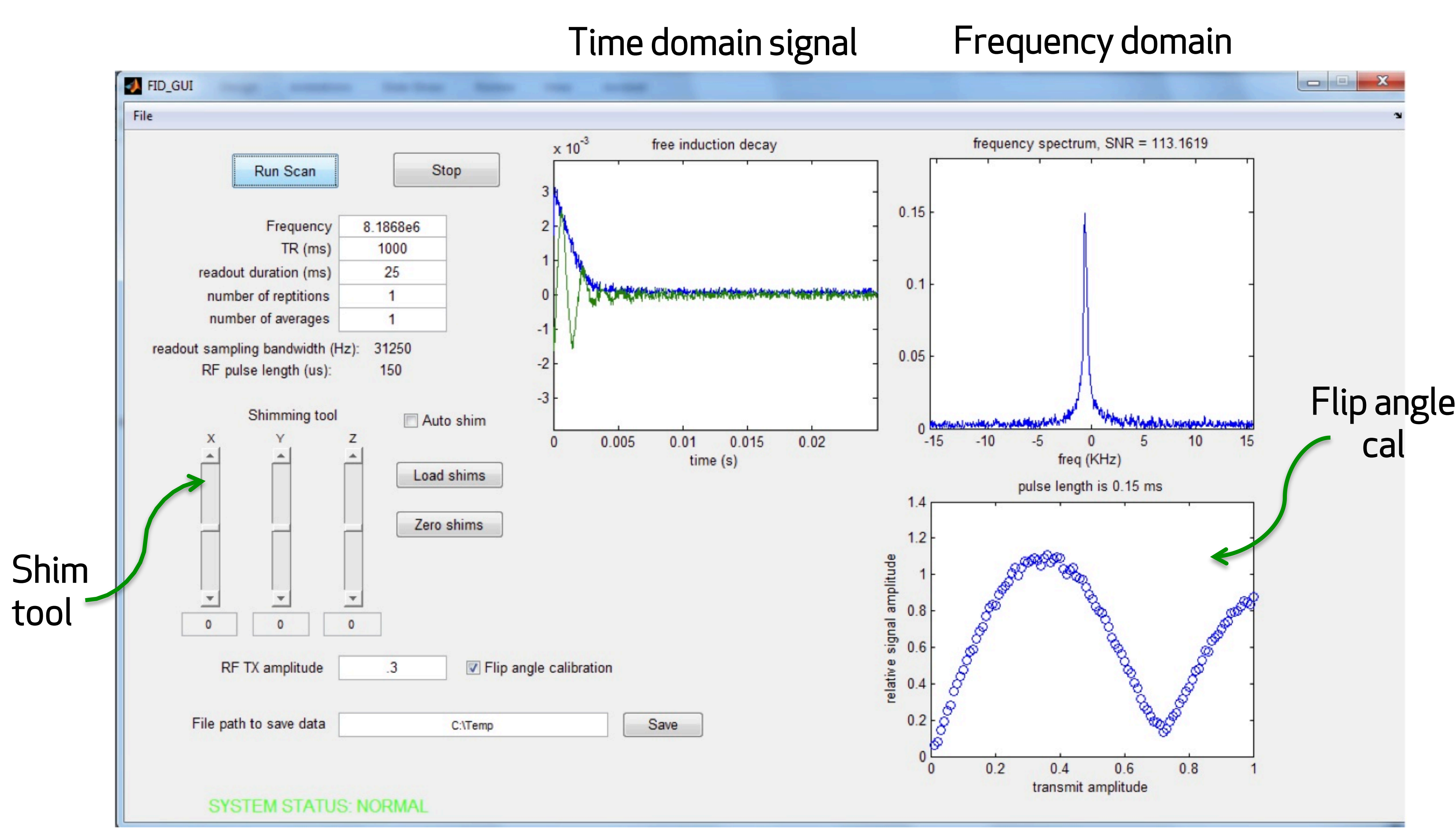
1W transmit RF amp

Transmit blanking circuit

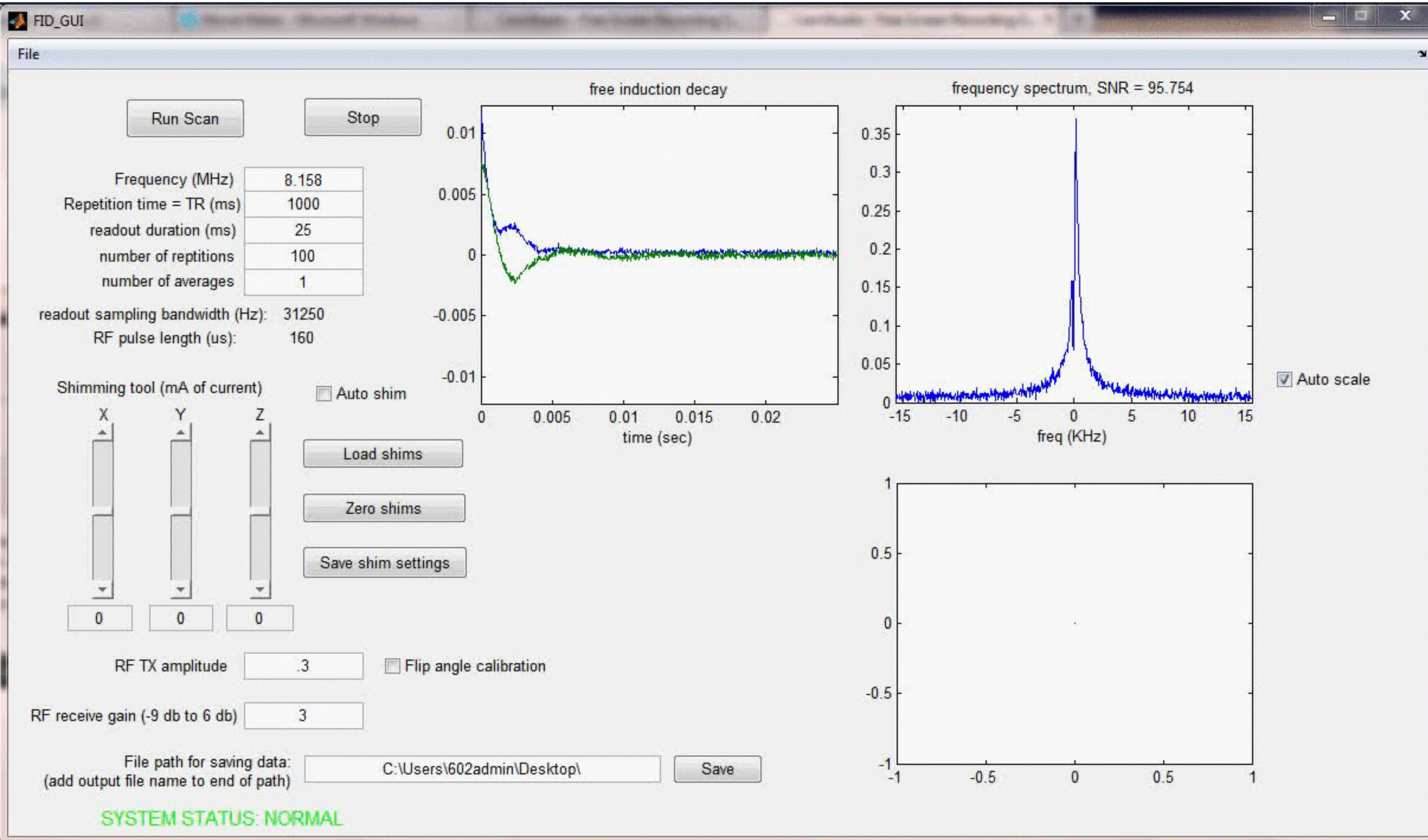
MEDUSA console



