Biomedical Imaging

Magnetic Resonance Imaging

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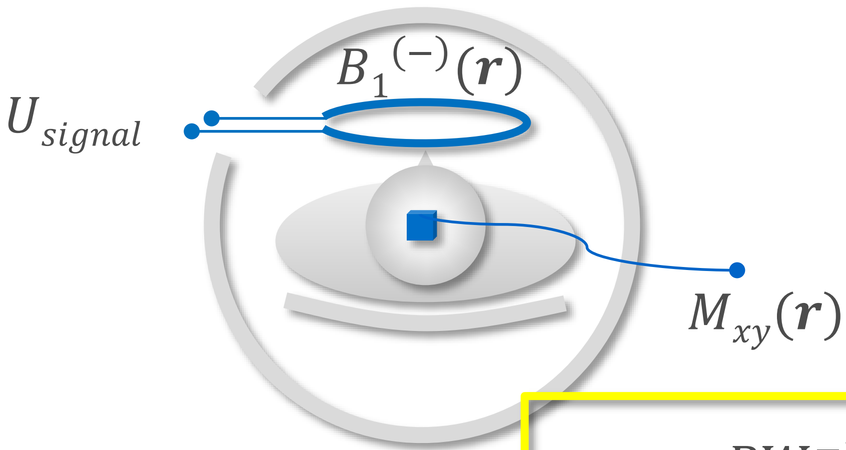
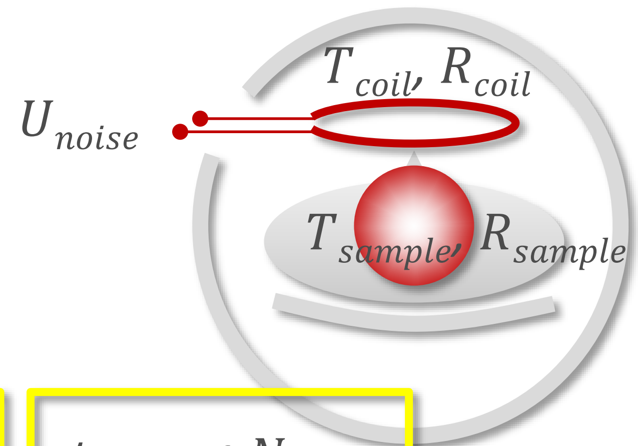
Signal-to-noise ratio

Signal



Noise



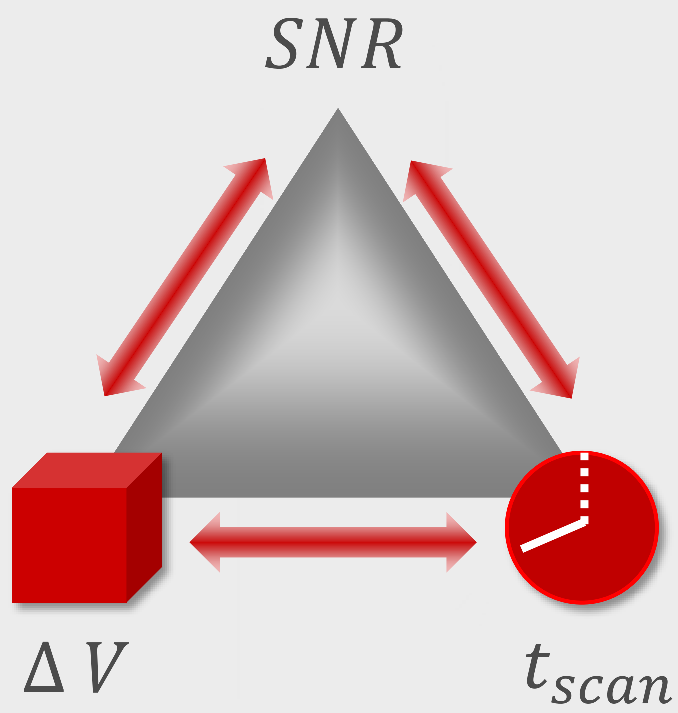
$t_{acq} \propto BW^{-1}$

$t_{scan} \propto N_{avg}$

$$SNR = \frac{U_{signal}}{\sigma(U_{noise})} = \frac{\omega\, B_1^{(-)}(\boldsymbol{r})\, M_{xy}(\boldsymbol{r})\, \Delta V}{\sqrt{4 k_B BW \left(T_{sample} R_{sample} + T_{coil} R_{coil}\right)}} \sqrt{N_{avg}}$$

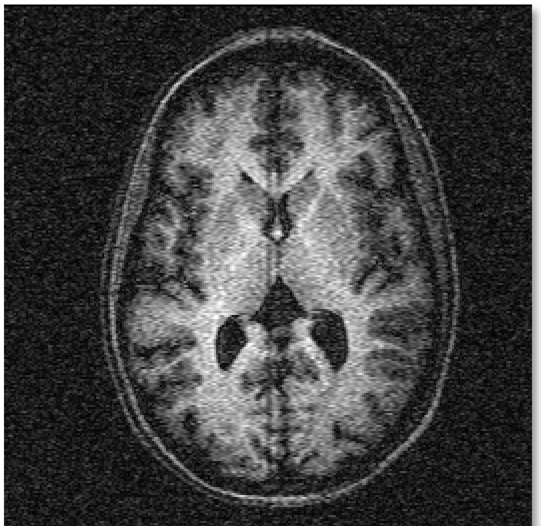
SNR – Resolution – Speed

$$SNR \propto \Delta V \sqrt{t_{scan}}$$



SNR – Speed – Image quality

SNR = 8



$N_{avg} = 1$

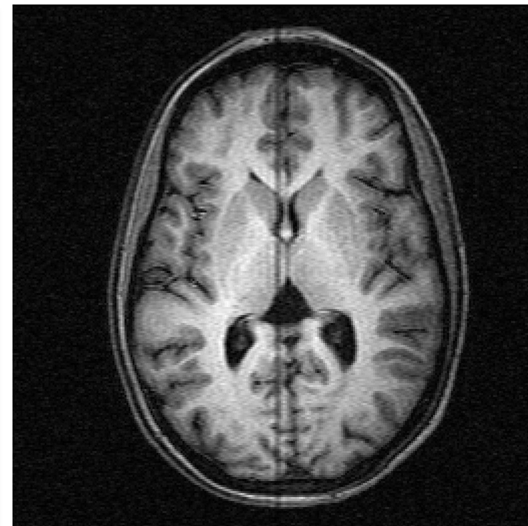
3 sec

SNR = 16

$N_{avg} = 4$

12 sec

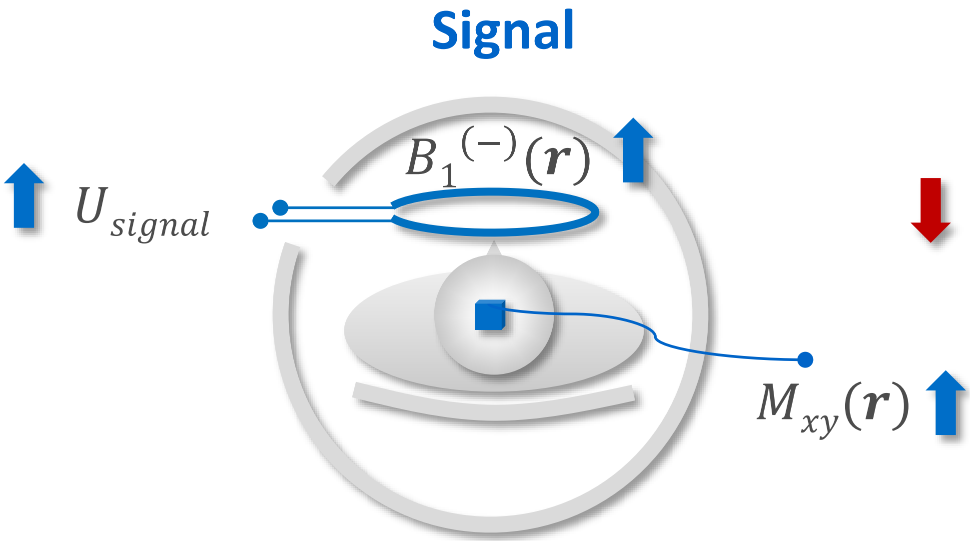
SNR = 23

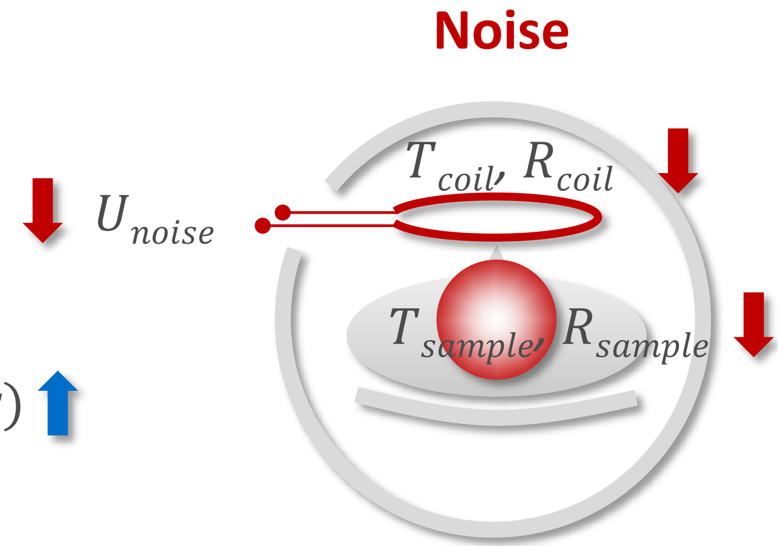


$N_{avg} = 8$

24 sec

Increasing SNR efficiency





Increase signal voltage

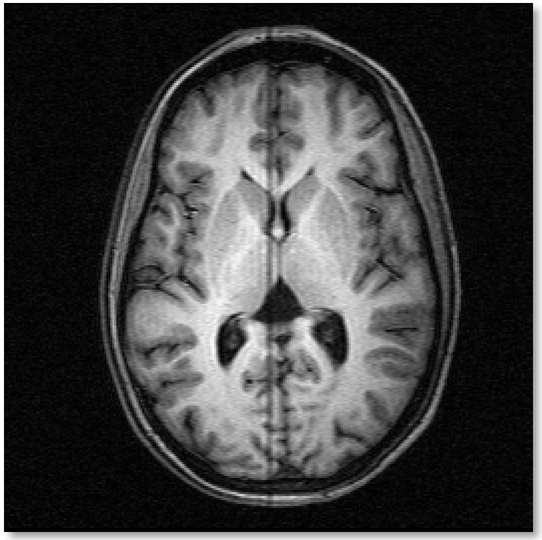
- Increase $B_1^{(-)}(\boldsymbol{r})$
- Increase magnetization $M_{xy}(\boldsymbol{r})$
- Increase frequency ω

Reduce noise voltage

- Minimize sample losses R_{sample}
- Minimize coil temperature T_{coil}
- Reduce coil resistance R_{coil}

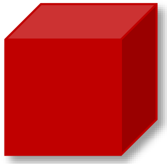
Spatial resolution

MR imaging



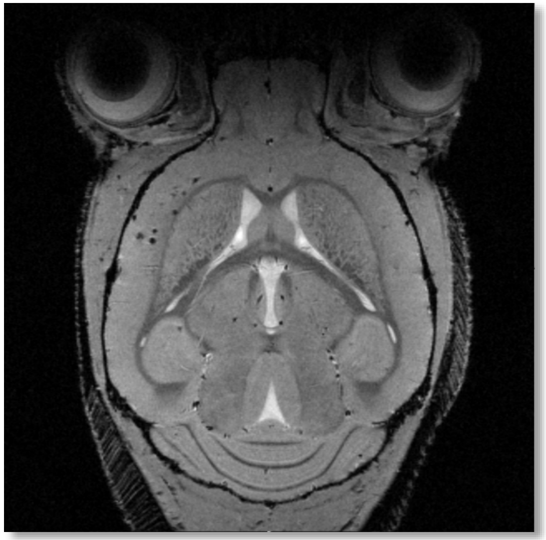
0.7 x 0.7 x 2 mm^3, 1 min

1 mm^3



$3 \cdot 10^{19}$ water molecules/voxel

MR microscopy



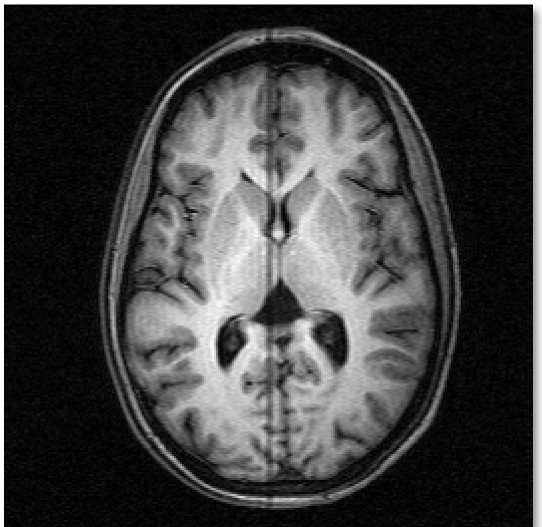
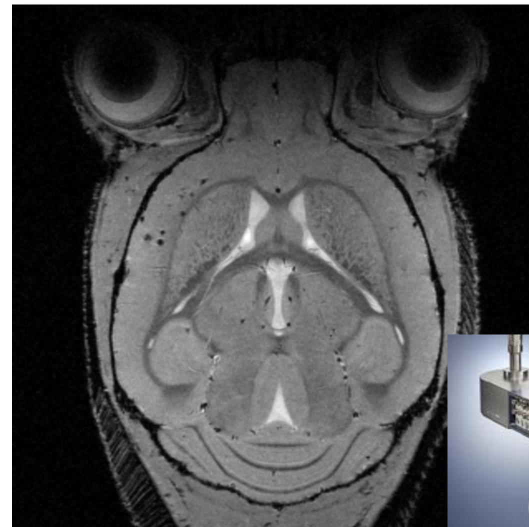
50 x 50 x 200 μm^3, 1 min

0.0005 mm^3

$1.5 \cdot 10^{16}$ water molecules/voxel

2000 : 1

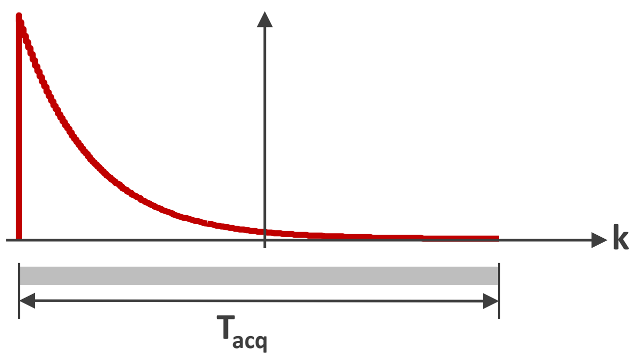
Maximizing signal-to-noise

MR imaging	MR microscopy
	  CryoProbe
0.7x0.7x2 mm^3	50x50x200 μm^3

	MR imaging	MR microscopy
Field B_0	3.0 Tesla	9.4 Tesla
Frequency ω	128 MHz	400 MHz
Sensitivity S	20 cm coil	1 cm coil
Coil temp T_{coil}	300 K	30 K

