Publications of the Speaker to the Topic

Publications used in this talk

T. Skinner, T. Reiss, B. Luy, N. Khaneja, S. J. Glaser, "Application of Optimal Control Theory to the design of broadband excitation pulses for high resolution NMR ", *J. Magn. Reson.* **163**, 8-15 (2003).

T. E. Skinner, T. O. Reiss, B. Luy, N. Khaneja, S. J. Glaser, "Reducing the duration of broadband excitation pulses using optimal control with limited RF amplitude", *J. Magn. Reson.* **167**, 68-74(2004).

K. Kobzar, T. E. Skinner, N. Khaneja, S. J. Glaser, B. Luy, "Exploring the limits of broadband excitation and inversion pulses", *J. Magn. Reson*. **170**, 236-243 (2004).

T. E. Skinner, T. O. Reiss, B. Luy, N. Khaneja, S. J. Glaser, " Tailoring the optimal control cost function to enable shorter broadband excitation pulses ", *J. Magn. Reson*. **172**, 17-23 (2005).

K. Kobzar, Luy, B., N. Khaneja, S. J. Glaser, "Pattern pulses: design of arbitrary excitation pulses as a function of pulse amplitude and offset", *J. Magn. Reson.* **173**, 229-235.

B. Luy, K. Kobzar, T. E. Skinner, N. Khaneja, S. J. Glaser, "Construction of universal rotations from point to point transformations", *J. Magn. Reson*. **176**, 179-186 (2005).

T. E. Skinner, K. Kobzar, B. Luy, R. Bendall, W. Bermel, N. Khaneja, S. J. Glaser, "Optimal control design of constant amplitude phase-modulated pulses: application to calibration-free broadband excitation", *J. Magn. Reson.* **179**, 241-249 (2006).

K. Kobzar, T.E. Skinner, N. Khaneja, S. J. Glaser, B. Luy, "Exploring the limits of broadband excitation and inversion pulses II: RF-power optimized pulses", *J. Magn. Reson.* **194**, 58-66 (2008).

Other related OCT publications

N. Khaneja, T. Reiss, B. Luy, S. J. Glaser, "Optimal Control of Spin Dynamics in the Presence of Relaxation", preprint quant-ph/0208050 (2002), *J. Magn. Reson.* **162**, 311-319 (2003).

N. Khaneja, B. Luy, S. J. Glaser, "Boundary of Quantum Evolution under Decoherence", preprint: quant-ph/0302060, *Proc. Natl. Acad. Sci. USA* **100**, 13162-13166 (2003).

N. Khaneja, J.S. Li, C. Kehlet, B. Luy, S. J. Glaser, ”Broadband relaxation-optimized polarization transfer in magnetic resonance”, *Proc. Natl. Acad. Sci. USA* **101**, 14742-14747 (2004).

N. I. Gershenzon, K. Kobzar, B. Luy, S. J. Glaser, T. E. Skinner, "Optimal control design of excitation pulses that accomodate relaxation", *J. Magn. Reson.* **188**, 330-336 (2007).

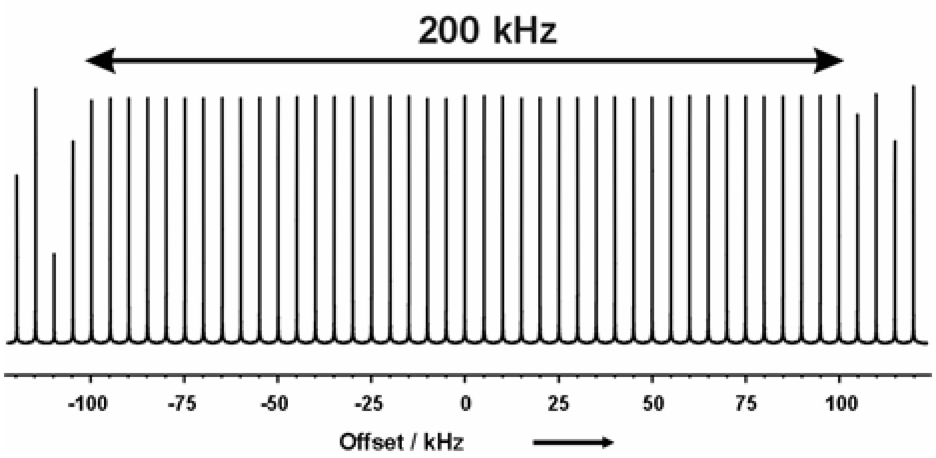
N. I. Gershenzon, T. E. Skinner, B. Brutscher, N. Khaneja, M. Nimbalkar, B. Luy, S. J. Glaser, "Linear phase slope in pulse design: Application to coherence transfer", *J. Magn. Reson.* **192**, 235-243 (2008).

Related Publications

T. Untidt, T. Schulte-Herbrüggen, B. Luy, S. J. Glaser, C. Griesinger, O. W. Sørensen, N. C. Nielsen, "Design of NMR Pulse Experiments with Optimum Sensitivity. Coherence-Order-Selective Transfer in I_2S and I_3S Spin Systems", *Molecular Physics*, **95**, 787-796 (1998).

A. Enthart, J. C. Freudenberger, J. Furrer, H. Kessler, B. Luy, "The CLIP/CLAP-HSQC: Pure absorptive spectra for the measurement of one-bond couplings", *J. Magn. Reson.* **192**, 314-322 (2008).

NMR Pulse Design by OCT: Introduction, Applications and What we can learn from it



Kyryl Kobzar, Naum Gershenzon, Tom Skinner, Navin Khaneja, Steffen Glaser, Burkhard Luy

Why bother with NMR spectroscopy?

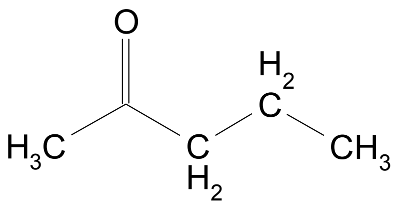
Broadband ‘State-To-State’ Pulses

Broadband ‘Universal Rotation’ Pulses

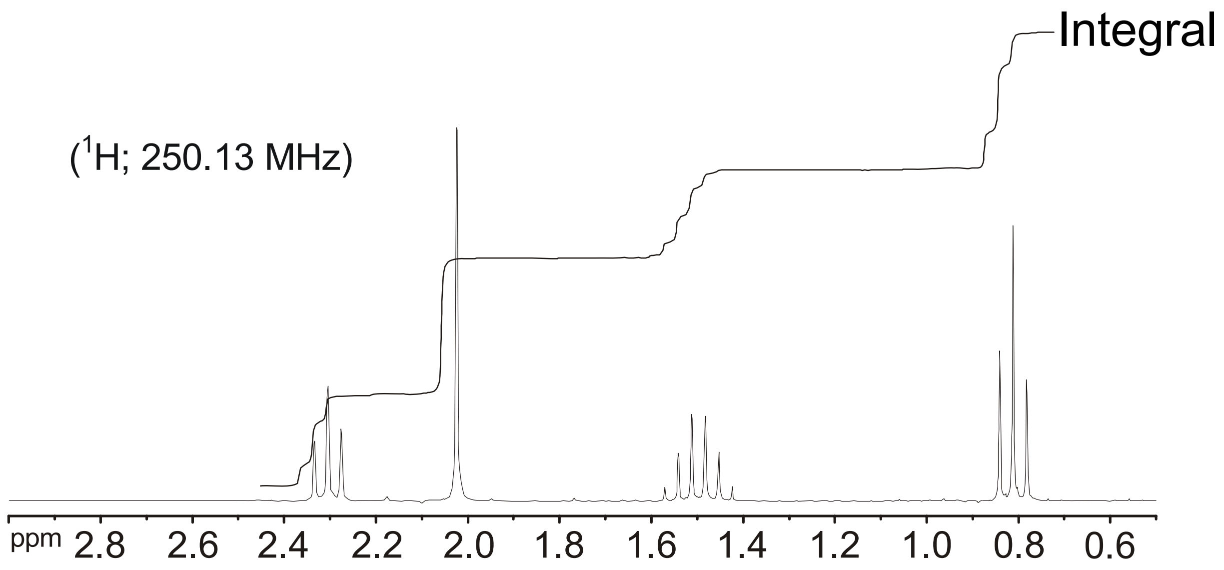
Ultrabroadband Excitation

Pattern Pulses

Simple ^{1}H-1D Spectrum



Pentan-2-on, Methylpropylketon



Chemical Shift

Intensity

J-Couplings

Drift Hamiltonians

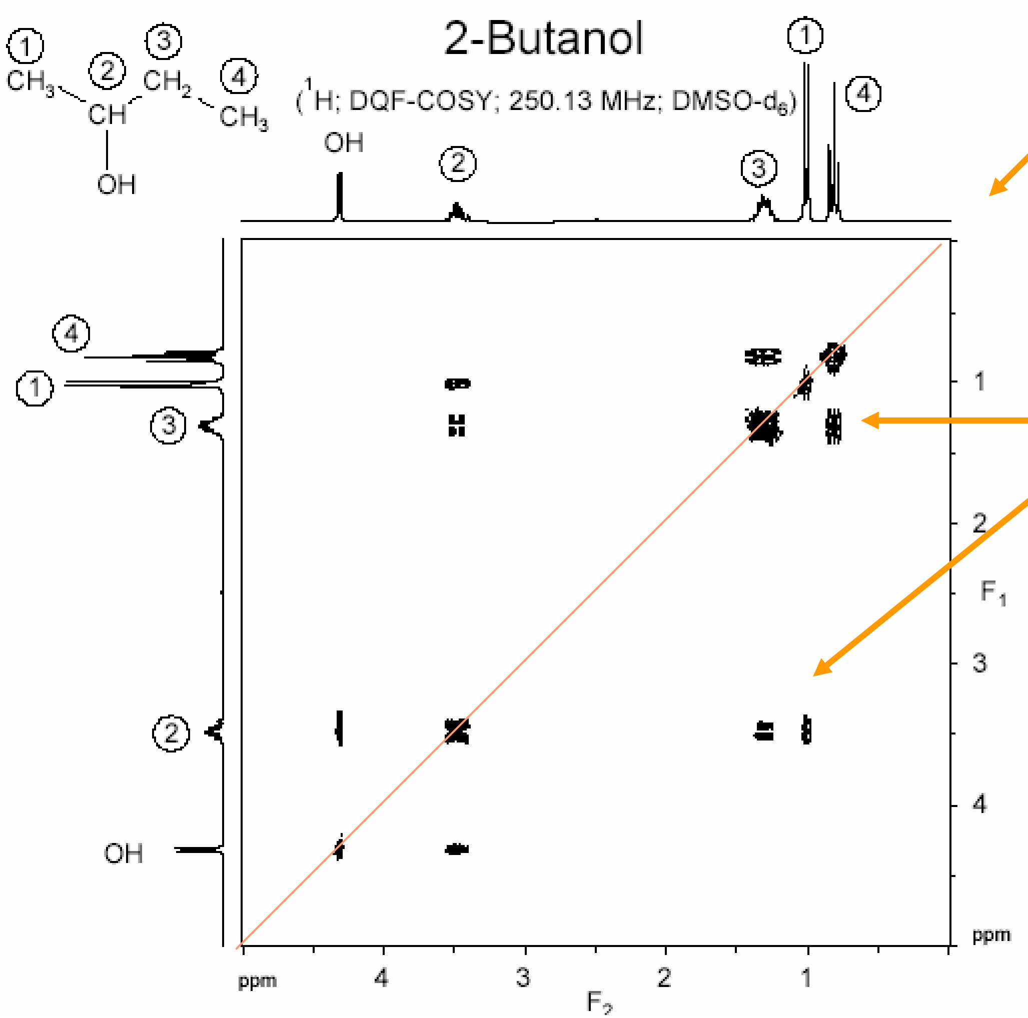
chemical shift: $H_{cs} = \omega_I \, I_z$

hom. J-coupl.: $H_{iso} = 2\pi J_{12} \, (I_{1x}I_{2x} + I_{1y}I_{2y} + I_{1z}I_{2z})$

het. J-coupl.: $H_{long} = 2\pi J_{IS} \, I_z S_z$

(no relaxation considered)

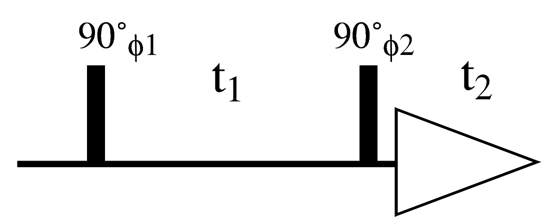
Correlation via J-Couplings: COSY



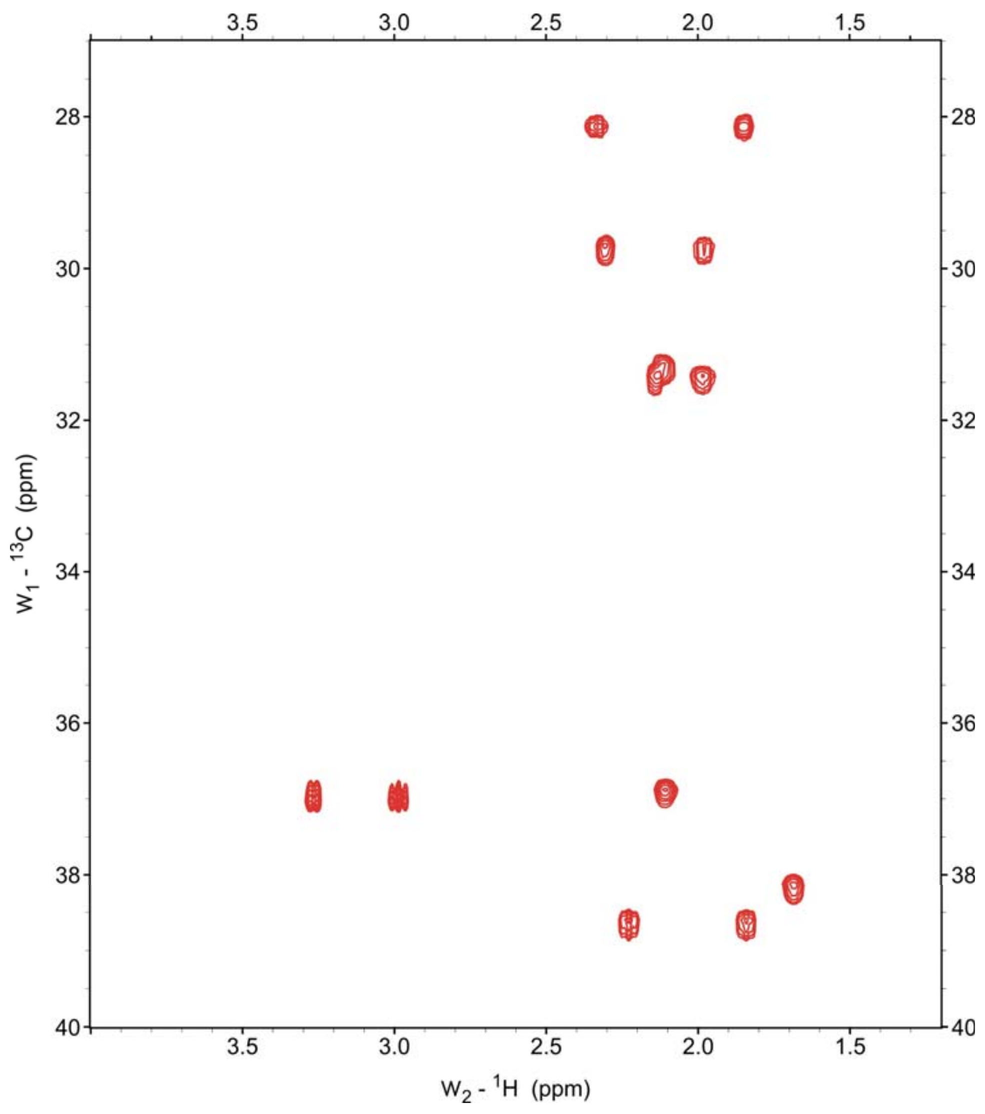
Diagonal

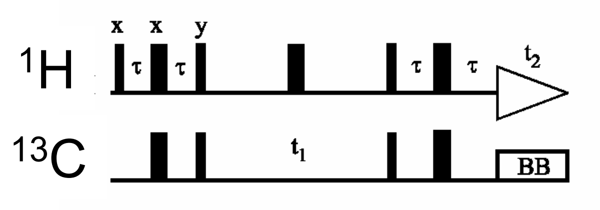
Cross peaks:

J-couplings between neighboring protons



Heteronuclear Correlations: HSQC

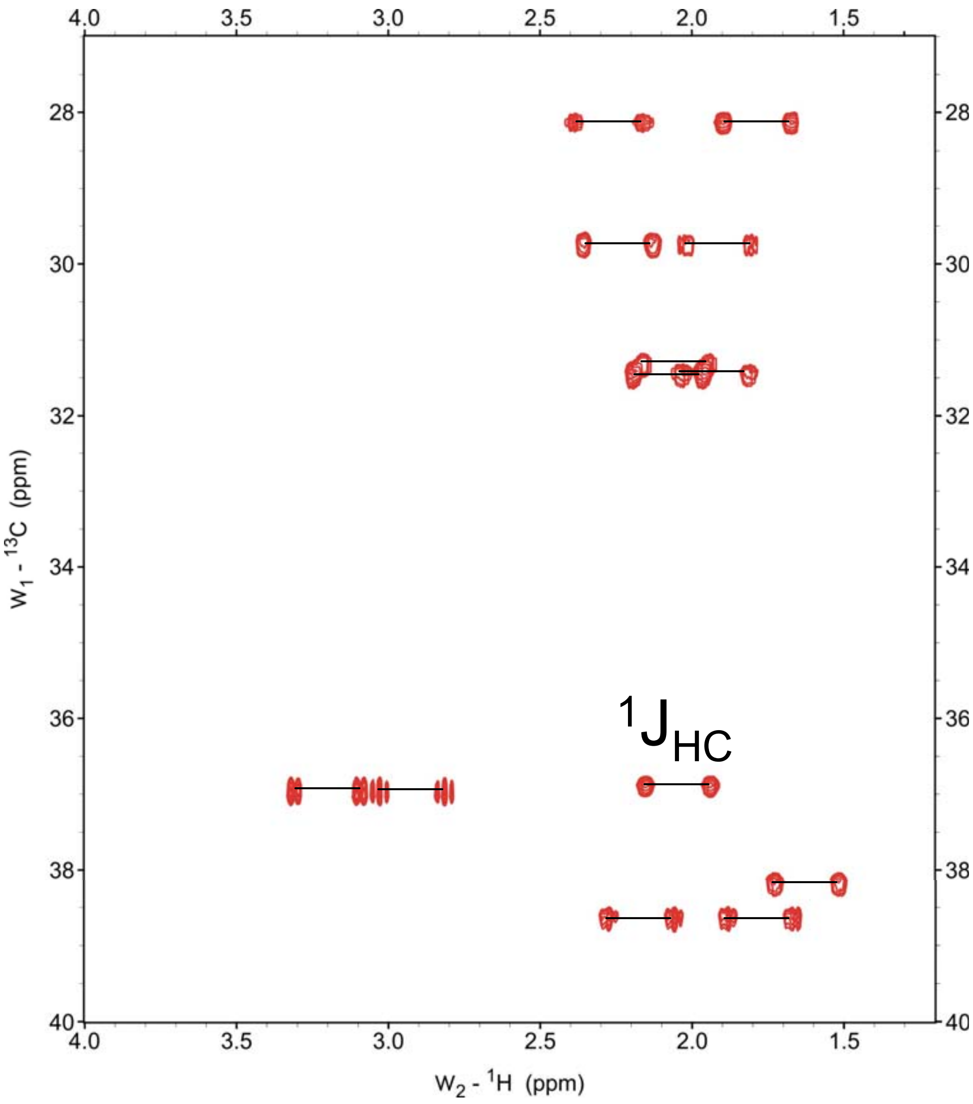


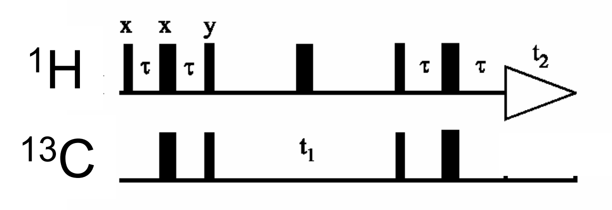


Correlation of protons to directly attached ^{13}C-atoms

with decoupling

Heteronuclear Correlations: HSQC

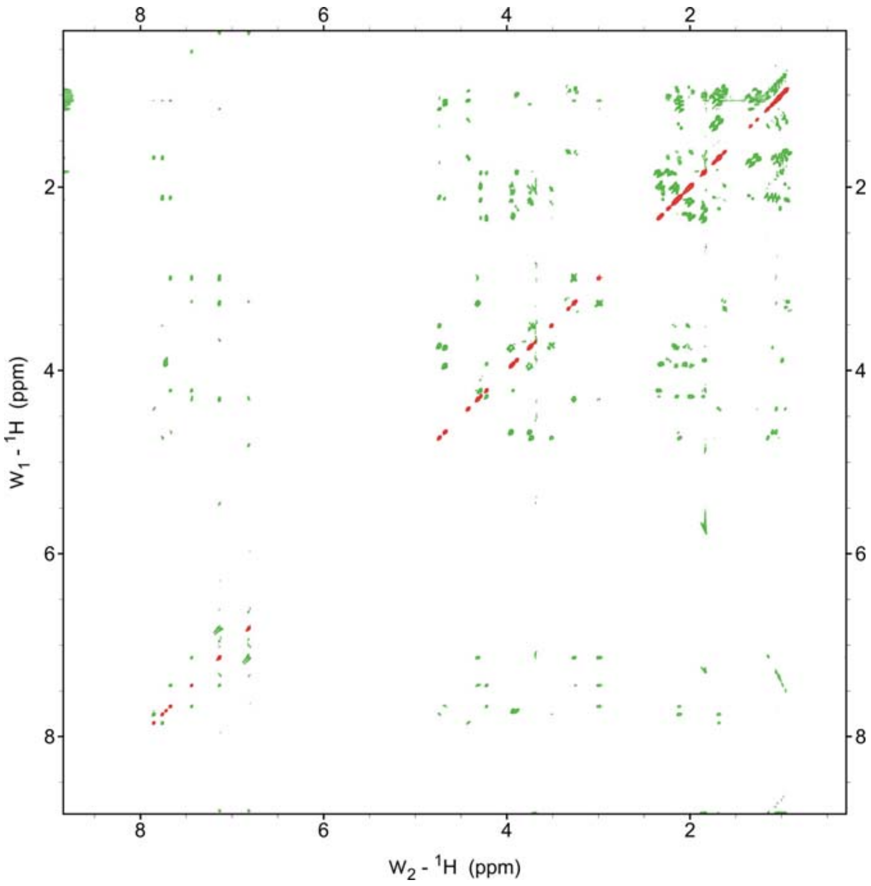


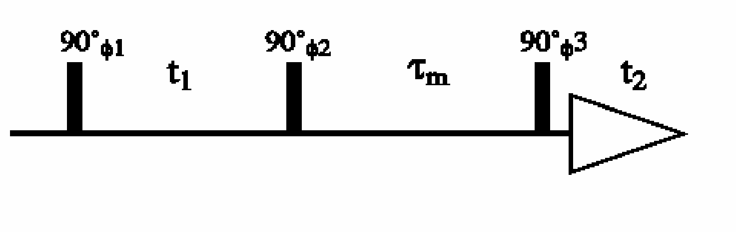


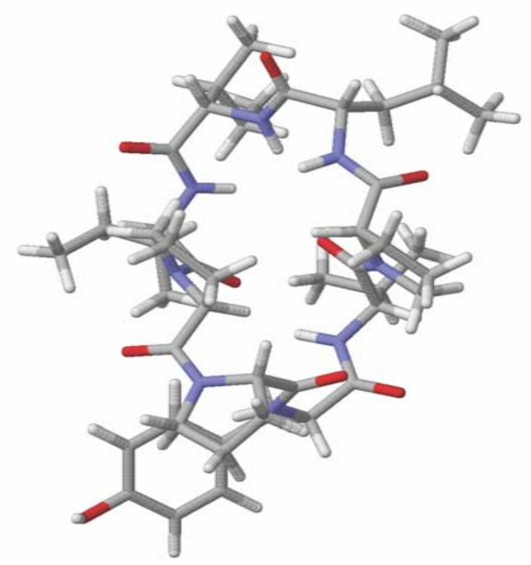
Correlation of protons to directly attached ^{13}C-atoms

