Molecular diffusion in micro-MRI: friend or foe?

Markus Weiger

Bruker BioSpin AG, Faellanden, Switzerland

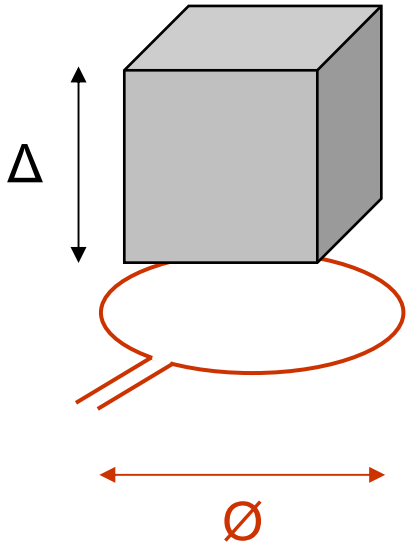
Bruker BioSpin MRI GmbH, Ettlingen, Germany

Introduction

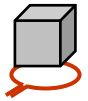
- Conventional MRI (inductive detection, gradient encoding)
- Target: cell layers
- Spatial resolution: 10 – 1 µm, 3D isotropic
- Limitations
  - SNR
  - Diffusion (cell fluids)

- Approaches to diffusion effects
  - Foe: Minimise
  - Friend: Utilise

Signal-to-Noise



×1/10



$$SNR \propto \frac{1}{\Delta^3}$$ 1/10³

×1/10

