Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Open Source Medical Devices for Innovation, Education and Global Health

Case Study of Open Source Magnetic Resonance Imaging

Lukas Winter

MDC MAX DELBRÜCK CENTER FOR MOLECULAR MEDICINE IN THE HELMHOLTZ ASSOCIATION

HELMHOLTZ ASSOCIATION

Overview

- Introduction to magnetic resonance imaging (MRI)
- MR developments and state of the art (high field) MR research
- Affordable low field MR systems
- Open source ecosystem

Introduction to MRI

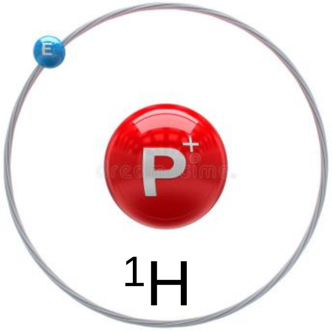
Total angular momentum

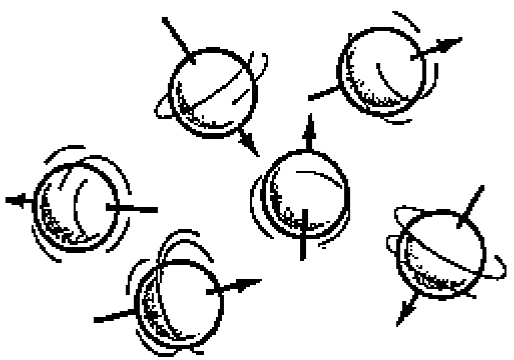
Magnetic moment: $\vec{\mu} = \gamma \vec{J}$

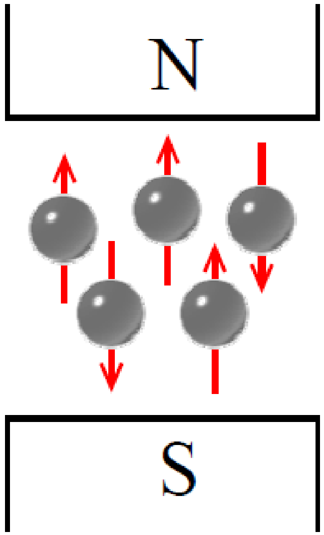
Larmor precession

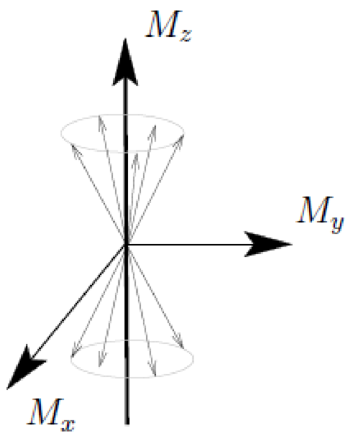
Gyromagnetic ratio: $\gamma = \frac{\omega_0}{B_0}$

Static magnetic field









Spin ensemble

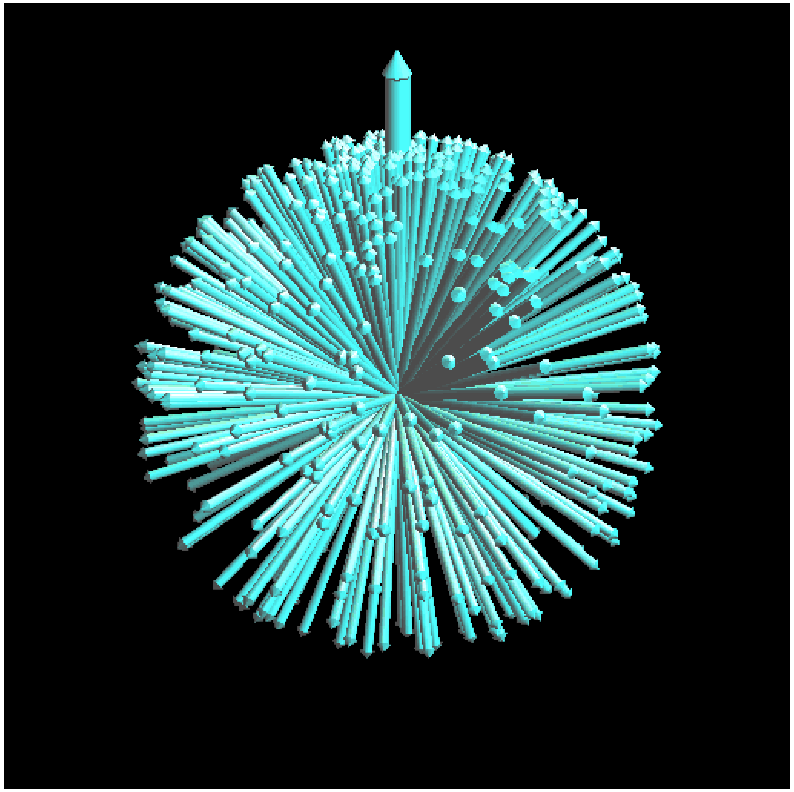
Boltzman distribution:

$$\frac{N_+}{N_-} = \exp(\frac{\hbar\omega_0}{k_B T})$$

Longitudinal magnetization:

$$M_0 \simeq \frac{1}{4}\rho_0 \frac{\gamma^2 \hbar^2}{k_B T} B_0)$$

Spin density per unit volume

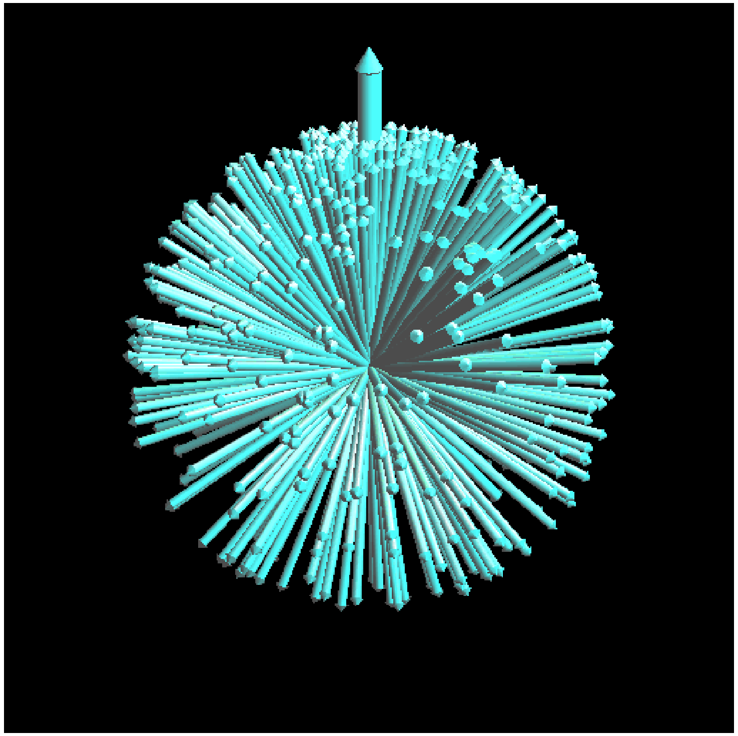


Animation from: Hanson LG, drcmr.dk/mmce2011

Radiofrequency Excitation

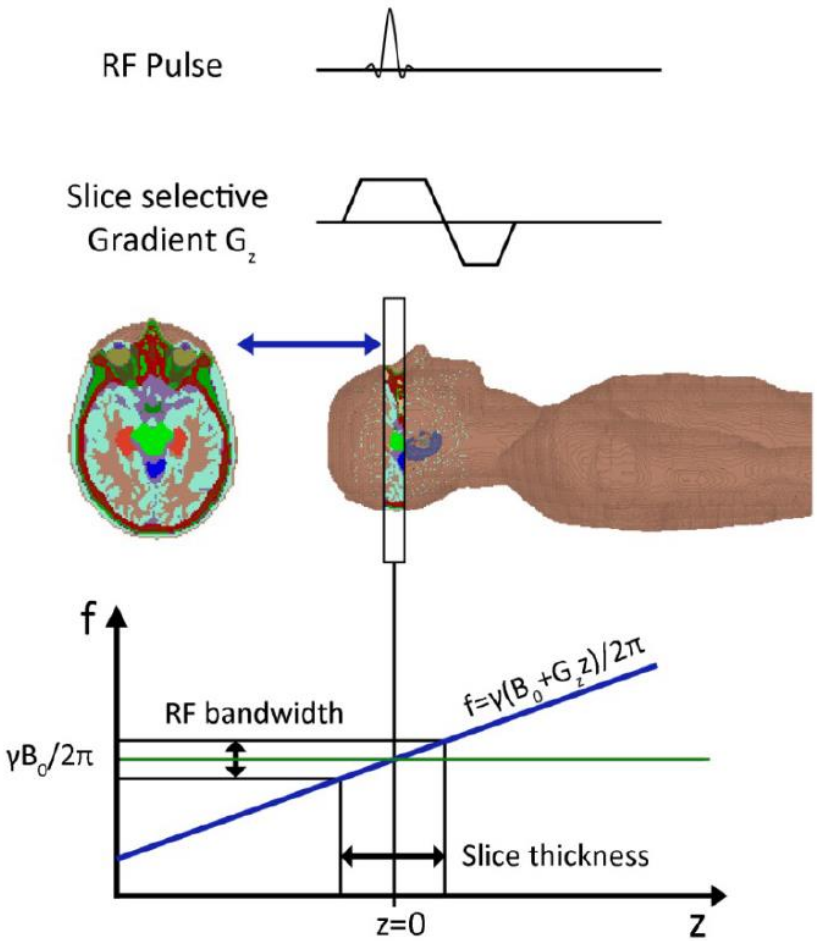
Bloch equation:

$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times \vec{B}_{ext} + \frac{1}{T_1}(M_0 - M_z)\vec{e}_z - \frac{1}{T_2}\vec{M}_{xy}$$



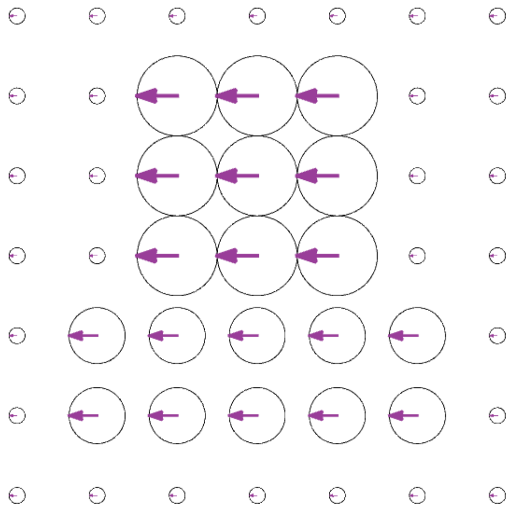
Animation from: Hanson LG, drcmr.dk/mmce2011

Spatial information: Slice selection

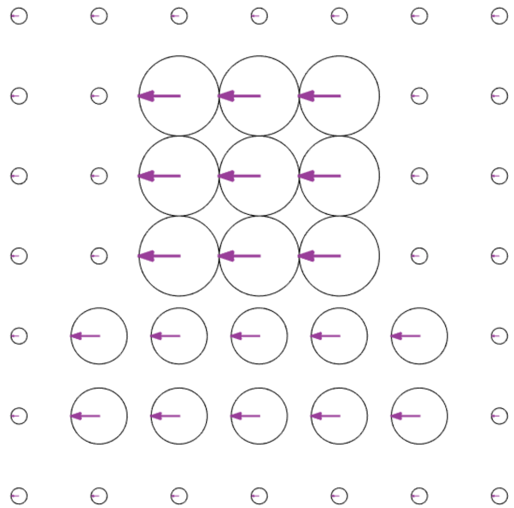


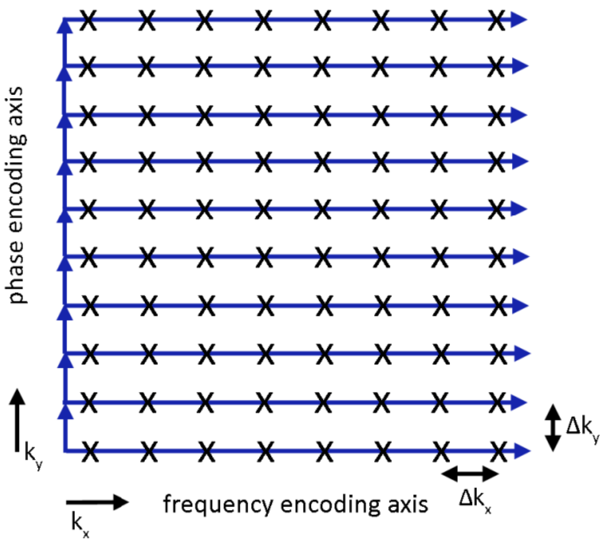
Spatial encoding in a 2D slice

No gradient



Gradient along x





Animations from: mriphysics.github.io

Spatial encoding

k-Space | Image

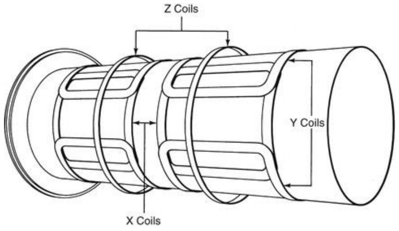
*courtesy Sebastian Schmitter

Summary: For MRI we need…

- Strong static magnetic field B_0

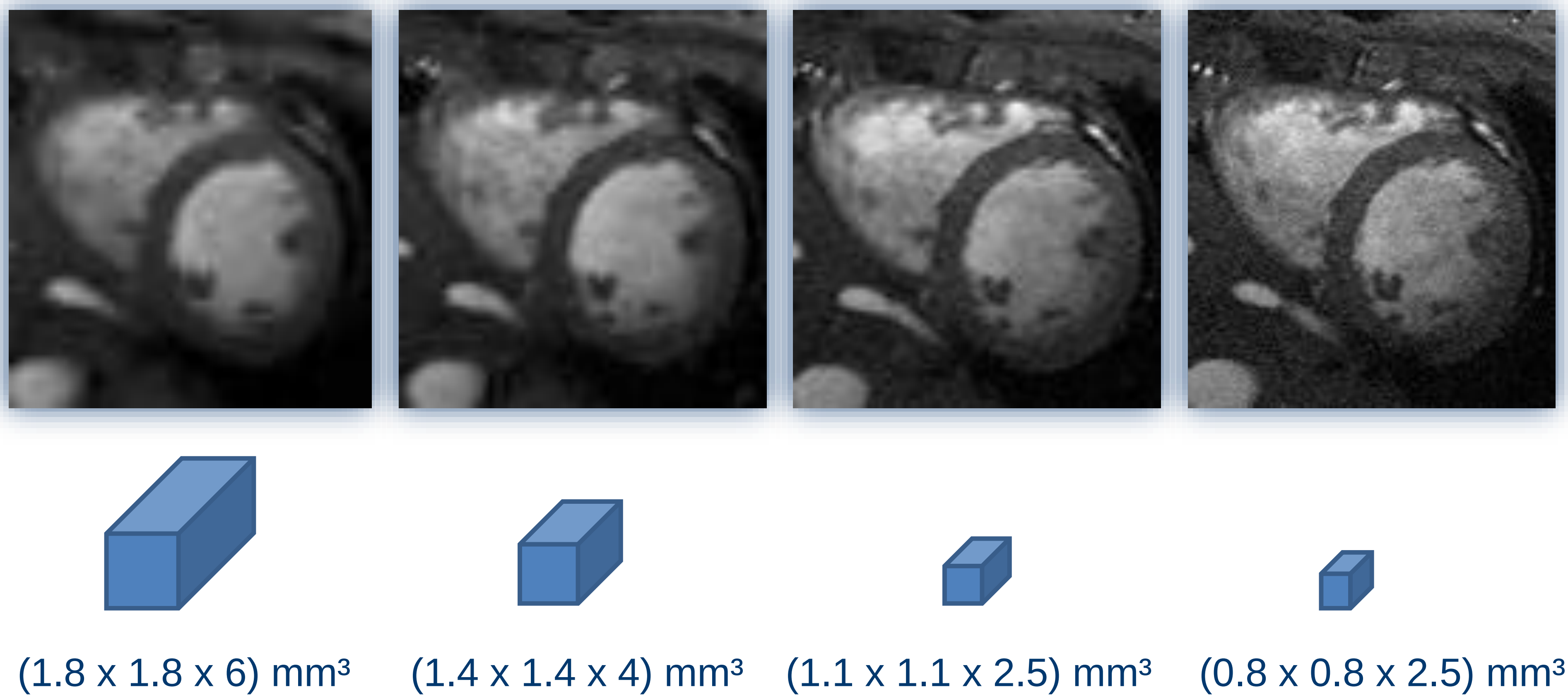
- Varying magnetic field B_1 perpendicular to B_0

