Spin Manipulating Polarized Deuterons*

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Outline

- Motivation
- Experimental apparatus at Forschungszentrum Jülich
- Manipulation of deuteron vector and tensor polarizations
- Chao's matrix formalism for describing spin dynamics
- Kondratenko Crossing to overcome depolarizing resonances
- Possible improvement of Kondratenko Crossing
- Summary

Motivation

- **Manipulation of deuteron vector and tensor polarizations:**
  - precise control over deuteron polarizations $\Rightarrow$
    reduce systematic errors in polarized scattering experiments

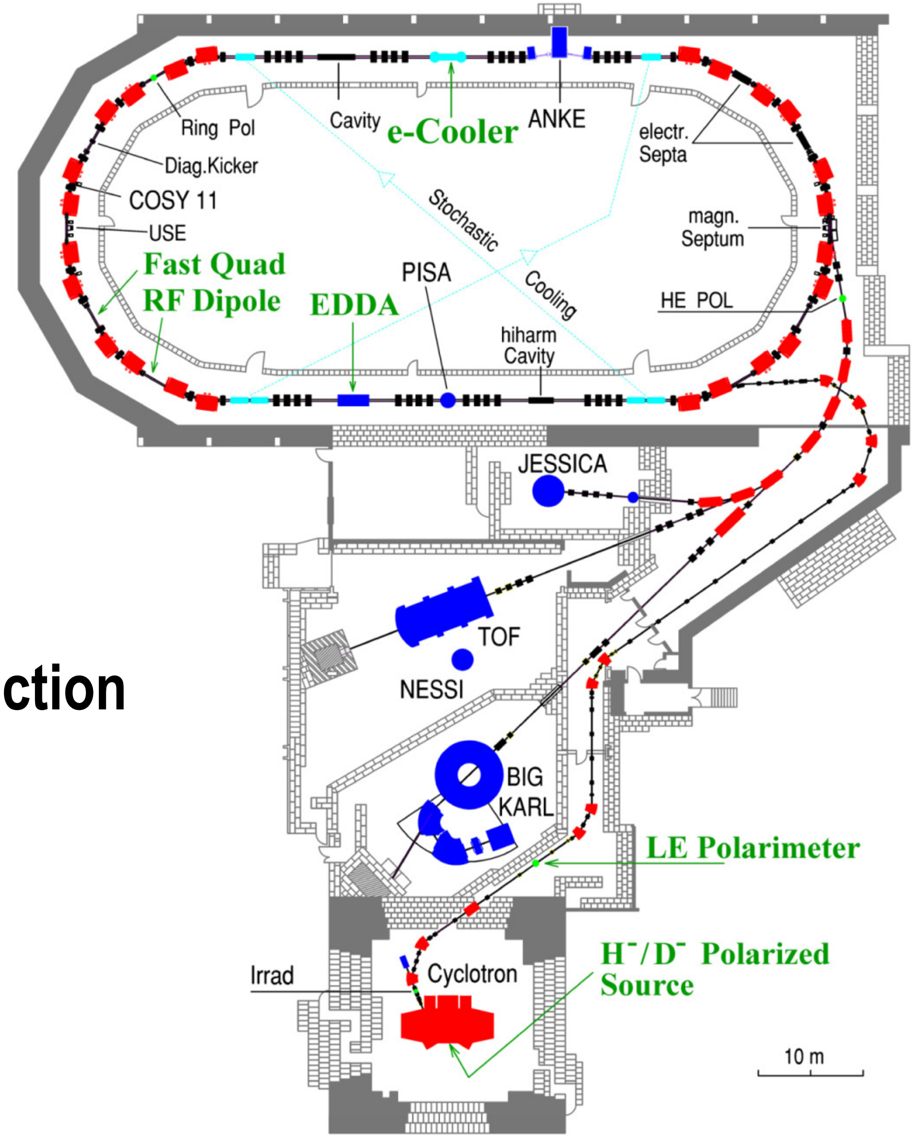
- **Chao's matrix formalism for describing spin dynamics:**
  - analytic calculation of polarization at any time during piecewise-linear spin resonance crossing

- **Kondratenko Crossing to overcome depolarizing resonances:**
  - better preserve polarization when going through spin resonance even with moderate crossing rate

- **Possible improvement of Kondratenko Crossing:**
  - easier practical implementation,
  - possibly less sensitive to beam's momentum spread