$$SNR \propto \frac{1}{Ø}$$ 10

B_0 ×3

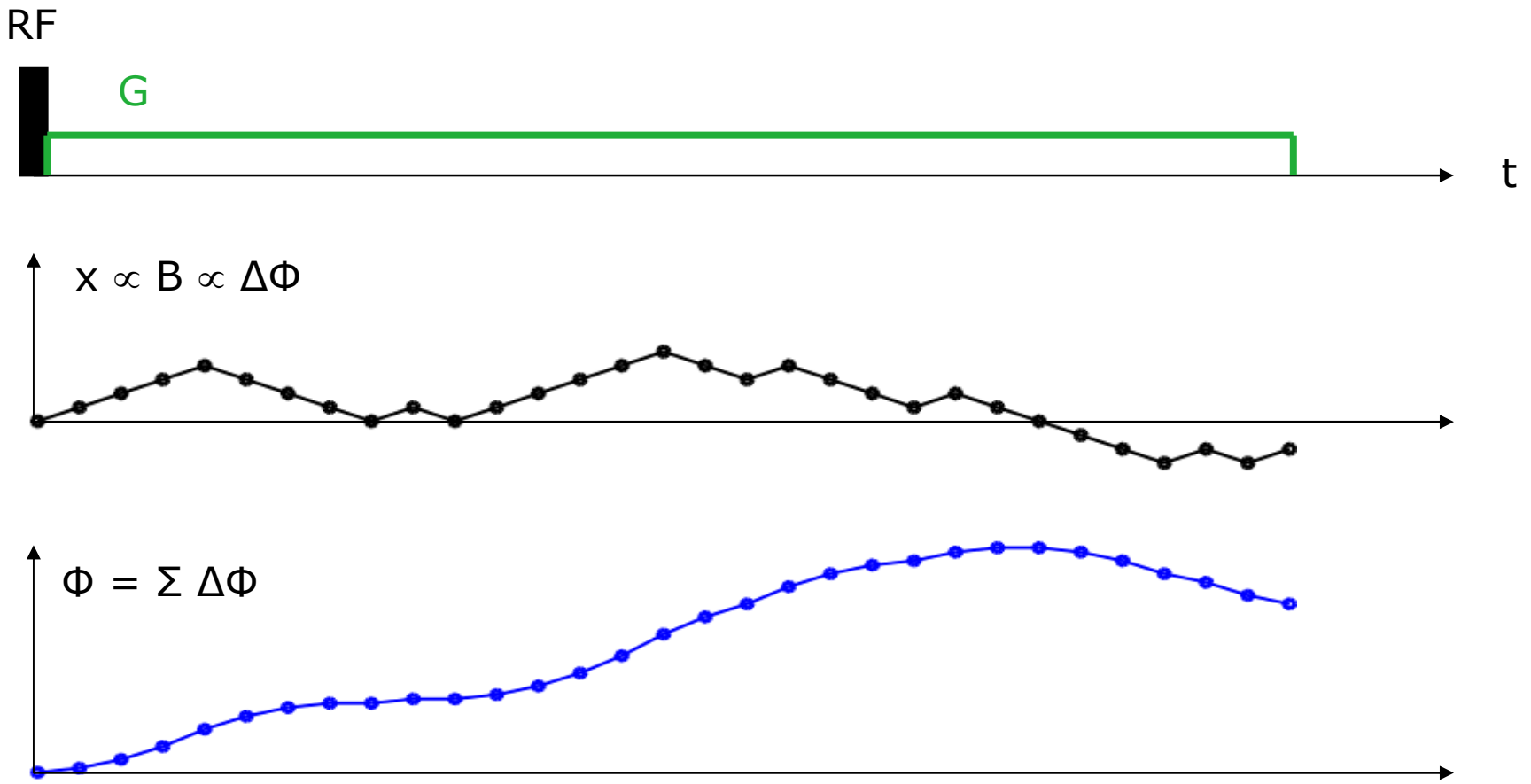
$$SNR \propto B_0^{7/4}$$ 6.8

T ×214

$$SNR \propto \sqrt{T}$$ 14.6

Molecular Diffusion

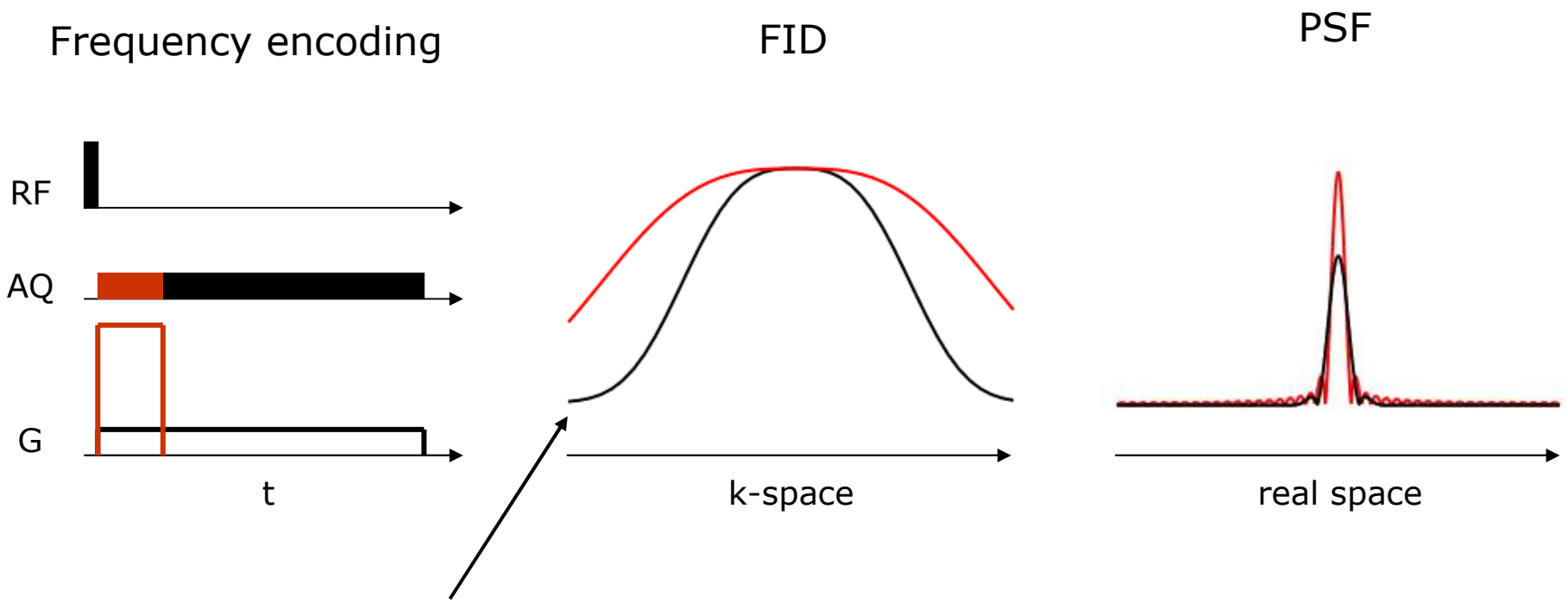
$$\Delta = O\left(\sqrt{Dt}\right)$$



Ensemble average:

$$S \propto \exp\left(-\frac{1}{3} D\gamma^2 G^2 t^3\right)$$

Foe: Diffusion affects resolution and SNR



$$S \propto \exp\left(-\frac{\pi^3}{3\gamma}\frac{D}{G\Delta^3}\right)$$

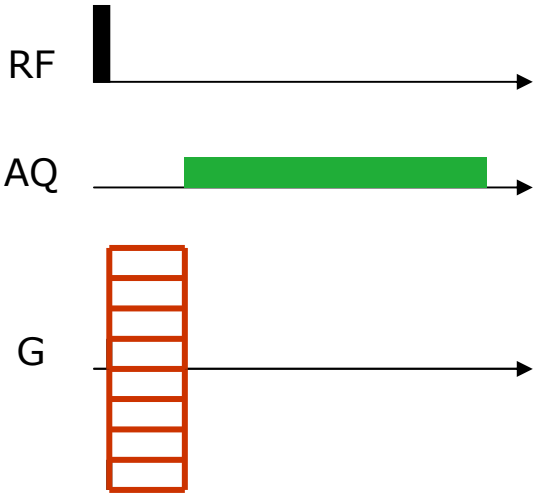
$$SNR \propto \sqrt{AQ} \propto \frac{1}{\sqrt{G}}$$

→ resolution versus SNR loss

Constant Time Imaging (CTI)

