technische universität
dortmund

Exp. Physik III

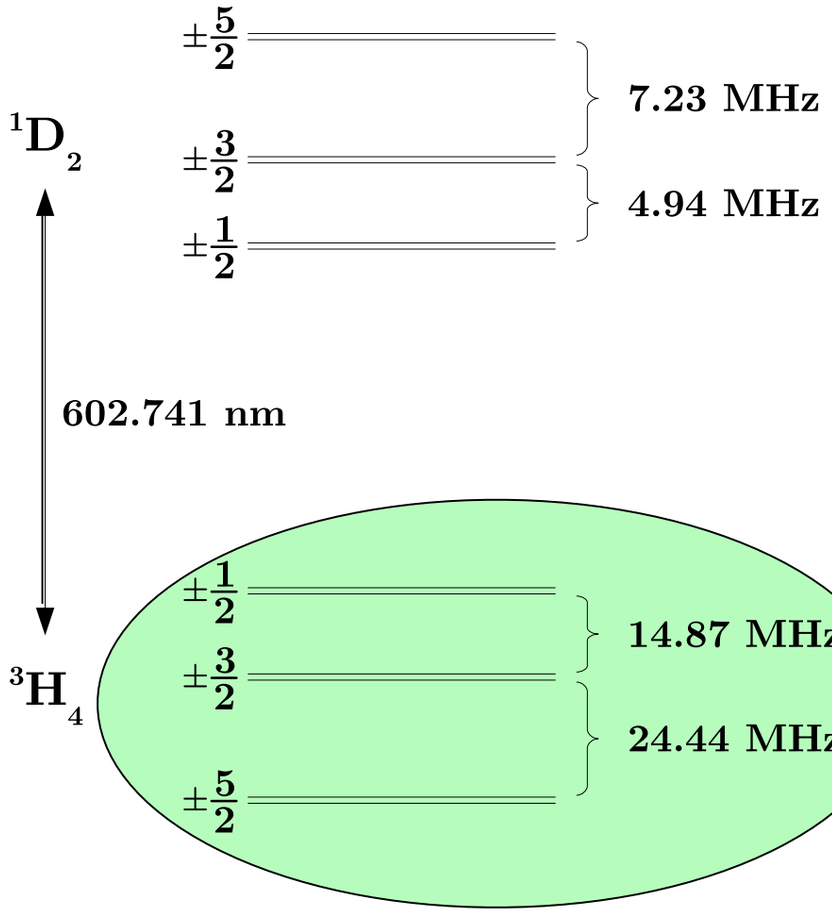
Optical storage and (RF-) dynamical decoupling in $Pr^{3+}:La_2(WO_4)_3$

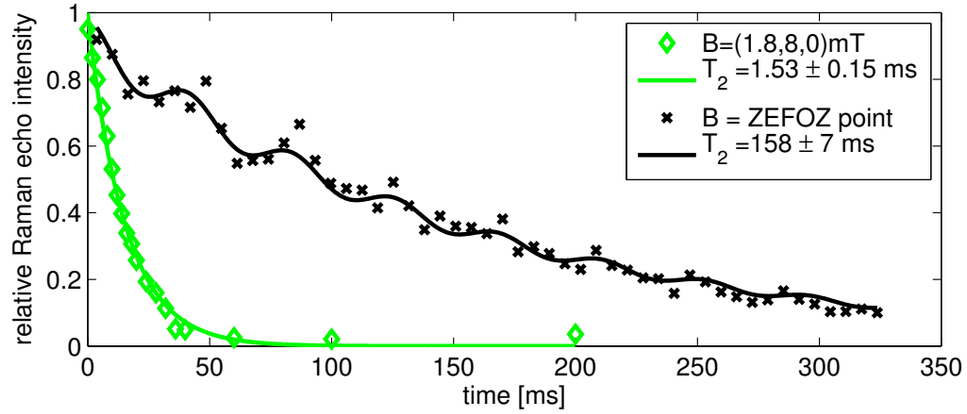
Marko Lovrić, Philippe Goldner, Dieter Suter

System and motivation

$Pr^{3+}:La_2(WO_4)_3$

Optical:
$T_1 \approx 120\ \mu s$
$T_2 \approx 16\ \mu s$





Hyperfine:

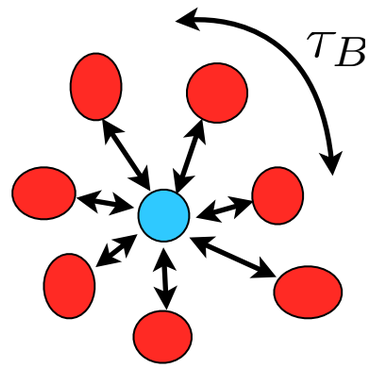
$T_1 \approx 16\ s$
T_2 (B=0mT) $\approx 250\ \mu s$
T_2 (B>0.5mT) $\approx 1\text{–}4\ ms$
T_2 (ZEFOZ) $\approx 200\ ms$

B≈1–10 mT – 1–4 ms coherence lifetimes:

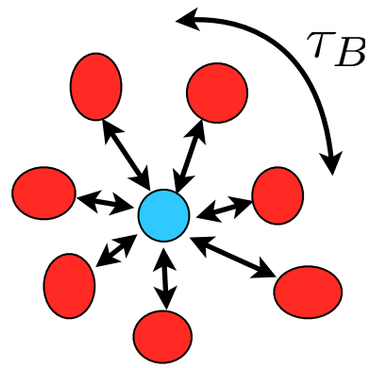
Will Dynamical Decoupling techniques work?

Dynamical Decoupling (DD)

System (S) couples to environment (E): $\mathcal{H}_0 = \mathcal{H}_S + \mathcal{H}_{SE} + \mathcal{H}_E$

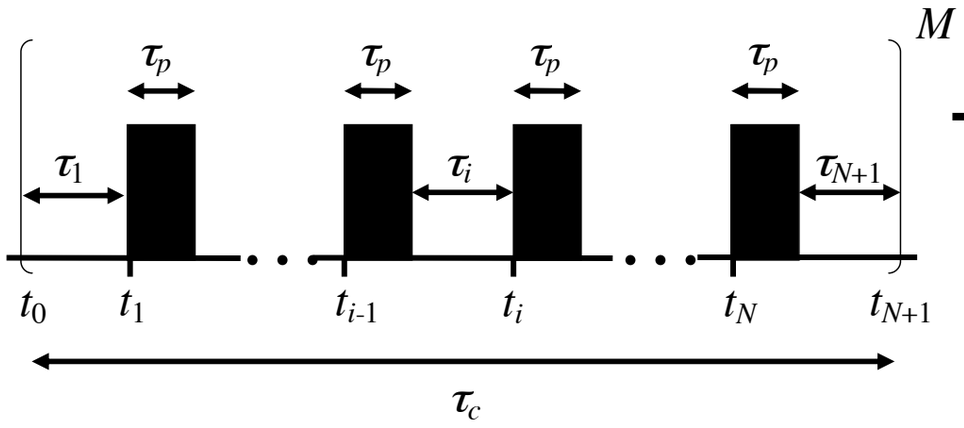


Dynamical Decoupling (DD)



System (S) couples to environment (E): $\mathcal{H}_0 = \mathcal{H}_S + \mathcal{H}_{SE} + \mathcal{H}_E$

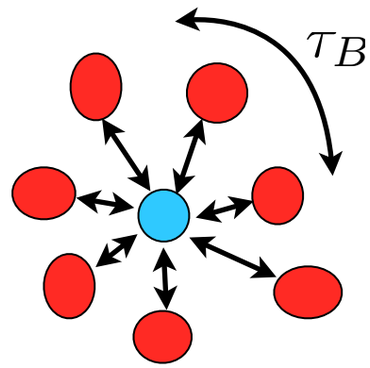
Can apply control operation to system only -> DD sequence(s)



$$U_{eff}(t) = e^{-i\mathcal{H}_{eff}t}$$

$$\mathcal{H}_{eff} = \mathcal{H}^{(0)} + \mathcal{H}^{(1)} + \mathcal{H}^{(2)} ...$$

Dynamical Decoupling (DD)



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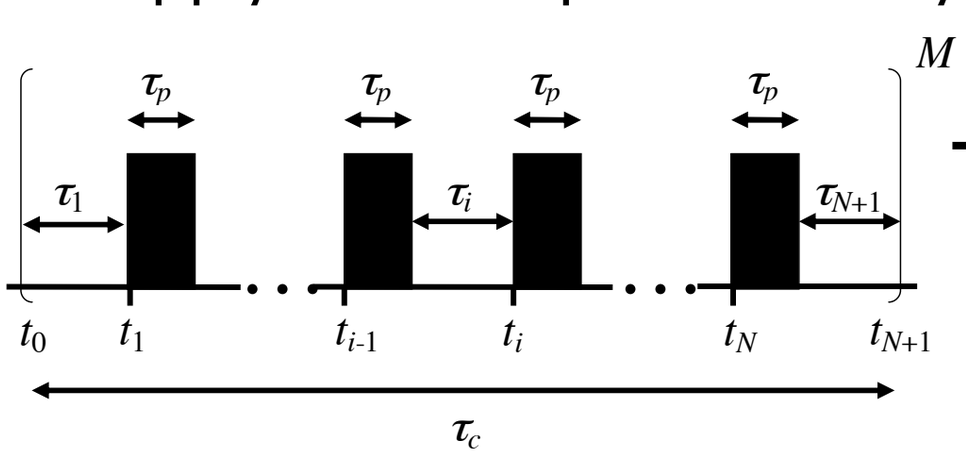


$$U_{eff}(t) = e^{-i\mathcal{H}_{eff}t}$$

$$\mathcal{H}_{eff} = \mathcal{H}^{(0)} + \mathcal{H}^{(1)} + \mathcal{H}^{(2)} \ldots$$

Ideal DD $\longrightarrow \mathcal{H}^{(0)} = \mathcal{H}_E \xrightarrow[\tau_c << \tau_B]{b_{SE} \cdot \tau_B << 1} U_{eff}(t) = exp\left\{-i\mathcal{H}_E t + \mathcal{O}\left((\tau_c/\tau_B)^{n+1}\right)\right\}$

$\longrightarrow$ „$\mathcal{H}_0 = \cancel{\mathcal{H}_S + \mathcal{H}_{SE}} + \mathcal{H}_E$“

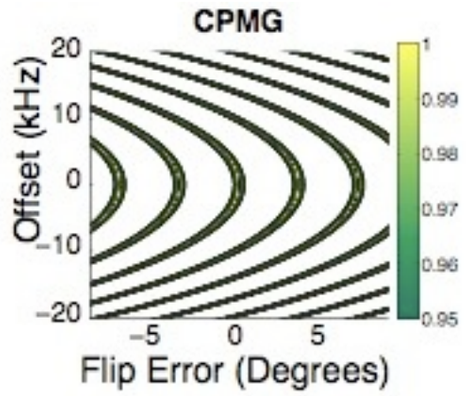
L. Viola et al, PRL **82**, 2417 (1999)

G. A. Álvarez et al, Phys. Rev. A **82**, 042306 (2010)

(so far tested) some used DD sequences

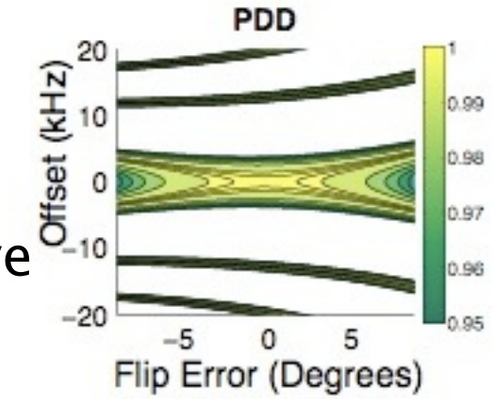
$$\frac{X}{2} - (\tau/2 - X - \tau - X - \tau/2)^N$$ Carr Purcell (CP): most basic cycle

H.Y. Carr et al, Phys. Rev. **94**, 630 (1954)



$$\frac{X}{2} - (\tau/2 - Y - \tau - Y - \tau/2)^N$$ CPMG: corrects for flip angle errors

S. Meiboom et al, Rev. Sci. Instrum. **29**, 688 (1958)



$$\frac{X}{2} - (\tau/2 - X - \tau - Y - \tau - X - \tau - Y - \tau/2)^N$$ XY-4/PDD: less phase sensitive

A.A. Maudsley, et al, J. Mag. Reson. **69**, 488 (1986)

K. Khodjasteh et al, Phys. Rev. A **75**, 062310 (2007)

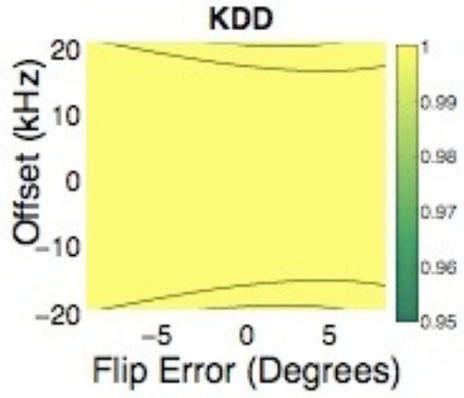
KDD: „combination“ of XY-4 and robust (composite) pulse

$$\frac{X}{2} - \left(\tau/2 - X_{\frac{\pi}{6}+\phi_N} - \tau - X_{\phi_N} - \tau - X_{\frac{\pi}{2}+\phi_N} - \tau - X_{\phi_N} - \tau - X_{\frac{\pi}{6}+\phi_N} - \tau/2\right)^N$$

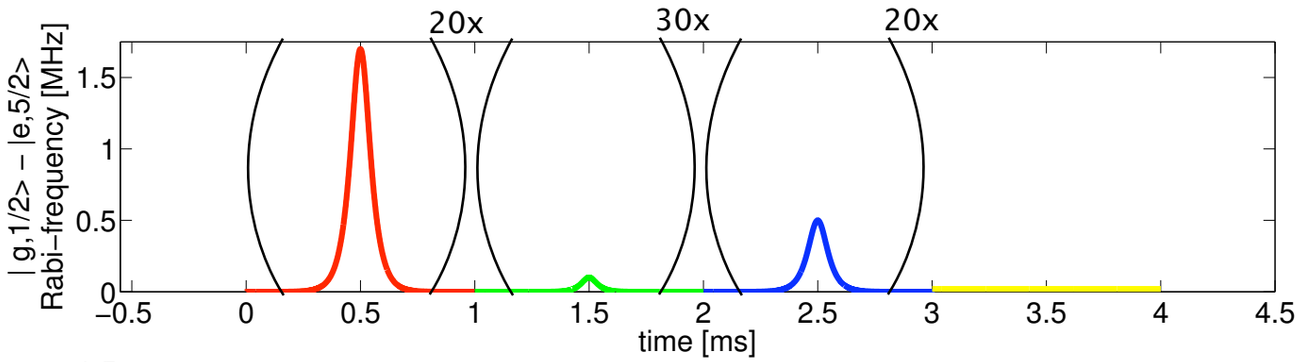
ϕ_N=0 for odd N, else $\phi_N=\frac{\pi}{2}$