Resolution limits

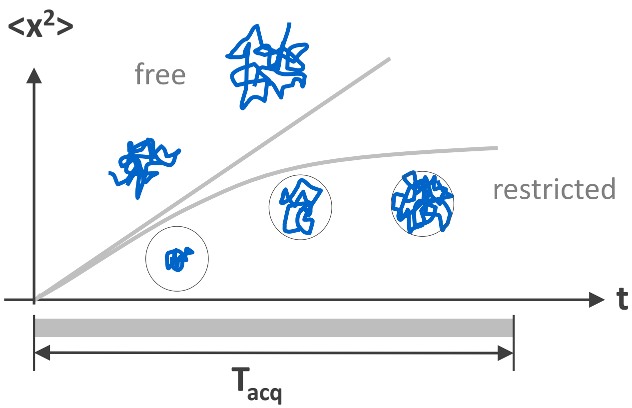
Relaxation



$$H(k) = rect\left(\frac{k}{2k_{max}}\right) e^{-t/T_2^*}$$

$$\Delta x \geq \frac{\pi}{\gamma\, G_{max}\, T_2^*}$$

Diffusion

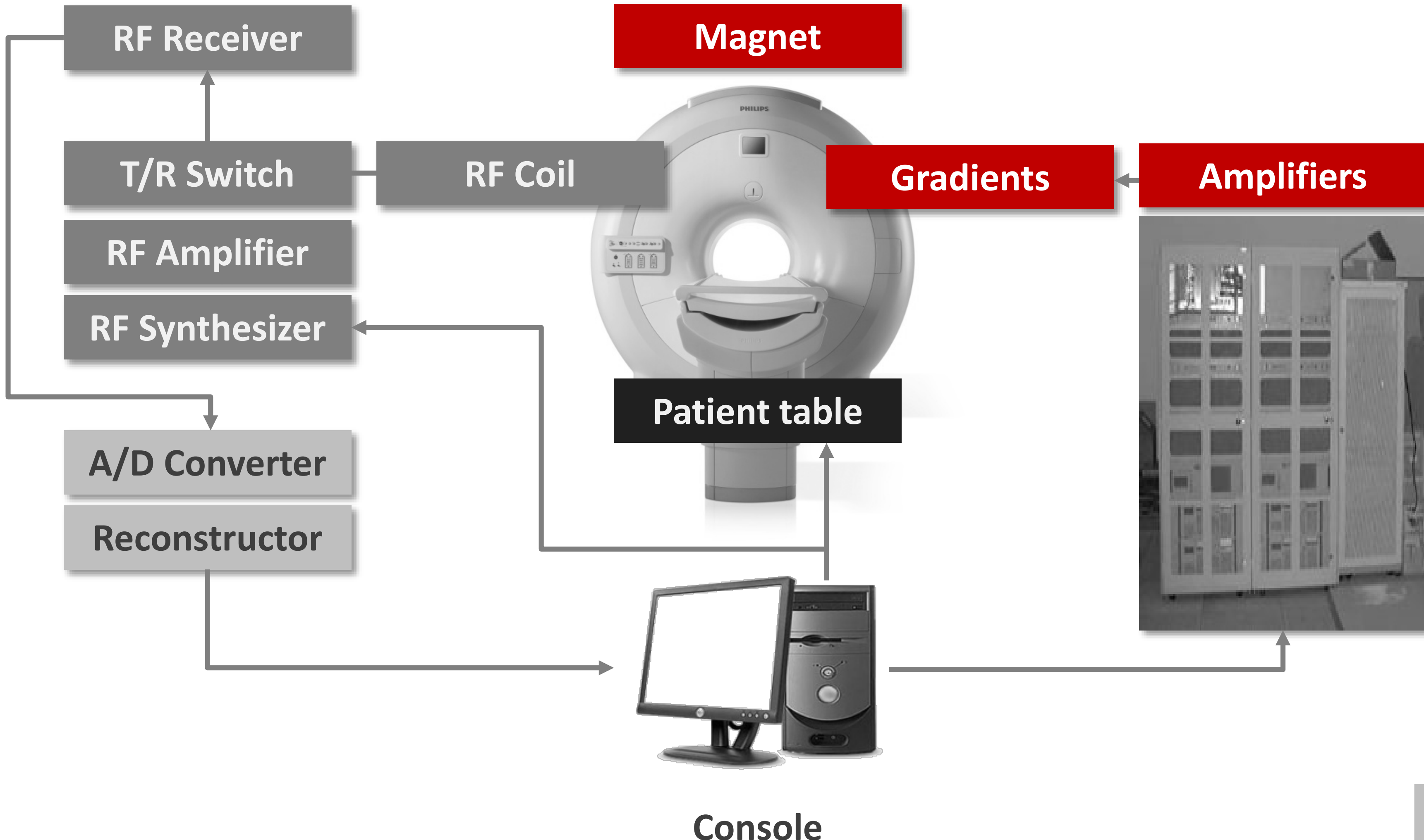


$$\langle \Delta x^2 \rangle = 6DT_{acq}$$

$$D = 1 \cdot 10^{-3} \frac{mm^2}{s}$$

$$T_{acq} = 10\ ms \implies \Delta x \geq 8\ \mu m$$

Magnetic Resonance Hardware

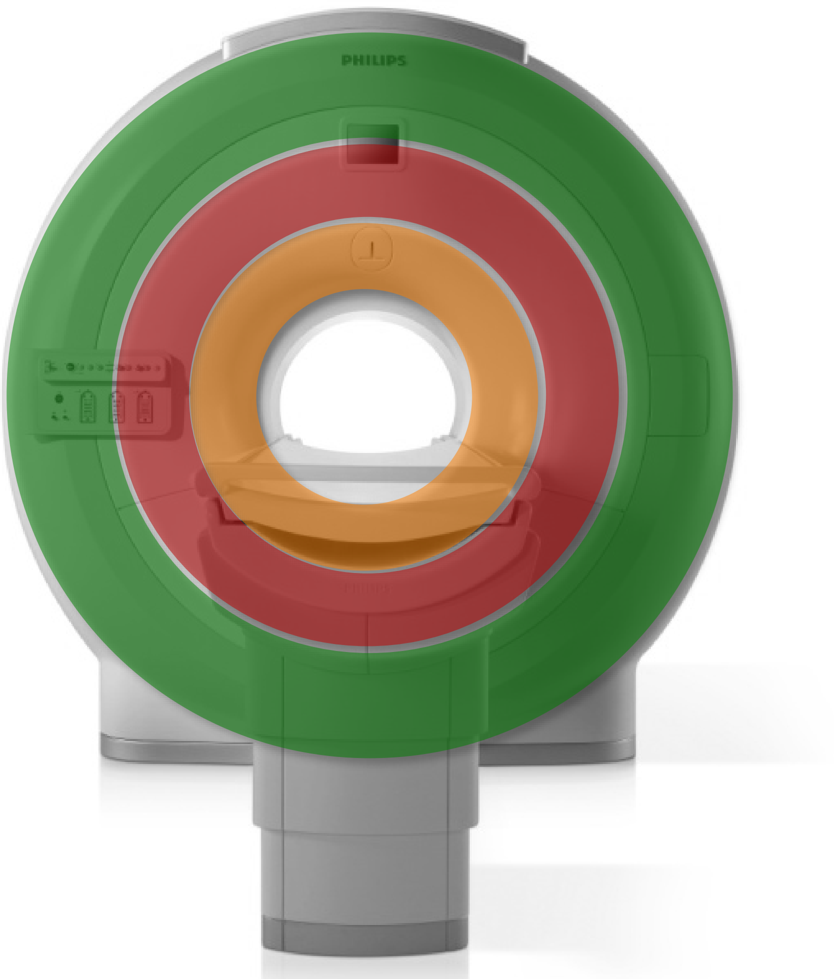


Magnetic Resonance Hardware

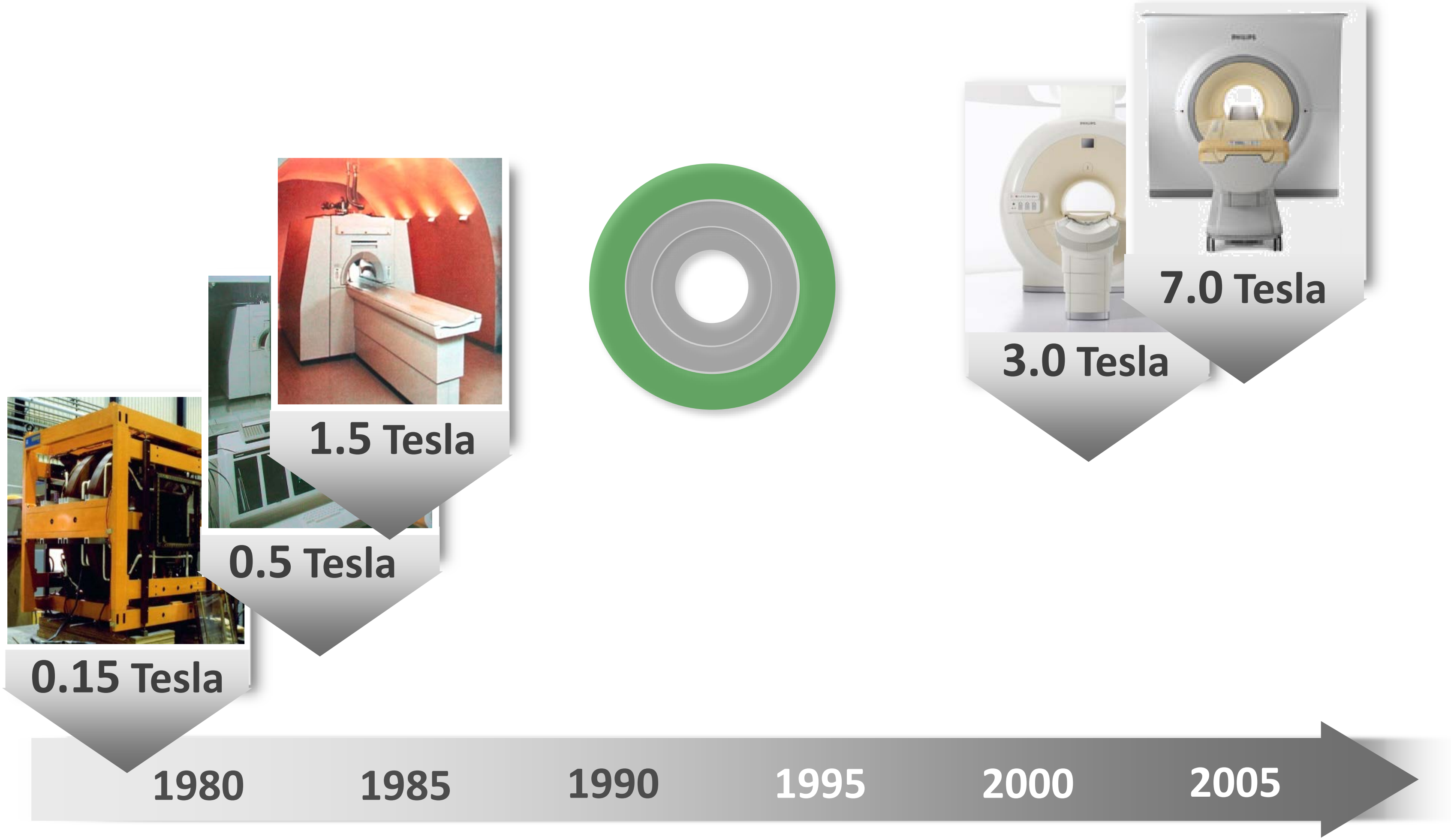
Magnet, Cryogenics

Gradients

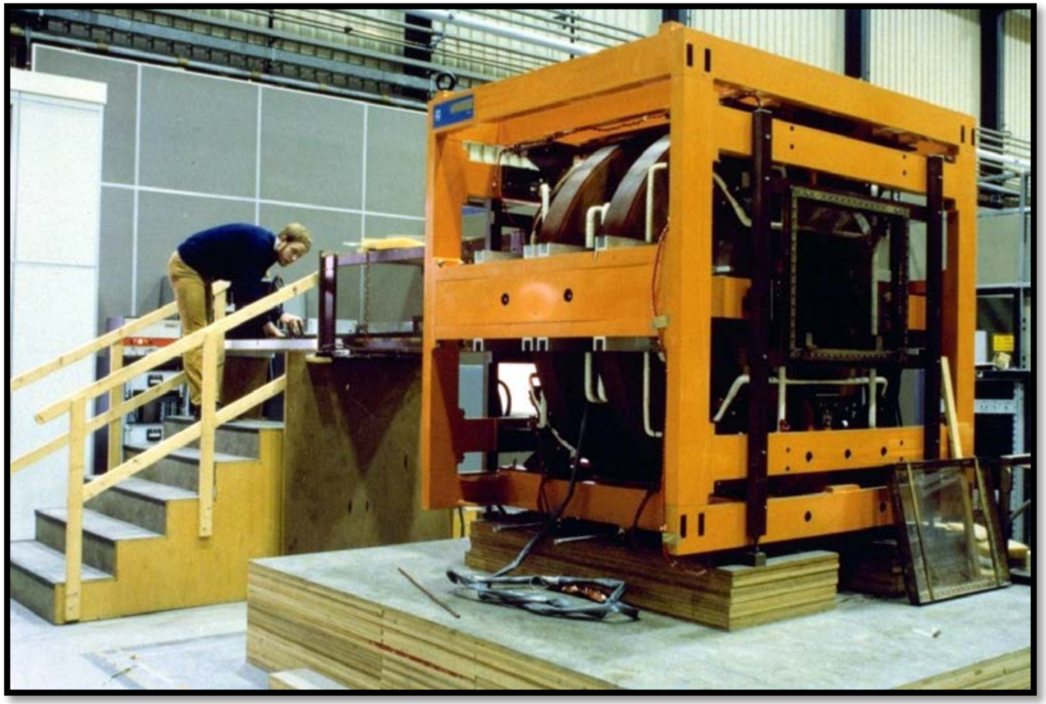
RF Body Coil



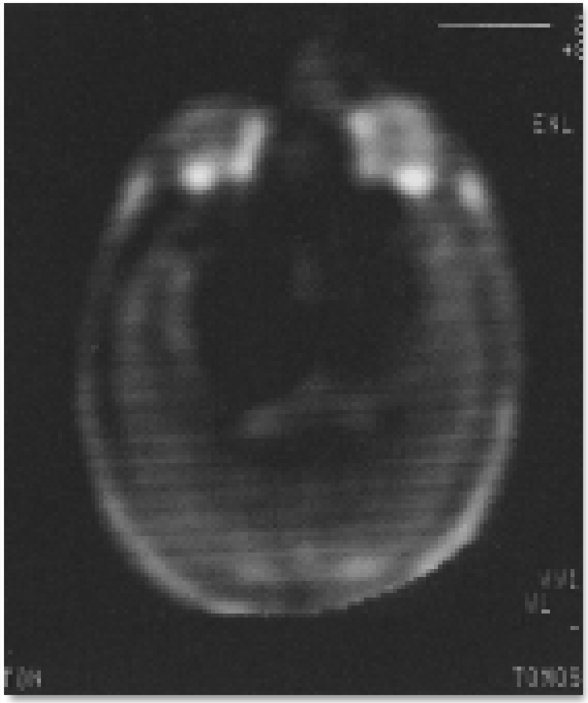
Magnet


0.15 Tesla
0.5 Tesla
1.5 Tesla
3.0 Tesla
7.0 Tesla
1980
1985
1990
1995
2000
2005

Magnet



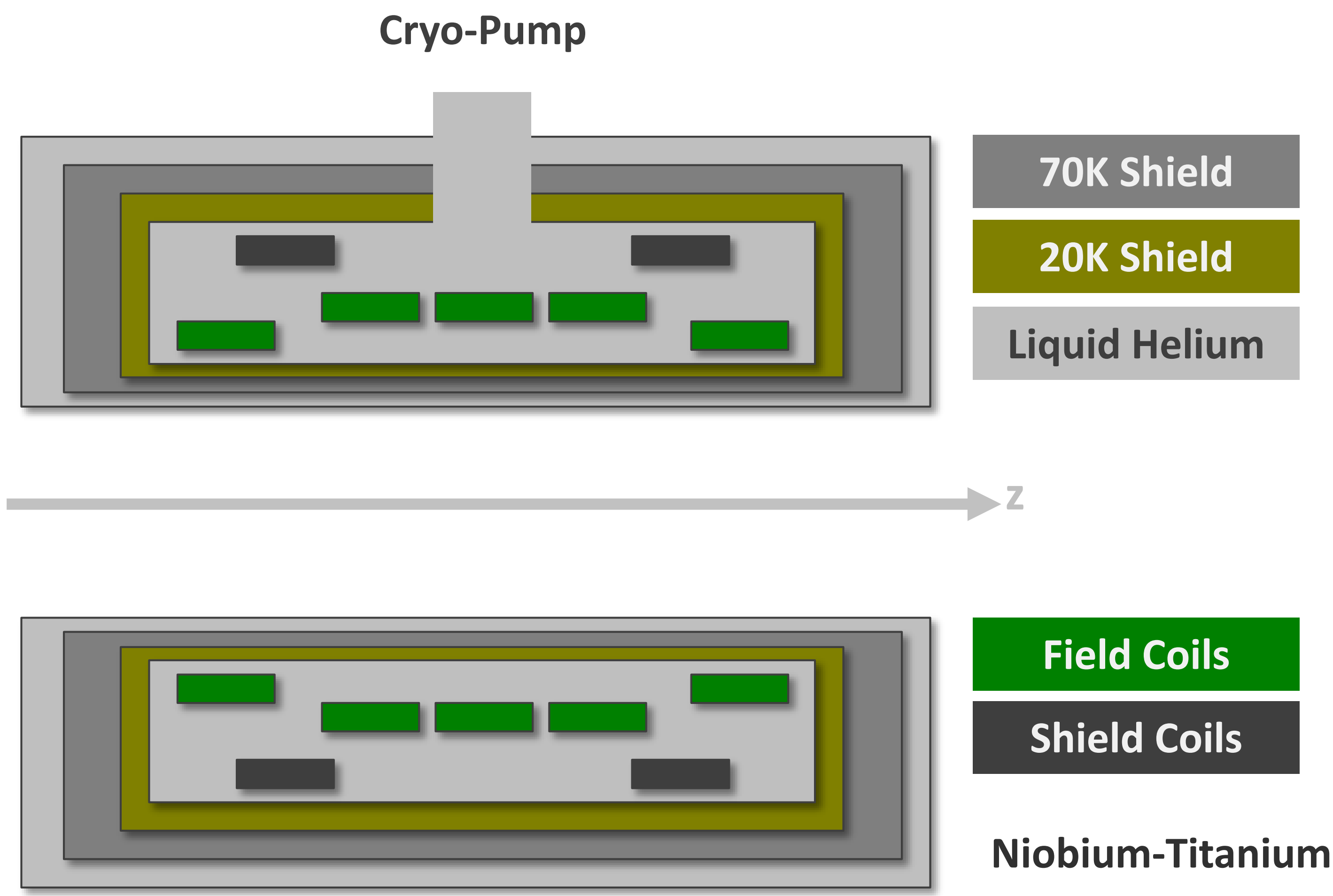
0.15 Tesla, resistive magnet (50 kW)



First human image (in Europe)

December 3, 1980

Superconducting Magnets



Niobium-Titanium

Magnet

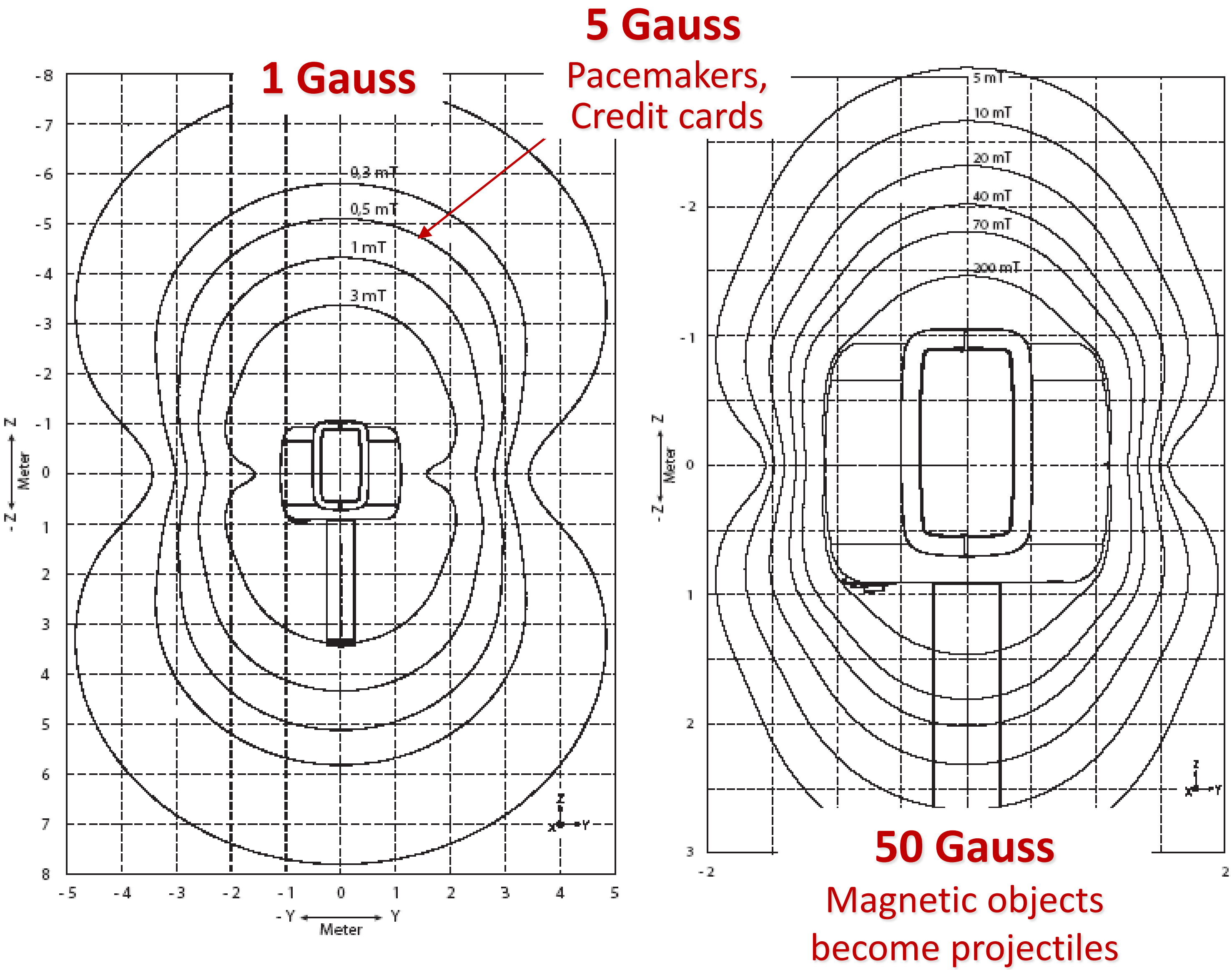
1.0 Tesla vertical field

3.0 Tesla horizontal field

Magnet

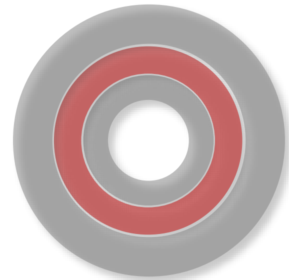

Europe's First
3.0T Mobile MRI
With MultiTransmit Technology
www.cobalthealth.co.uk
COBALT

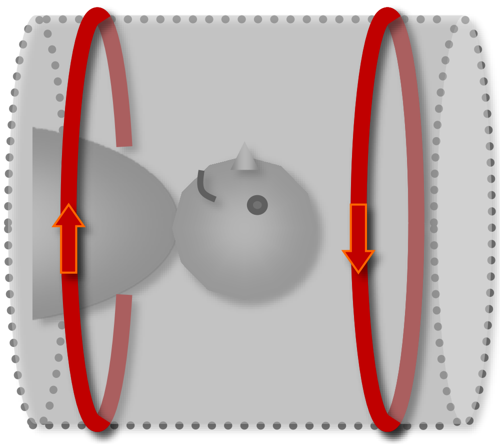
Magnet stray field



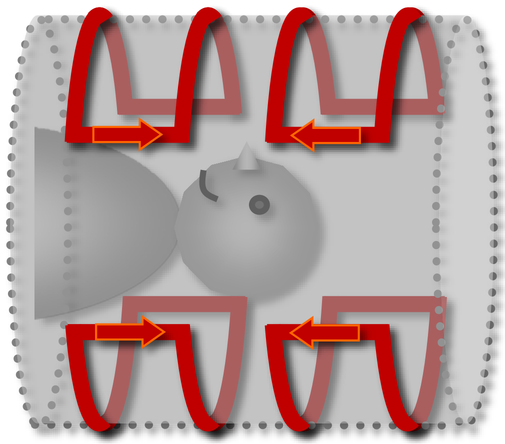
Magnetic stray field hazards

Gradients

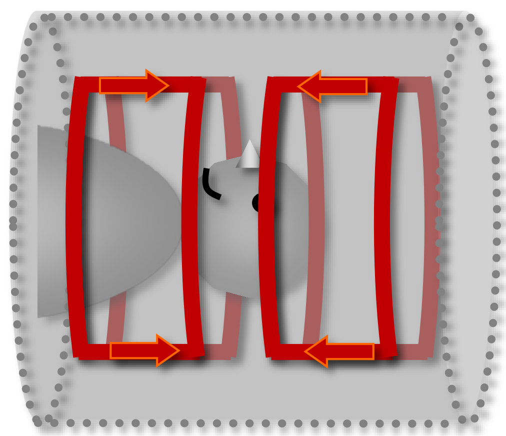




“Maxwell” pair



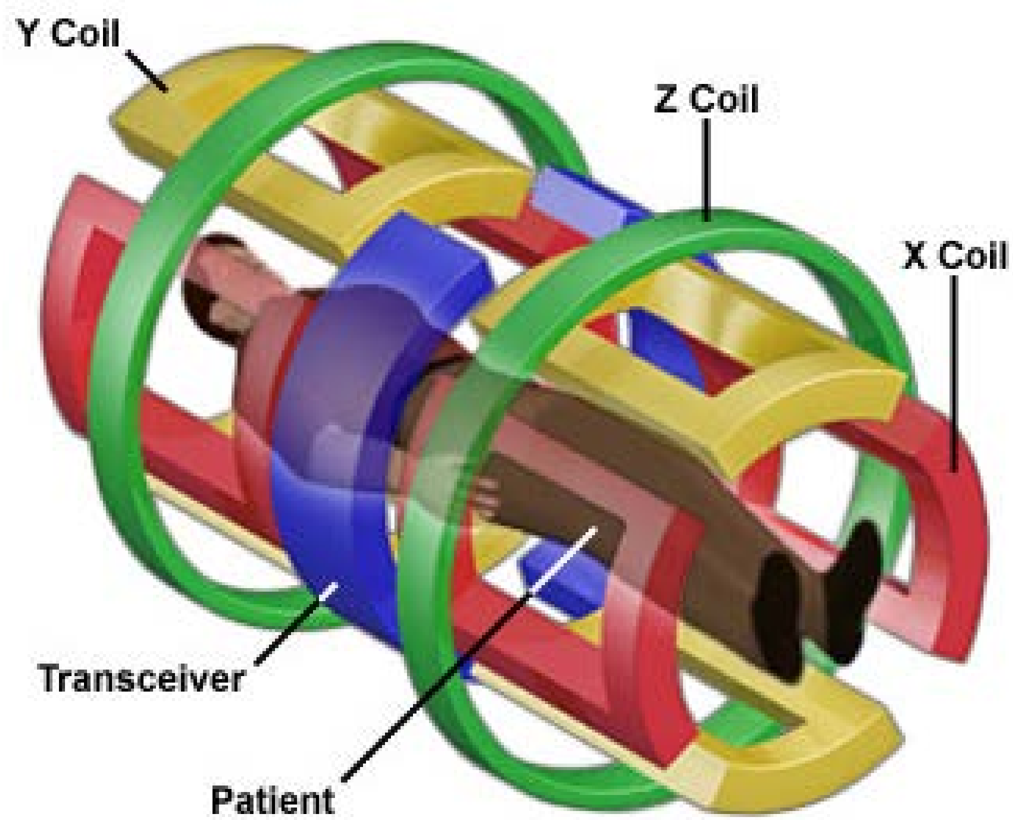
“Golay” pair



“Golay” pair

Gradients

Basic Design

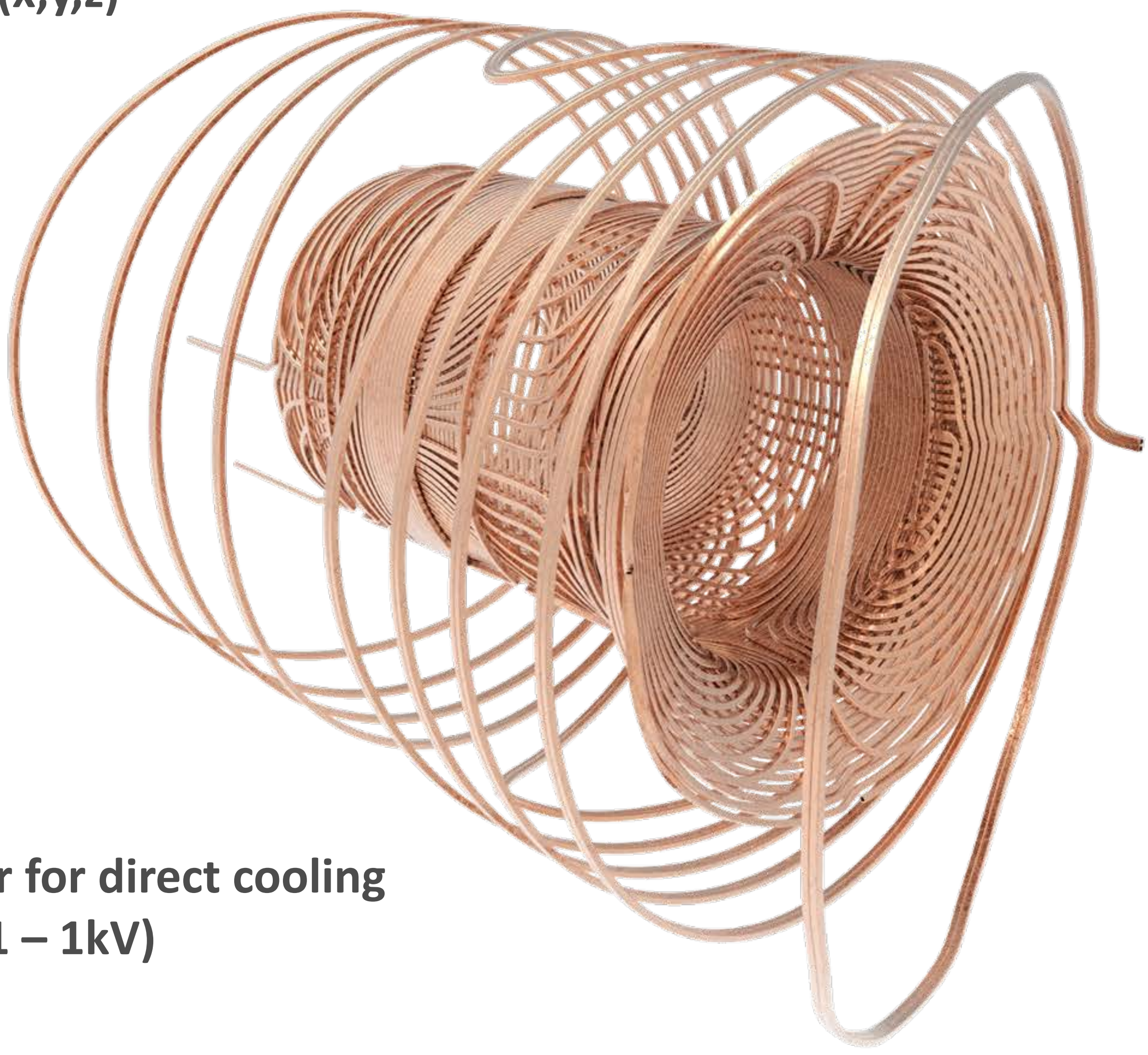


Gradients

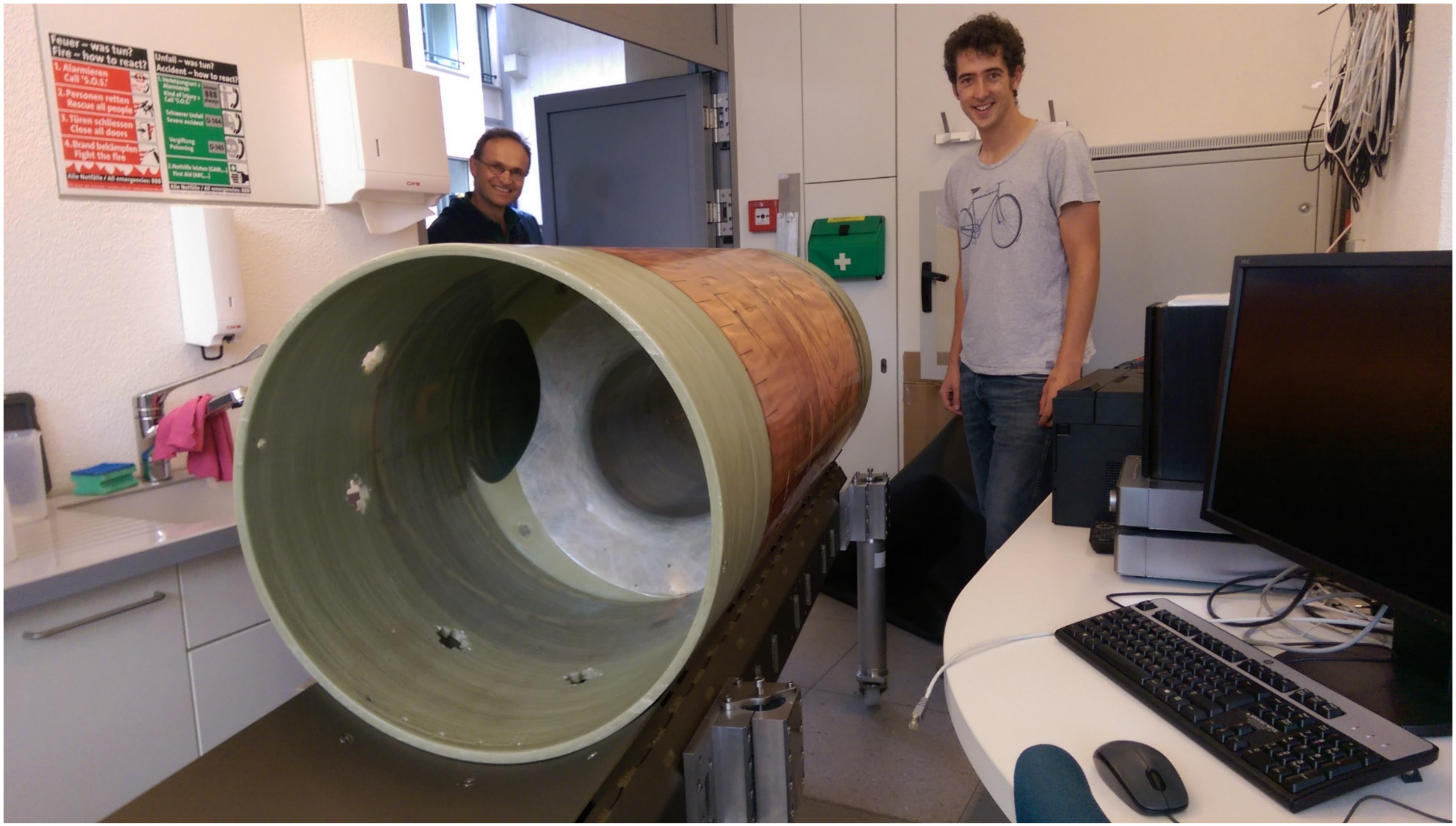
Advanced Design (x,y,z)

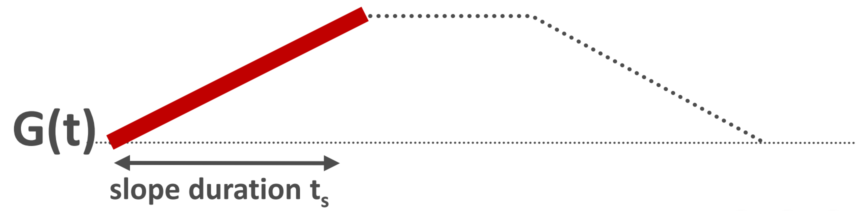
shield windings

hollow conductor for direct cooling
(100 - 1000 A, 0.1 – 1kV)



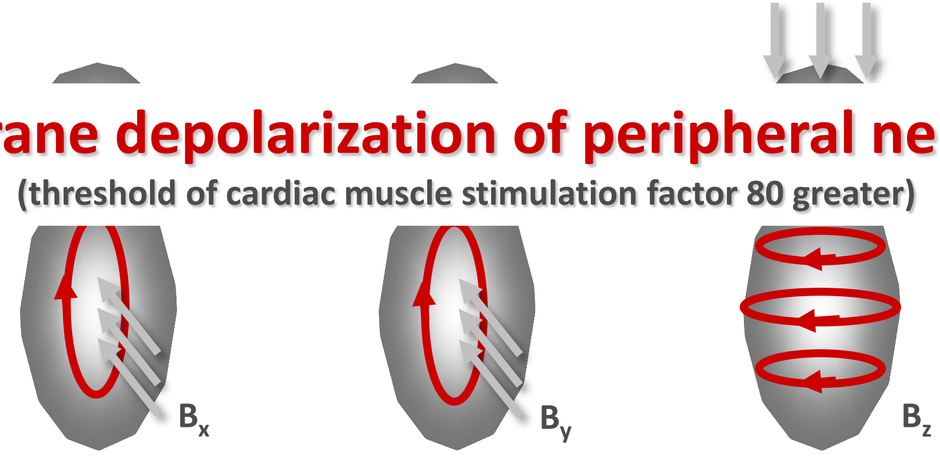
Gradients


Feuer – was tun?
Fire – how to react?
1. Alarmieren
Call 'S.O.S.'
2. Personen retten
Rescue all people
3. Türen schliessen
Close all doors
4. Brand bekämpfen
Fight the fire
Alle Notfälle / All emergencies: 888
Unfall – was tun?
Accident – how to react?
Schwerer Unfall
Severe accident
Vergiftung
Poisoning
First Aid (ABC...)
Alle Notfälle / All emergencies: 888



Membrane depolarization of peripheral nerve cells…

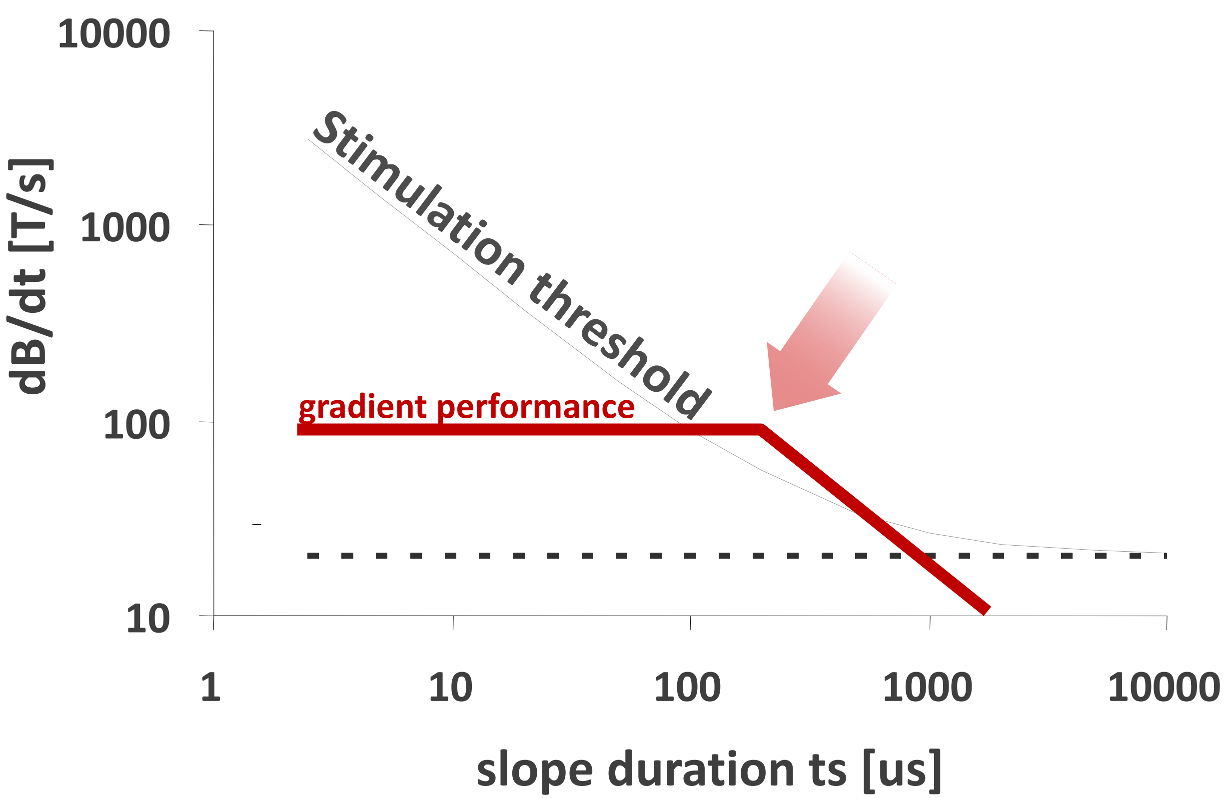
(threshold of cardiac muscle stimulation factor 80 greater)