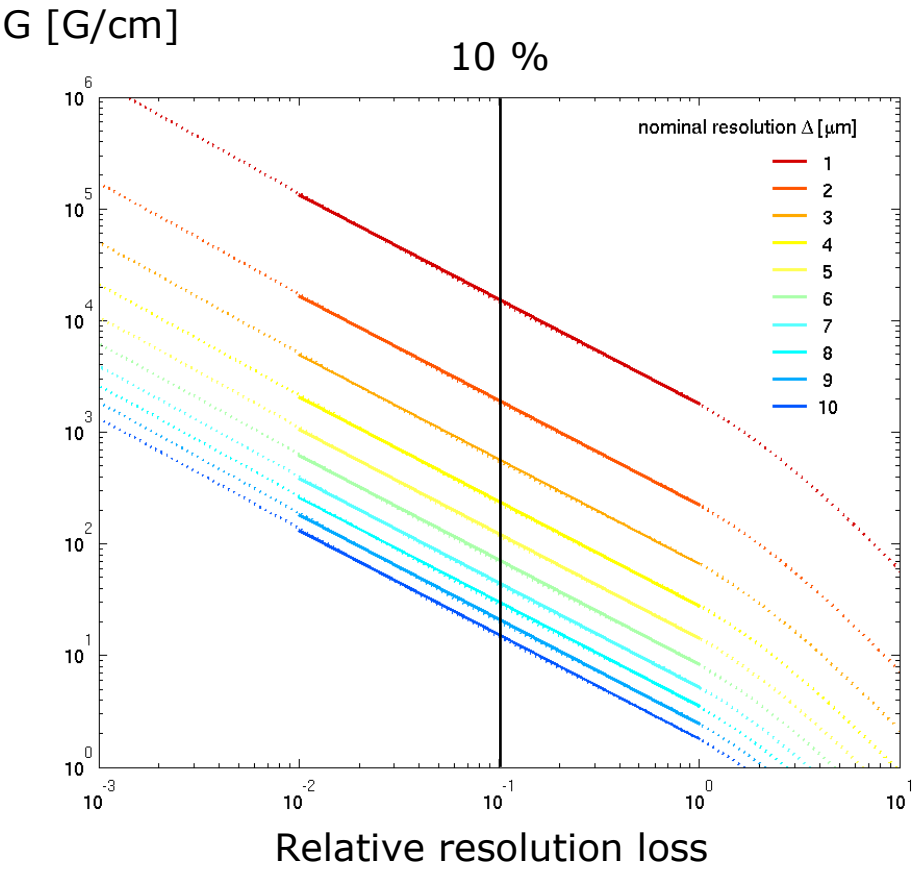
S. Choi, X. W. Tang, D. G. Cory,
Int J Imaging Syst Technol 8, 263 (1997)

Phase encoding



According to T_2^*

All 3 dimensions

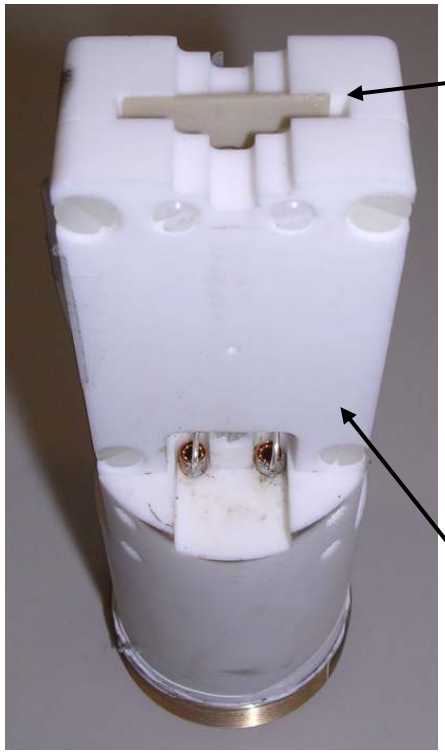


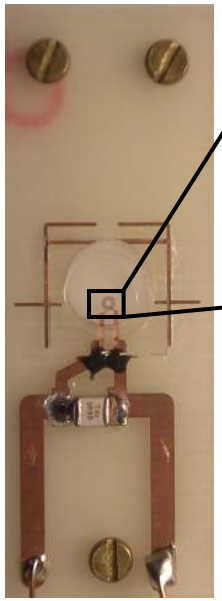
CTI with large G:

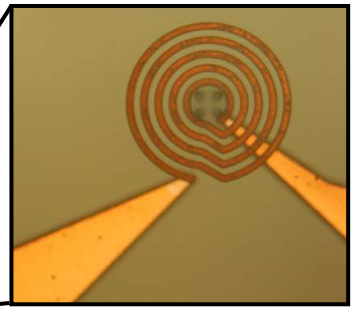
- No resolution loss
- No SNR loss
- Robust against B0 off-resonance