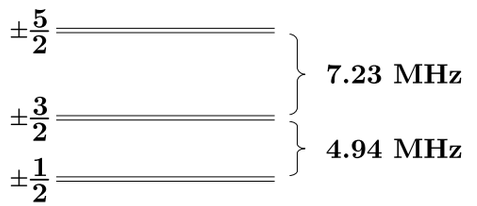
A. M. Souza et al, arXiv:1103.4563v1 [quant-ph] (2011)

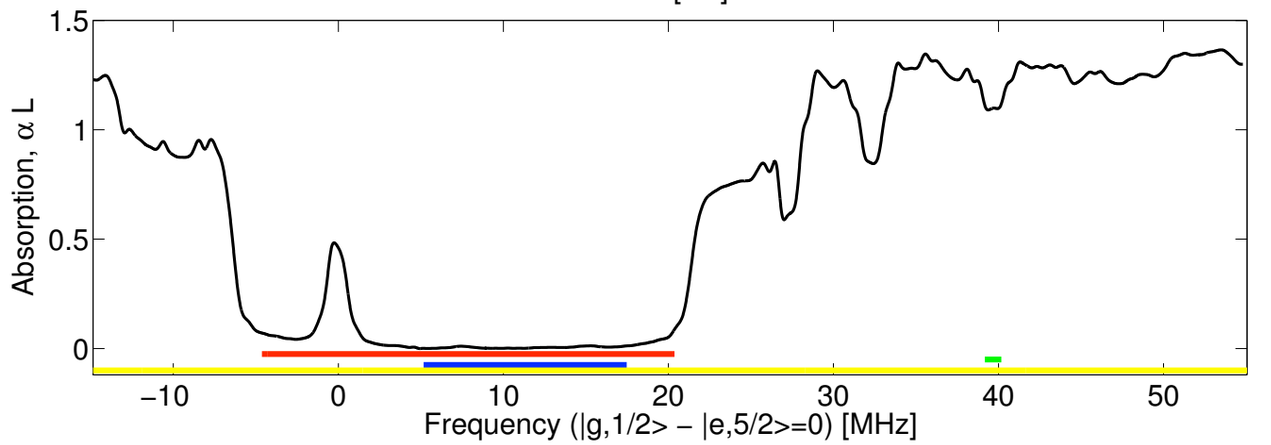
C. A. Ryan et al, Phys. Rev. Lett **105**, 200402 (2010)

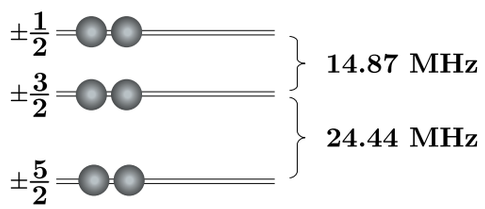


Optical preparation and setup









(later probe here for Raman-Heterodyne)

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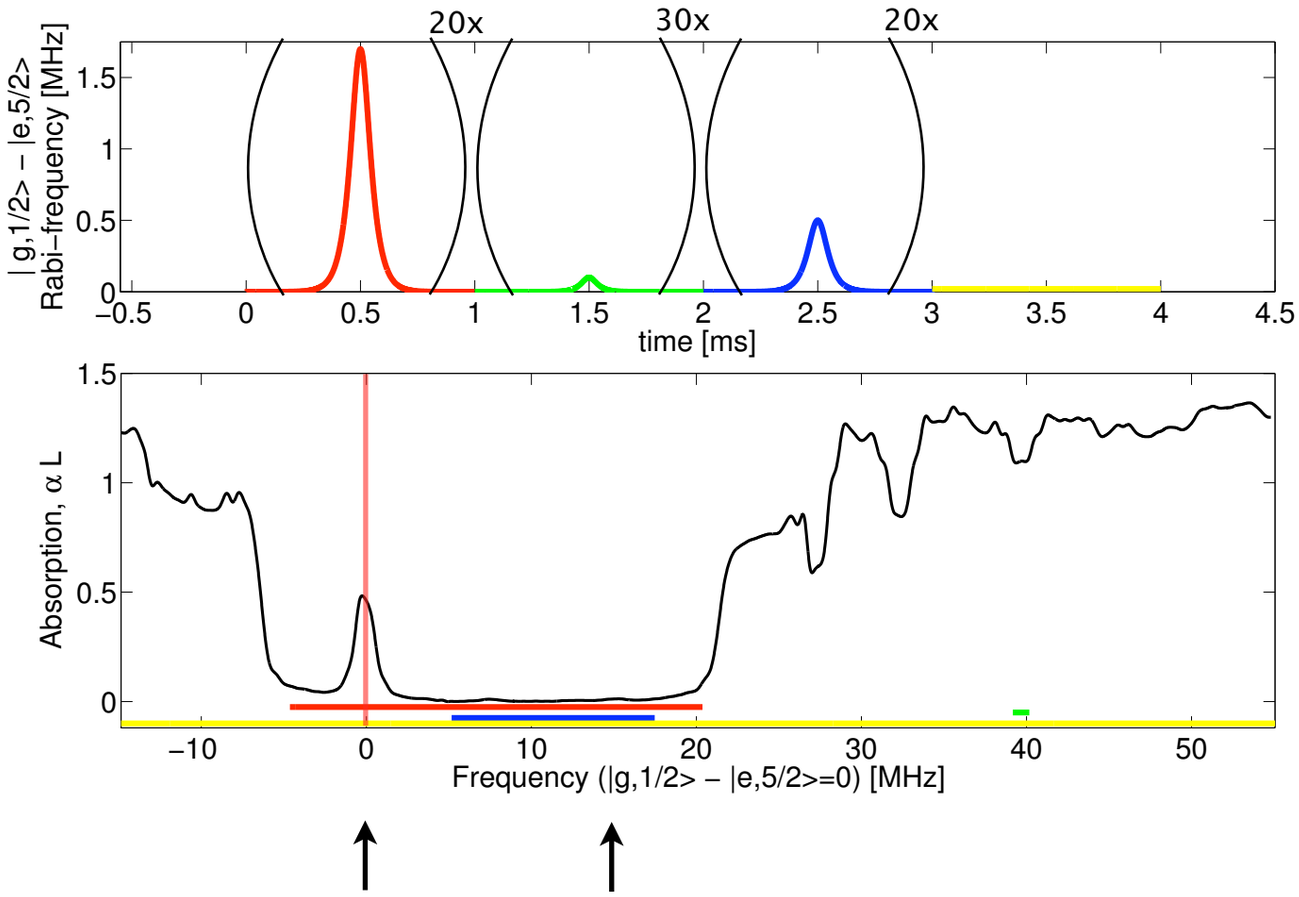

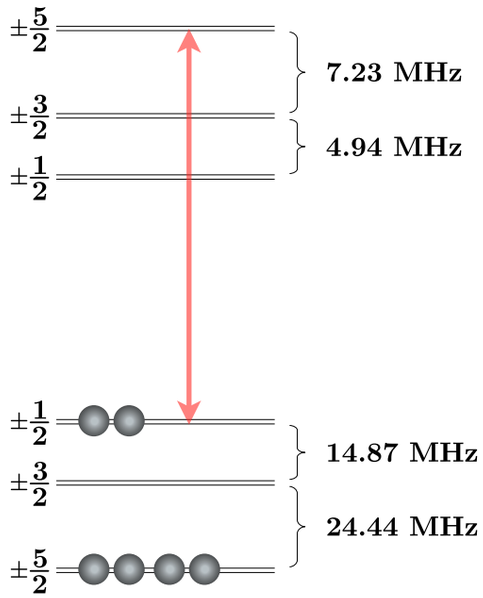

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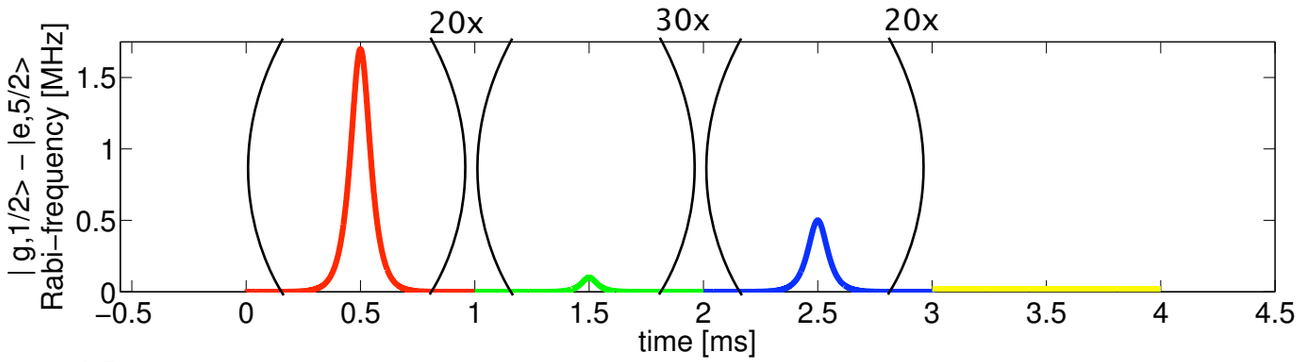
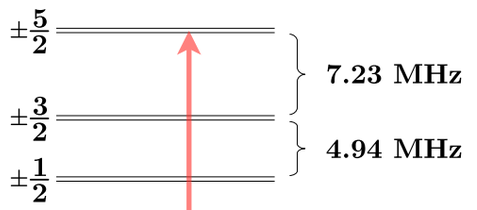
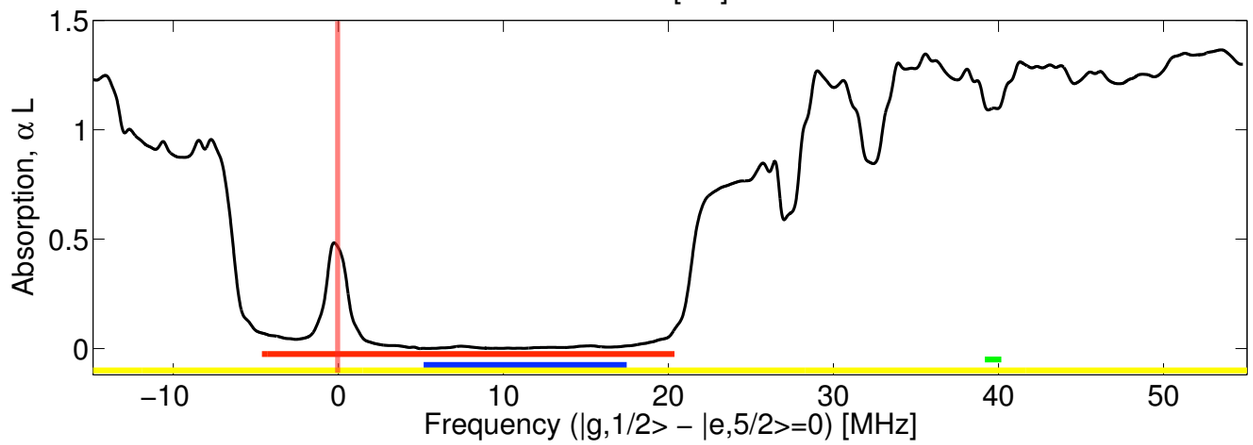
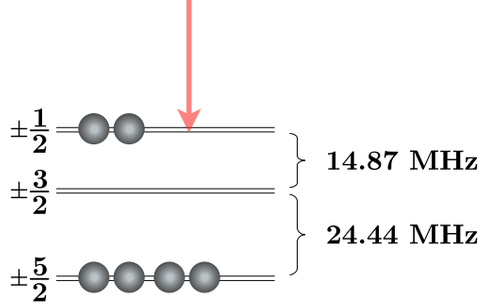






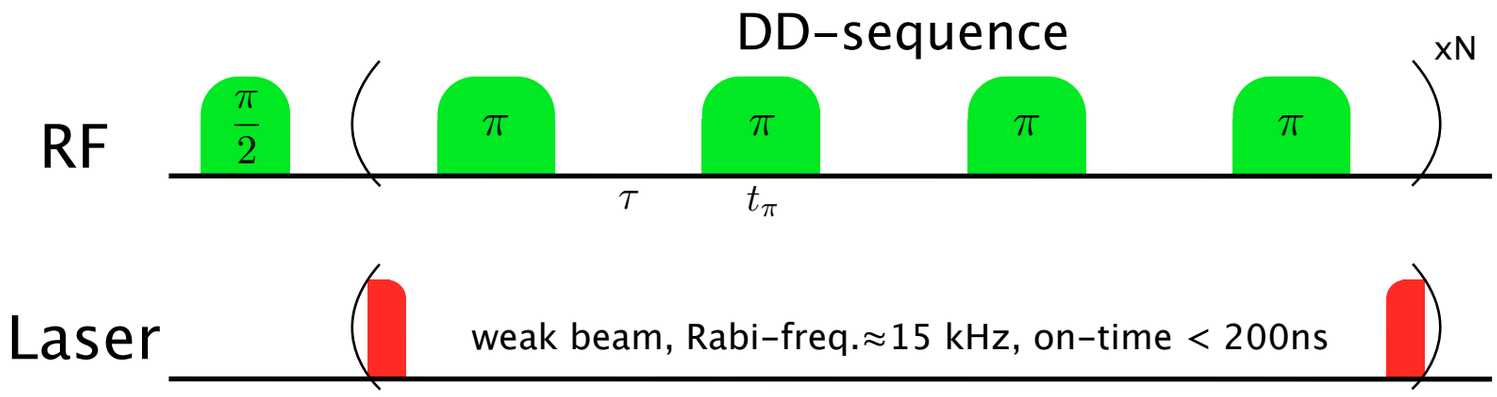


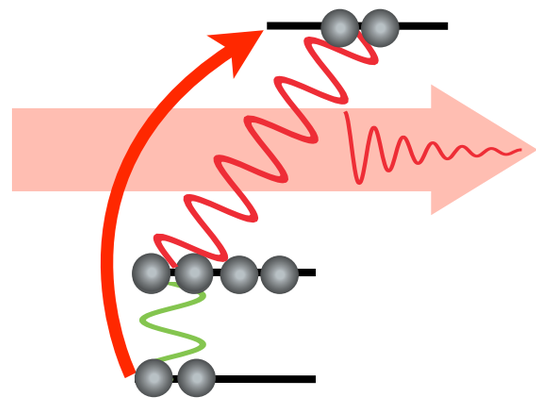
(later probe here for Raman–Heterodyne)