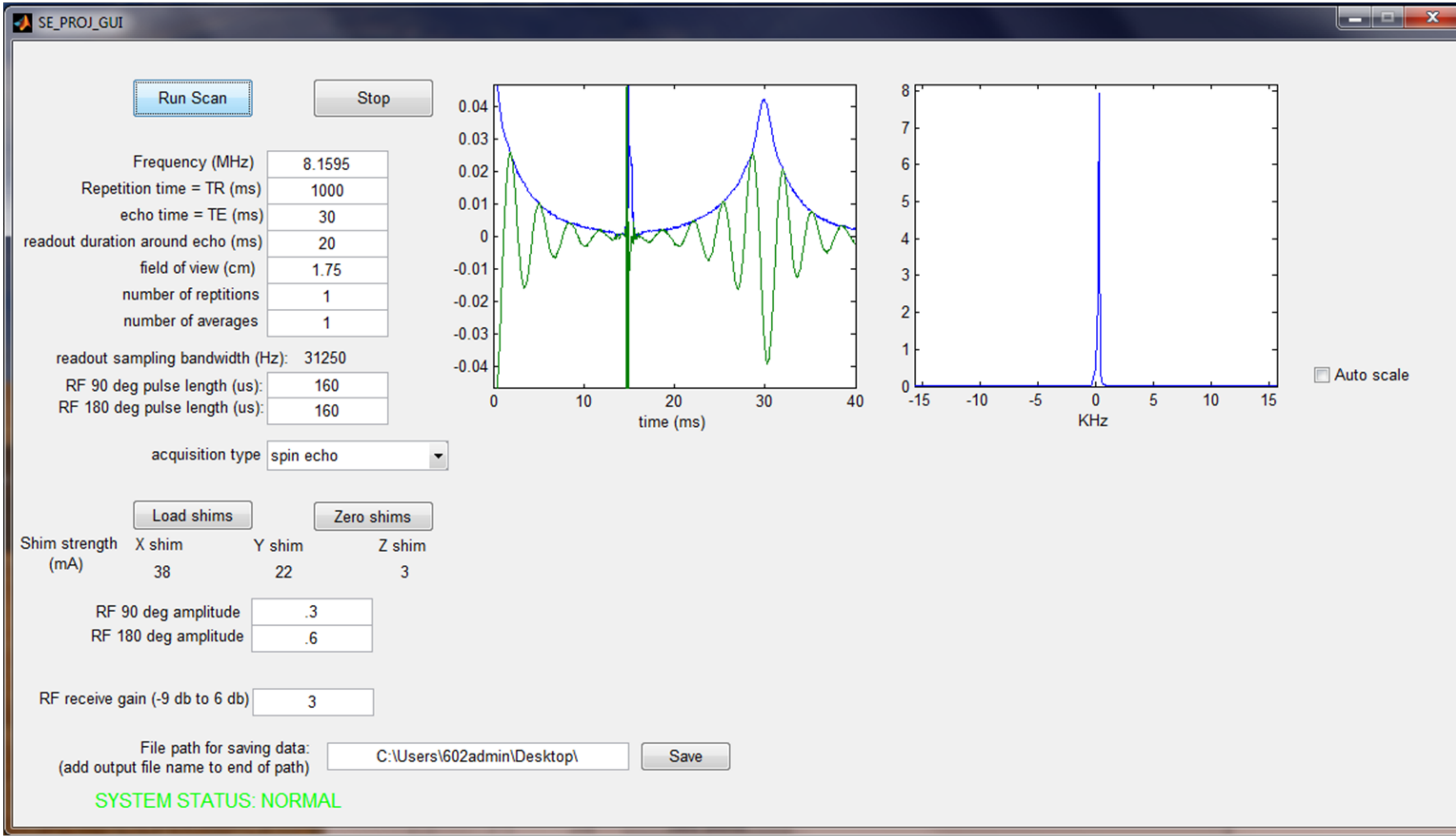
Matlab GUIs: Free induction decay



Matlab GUIs: Free induction decay → shimming demo