Dedicated Planar Probe Design

B_0 = 7.0 / 18.8 T



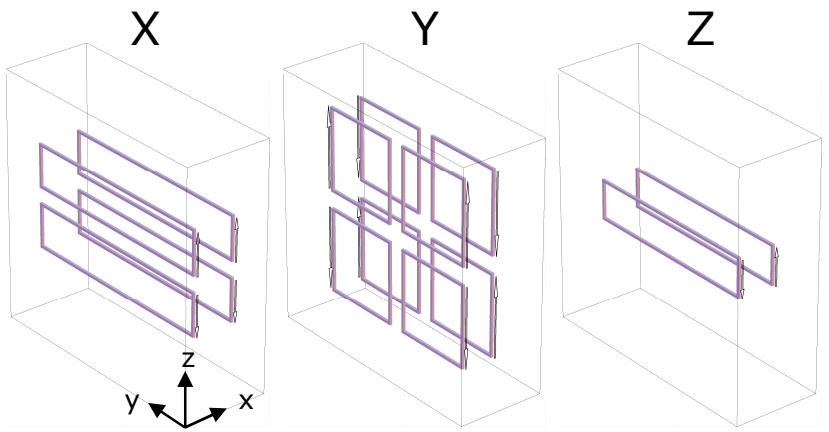




Multi-turn surface coil

Ø = 1000 – 20 µm

micro-fabricated

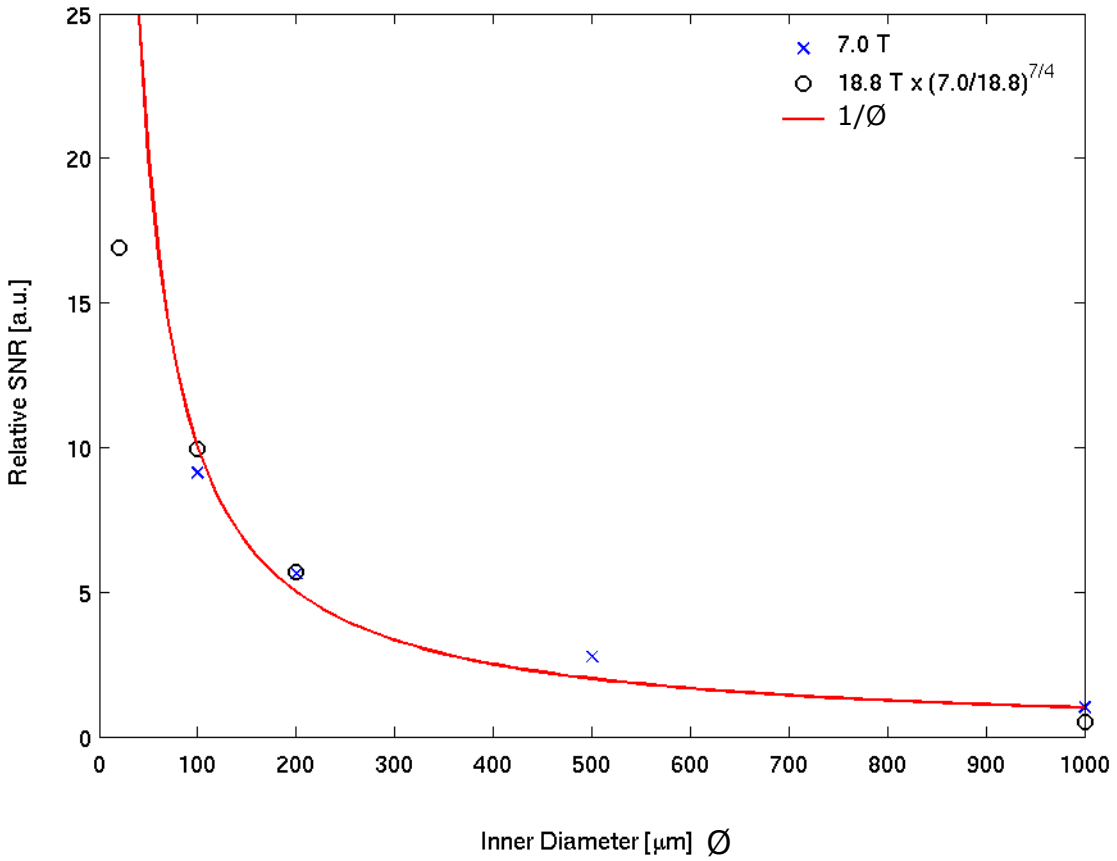


Planar gradient

6500 G/cm @ 60 A

Range ≈ 1 mm

SNR versus Ø and B_0

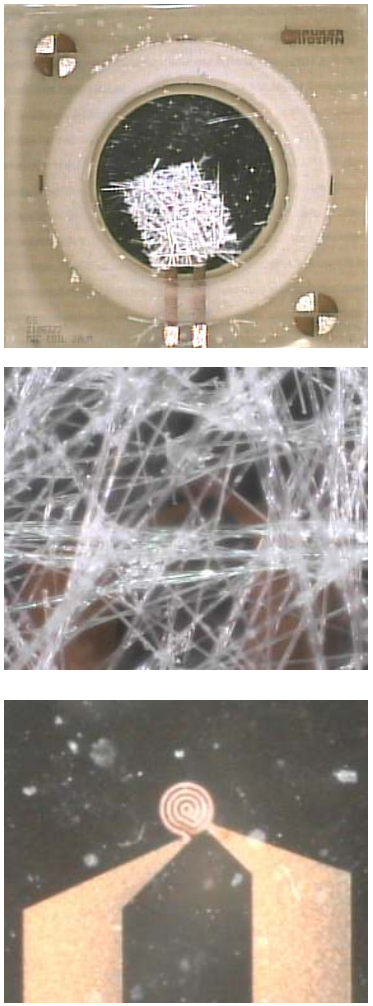


$$SNR \propto \frac{1}{Ø} B_0^{7/4}$$ ~ skin depth regime

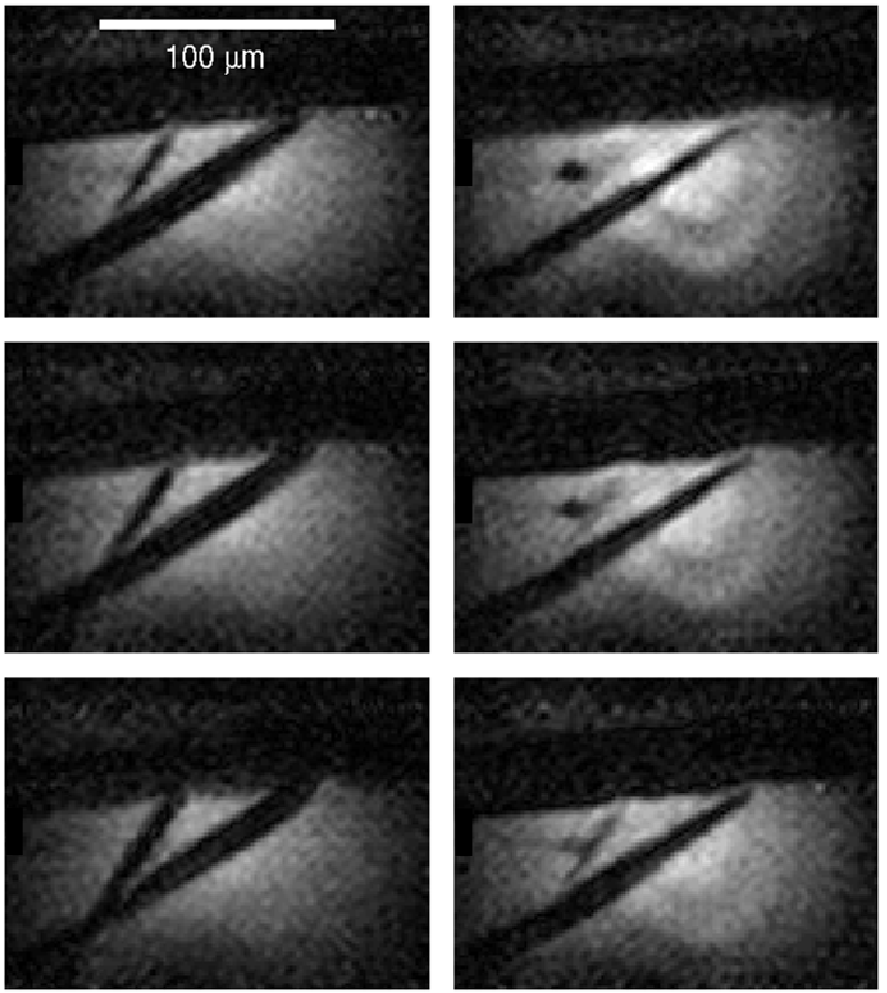