- Small varying magnetic field G_x, G_y, G_z for spatial encoding



- And some mathematics, computer science, engineering, biology, medicine…

Increasing spatial resolution

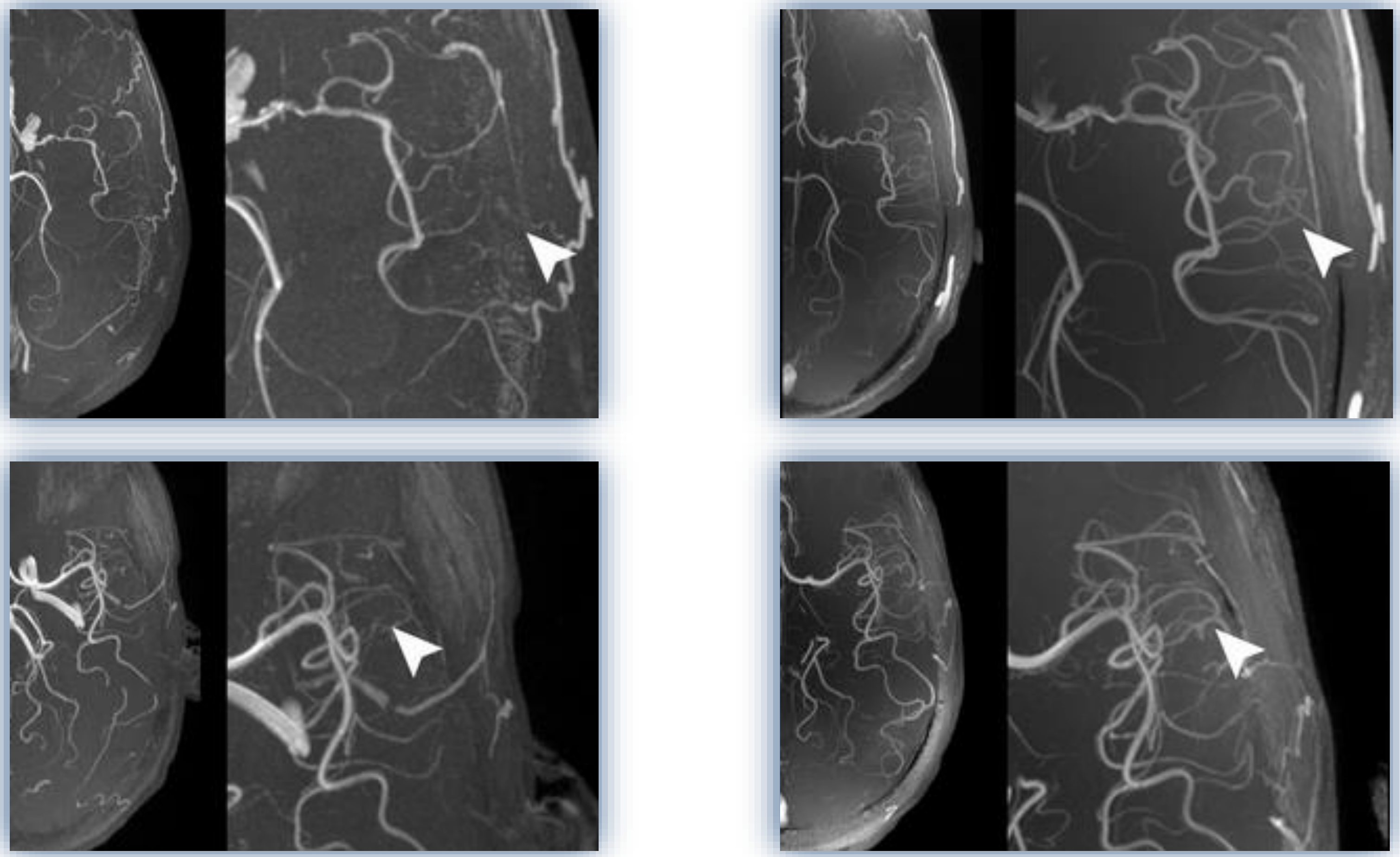


*courtesy Celal Özerdem

Ultra-high field MRI

3.0 Tesla

7.0 Tesla



V. Madai et.al. , PLoS One 7(5):e37631. (2012)

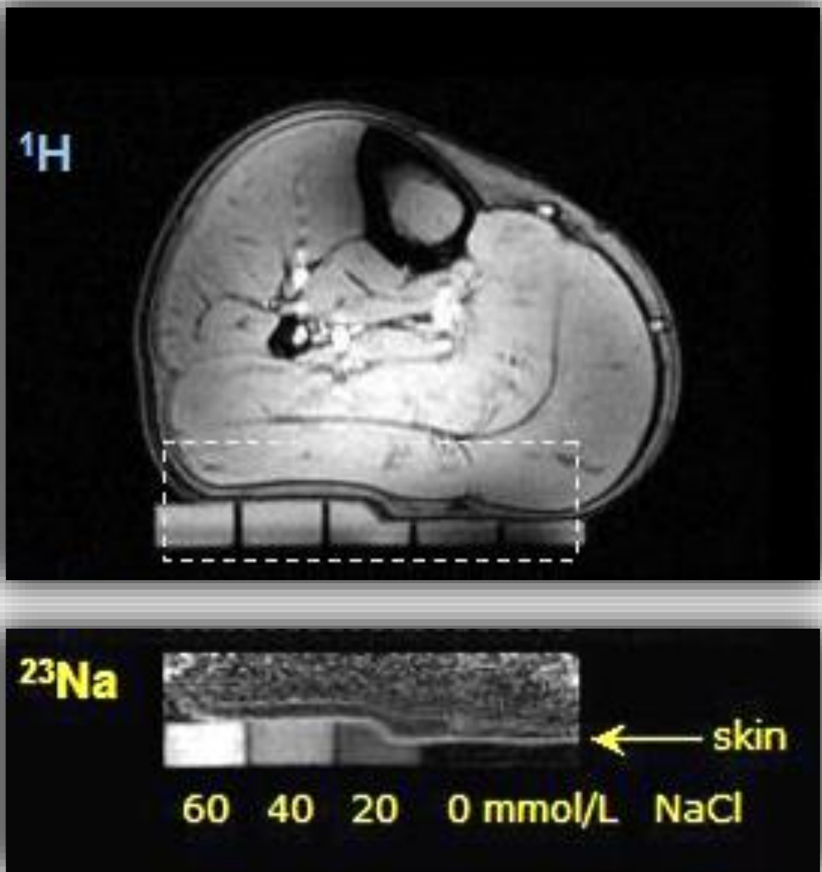
X-nuclei MRI

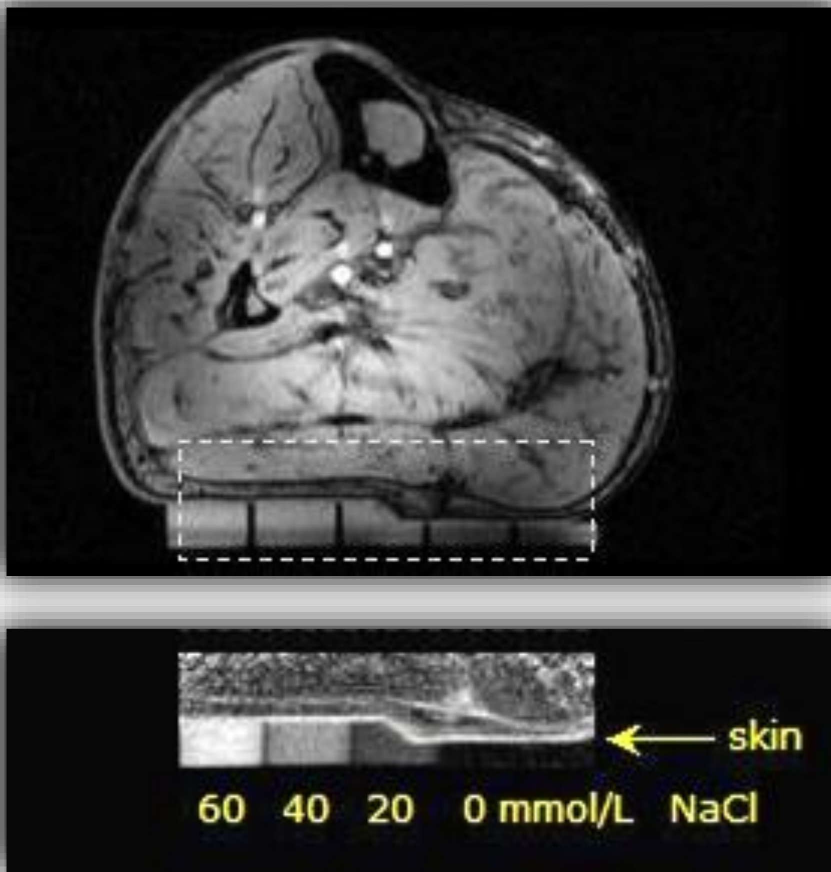
male, 25 years

male, 68 years

^{1}H

^{23}Na

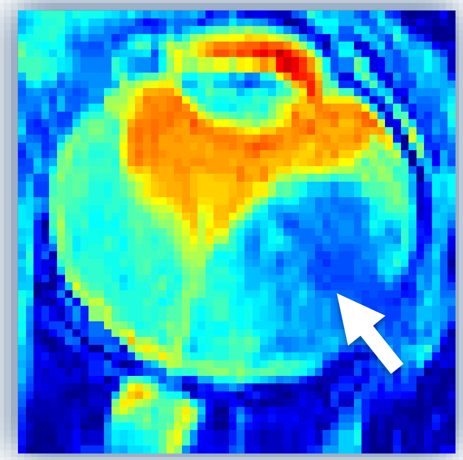
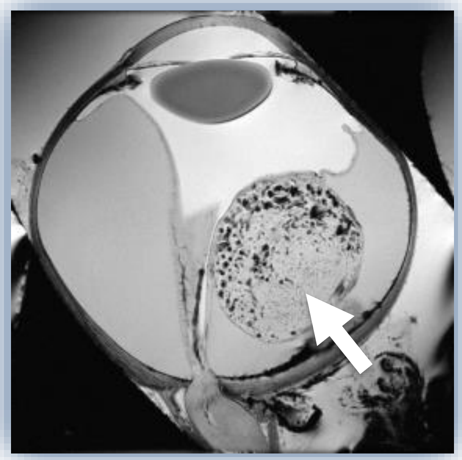




Linz P, et al., NMR in Biomed, 2015, 28(1):54-62

Varying contrasts

in vivo @ 3.0 T	**in vivo @ 3.0 T**	**ex vivo @ 9.4 T**
T_1-weighting	Diffusion	T_1-weighting
(FLASH)	(RARE)	(FLASH)

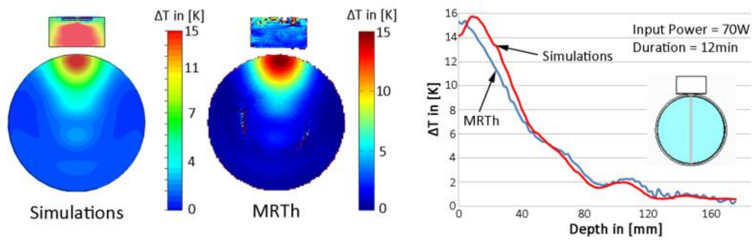
spatial resolution (0.5 x 0.5 x 0.2)mm^3	spatial resolution (0.5 x 0.5 x 5.0)mm^3	spatial resolution (0.05 x 0.05 x 0.25)mm^3

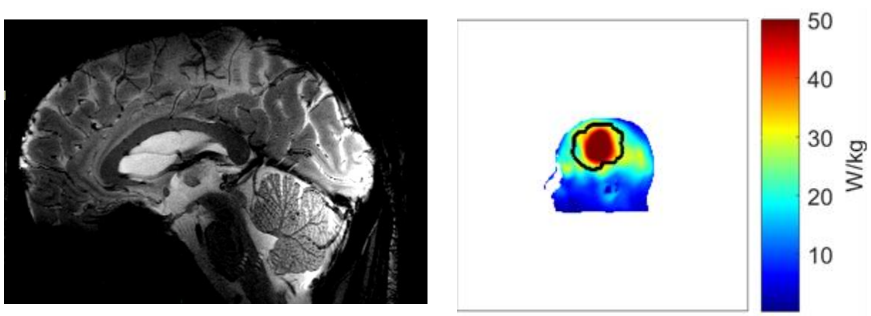
*courtesy Thoralf Niendorf

Paul K, et al., Invest Radiol, 2015, 50(5):309-321

Other MR applications

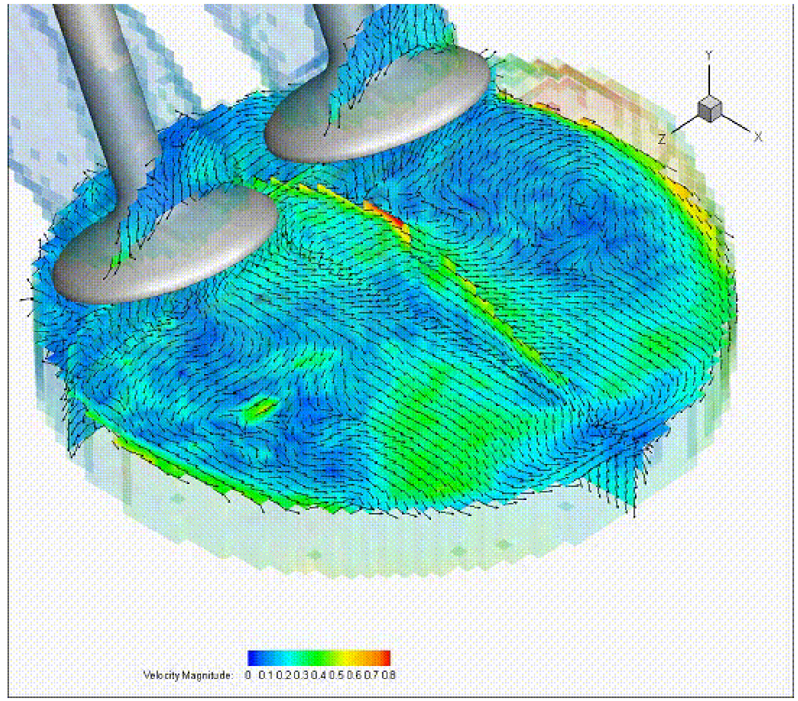
Thermal magnetic resonance





Winter L, et al, PLOS ONE, 2013, 8(4):e61661
Oberacker E, Winter L and Niendorf T, Physik Journal, 2018

Complex flow investigations



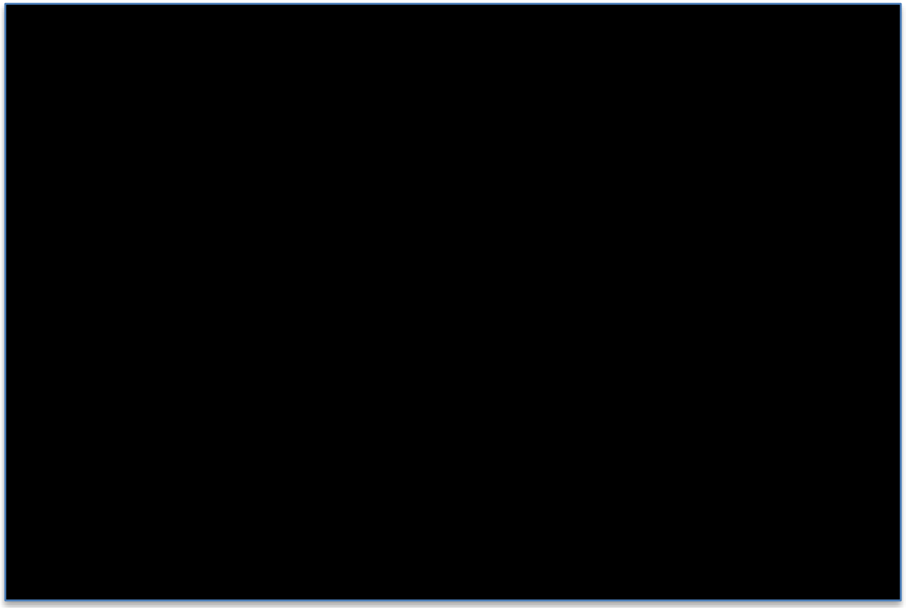
*Lehrstuhl Strömungsmechanik, Universität Rostock

Summary so far

MRI offers:

- Multitude of imaging contrasts (relaxation, susceptibility, diffusion, perfusion, temperature, flow, functional…)
- Non-invasive and safe (no ionizing radiation) whole body diagnostics
- High spatial (and application dependent high temporal) resolution imaging
- Multitude of clinical diagnostic and therapeutic applications (thermal magnetic resonance, targeted drug delivery, interventional applications etc.)
- Multitude of non-clinical applications (material science, biology, engineering, etc.)