without decoupling

Dipole-Dipole-Relaxation: NOESY





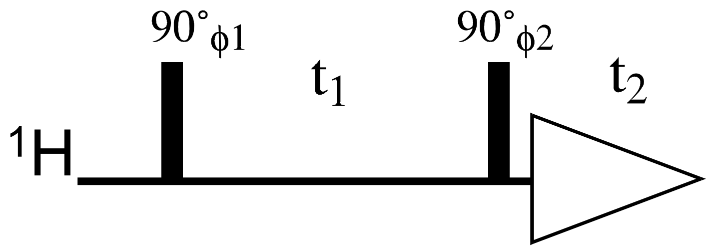


NOESY: relaxation-based transfer ~ $1/r^6$

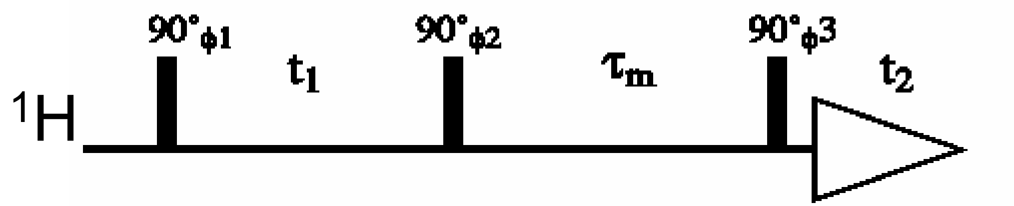
=> Structure calculations

Common Scheme: Coherence/Polarization Transfer

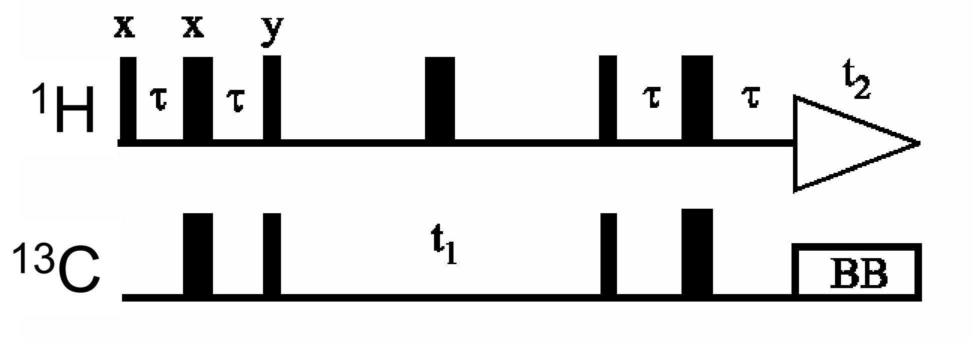
COSY



NOESY

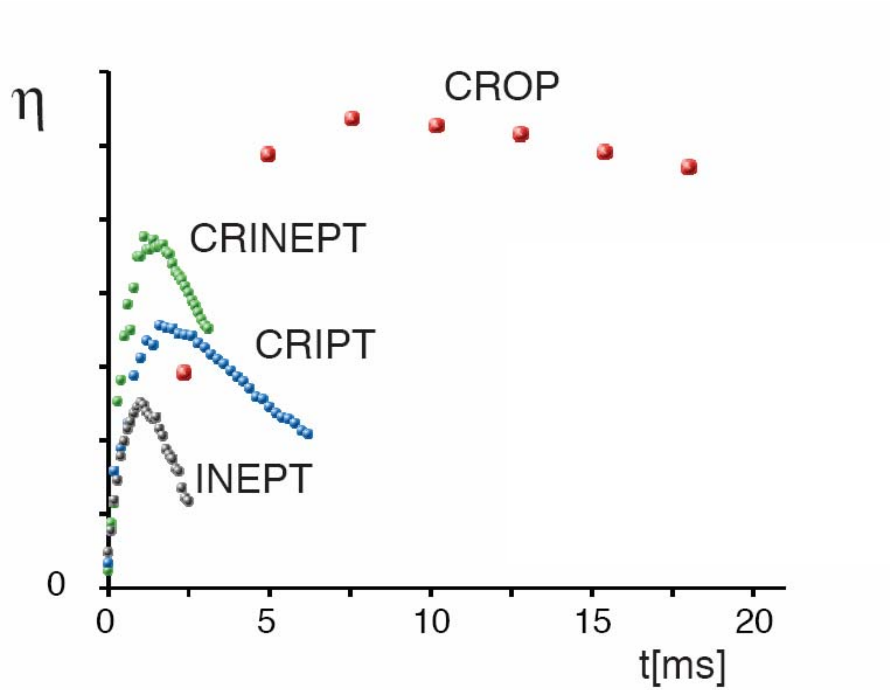


HSQC

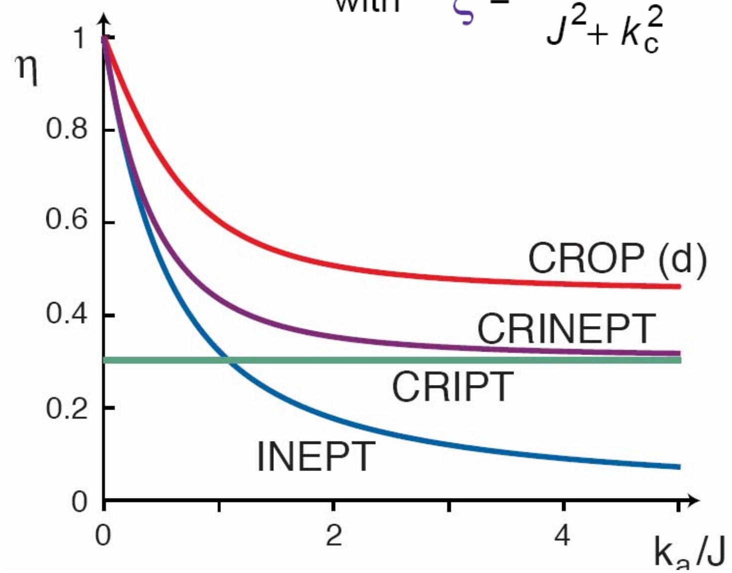


Future Transfer Building Block: CROP

$$\eta = \sqrt{1 + \xi^2} - \xi$$



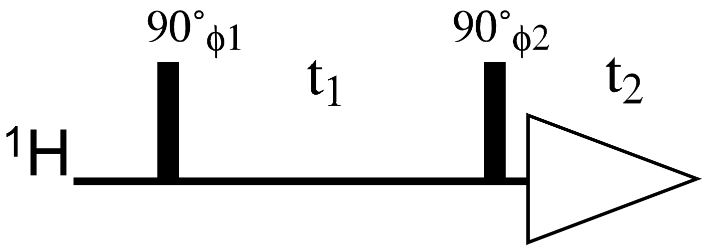
with $\xi^2 = \dfrac{k_a^2 - k_c^2}{J^2 + k_c^2}$



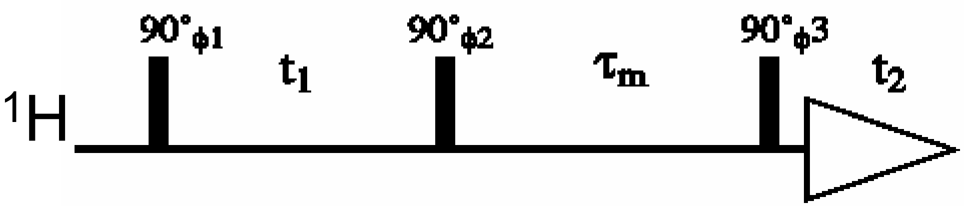
Khaneja, Luy, Glaser, Proc. Natl. Acad. Sci. USA 100, 1316 (2003)

90° and 180° Pulses: Todays Work Horses

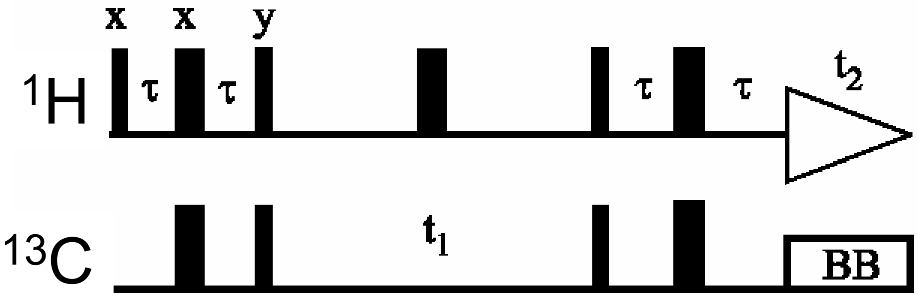
COSY



NOESY



HSQC



Why bother with NMR spectroscopy?

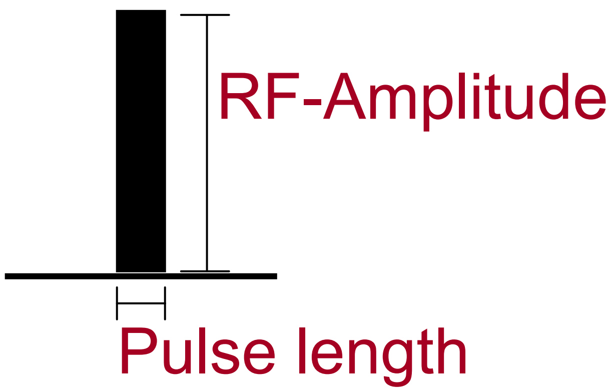
Broadband 'State-To-State' Pulses

Broadband 'Universal Rotation' Pulses

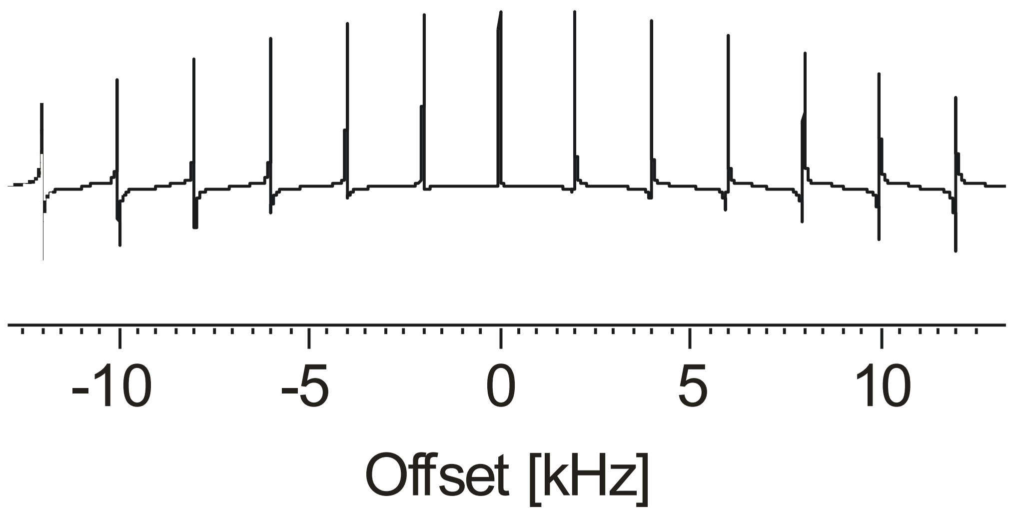
Ultrabroadband Excitation

Pattern Pulses

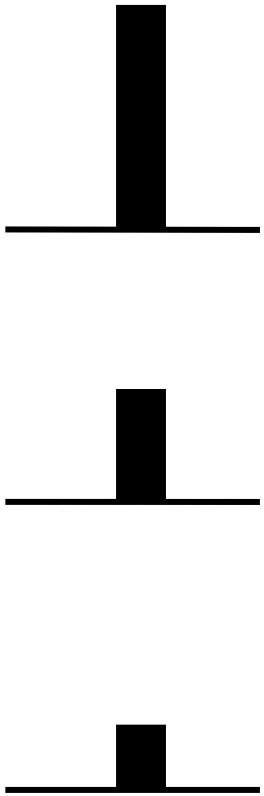
Offset-Dependence of RF-Pulses

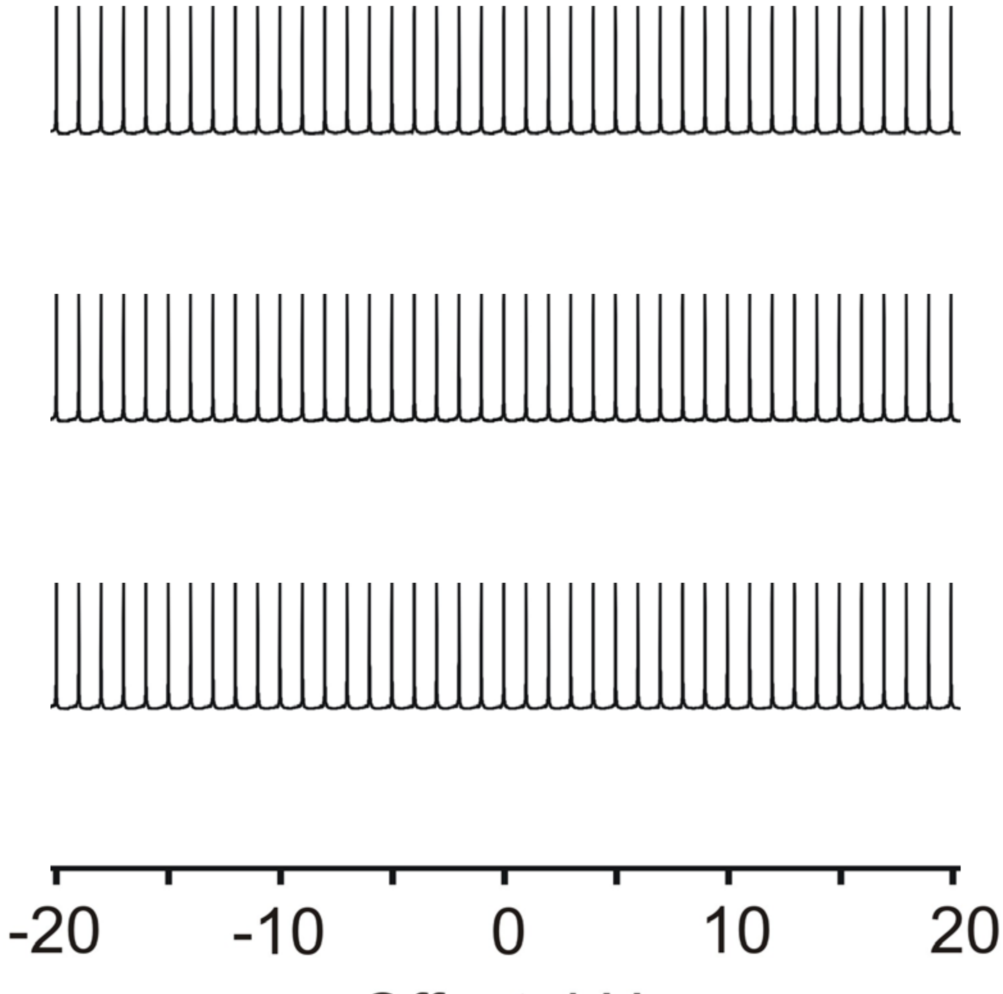


Phase distortions and loss of signal due to offset (e.g. ^{13}C, ^{19}F)



‚The Ideal Pulse‘





Same flip angle for all offsets and RF-amplitudes

Optimization Setup

Approximation: pulse length is short

=> J-coupling / relaxation is neglected

$$H_{cs} = \omega_{offs}\, I_z$$

$$H_{ctrl} = \omega_{RF} = \omega_1 \left(\cos\varphi\, I_x + \sin\varphi\, I_y\right)$$

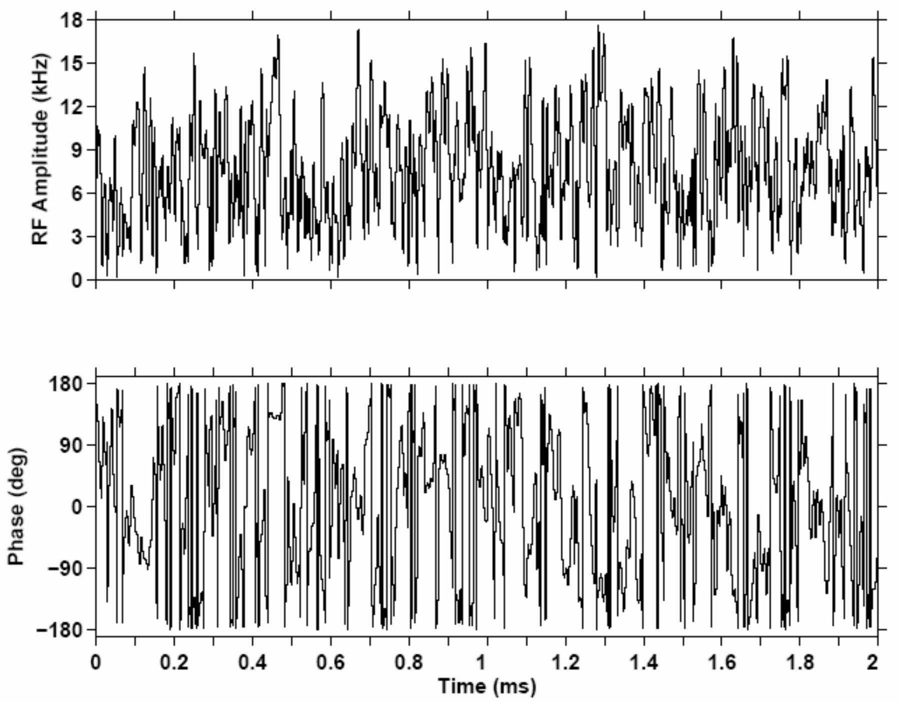
Goal: Same transfer for all $\omega_{RF} \pm \sigma_{RF}$ and ω_{offs}

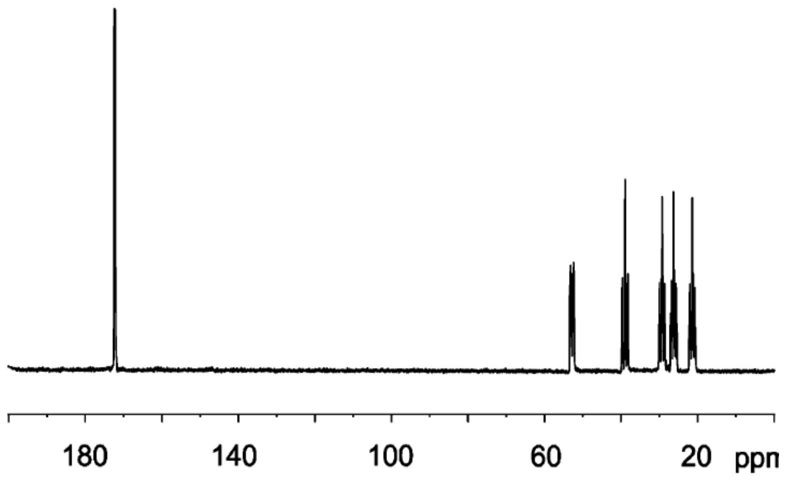
Optimization Algorithm

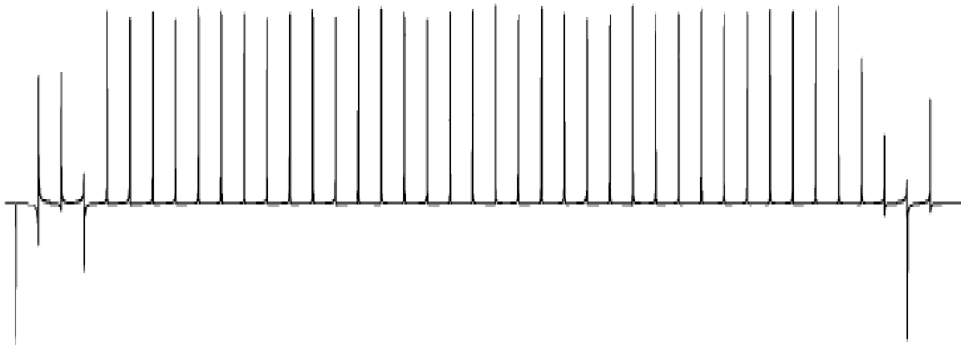
1. Choose an initial rf sequence $\omega_{rf}^{(0)}$.
2. Evolve $\mathbf{M}$ forward in time starting from $\mathbf{M}(t_0)$.
3. Calculate $\Gamma(t_p) = \mathbf{M}(t_p) \times \mathbf{F}$ for all offsets and scaled rf-amplitudes and evolve it backwards in time.
4. $\omega_{rf}^{(k+1)}(t) \rightarrow \omega_{rf}^{(k)}(t) + \epsilon \cdot \overline{\boldsymbol{\Gamma}(t)}$.
5.
6.
7. Repeat steps 2–6 until a desired convergence of Φ is reached.