Peck TL, J Magn Reson B 108, 114 (1995)

MRI with 3.0 µm isotropic resolution

glass fibres Ø ≈ 15 µm
in doped water



measurement time 58 h



M. Weiger, Concepts Magn Reson B 33, 84 (2008)

Foe: Conclusion

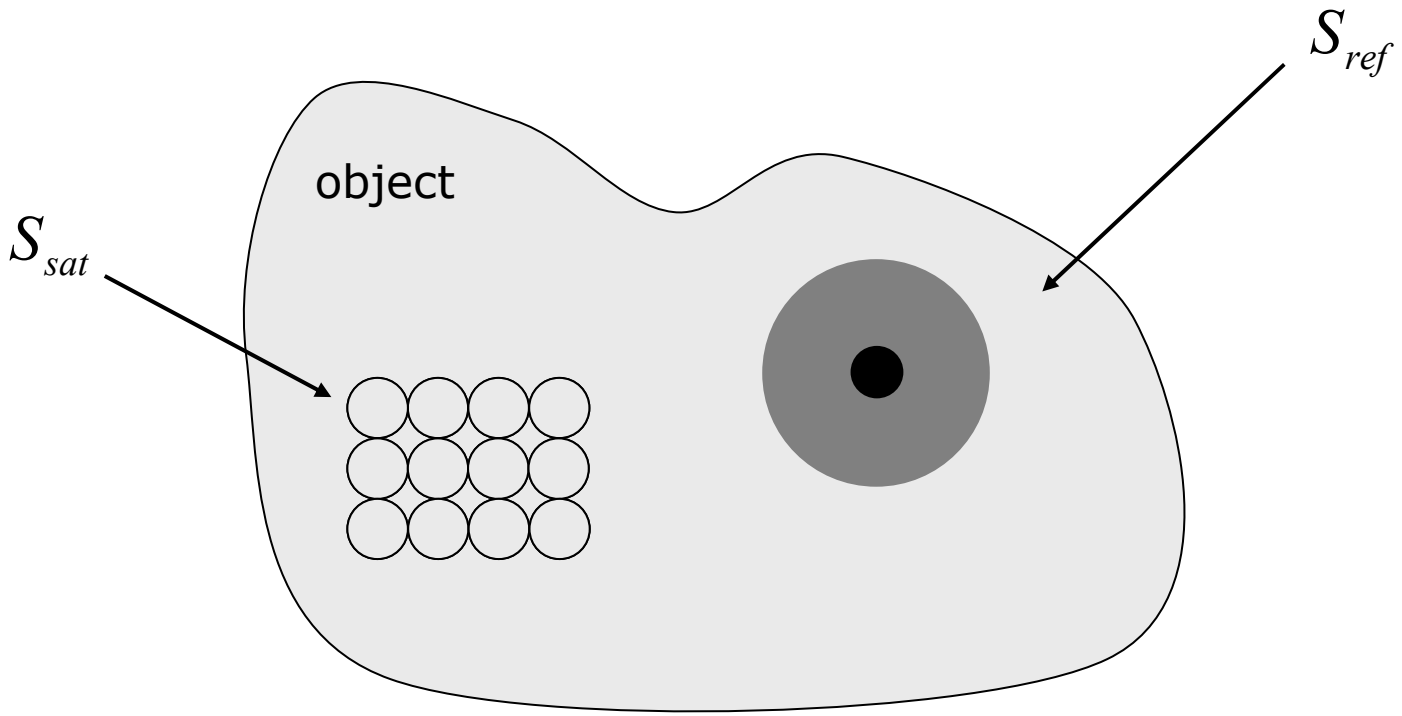
- CTI: resolution loss due to diffusion suppressed without SNR loss
- Dedicated hardware: resolution of 3 µm within 58 h can be achieved
- Some improvements possible by further optimisation (B_0, RF coil)