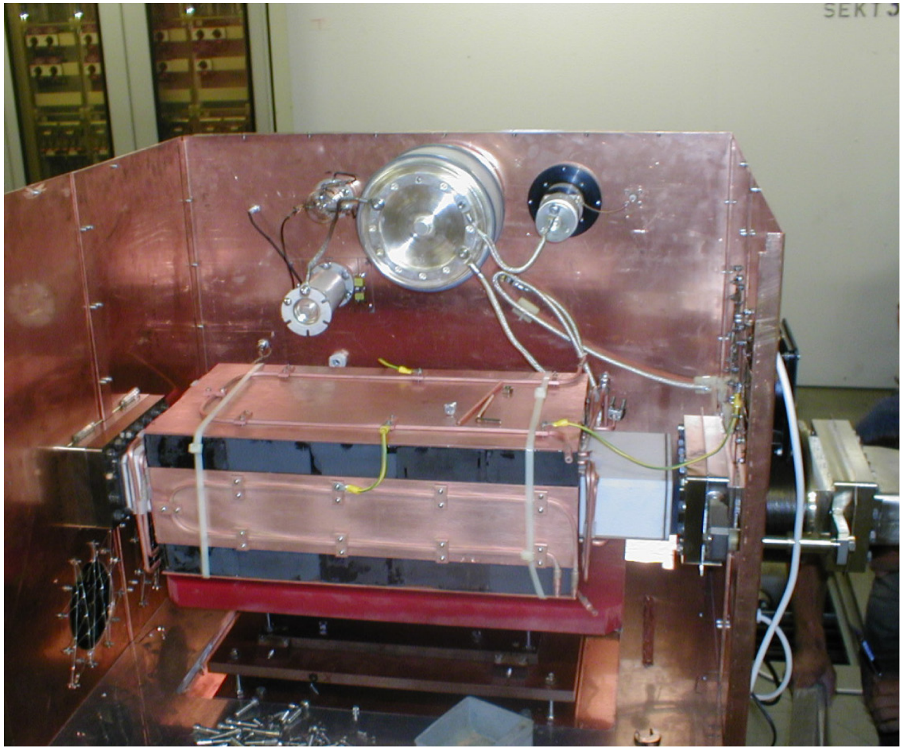
COSY COoler SYnchrotron

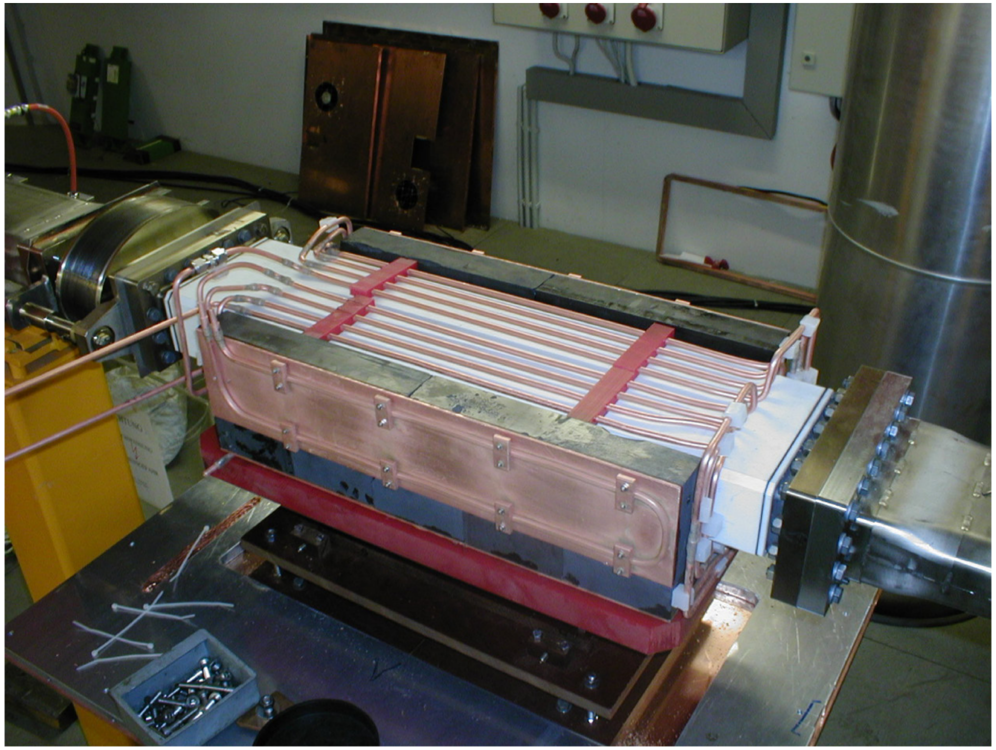
- Deuterons: 1.85 GeV/c
- D⁻ source
  cycled through 5 spin states
- LE Polarimeter
  monitored injected polarization
- e-Cooler
  reduced momentum spread at injection
- RF Dipole or RF Solenoid
- EDDA detector as polarimeter