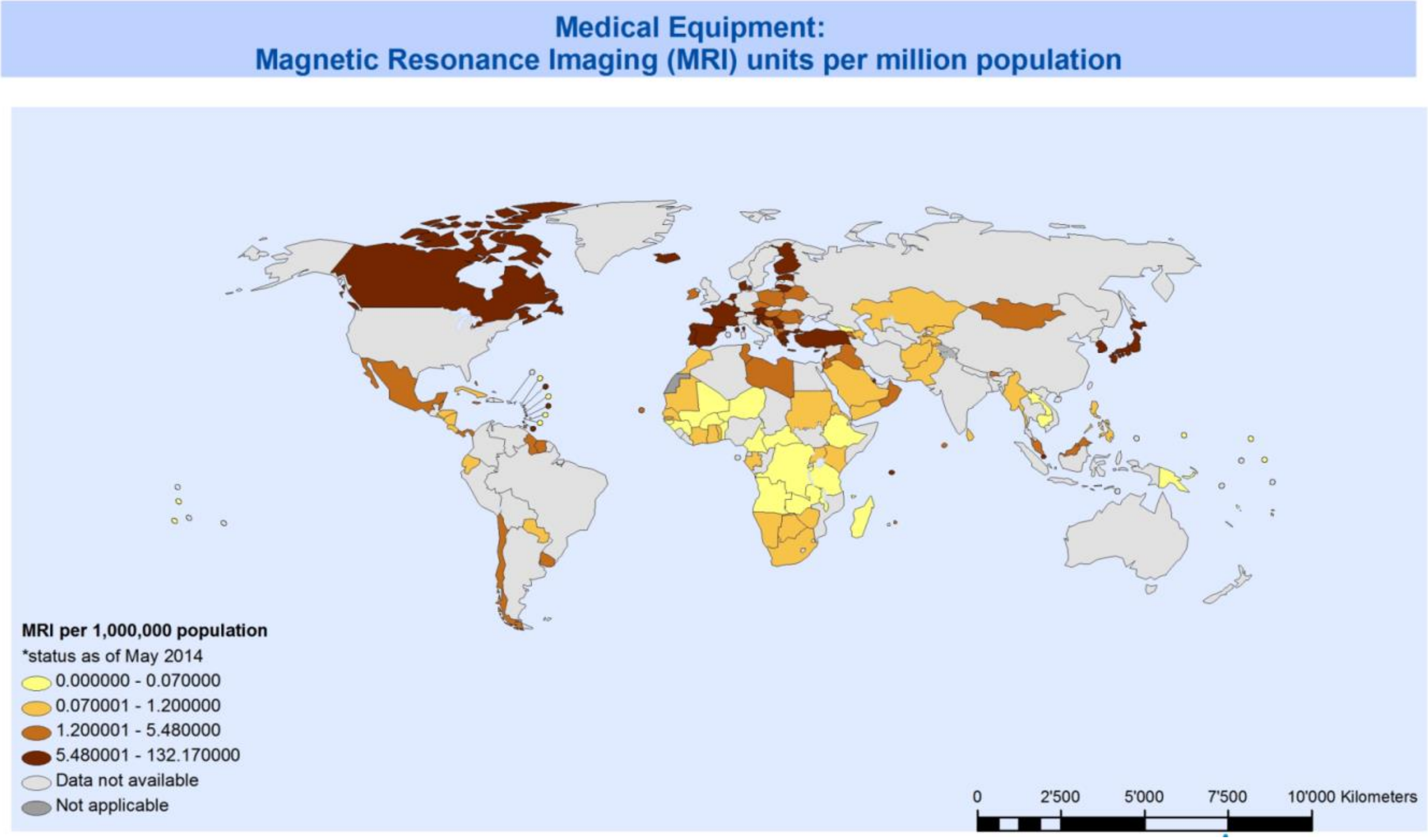
Sitting inside my (black) box



Looking outside the (black) box

Global perspective

Magnetic Resonance Imaging (MRI) is an essential medical diagnostic tool that is beyond the reach of many patients throughout the world[1]



[1] World Health Organization (WHO), (2013, 25. Feb.), *Essential Health Technologies: Medical Equipment – Data by Country*; Available: http://gamapserver.who.int/gho/interactive_charts/health_technologies/medical_equipment/atlas.html

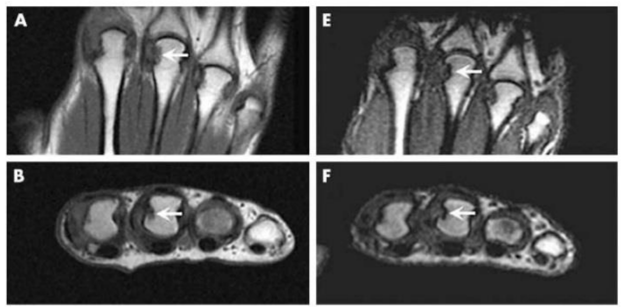
Towards affordable MRI

Open Source Hardware Development

MR Technology ($\sqrt{-1}$ + €)

- Clinical MR systems ($B_0 \geq 1.5T$)
  - Superconducting magnets
  - Liquid helium
  - Supervision system

- Low field (0.2T) systems
  - Permanent magnets
  - Good diagnostic accuracy[1-10]



[1] Breitenseher, M., et al., Radiologe, 1997. 37(10): p. 812-818 [2] Ejbjerg, B., et al., Ann rheumat dis, 2005. 64(9): p. 1280-1287 [3] Kersting-Sommerhoff, B., et al., Eur Radiol, 1996. 6(4): p. 561-565. [4] Kladny, B., et al., arch ortho trauma surg, 1995. 114(5): p. 281-286 [5] Merl, T., et al. Eur J Radiol, 1999. 30(1): p. 43-53 [6] Pääkkö, E., et al., Eur Radiol, 2005. 15(7): p. 1361-1368 [7] Parizel, P.M., et al., Eur J Radiol, 1995. 19(2): p. 132-138 [8] Savnik, A., et al., Eur Radiol, 2001. 11(6): p. 1030-1038 [9] Shellock, F.G., et al., J Magn Res Imaging, 2001. 14(6): p. 763-770 [10] Zangos, S., et al., Eur Radiol, 2005. 15(1): p. 174-182. [11] Wu Z, et al., PLOS ONE, 2016. 11(5):e0154711

Strategy

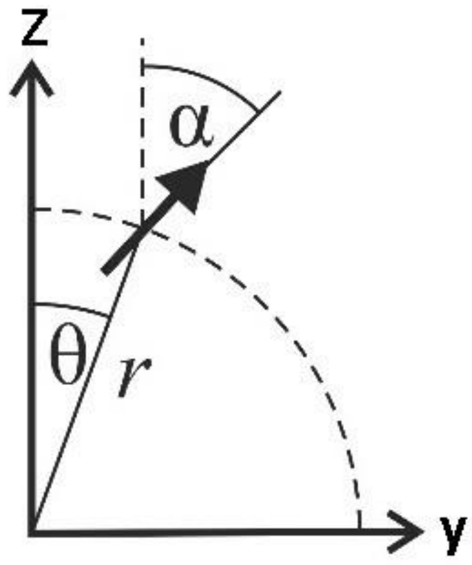
Affordable research toy:
Desktop MR

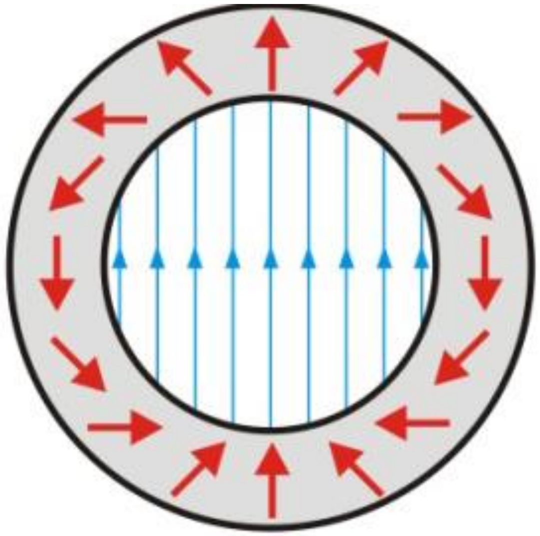
Clinical system (B_0~0.2T)
For dedicated appplications

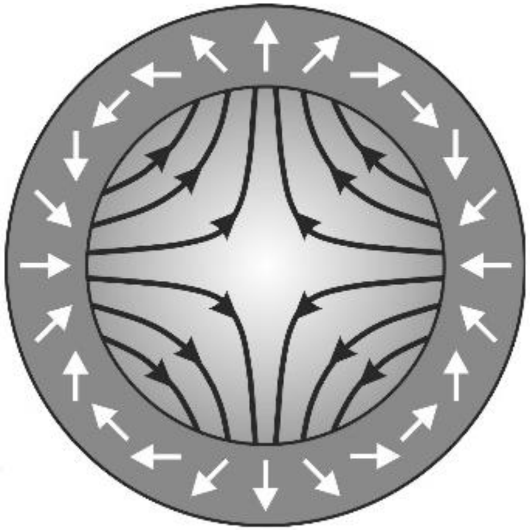
Whole body universal
workhorse

Focus on modularity, reproducibility and scalability

Halbach Multipoles







$$\alpha = (1 + \mathrm{N})\theta$$

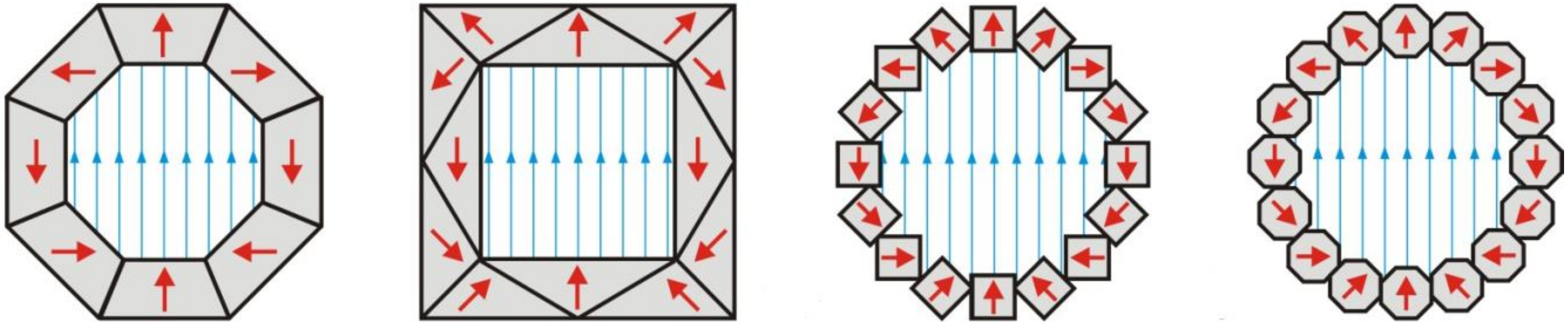
Dipole: $\mathrm{B}(\mathrm{z}_0) = \mathrm{Br} * \ln\left(\frac{r_1}{r_2}\right),\ for\ N = 1$

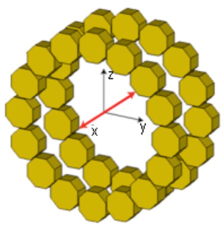
Multipole: $B(z_0) = Br * \left(\frac{z_0}{r_1}\right)^{N-1} \frac{N}{N-1}\left[1 - \left(\frac{r_1}{r_2}\right)^{N-1}\right], for\ N \geq 2$

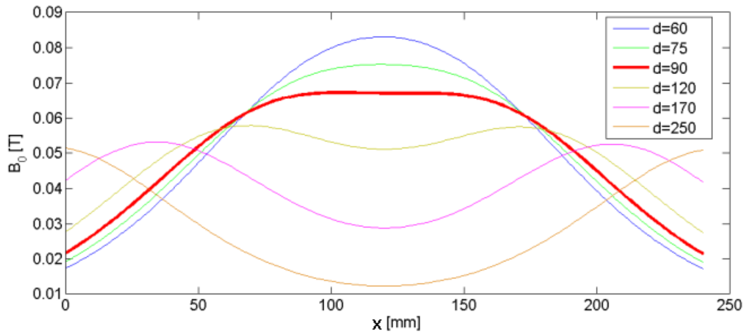
[9] Soltner, H. and Blümler, P., Conc Magn Res Part A, 2010, 36(4):211-222.

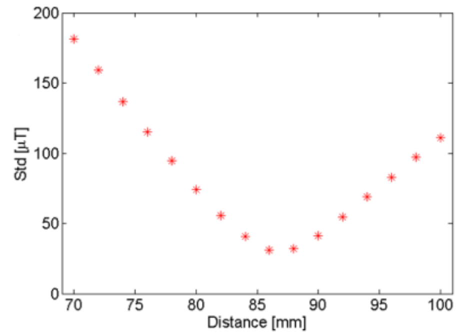
[10] Blümler, P. Conc Magn Reson Part B, 2016.

Homogeneous Halbach Magnets

- **Mandhala (M**agnet **A**rrangements for **N**ovel **D**iscrete **Ha**lbach **La**yout)
  - 





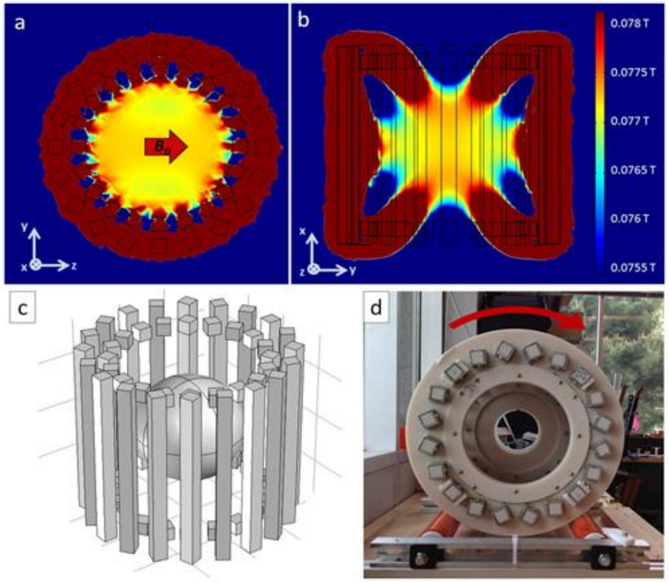


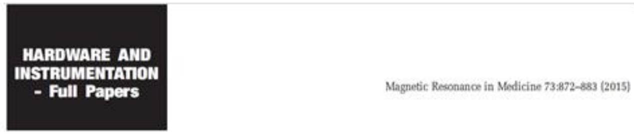
[9] Soltner, H. and Blümler, P., Conc Magn Res Part A, 2010, 36(4):211-222.

[10] Blümler, P. Conc Magn Reson Part B, 2016.