- But: no considerable improvements are expected on this conventional path

- Hence: become friends with diffusion

Friend: DESIRE Diffusion Enhancement of SIgnal and REsolution

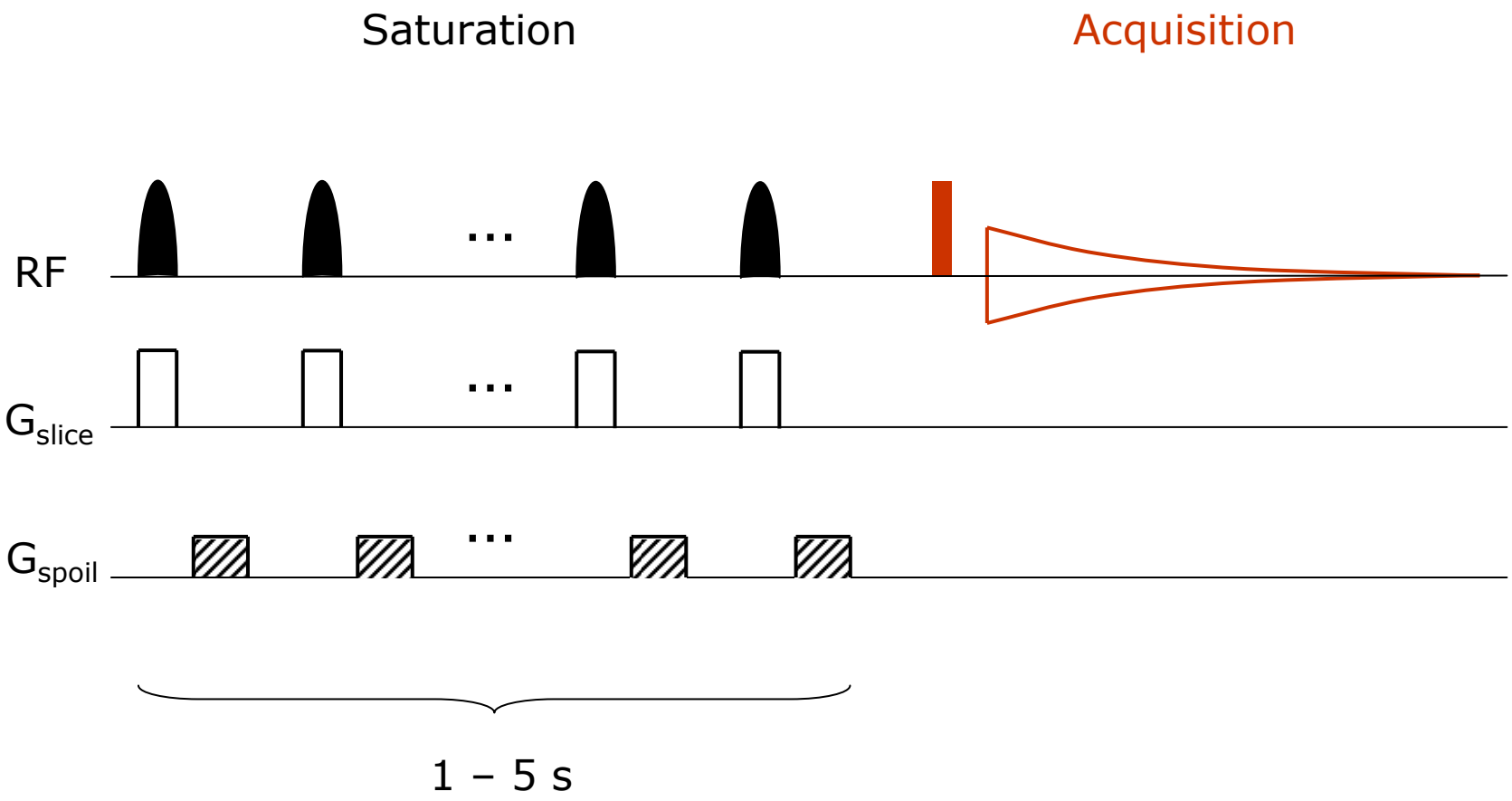
real-space, non-Fourier approach



$$I(r) \propto S_{ref} - S_{sat}(r)$$

H.D. Morris, SMR 1994, p. 376; C. H. Pennington, Concepts Magn Reson A 19, 71 (2003); L. Ciobanu, J Magn Reson 170, 252 (2004)