$\mathbf{M} = (I_x, I_y, I_z)$ Γ = Gradient

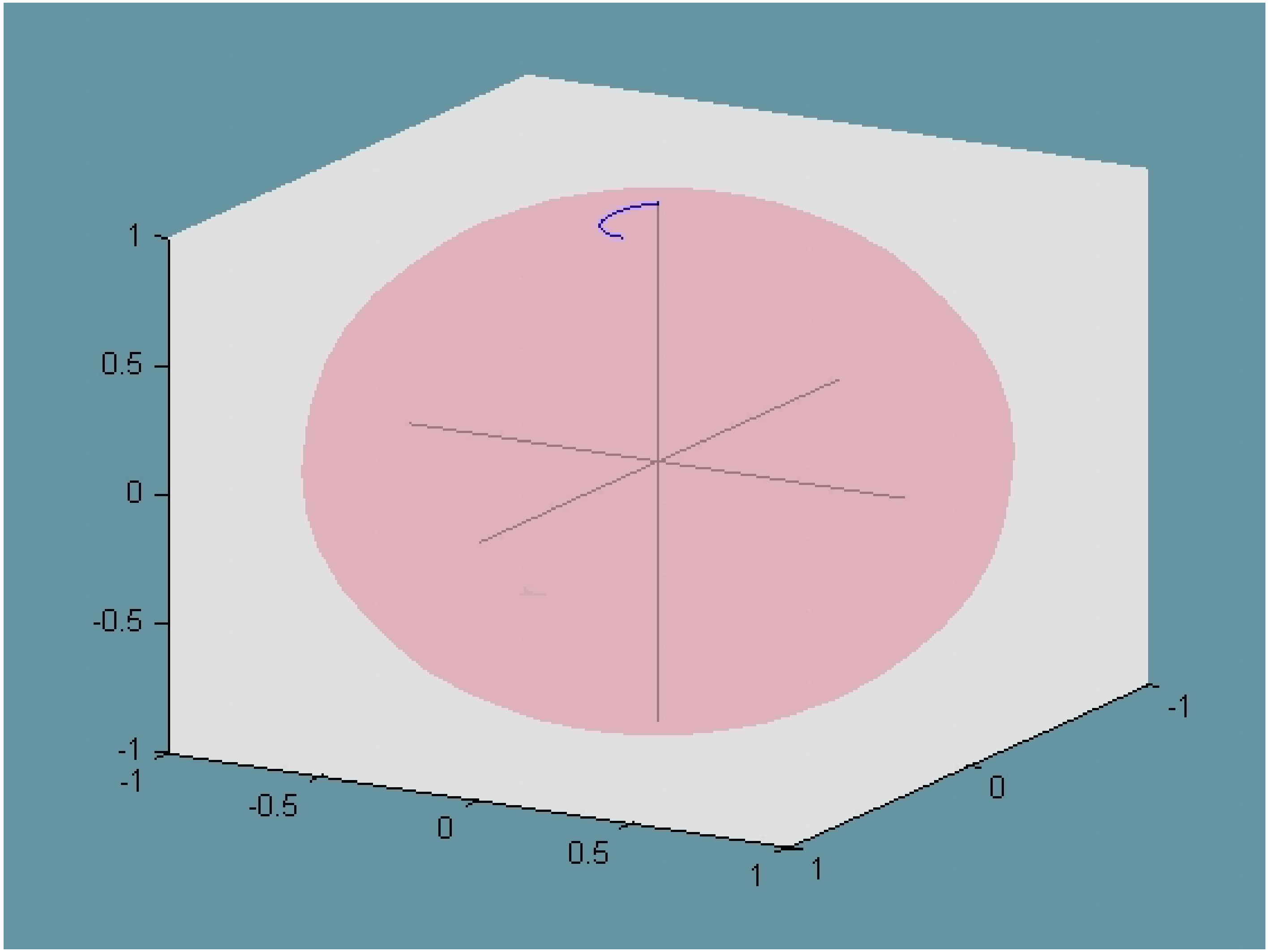
2 ms BEBOP no RF-constraints



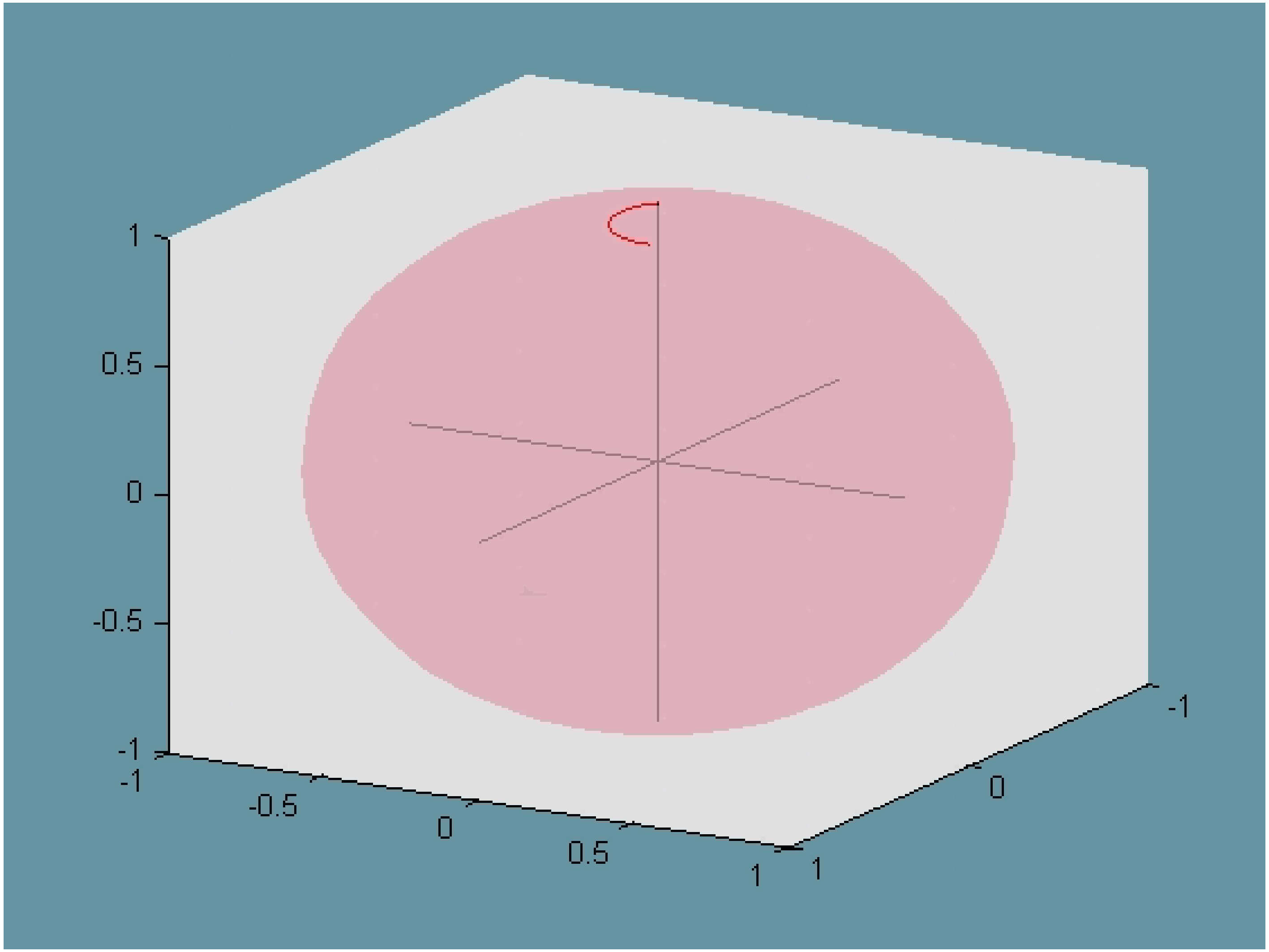




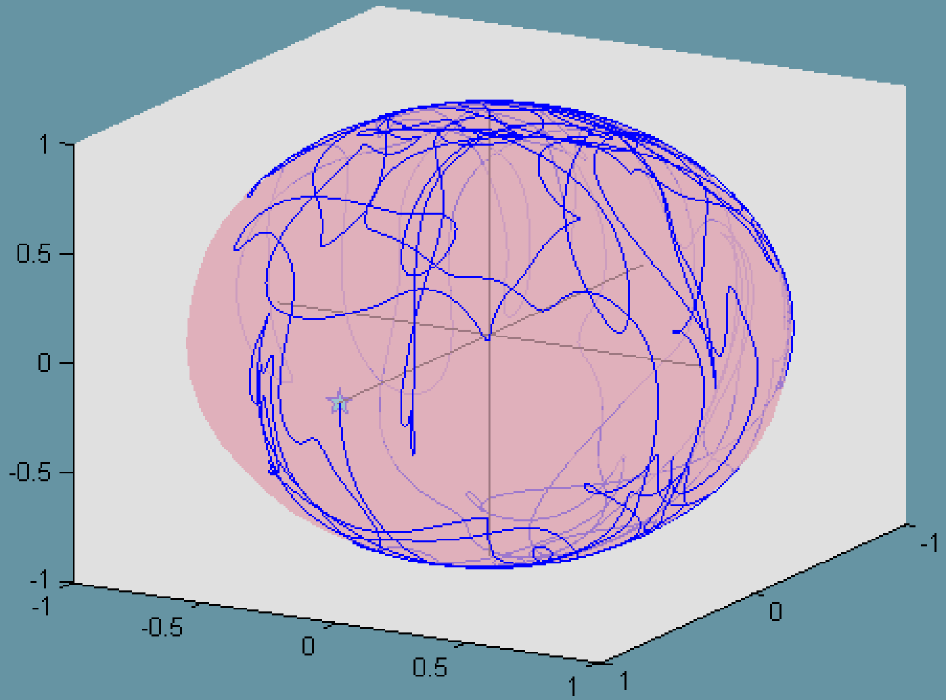
Trajectory (0 Hz Offset)



Trajectory (16 kHz Offset)



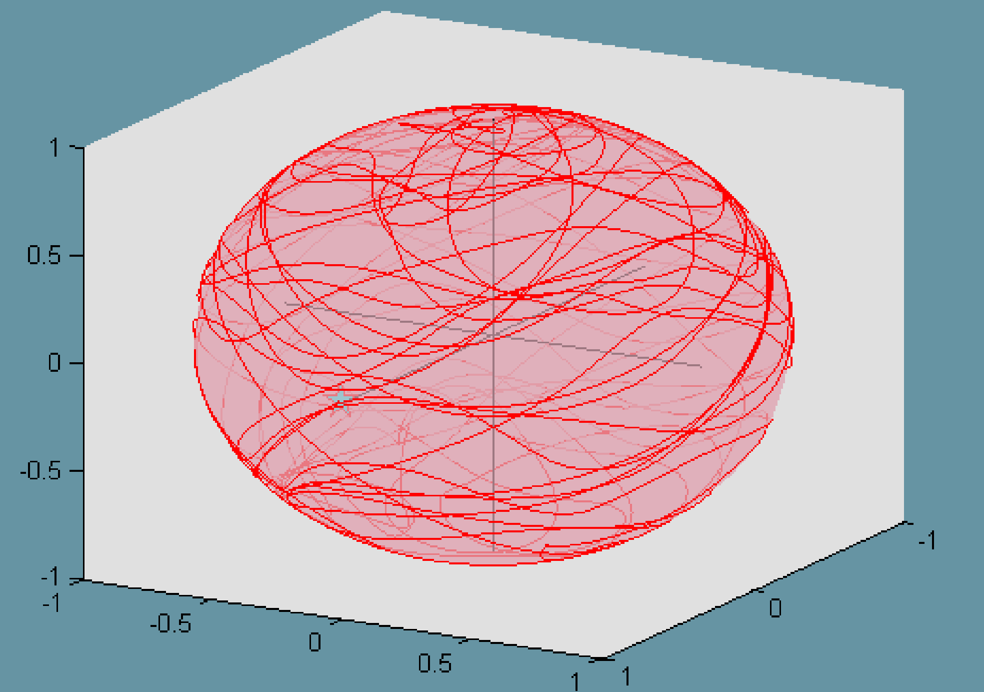
Pulse-Trajectories



ω_I = 0 Hz

despite different trajectories final magnetization in x

ω_I = 16 kHz



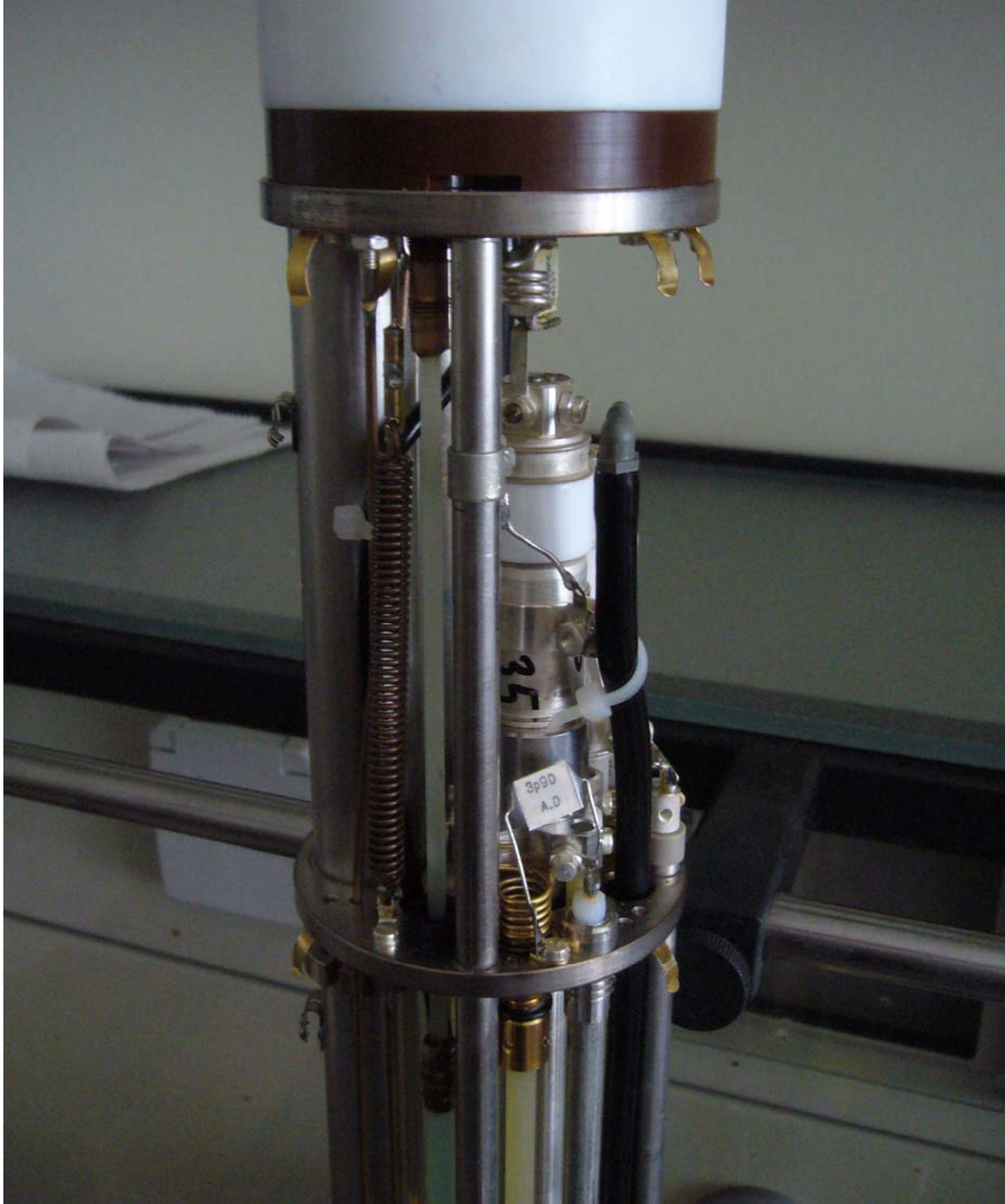
Shorter Pulses ?

Shorter Pulses: RF-constraints Needed in Optimization

Max. RF-amplitude !

&

Max. RF-energy !



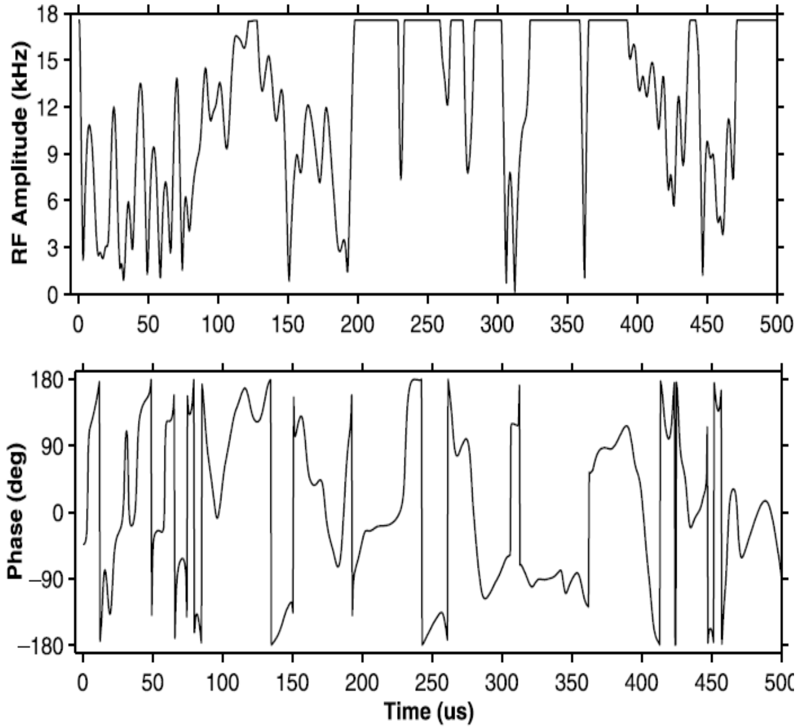
Modified Algorithm

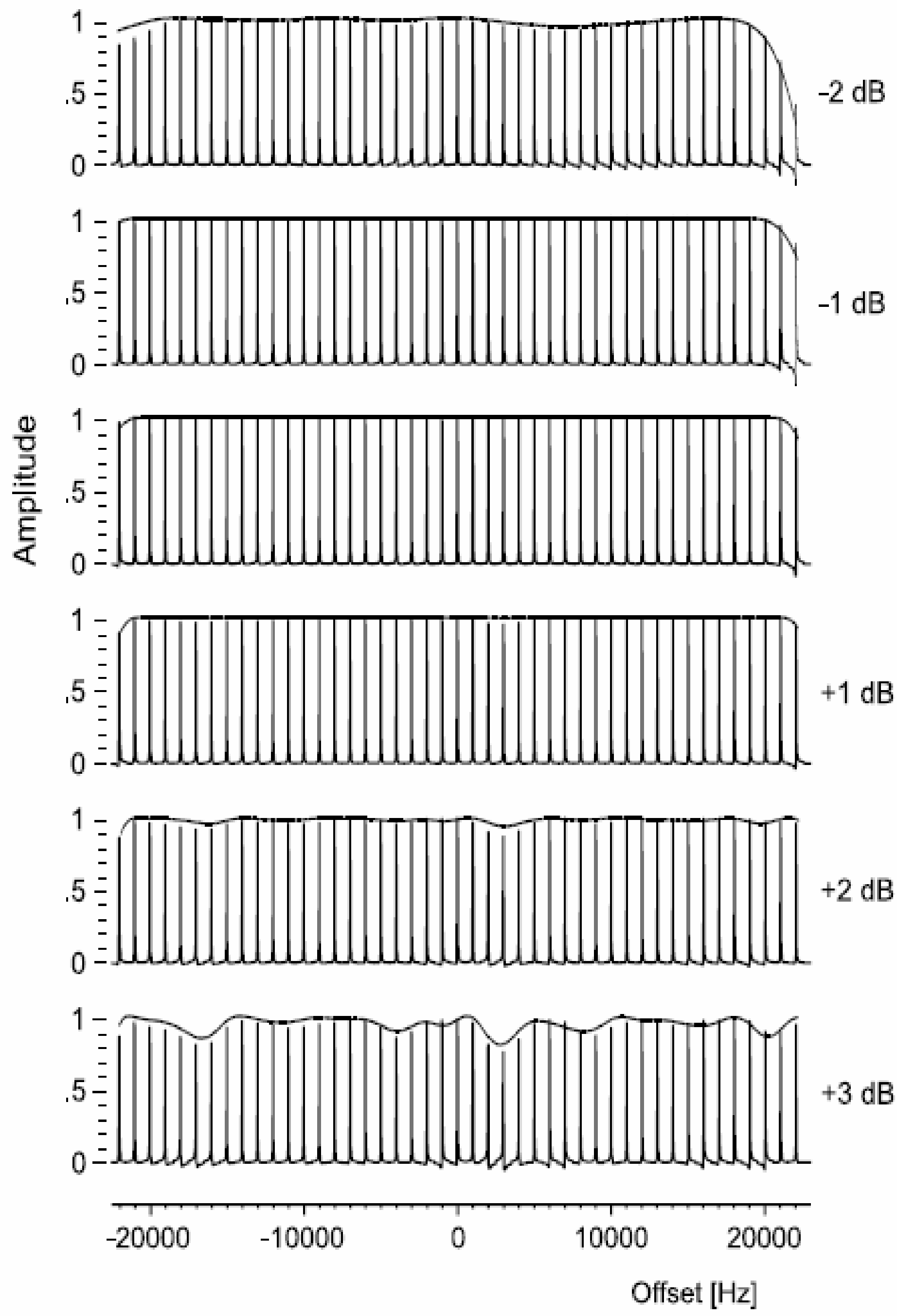
1. Choose an initial rf sequence $\omega_{\mathrm{rf}}^{(0)}$.
2. Evolve $\mathbf{M}$ forward in time starting from $\mathbf{M}(t_0)$.
3. Calculate $\Gamma(t_{\mathrm{p}}) = \mathbf{M}(t_{\mathrm{p}}) \times \mathbf{F}$ for all offsets and scaled rf-amplitudes and evolve it backwards in time.
4. $\boldsymbol{\omega}_{\mathrm{rf}}^{(k+1)}(t) \rightarrow \boldsymbol{\omega}_{\mathrm{rf}}^{(k)}(t) + \epsilon \cdot \overline{\boldsymbol{\Gamma}(t)}$.
5. Calculate $\overline{P} = \frac{1}{t_{\mathrm{p}}} \int_{t_0}^{t_{\mathrm{p}}} \mathrm{d}t(\omega_1(t))^2$.
6. If $\overline{P} > P_{\mathrm{max}}$, set $\omega_1(t) \rightarrow \omega_1(t) \cdot \sqrt{\frac{P_{\mathrm{max}}}{\overline{P}}}$.
7. Repeat steps 2–6 until a desired convergence of Φ is reached.

or for max. RF-amplitude:

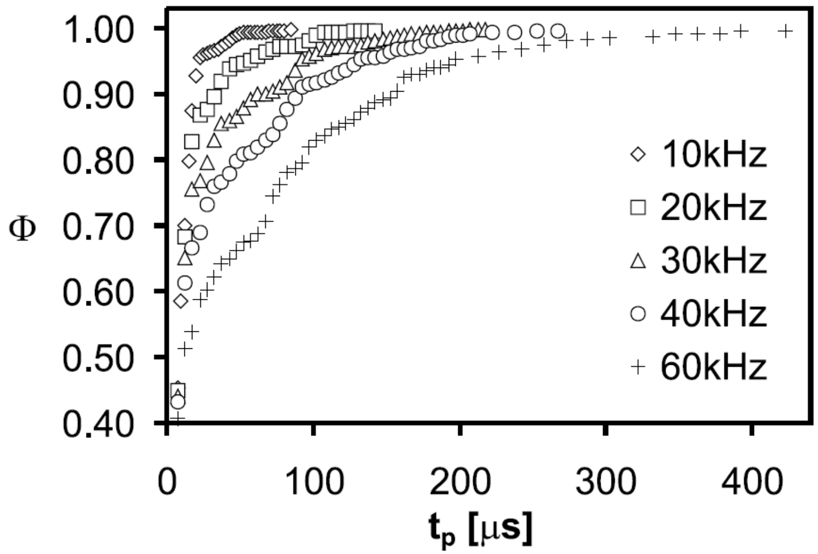
5./6. If $\omega_1(t) > \omega_{max}$ set $\omega_1(t) = \omega_{max}$

500 µs BEBOP with max. Ampl.