Laser: – jitter < 20 kHz (1ms)
– calibrated retro.reflec. AOM
– AWG/DDS

RF: – LCR, BW ≈ 0.1–0.5 MHz
– 300W -> Rabi <≈ 1 MHz
– DDS/AWG

Coherent Raman Scattering with DD





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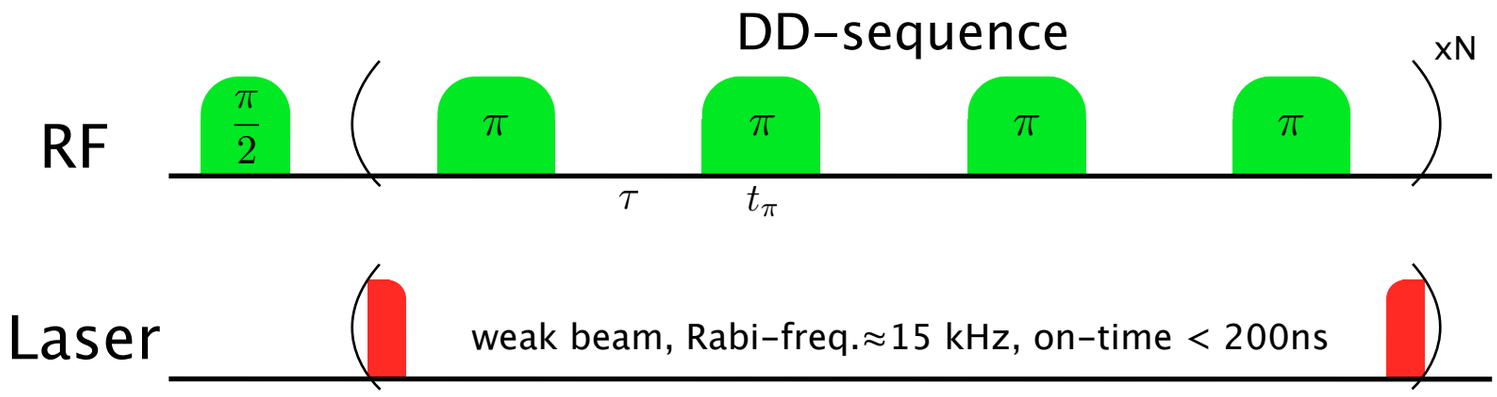
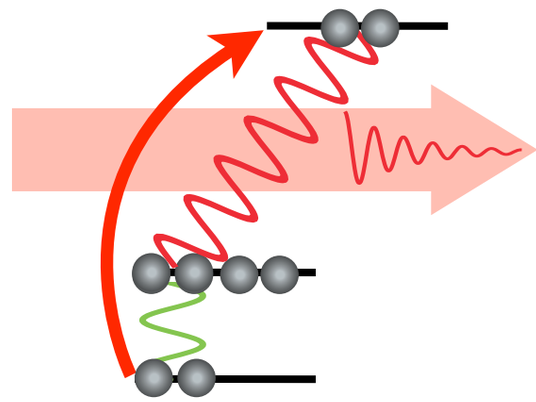
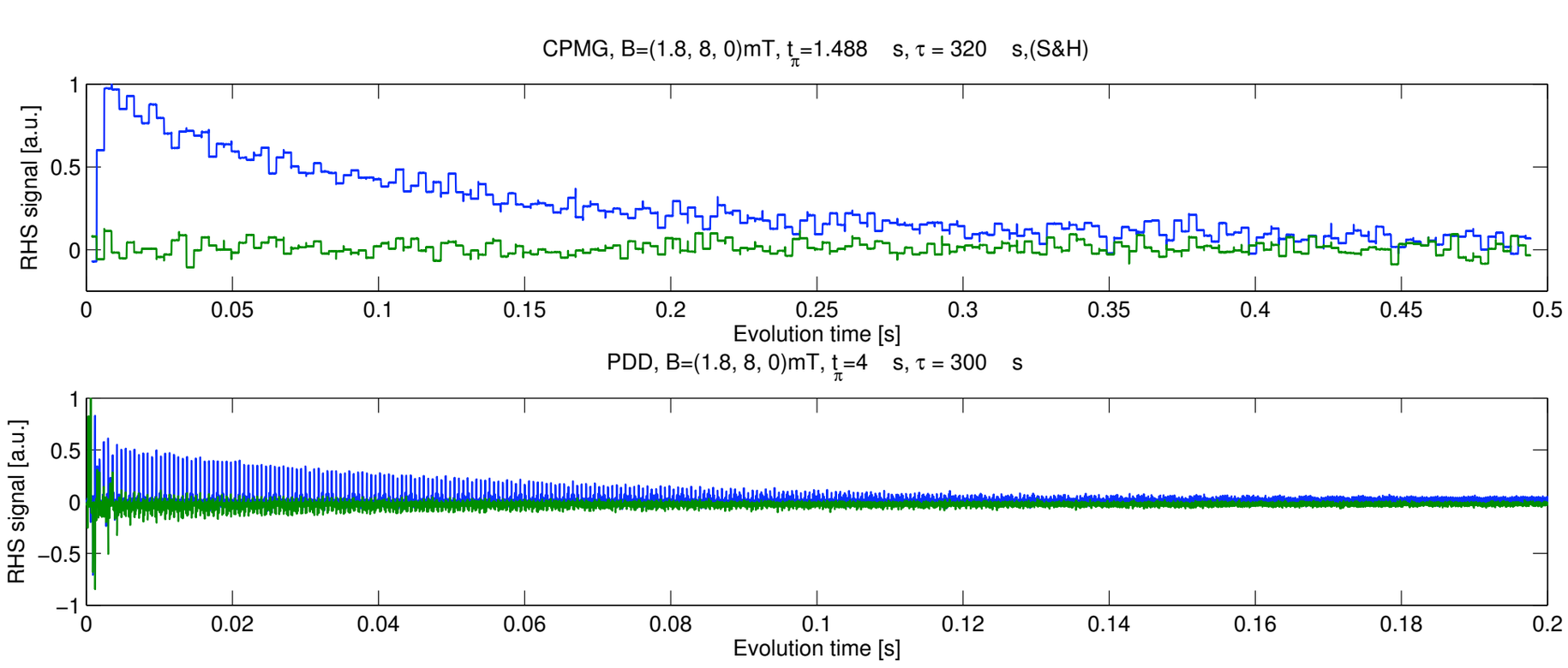
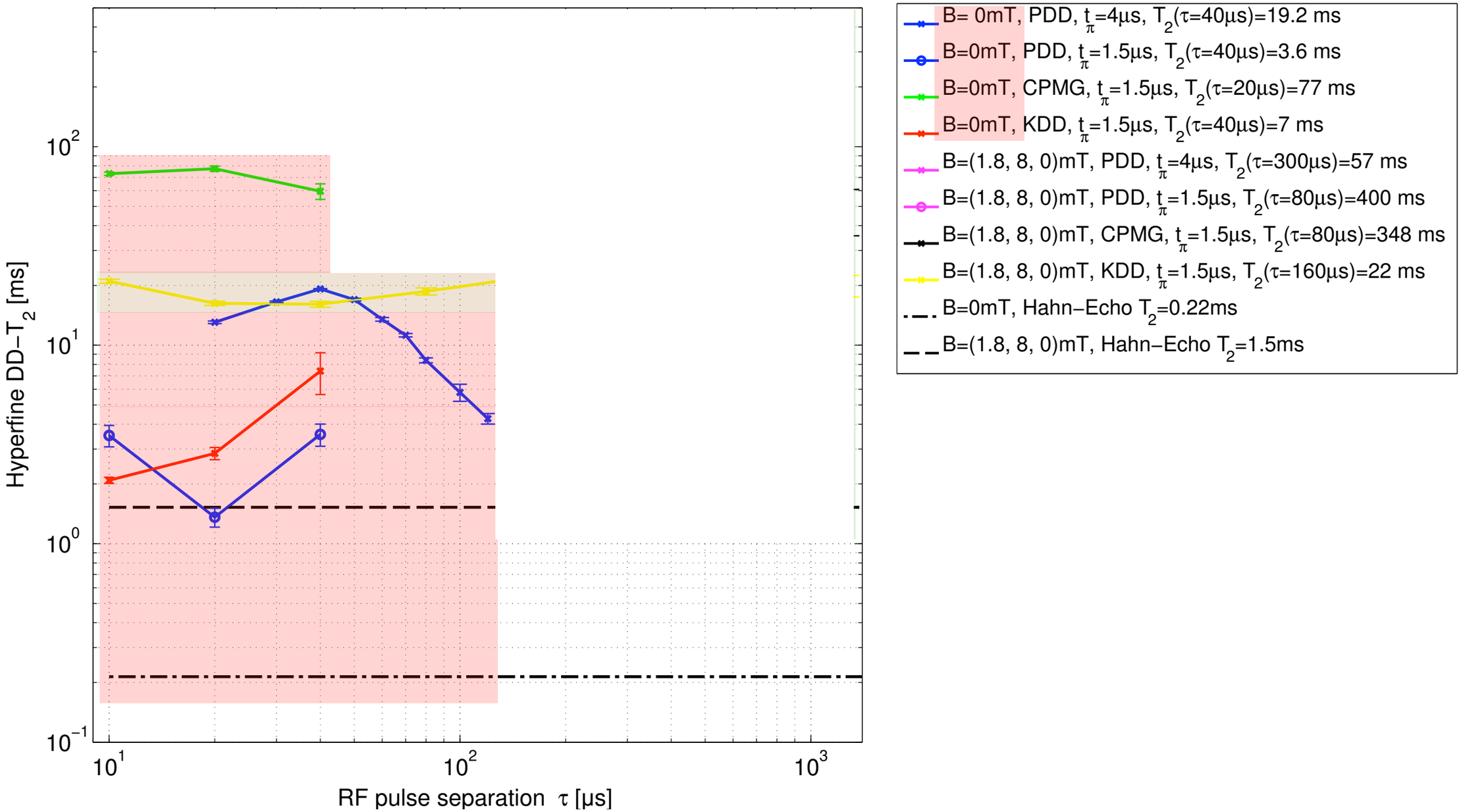






DDC ground state coherence time by CRS



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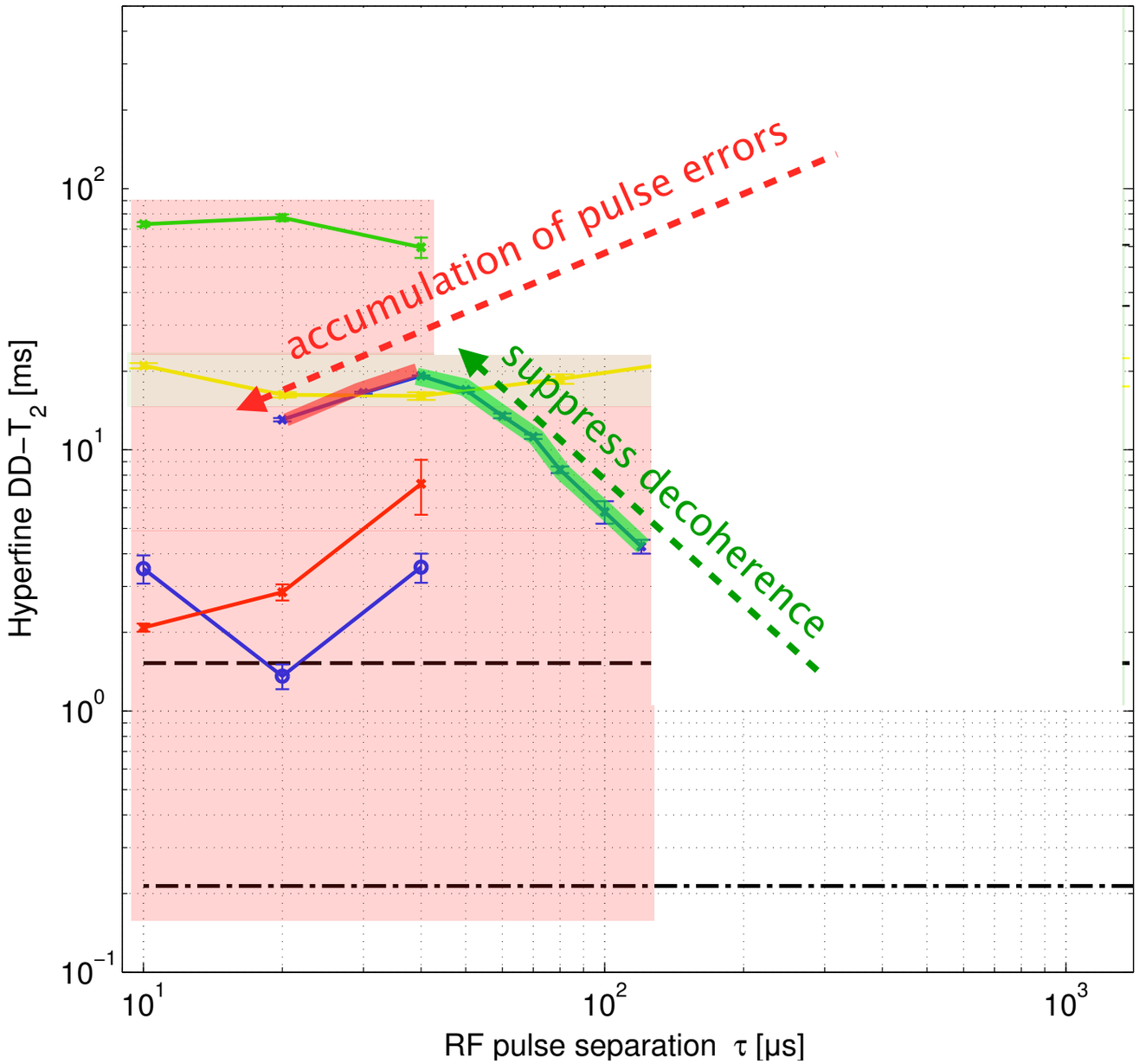