1D Acquisition Scheme



Upper Limit of SNR Gain

V = object volume
Δ = voxel volume
} N = V / Δ = # voxels

assume complete saturation

$$\frac{SNR_{DESIRE}}{SNR_{Fourier}} = \frac{N}{\sqrt{N}}$$

acquisition steps

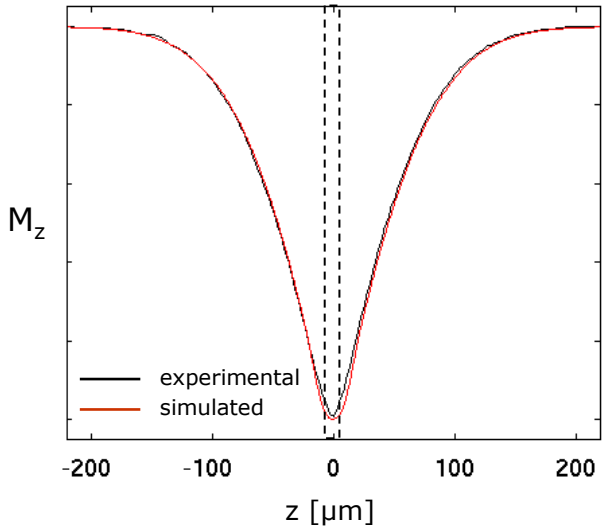
constant volume

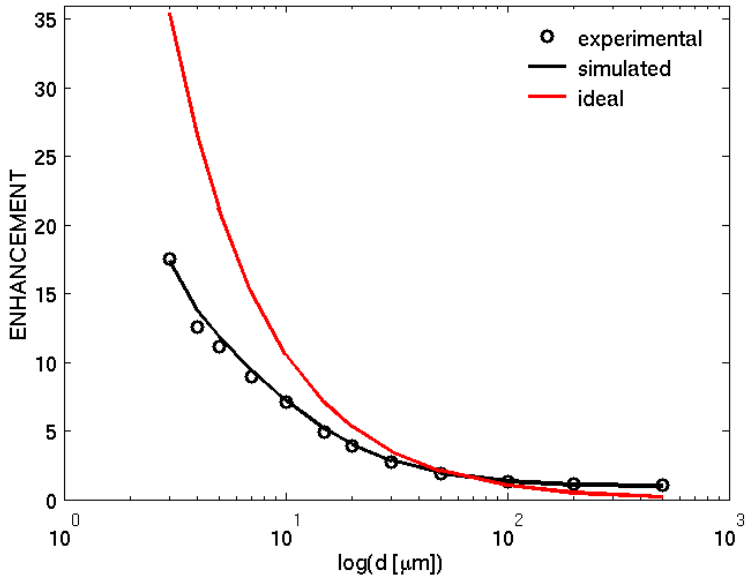
Example: N = 64^3, SNR gain = 8^3, time saving = 8^6