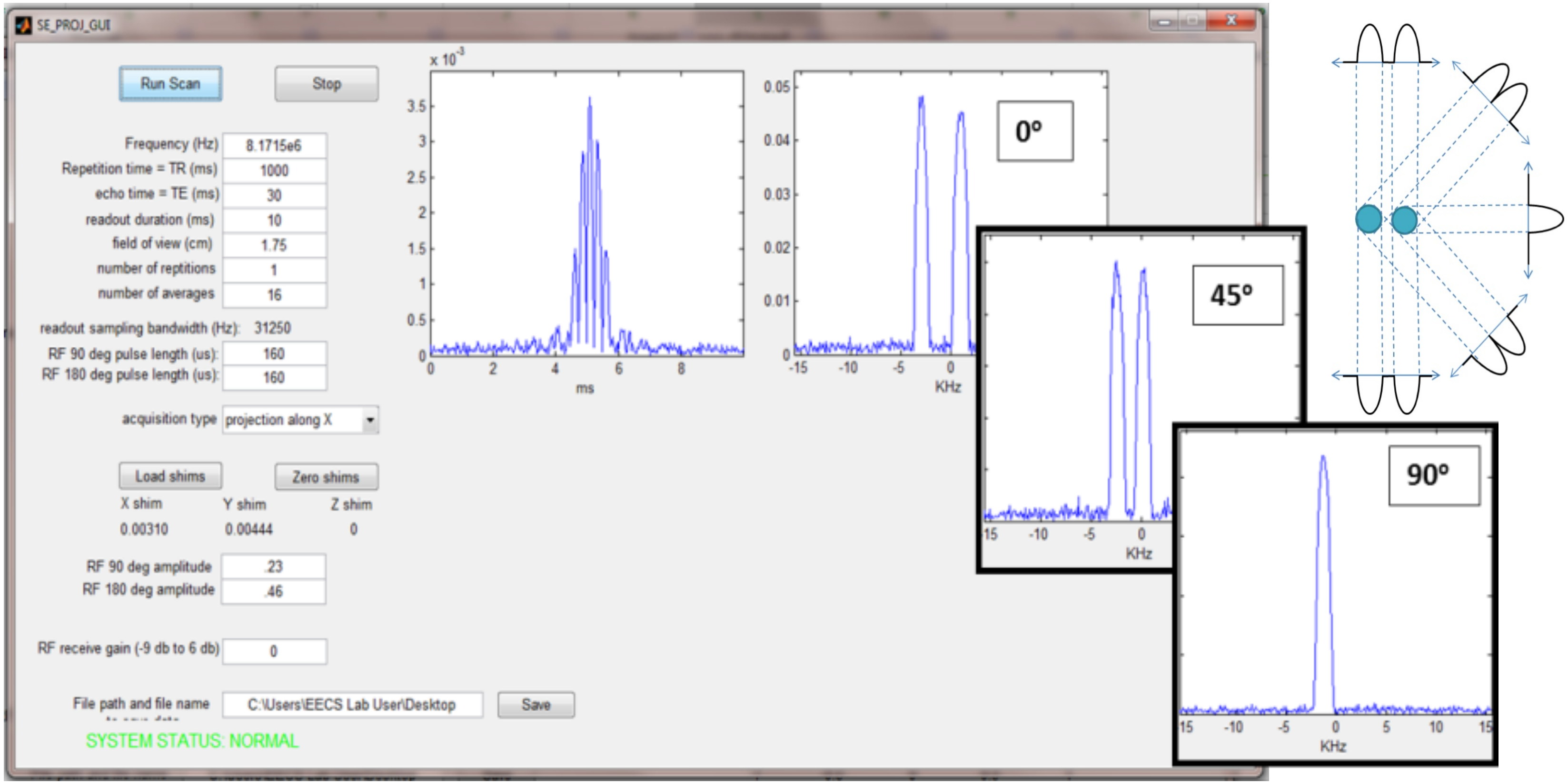


Matlab GUIs: Spin echo & 1D projections

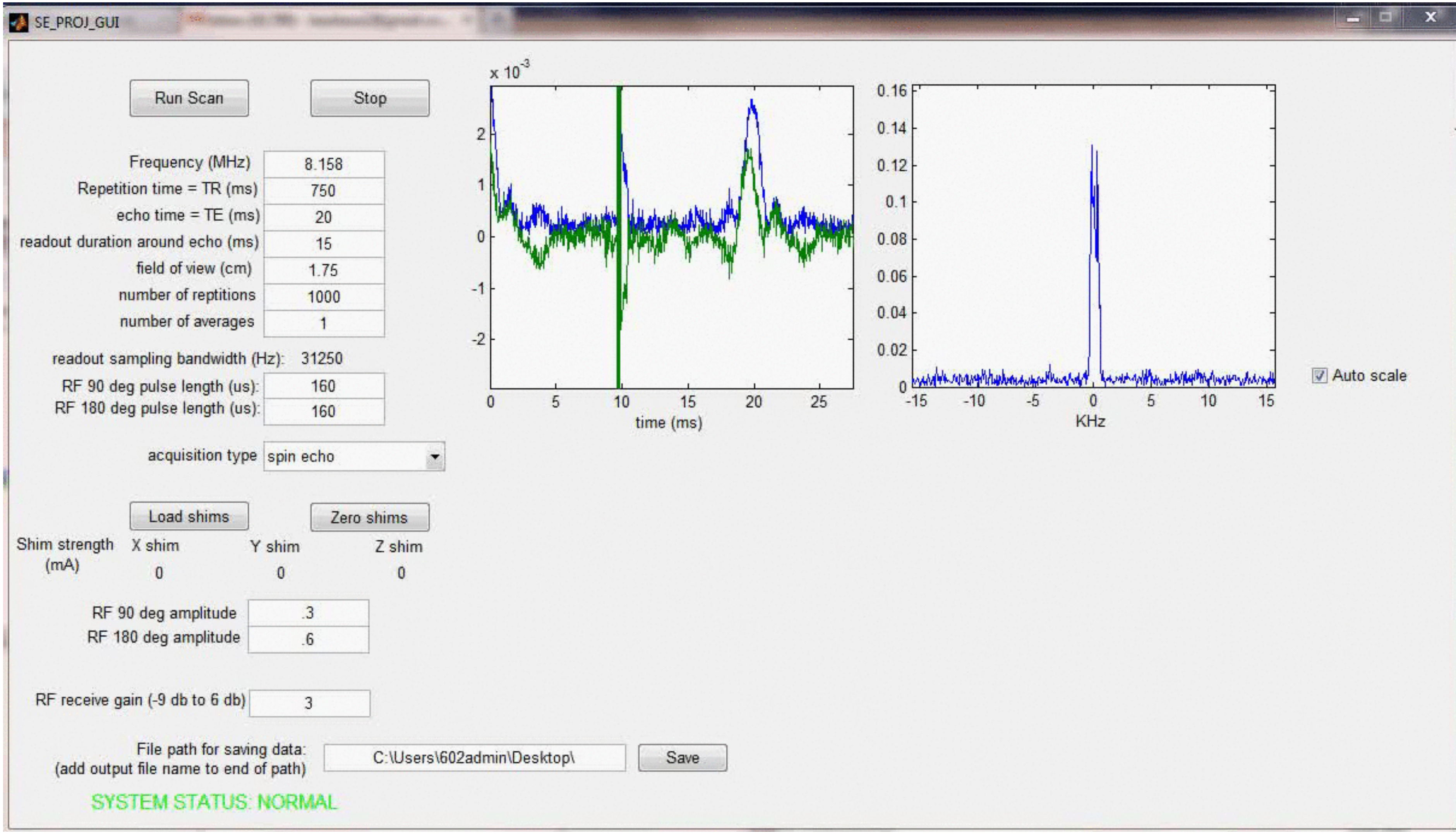


Matlab GUIs: Spin echo & 1D projections