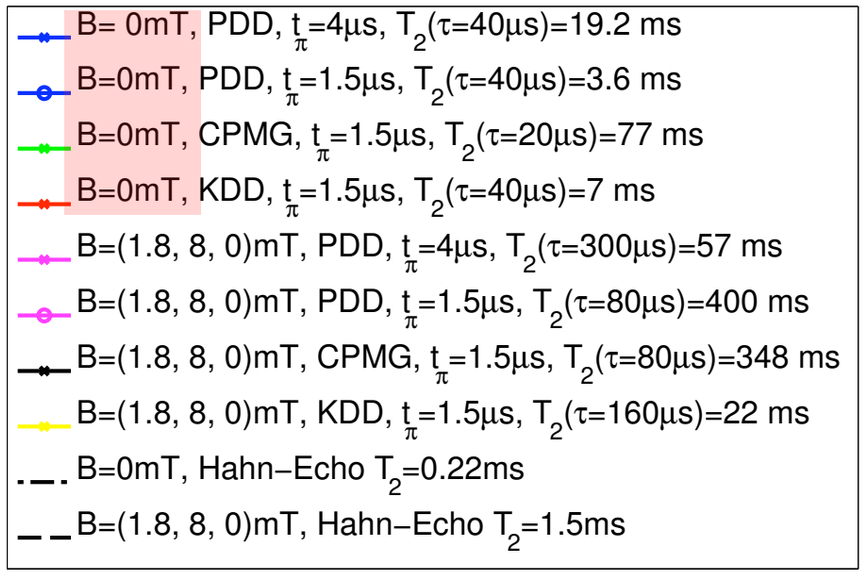

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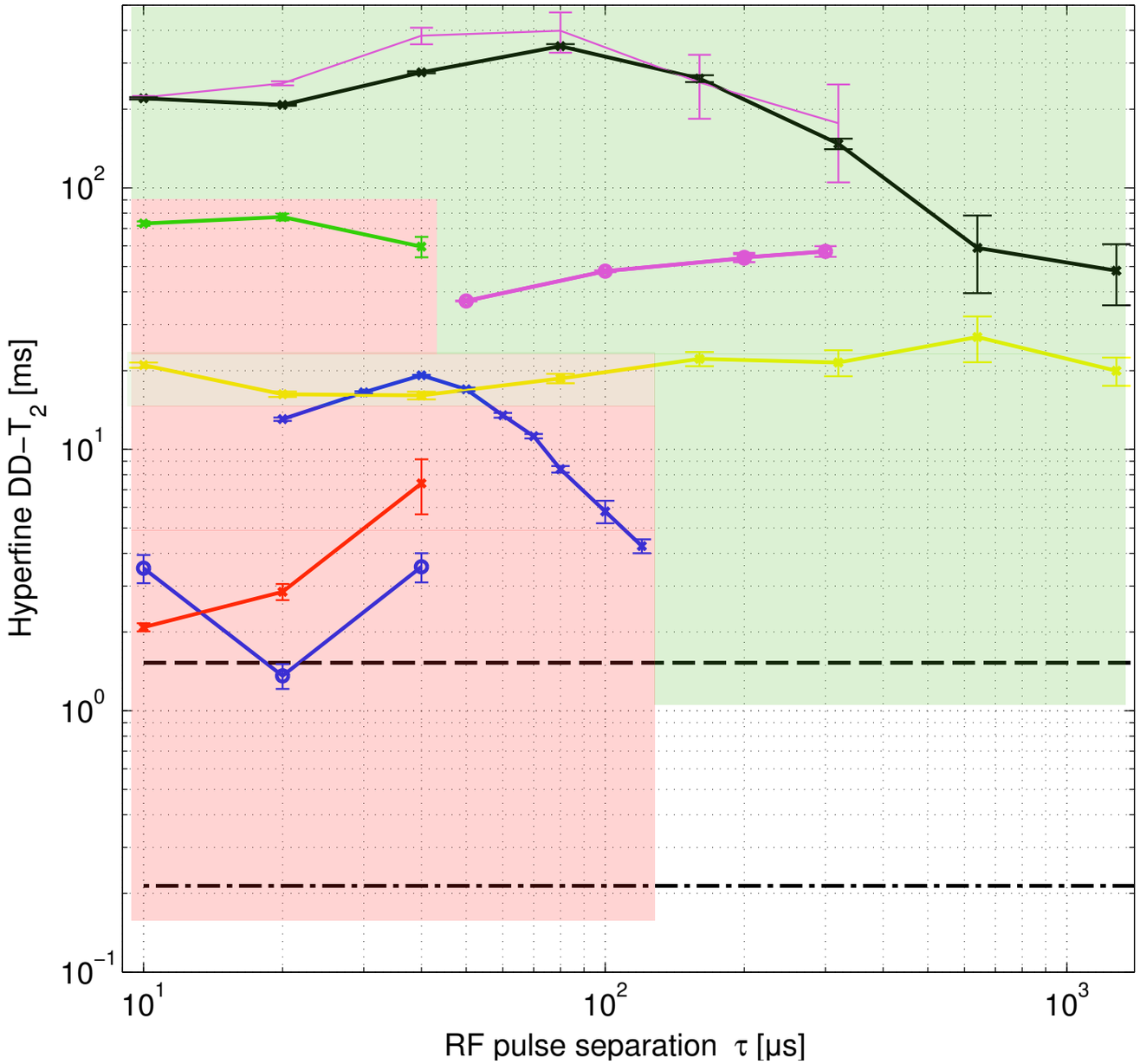
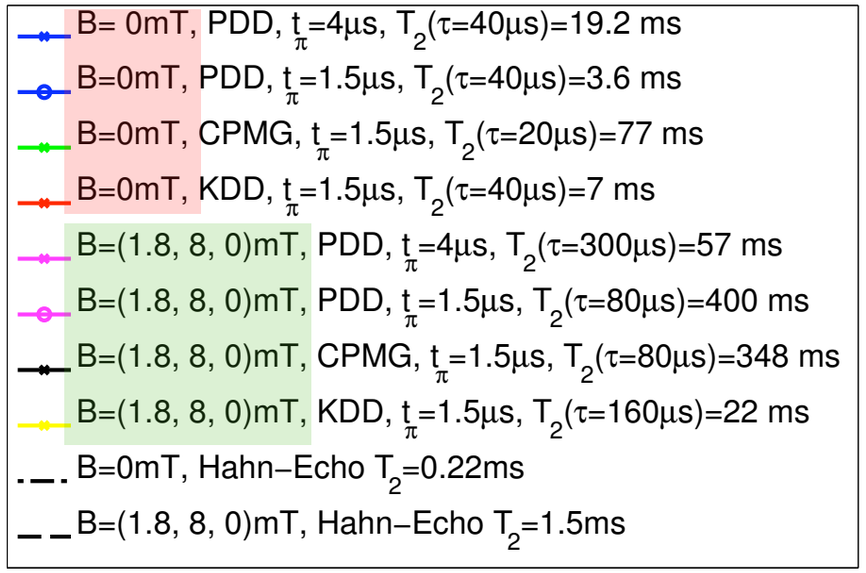


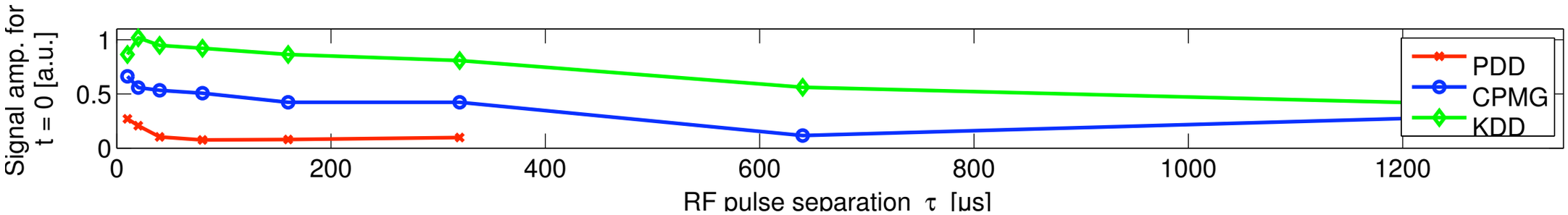


Quite promising:
- B=0mT: up to ≈300 fold increase
- B≈10mT: up to ≈230–300 fold increase

But:
- quite some parameters to optimize (pulse-length/separation, B...)

- KDD not as good as expected (B≠0mT?)

Signal amplitude and Input-phase sensitivity



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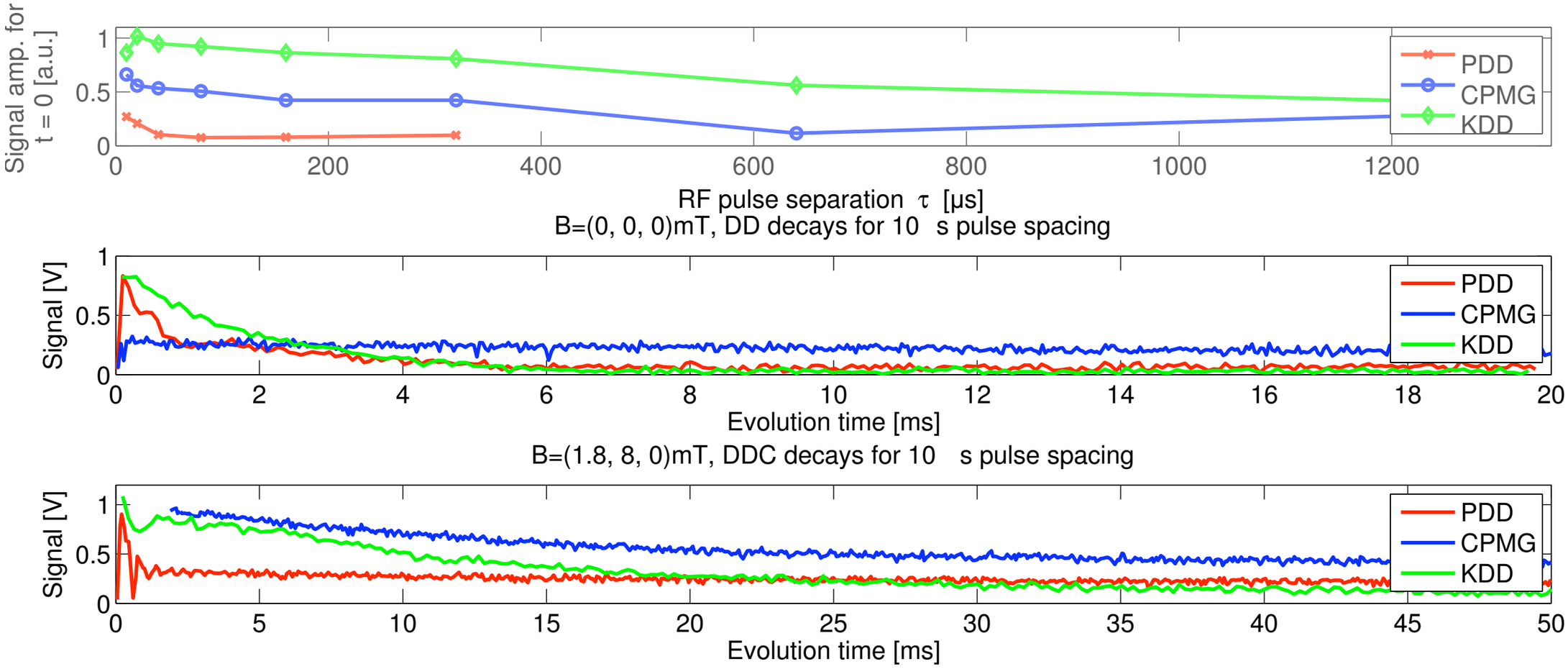

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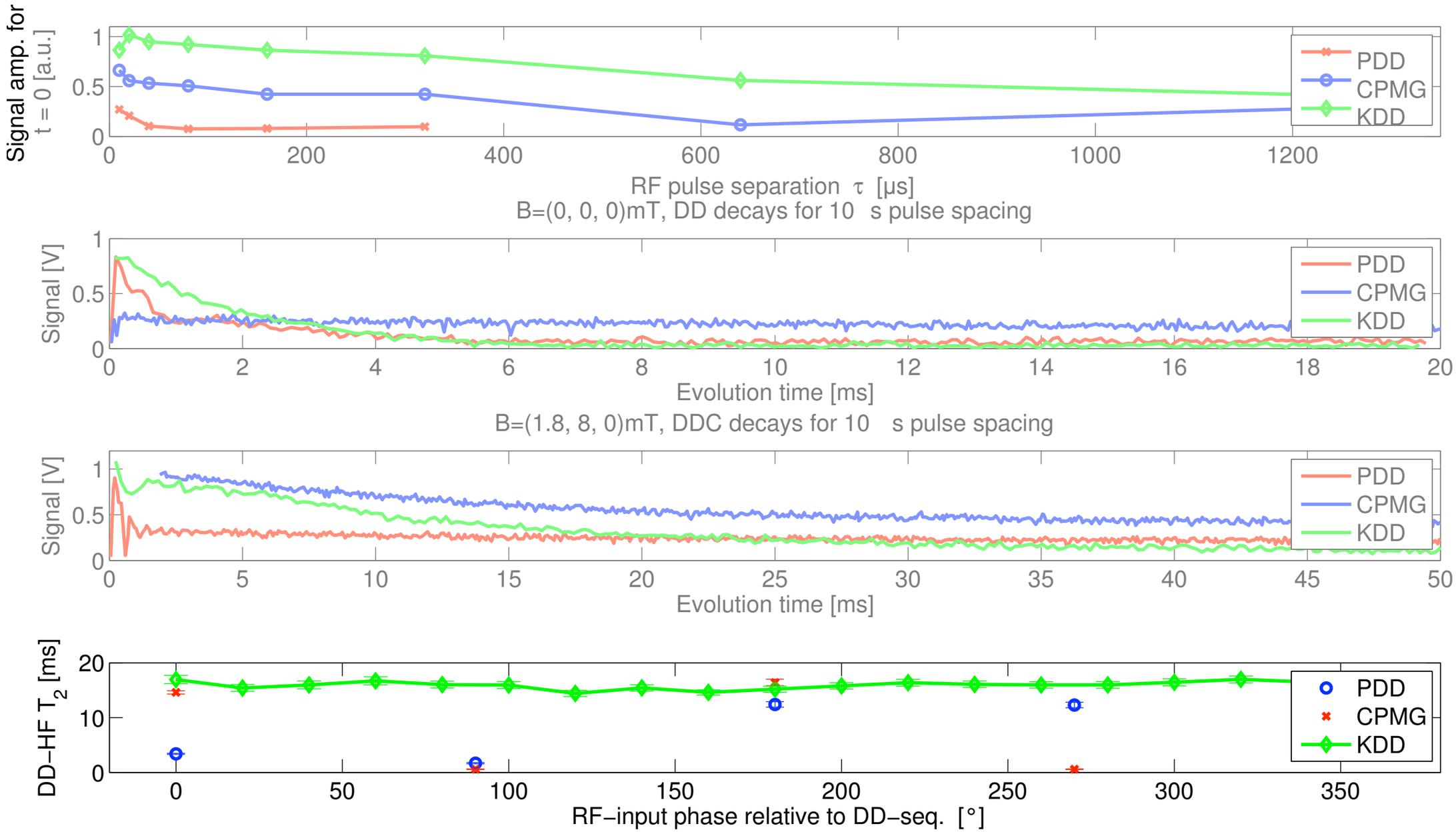
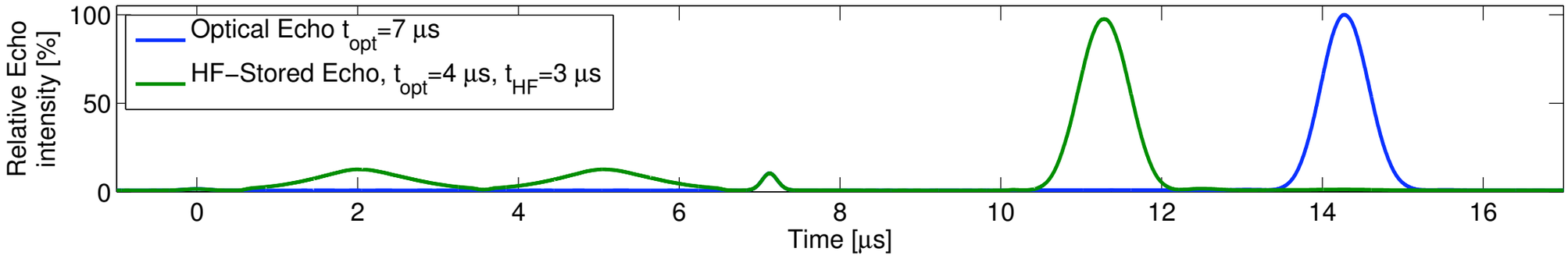