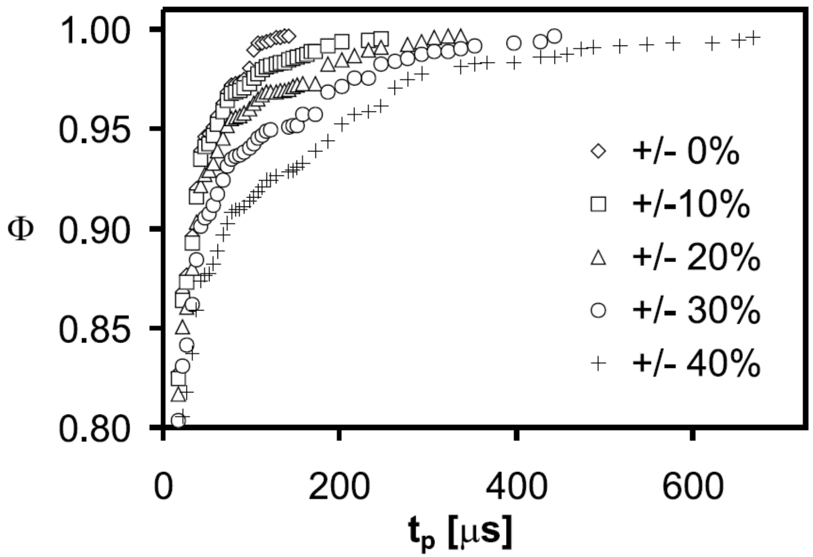




Limits of Excitation



Offset

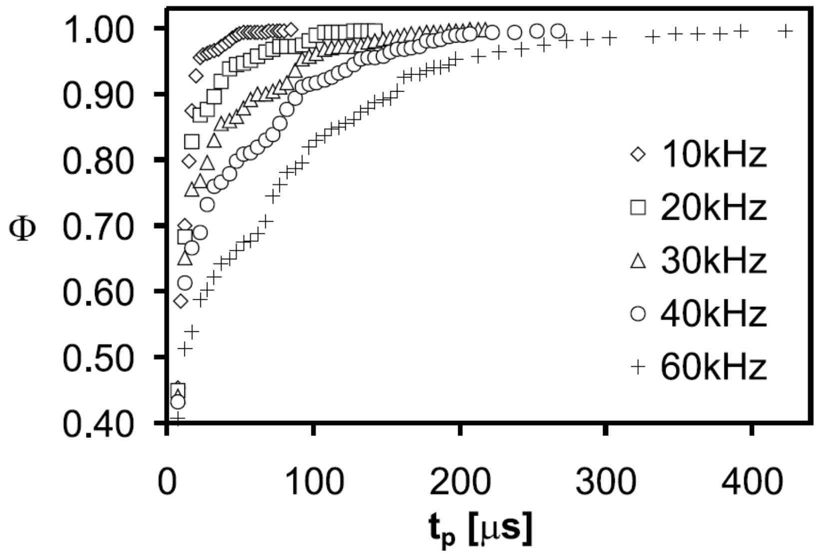


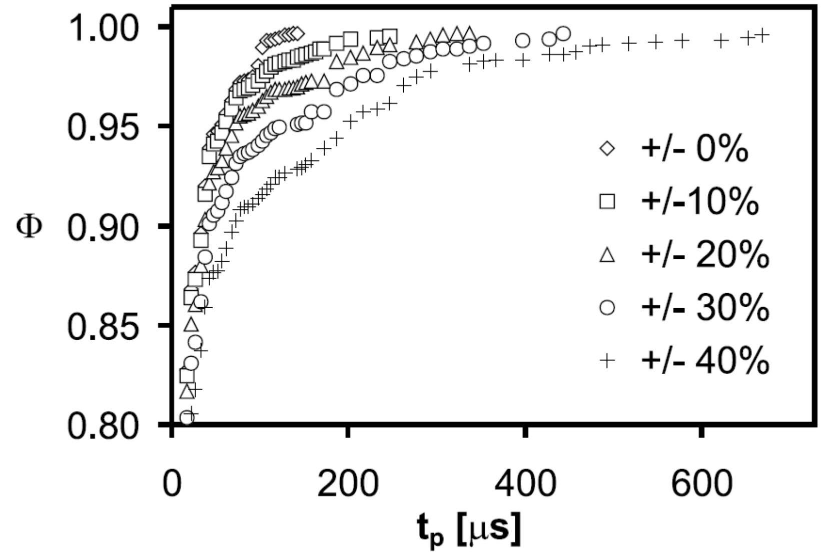
B_1-Inhomogeneity

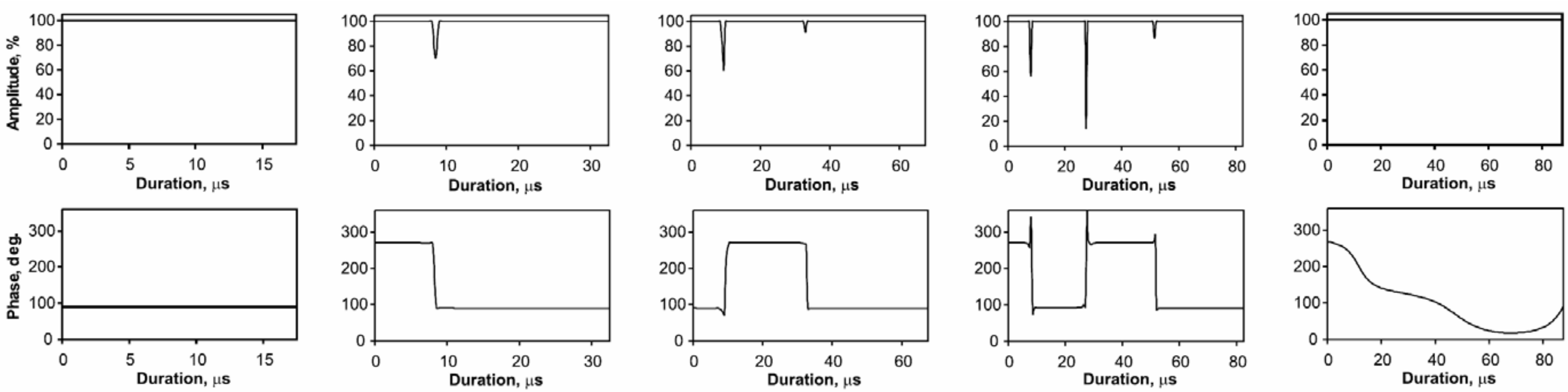
RF-Limit: 10 kHz

*K. Kobzar et al., JMR **173**, 229 (2005).*

Limits of Excitation

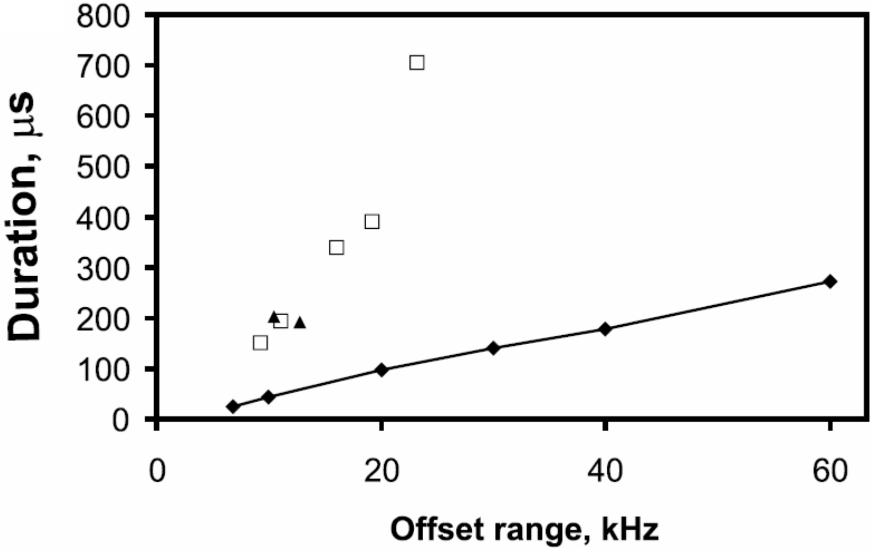


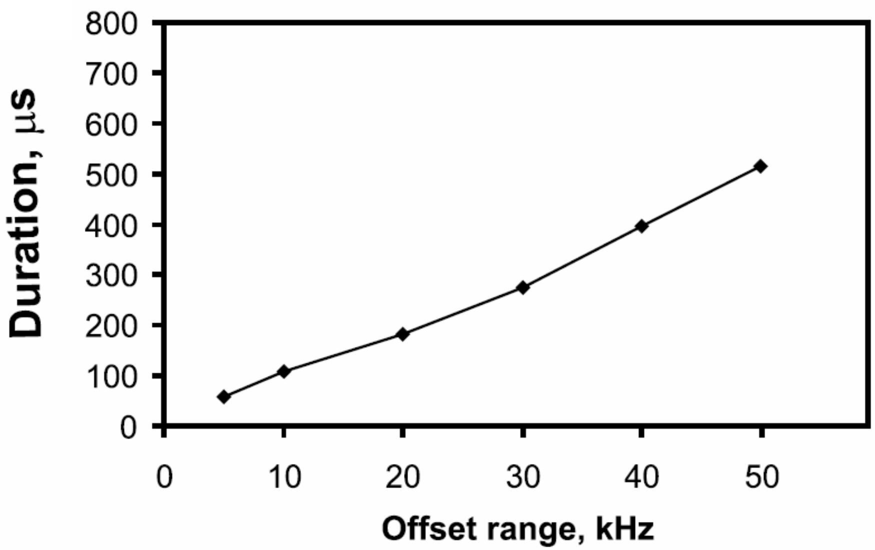




*K. Kobzar et al., JMR **173**, 229 (2005).*

Limits of Excitation



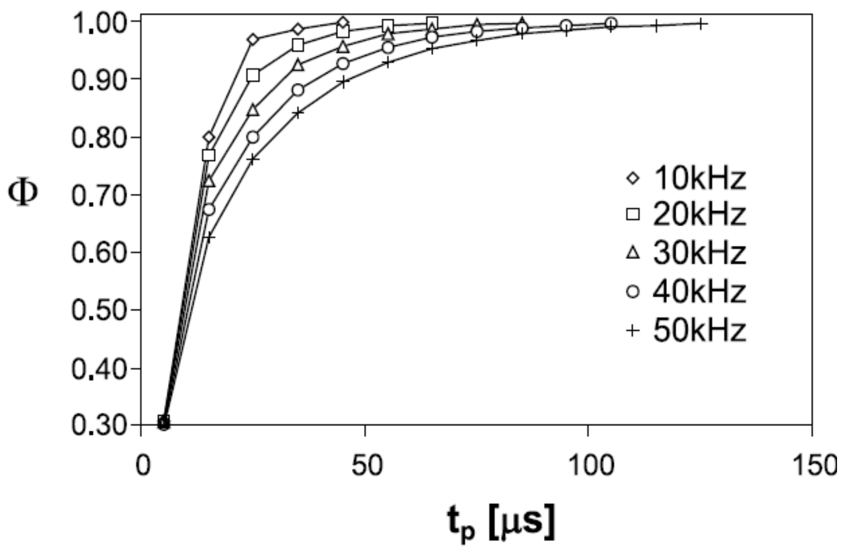


± 0% B_1 ± 20% B_1

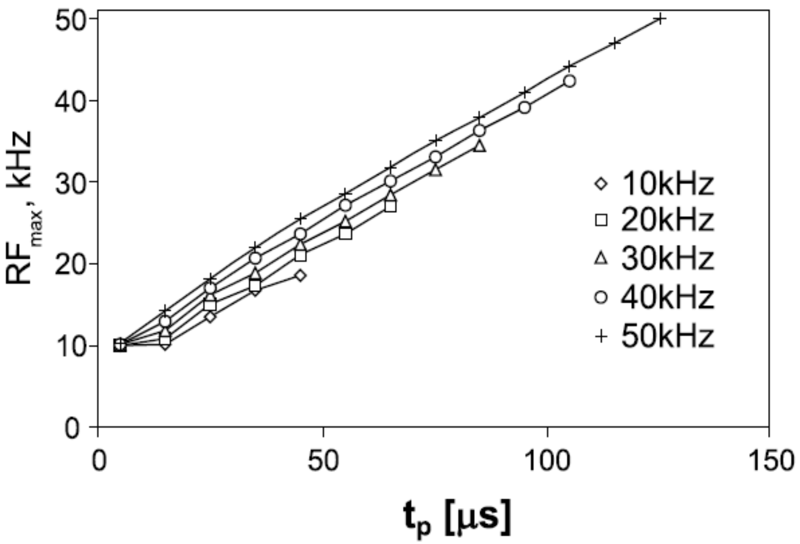
Comparison with other excitation pulses

K. Kobzar et al., JMR ***173****, 229 (2005).*

RF-Energy Limits of Excitation



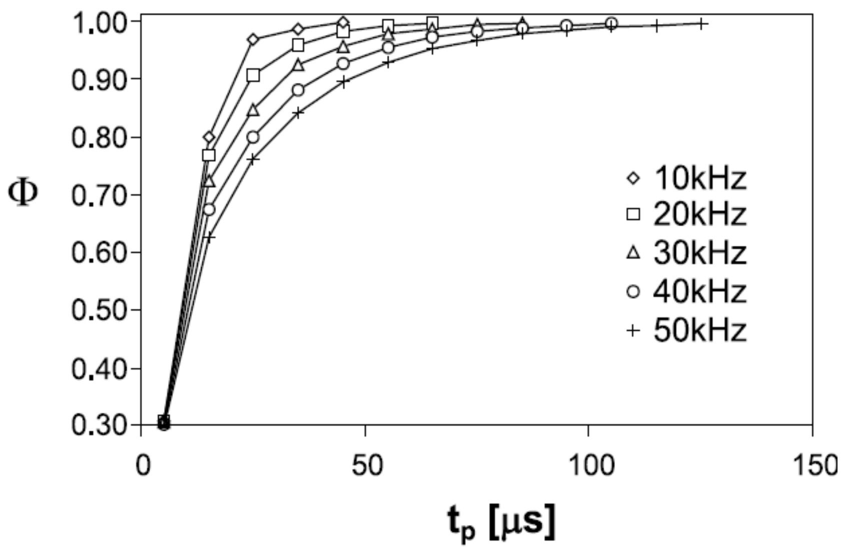
Offset

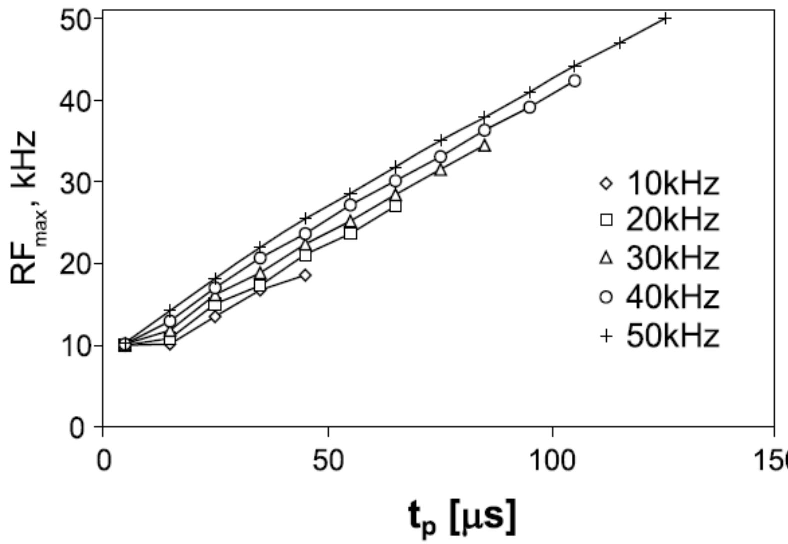


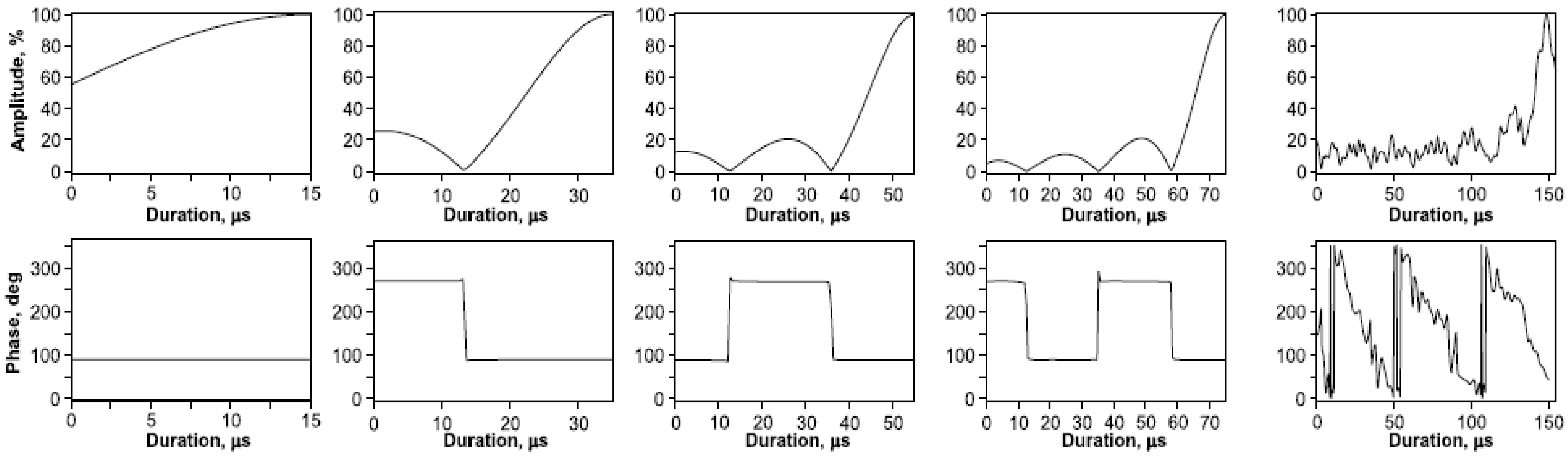
max. ampl.