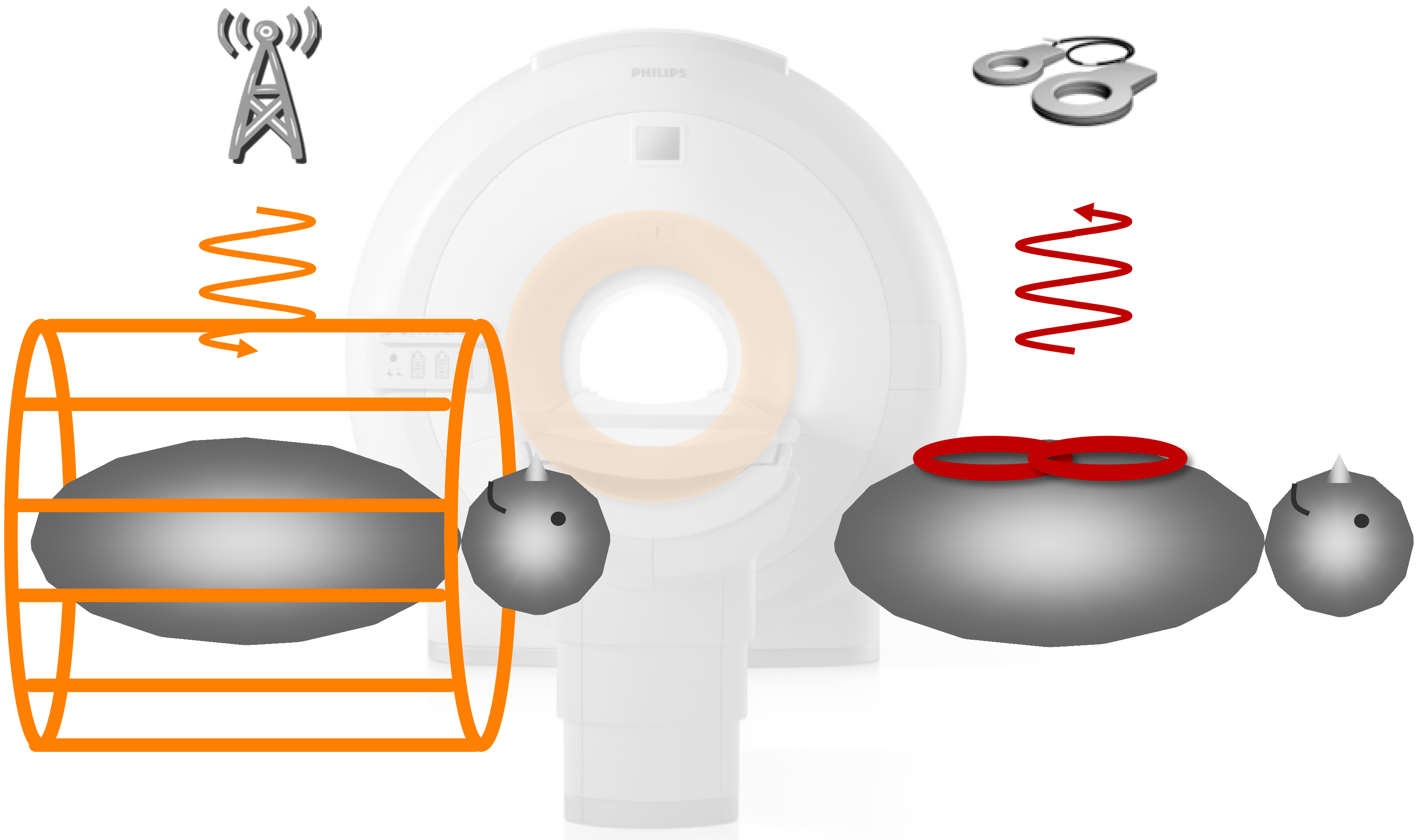
$$\sqrt{\sum\left(w\frac{\partial B}{\partial t}\right)^2} < 20\frac{T}{s}\left(1+\frac{0.36\mathrm{ms}}{t_s}\right)$$

Safety limit IEC 2002

Peripheral nerve stimulation



40 cm off-centre, max grad strength: 40mT/m, min slope dur: 200us, G_x, G_y, G_z active

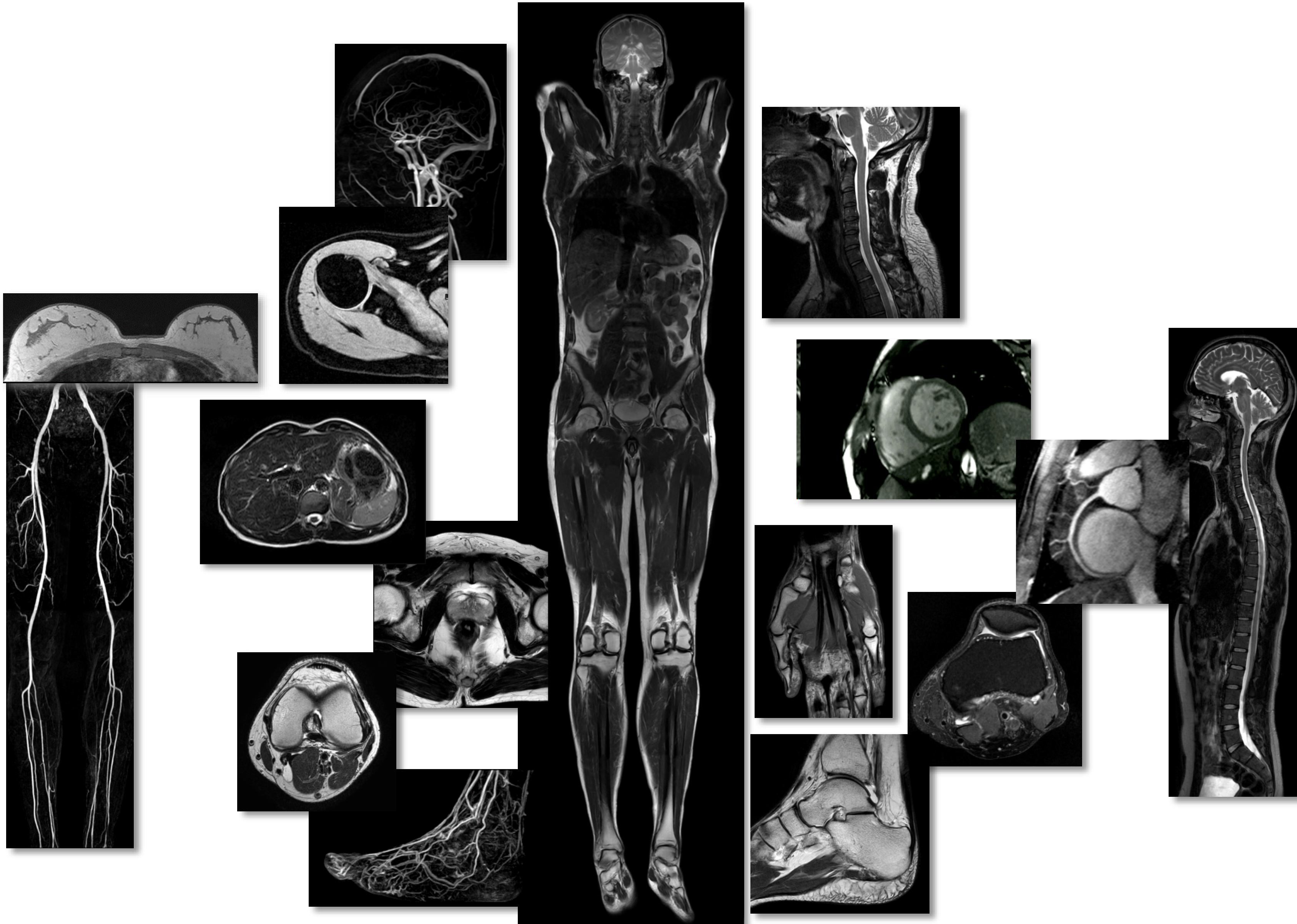

PHILIPS

Summary

- **Superconducting, shielded magnets** (0.5-7.0 Tesla)
- **Magnetic stray field poses potential hazards** (projectiles)
- **Magnetic material not permitted within stray field**
- **Nerve stimulation threshold** constrains gradient fields
- **Body coil** to transmit, **surface coils** to receive

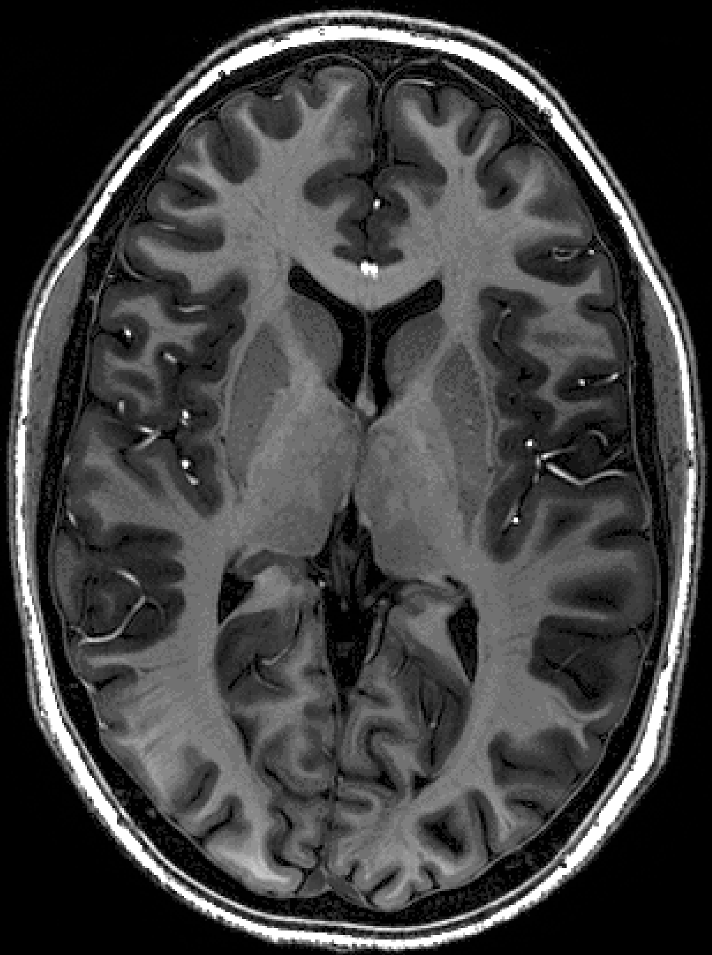
Anatomical Imaging

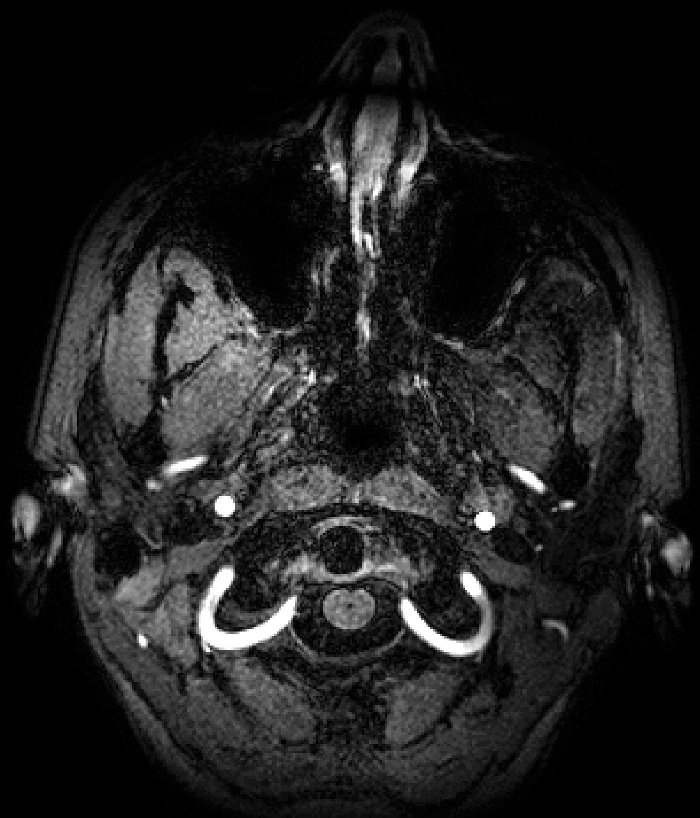
Overview



Human MRI at 7 Tesla

T_1 - weighted brain anatomy

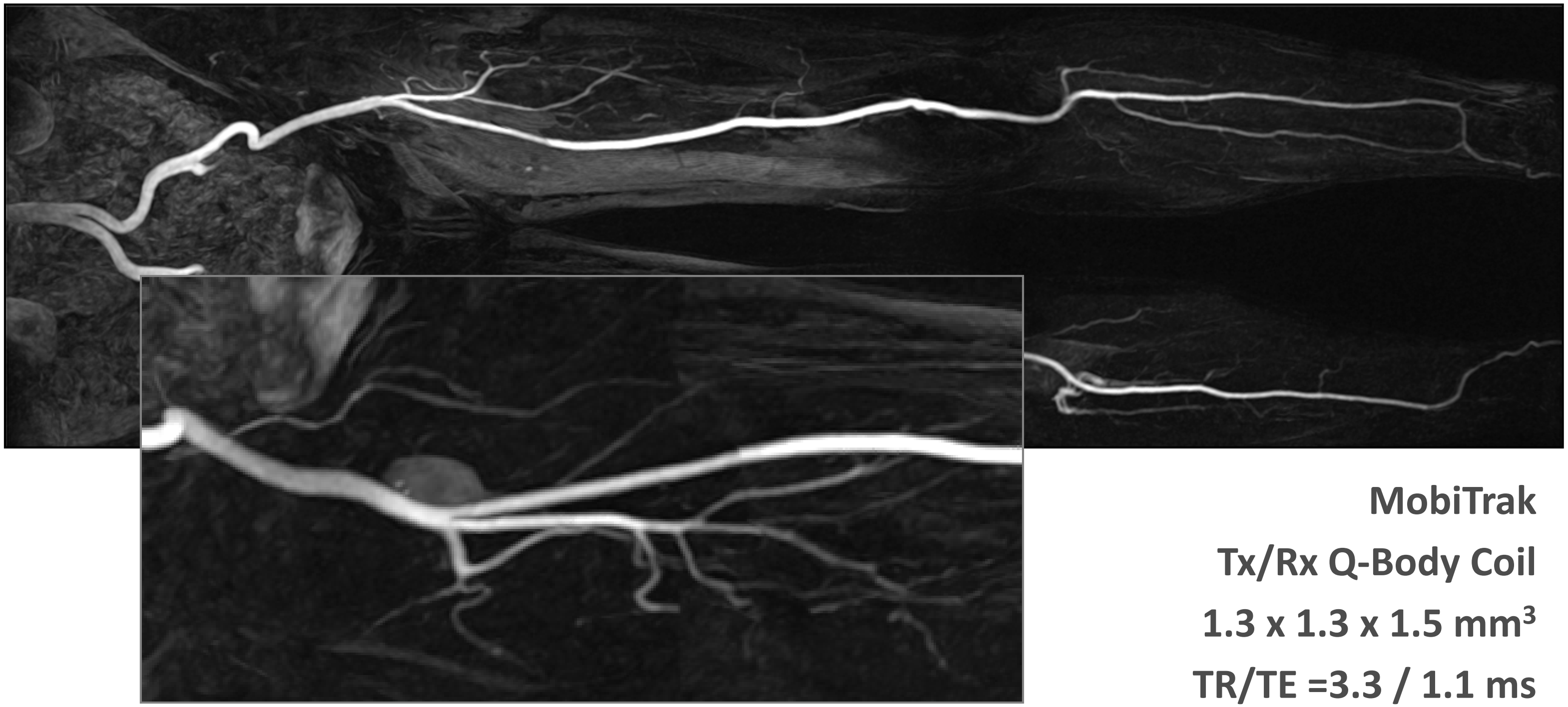




Human MRI at 7 Tesla

Angiography

Extremities



MobiTrak

Tx/Rx Q-Body Coil

1.3 x 1.3 x 1.5 mm^3

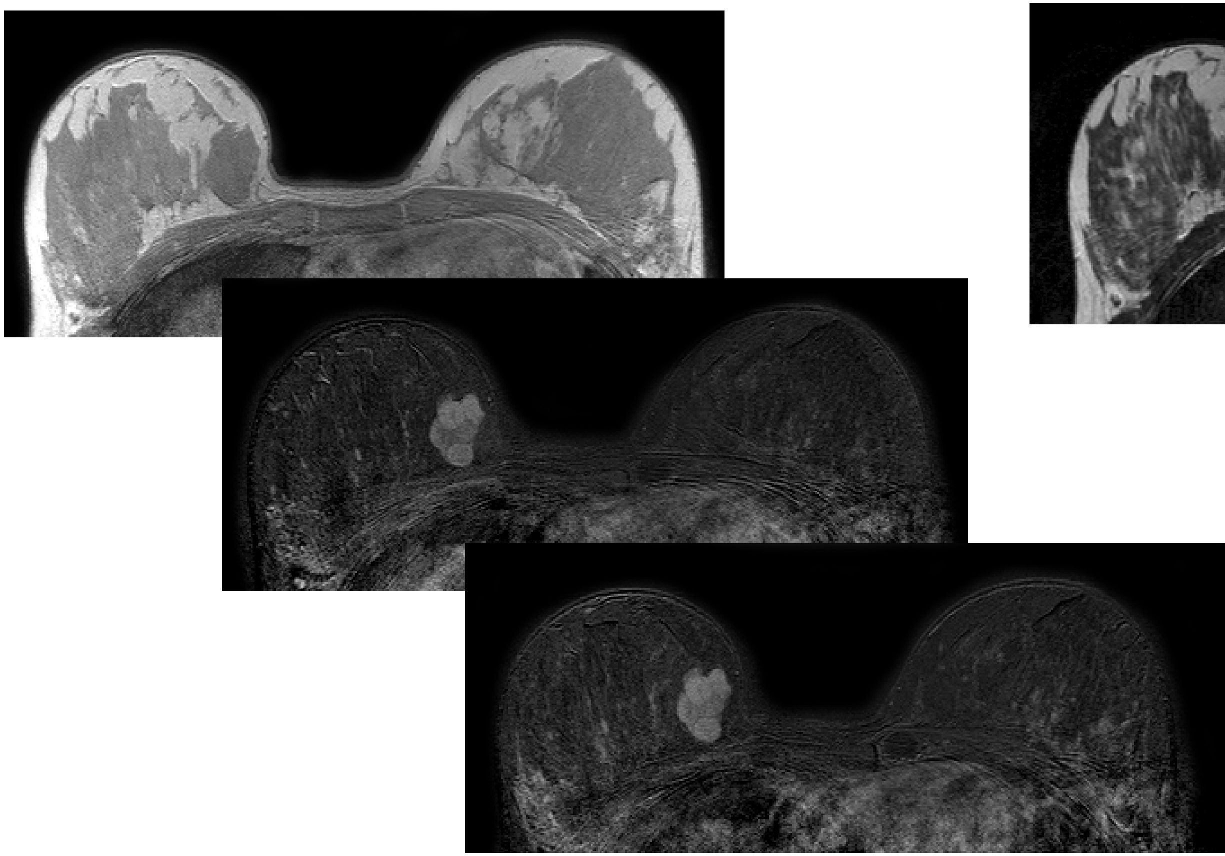
TR/TE =3.3 / 1.1 ms

2:07 min

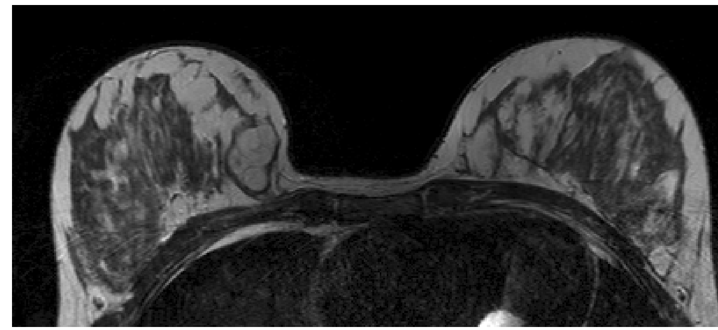
Courtesy: Dept. of Radiology, University of Bonn, Germany

Breast imaging

3D Gradient Echo, 0.7 x 0.7 x 2.5 mm^3



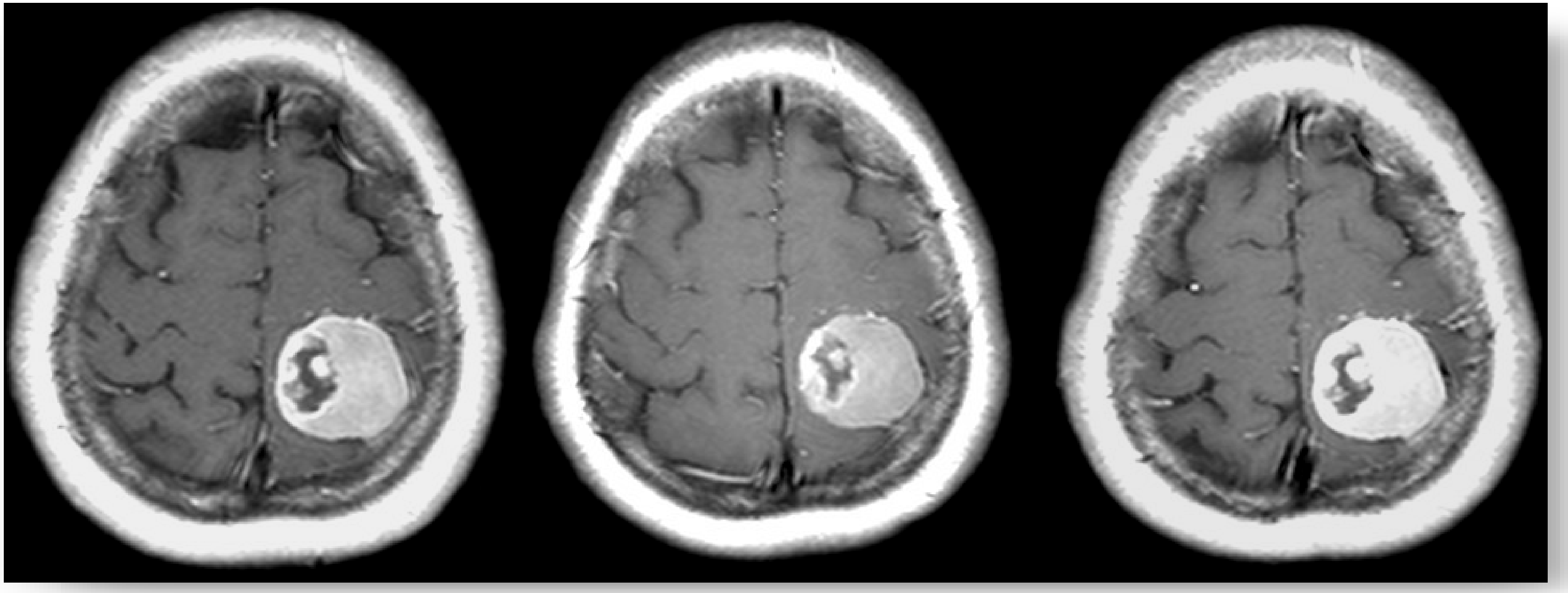
Spin Echo, 0.7 x 0.7 x 2.5 mm^3



Courtesy: Dr. C. Kuhl, Dept. of Radiology, University of Bonn, Germany

Contrast-enhanced imaging

0.1 mmol/kg Gd-DTPA | 0.05 mmol/kg Gd-DTPA | 0.1 mmol/kg Gd-DTPA

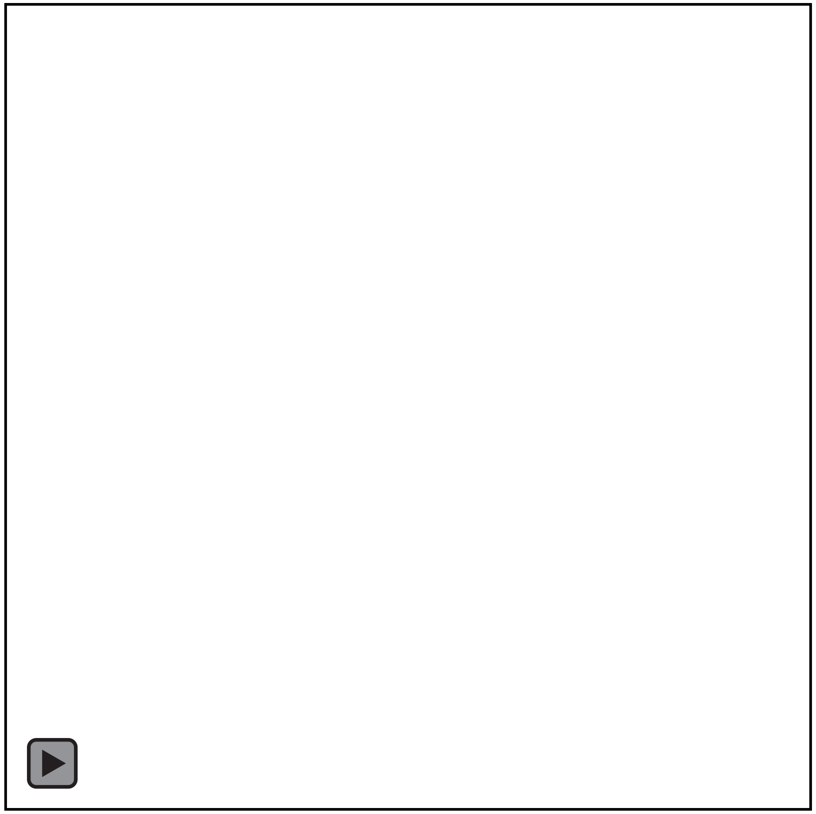


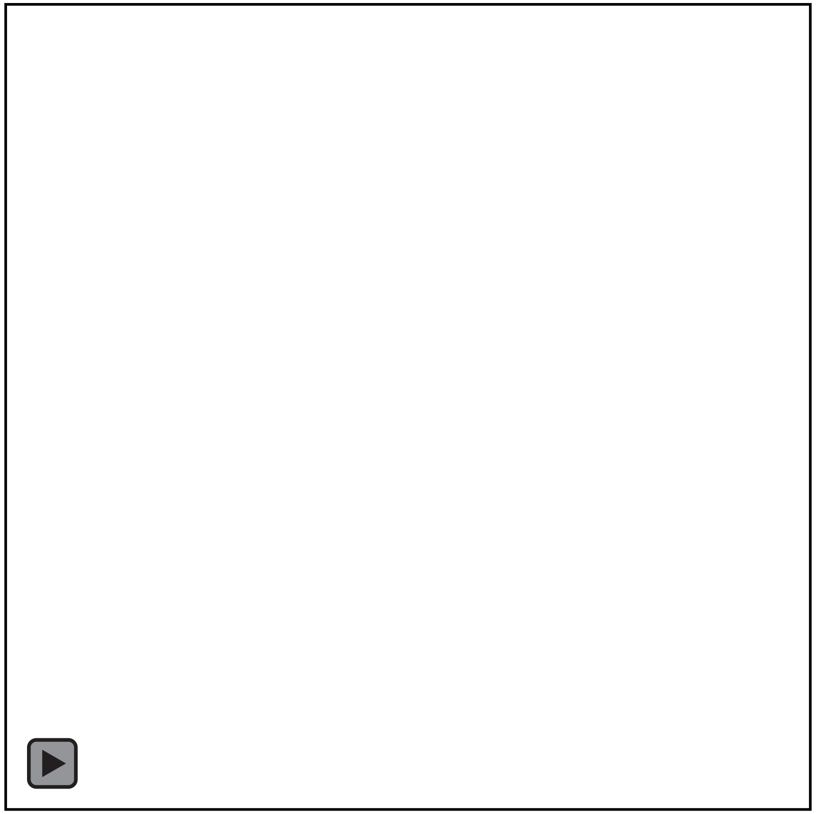
1.5T | 3T | 3T

Willinek WA et al.: Neuroimag Clin N Am 2006; 16: 217-228

Time-resolved cardiac imaging

Image each heart phase separately, ECG-triggered





Human MRI at 7 Tesla

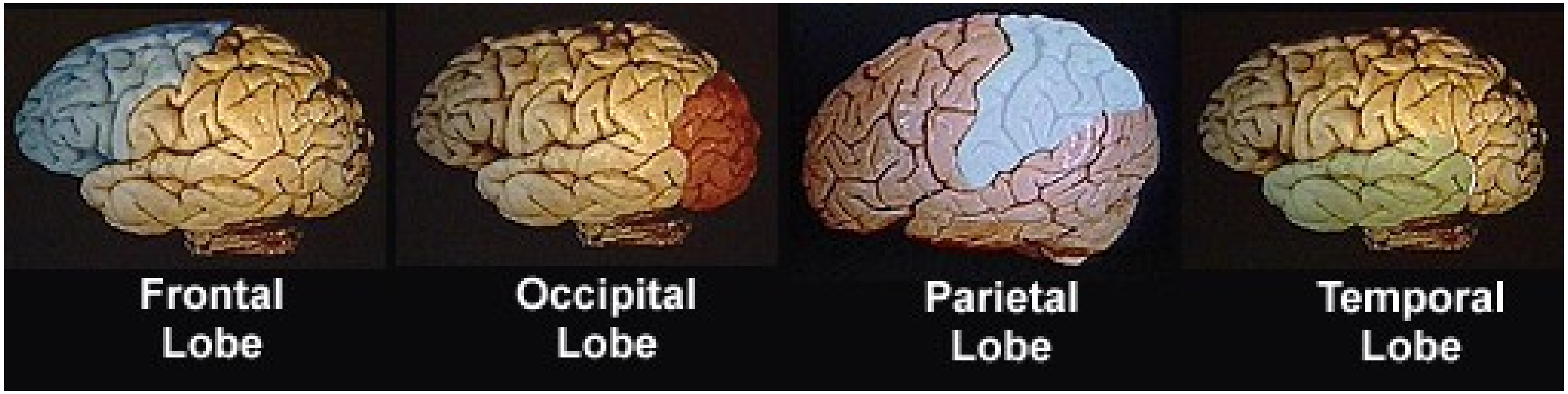
Angiography

Functional Imaging

Functional Magnetic Resonance Imaging - fMRI

reasoning, planning,
parts of speech,
movement (motor cortex),
emotions,
problem-solving