Ferrite RF Dipole

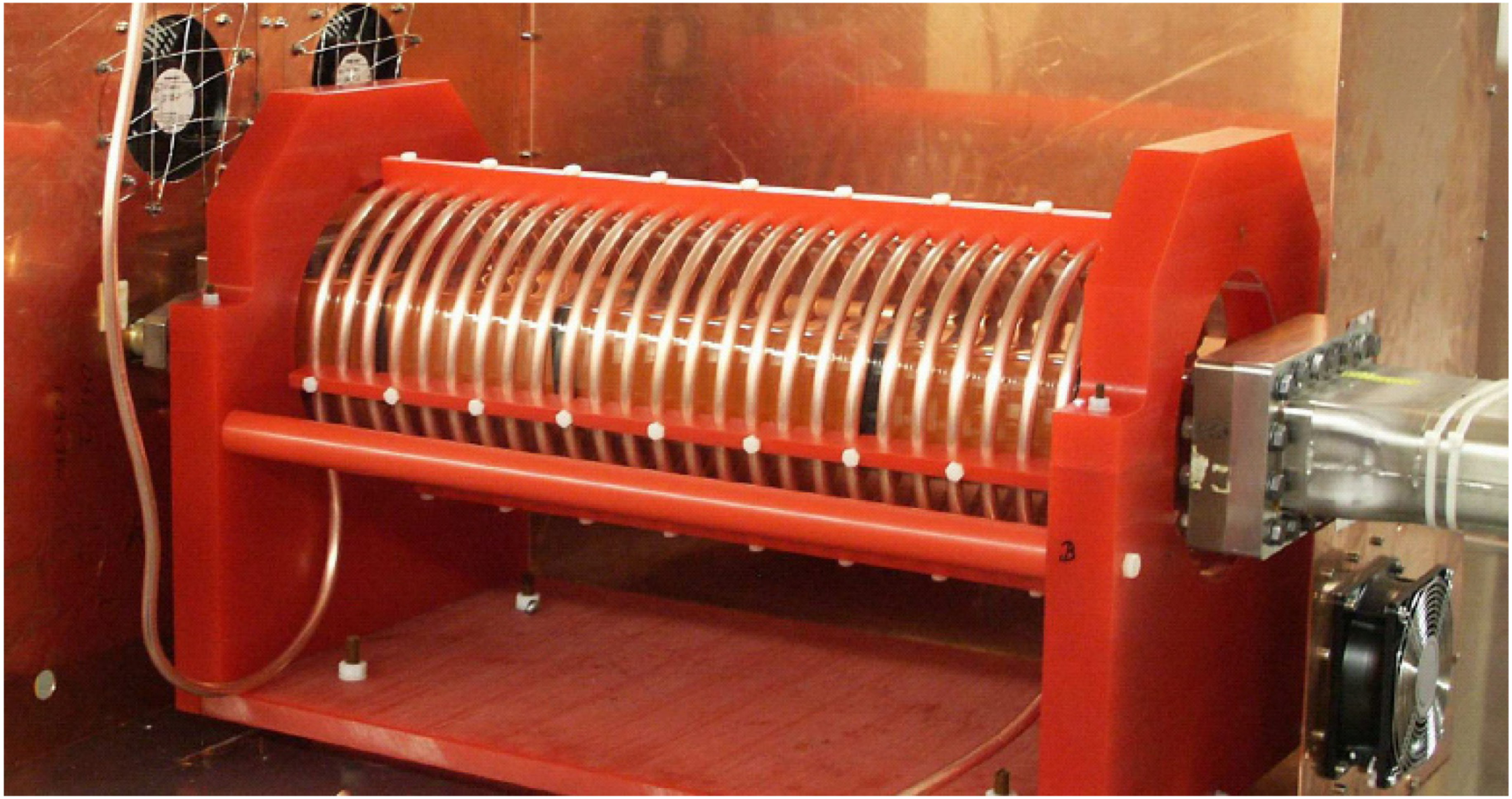
- Ceramic vacuum pipe
- $\int B_{rms} \cdot dl$ = 0.54 T·mm at ~917 kHz