- Spin echo / projection GUI shows projections of rotated 2-tube phantom with x-gradient on
- Students gain exercise with backprojection reconstruction from data



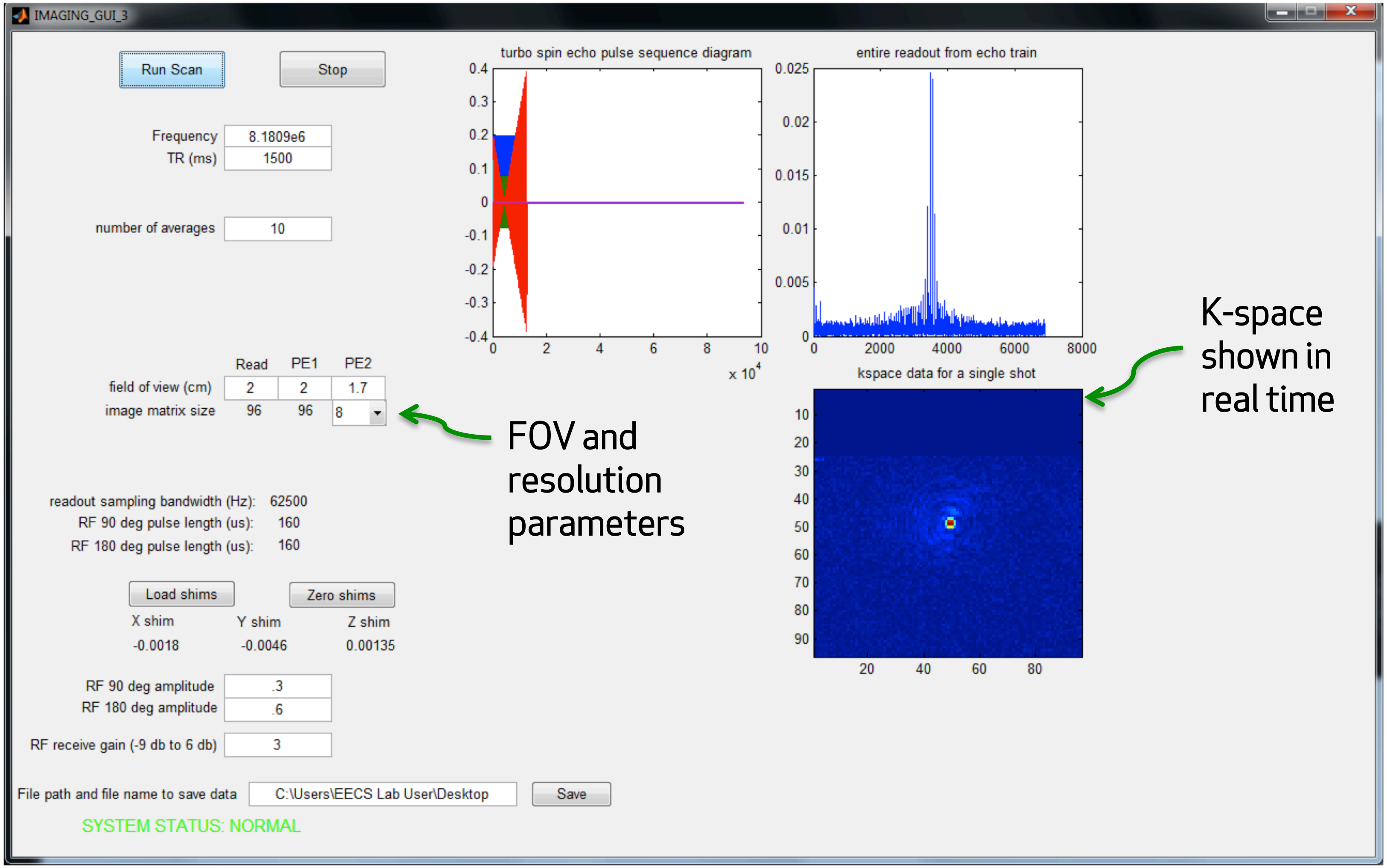
Spin echo and 1D projection demo with 3-tube phantom:



Matlab GUIs: 2D & 3D imaging with RARE echo train

Sequence diagram

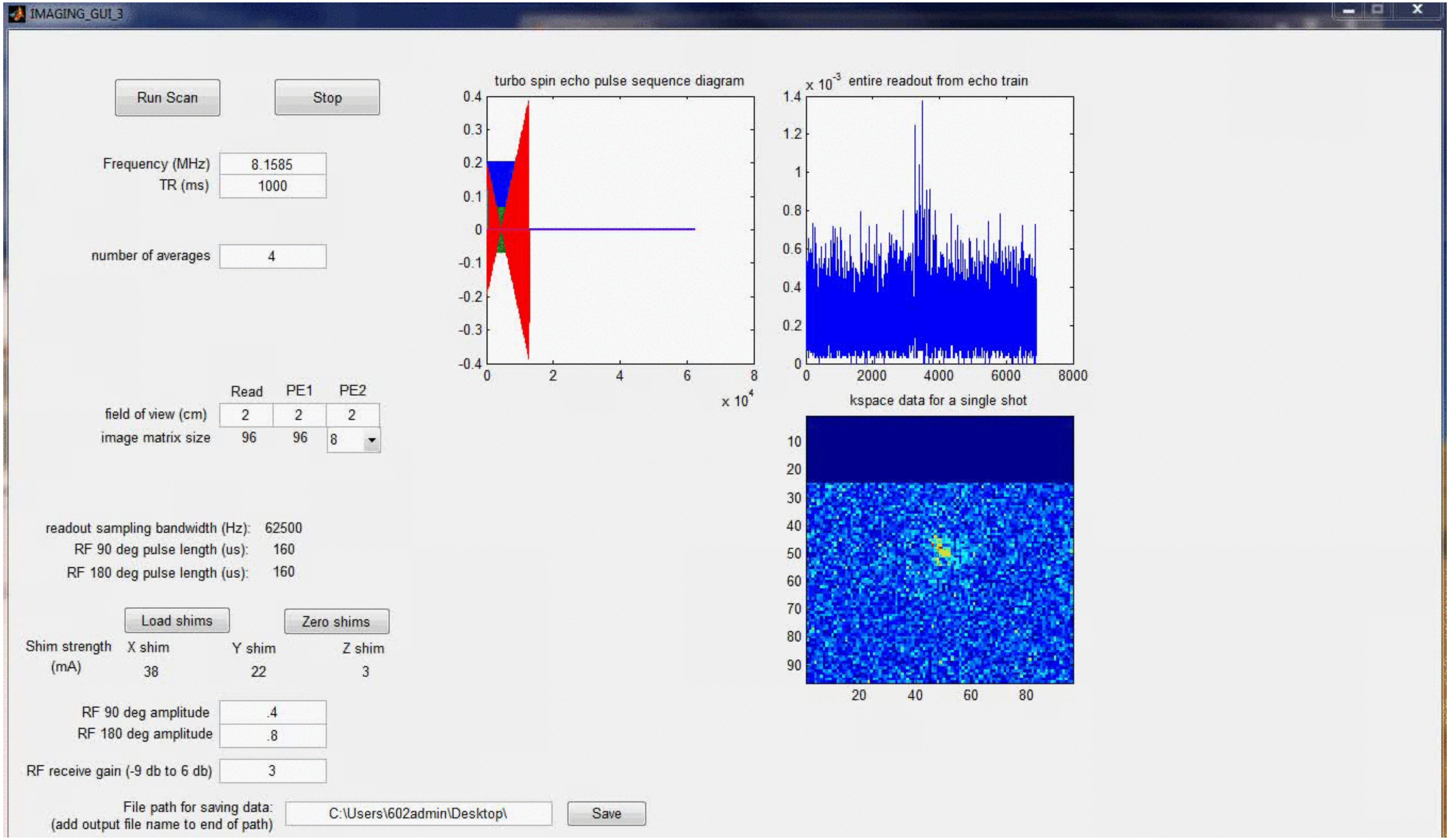
Raw time domain data



FOV and resolution parameters

K-space shown in real time

Matlab GUIs: 2D & 3D imaging with RARE echo train



Scanners in action: Spring 2014 6.S02 lab at MIT