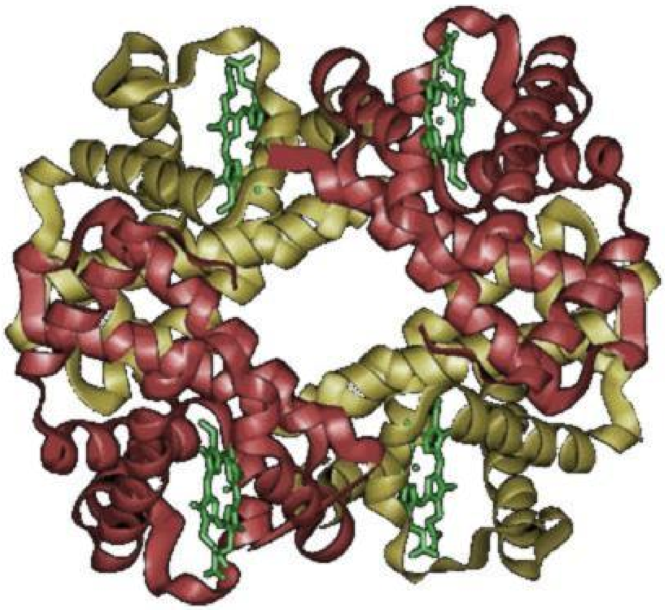
perception of stimuli
related to touch,
pressure, temperature,
pain



aspects of
vision

perception/recognition of
auditory stimuli (hearing),
memory (hippocampus)

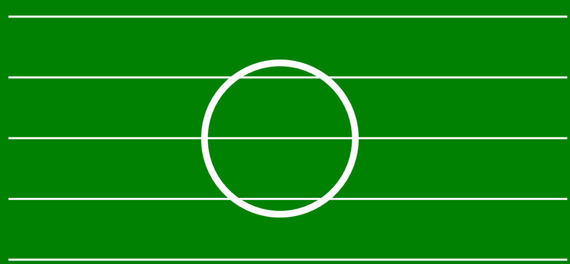
Hemoglobin – “the molecule to breathe with”



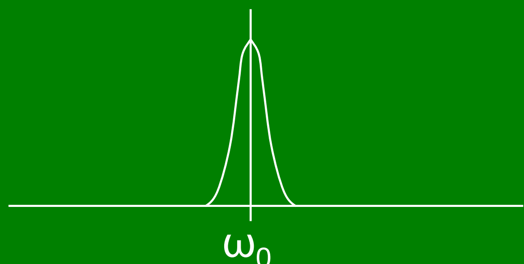
Hemoglogin (Hgb):

- four globin chains
- each globin chain contains a heme group
- at center of each heme group is an iron atom (Fe^{2+})
- each heme group can attach an oxygen atom (O_2)
- oxy-Hb is diamagnetic
- deoxy-Hb is paramagnetic

oxy-hemoglobin: diamagnetic



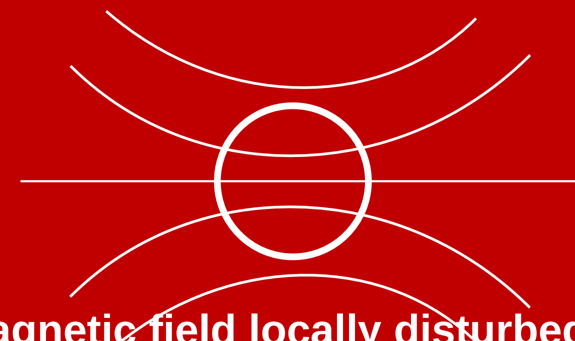
magnetic flux



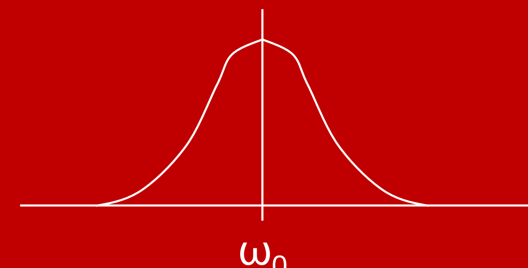
sharp resonance-frequency

long T_2*

deoxy-hemoglobin: paramagnetic



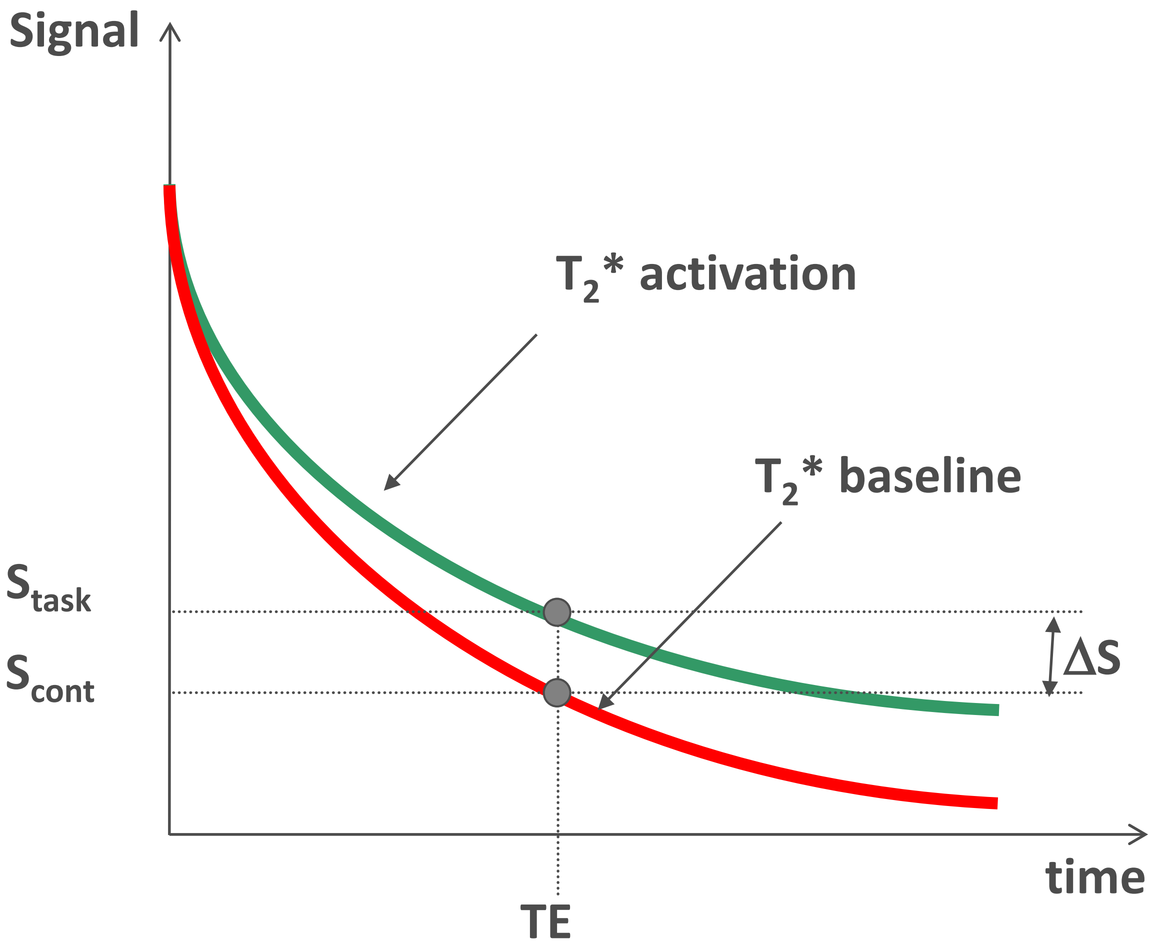
magnetic field locally disturbed



distribution of resonance frequencies

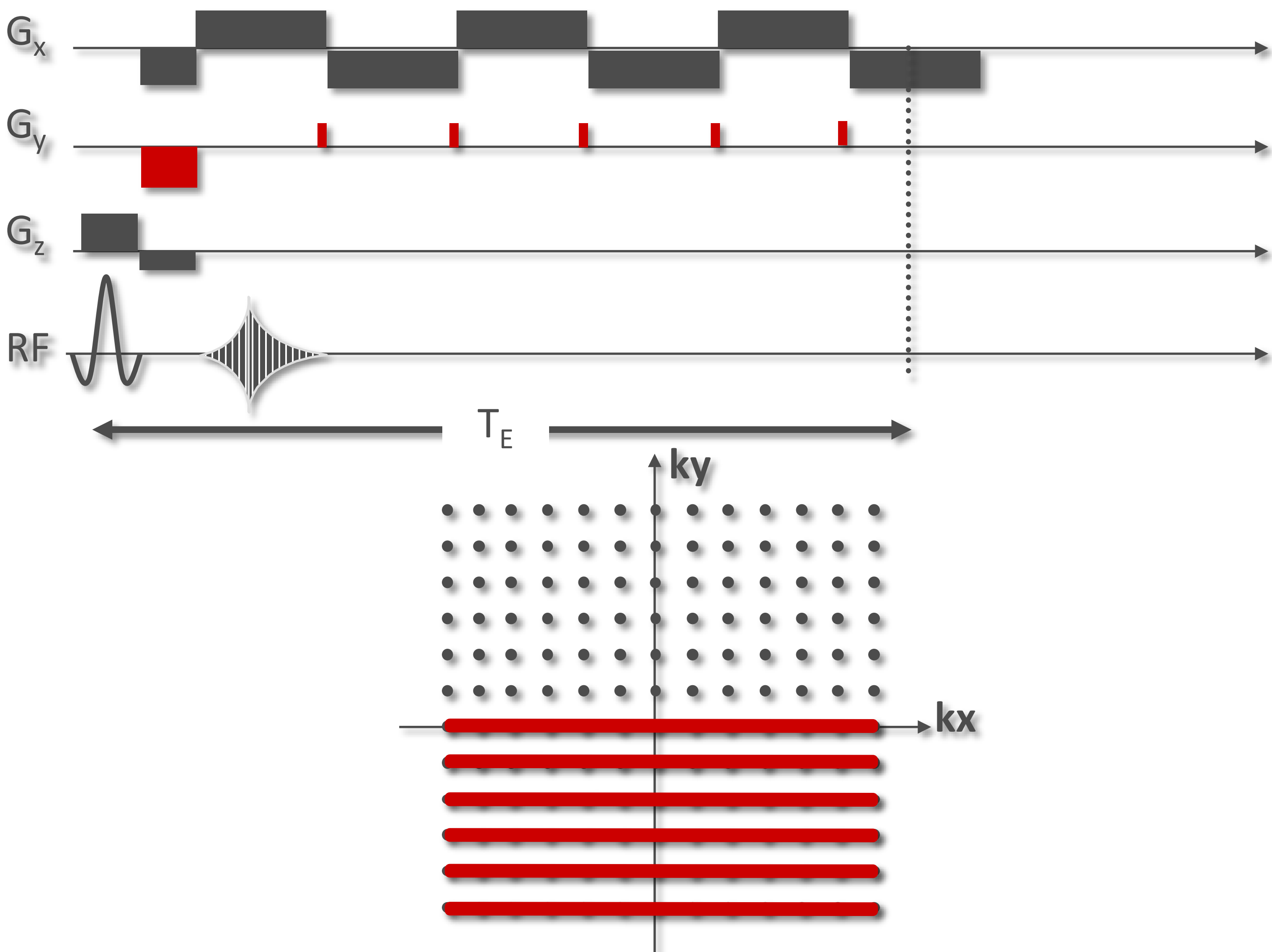
short T_2*

fMRI – contrast

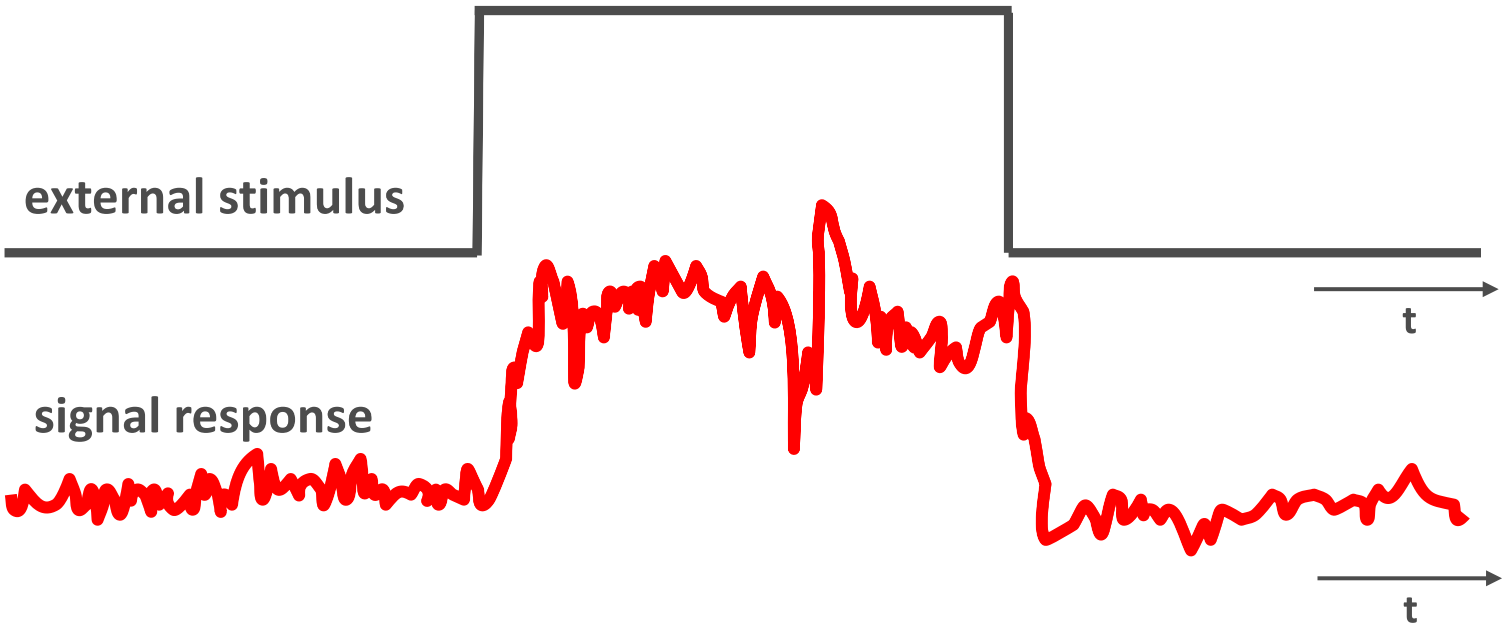


Signal change very small: 0.3-5%

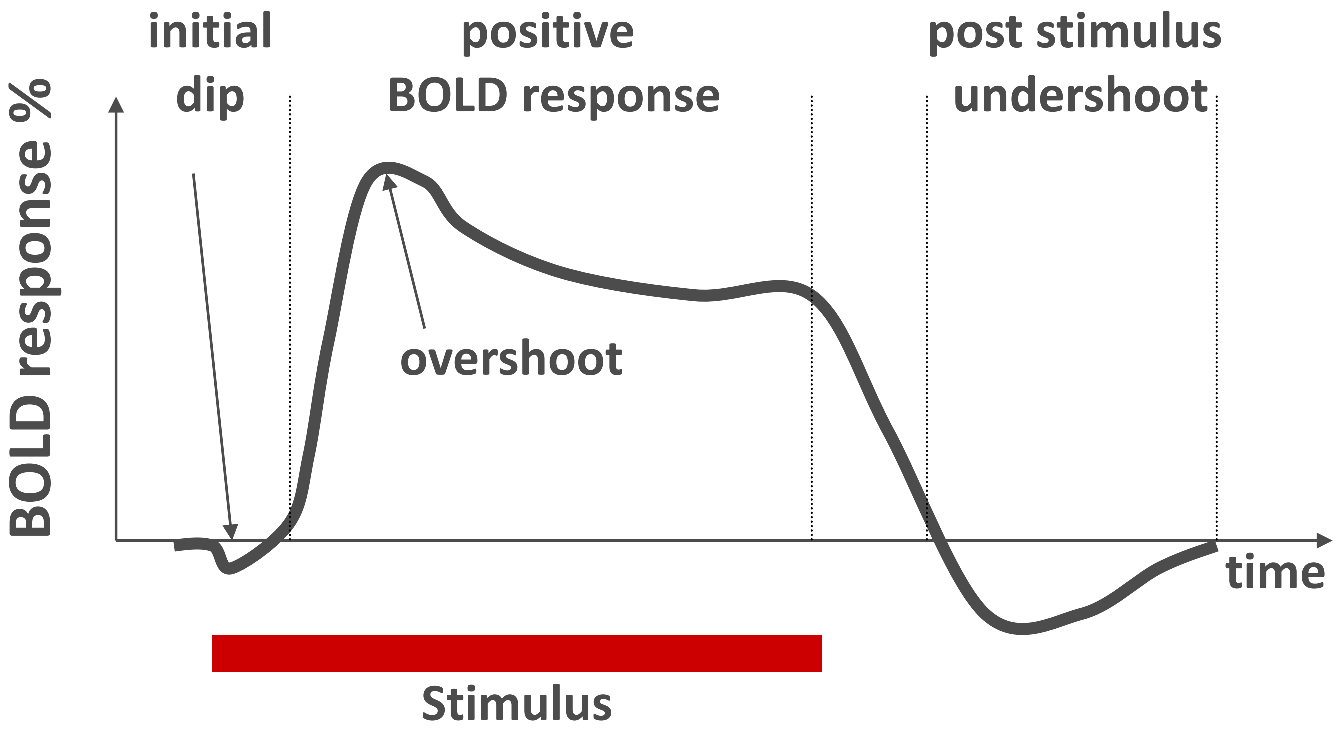
fMRI – echo planar imaging (EPI)



fMRI – stimulation

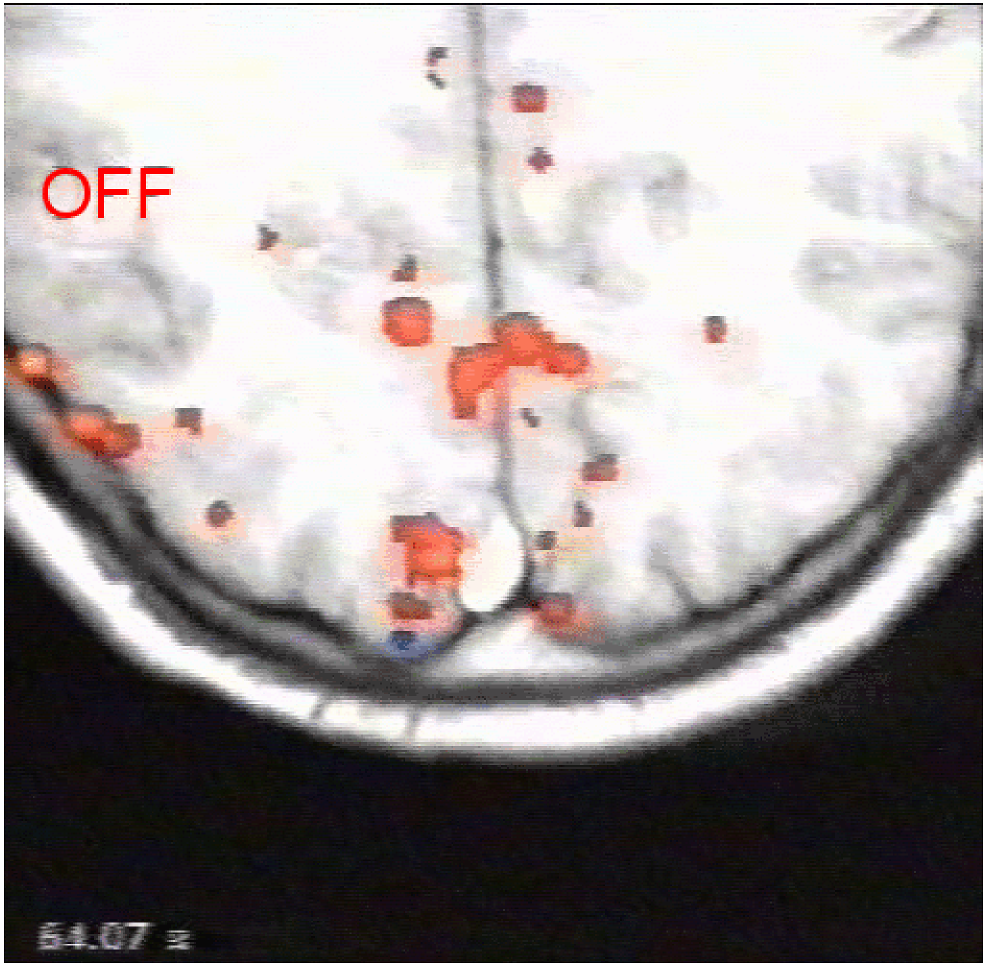


fMRI – temporal BOLD response



Measurement of slice images before, during and after stimulation

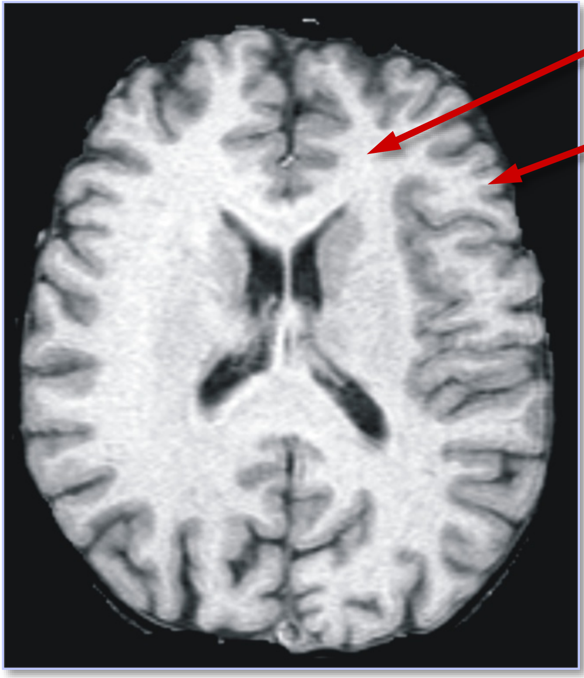
fMRI – visual stimulation



Summary

- **Blood oxygenation level dependent** (BOLD) contrast
- **BOLD signal** is relative and very weak
- **Image intensity changes** are due to several effects
- **Series of activation/deactivation** for statistical power

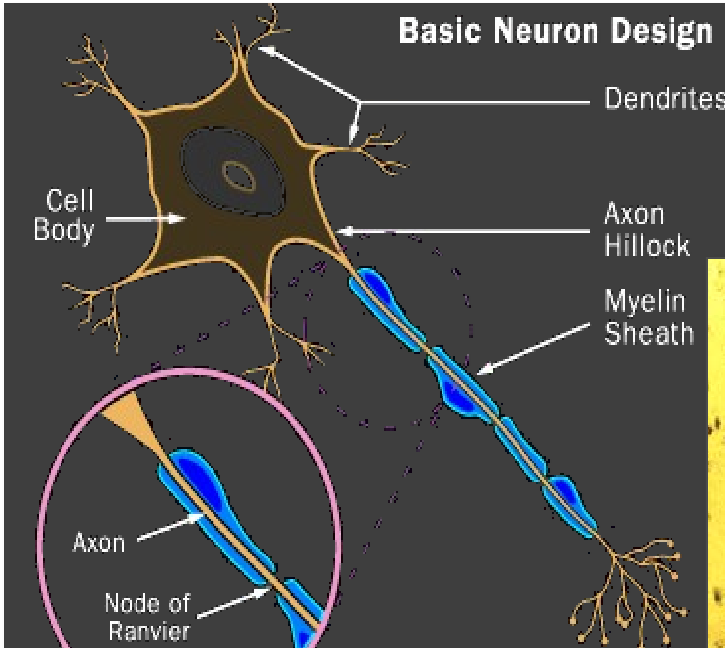
Anatomical connectivity

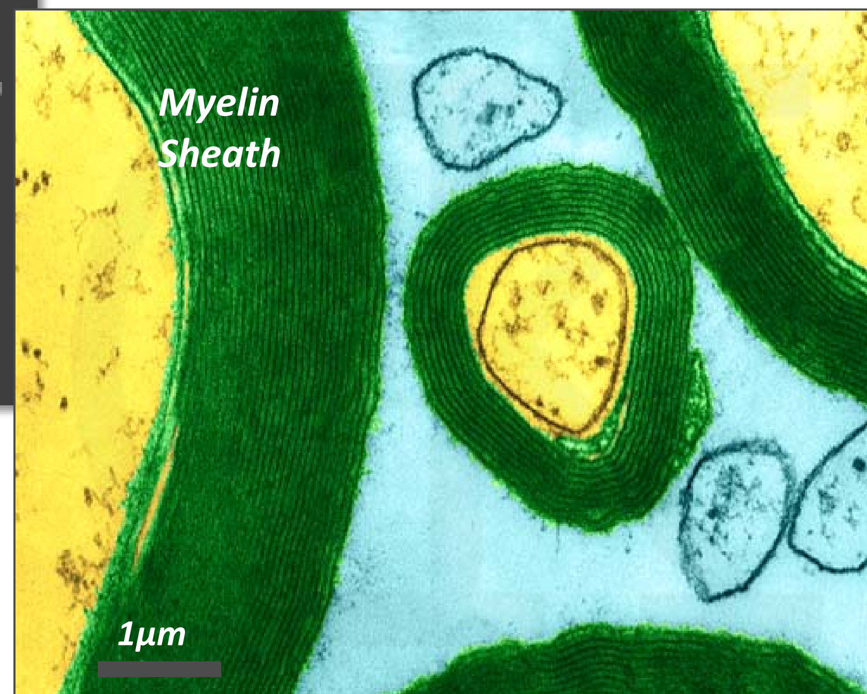


White brain matter

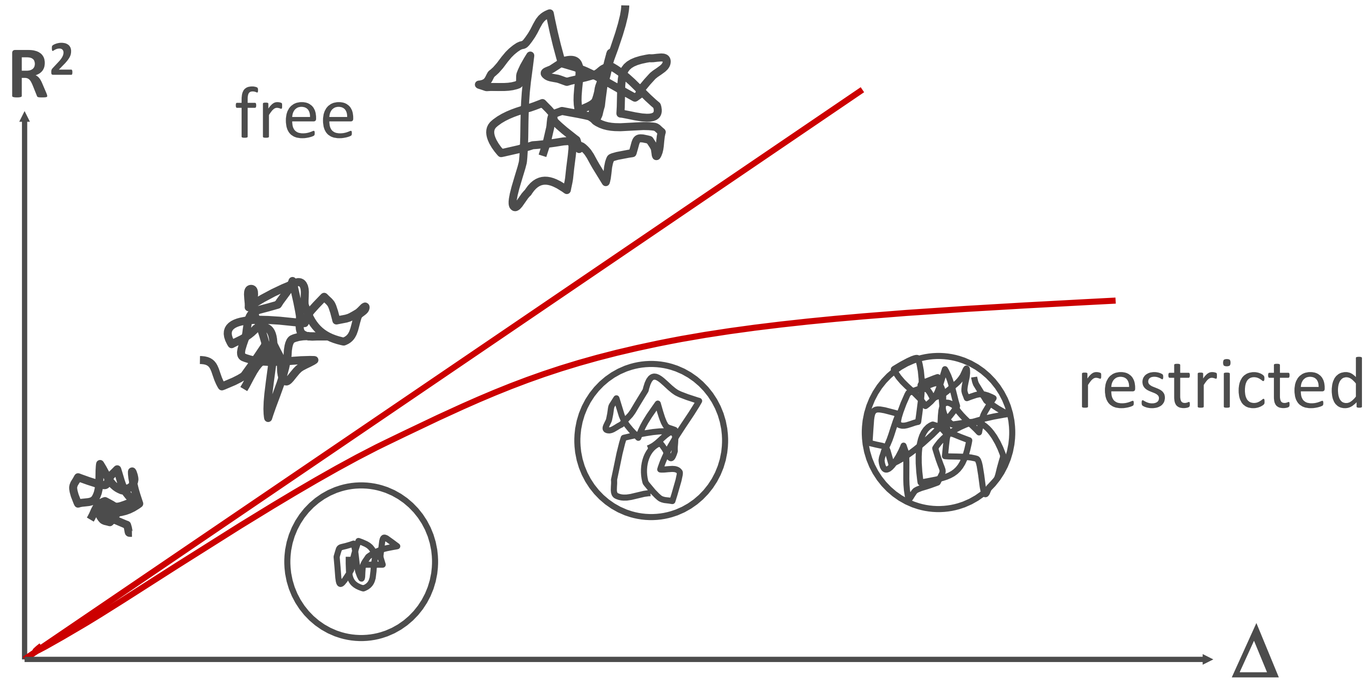
Gray brain matter

Axon


Basic Neuron Design
Dendrites
Cell Body
Axon Hillock
Myelin Sheath
Axon
Node of Ranvier