[11] Baarghorn, A, BSc Thesis, TU-Berlin, 2015

Spatial encoding without gradient coils



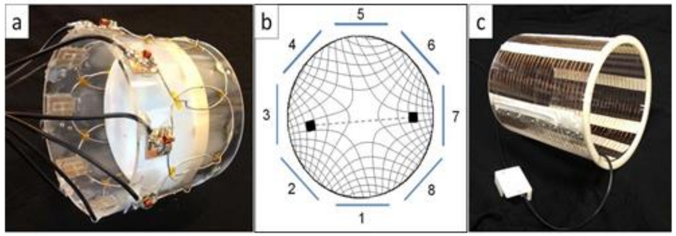


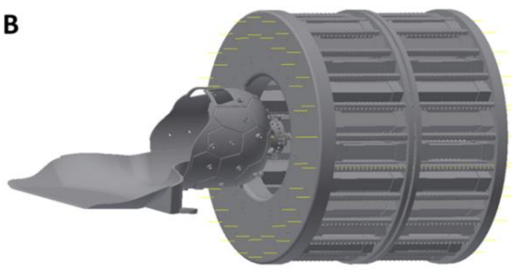
HARDWARE AND INSTRUMENTATION - Full Papers

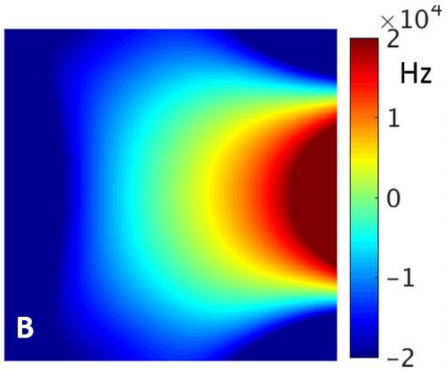
Magnetic Resonance in Medicine 73:872–883 (2015)

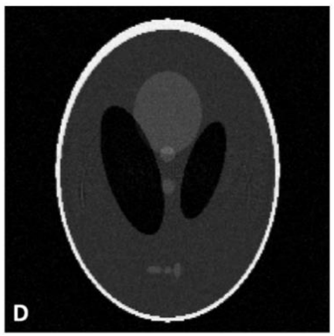
Two-Dimensional Imaging in a Lightweight Portable MRI Scanner without Gradient Coils

Clarissa Zimmerman Cooley,[1,2]* Jason P. Stockmann,[1,3] Brandon D. Armstrong,[1,3] Mathieu Sarracanie,[1,3] Michael H. Lev,[4,5] Matthew S. Rosen,[1,3,5] and Lawrence L. Wald[1,5,6]







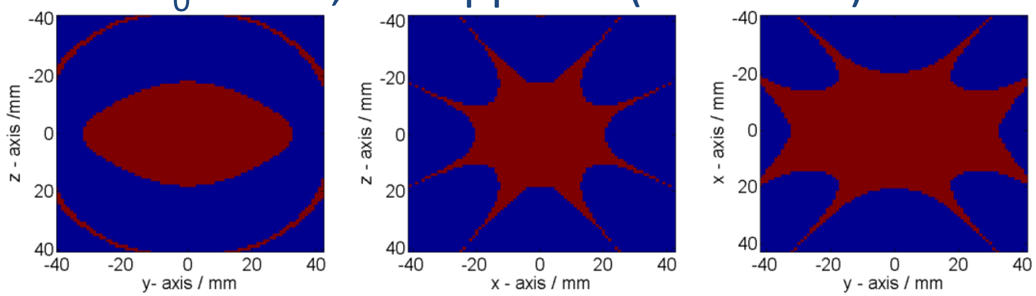


Cooley CZ, et al., Magn Reson Med, 2015, 73:p872-883

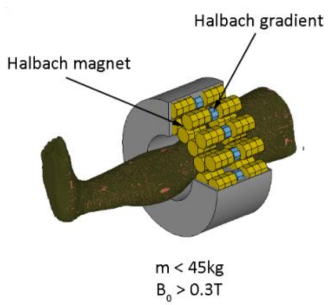
Magnet development

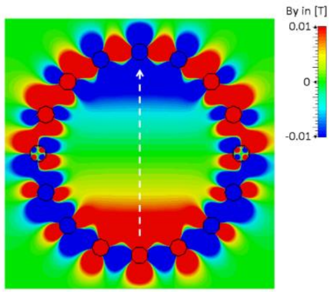
- Magnetostatic field simulations of Halbach magnets
- Homogeneous main magnet

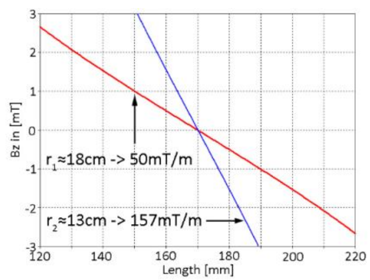
B_0=0.09T, 1000ppm -> (40x64x36)mm³

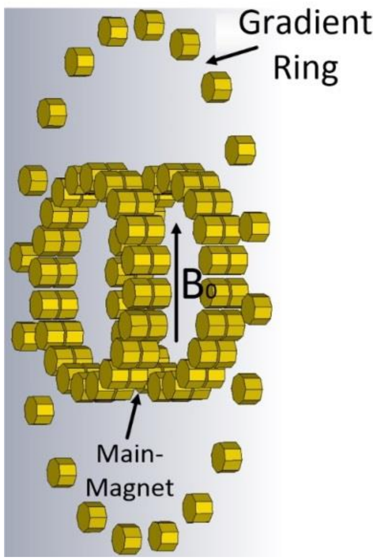


- Rotated linear Halbach gradient for spatial encoding[1-4]







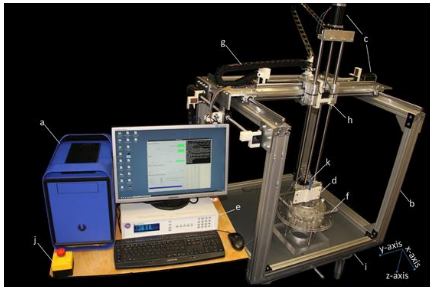


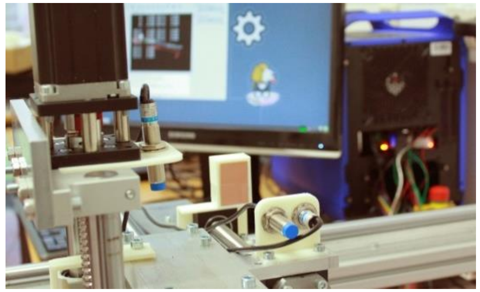
- Validation measurements: simulation vs. experiment

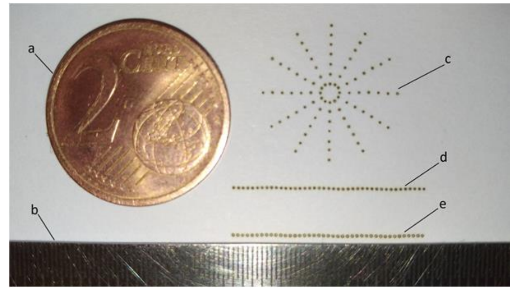
[1] Cooley CZ, et al., Magn Reson Med, 2015, 73:p872-883 [2] Cooley CZ, et al., ISMRM, 2016, #3556
[3] Winter L, et al., ISMRM, 2016, #3586 [4] Blümler P, Concepts Magn Reson Part B Magn Reson Eng, 2016

Open source lab equipment

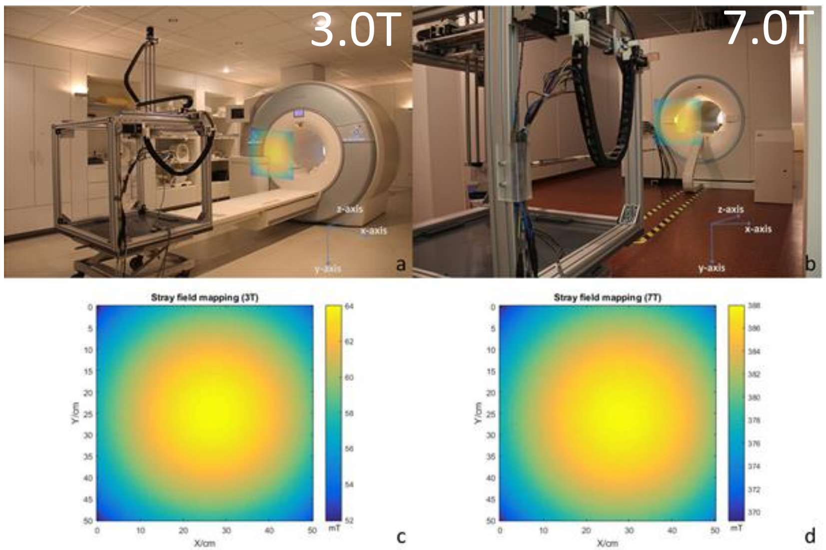
- 3D multipurpose measurement system with submillimeter precision





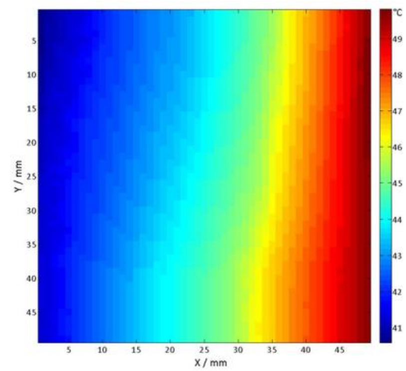


- Adjustable to various research applications

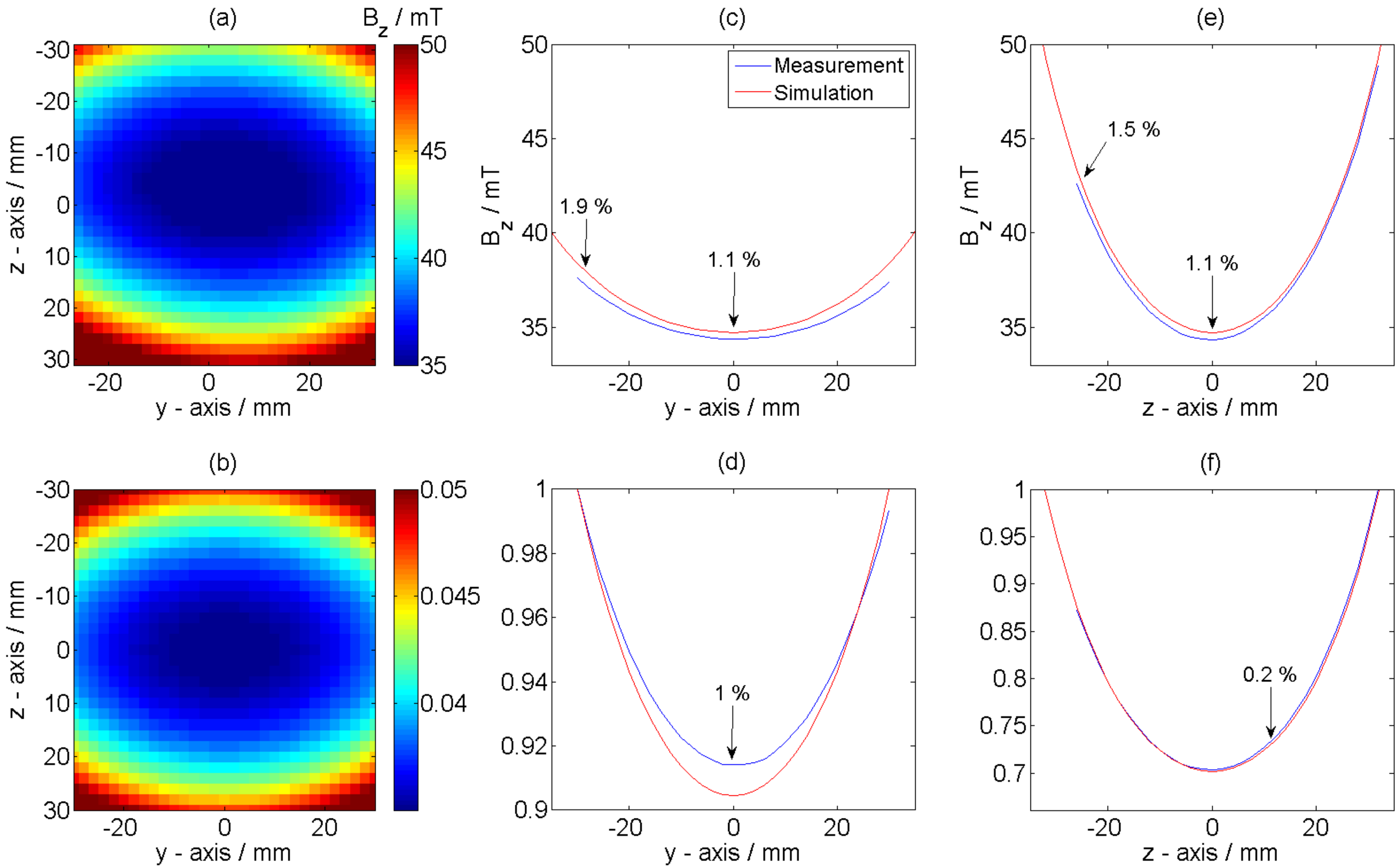


Han H, et al., Scientific Reports, 2017, 7:13452

2D fiber optic temperature mapping



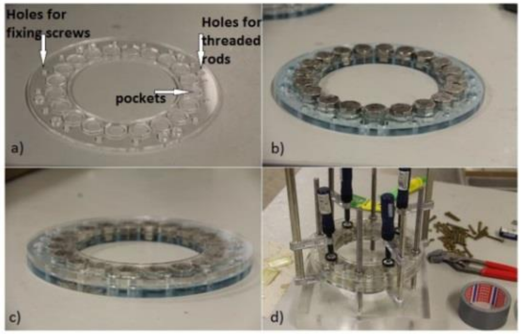
Single Halbach Ring validation

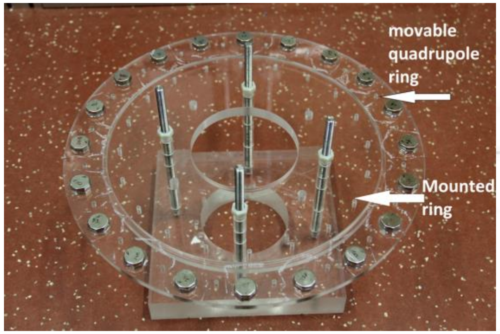


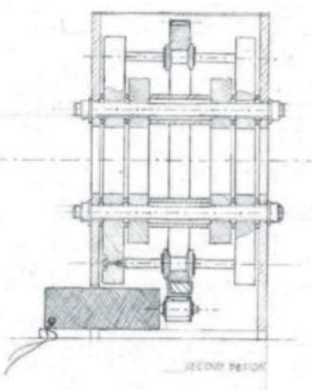
Moritz R, Master thesis, TU-Berlin, 2017