Optical storage „efficiency“



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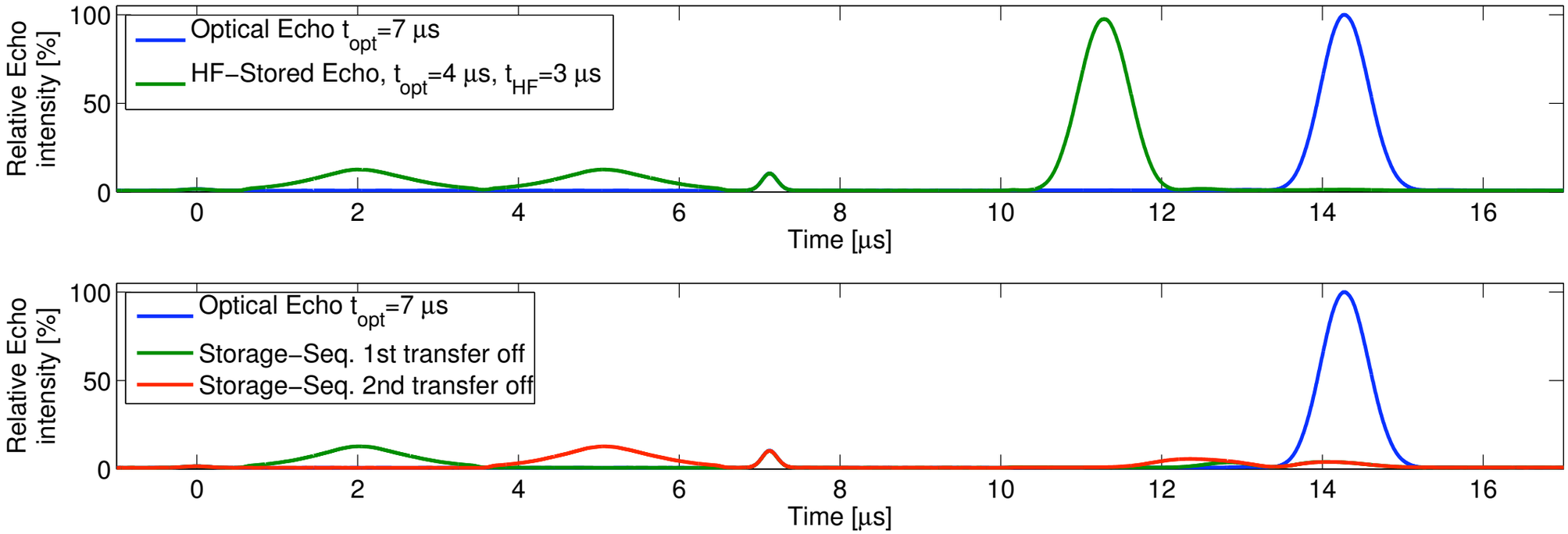

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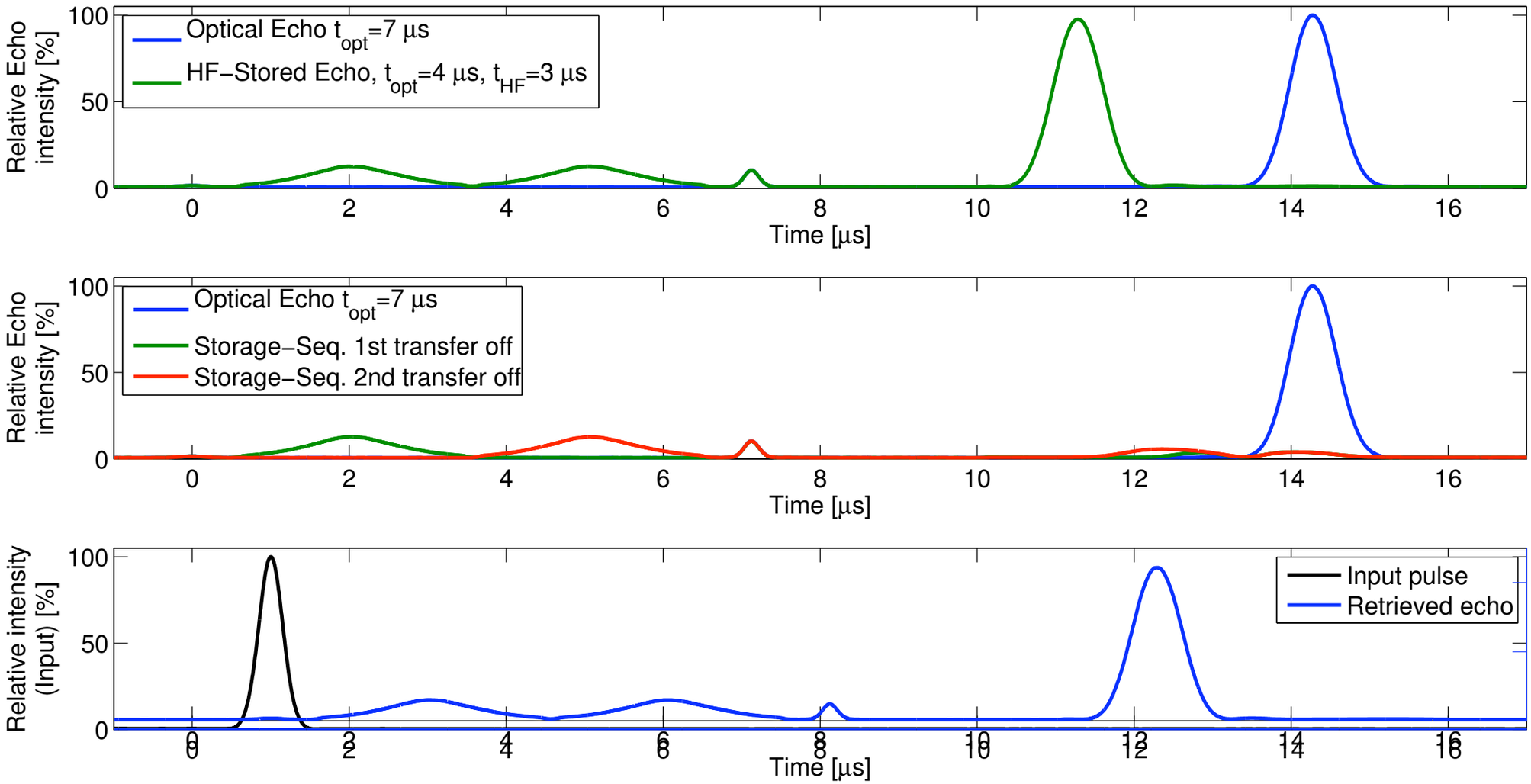
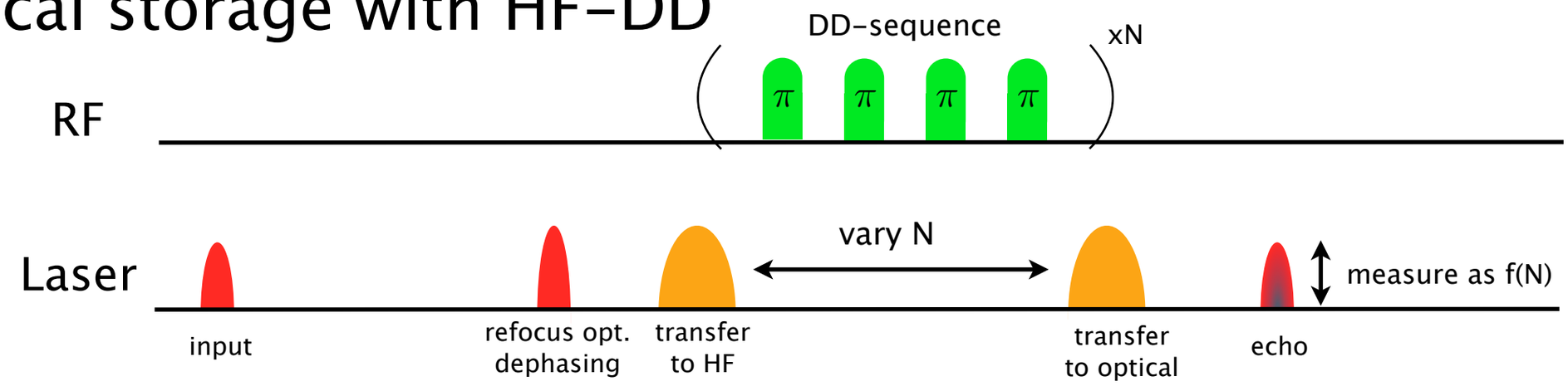


... simple, poor efficiency, just want to have some stored „optical“ coherence...

Optical storage with HF-DD



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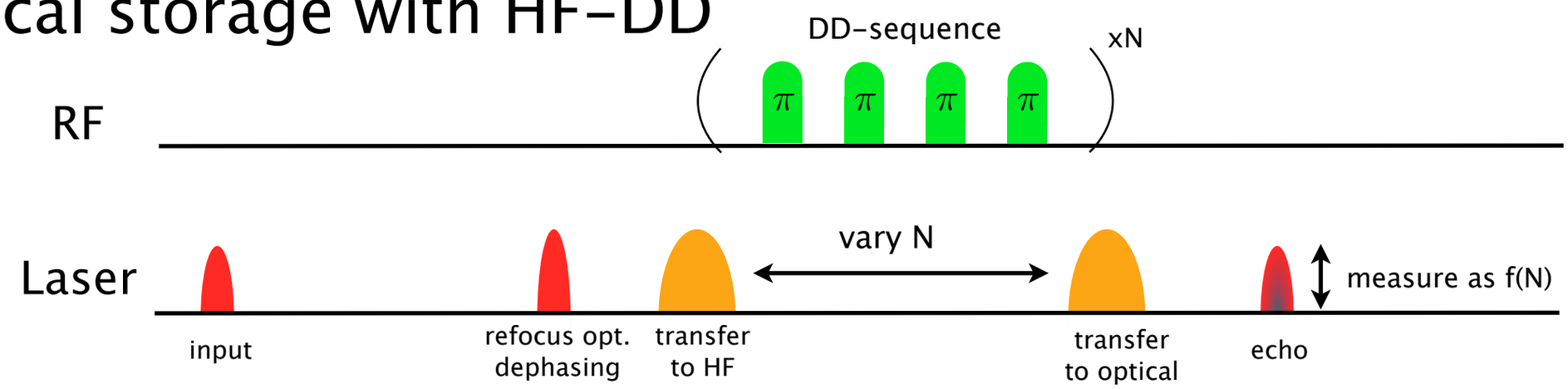
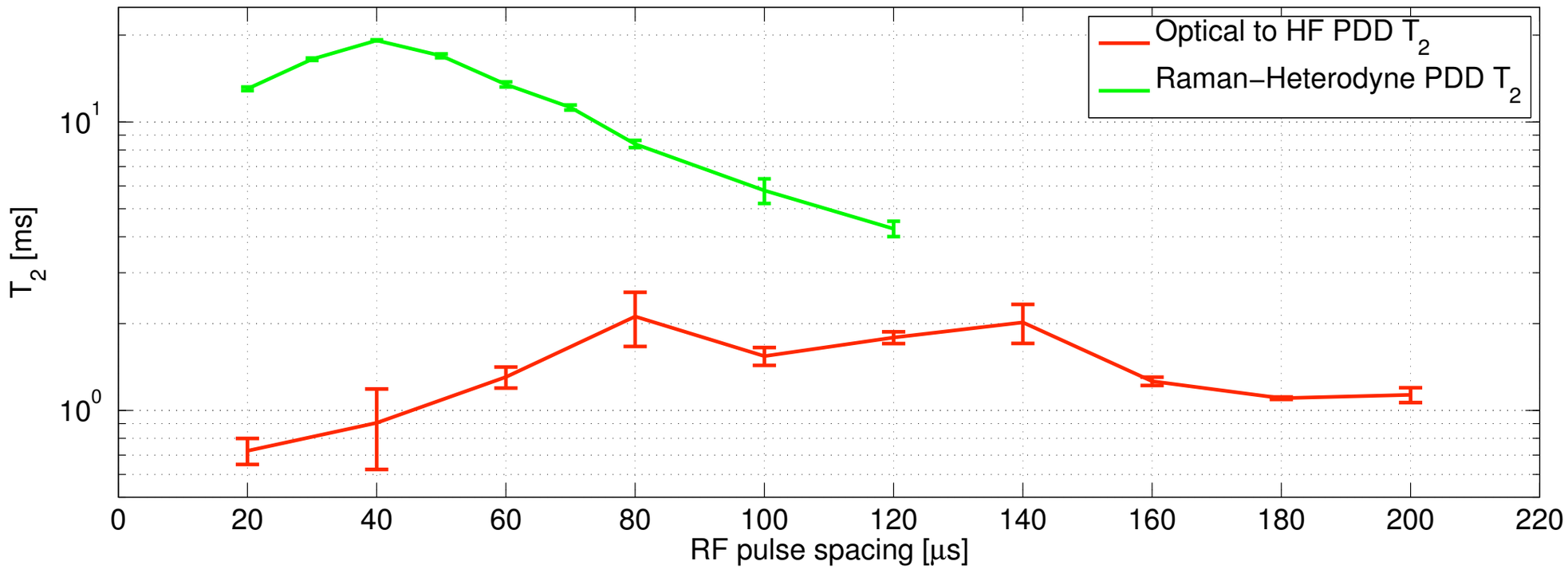
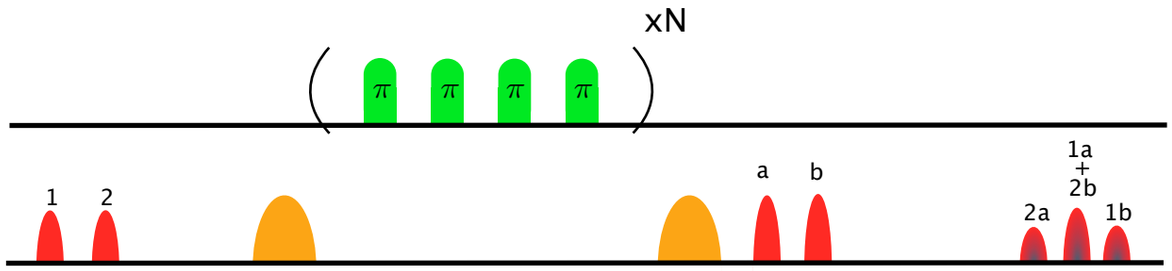