Myelin Sheath
1μm

Self-Diffusion vs. Restricted Diffusion



$$R = \sqrt{2 \cdot D \cdot \Delta}$$

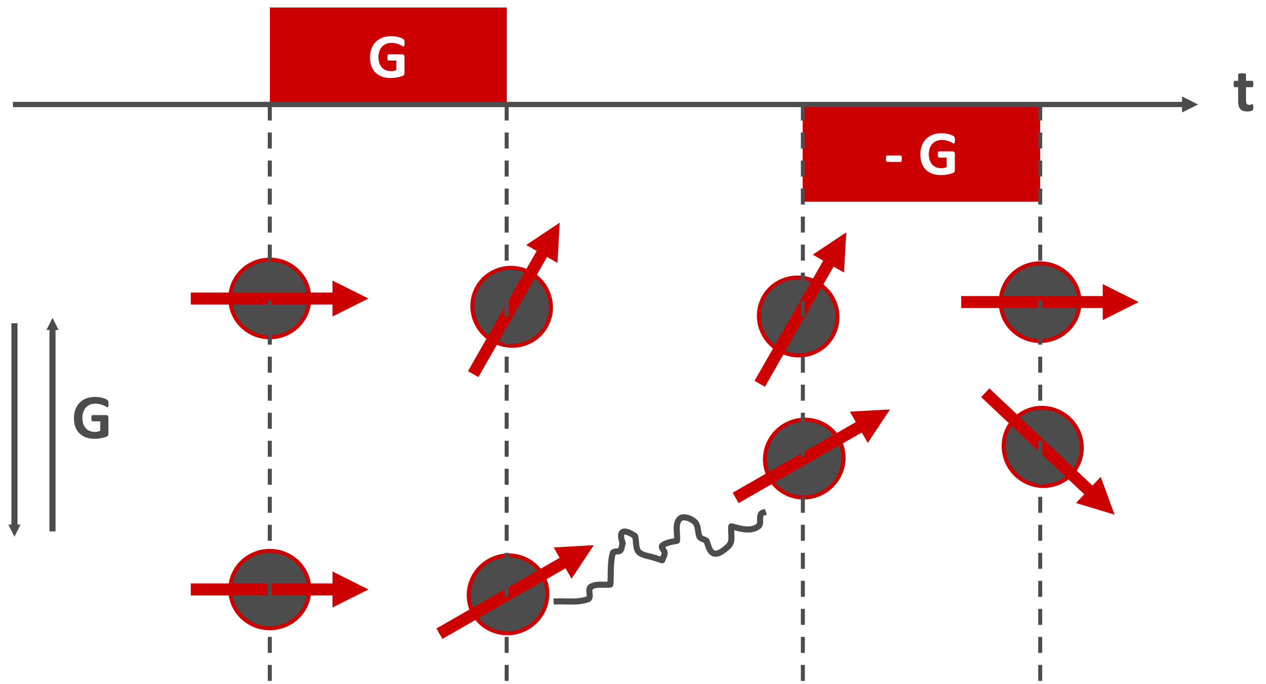
Diffusion coefficients

$$D = \frac{\langle \lambda \rangle \cdot \langle v \rangle}{6}$$

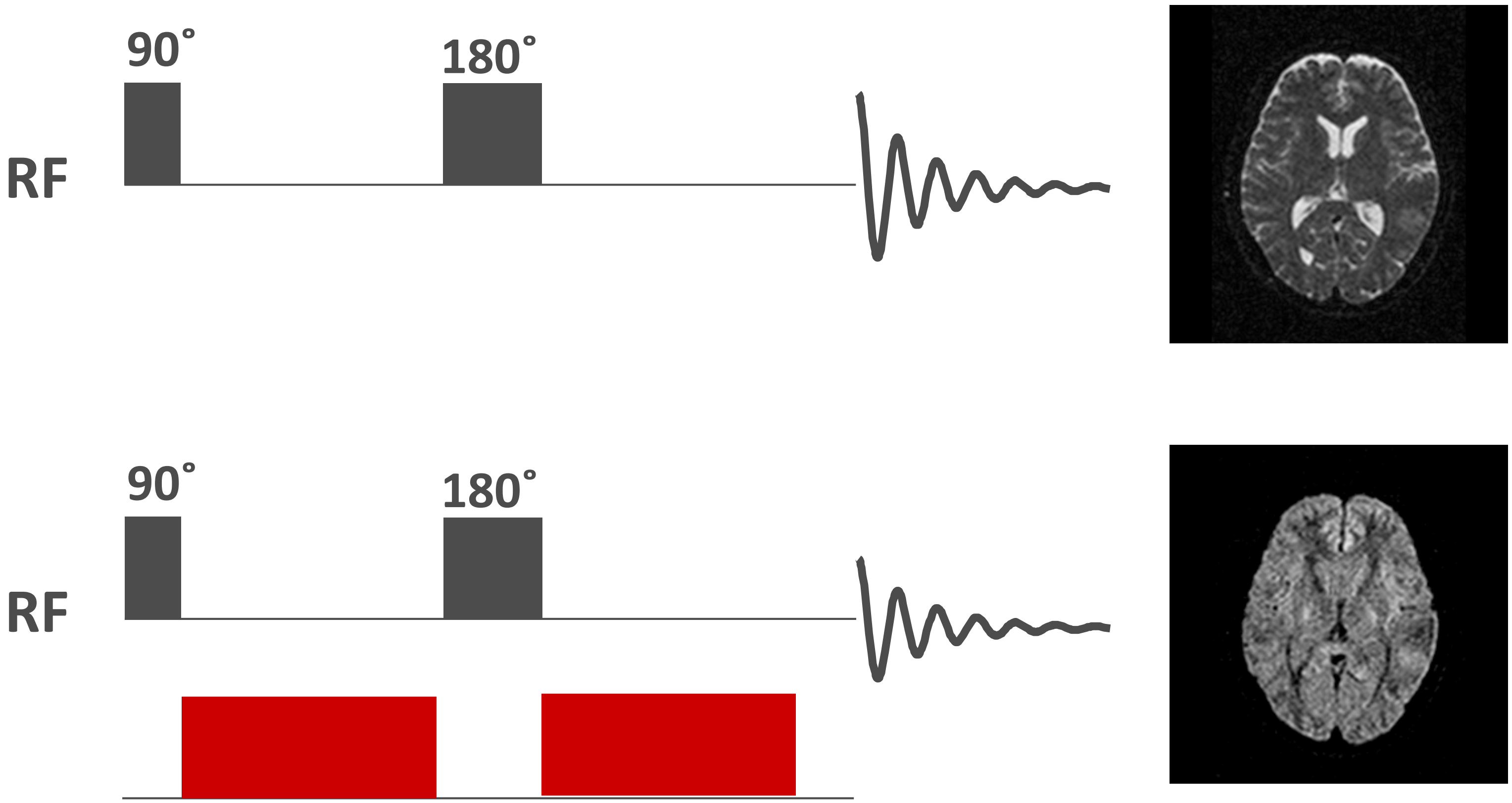
λ free path length
v molecular velocity
D diffusion coefficient

Tissue	D [$10^{-3} \cdot mm^2/s$]
Water T=22°C	2.0 – 2.5
Myocardium	0.2 – 0.7
White Matter	0.1 – 0.6
Gray Matter	0.8

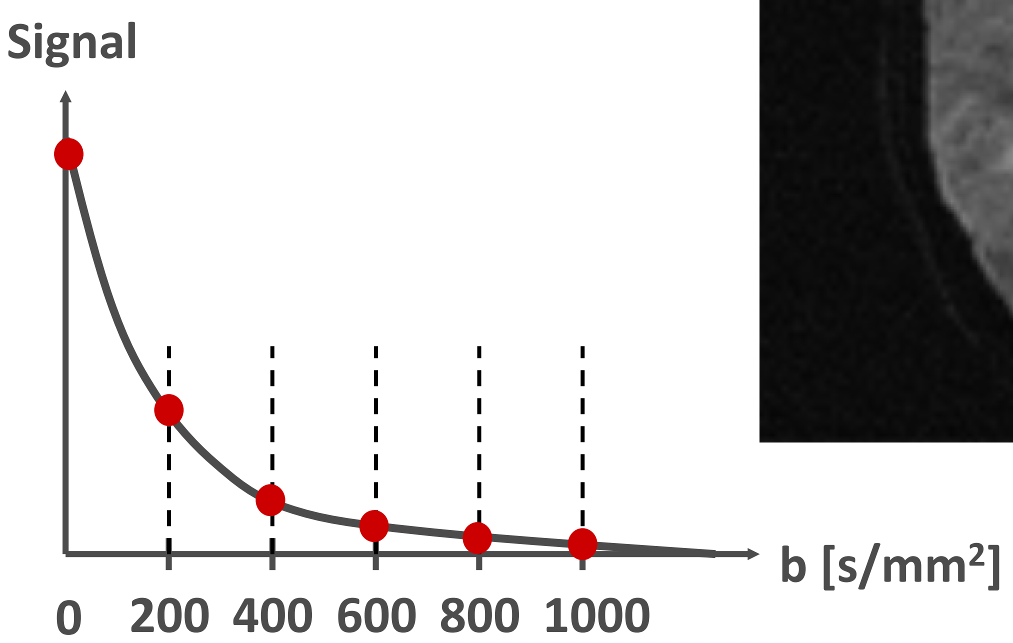
Diffusion weighting

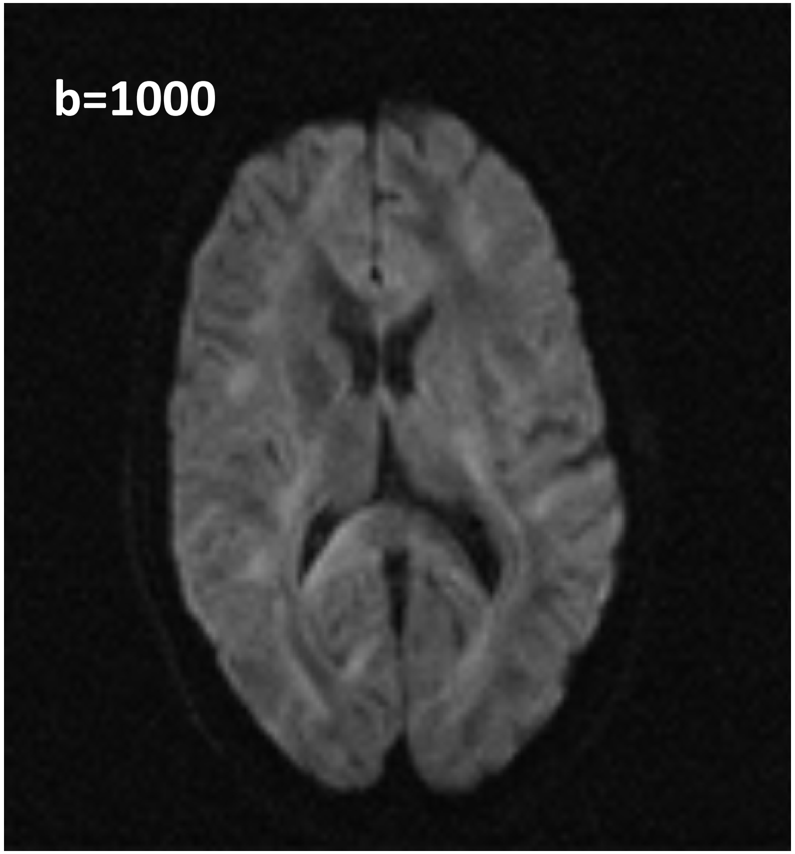


Diffusion weighted imaging (DWI)

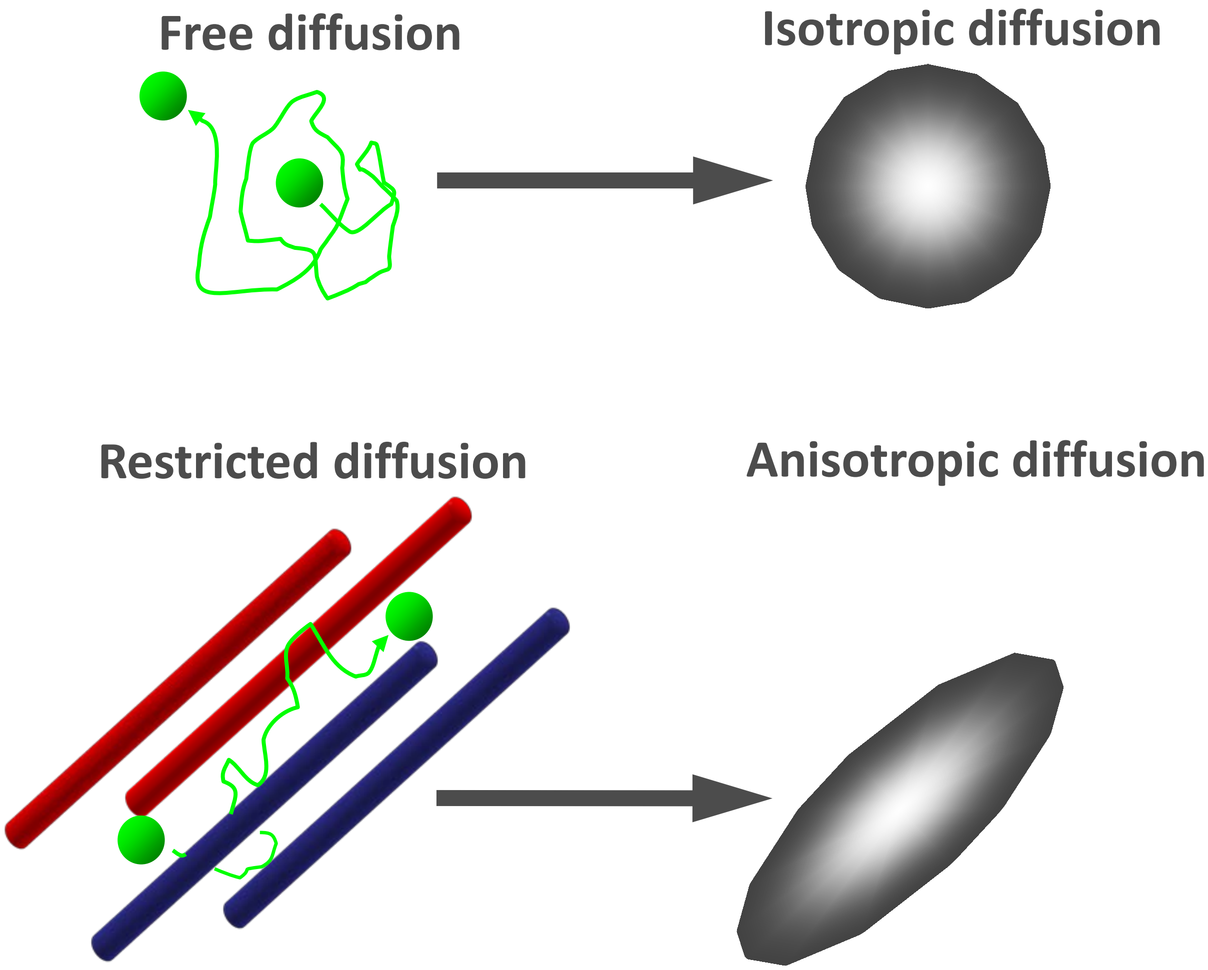


Diffusion weighted imaging

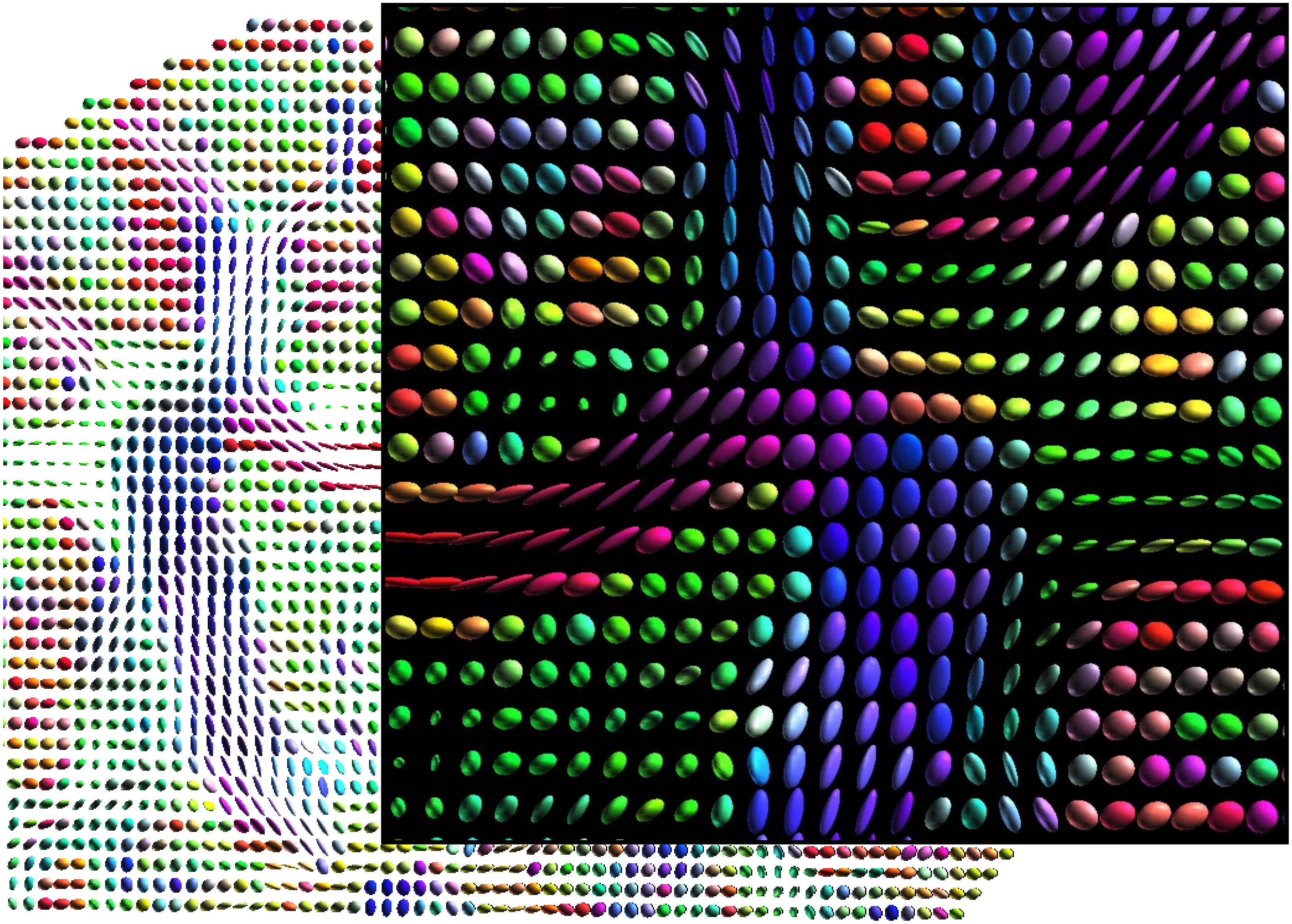




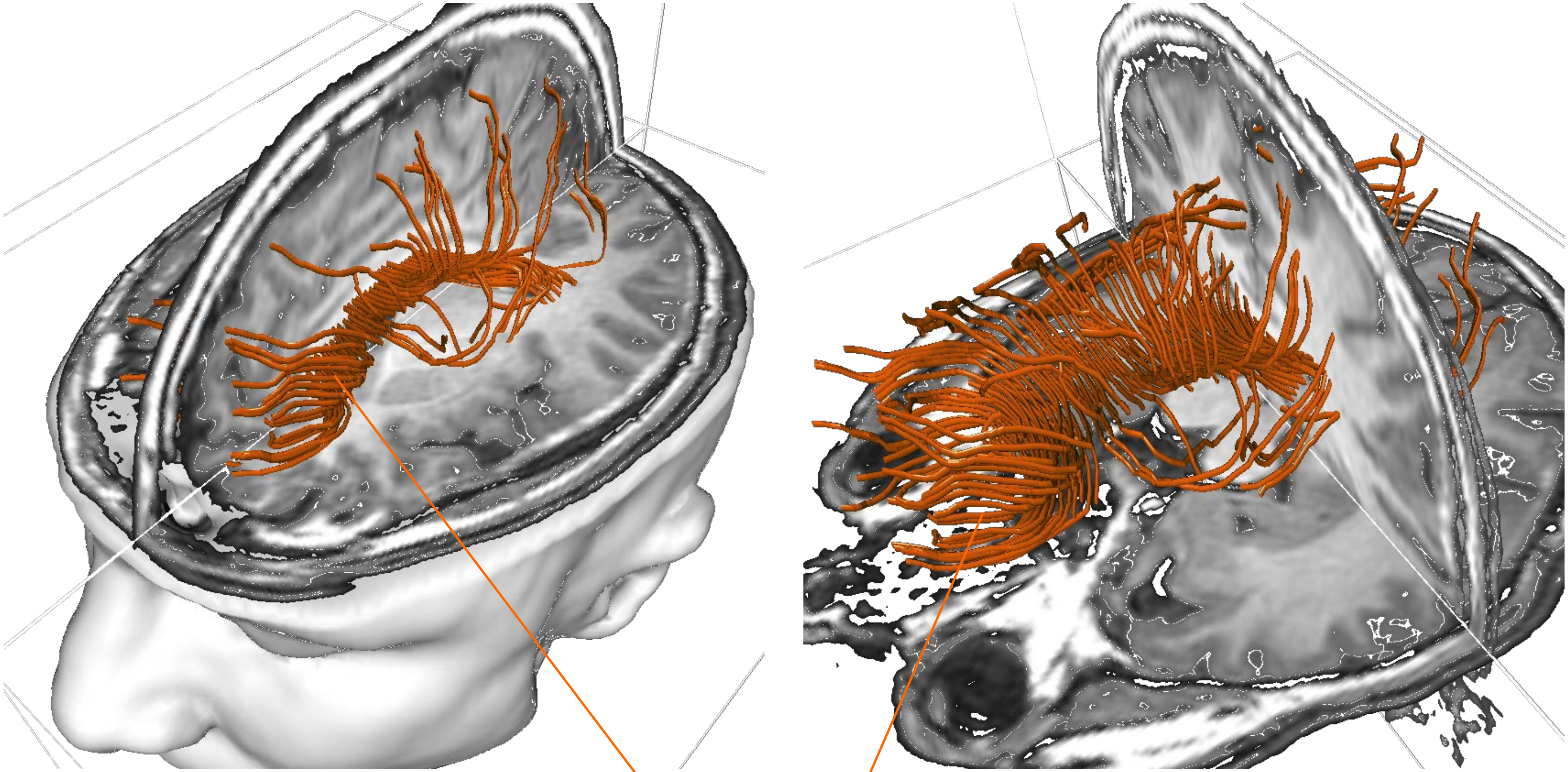
Diffusion Tensor Imaging (DTI)



Diffusion Tensor Imaging

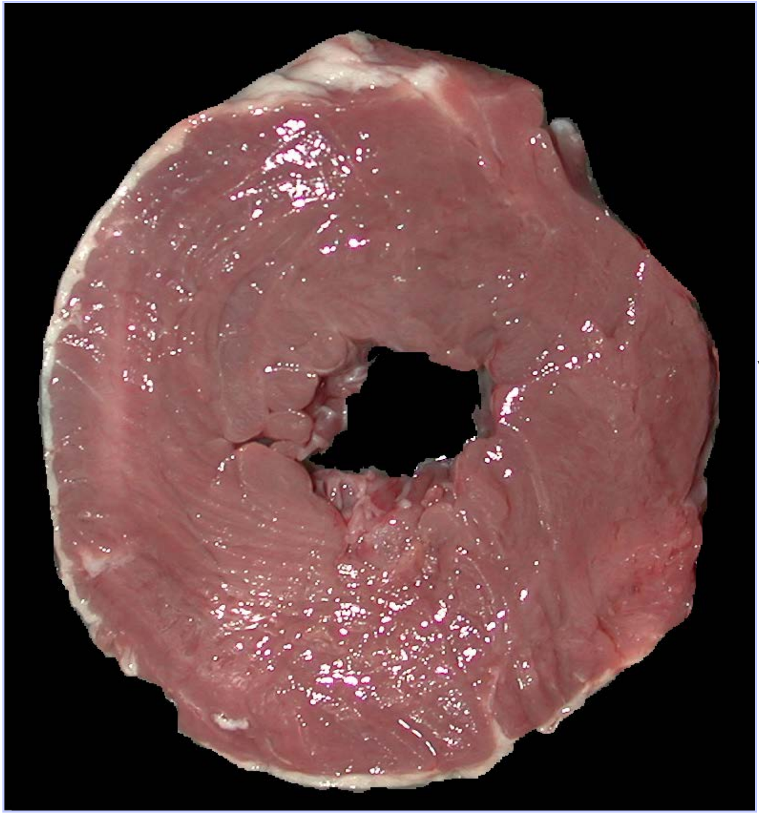


Fiber Tracking

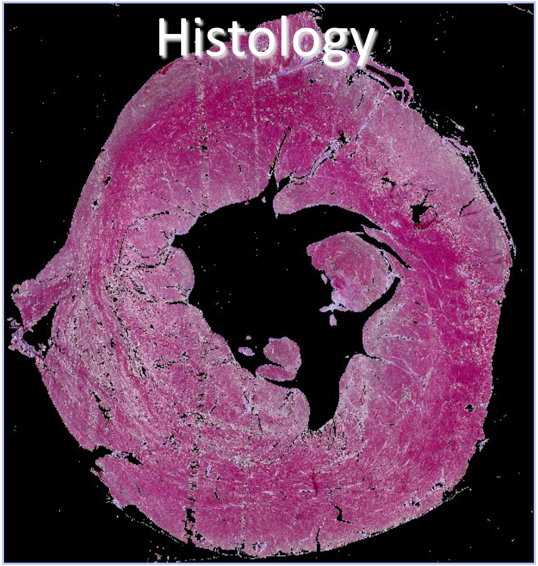


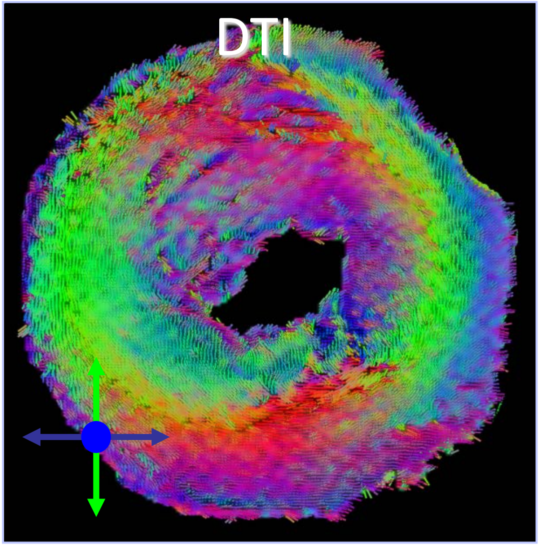
radiation of corpus callosum

Pig heart (ex-vivo)