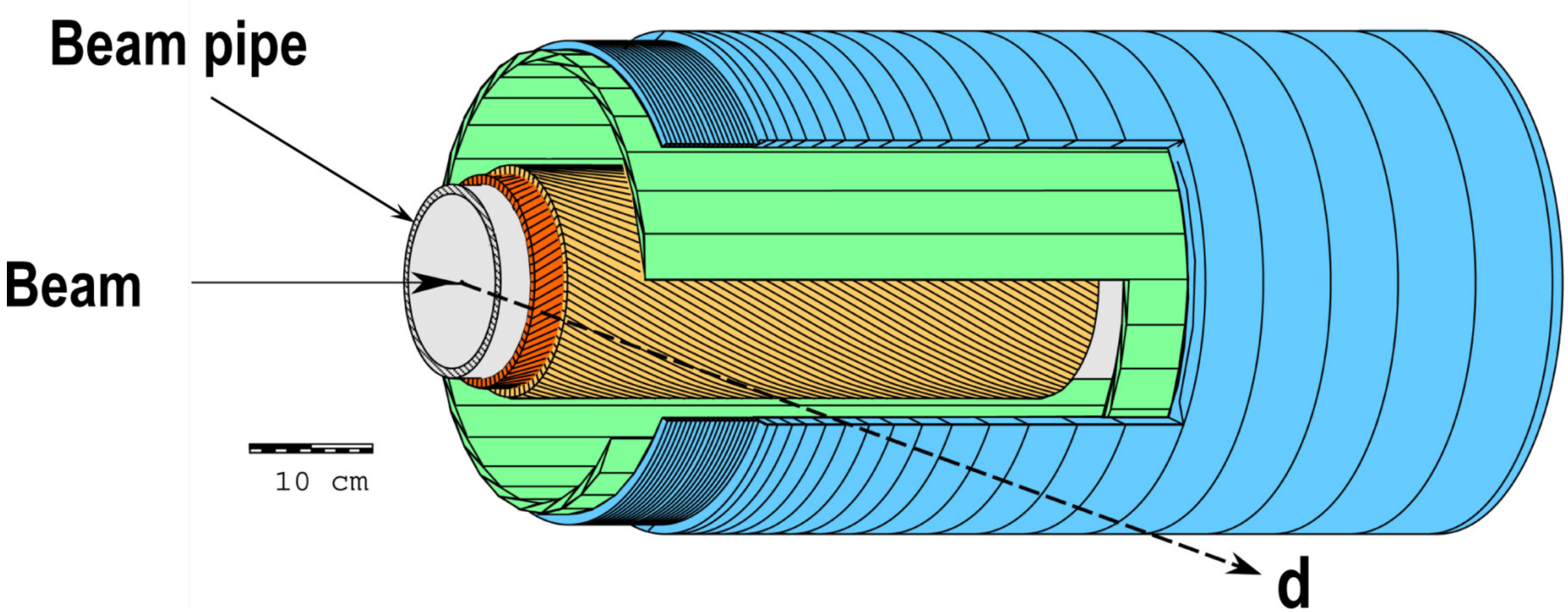
RF Solenoid

- Ceramic vacuum pipe
- $\int B_{rms} \cdot dl$ = 0.67 T·mm at ~917 kHz



EDDA Detector

- C or CH_2 fiber target
- Two cylindrical double layers
  - Outer double layer: 32 scintillator slabs ($\Delta\phi$ = 11.25°), 2×29 scintillator half-rings ($\Delta\theta_{lab}$ = 2.5°)
  - Inner double layer: 640 scintillating fibers
- Fast deuteron polarimeter
  - Inclusive scaler counts in Left, Right, Top & Bottom quadrants



Spin-1 Beam Polarization

- Deuteron's gyromagnetic anomaly $G_d = -\,0.142\ 987$ (~12.5 x smaller than proton's)
- Three possible spin components along vertical axis: $|+1\rangle$, $|0\rangle$ & $|-1\rangle$
- Vector polarization

$$P_V = \frac{N_+ - N_-}{N_+ + N_0 + N_-}$$

- Tensor polarization

$$P_T = 1 - 3\frac{N_0}{N_+ + N_0 + N_-}$$

N_+, N_0 & N_- = number of particles in $|+1\rangle$, $|0\rangle$ & $|-1\rangle$ states.