Magnet development process

- Magnet construction



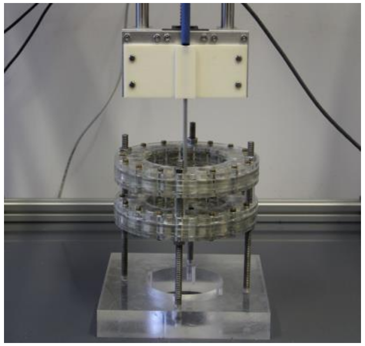


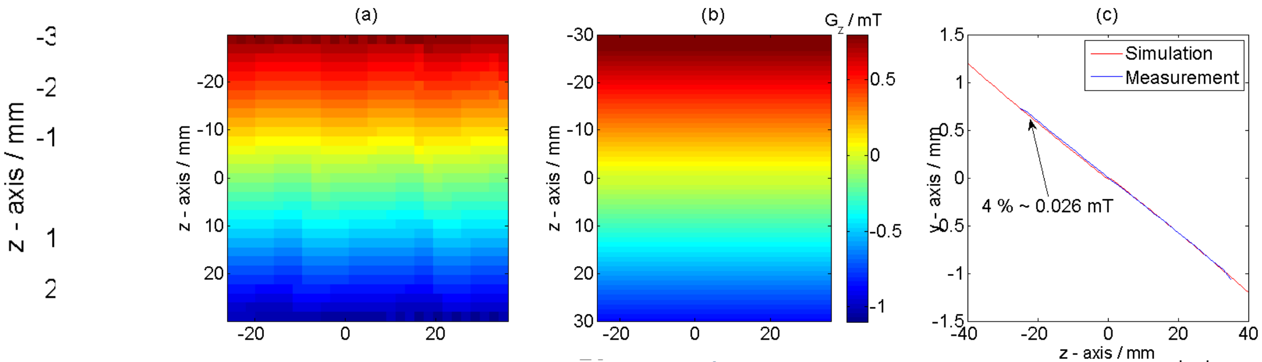


- 3D Validation measurements

Linear Halbach gradient

simulation



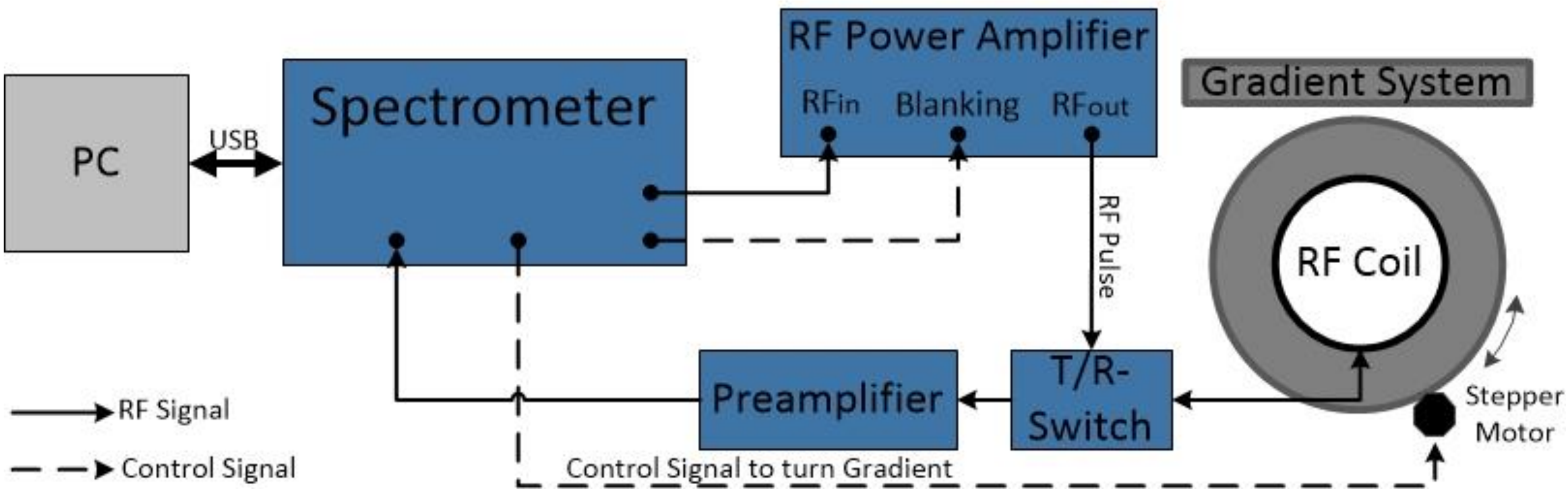


measurement simulation

Moritz R, Master thesis, TU-Berlin, 2017

Transmitter Architecture

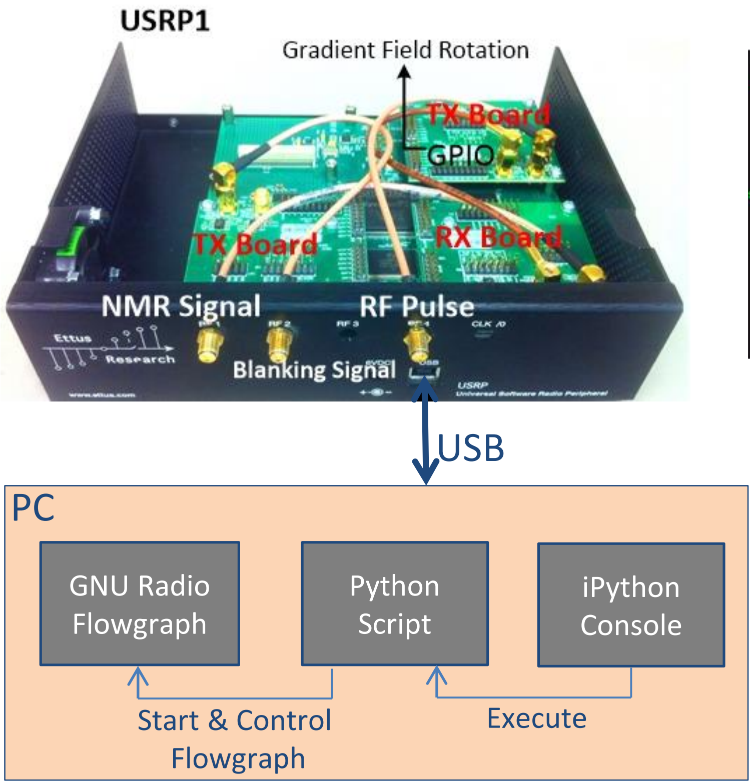
- Spectrometer (RF-pulse, signal reception, gradient rotation)
- RF power amplifier
- RF coil
- T/R switch
- Low noise preamplifier



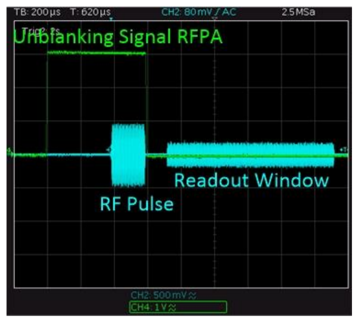
Blücher C, et al., Proc Int Soc Magn Reson Med, 2017, #1055

Spectrometer

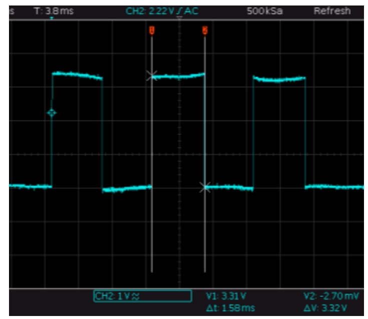
- Using GNUradio[1] compatible software defined radios (SDR) enables hardware independent pulse sequence developments in an OS-framework such as gr-MRI[2] or Pulseq[3]
- USRP1[4] together with gr-MRI[2] and extended the setup to drive rotating spatial encoding schemes



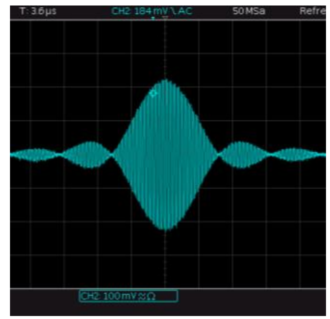
Blücher C, et al., Proc Int Soc Magn Reson Med, 2017, #1055



RF-pulse, unblanking and readout window



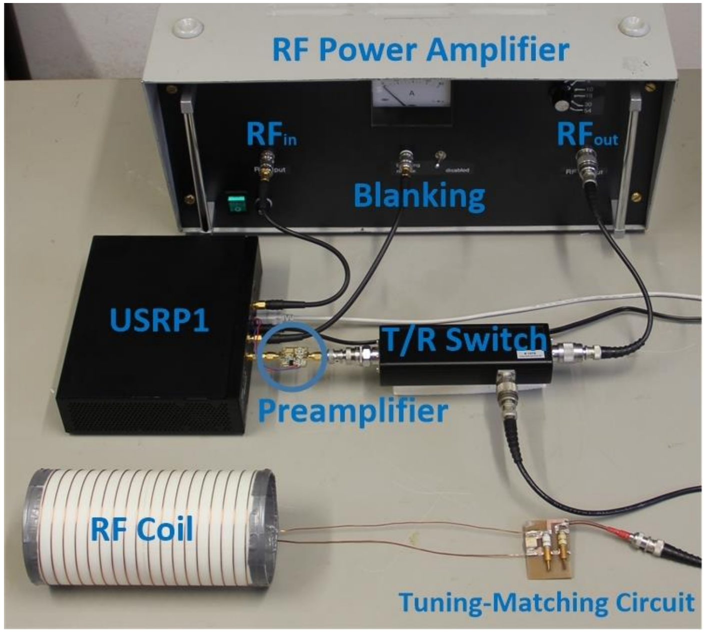
Stepper motor control signal



Sinc-pulse

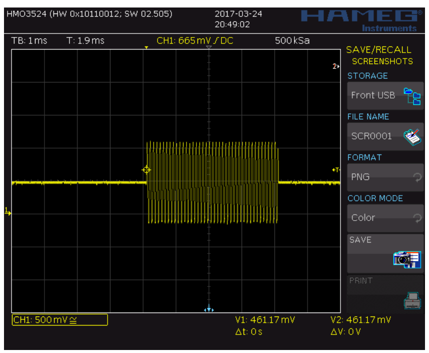
[1] GNU Radio, http://gnuradio.org [9] Hasselwander CJ, et al., J. Magn. Reson., 2016; 270:47:55 [3] Layton KJ, et al., MRM, 2016 [4] Ettus Research, USRP1

RF power amplifier

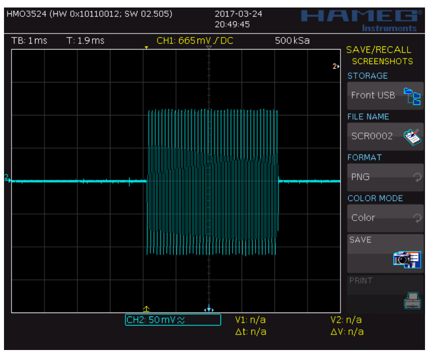


RF power amplifier (RFPA):

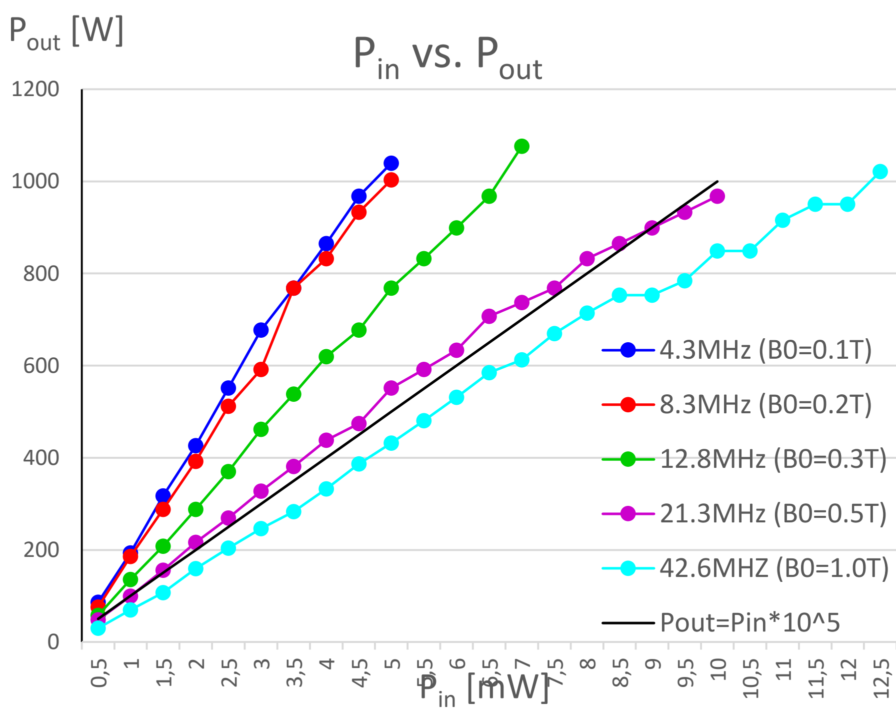
- Frequency range 1.8-54MHz (B_0=0.042-1.27T)
- P_{out}=1kW (peak)
- Blanking/unblanking circuit



SDR output



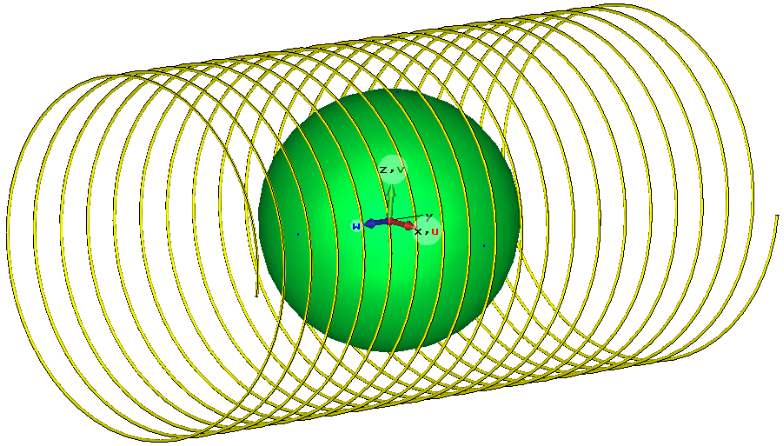
RFPA output



Blücher C, et al., Proc. ISMRM, 2017

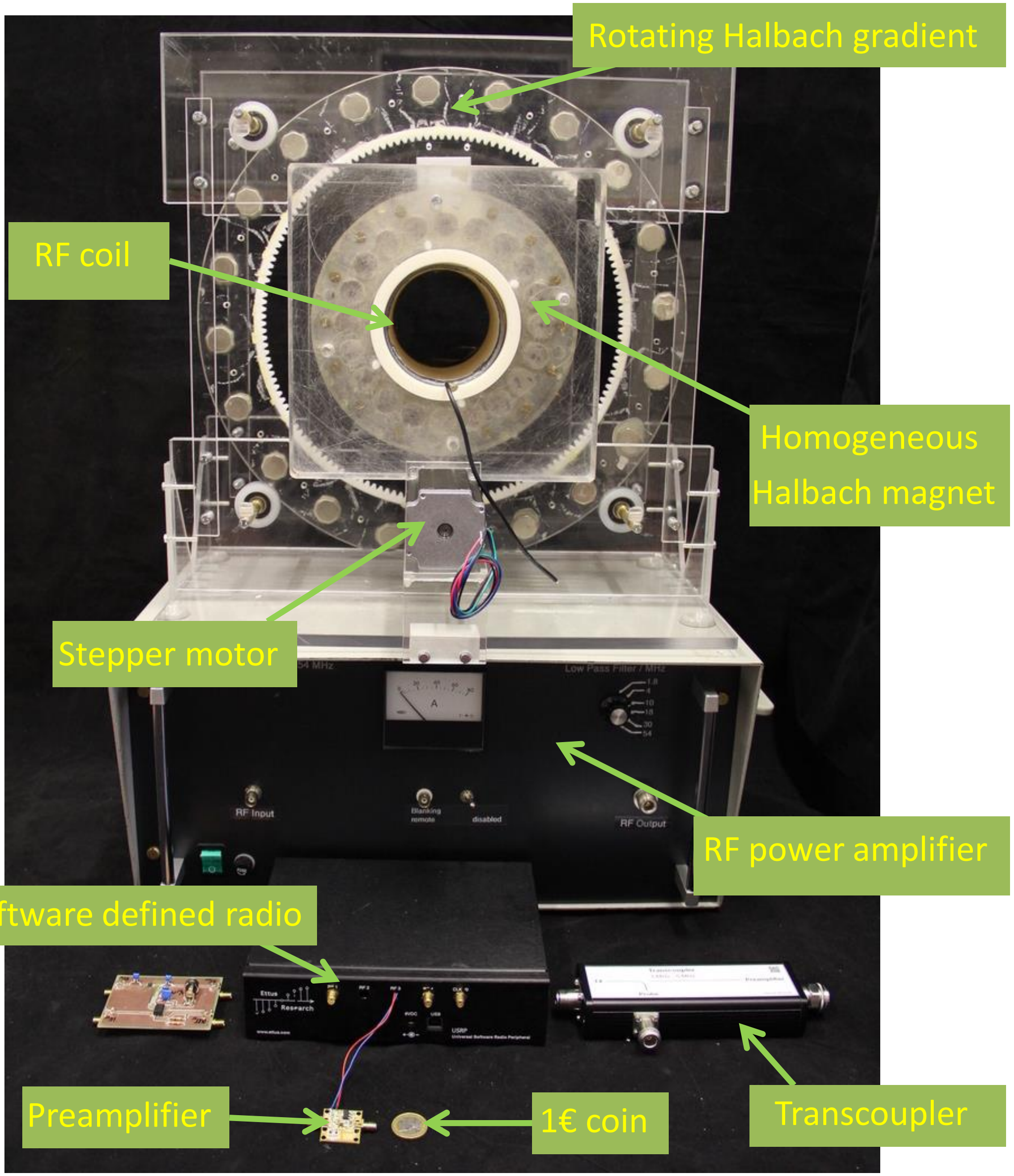
Radiofrequency (RF) Coil

- Electromagnetic simulations (CST MWS 2012)
- Solenoid RF coil to adapt to Halbach B0 field distribution
- Adaptation of RF coil length (l) and number of turns (N) in order to reach a homogeneous B_1^+ field distribution within a sphere (d=70mm)
- f=3.63MHz, d_{inner}=96mm based on prototype Halbach magnet
- AWG 20 copper wire as an electrical conductor
- Final design: l=200mm, N=20