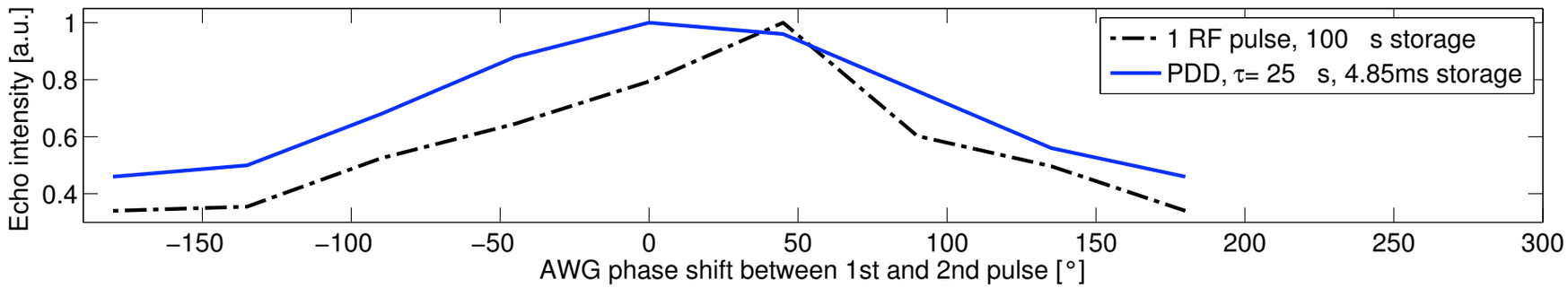


- same conditions (RF, B=0mT, ...) but DD significantly less efficient !?
- similar for all tested DD sequences (best achieved so far $T_2 \approx 4$ ms)

Some properties...

Do optical-input phases survive:





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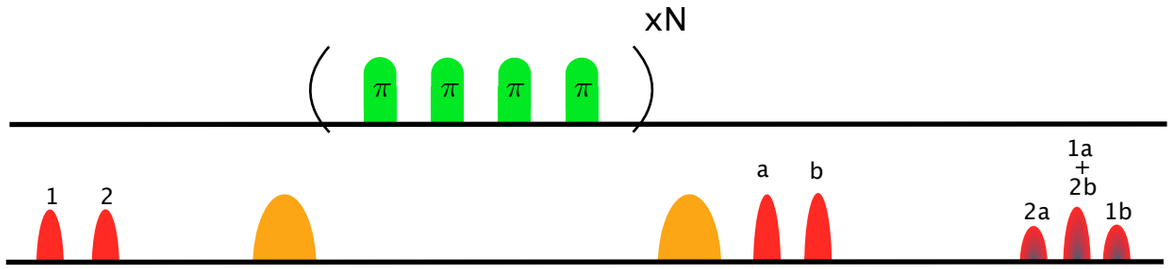

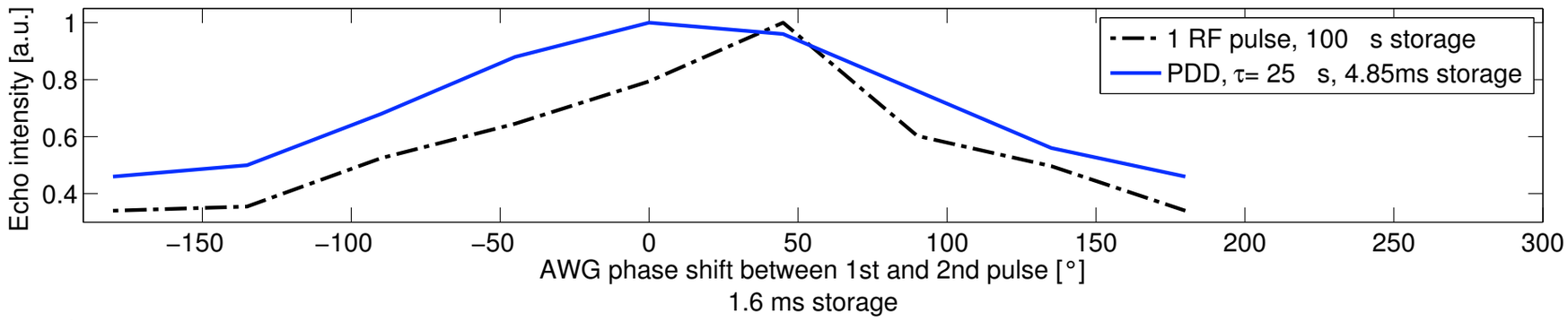

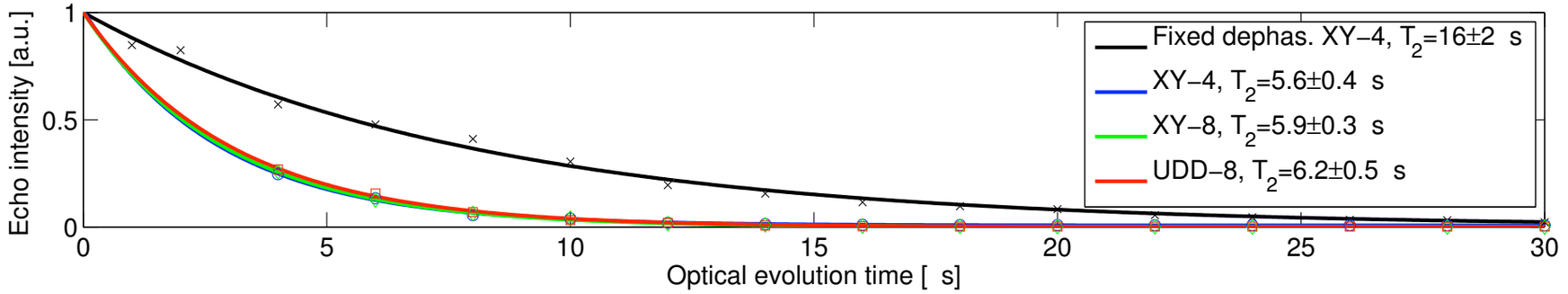

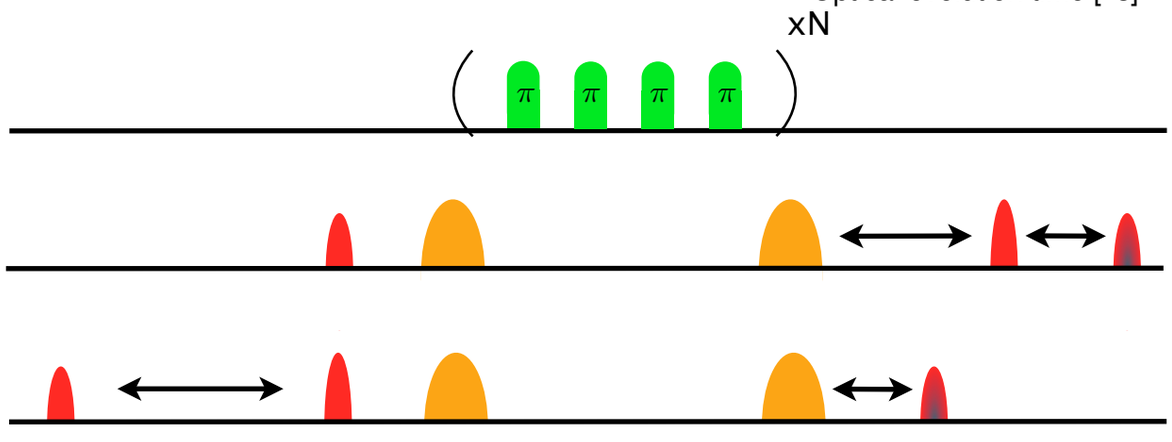

Optical phase distribution during storage:

-> fixed -> optical $T_2 \approx 16$us

-> varying -> optical $T_2 \approx 6$us only!?

Conclusions

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  - „interference“ with „wrong-class“ ions, shifted in pit by RF (addresses all)
  - ...?

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  - ...?

- something else?

Conclusions

- DD works very well for a RF-induced HF-coherence
  - increase HF-T_2 to up to 400 ms (without ZEFOZ)
  - sequences independent of „initial“-phase identified (KDD (and PDD))

- Optical to HF storage works ≈ ok
  - low (but expected) efficiency
  - input phase conserved
  - optical inputs retrievable for „storage-times“ of about 10 ms (T_2 (1/e) ≈ 4 ms)

- DD/RF-refocusing seems „inefficient“ for optically-induced HF-coherences ?!
  - 10x smaller HF-T_2 compared to Raman heterodyne data
  - (greater) shot to shot instability

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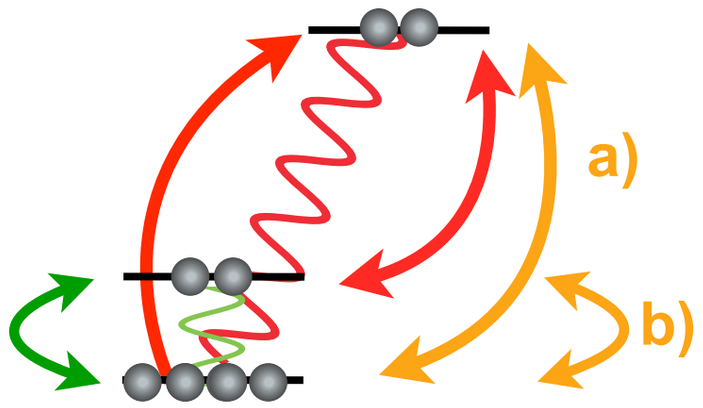
  - ...?

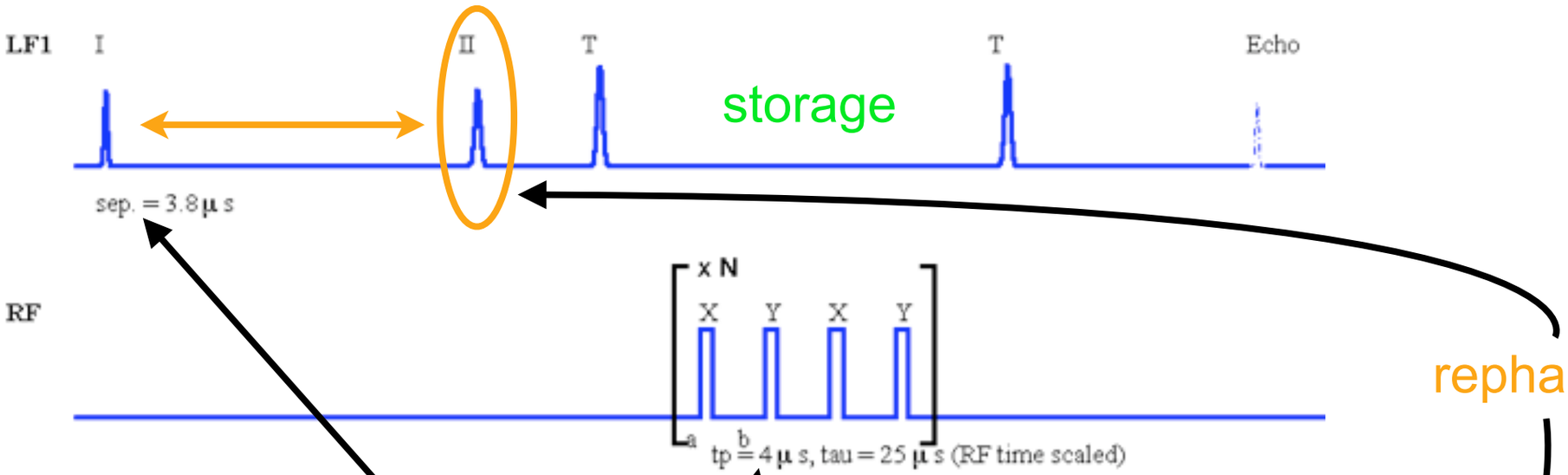
- something else?

Thank you!

Two „protocols“ tested



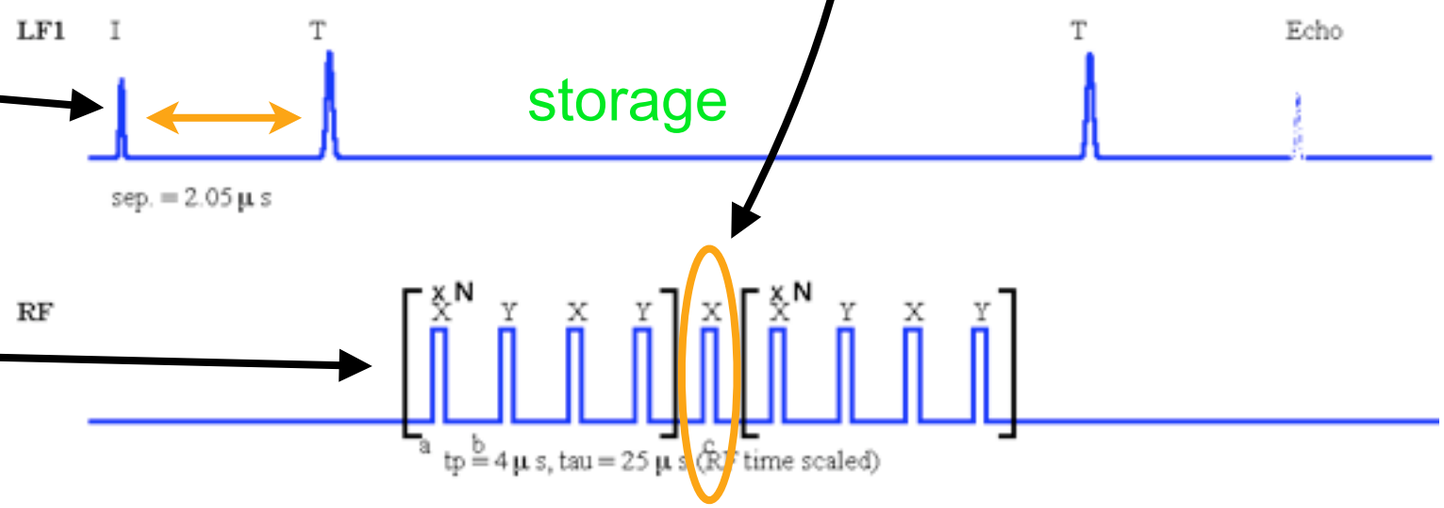
a)