Spin Motion and Spin Flipping

- Unperturbed spin motion
  - precession about vertical axis with frequency $\nu_s = G\gamma \equiv$ spin tune
- RF magnet can create spin resonance centered at

$$f_r = f_c(n \pm \nu_s)$$

$f_c \equiv$ beam's circulation frequency

- Sweeping rf magnet's frequency through $f_r \Rightarrow$ flip P_V direction
- Froissart-Stora equation gives final polarization

$$P_V = P_V^i \left\{ 2\exp\left[\frac{(\pi\,|\mathcal{E}|\,f_c)^2}{\Delta f / \Delta t} \right] - 1 \right\}$$

$\mathcal{E}$ = resonance strength

Δf = frequency ramp range

Δt = ramp time

- Spin-flip efficiency $\eta \equiv -P_V / P_V^i$

Rotating Deuteron Polarization

- Sweeping rf magnet's frequency through f_r
  - rotates polarization by an angle θ.
  - vector and tensor polarizations transform as

$$P_V(\theta) = P_V^i \cos\theta, \qquad P_T(\theta) = P_T^i [\frac{3}{2}\cos^2\theta - \frac{1}{2}]$$

  - modified Froissart-Stora formula for P_V

$$\frac{P_V}{P_V^i} = (1+\hat{\eta})\exp\left[\frac{(\pi\,|\mathcal{E}|\,f_c)^2}{\Delta f/\Delta t}\right] - \hat{\eta}$$