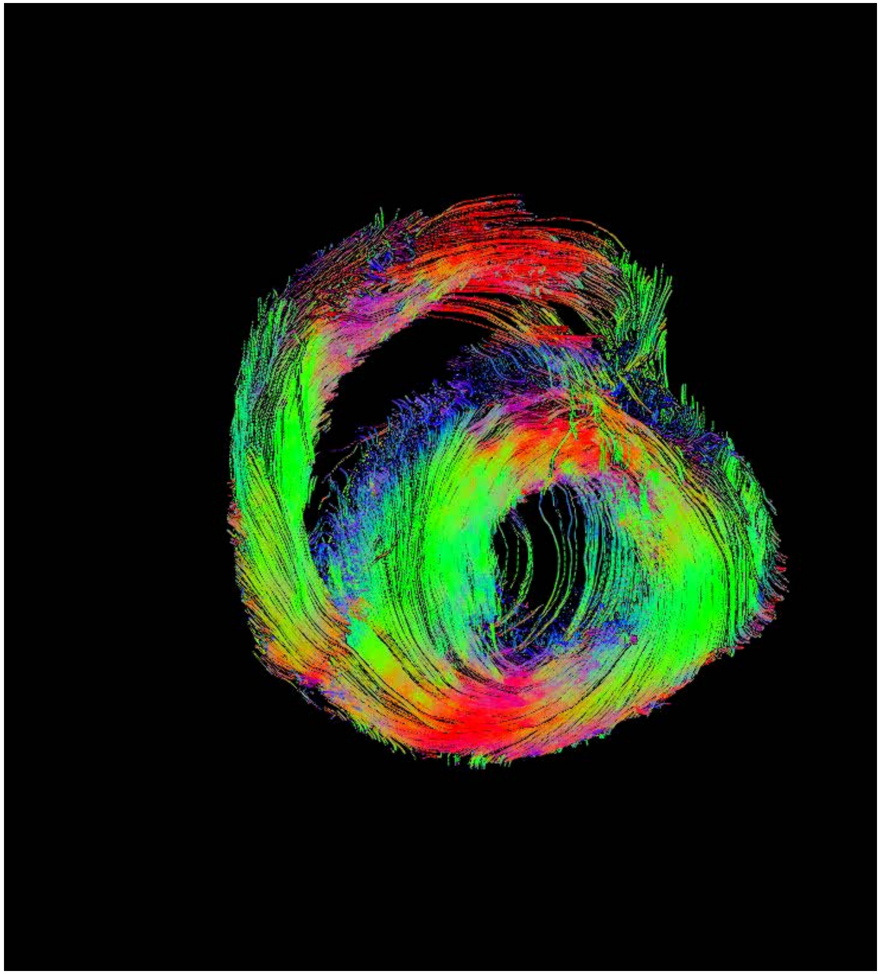


short axis heart slice

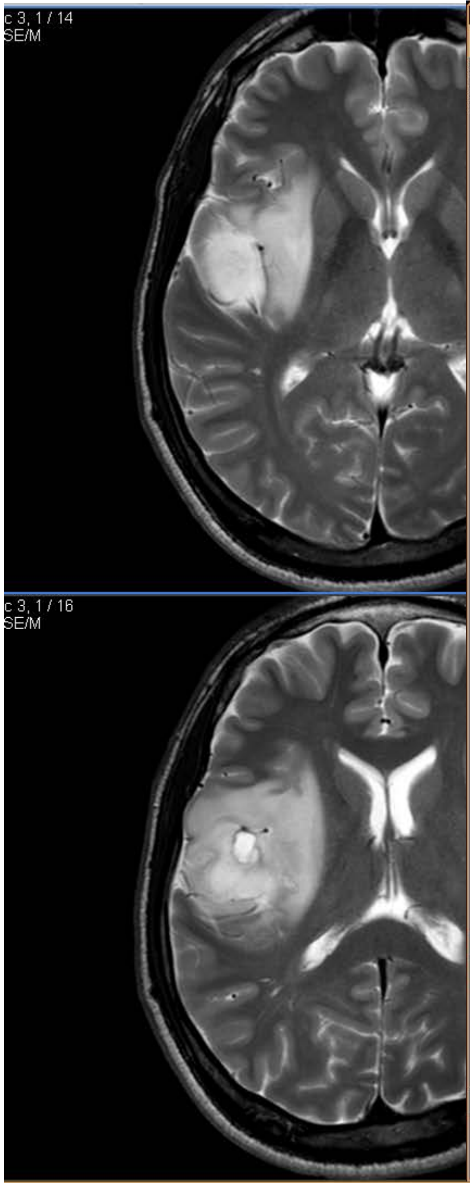


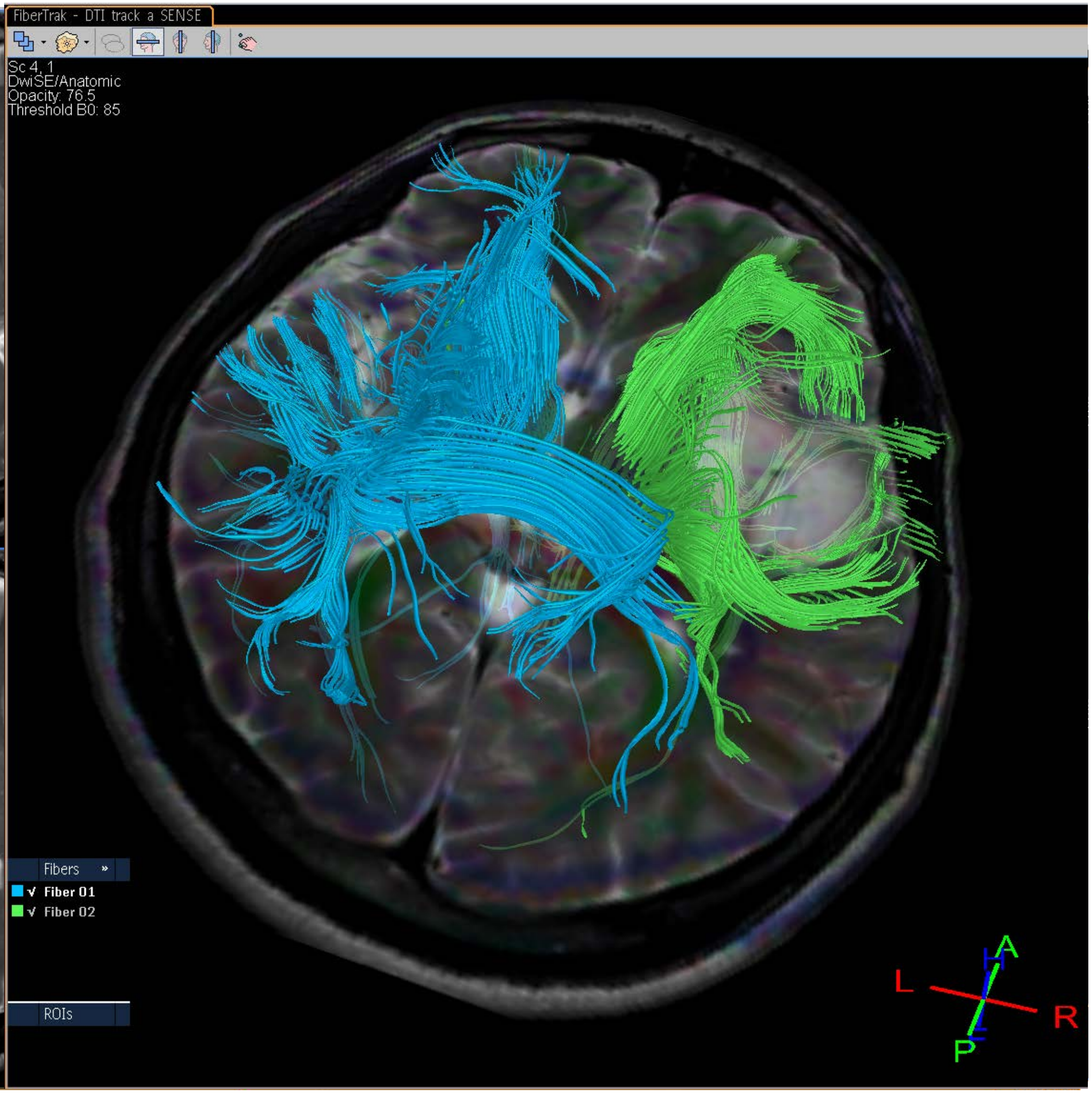


Diffusion Tensor Imaging (ex-vivo)



Tumor


c 3, 1 / 14
SE/M
c 3, 1 / 16
SE/M

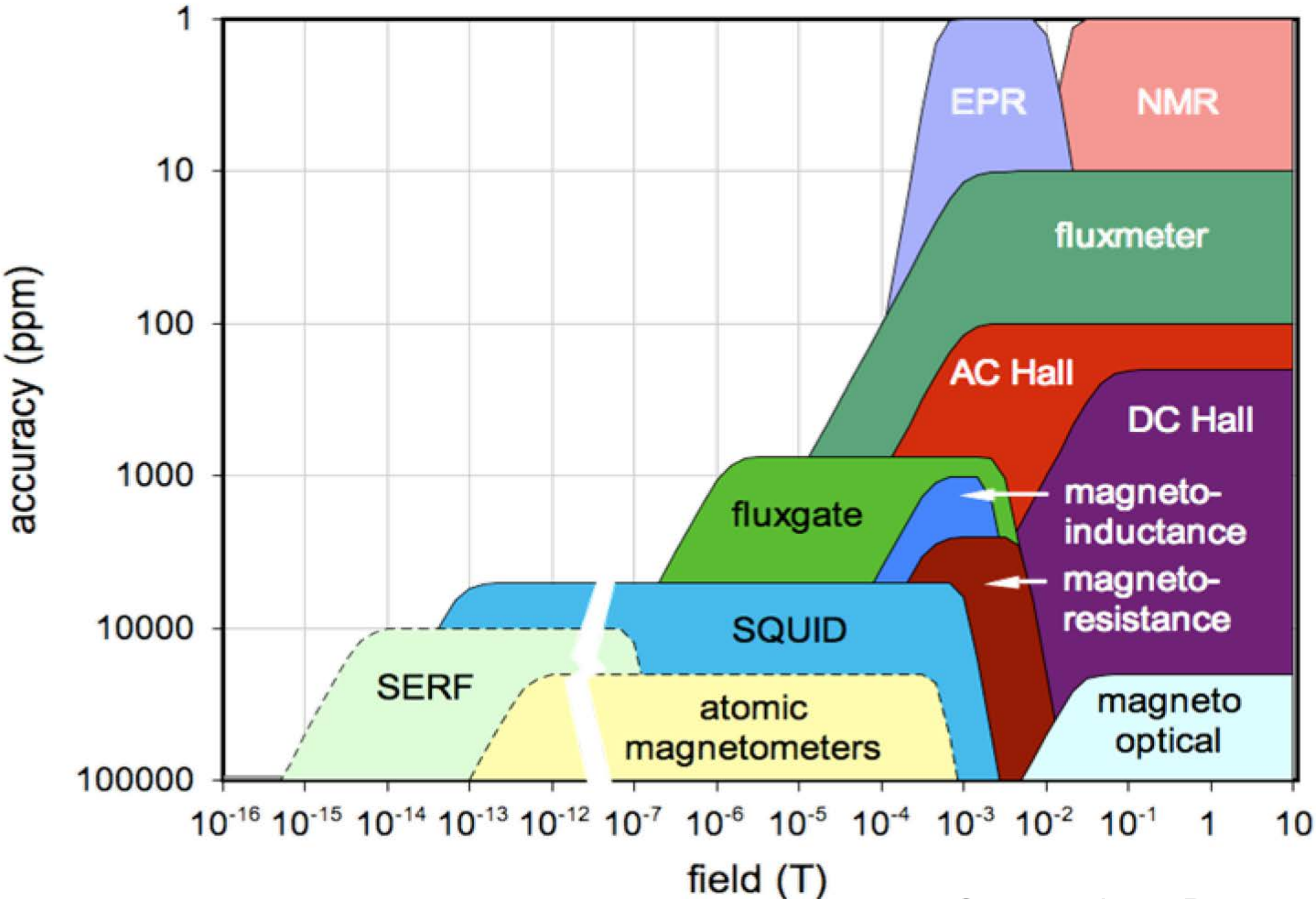

FiberTrak - DTI track a SENSE
Sc 4, 1
DwiSE/Anatomic
Opacity: 76.5
Threshold B0: 85
Fibers
Fiber 01
Fiber 02
ROIs
L
R
A
P
H

Summary

- **Water self-diffusion** constrained in different tissue types
- **Diffusion weighted imaging** to create diffusion contrast
- **Diffusion tensor imaging** to infer diffusion directions
- **Fiber tracking** to visualize paths of fiber bundles
- **Measurement very sensitive** to bulk motion of subject

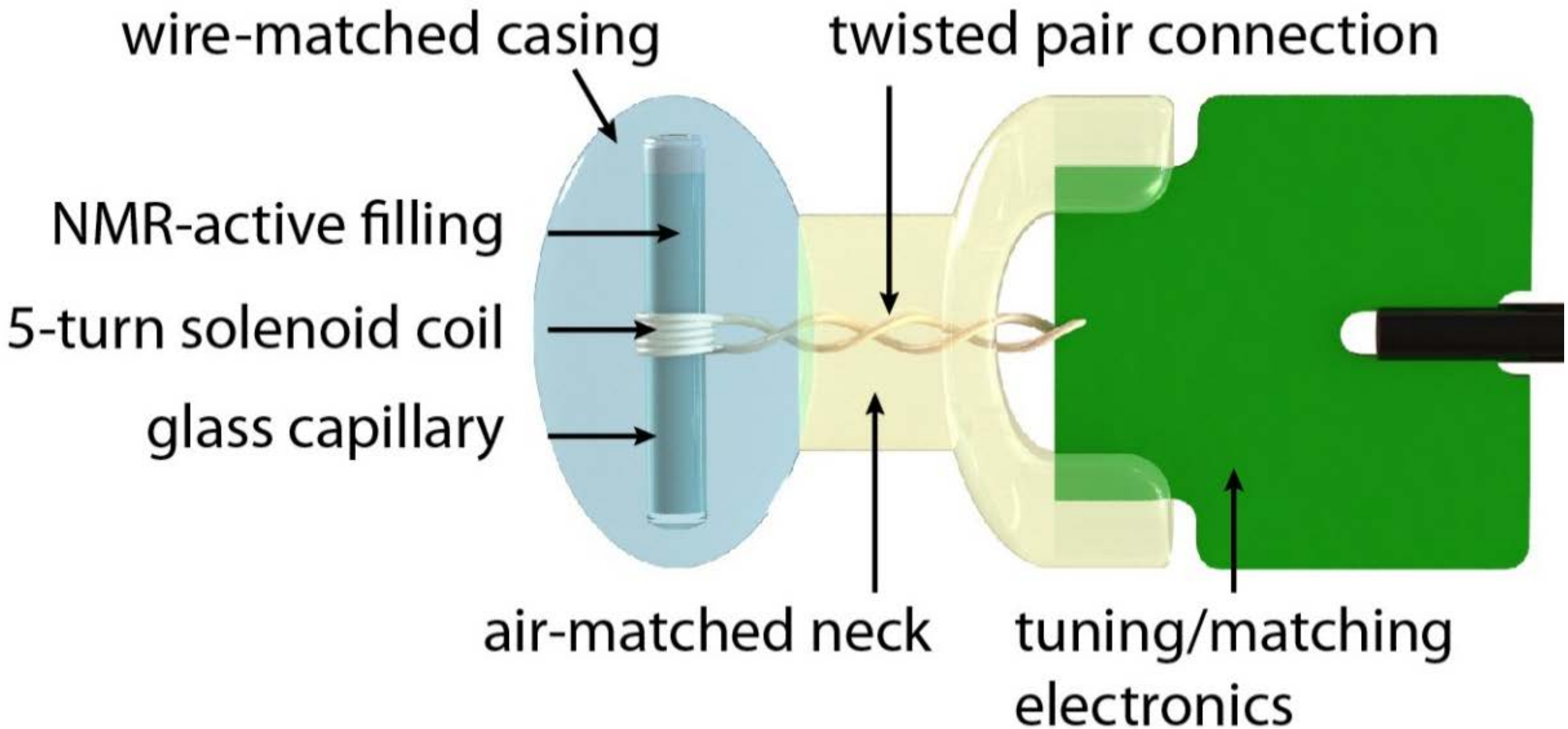
A peek into ongoing development…

Field Sensing for MRI



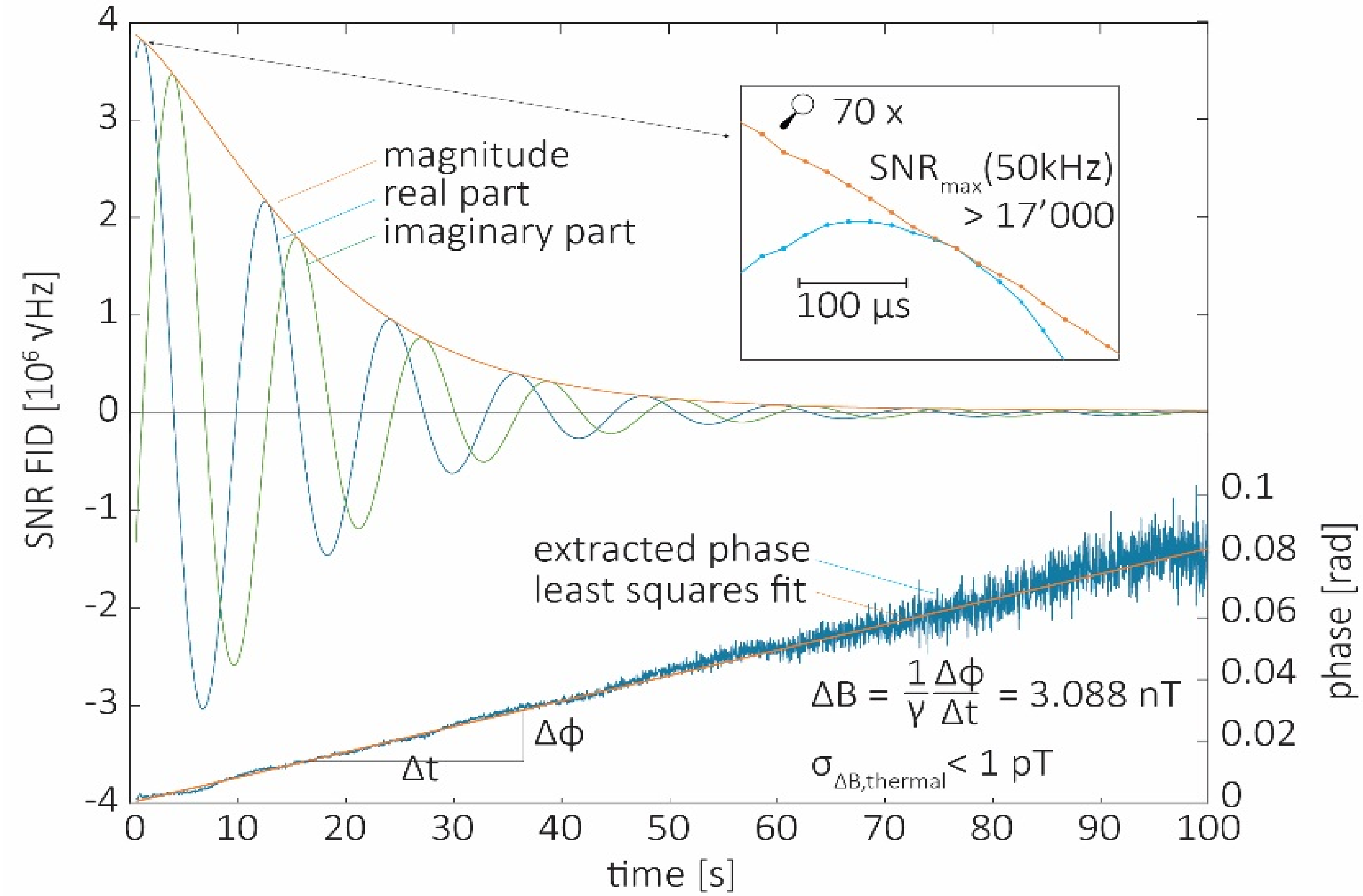
Courtesy Luca Bottura, CERN

NMR field probes



Gross S et al. Nature Communications 2016;7:13702.

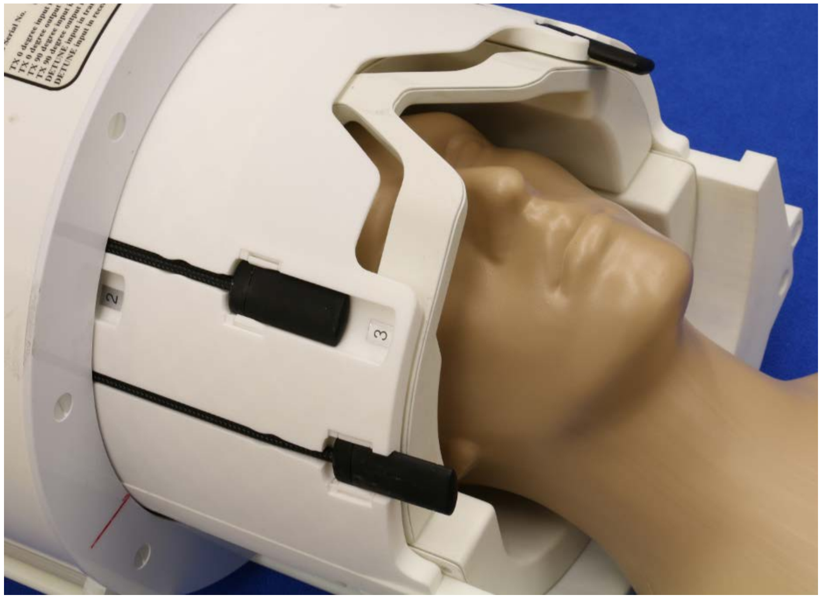
Sensing Performance



Phase noise: 0.23 μrad / $Hz^{1/2}$ ⇨ ΔB ≈ 6 pT

Gross S et al. Nature Communications 2016;7:13702.

Concurrent Field Sensing



Fit spatiotemporal phase model:

$$\varphi(\mathbf{r},t) = \sum_i k_i(t) \cdot f(\mathbf{r})$$

Field expansion: $\frac{d}{dt} k_i(t)$

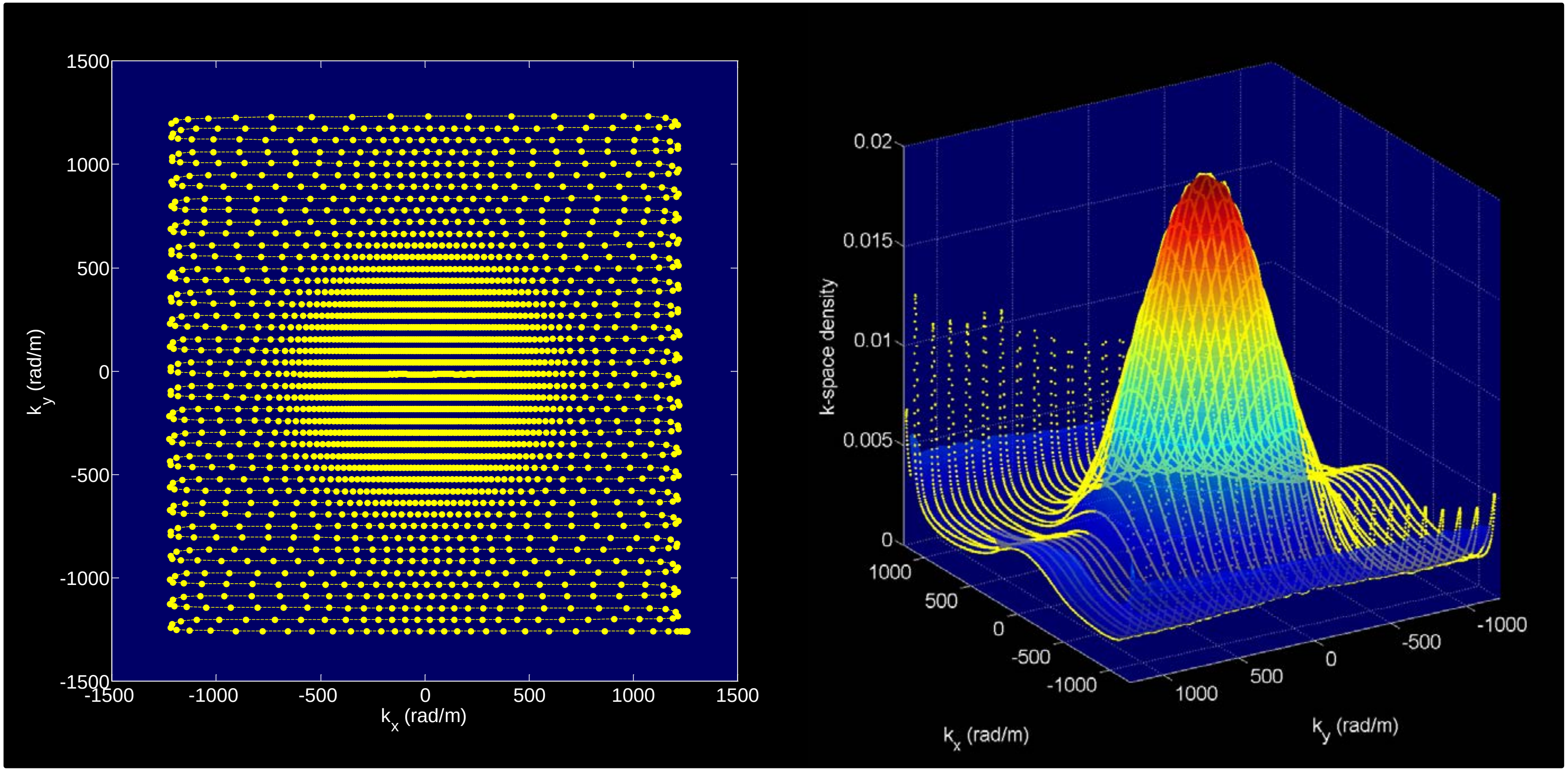
3rd-order spherical harmonics

order	basis function $f(\mathbf{r})$
0	1
	X
1	Y
	Z
	XY
	ZY
2	$3Z^2 - (X^2 + Y^2 + Z^2)$
	XZ
	$X^2 - Y^2$
	$3X^2Y - Y^3$
	XYZ
	$Y(5Z^2 - (X^2 + Y^2 + Z^2))$
3	$5Z^3 - 3Z(X^2 + Y^2 + Z^2)$
	$X(5Z^2 - (X^2 + Y^2 + Z^2))$
	$X^2Z - Y^2Z$
	$X^3 - 3XY^2$