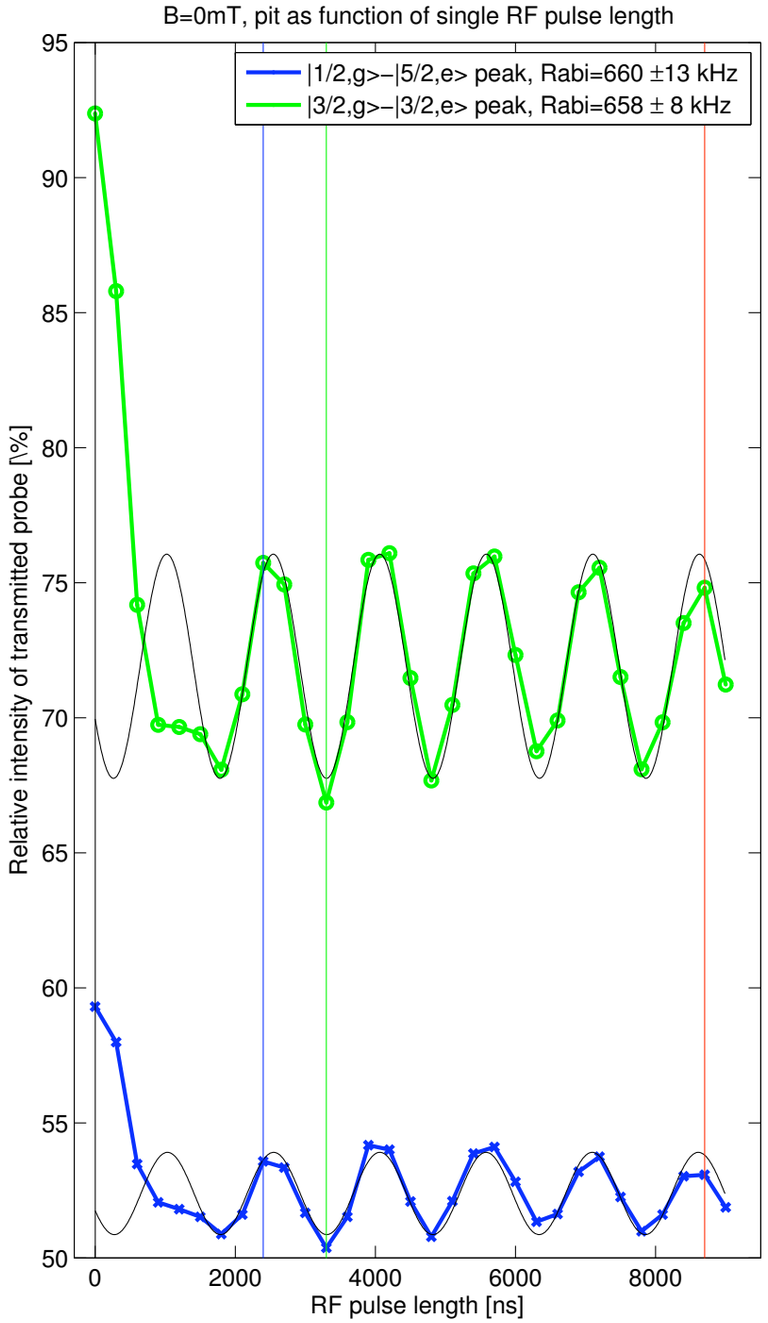


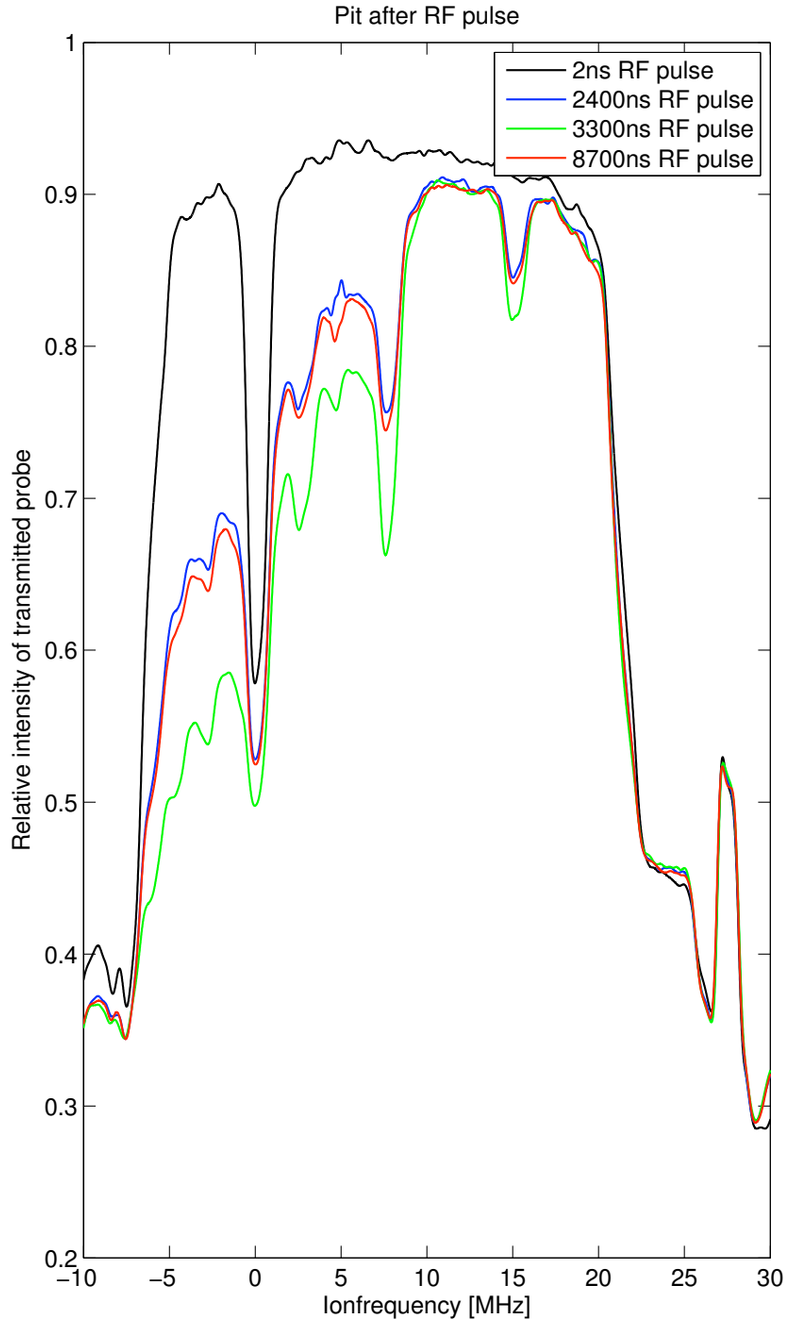
rephasing of „optical“ phase

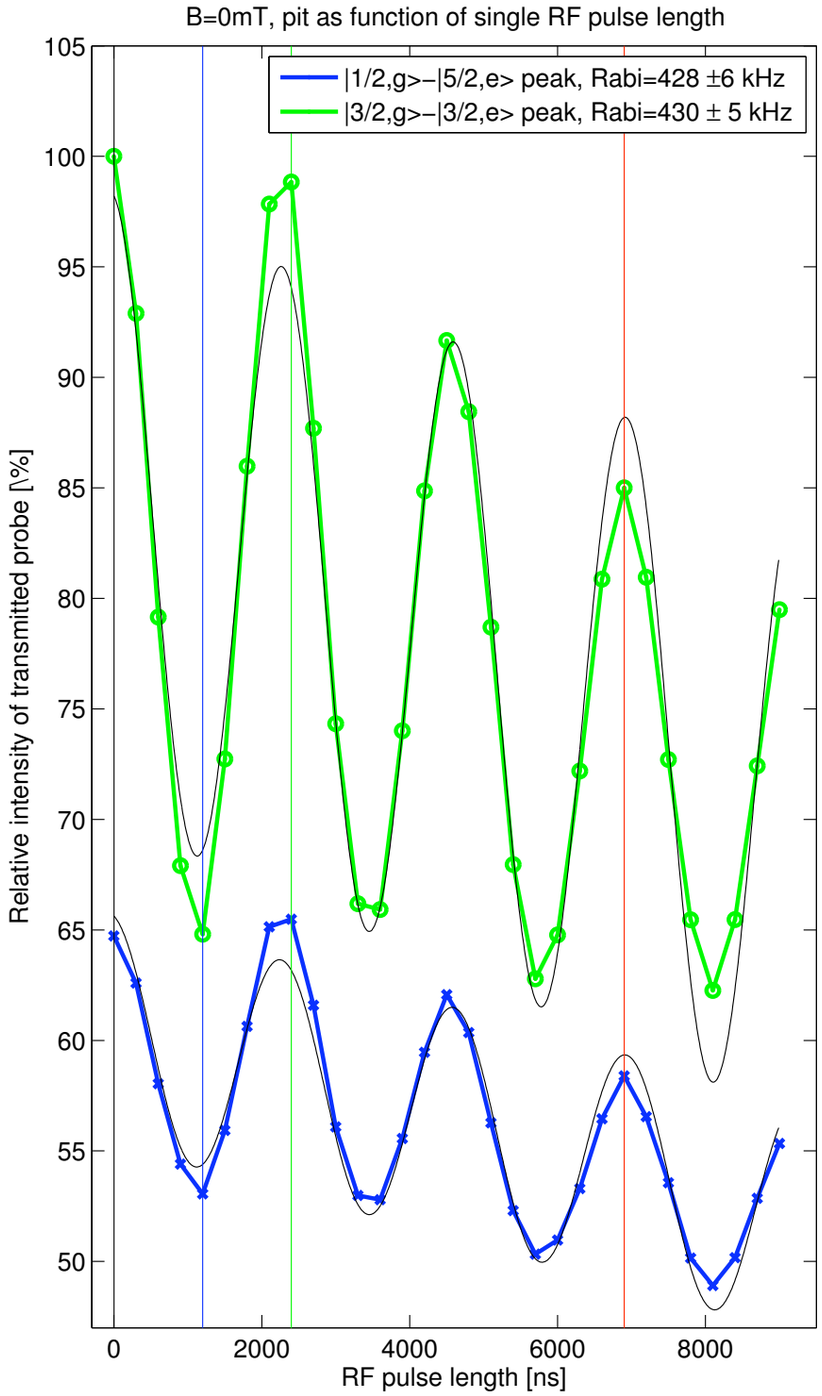
input mode

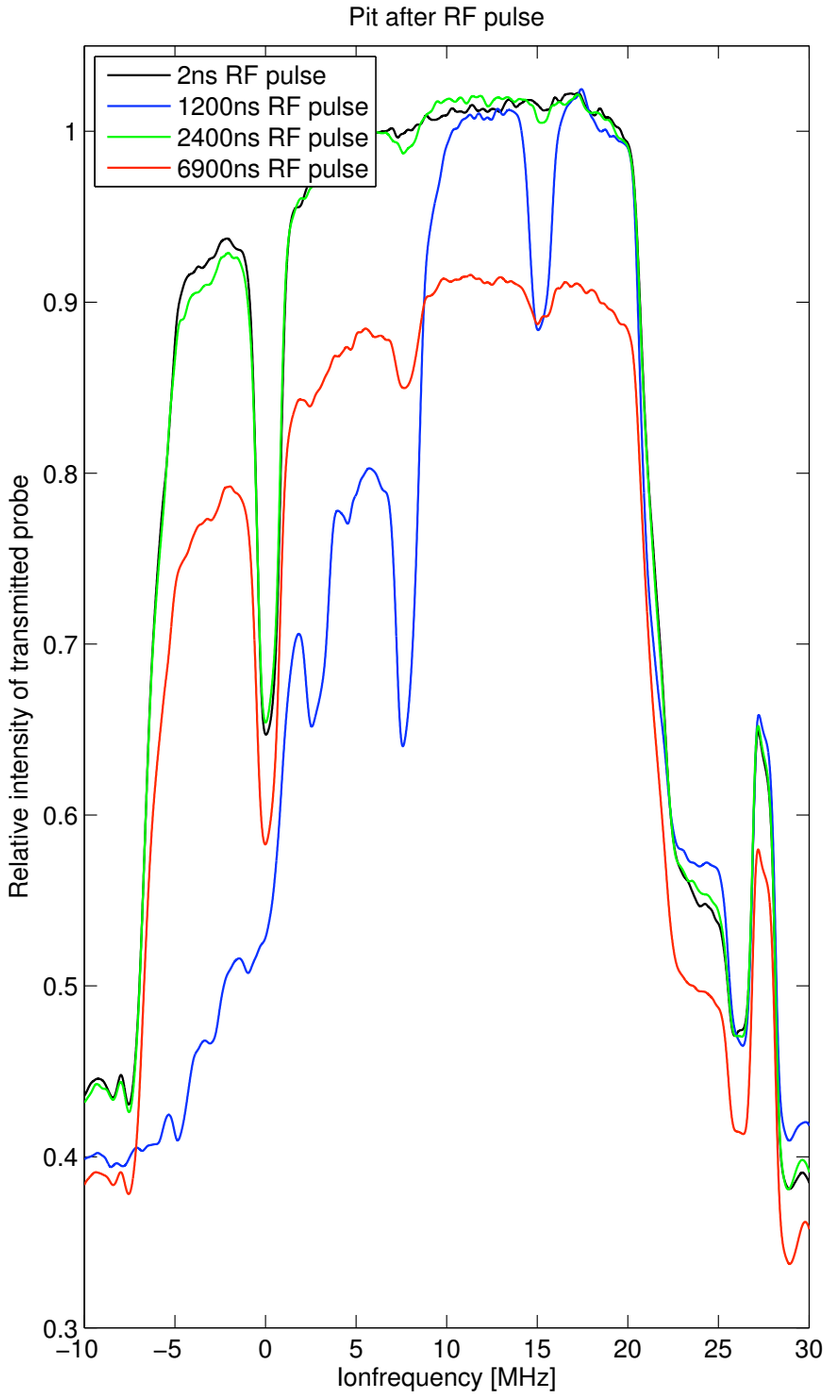
b)