restricted to RF-energy of const. ampl. 10 kHz pulse

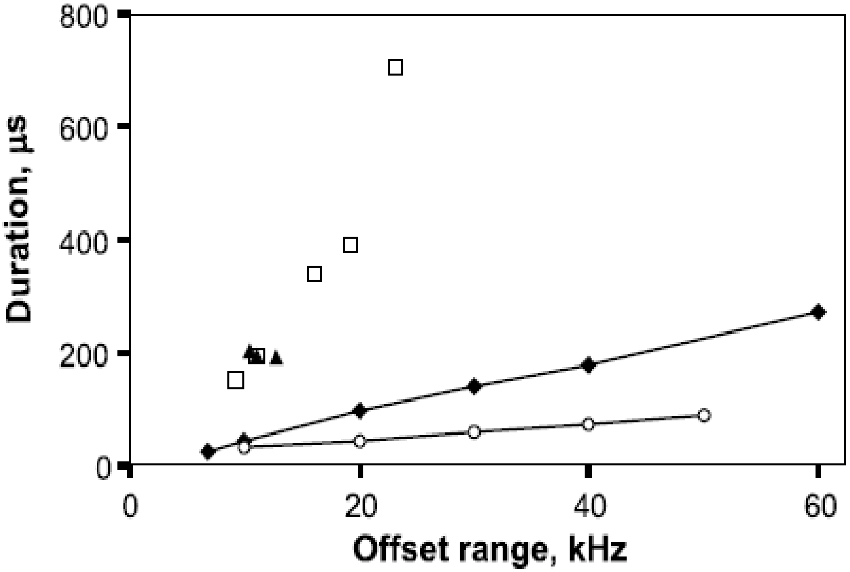
RF-Energy Limits of Excitation

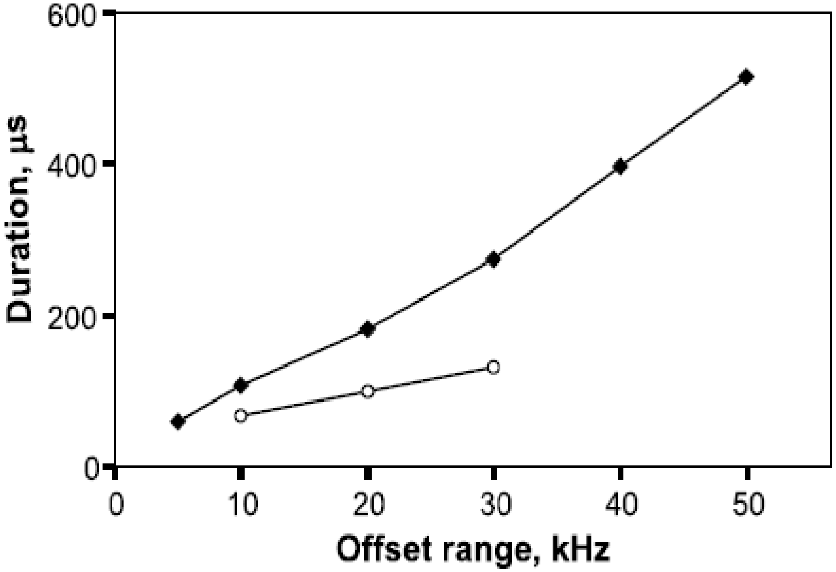






RF-Energy Limits of Excitation

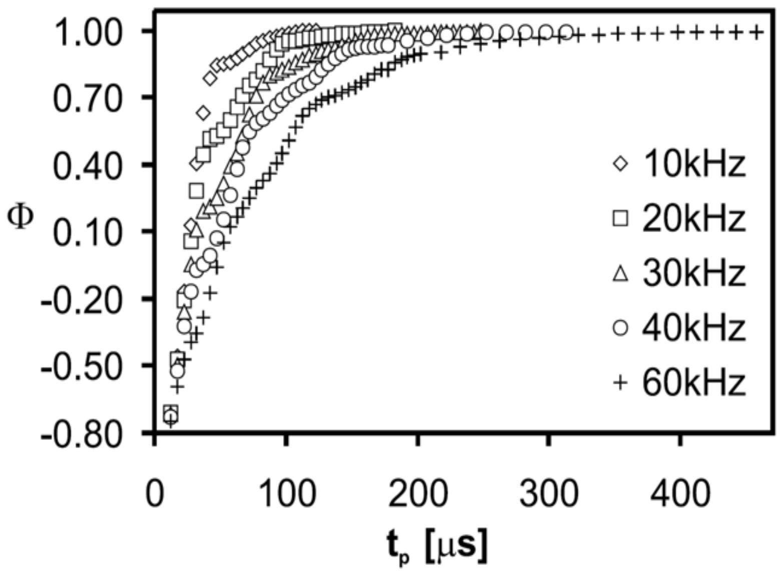




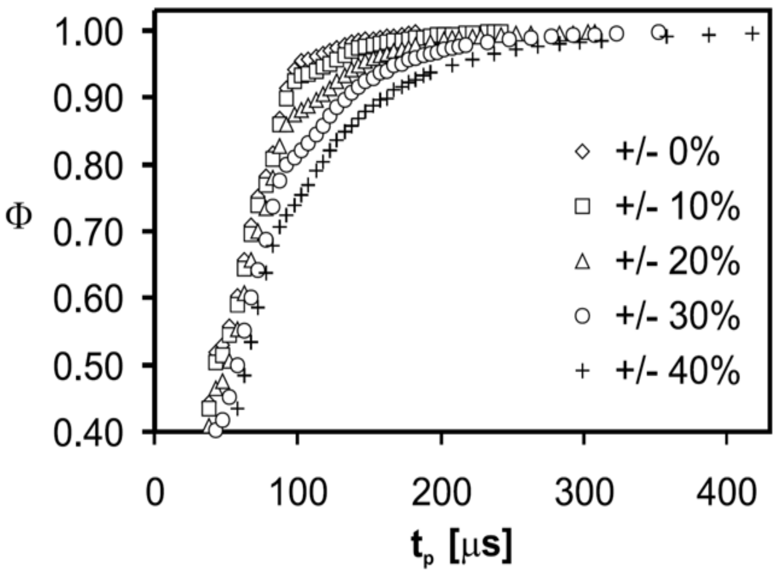
$\pm$ 0% B_1

$\pm$ 20% B_1

Limits of Inversion



Offset

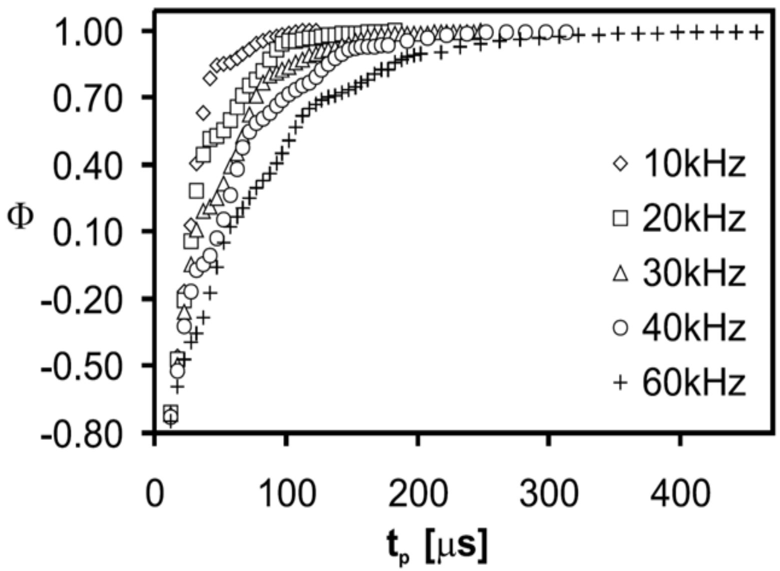


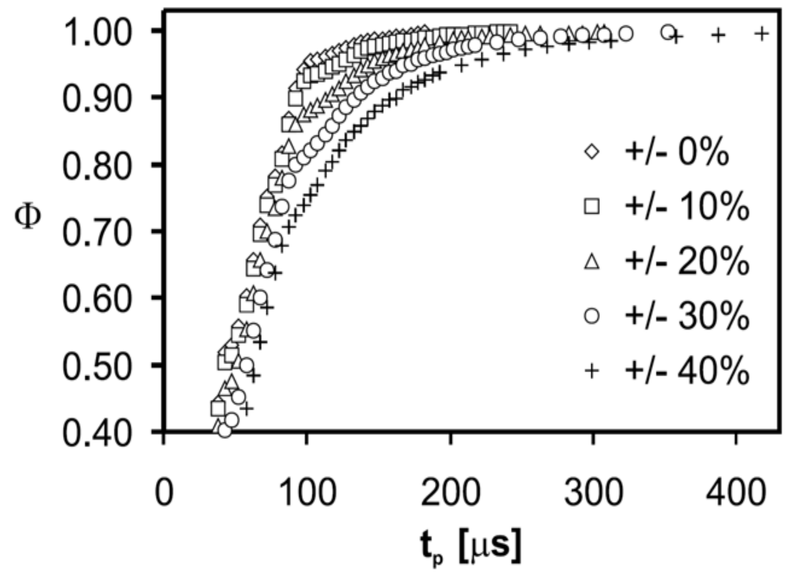
B_1-Inhomogeneity

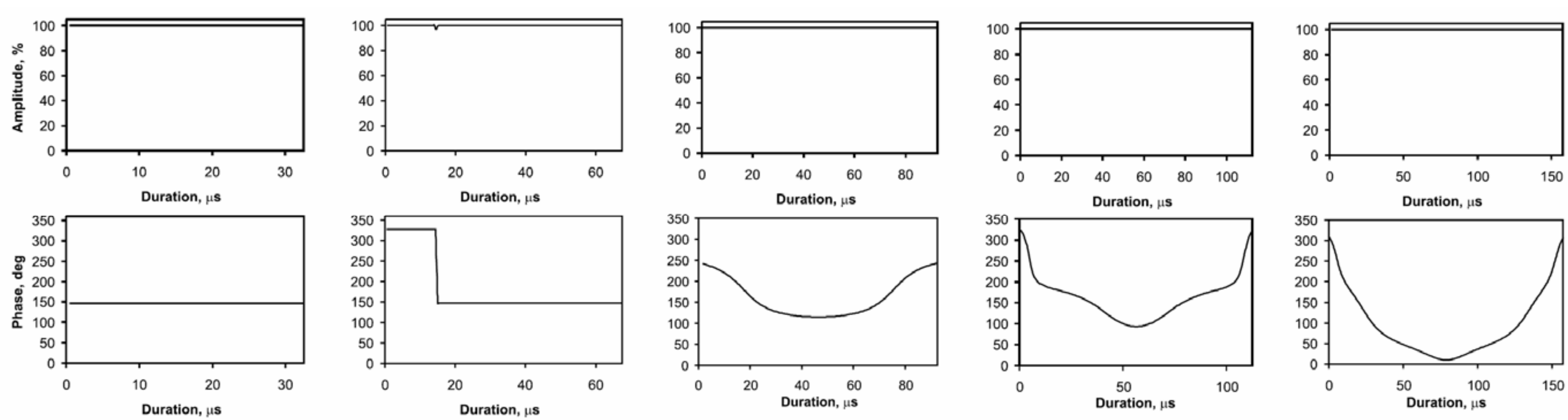
RF-Limit: 10 kHz

*K. Kobzar et al., JMR **173**, 229 (2005).*

Limits of Inversion



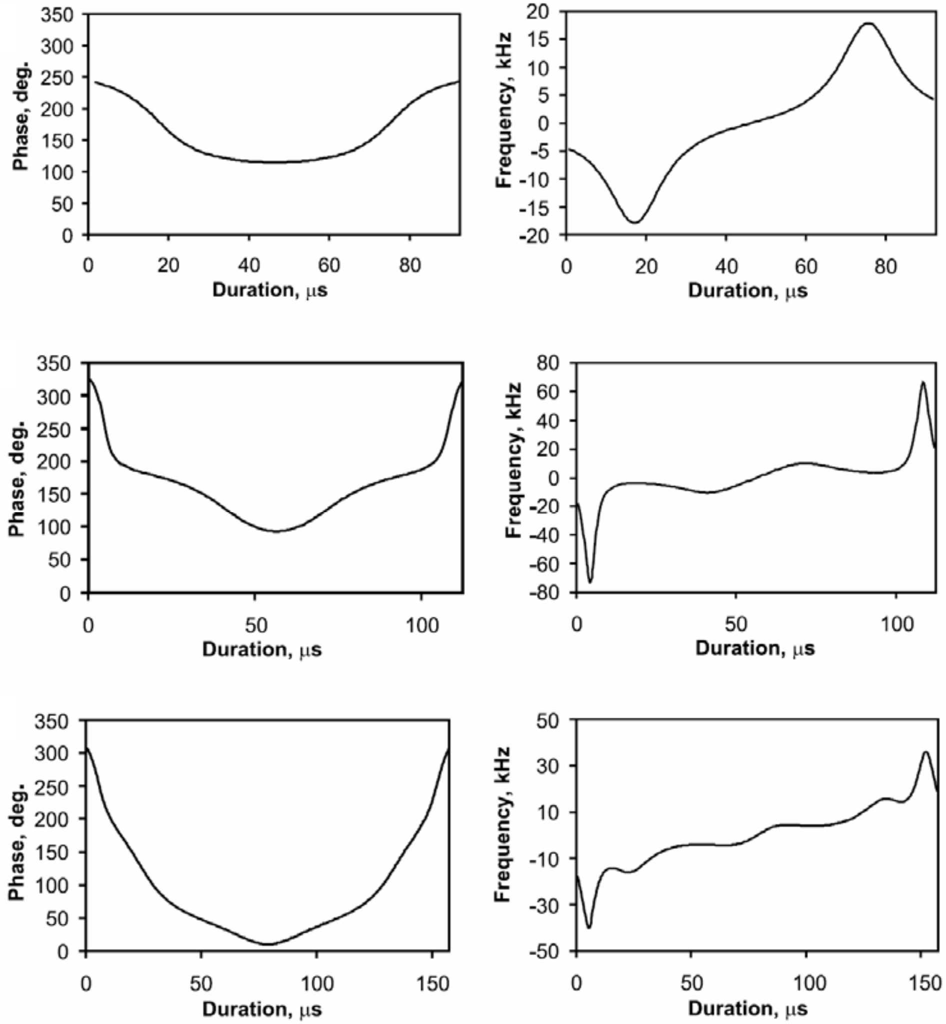




K. Kobzar et al., *JMR* **173**, 229 (2005).

„Half-adiabatic“ Inversion Pulses

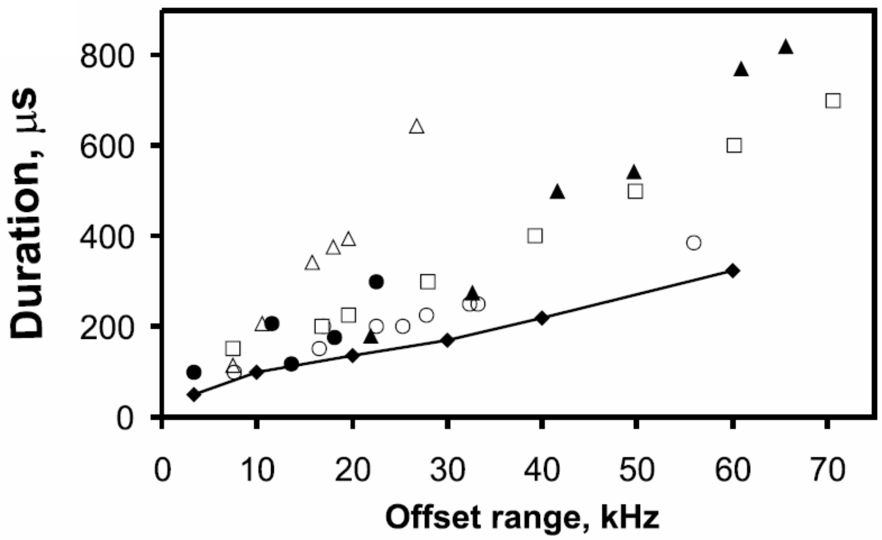
Phase

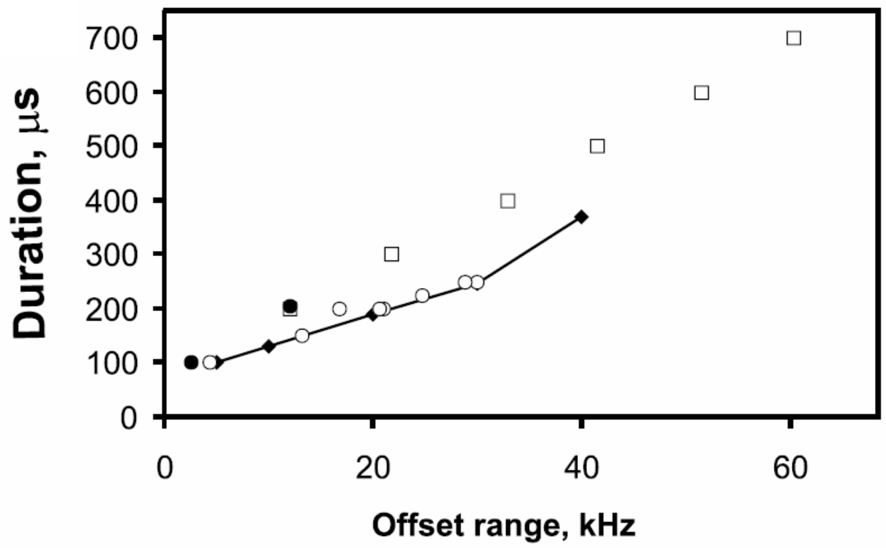


Frequency

K. Kobzar et al., JMR ***173****, 229 (2005).*

Limits of Inversion





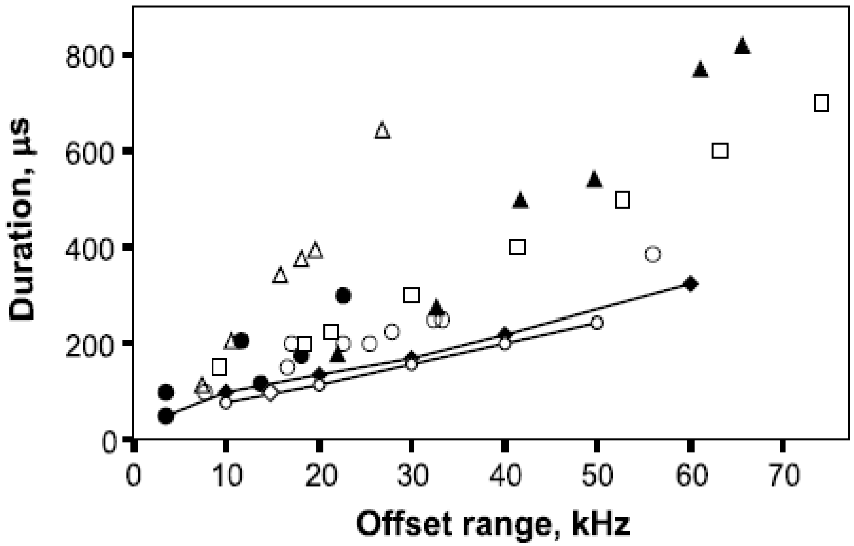
± 0% B_1

± 20% B_1

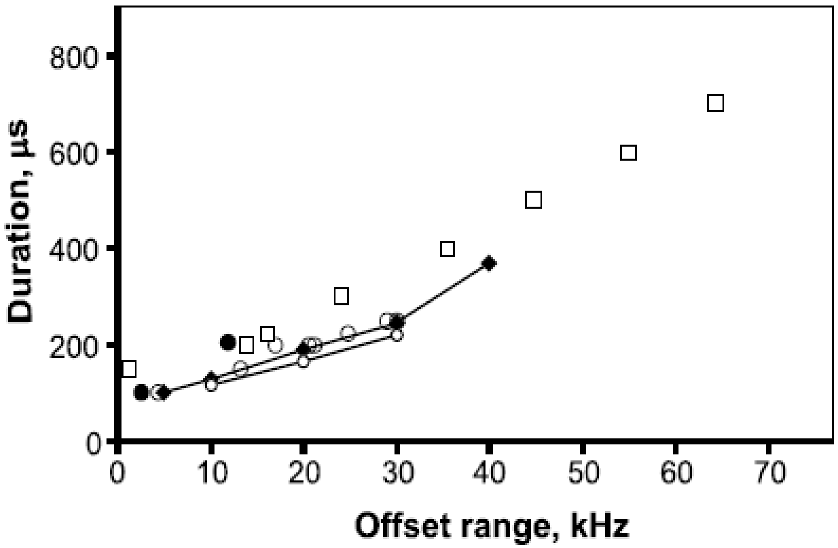
Comparison with other inversion pulses

K. Kobzar et al., JMR ***173****, 229 (2005).*

Limits of Inversion



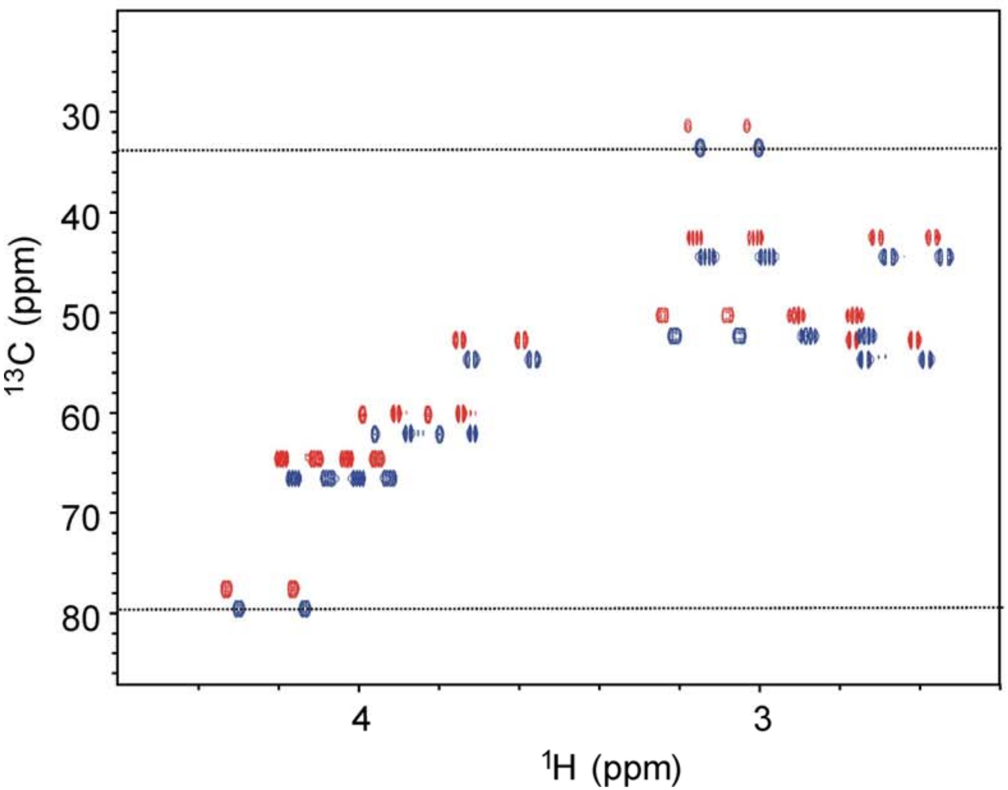
± 0% B_1

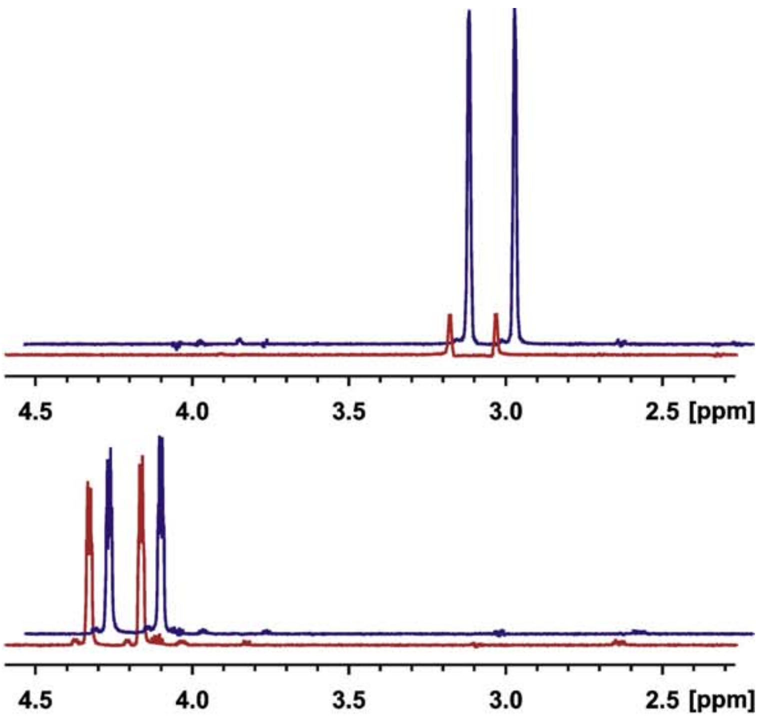


± 20% B_1

Comparison with other inversion pulses

BEBOP/BIBOP and hard Pulses





CLIP-HSQC (900MHz) with and without BEBOP/BIBOP on ^{13}C

Why bother with NMR spectroscopy?