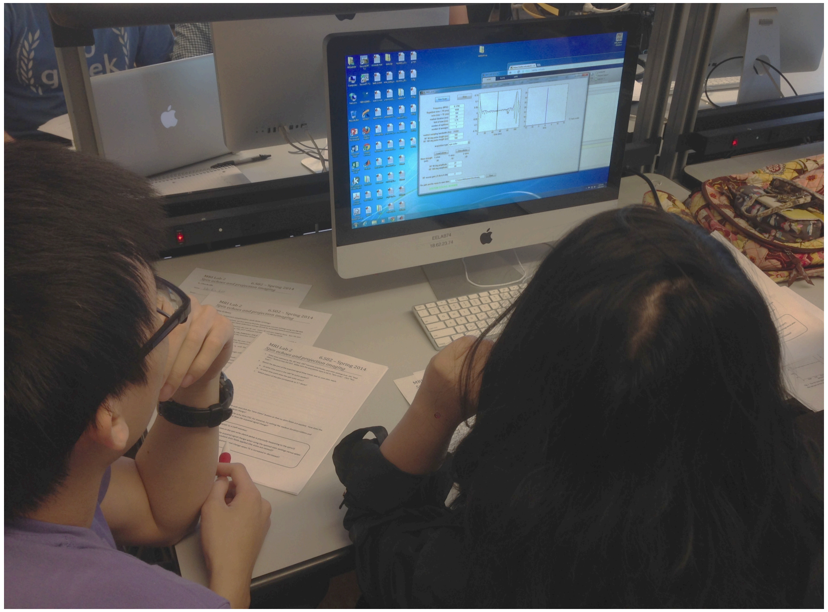
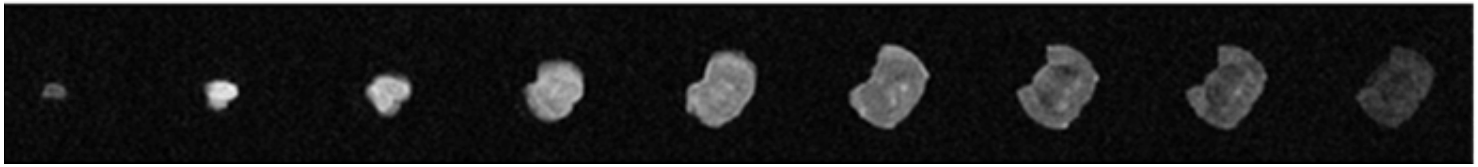


Image gallery



Mouse brain. 3D RARE, FOV = 1.75 cm, matrix = [96 × 96 × 9], 6/8 partial Fourier, BW = 62 KHz, NA=32

3D-printed star phantom. Single-shot 2D RARE, FOV = 1.25 cm, matrix = [96 × 96 × 9], 6/8 partial Fourier, BW = 62 KHz, NA = 1.