Matched-Filter Acquisition for BOLD fMRI

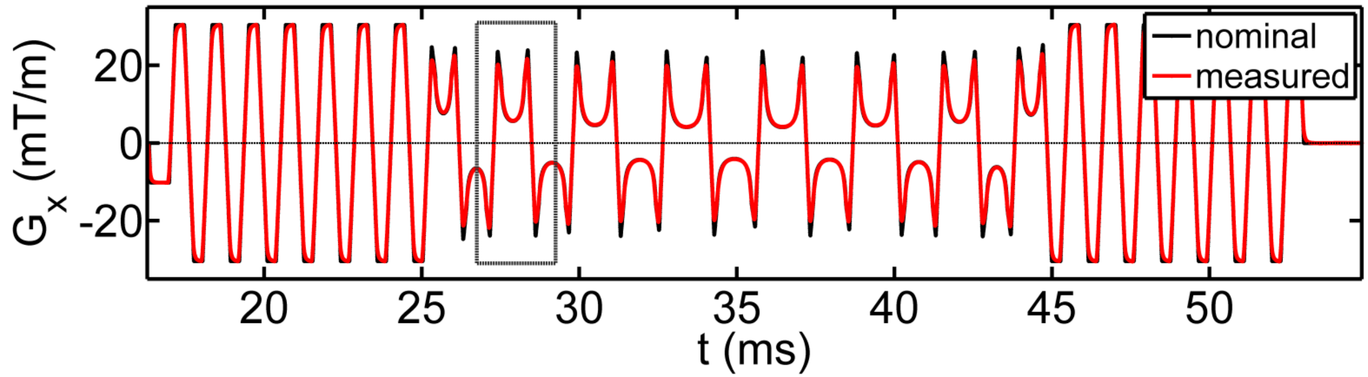
BOLD analysis often based on Gaussian statistics → k-space filtering / smoothing

For optimal SNR yield: Distribution of AQ time should match the k-space filter

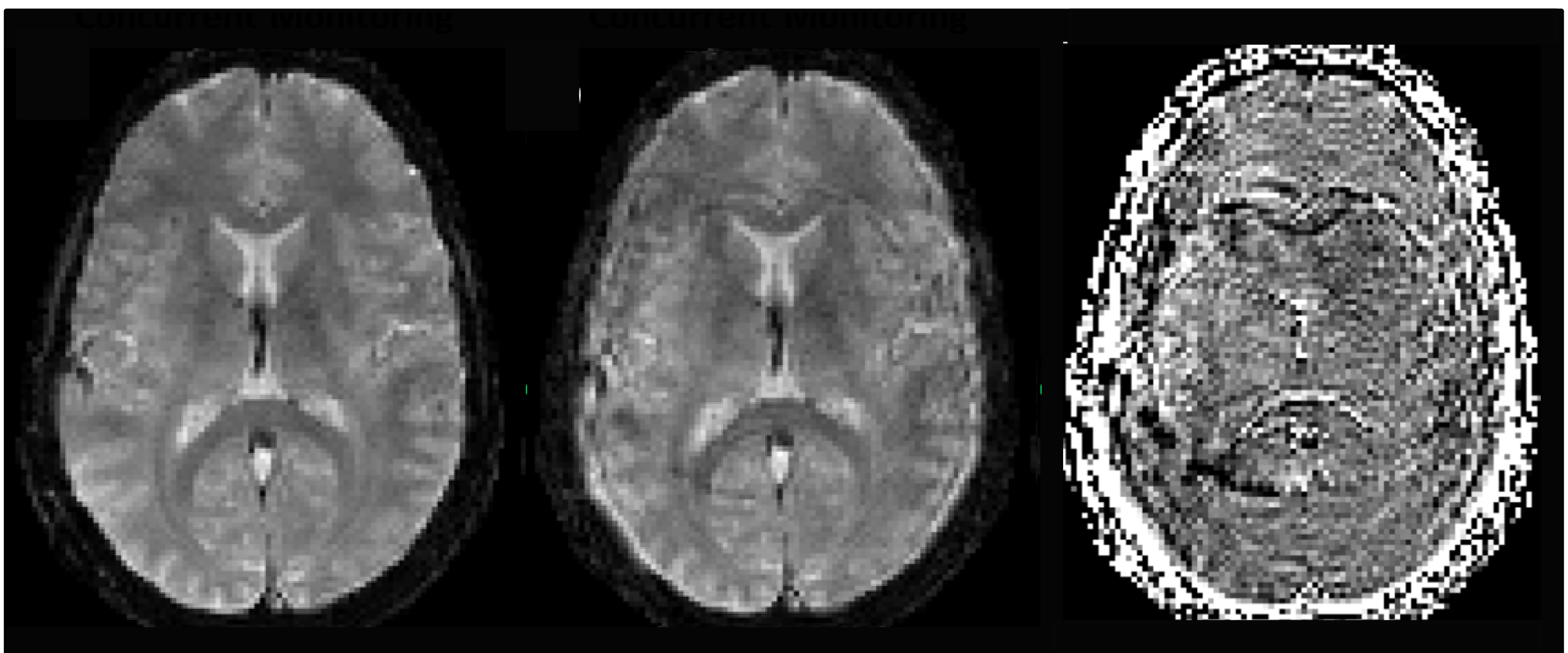


Magnetic Field Sensing & Control

Rapid readout:
41 msec



Field monitoring | Nominal evolution | Difference



Magnetic Field Sensing & Control

Rapid readout:
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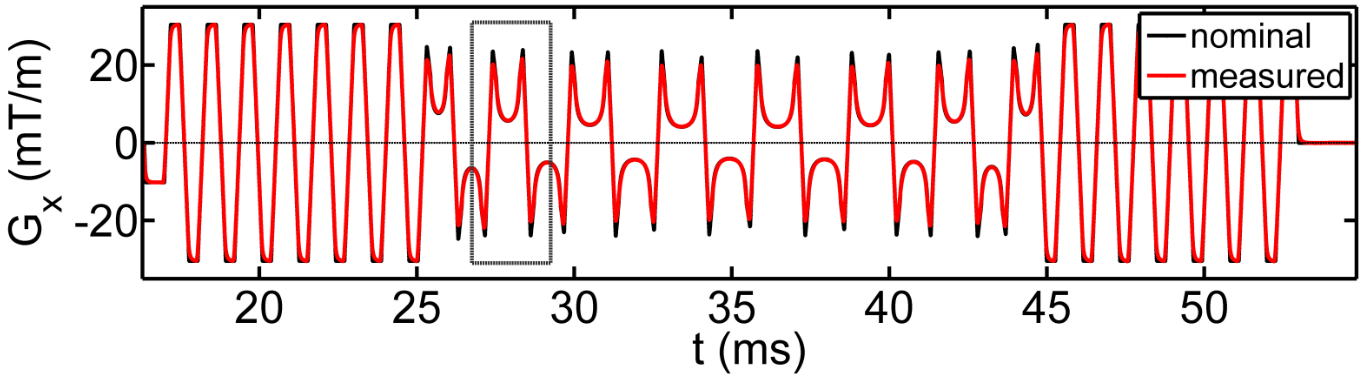
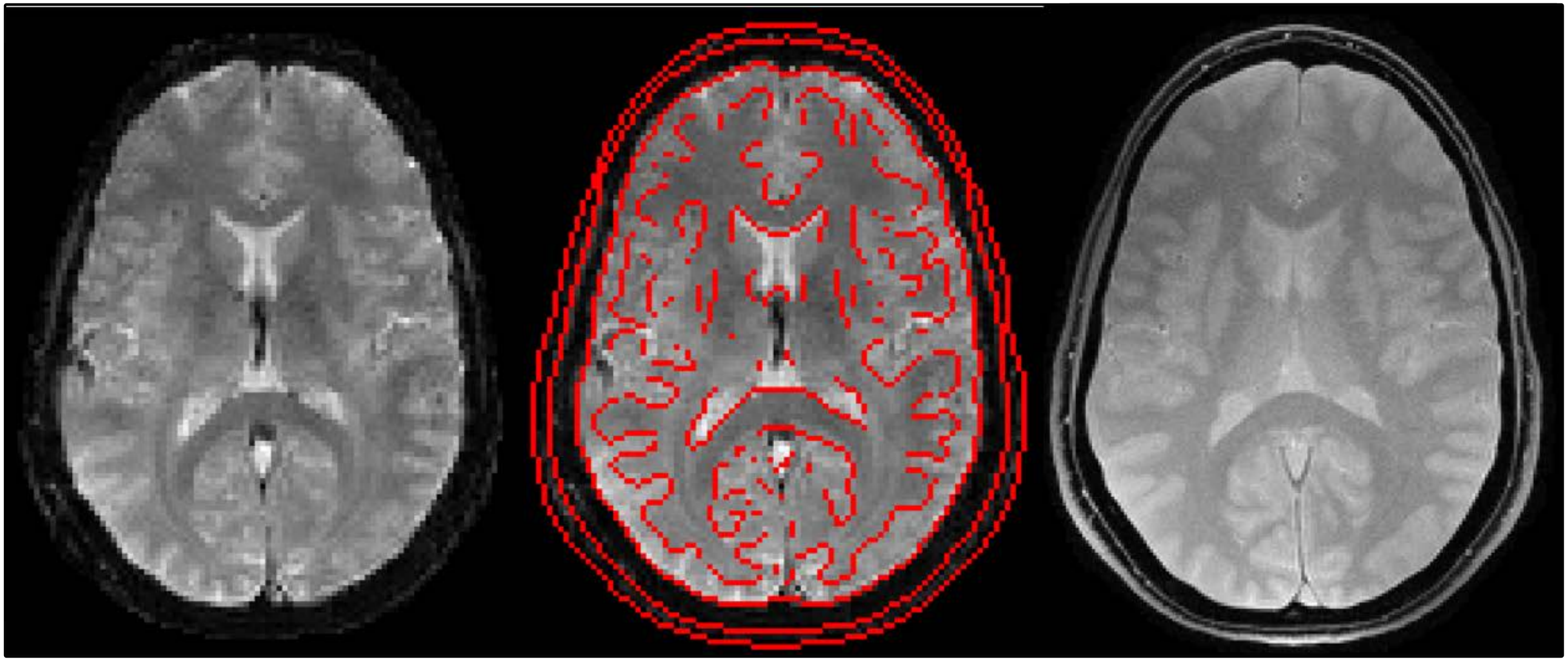
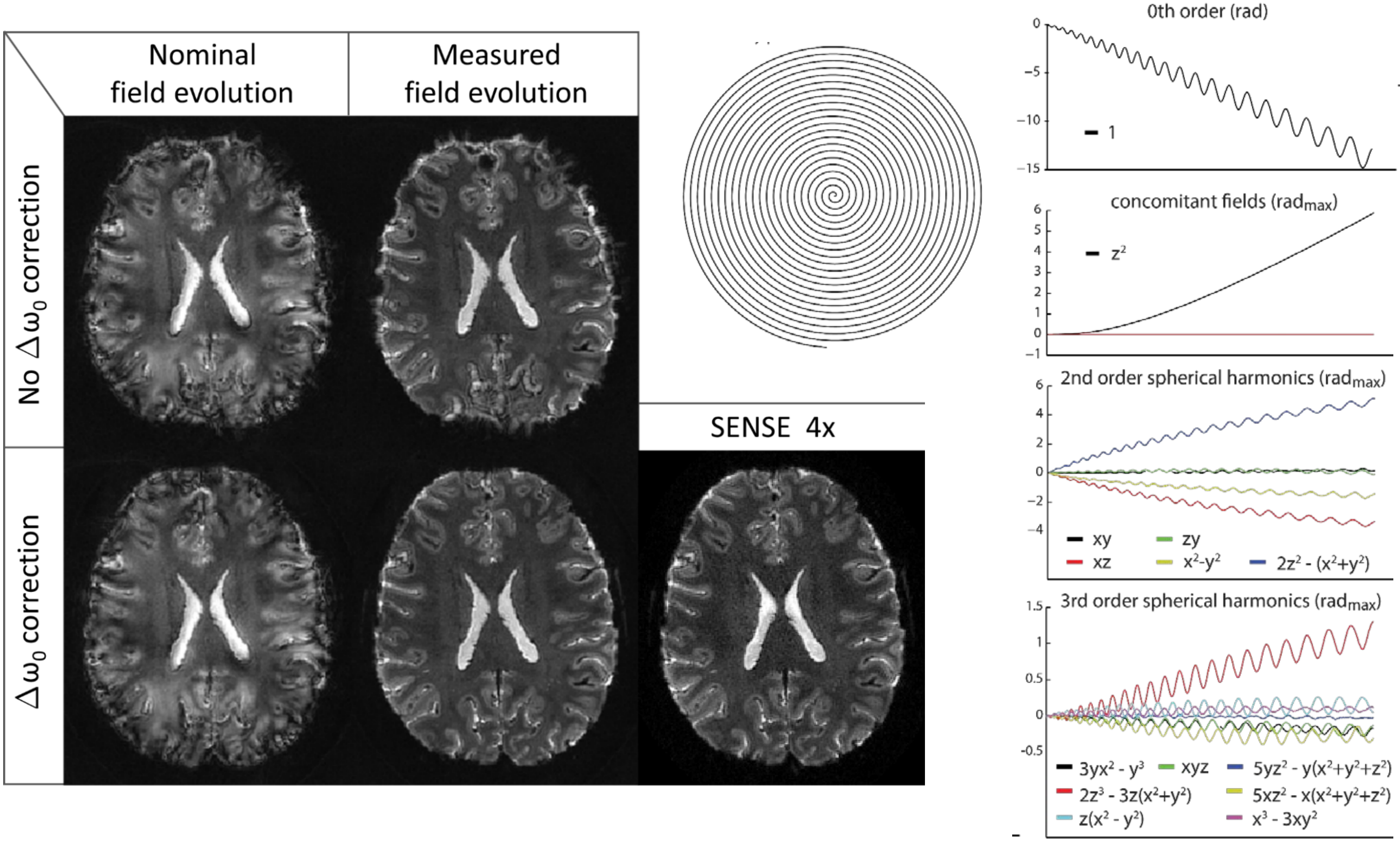


Field monitoring enforces consistent geometry:



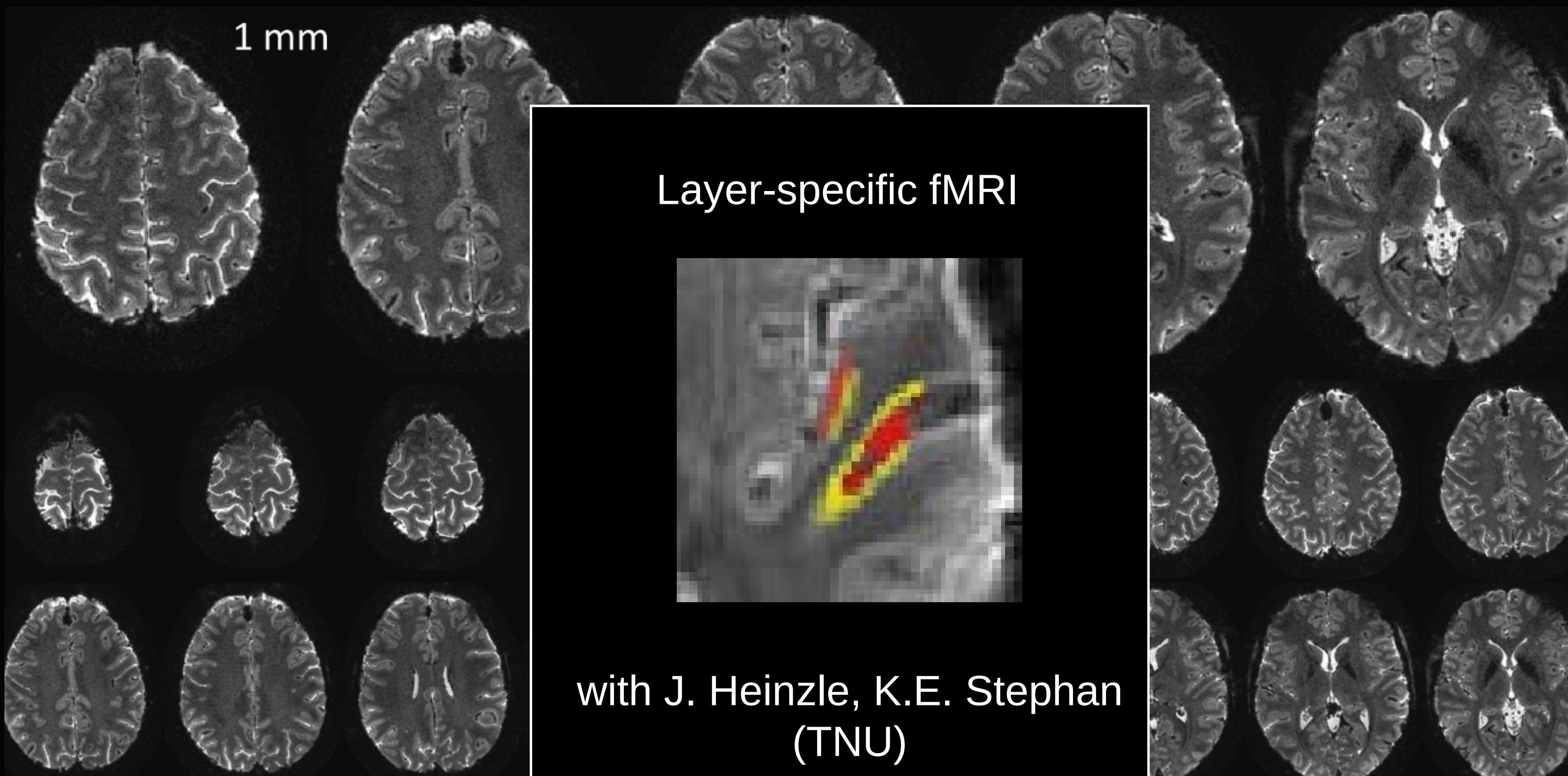
Single-Shot Spiral Imaging at 7T



M. Engel et al., MRM (2018)

Single-Shot Spirals

7 T, Δx = 800 μm, TE = 25 ms, AQ = 58 ms



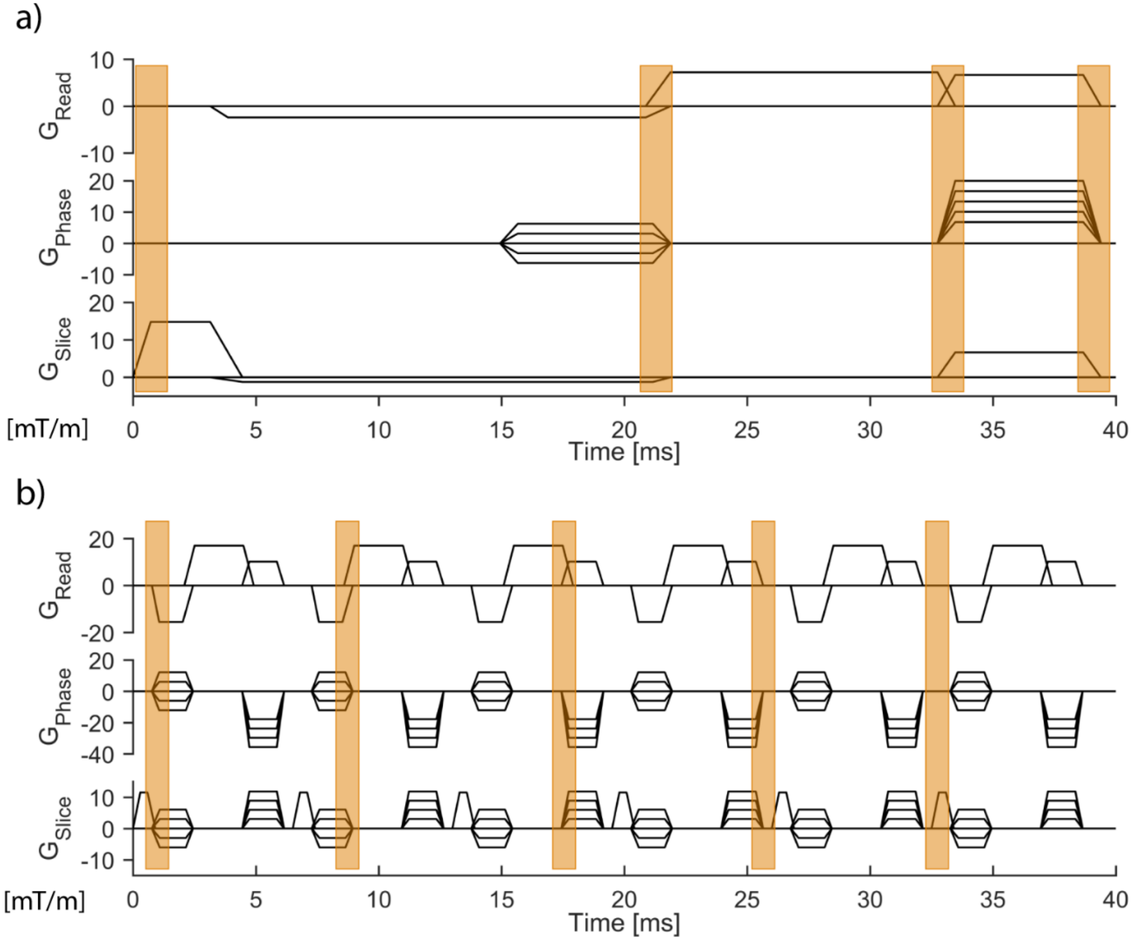
Layer-specific fMRI

with J. Heinzle, K.E. Stephan (TNU)