Broadband ‘State-To-State’ Pulses

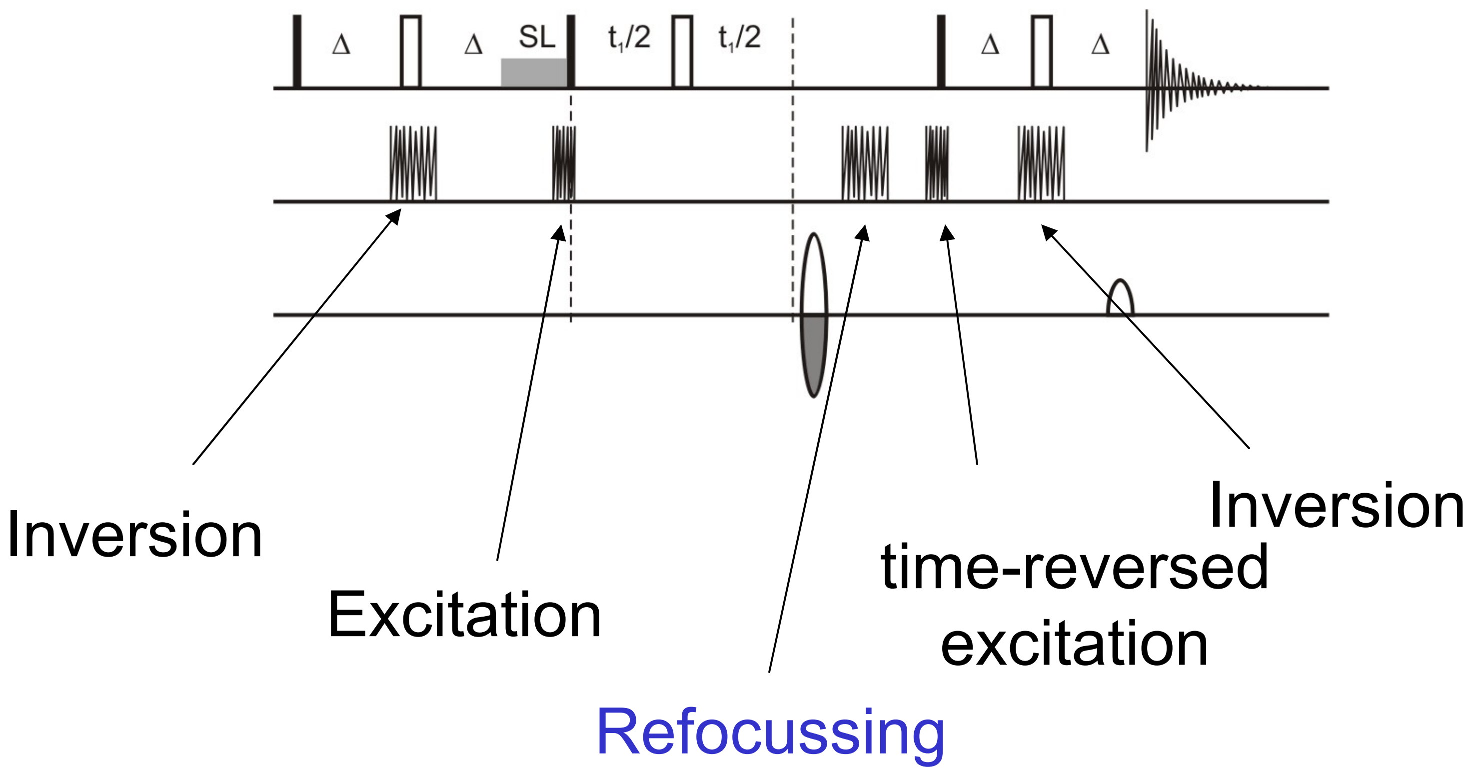
Broadband ‘Universal Rotation’ Pulses

Ultrabroadband Excitation

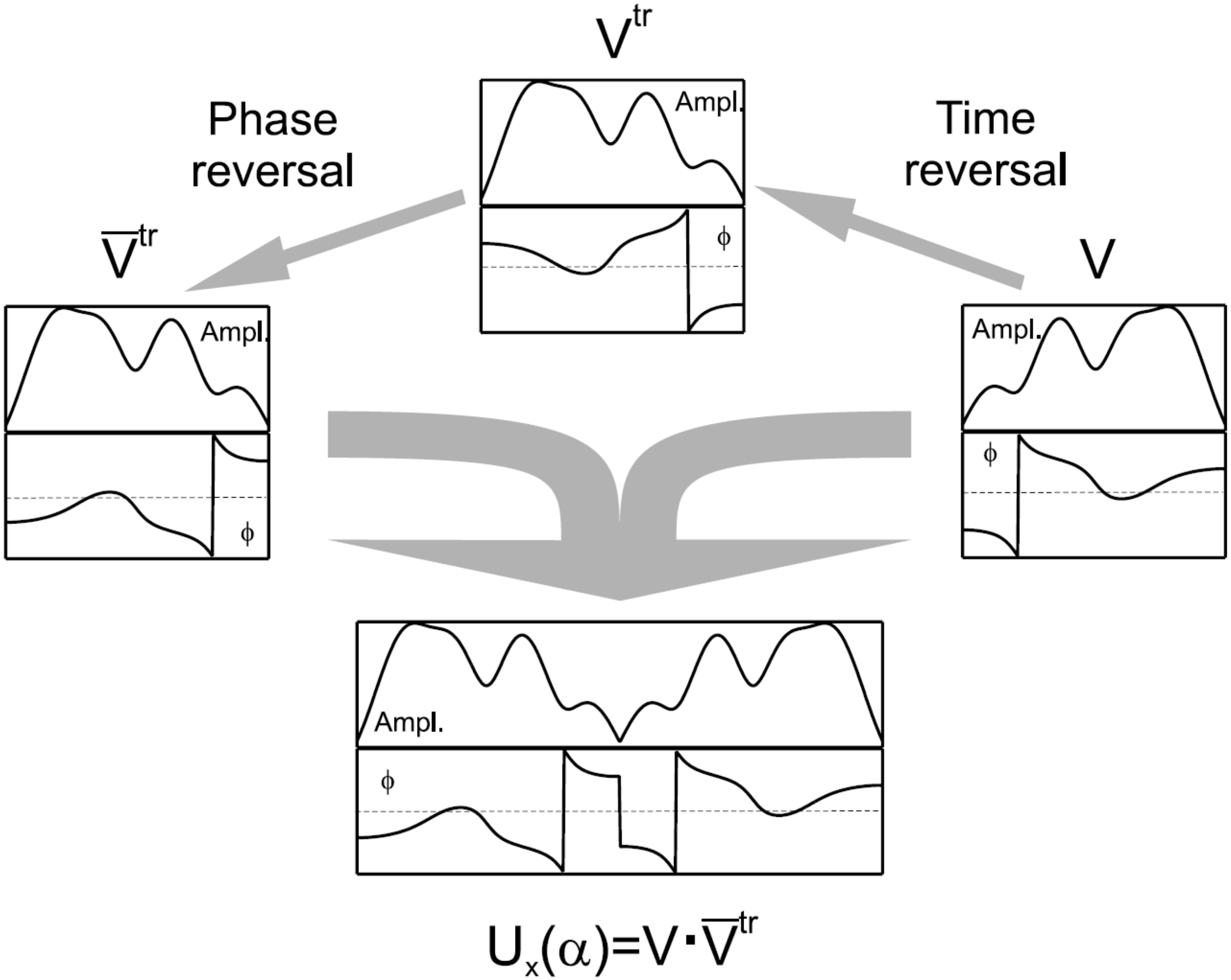
Pattern Pulses

UR-Pulses

HSQC with ^{13}C-BEBOP/BIBOP



Construction Principle for UR Pulses

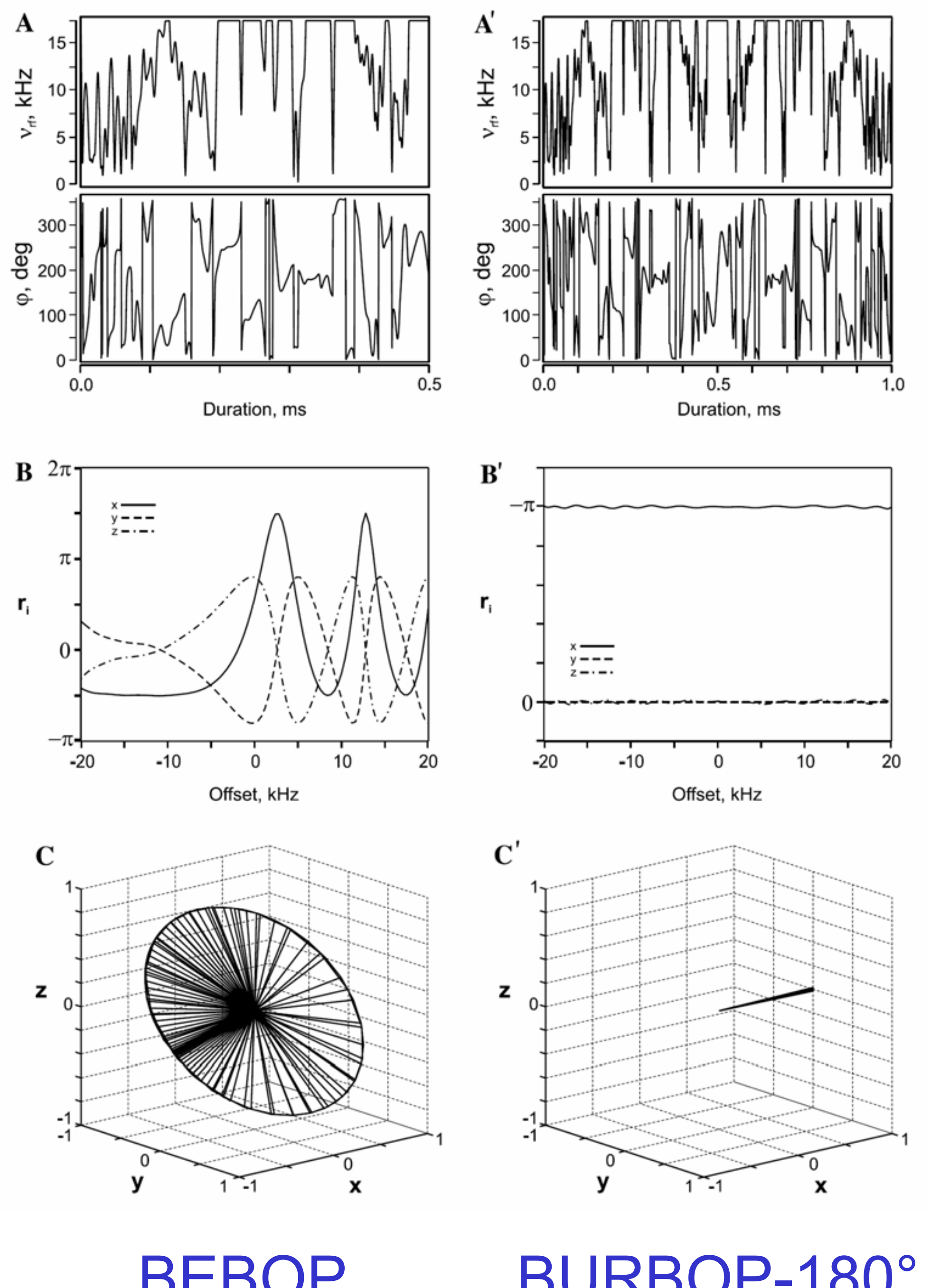


V = State-to-State Pulse

half flip angle α from I_y

B. Luy et al., JMR ***176****, 179 (2005).*

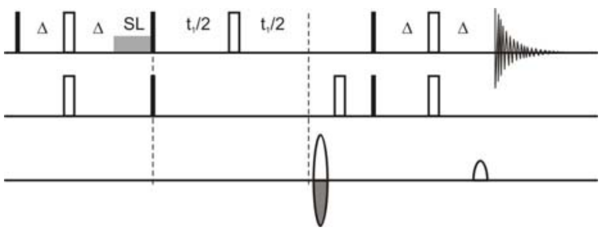
Example: Refocussing from 2 x BEBOP

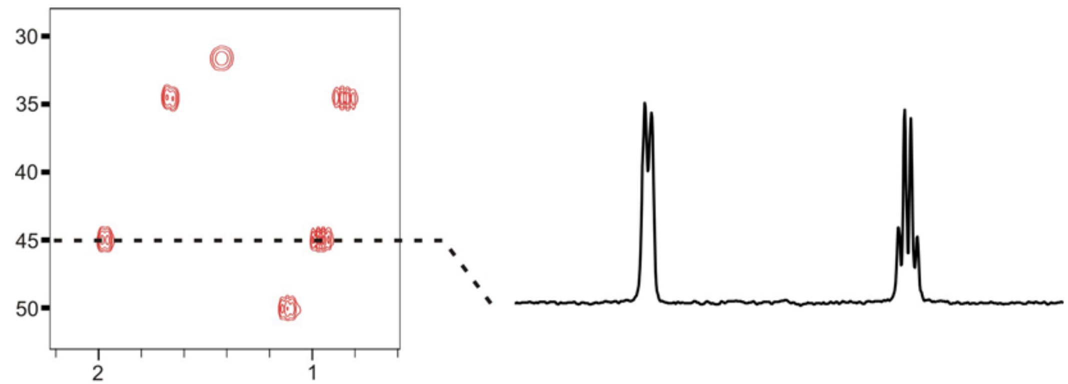


B. Luy et al., JMR ***176***, *179 (2005).*

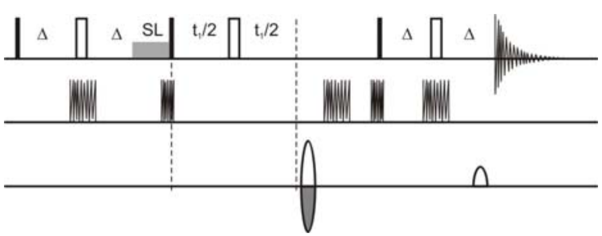
Almost Calibration-free 90°- and 180°-Pulses: HSQC of Menthol

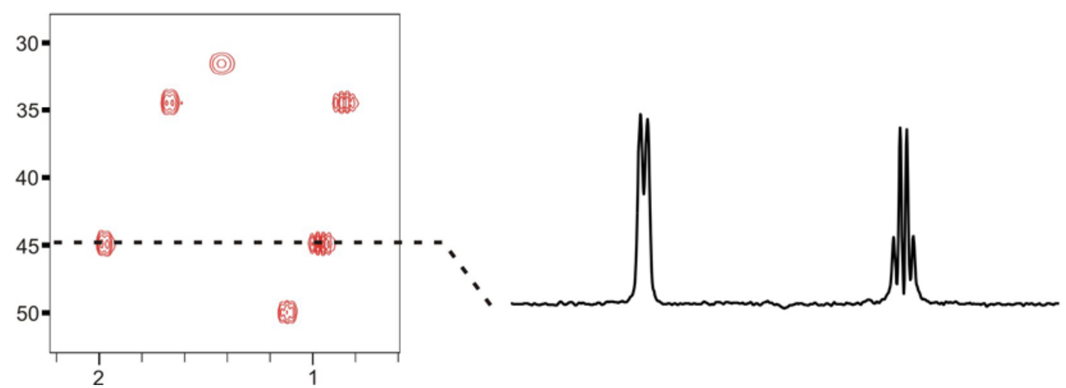
conventional HSQC





HSQC with ^{13}C-BEBOP

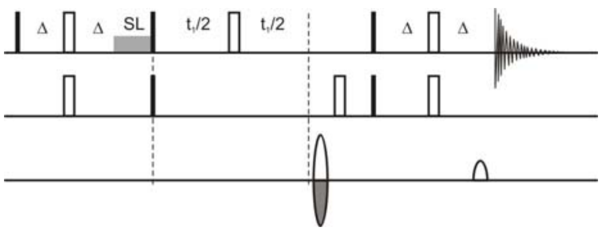


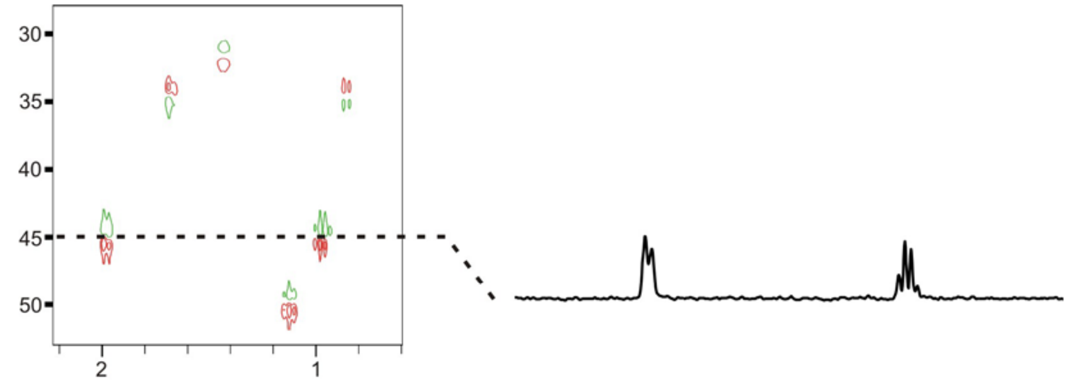


calibrated, no Offset

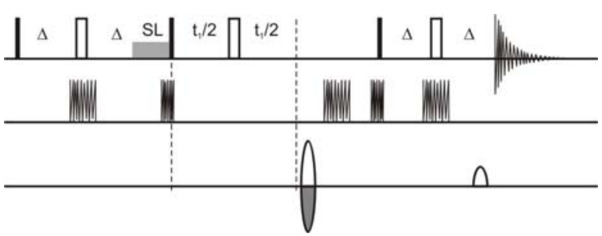
Almost Calibration-free 90°- and 180°-Pulses: HSQC of Menthol

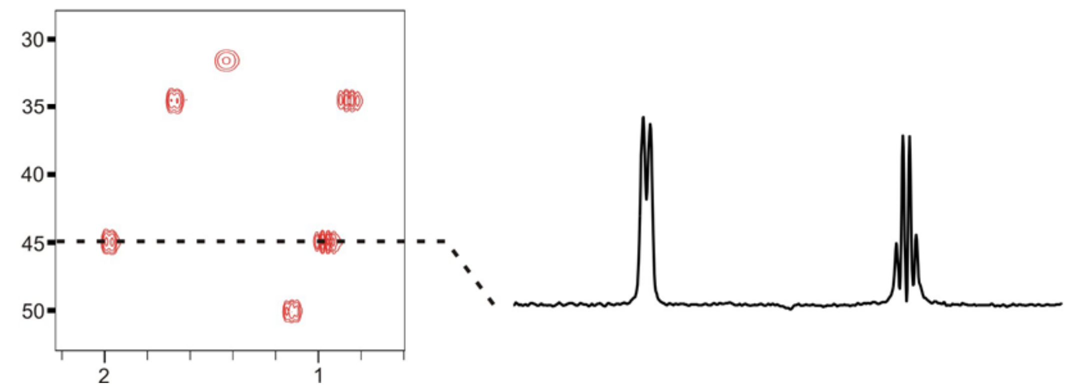
conventional HSQC





HSQC with ^{13}C-BEBOP

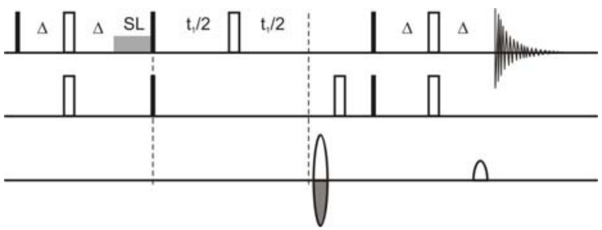


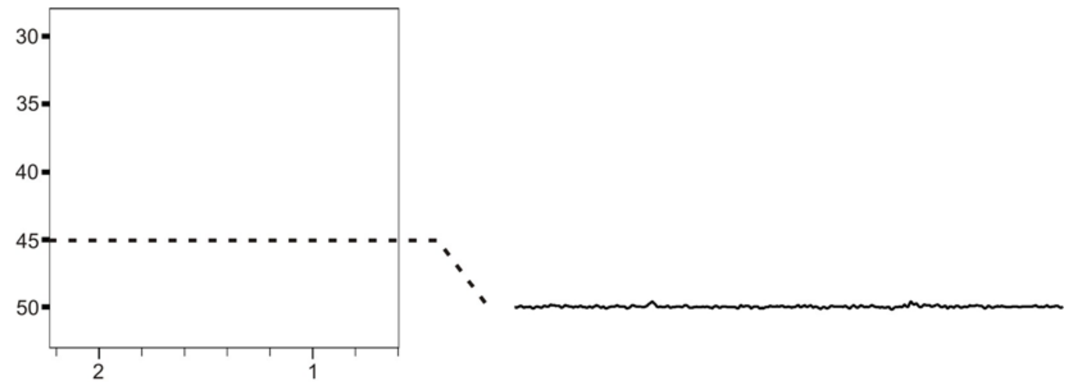


3dB miscalibrated, 8kHz Offset

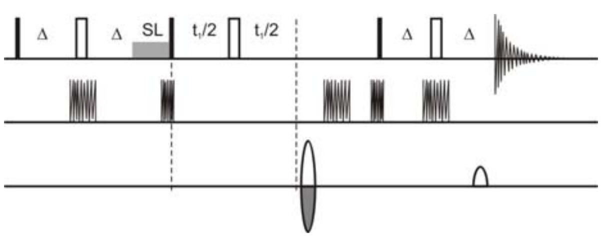
Almost Calibration-free 90°- and 180°-Pulses: HSQC of Menthol

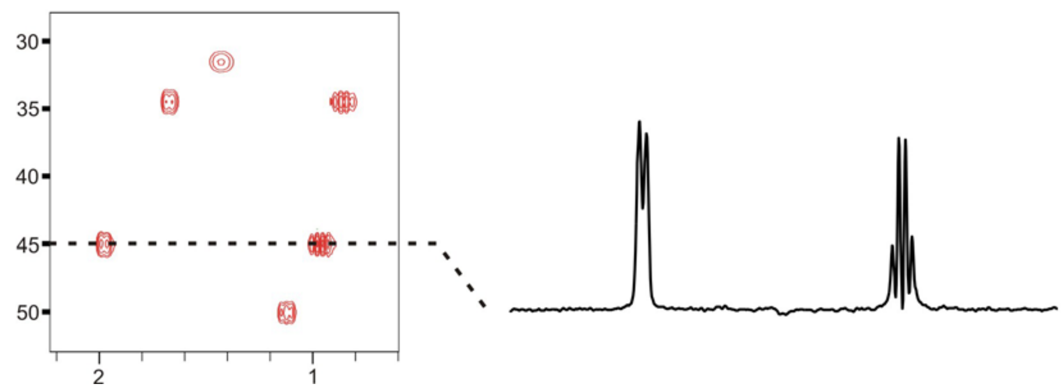
conventional HSQC





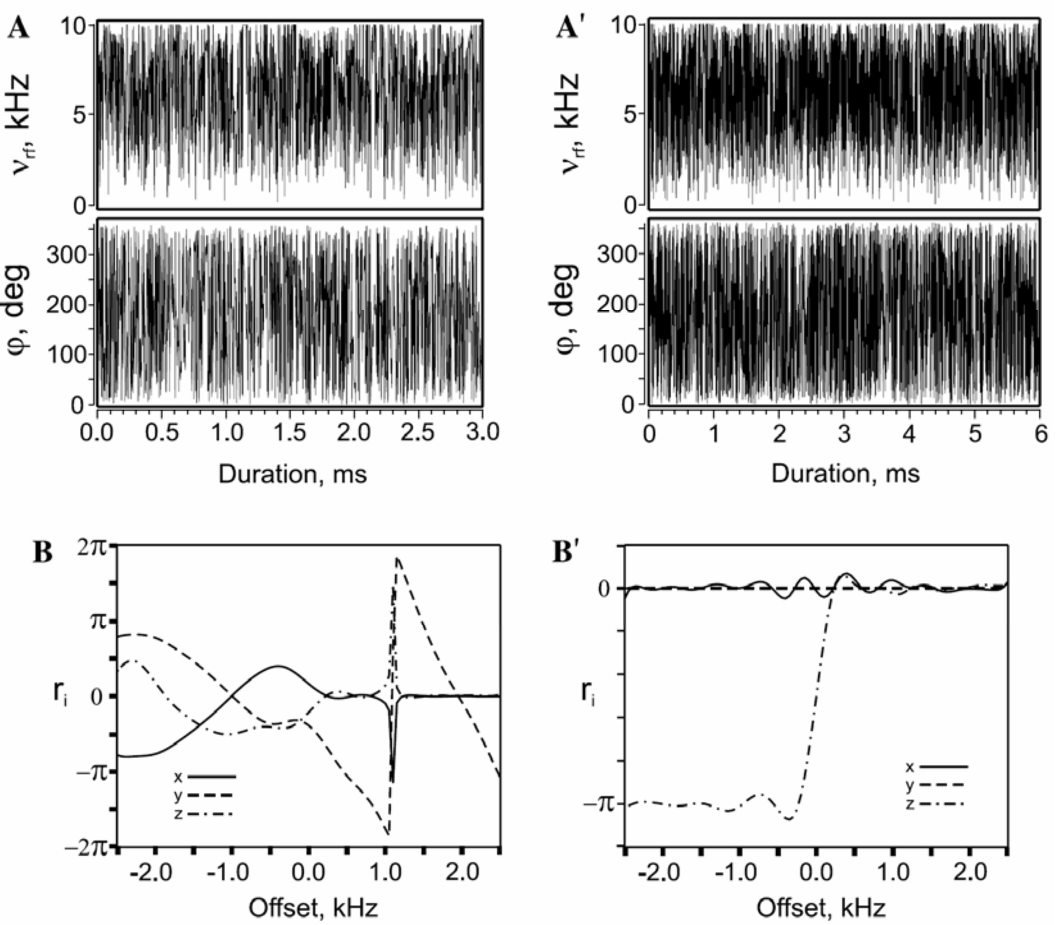
HSQC with ^{13}C-BEBOP

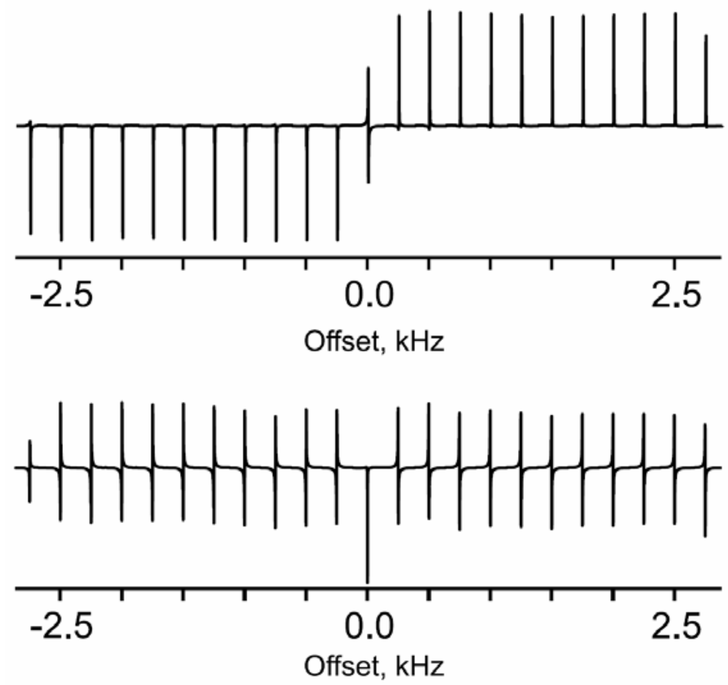




3dB miscalibrated, 16kHz Offset

Example: Construction of 180° z-Rotation





B. Luy et al., JMR ***176****, 179 (2005).*

Optimization of UR-Pulses from Scratch

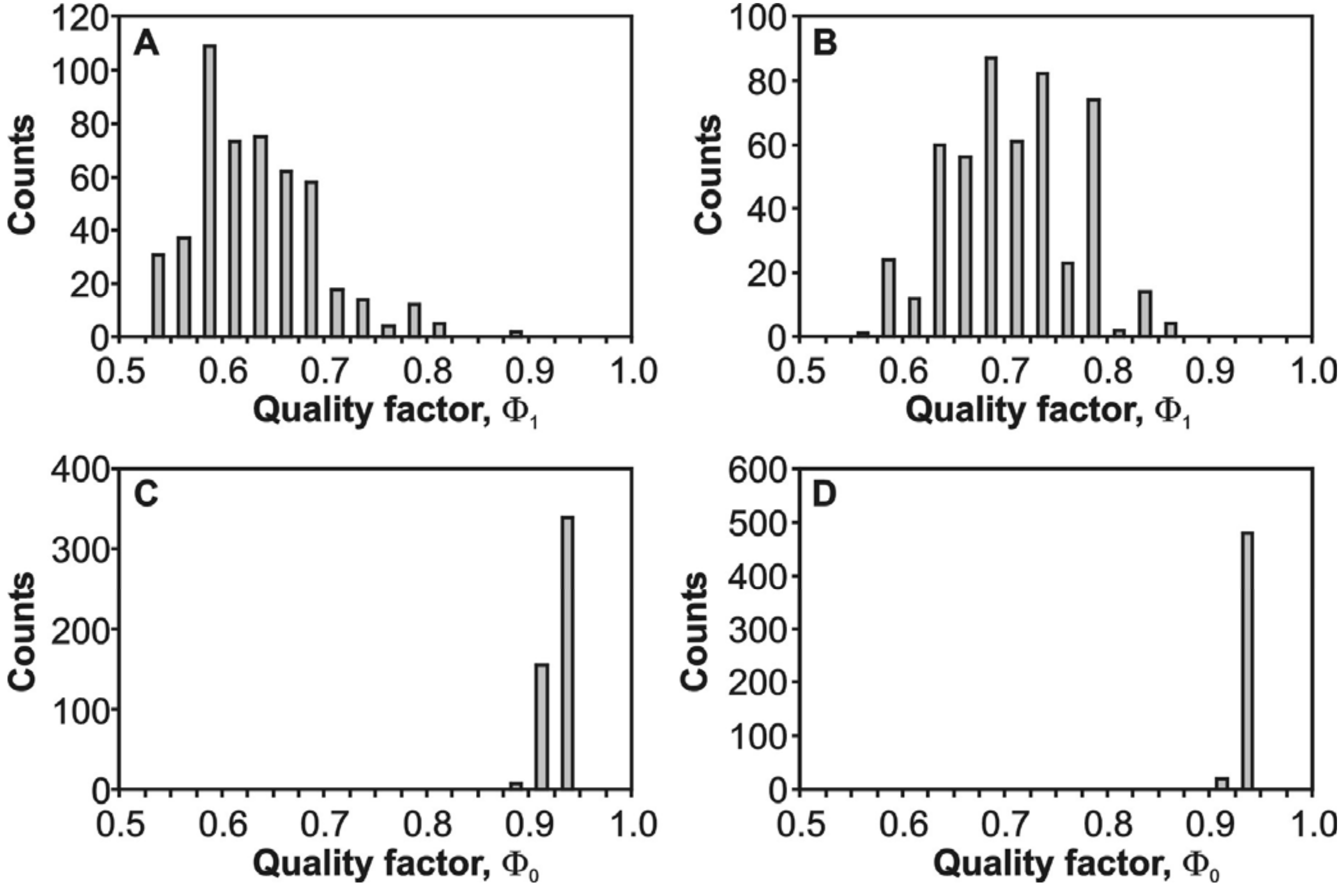
$$\Phi_1 = |\uparrow U_F \,|\, U(T) \Uparrow|^2$$

$$\Phi_0 = \mathrm{Re}\,\{\uparrow U_F \,|U(T) \Uparrow\}$$

Comparison of Convergence

Φ_1

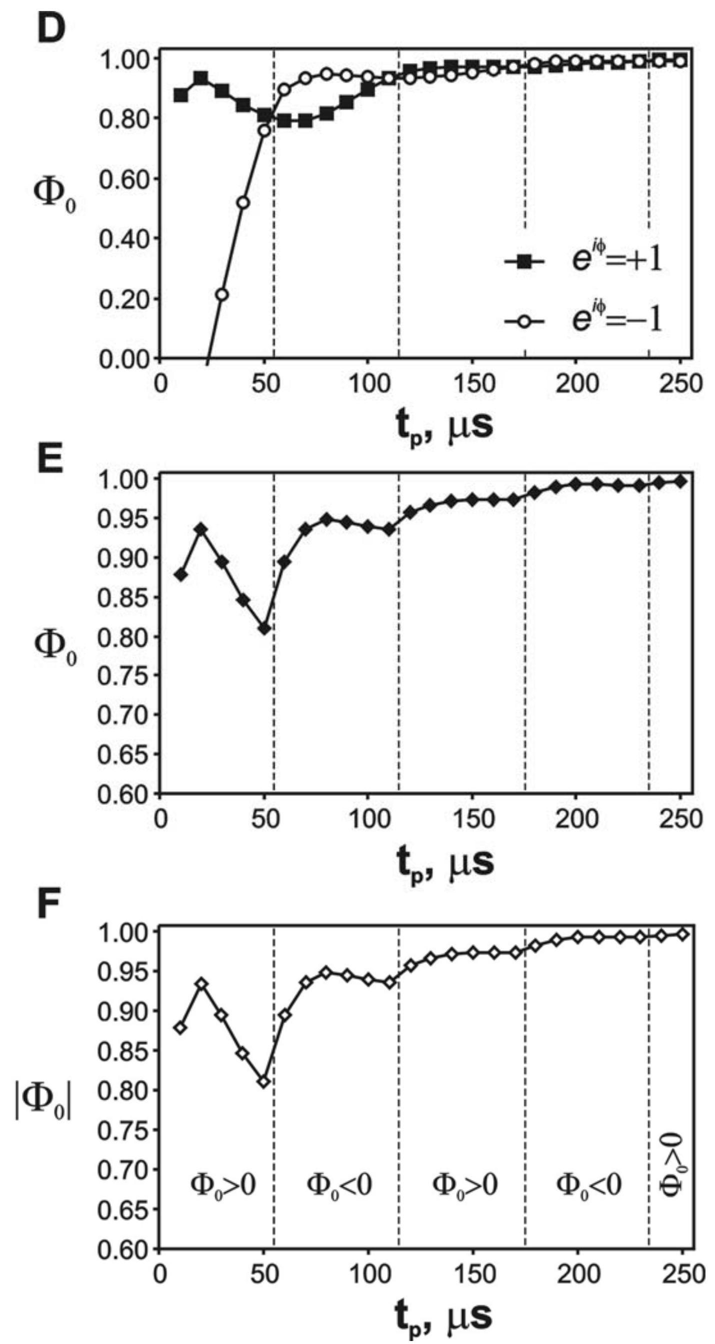
Φ_0



90°, 40kHz BW

180°, 40kHz BW

Comparison of Results for Φ_1 / Φ_0



90° UR-Pulse
20 kHz BW

(several unpublished slides have been removed. Please contact Burkhard.Luy@ch.tum.de if interested)

Why bother with NMR spectroscopy?