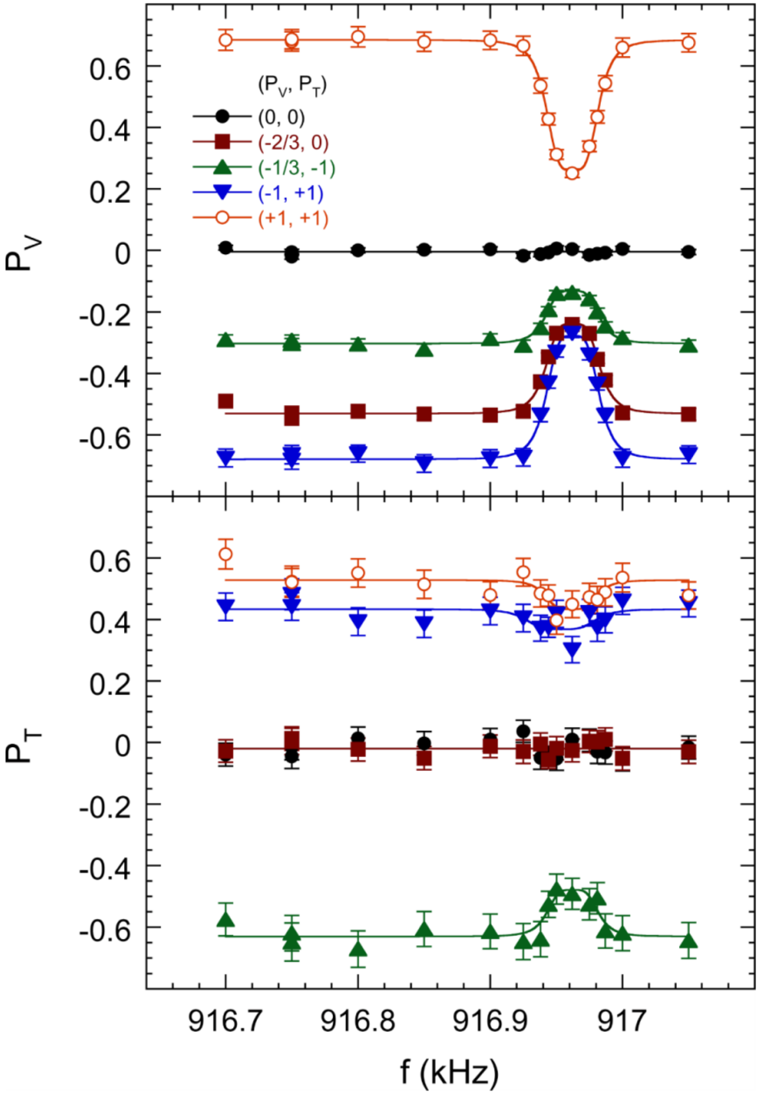
  - formula for P_T

$$\frac{P_T}{P_T^i} = \frac{3}{2}\left(\frac{P_V}{P_V^i}\right)^2 - \frac{1}{2} = \frac{3}{2}\left\{(1+\hat{\eta})\exp\left[\frac{(\pi\,|\mathcal{E}|\,f_c)^2}{\Delta f/\Delta t}\right] - \hat{\eta}\right\}^2 - \frac{1}{2}$$

$\hat{\eta} \equiv$ limiting spin-flip efficiency

Resonance Map at Fixed Frequency (Dec 03)

V.S. Morozov *et al.*, Phys. Rev. ST-AB 8, 061001 (2005)



Measured Resonance Frequency and Width

$$f_V = 916.9622 \pm 0.0003 \text{ kHz}$$

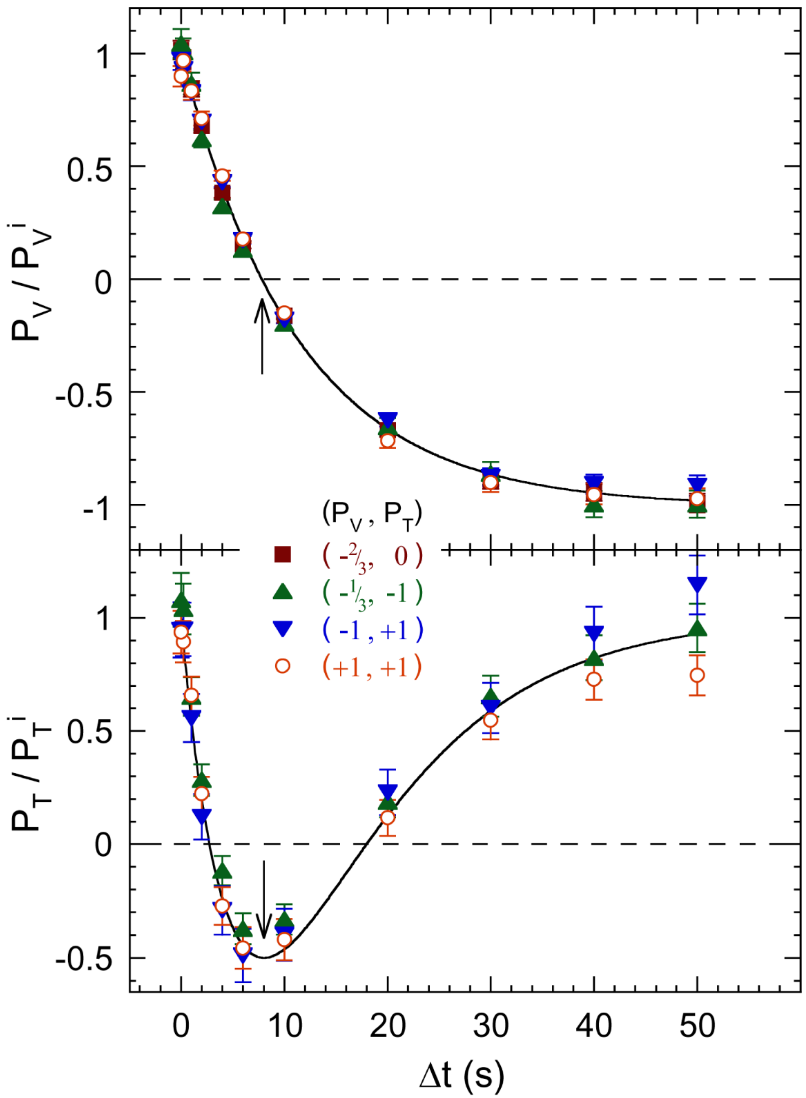
$$\omega_V = 40.8 \pm 0.8 \text{ Hz}$$

$$f_T = 916.961 \pm 0.003 \text{ kHz}$$

$$\omega_T = 39 \pm 7 \text{ Hz}$$

Varying Ramp Time (Dec 03)