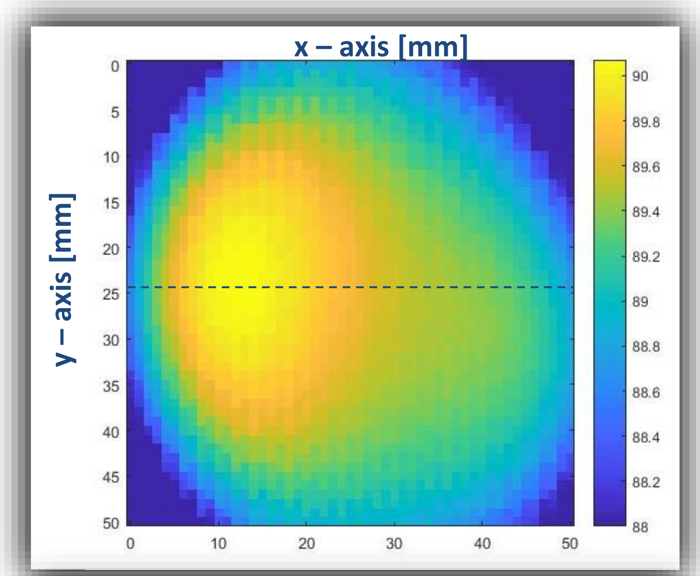
Blücher C, et al., Proc. ISMRM, 2017

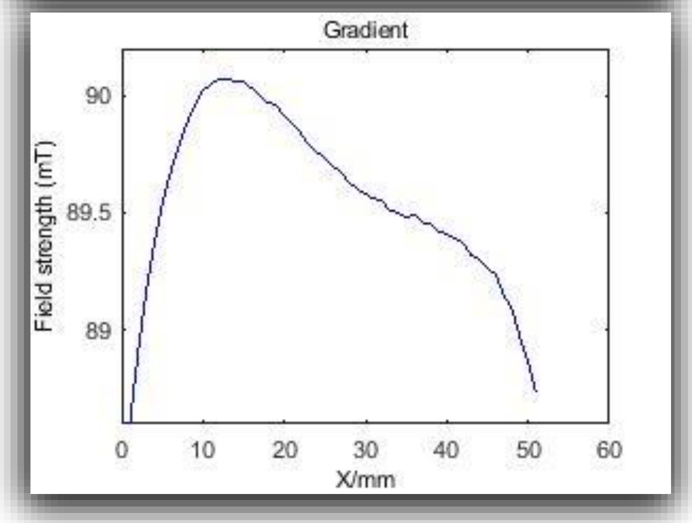
Current progress



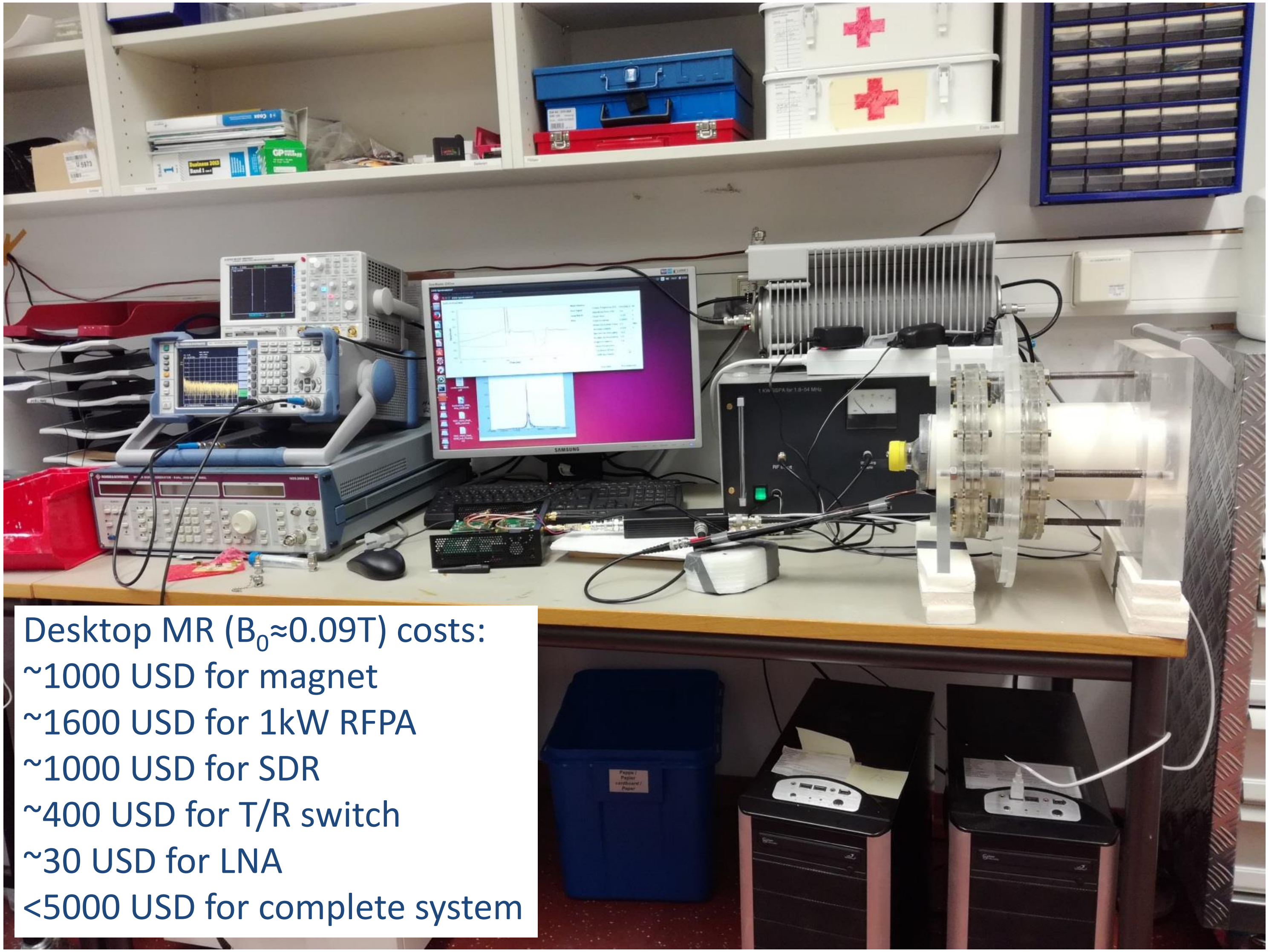
Eva Behrens, Bachelor thesis, TU-Berlin, 2018

Magnetic field at 0°





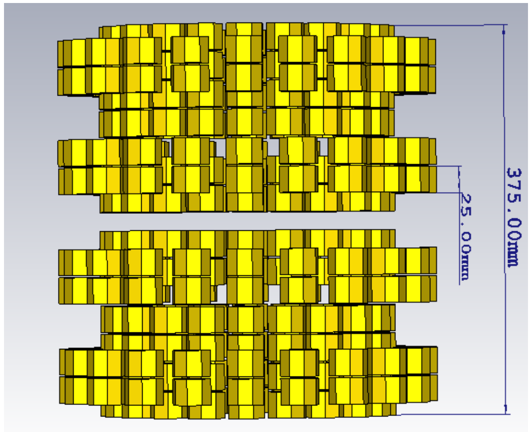
Towards an open source desktop MR



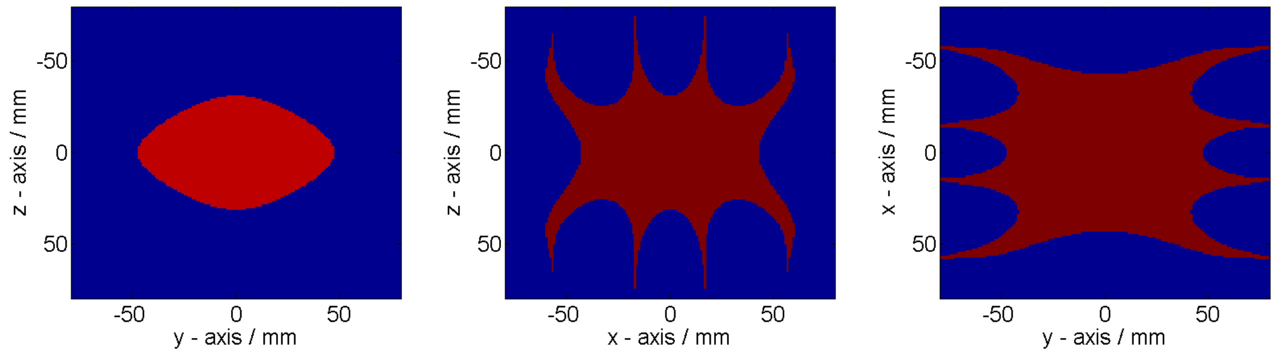
Desktop MR ($B_0 \approx 0.09$T) costs:
~1000 USD for magnet
~1600 USD for 1kW RFPA
~1000 USD for SDR
~400 USD for T/R switch
~30 USD for LNA
<5000 USD for complete system

Scalability: Magnetic field simulations

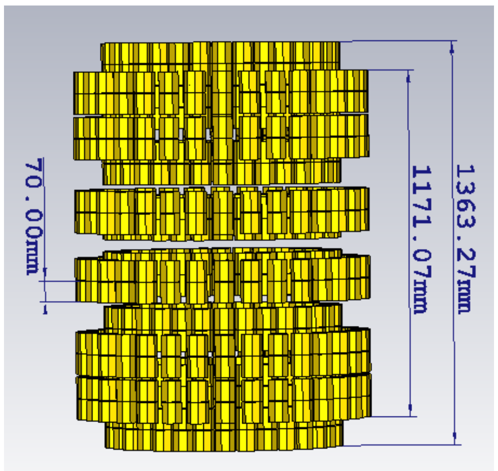
- Extremity MR Magnet:
  B_0=0.26T, bore=22cm, ~72kg, ~$2400



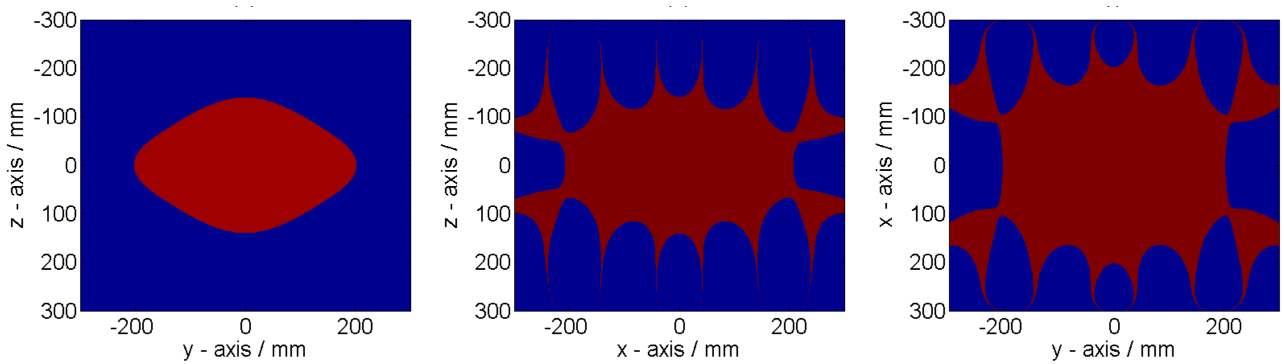
Field of view (1000ppm) = $(9x9x6)cm^3$



- Whole Body MR Magnet:
  B_0=0.2T, bore=67cm, ~1700kg, ~$50000



Field of view (1000ppm) = $(41x40x28)cm^3$

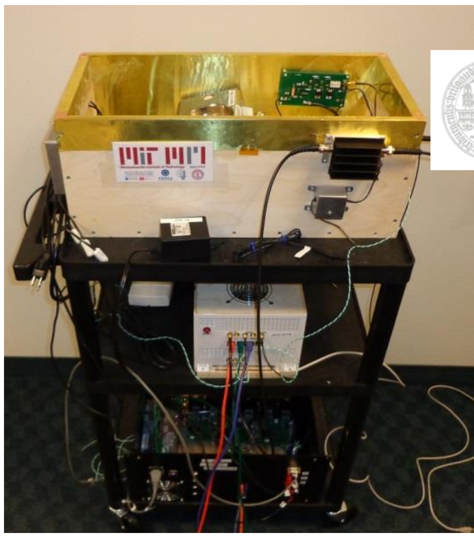


Moritz R, Master thesis, TU-Berlin, 2017

It is an international effort!

Current Driver for B0-shimming[1]

Tabletop MRI[2]



Towards an affordable OS MR for Uganda

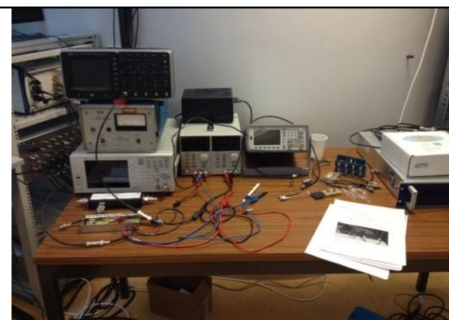
Open Mind 2016: Goedkope MRI voor het opsporen van waterhoofden

Met een uitgeklede, maar krachtige versie van de huidige MRI-apparaten moet het mogelijk zijn om ook in arme gebieden de diagnose waterhoofd te stellen. Een drietal onderzoekers ontving voor dat idee een Open Mind-beurs van 50.000 euro. Het team bestaat uit Martin van Gijzen (Technische Universiteit Delft), Rob Remis (Technische Universiteit Delft) en Andrew Webb (LUMC).

Van Gijzen: 'Een waterhoofd is redelijk gemakkelijk in beeld te krijgen. Het gaat om relatief grote hoeveelheden water, en juist dat kun je met MRI gemakkelijk zichtbaar maken. Het is bovendien een groot probleem in Afrika, vooral omdat daar vaker hersenvliesontstekingen voorkomen. Je wilt de diagnose zo vroeg mogelijk stellen, het liefst voor het hoofdje opzwelt. En als het toch zover is, wil je de vochtafvoer kunnen monitoren.'

Webb: 'Een normaal MRI-apparaat is echter duur en complex. Je hebt goed getraind personeel nodig om hem te bedienen, en als 'ie stuk gaat moet er een monteur komen. Hier is dat prima, maar het is niet handig als je machine in Oeganda staat.

Een doorsnee MRI bestaat uit een enorm krachtige magneet en een gewone pc om de data te verwerken. Wij willen proberen of het ook andersom kan: met een goedkope, zwakkere MRI-magneet en juist krachtiger rekenwerk. Computers zijn namelijk gemakkelijker in de omgang dan de superkoeler die een normale MRI magnetisch maakt. Daarnaast wordt rekencapaciteit steeds goedkoper. Het probleem is dat je met een zwakker magneetveld ook een zwakker signaal krijgt, en meer verstoringen. Vandaar dat we Martins wiskunde heel hard nodig hebben, om uit dat zwakkere signaal toch nog bruikbare gegevens te krijgen.'



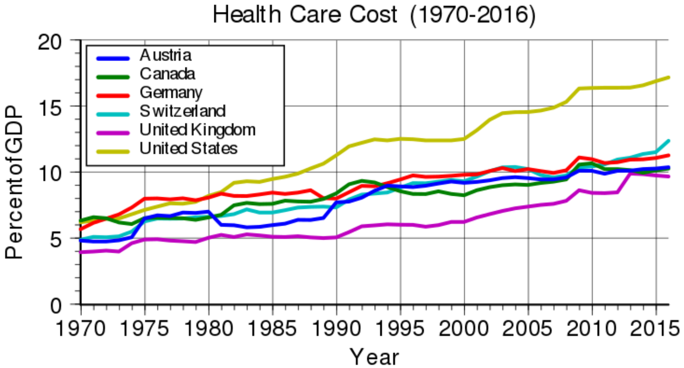
[1] Arango N, et al., ISMRM 2016, #1157 [2] https://tabletop.martinos.org

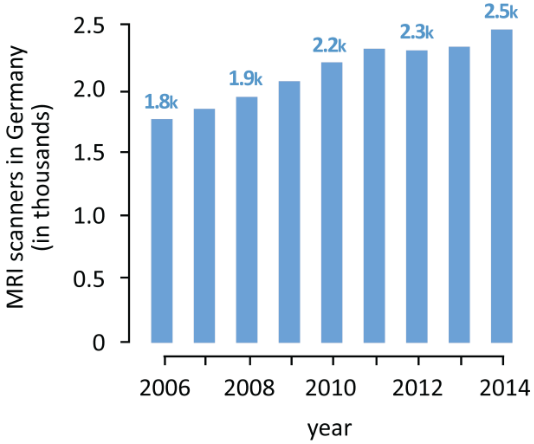
Looking outside the (black) box

Stepping outside the (black) box

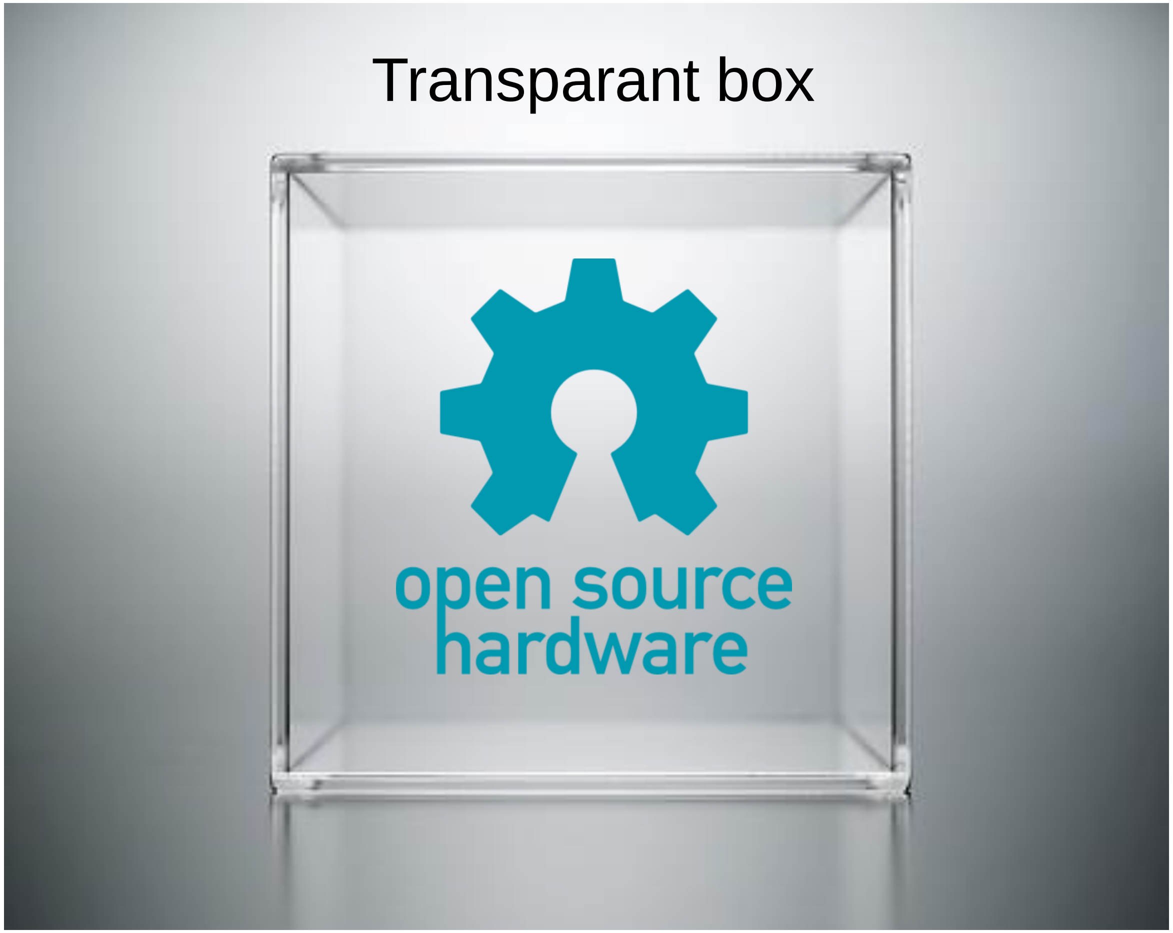
The challenge of healthcare

- Increasing Healthcare costs
- Monopolization in many healthcare sectors
- Globally healthcare is far from available, accessible, appropriate and affordable (4As)
- Do technological innovations lead to more affordable medical technology?