Broadband ‘State-To-State’ Pulses

Broadband ‘Universal Rotation’ Pulses

Ultrabroadband Excitation

Pattern Pulses

Chemical Shift Ranges (600 MHz)

^{1}H	~15 ppm / 9kHz
^{13}C (org.)	~250 ppm / 37kHz
^{15}N (org.)	~600 ppm / 36kHz

M. Hesse, H. Meier, B. Zeeh, Spectroscopic Methods in Organic Chemistry, Thieme (2008).

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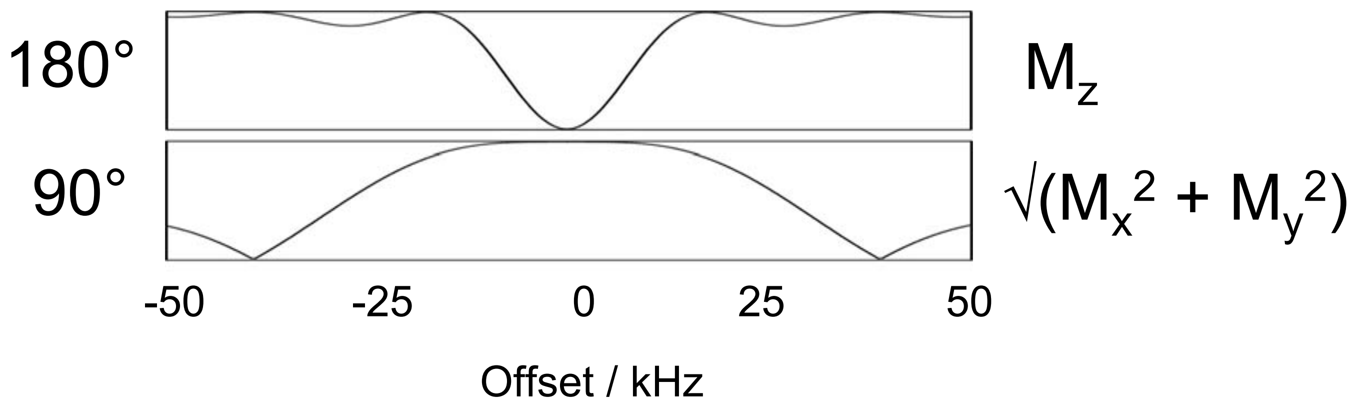
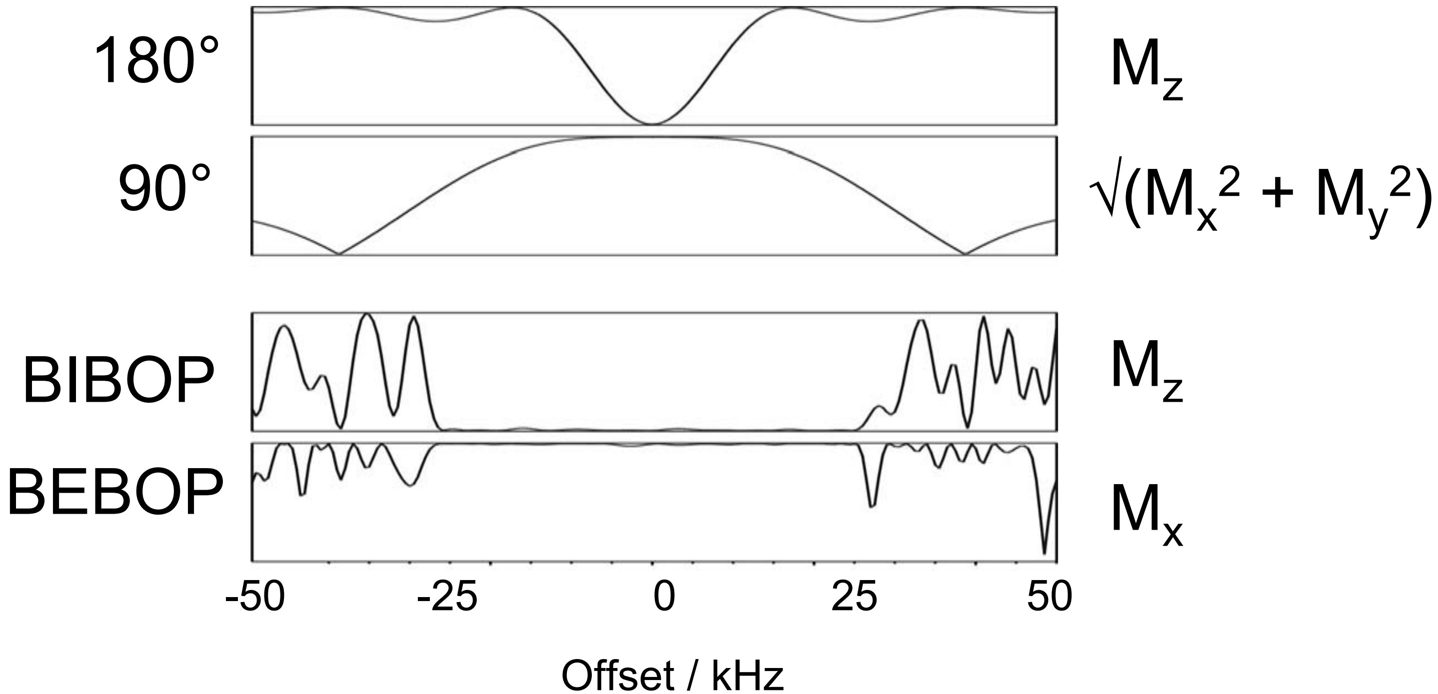


Chemical Shift Ranges (600 MHz)

^{1}H ↔ ~15 ppm / 9kHz

^{13}C (org.) ↔ ~250 ppm / 37kHz

^{15}N (org.) ↔ ~600 ppm / 36kHz



Chemical Shift Ranges (600 MHz)

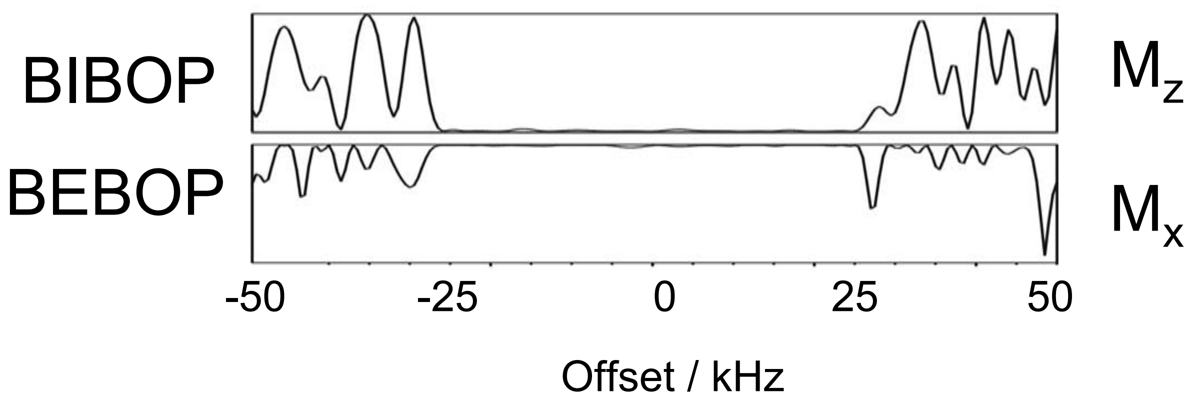
^{1}H ~15 ppm / 9kHz

^{13}C (org.) ~250 ppm / 37kHz

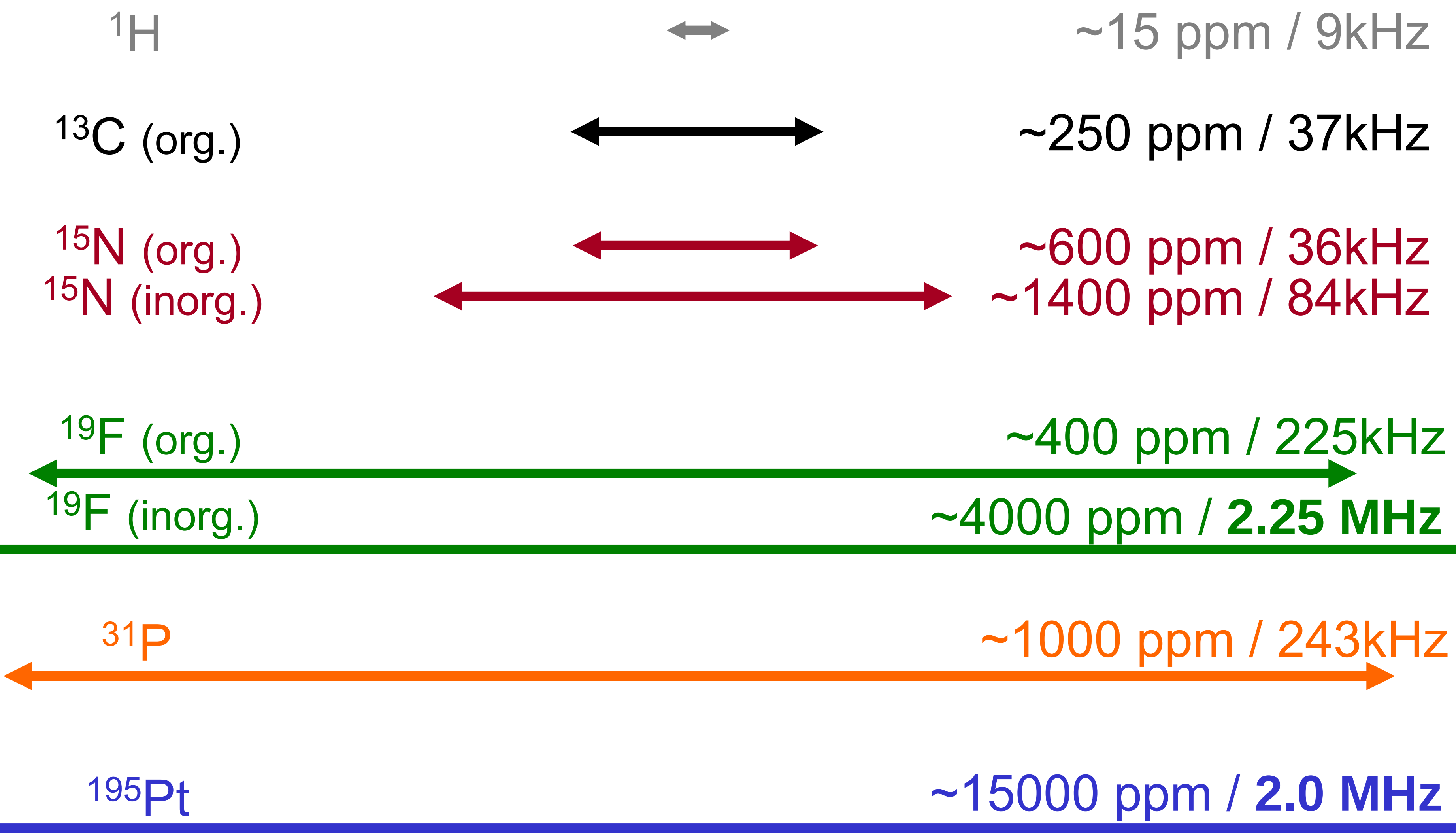
^{15}N (org.) ~600 ppm / 36kHz

^{19}F (org.) ~400 ppm / 225kHz

^{31}P ~1000 ppm / 243kHz

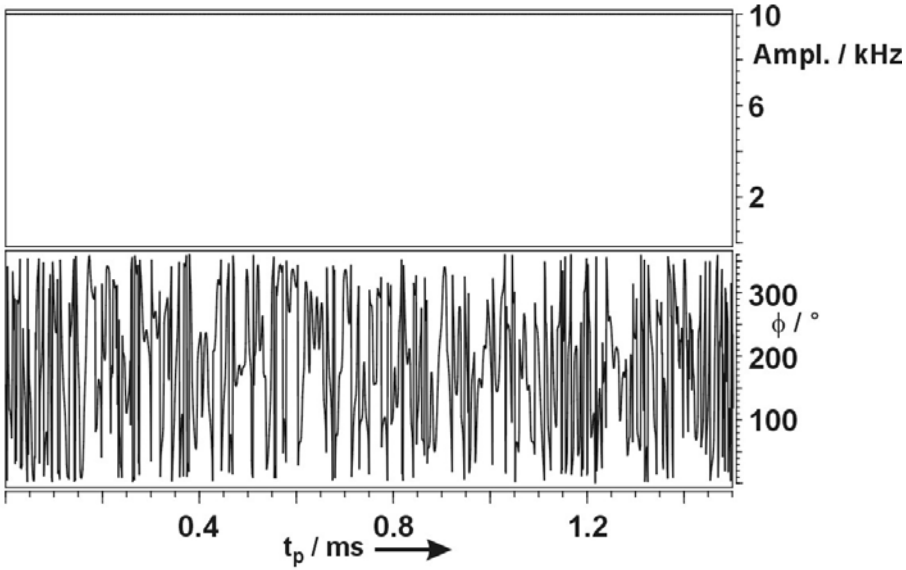


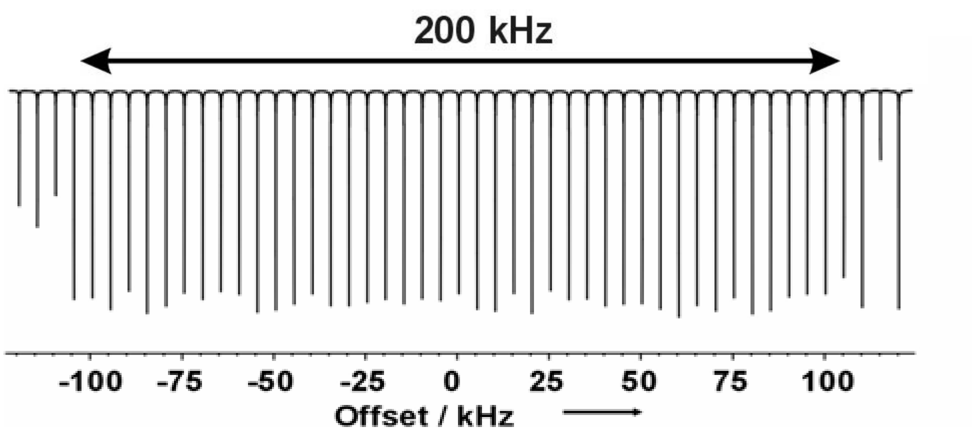
Chemical Shift Ranges (600 MHz)



M. Hesse, H. Meier, B. Zeeh, Spectroscopic Methods in Organic Chemistry, Thieme (2008).

Situation at 200 kHz Bandwidth





For 10 kHz RF-amplitude:

- BIBOP inversion pulse
  1.5 ms duration

- **no** excitation pulse ○ 2 ms

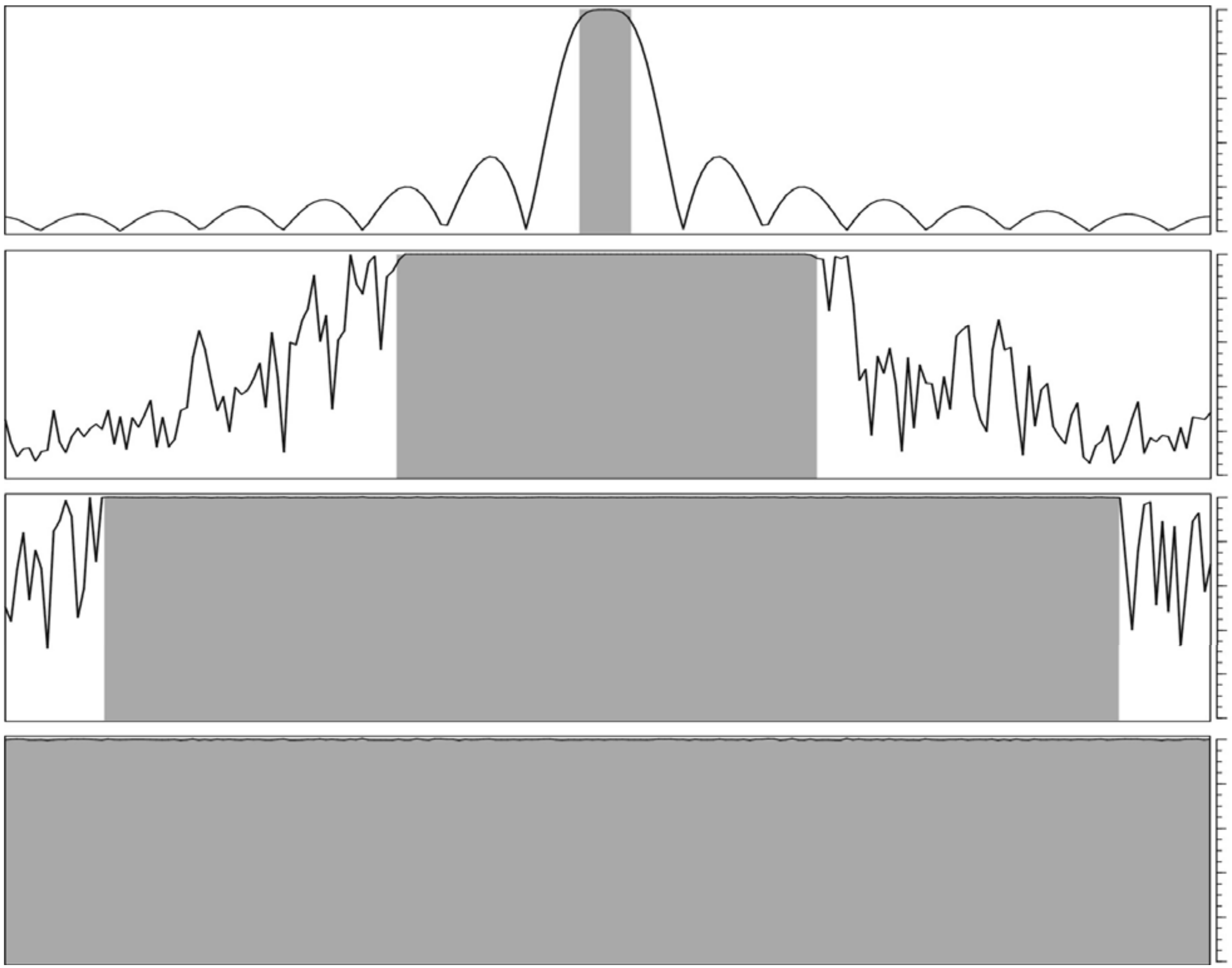
- **no** refocussing pulse ○ 2 ms

no conventional NMR possible !

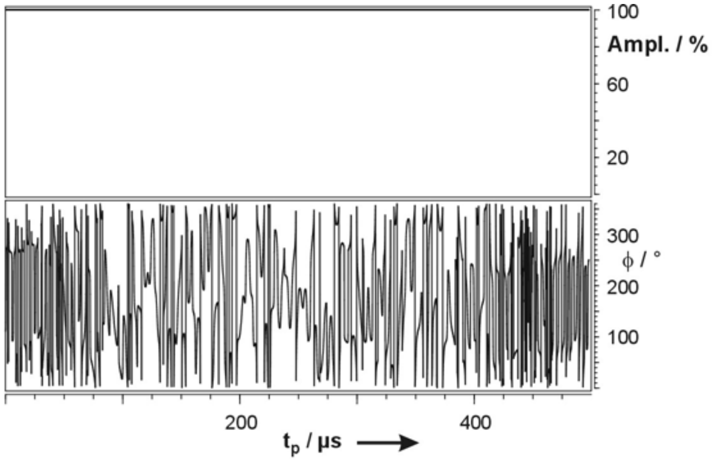
K. Kobzar, B. Luy, unpublished.

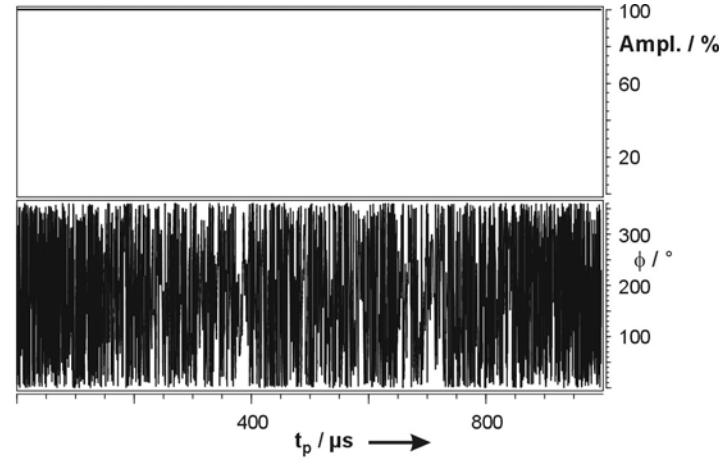
(several unpublished slides have been removed. Please contact Burkhard.Luy@ch.tum.de if interested)

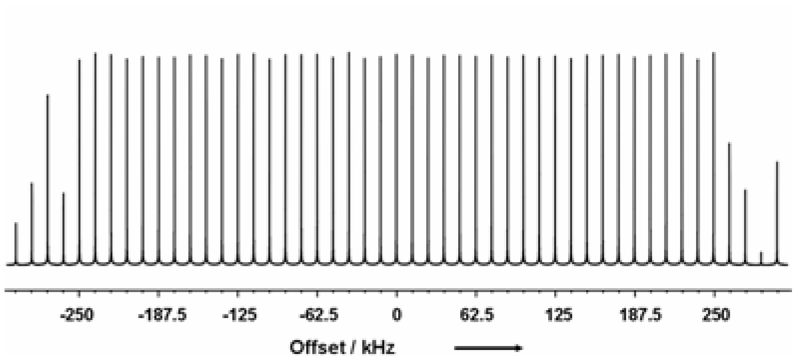
Even Larger Bandwidths ?

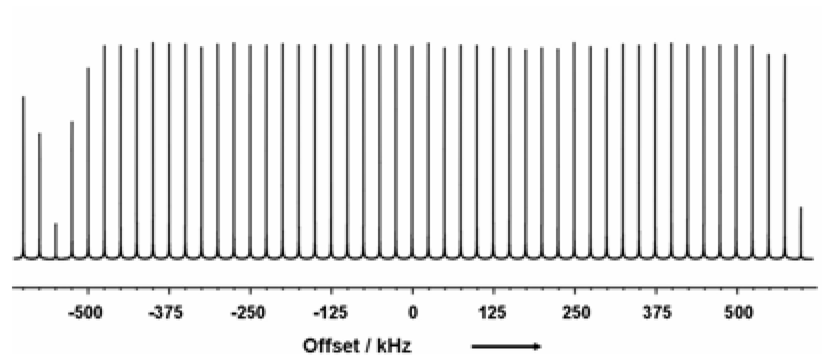


Reaching the MHz ...