M. Engel, L. Kasper

Motion Tracking and Correction

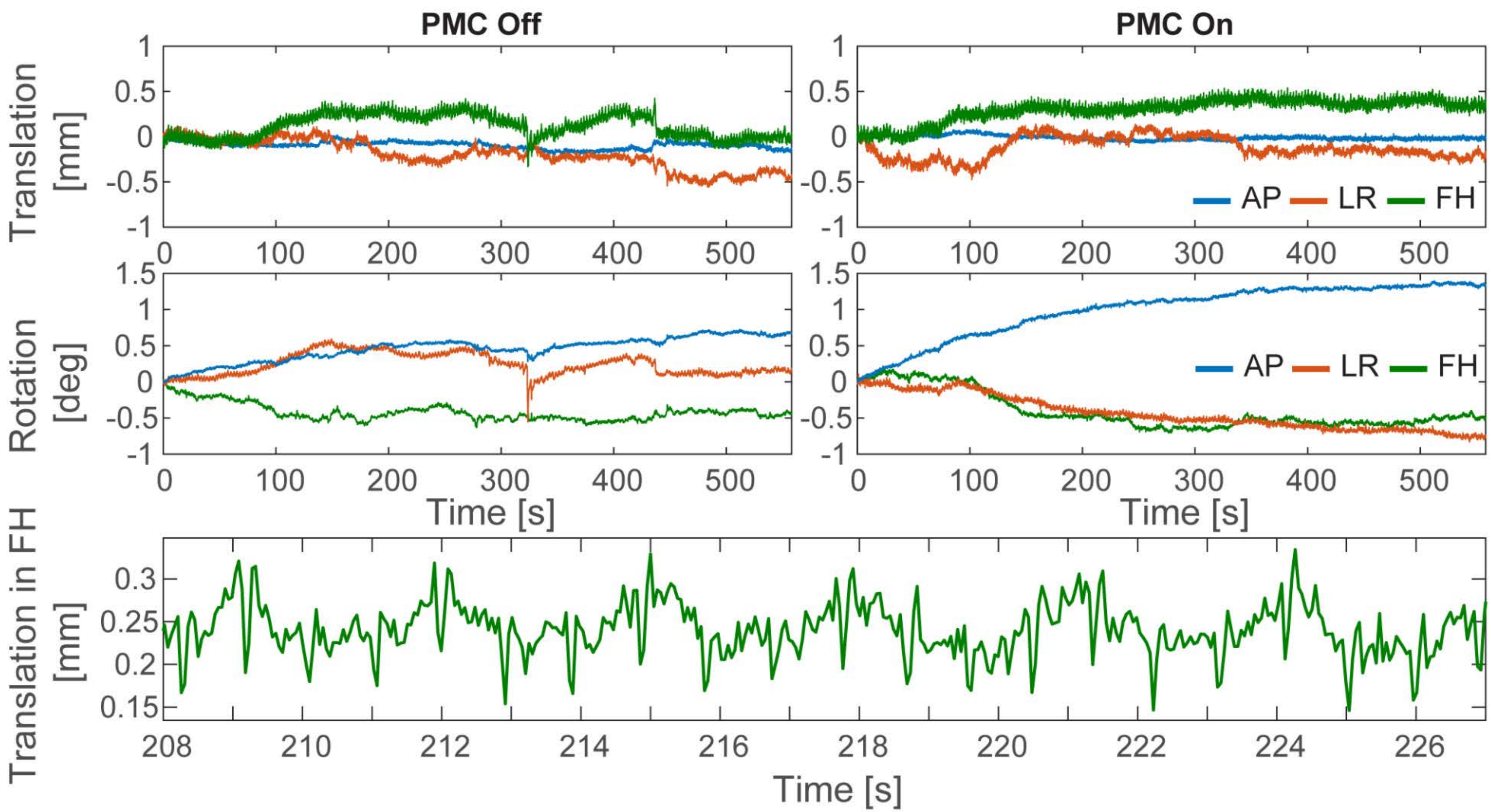
Measure field during imaging sequence



A. Aranovitch et al. MRM (2018)

Motion Tracking and Correction

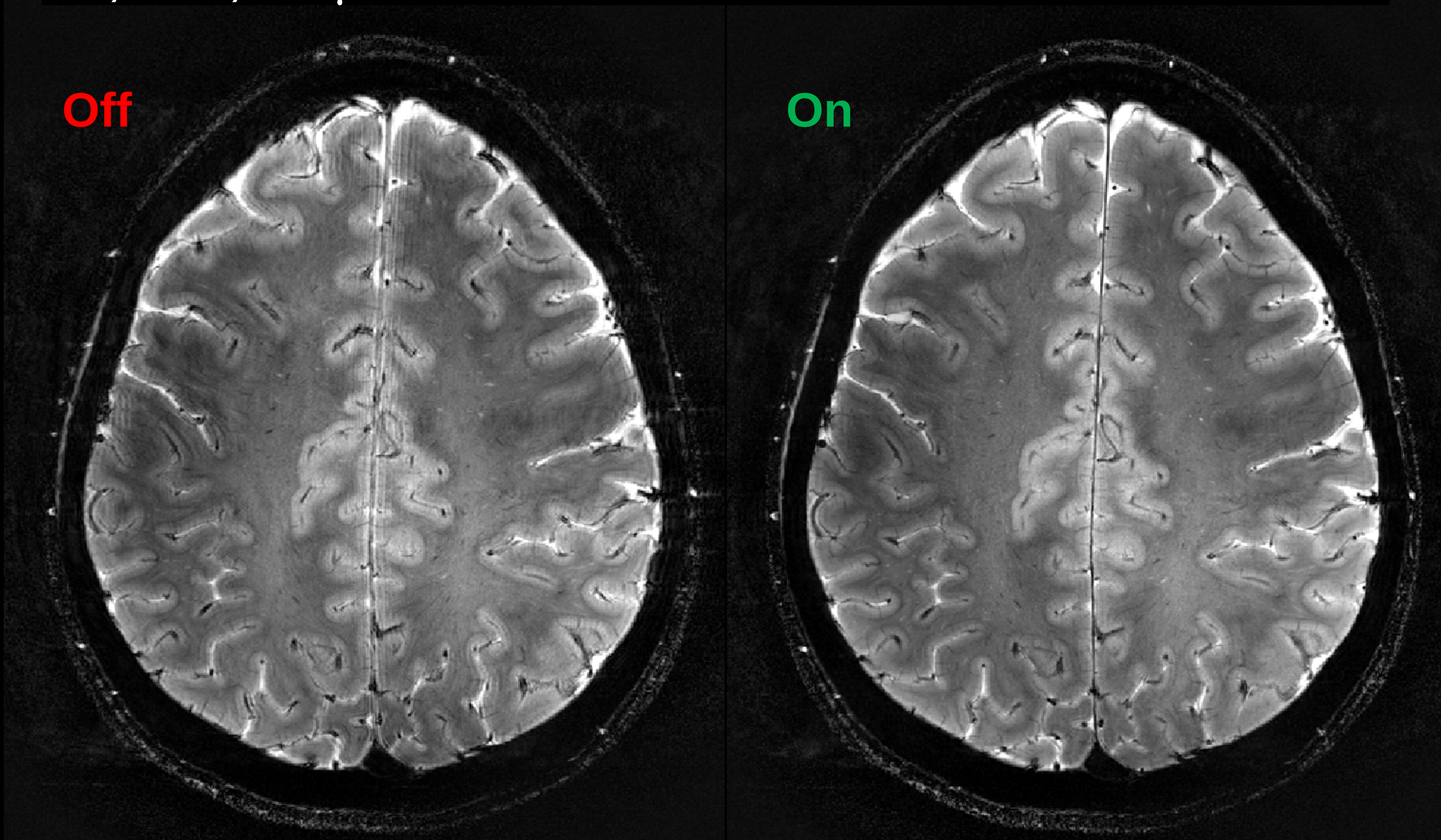
Precision: 5-20 μm, 0.01°



A. Aranovitch et al. MRM (2018)

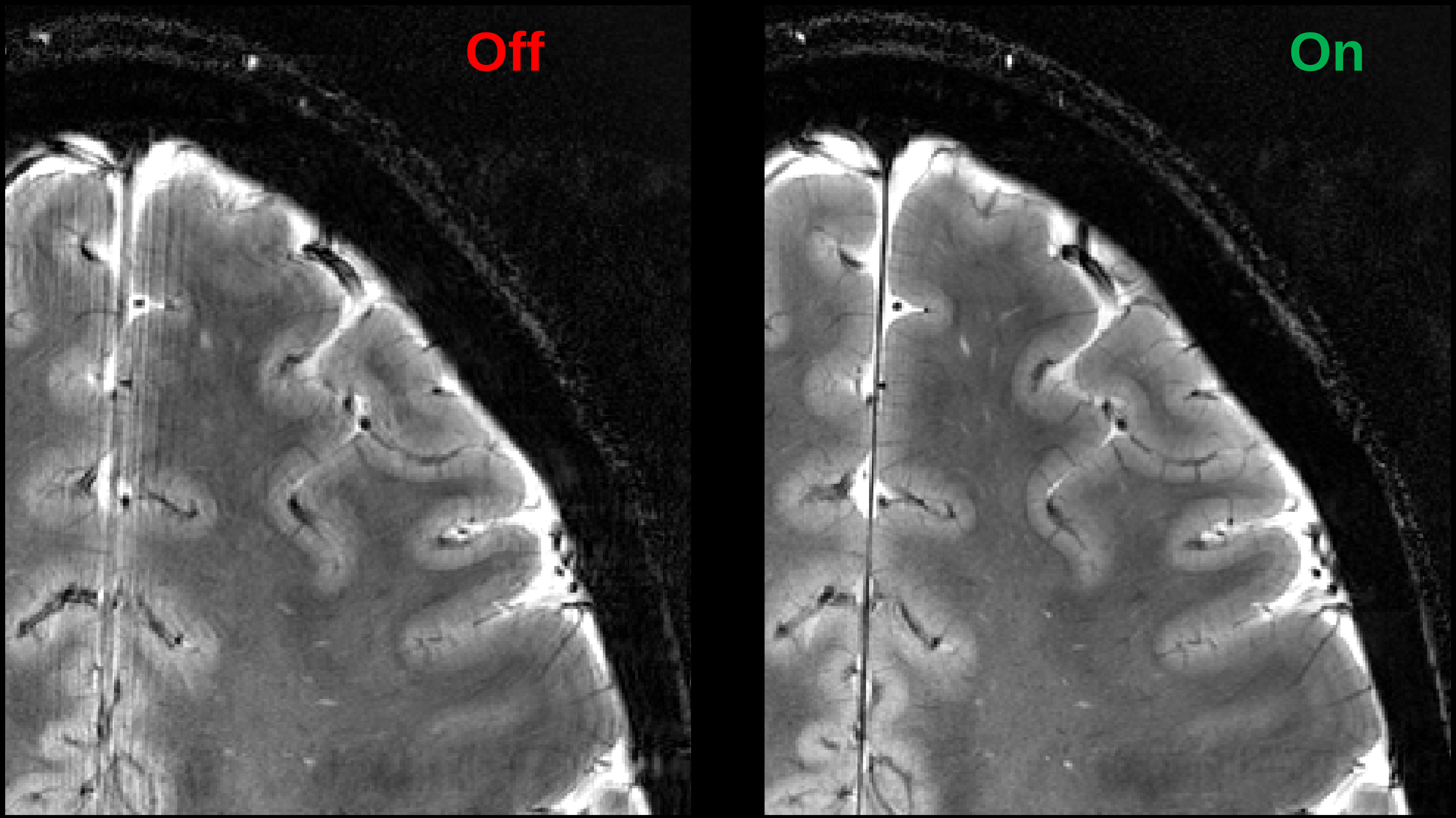
Motion Tracking and Correction

7T, T2*w, 300 μm

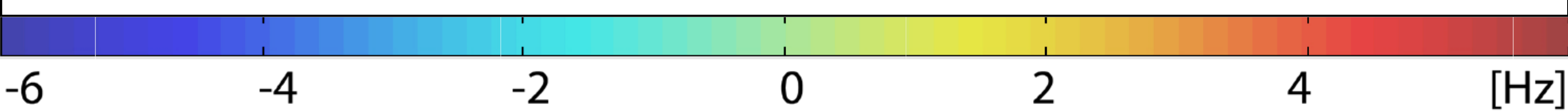


Motion Tracking and Correction

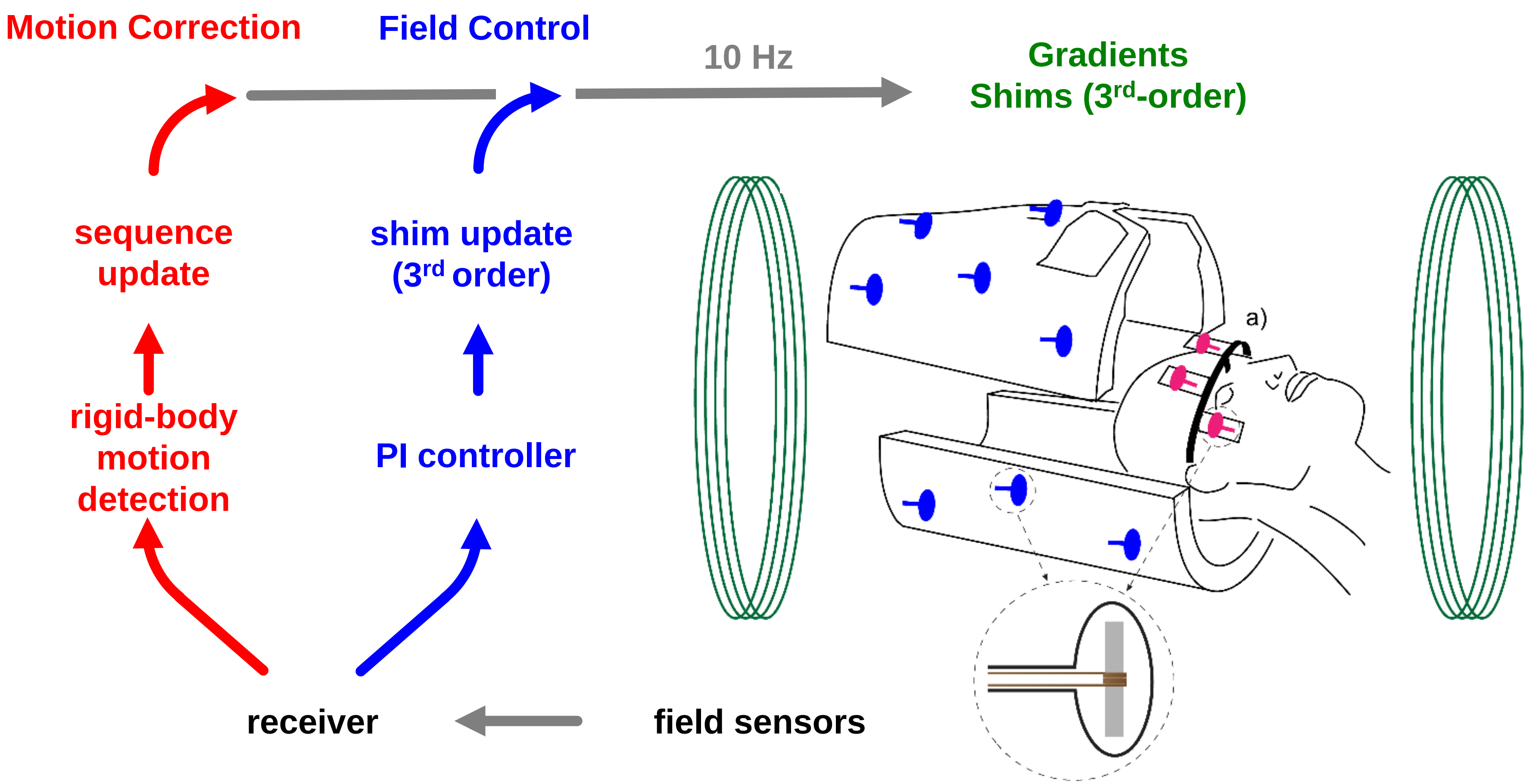
7T, T2*, high-resolution (300 μm)



Breathing Fluctuations at 7T

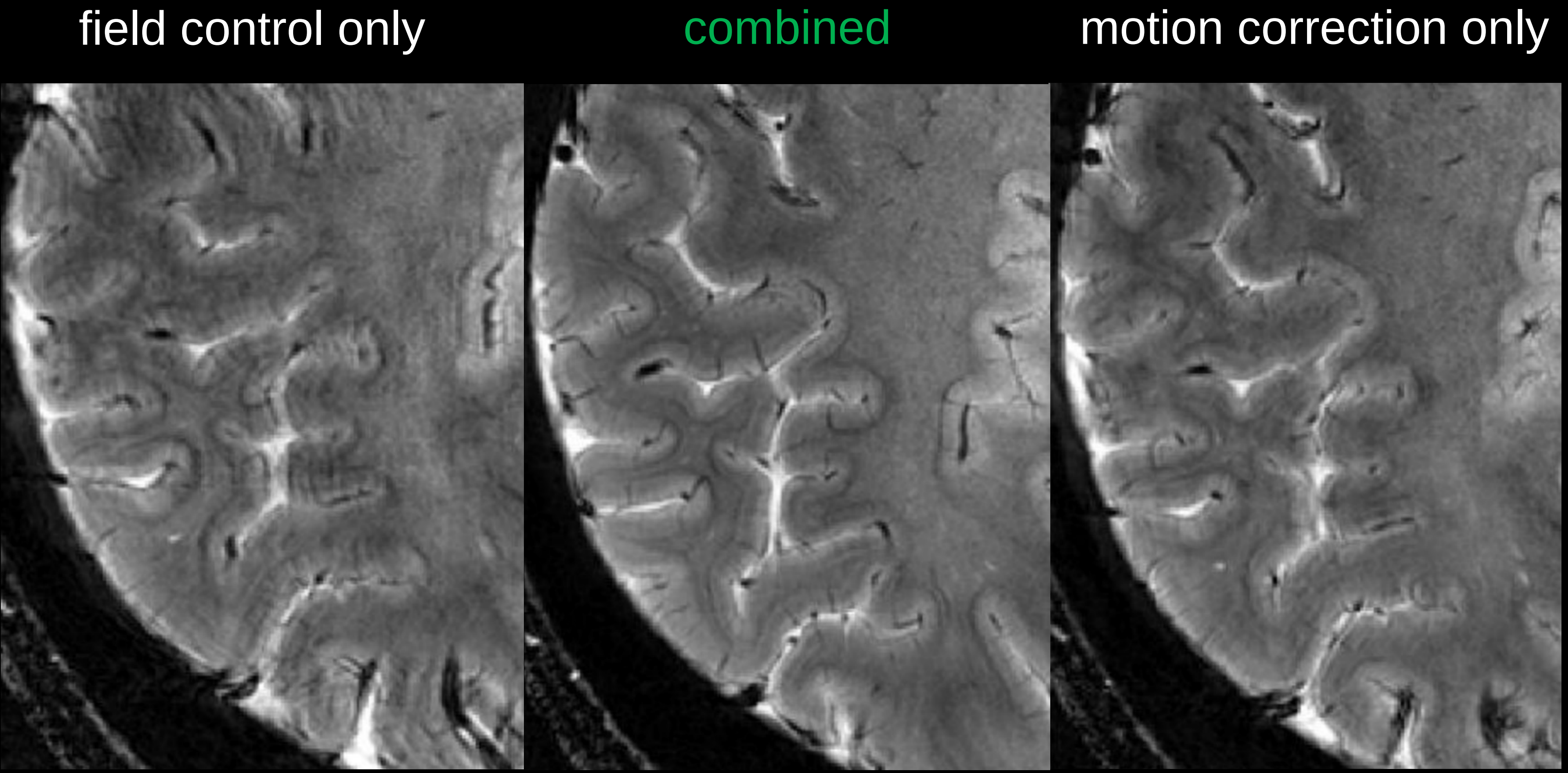


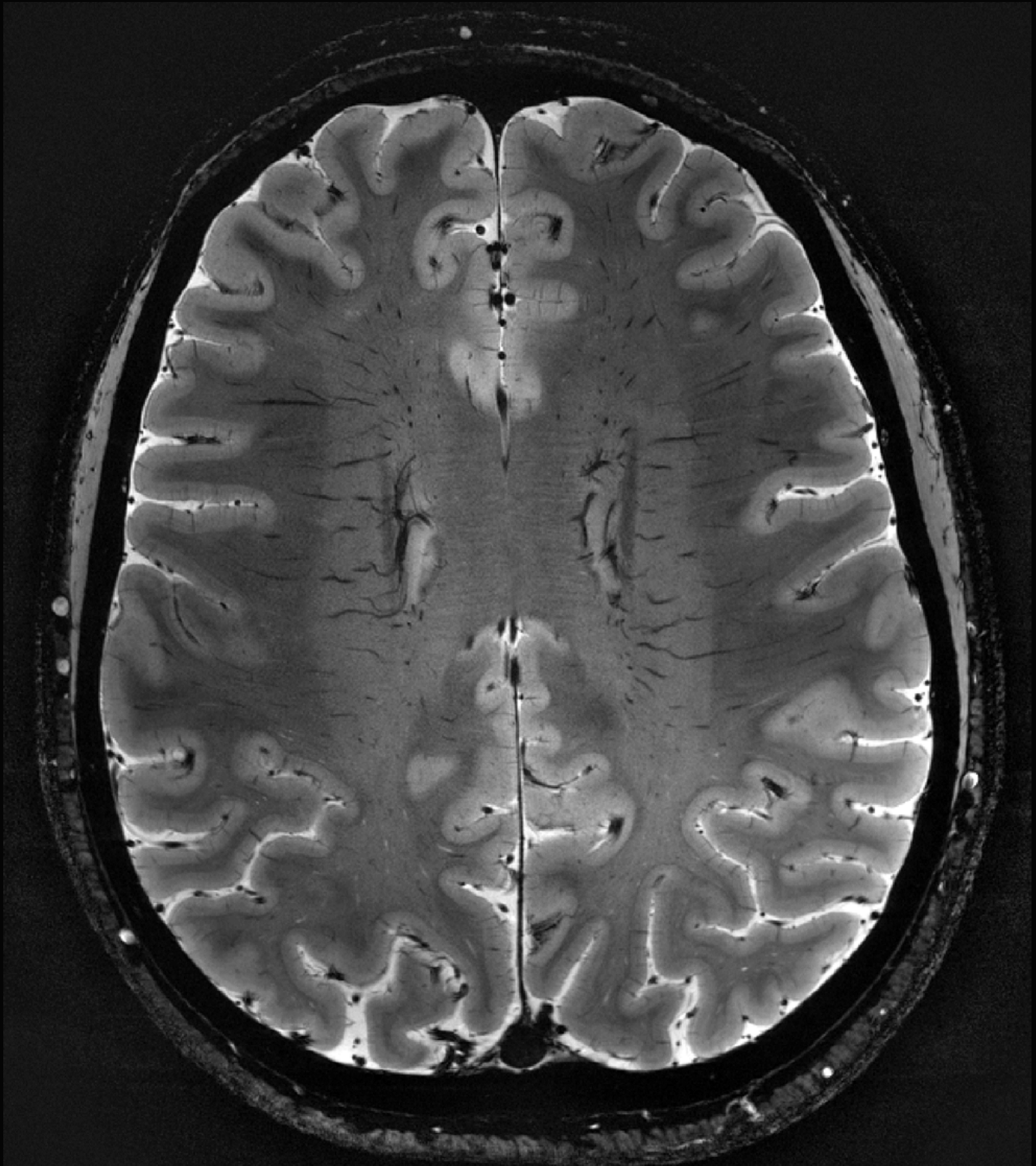
Real-Time Field and Motion Correction

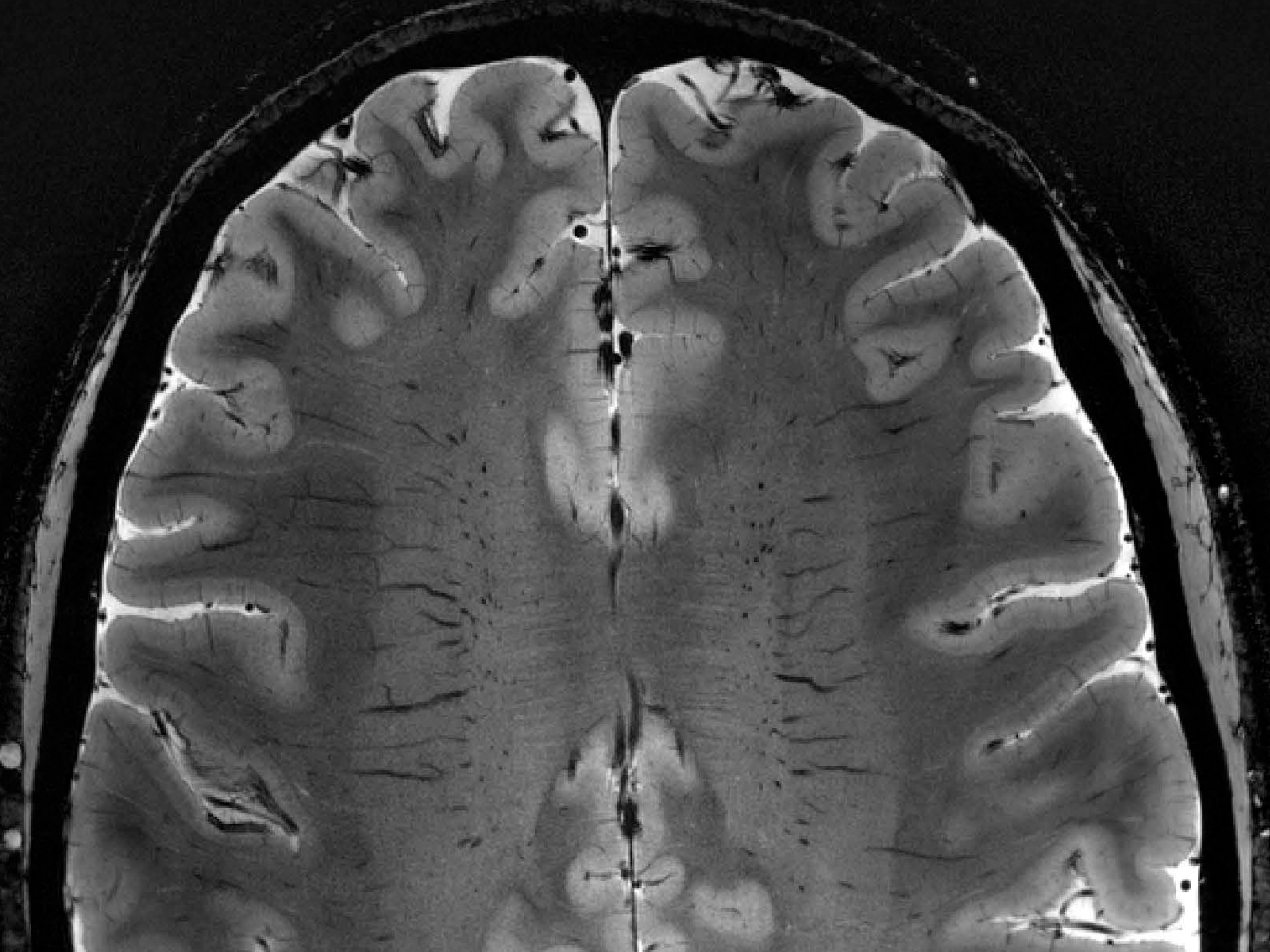


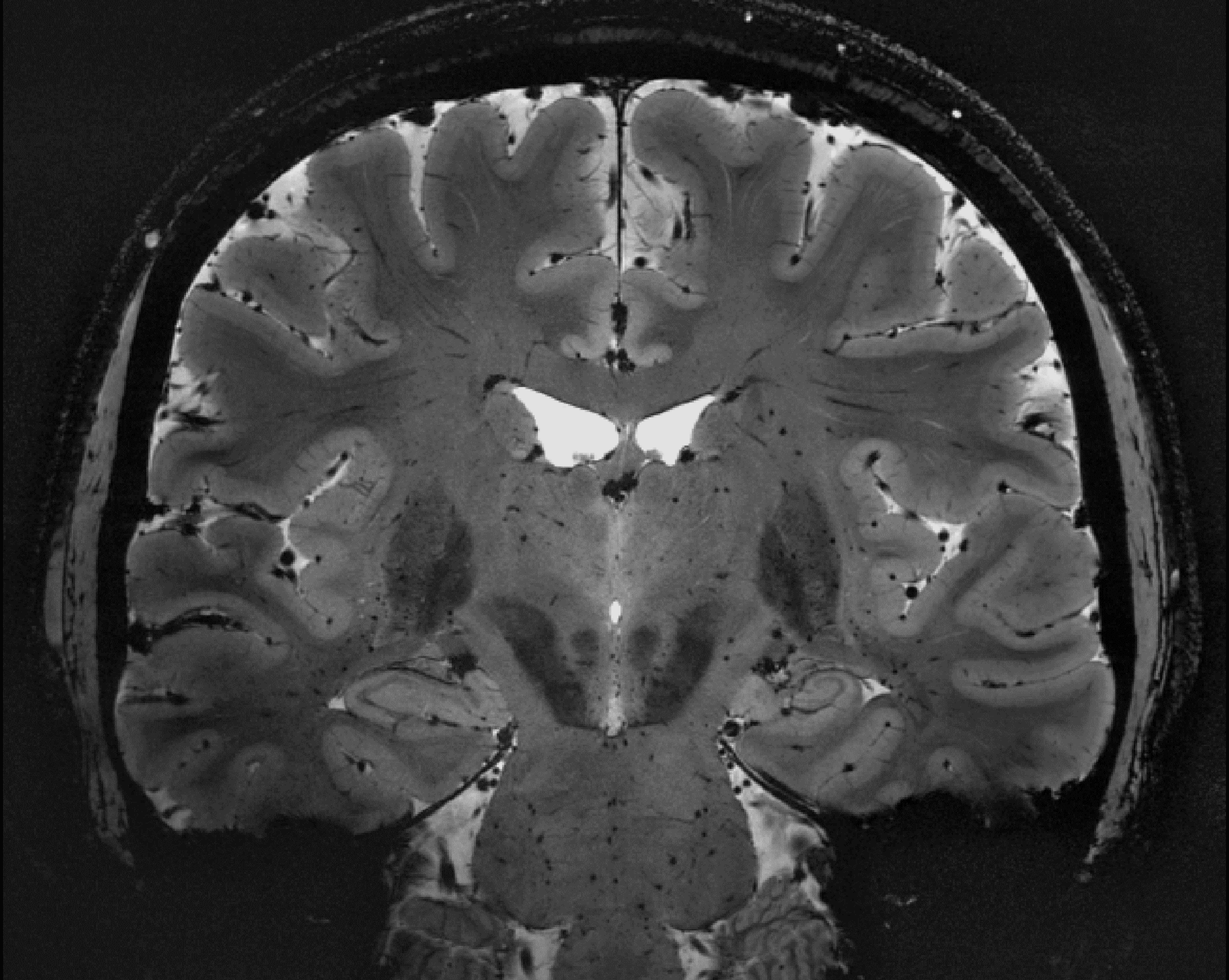
Real-Time Field and Motion Correction

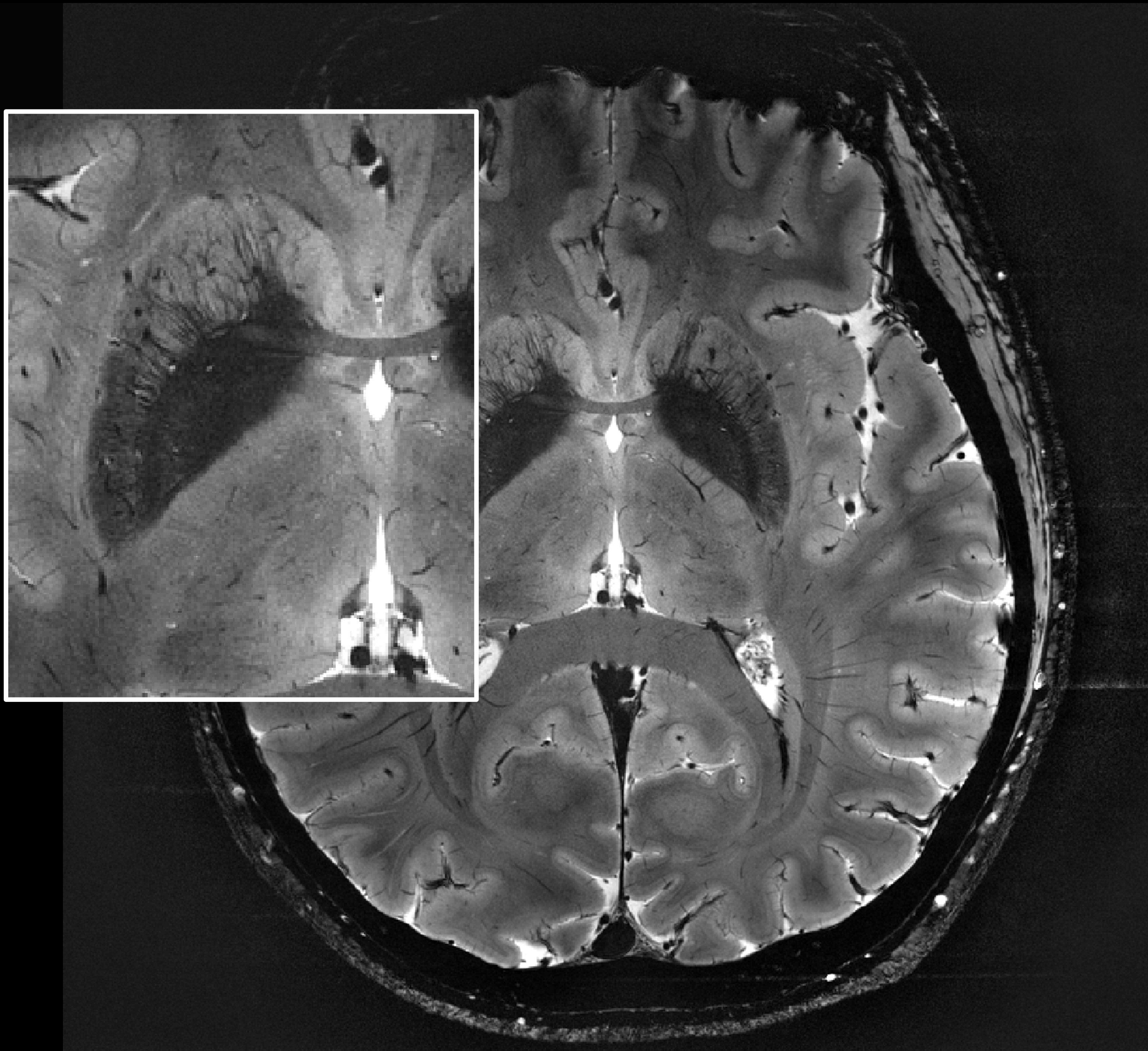
T2*w at 7T











Imaging Mode: Magnetic Resonance

- Probe: radiofrequency waves
- Wavelength: 5 – 150 cm
- Matter interaction: nuclear spin transitions
- Modalities: Magnetic Resonance Imaging (MRI)
  Magnetic Resonance Spectroscopy (MRS)
  Functional MRI (fMRI)
- Resolution: µm – mm
- Applications: body, neuro, cardiovascular, animal, economics, …
- Advantages: noN-ionizing, versatile contrast, function, metabolism
- Limitations: sensitivity, imaging speed, cost