Biggest innovation of human kind



Magnetic Resonance Imaging: Costs

Total cost of ownership (TCO):

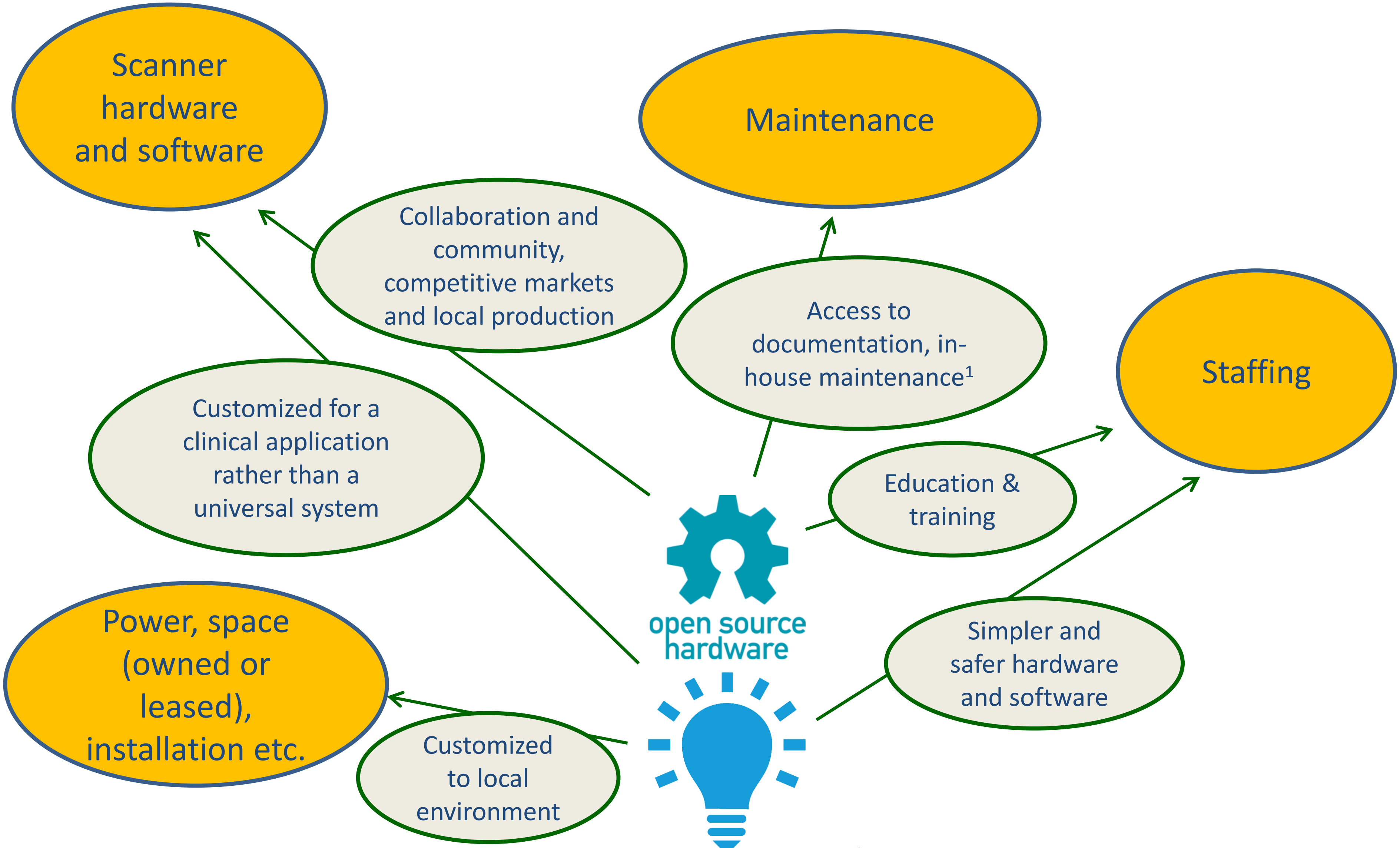
- scanner
- maintenance
- staffing
- power, space (owned or leased), installation etc.

Innovation

Open Source

open source hardware

Ingredients needed to reduce TCO



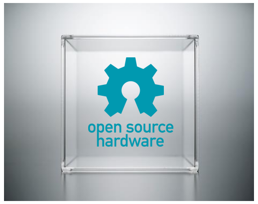
[1] Sferrella S, Equipment Service: Total Cost of Ownership, www.radiologybusiness.com, Dec 2012

Entanglement in the healthcare system…

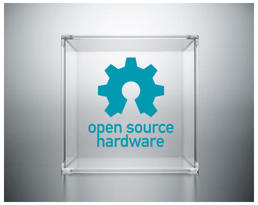
- The person odering the service does not receive the service
- The person receiving the service does not pay for the service
- Providers of the service do not determine what they are paid for the service
- The payers for the service determine the price but do not receive the service

Simple Solution: Transparent Box!

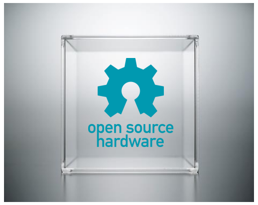
- How well can the medical doctor determine what technology is best for the patient or for the hospital?



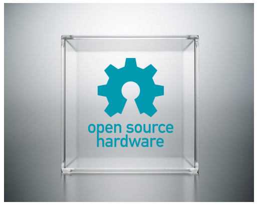
- How well can the patient determine efficiency and safety of the procedure using a given technology?



- How well can health insurances estimate the costs for medical procedures?



- How well can the knowledge from patients, doctors, scientists, hospital staff and management be used to improve products?



Open Source Imaging Initiative (OSI²)

[1] Winter L, et al., „The Open Source Imaging Initiative“, ISMRM, 2016

[2] Arndt F, et al., „The Open Source Imaging Initiative (OSI²) – Update and Roadmap“, ISMRM, 2017

It‘s a community effort: 52 authors*, 35 institutions

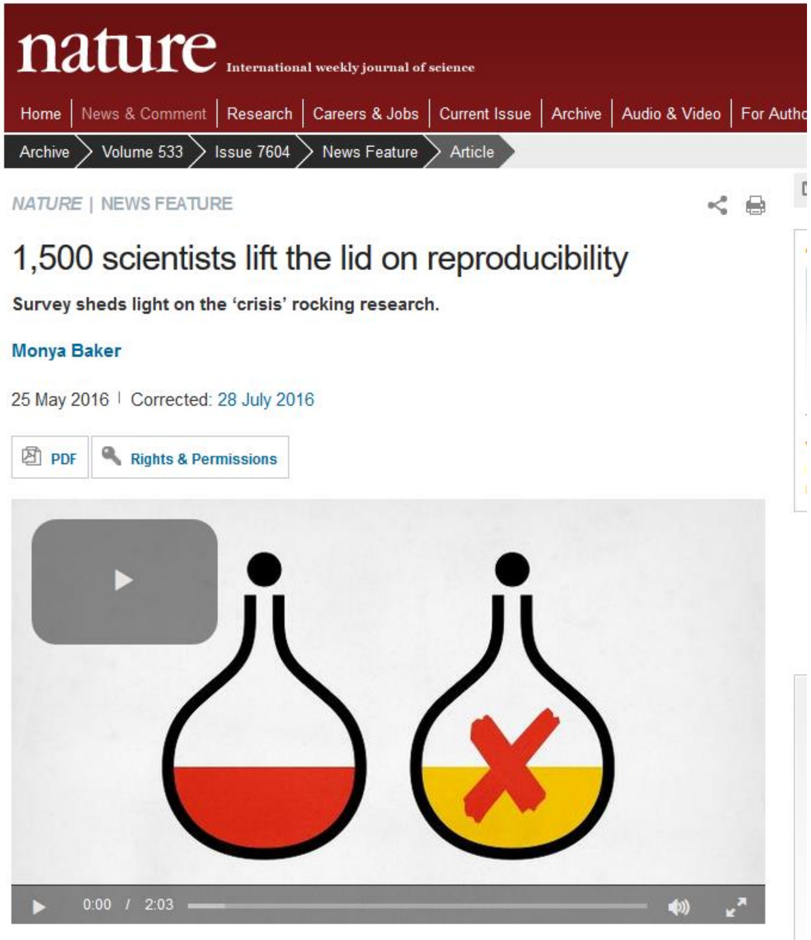
Felix Arndt[1], Sebastian Aussenhofer[2], Eva Behrens[3], Christian Blücher[3], Peter Blümler[4], Janko Brand[5], Kate Michi Ettinger[6], Ariane Fillmer[7], William Grissom[8], Bernhard Gruber[9,10], Bastien Guerin[11,12], Sergej Haas[13], Haopeng Han[3], Michael Hansen[14], Christopher Jordan Hasselwander[8], Russ Hodge[3], Werner Hoffmann[7], Bernd Ittermann[7], Marcin Jakubowski[15], Andre Kühne[16], Stefan Klein[17], Stefan Kroboth[18], Mark Ladd[19,20], Kelvin Layton[21], Brian Leiva, Sebastian Littin[18], Blanca López-Aranguren Blázquez, Kasper Marstal[17], Ralf Mekle[22], Manuel Moritz[23], Raphael Moritz[3], Thoralf Niendorf[3,16,24], Ruben Pellicer[25], Mihir Pendse[26], Athanasios Polimeridis[27], Tobias Redlich[23], Henning Reiman[3], Reiner Seemann[7], Frank Seifert[7], Ludger Starke[3], Jason Stockmann[28], Tony Stoecker[29], Kazuyuki Takeda[30], Lukas Thiele, Martin Uecker[31], Florian von Knobelsdorff-Brenkenhoff[32], Robert Wahlstedt[33], Andrew Webb[34], Simone Winkler[35], Lukas Winter[3], Huijun Yu[18], and Maxim Zaitsev[18]

[1]Facility for Antiproton and Ion Research in Europe GmbH, Darmstadt, Germany, [2]Noras MRI products GmbH, Höchberg, Germany, [3]Berlin Ultrahigh Field Facility (B.U.F.F.), Max Delbrück Center for Molecular Medicine in the Helmholtz Association, Berlin, Germany, [4]Institute of Physics, University of Mainz, Mainz, Germany, [5]One World Doctors, Berlin, Germany, [6]Mural Institute, San Francisco, CA, United States, [7]Physikalisch Technische Bundesanstalt (PTB), Berlin, Germany, [8]Biomedical Engineering, Vanderbilt University, Nashville, TN, United States, [9]Institute of Biomedical Mechatronics, Johannes Kepler University, Linz, Austria, [10]Department of Radiology, University Medical Center Utrecht, Utrecht, Netherlands, [11]Department of Radiology, Massachusetts General Hospital, Charlestown, MA, United States, [12]Harvard Medical School, Boston, MA, United States, [13]Haasdesign, Erkrath, Germany, [14]National Heart, Lung, and Blood Institute, National Institutes of Health, Bethesda, MD, United States, [15]Open Source Ecology, MO, United States, [16]MRI.TOOLS GmbH, Berlin, Germany, [17]Biomedical Imaging Group Rotterdam, Depts. of Medical Informatics & Radiology, Erasmus MC, Rotterdam, Netherlands, [18]Department of Radiology – Medical Physics, Medical Center - University of Freiburg, Freiburg, Germany, [19]Medical Physics in Radiology, German Cancer Research Center (DKFZ), Heidelberg, Germany, [20]Erwin L. Hahn Institute for Magnetic Resonance Imaging, University of Duisburg-Essen, Essen, Germany, [21]Institute for Telecommunications Research, University of South Australia, Mawson Lakes, Australia, [22]Center for Stroke Research Berlin (CSB), Charité Universitätsmedizin, Berlin, Germany, [23]Institute for Production Engineering, Helmut Schmidt University, Hamburg, Germany, [24]Experimental and Clinical Research Center (ECRC), a joint cooperation between the Charité Medical Faculty and the Max Delbrück Center for Molecular Medicine, Berlin, Germany, [25]Centre for Advanced Imaging, University of Queensland, Brisbane, Australia, [26]Stanford University, Stanford, CA, United States, [27]Skolkovo Institute of Science and Technology, Moscow Region, Russian Federation, [28]A. A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Charlestown, MA, United States, [29]German Center for Neurodegenerative Diseases (DZNE), Bonn, Germany, [30]Division of Chemistry, Graduate School of Science, Kyoto University, Kyoto, Japan, [31]Institute for Diagnostic and Interventional Radiology, University Medical Center Göttingen, Göttingen, Germany, [32]Cardiology at Agatharied Hospital, University of Munich, Hausham, Germany, [33]Regenerative Science Institute Spokane, Washington, WA, United States, [34]C.J. Gorter Center for High Field MRI, Dept of Radiology, Leiden University Medical Center, Leiden, Netherlands, [35]Lucas Center for Imaging, Dept of Radiology, Stanford University, Stanford, CA, United States

* Authors are listed in alphabetical order

[2]Arndt F, et al., ISMRM, 2017

Science needs reproducibility



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NATURE | NEWS FEATURE

1,500 scientists lift the lid on reproducibility

Survey sheds light on the 'crisis' rocking research.