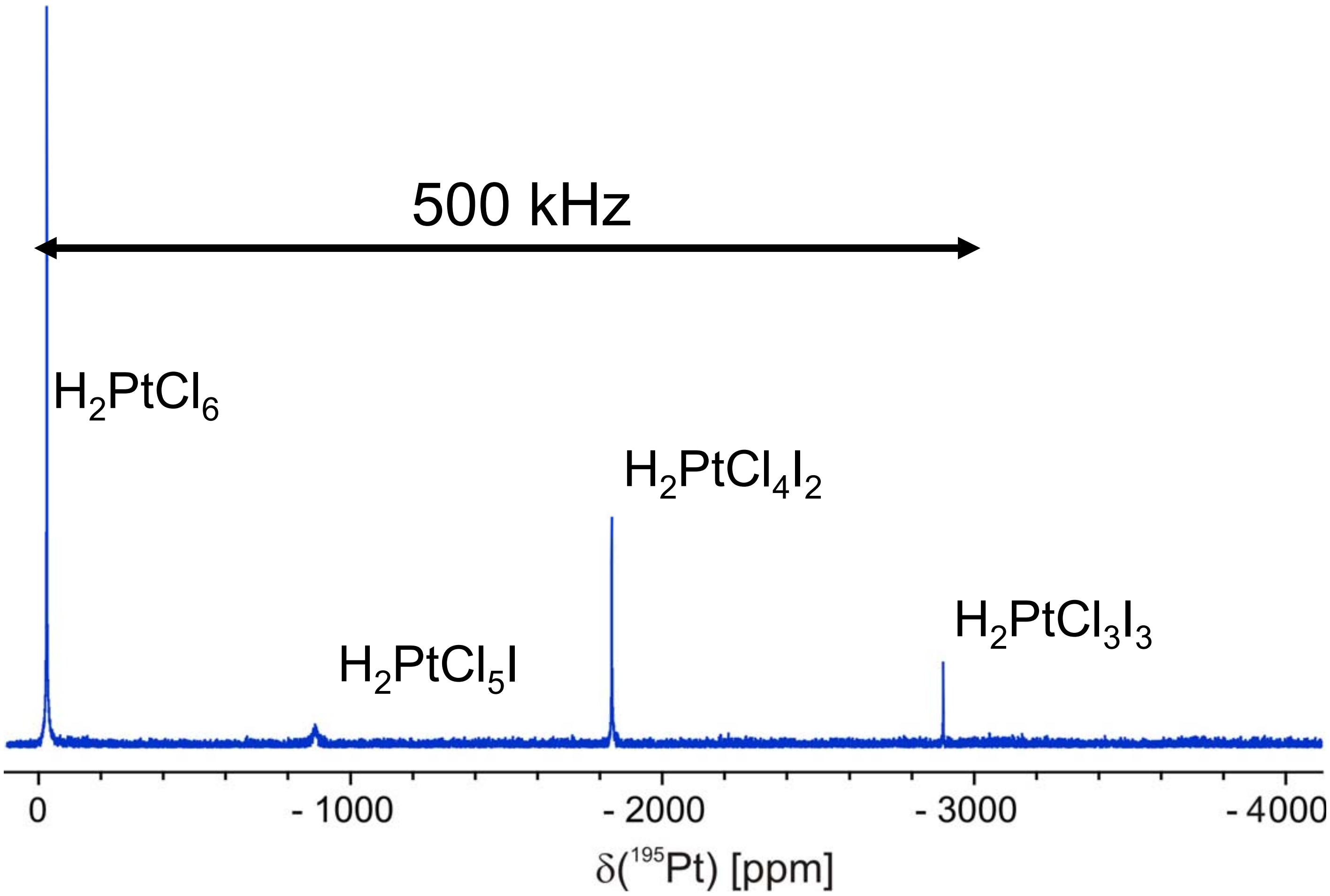






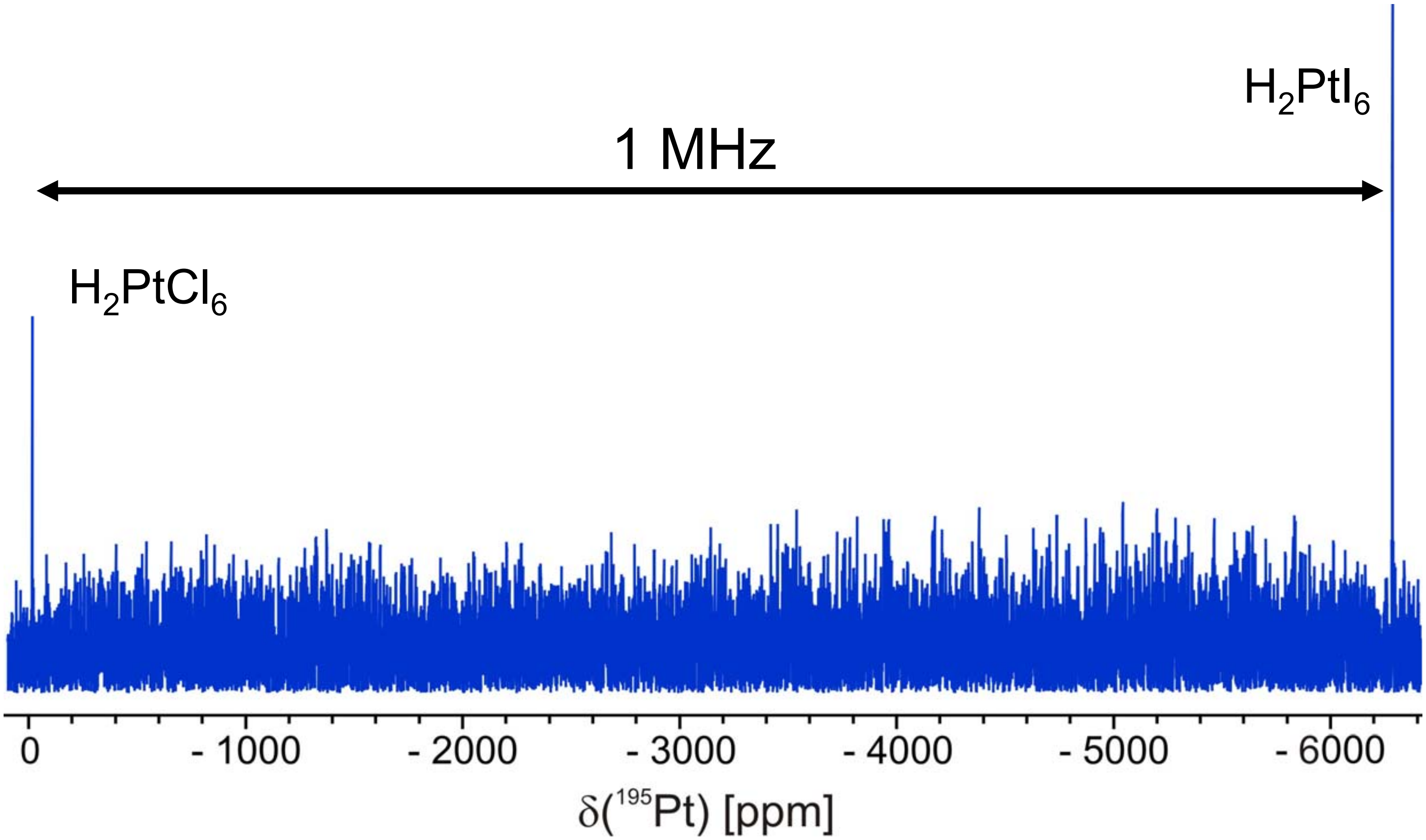
B. Luy, unpublished.

^{195}Pt-Spectra



R. Marx, S. Faul, J. Eppinger, B. Luy, unpublished.

^{195}Pt-Spectra



R. Marx, S. Faul, J. Eppinger, B. Luy, unpublished.

Why bother with NMR spectroscopy?

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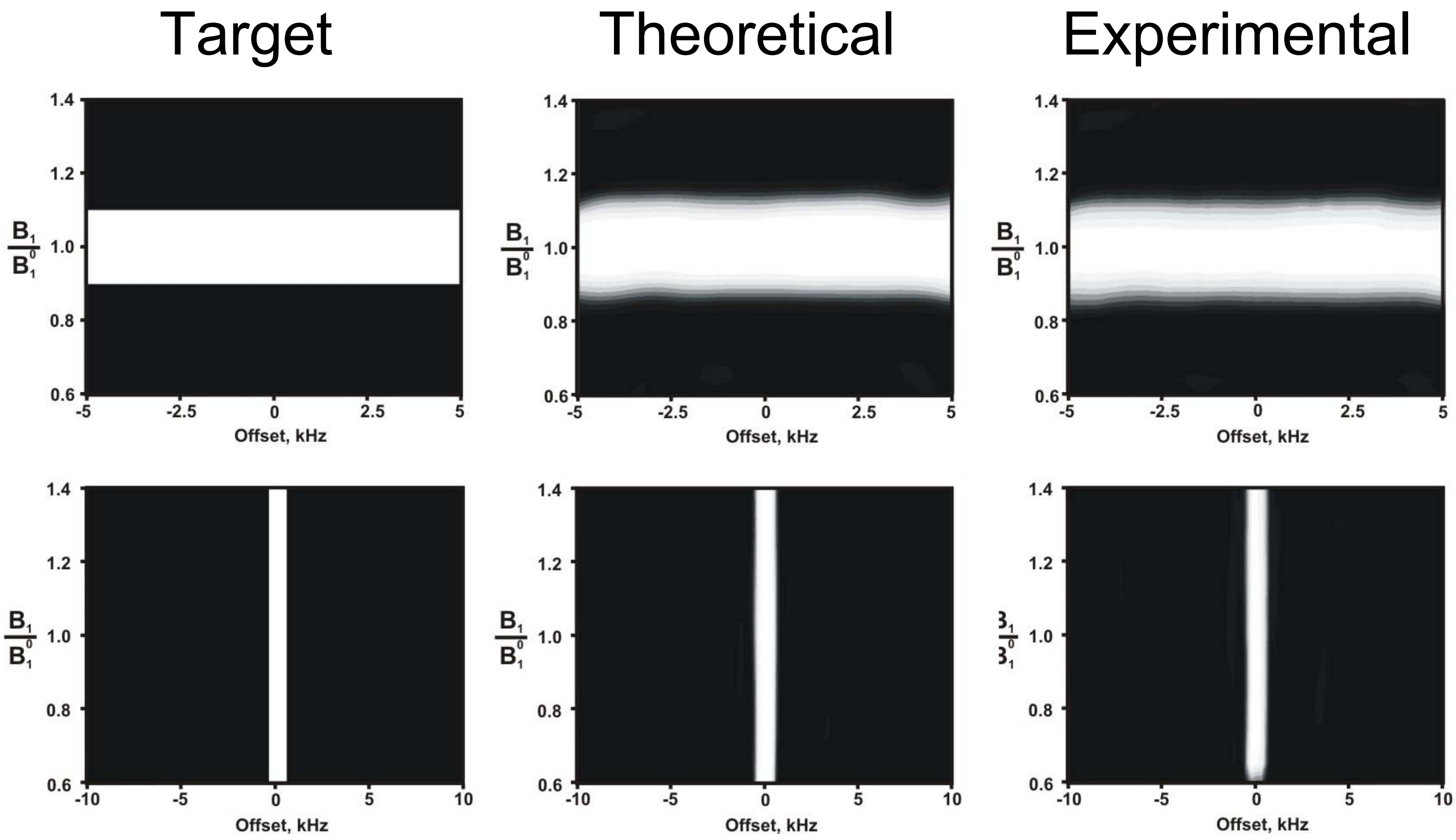
Broadband ‘Universal Rotation’ Pulses

Ultrabroadband Excitation

Pattern Pulses

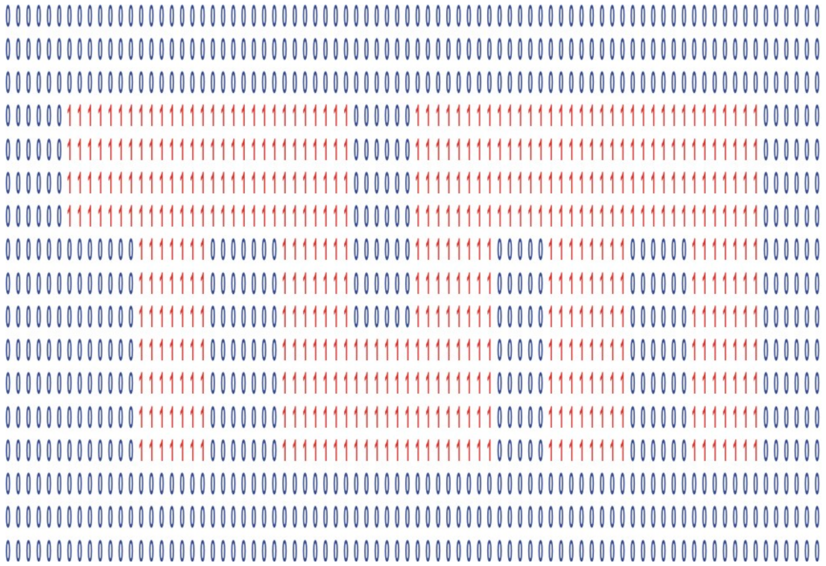
Pattern Pulses



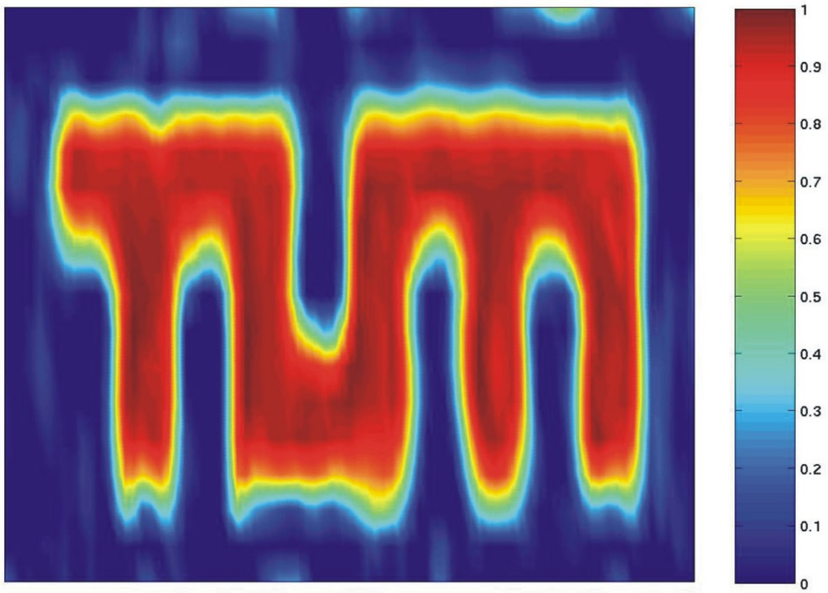
RF- and offset-selective pulses

Pattern Pulses

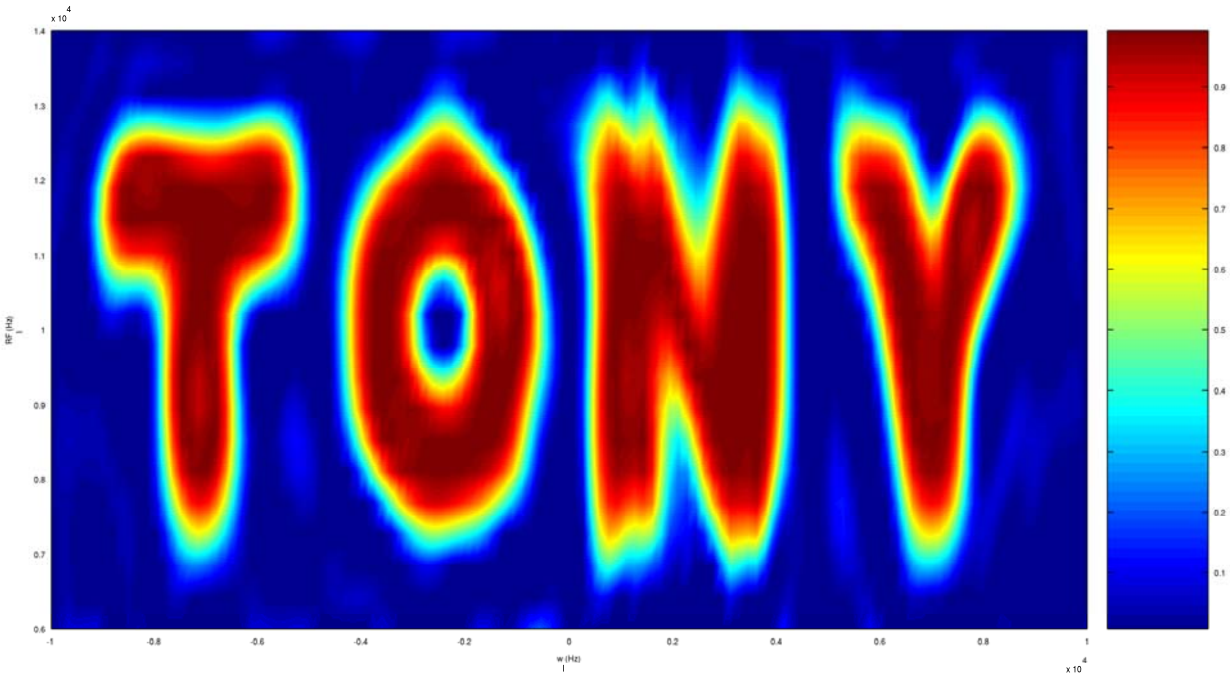
Target



Experiment

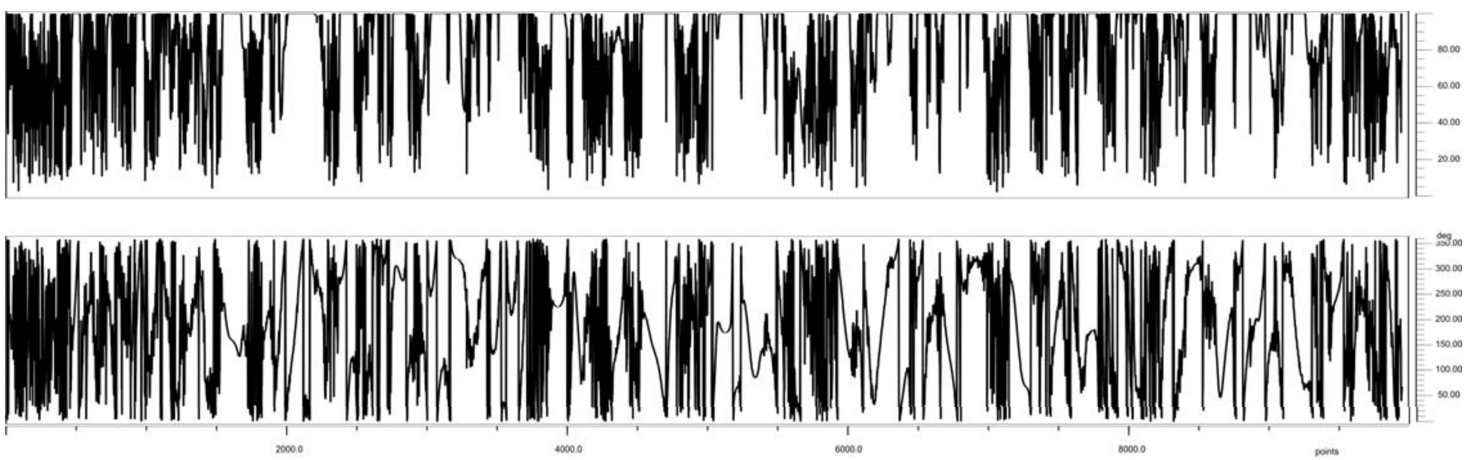


Almost arbitrary RF- and Offset dependence possible for excitation profile



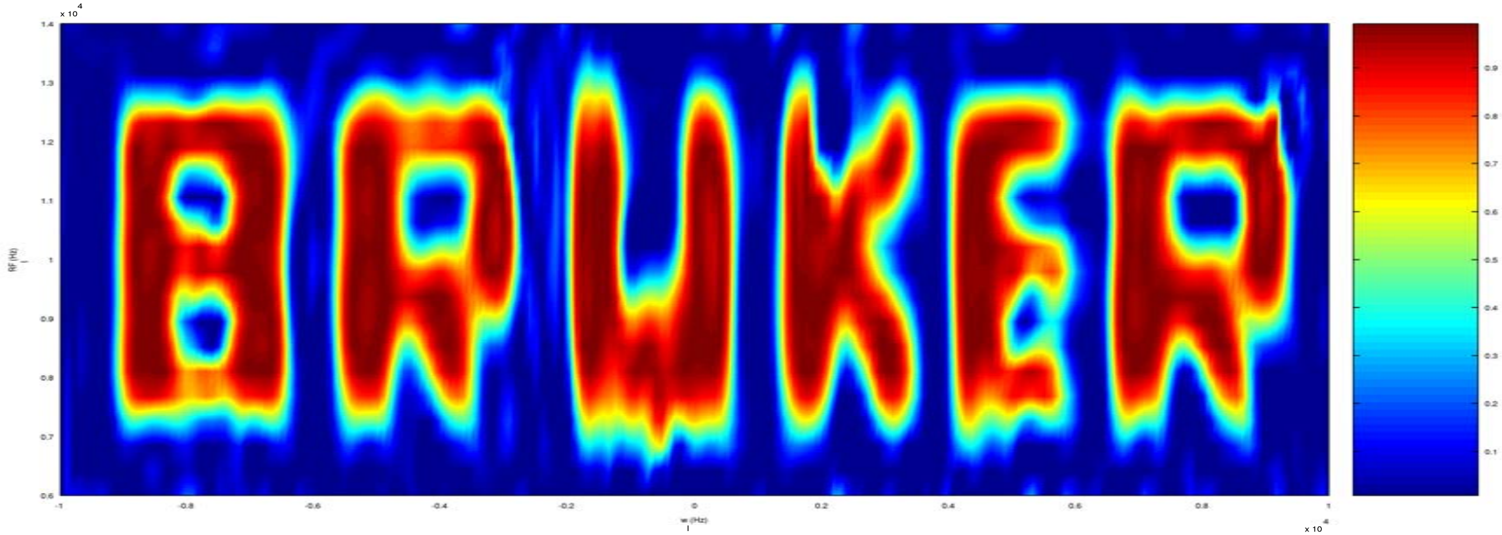
Ampl.

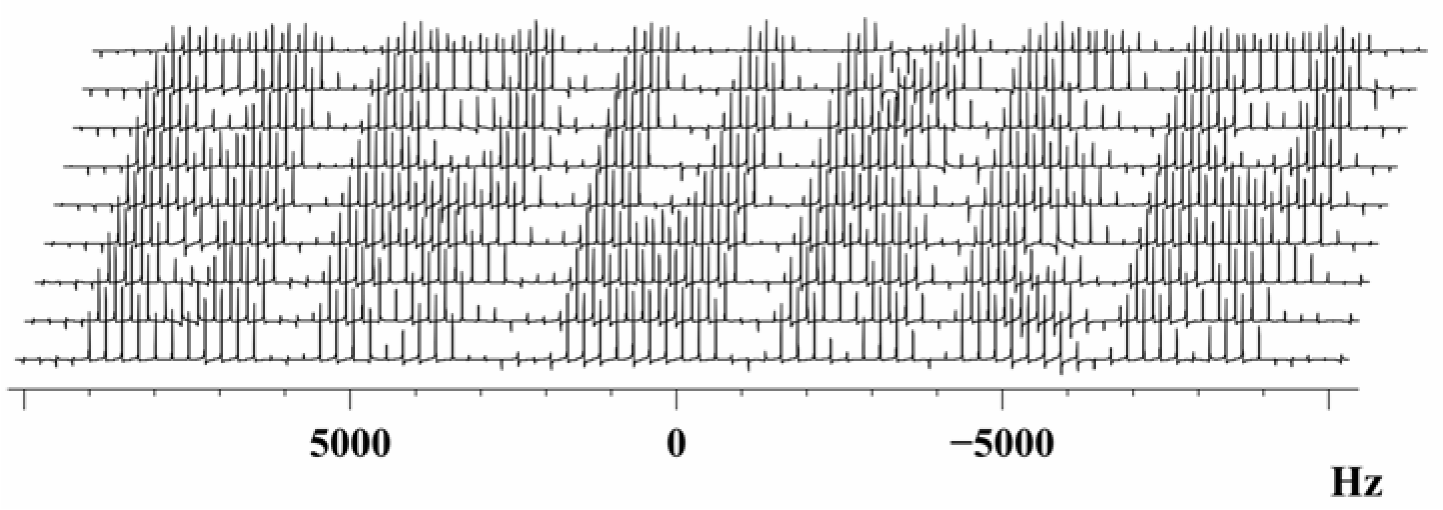
ϕ



Kyryl Kobzar, Burkhard Luy, unveröffentlicht.

Pattern Pulses





Kyryl Kobzar, Markus Wälchli, Burkhard Luy, unpublished.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