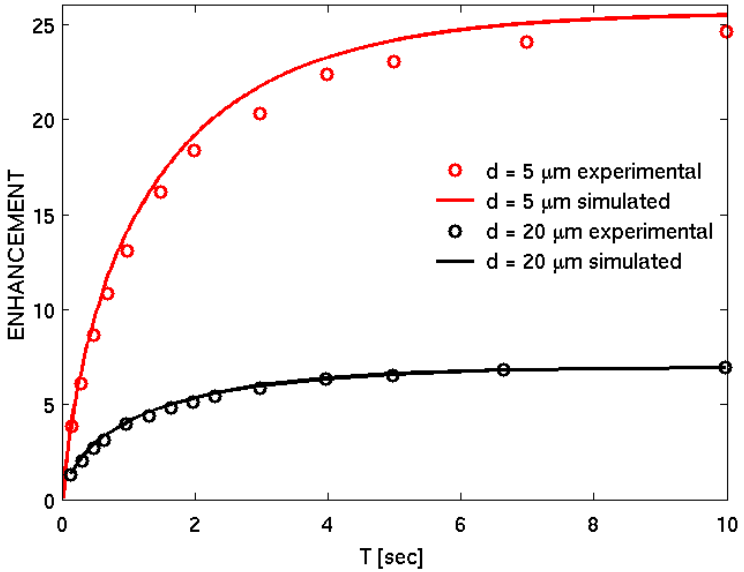
Experimental 1D Results

M. Weiger, J Magn Reson 190, 95 (2008)

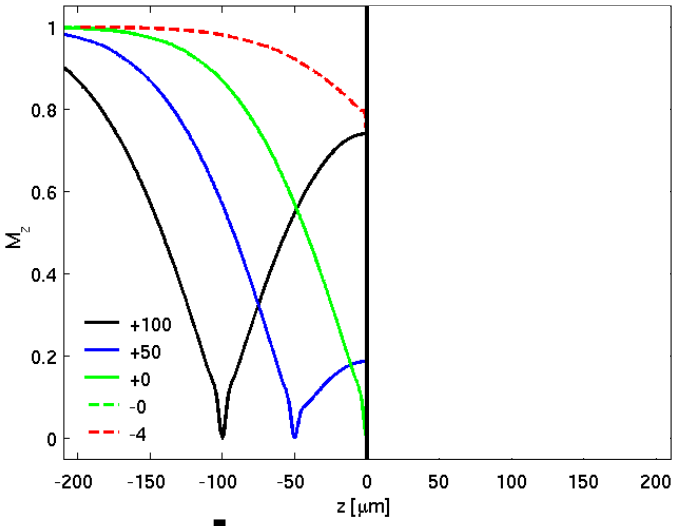
Simulations:
Bloch-Torrey



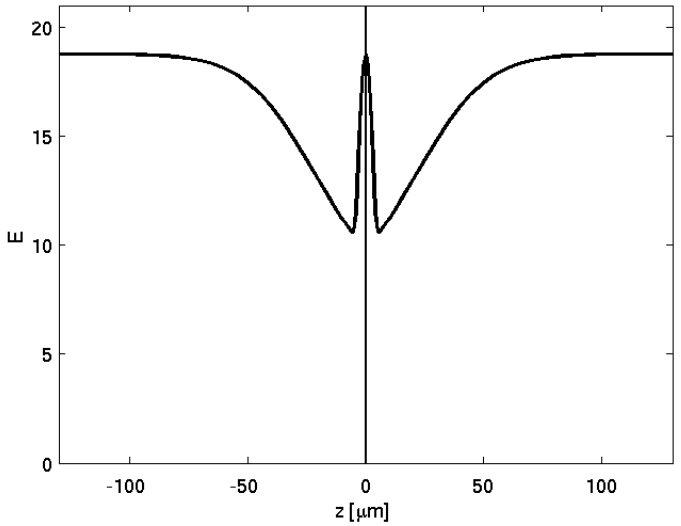


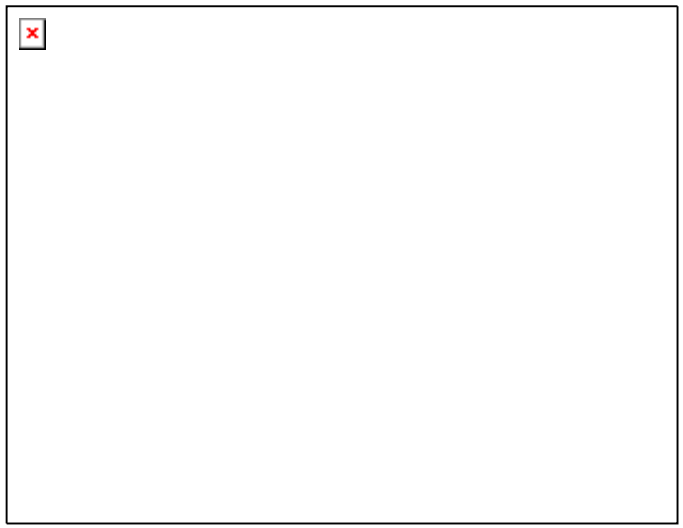


Restricted Diffusion

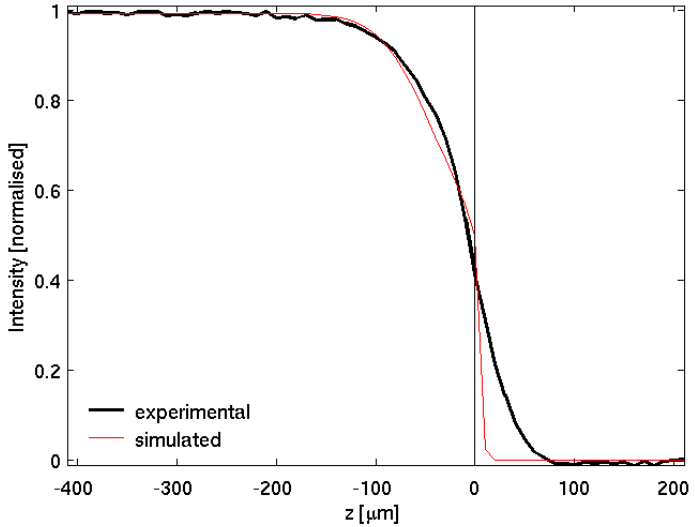


Signal peak at barrier position





Signal depends on D and compartment size



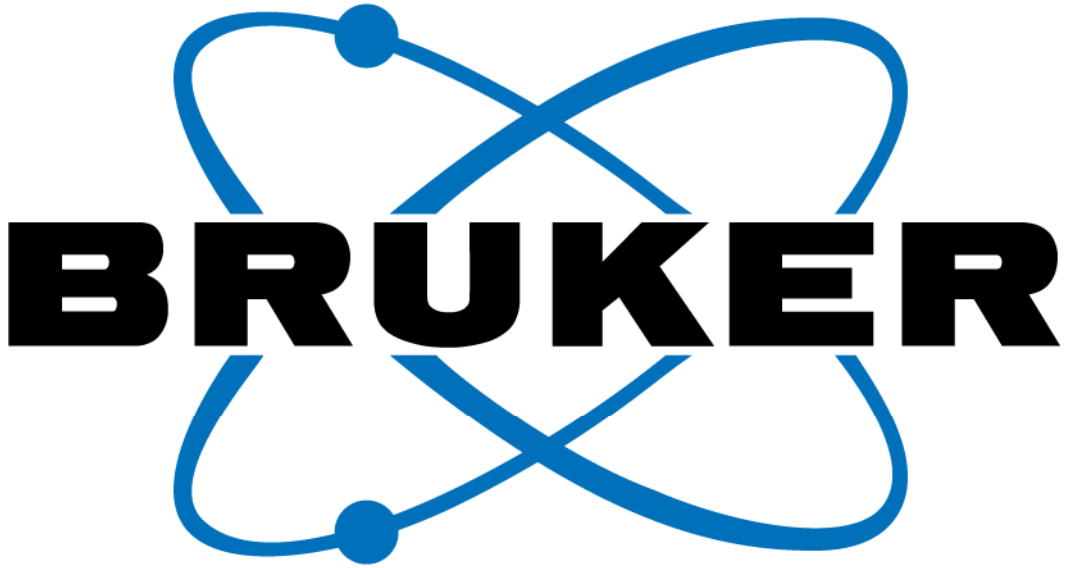
1D DESIRE image

Friend: Discussion

- DESIRE principle promises largely increased SNR
- Contrast is strongly diffusion-weighted
  - Contains a lot of unique information
  - Interpretation is not trivial
- Various experimental problems
  - 3D saturation pulse
  - Signal dynamics
  - Repetition time
- Path is demanding but probably worth to go

Acknowledgements

- Michael Fey — principle investigator
- Daniel Schmidig — RF coils
- Charles Massin — RF coils
- Franck Vincent — RF coils
- Schimun Denoth — gradient coil
- Michael Schenkel — digital receiver
- Yi Zeng — intern DESIRE



www.bruker-biospin.com