Monya Baker

25 May 2016 | Corrected: 28 July 2016

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0:00 / 2:03

https://www.nature.com/news/1-500-scientists-lift-the-lid-on-reproducibility-1.19970

Open (source) science

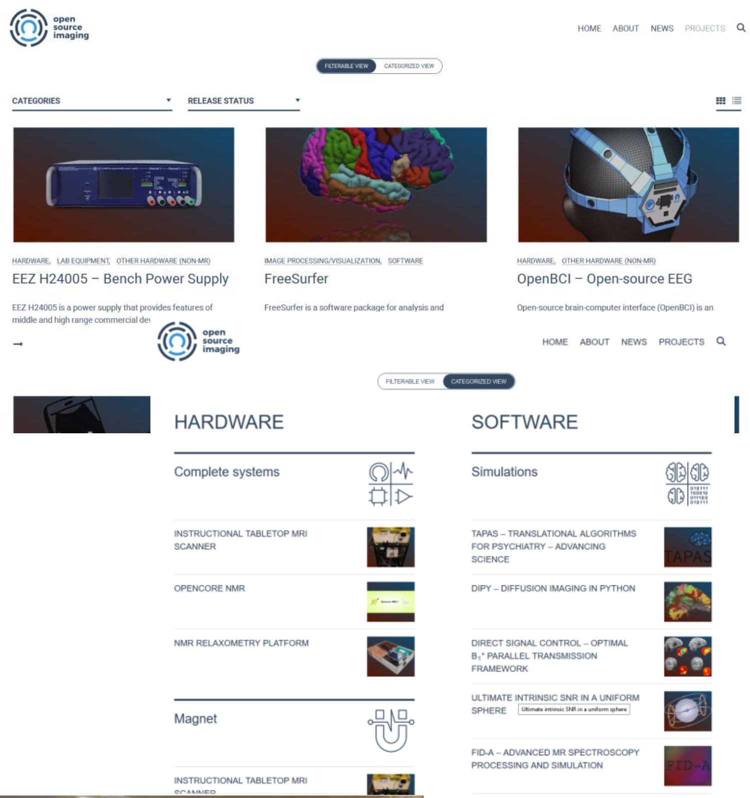
- OSI² kick-off at ISMRM 2016, Singapore[1]
- www.opensourceimaging.org launched May 2016

Platform for OS projects

- Currently around 50 projects online
- Ouick project overview: description, publications, links, contact person etc…
- More to come: stay tuned, stay open

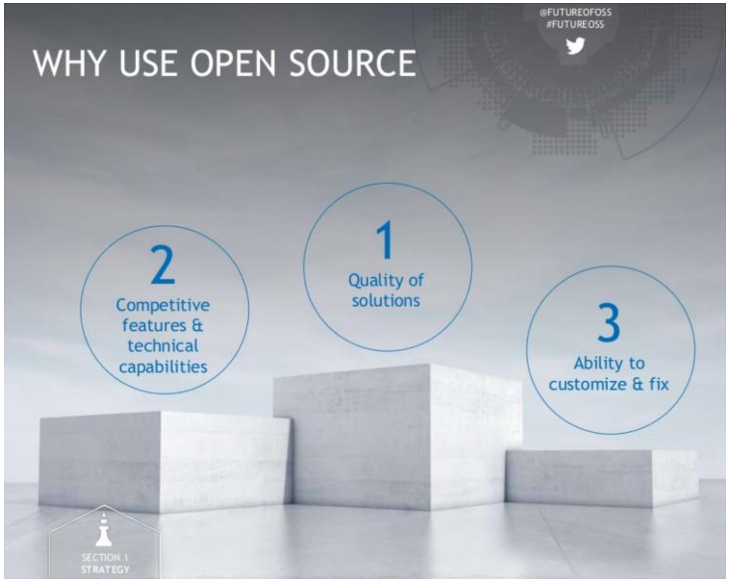
Community work

- ISMRM study group for reproducible research
- ISMRM working group on OS hardware
- Cross-domain collaborations



[1] Winter L, et al., „The Open Source Imaging Initiative“, ISMRM, 2016

Open (source) innovation



https://de.slideshare.net/blackducksoftware/2016-future-of-open-source-survey-results

Market impact

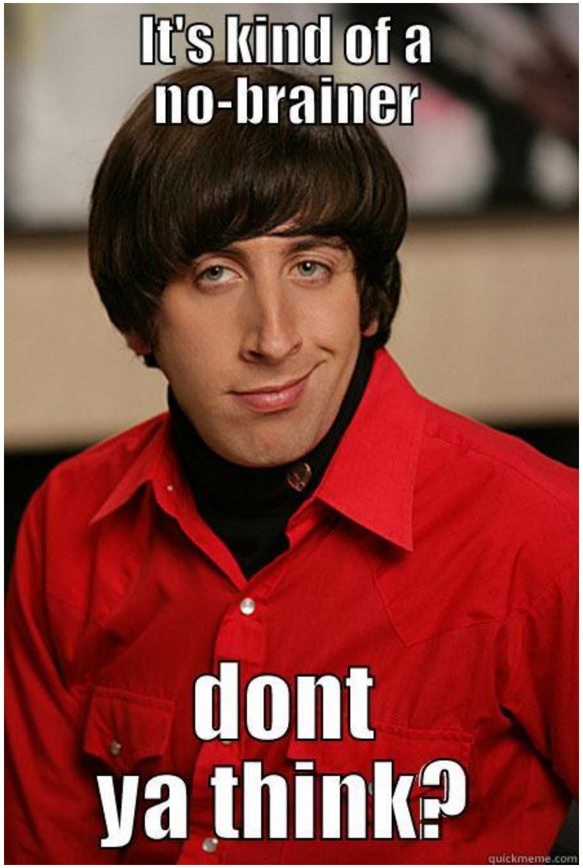
- Democratizing healthcare through competitive local/regional markets (role model: 3D printer market)

- OEM service vs. In-house service
  - Cost reduction through in-house maintenance and competitive third-party services[1]

- „Value" bonus

[1] Sferrella S, Equipment Service: Total Cost of Ownership, www.radiologybusiness.com, Dec 2012

Open and free education



Quality, Reliability and Safety

- Medical devices are regulated at a regional or nation-state level and are not globally harmonized
  - open source medTech may close gaps between countries, regions and between established and emerging markets
  - open source development has the potential to make high end medTech available worldwide
- Troubleshooting errors after a product has been marketed is difficult, particularly for closed and propietary software and hardware
  - open source has the potential to increaese safety and promote the development of sensor and internet of things (IoT) technologies to monitor quality, reliability and safety

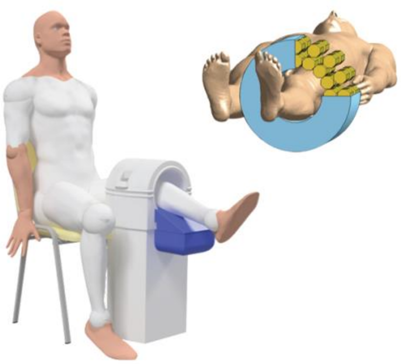
Ettinger KM, et al., J Med Eng Tech, 2016, 40(7-8):431-443

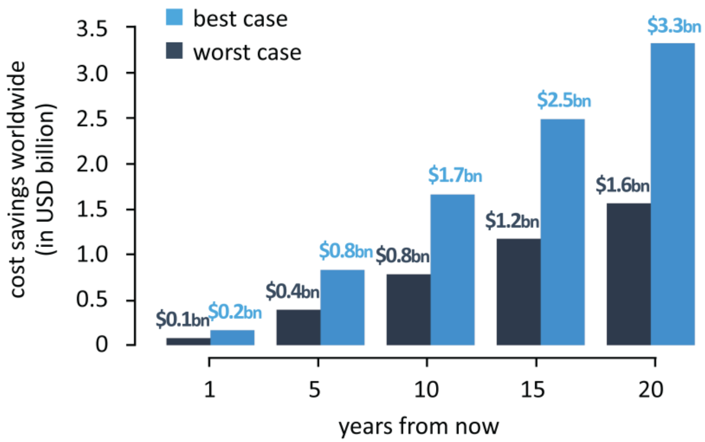
Open source medTech cost savings

- Estimated cost savings for the German healthcare system of an open source MRI based on our developments in relation to a commercially available MRI of similar performance[1-2]:

  $1.6bn - $3.3bn USD after 20years

COSI extremity MR

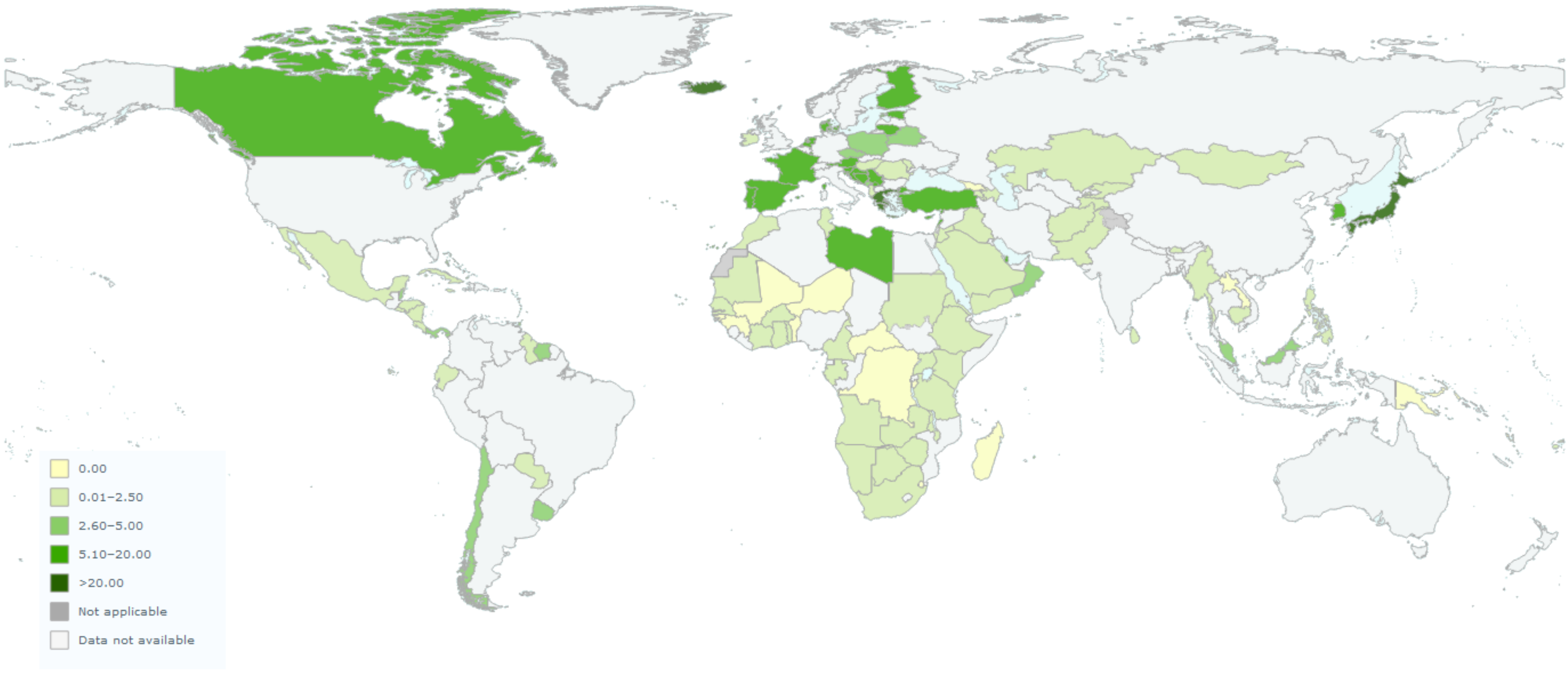




[1]Günyar S, Master Thesis, HWI Hamburg, 2017
[2]Winter L, et al., in „Management for Professionals“, Springer, 2018 [in press]

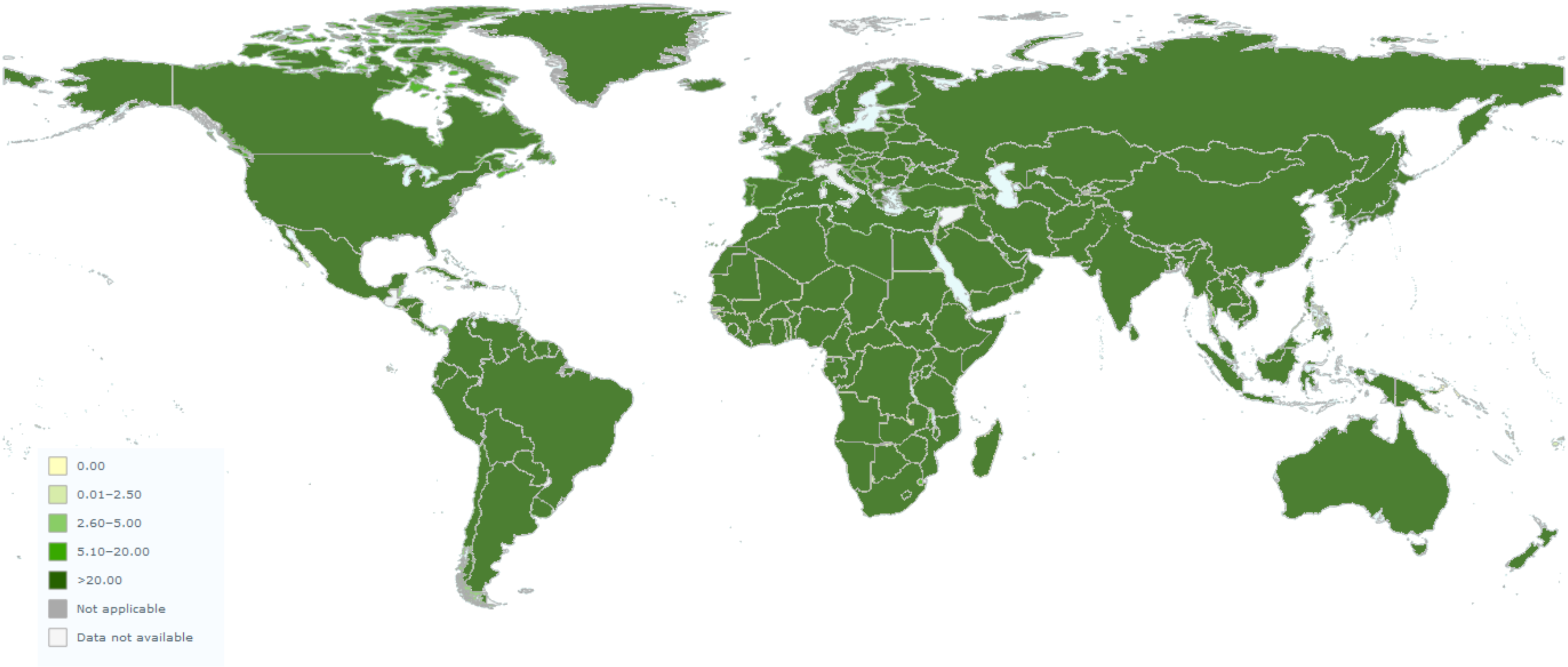
Reality

MRI devices per million population [1]



[1] World Health Organization (WHO). (2013, 25 Feb). *Essential Health Technologies: Medical Equipment – Data by Country*. Available: http://gamapserver.who.int/gho/interactive_charts/health_technologies/medical_equipment/atlas.html

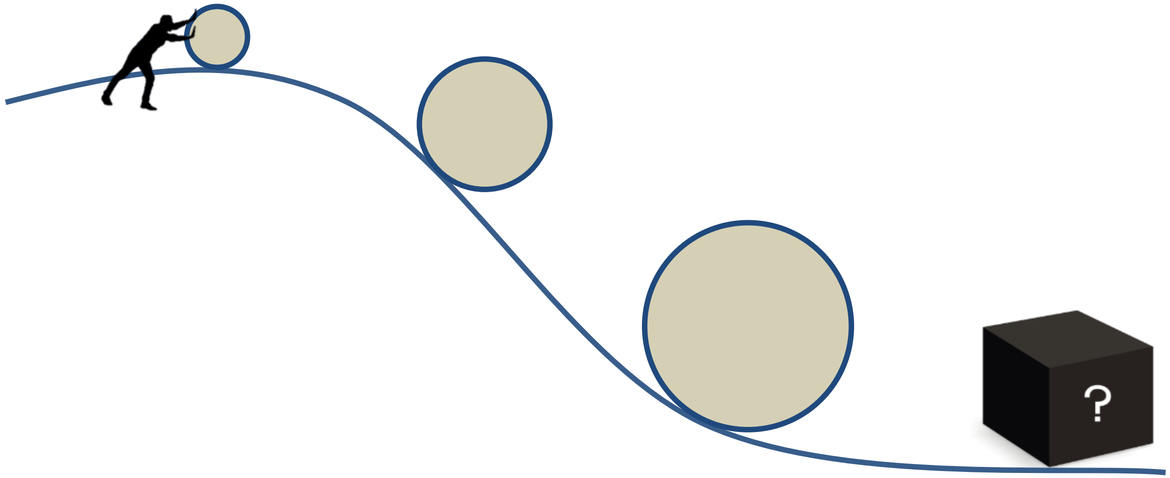
Vision


0.00
0.01–2.50
2.60–5.00
5.10–20.00
>20.00
Not applicable
Data not available

Conclusions

- MRI is a wonderful and safe diagnostic tool
- Open source research & development has the potential to impact global healthcare, education and science immensly
- Lets get rid of the black boxes
  - Publish/request code or hardware designs in publications
  - Failed commercial exploitation of a patent based project? No problem, open source it! If it‘s good it will be used.
  - More collaboration, less competition
    → more fun and more progress
    → let‘s build the Wikipedia of things together
- Desperately needed: More early stage funding opportunities for open source medTech projects

Thank You!



Physikalisch-Technische Bundesanstalt (PTB)
Abbestr. 2-12
10587 Berlin

Dr. Lukas Winter
Telefon: +49 30 3481 7573
E-Mail: lukas.winter@ptb.de

www.ptb.de
www.opensourceimaging.org