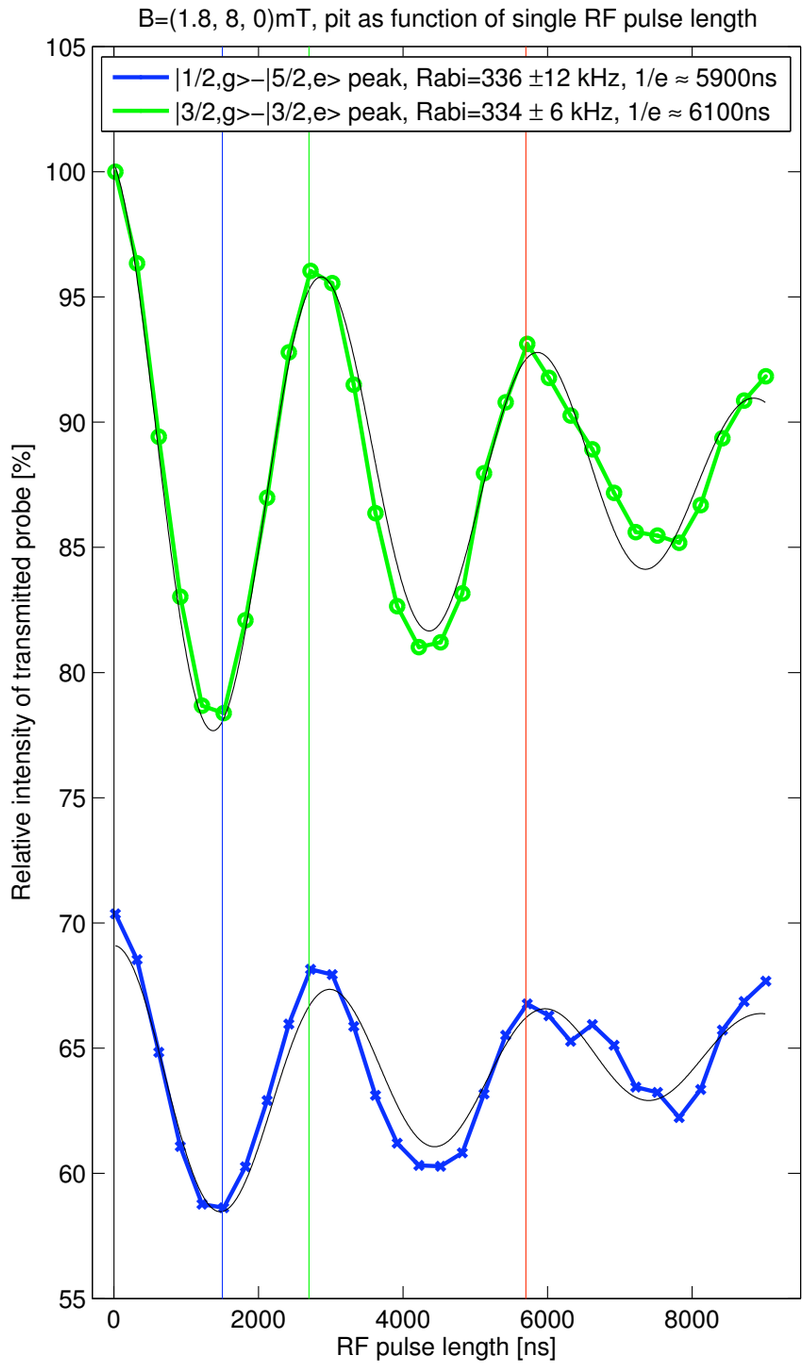


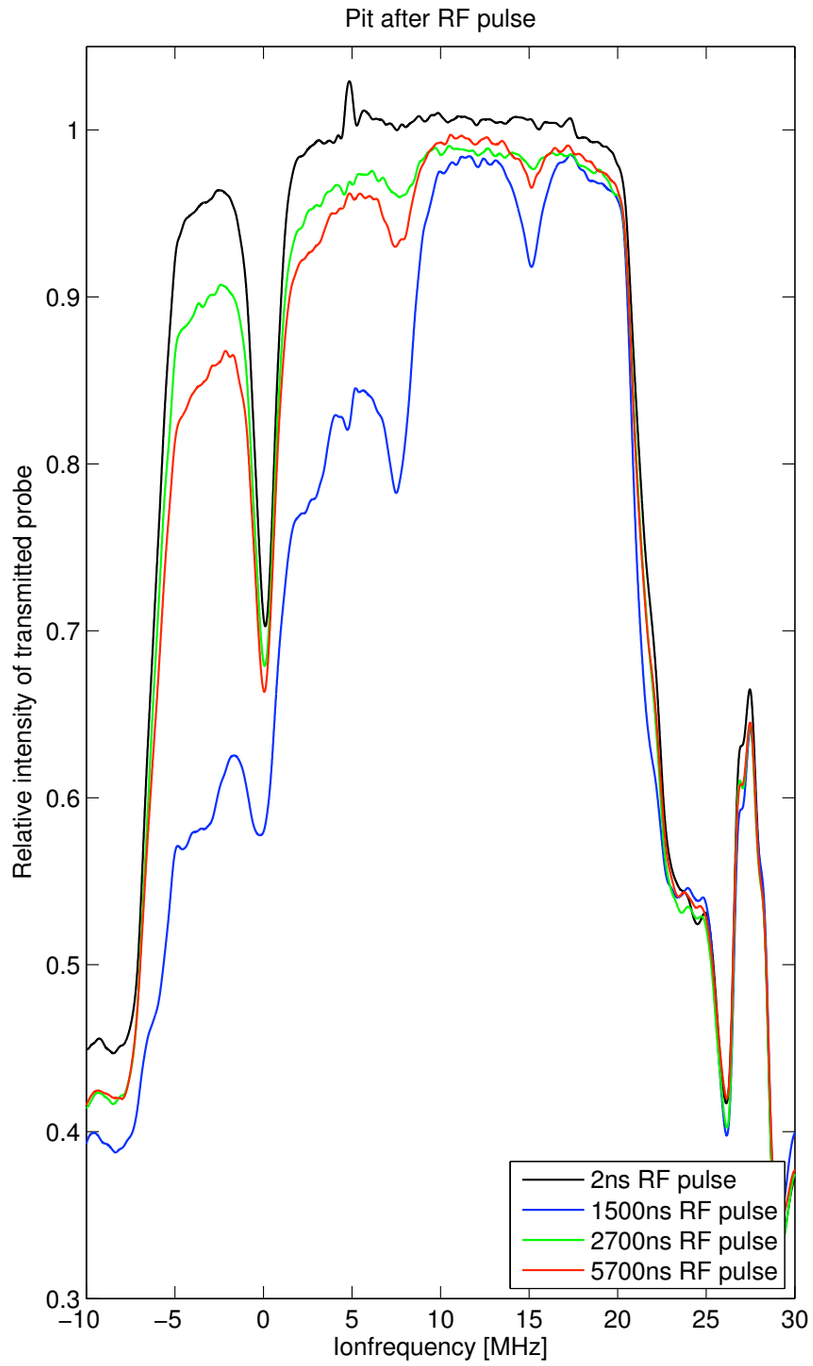

B=0mT, pit as function of single RF pulse length
|1/2,g>−|5/2,e> peak, Rabi=660 ±13 kHz
|3/2,g>−|3/2,e> peak, Rabi=658 ± 8 kHz
Relative intensity of transmitted probe [%]
RF pulse length [ns]
95
90
85
80
75
70
65
60
55
50
0
2000
4000
6000
8000

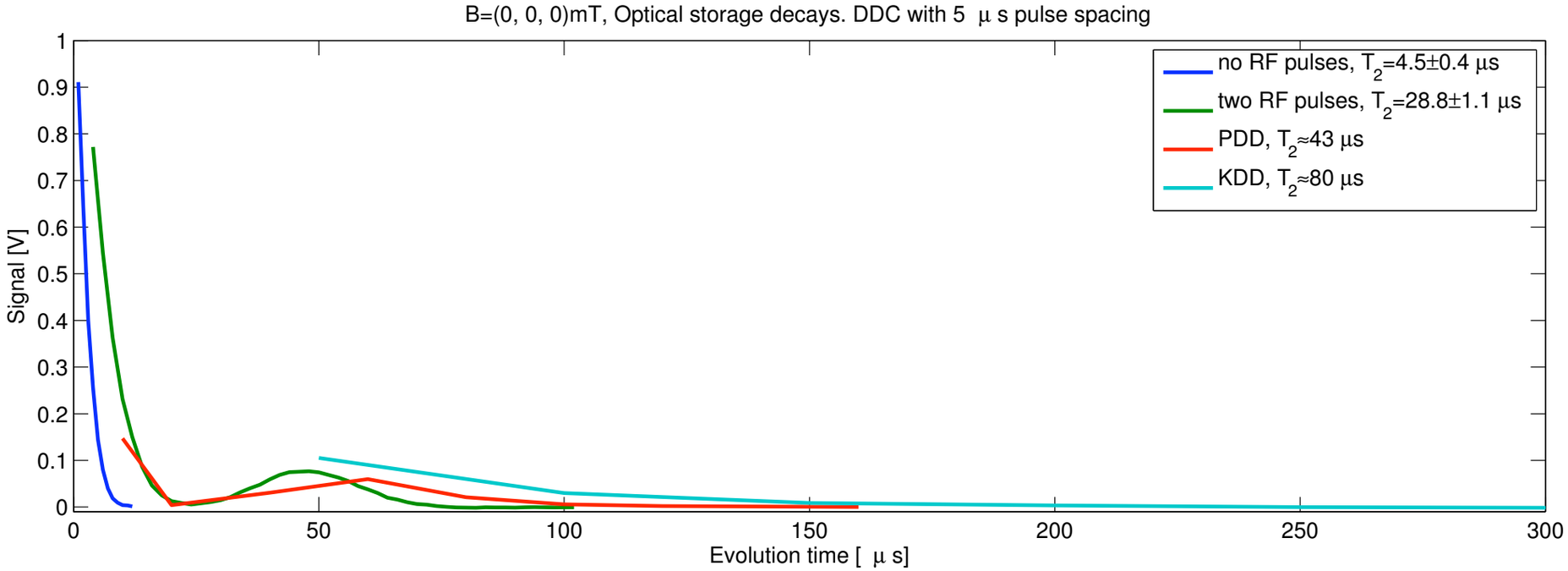

Pit after RF pulse
2ns RF pulse
2400ns RF pulse
3300ns RF pulse
8700ns RF pulse
Relative intensity of transmitted probe
Ionfrequency [MHz]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
−10
−5
0
5
10
15
20
25
30

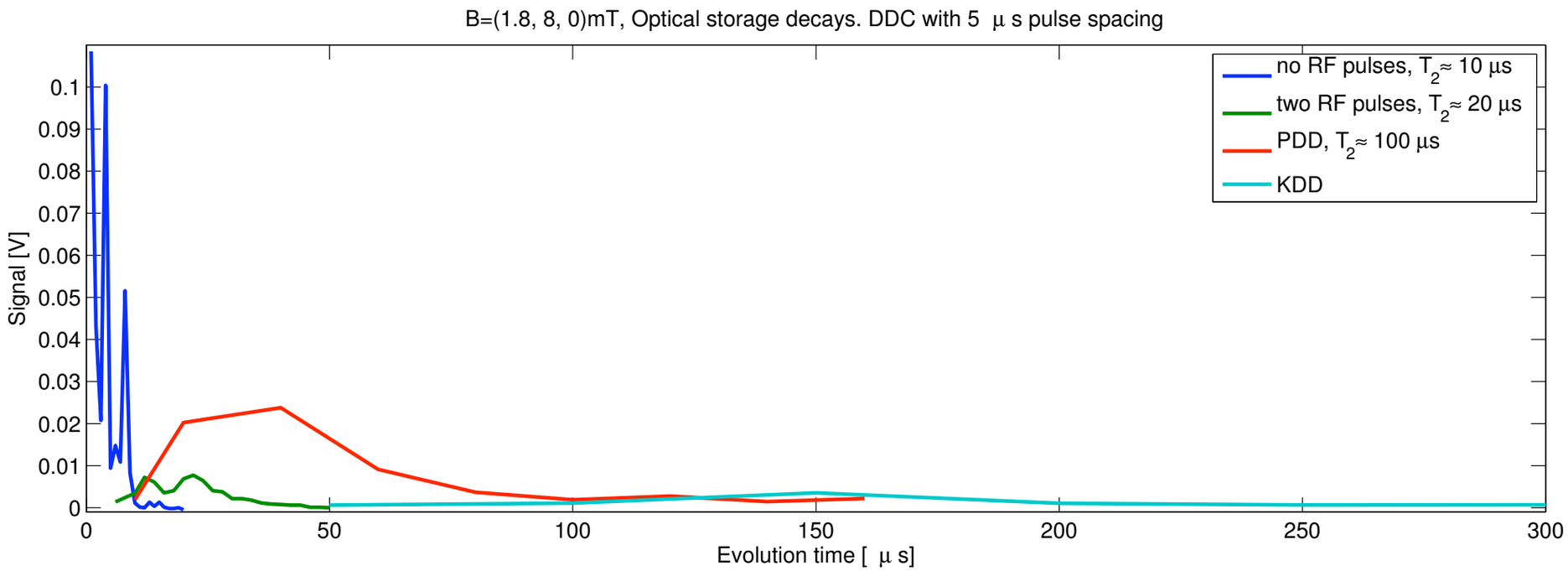

B=0mT, pit as function of single RF pulse length
|1/2,g>–|5/2,e> peak, Rabi=428 ±6 kHz
|3/2,g>–|3/2,e> peak, Rabi=430 ± 5 kHz
Relative intensity of transmitted probe [%]
RF pulse length [ns]
105
100
95
90
85
80
75
70
65
60
55
50
0
2000
4000
6000
8000


Pit after RF pulse
2ns RF pulse
1200ns RF pulse
2400ns RF pulse
6900ns RF pulse
Relative intensity of transmitted probe
Ionfrequency [MHz]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
–10
–5
0
5
10
15
20
25
30


B=(1.8, 8, 0)mT, pit as function of single RF pulse length
|1/2,g>–|5/2,e> peak, Rabi=336 ±12 kHz, 1/e ≈ 5900ns
|3/2,g>–|3/2,e> peak, Rabi=334 ± 6 kHz, 1/e ≈ 6100ns
Relative intensity of transmitted probe [%]
RF pulse length [ns]
105
100
95
90
85
80
75
70
65
60
55
0
2000
4000
6000
8000


Pit after RF pulse
Relative intensity of transmitted probe
Ionfrequency [MHz]
2ns RF pulse
1500ns RF pulse
2700ns RF pulse
5700ns RF pulse
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
–10
–5
0
5
10
15
20
25
30


B=(0, 0, 0)mT, Optical storage decays. DDC with 5 μ s pulse spacing
Signal [V]
Evolution time [μ s]
no RF pulses, T2=4.5±0.4 μs
two RF pulses, T2=28.8±1.1 μs
PDD, T2≈43 μs
KDD, T2≈80 μs


B=(1.8, 8, 0)mT, Optical storage decays. DDC with 5 μ s pulse spacing
Signal [V]
Evolution time [μ s]
no RF pulses, T2≈ 10 μs
two RF pulses, T2≈ 20 μs
PDD, T2≈ 100 μs
KDD