3D printed "M-I-T" phantom. 3D RARE, FOV = 2 cm, matrix = [96 × 96 × 9], 6/8 partial Fourier, BW = 62 KHz, NA=1

Wiki site for user community: http://tabletop.martinos.org

- Help build a user community and make info about the scanner freely available
- Publish all GUI and pulse sequence files and allow users to upload new sequences
- Available for download:
  - Gradient coil circuit board files
  - Gradient power amp and RF T/R switch circuit board files
  - Parts lists
  - Matlab files:
    - GUIs
    - Pulse sequences

Wiki site for user community: http://tabletop.martinos.org

Log in

Page | Discussion | Read | View source | View history | Go | Search

Navigation

- Main page
- Community portal
- Current events
- Recent changes
- Random page
- Help

Toolbox

- What links here
- Related changes
- Special pages
- Printable version
- Permanent link

Main Page

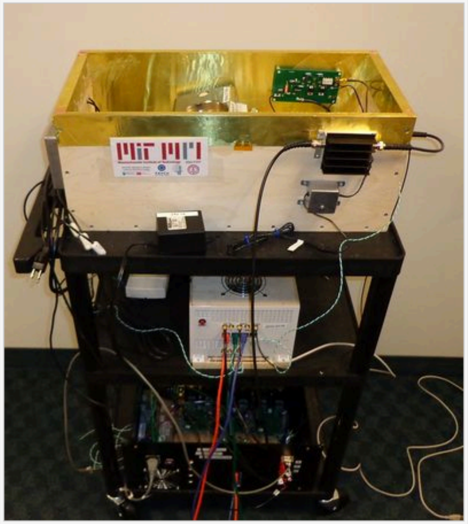
This Wiki is a resource for people who are assembling, programming, or using the instructional tabletop MRI scanner developed by Larry Wald's group at the Martinos Center for Biomedical Imaging, Massachusetts General Hospital.

The scanner design is a low-cost resource for demonstrating concepts like magnetic resonance, spatial encoding, and the Fourier transform in an educational setting. The system was first used in MIT's undergraduate course 6.S02 - Intro to EECS II from a Medical Technology Perspective. Most of the components are open source designs.

The project was made possible through a collaboration between MGH, the Chinese Academy of Sciences (who built the magnets), Pascal Stang of Stanford University (who provided the MEDUSA console), and Maxim Zaitsev's group at the University of Freiburg (who designed the gradient coil traces). During fabrication we also benefited from access to the equipment and resources of the Center for Bits and Atoms at the MIT Media Lab.

First delivery to MIT: photo here Systems ready to roll out: photo here

Contents [hide]



Introduction

Other low-cost tabletop imaging systems:

Desktop MRI system with 2 cm bore from Steve Wright's lab at Texas A&M.

Open Source Mobile MR Relaxometer from Mark Griswold's lab at Case Western.

Terranova-MRI earth's field system from Magritek.

MRIjx table top teaching system from Niumag in Shanghai.

Pure Devices 0.5T tabletop system from Würzburg, Germany.

Hardware

- Console
- Gradient coil
- GPA/Gradient Filters
- Magnet
- RF
- Parts list

Sequences

- Lab Screenshots
- GUI descriptions and Source Code

Images

- Image Screenshots

Conclusion

- Demonstrate tabletop scanner design based on 0.18T permanent magnet with 1cm FOV and ~200 μm resolution using spin echo train acquisitions
- $10K budget achieved through multi-institutional collaboration
- Created Wiki to foster an open-access user community for the scanners
  - Wiki includes designs, board layouts, and parts lists for gradients, gradient power amps, filters, and RF subsystem
  - Users can upload new pulse sequences to grow the library
- Scanner used by 180 MIT students in April 2014 for EECS 6.S02 undergrad lab

Future work:

- Build larger magnets for imaging objects like the human finger
- Increase B_0 field strength to improve SNR
- Implement more sequences
- Refine RF preamp design to recover SNR

Acknowledgements

Simon Sigalovsky
Bo Zhu

Aldis Elfarsdottir
Andrew Dai
Eli Siskind
Jacqueline Finkielsztein
Isaac Rosen
Sam Sorensen
Cuong Nguyen

Ben Peters

Neil Gershenfeld, Media Lab
Center for Bits and Atoms

Elfar Adalsteinsson
Jacob White
Colin Stultz

Parts funding provided by the MIT Department of Electrical Enginering and Computer Science