V.S. Morozov *et al.*, Phys. Rev. ST-AB 8, 061001 (2005)



Measured Resonance Strength

$$\hat{\eta}_V = 100 \pm 2\%$$

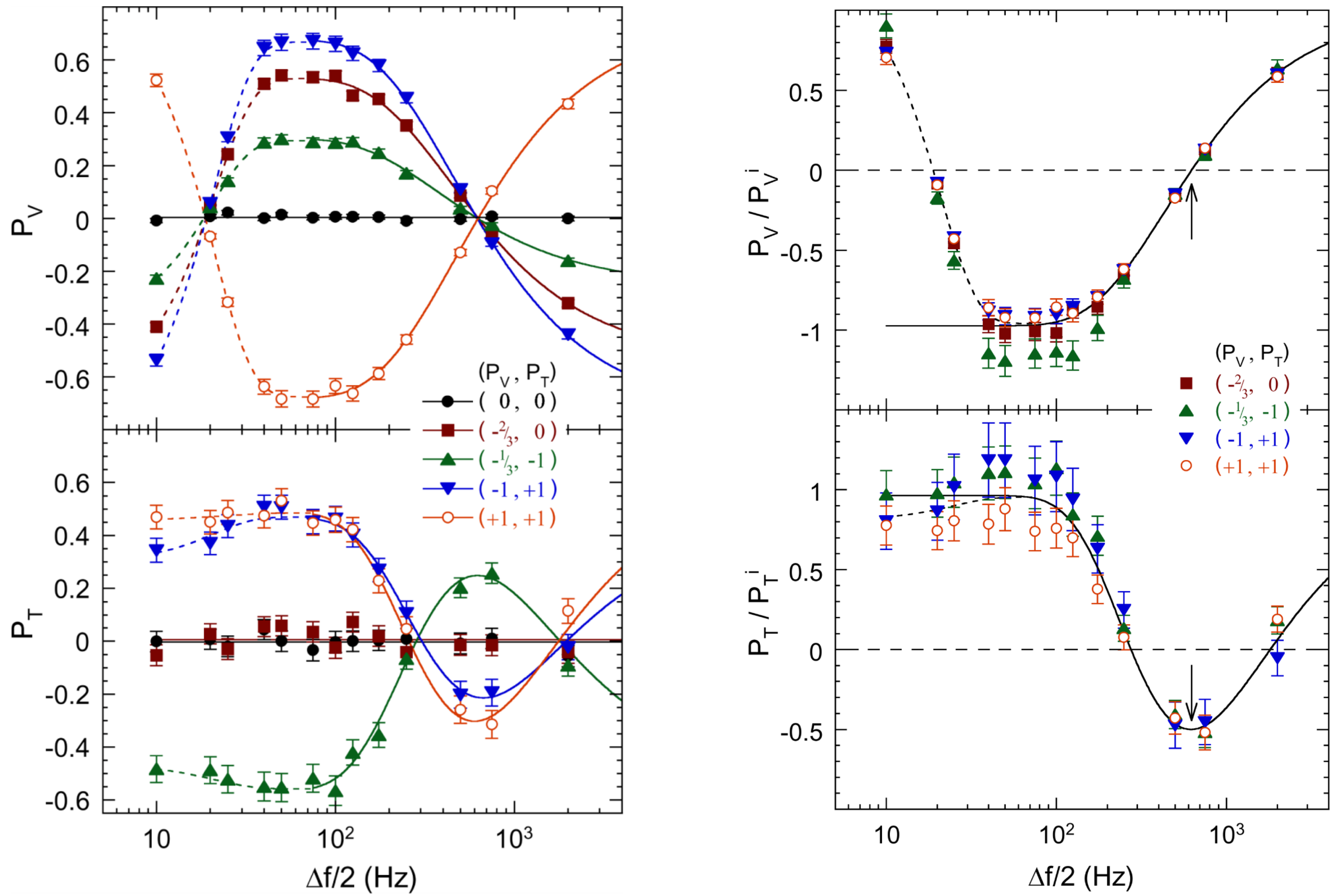
$$\varepsilon_V = (1.17 \pm 0.01) \times 10^{-6}$$

$$\hat{\eta}_T = 100 \pm 2\%$$

$$\varepsilon_T = (1.14 \pm 0.02) \times 10^{-6}$$

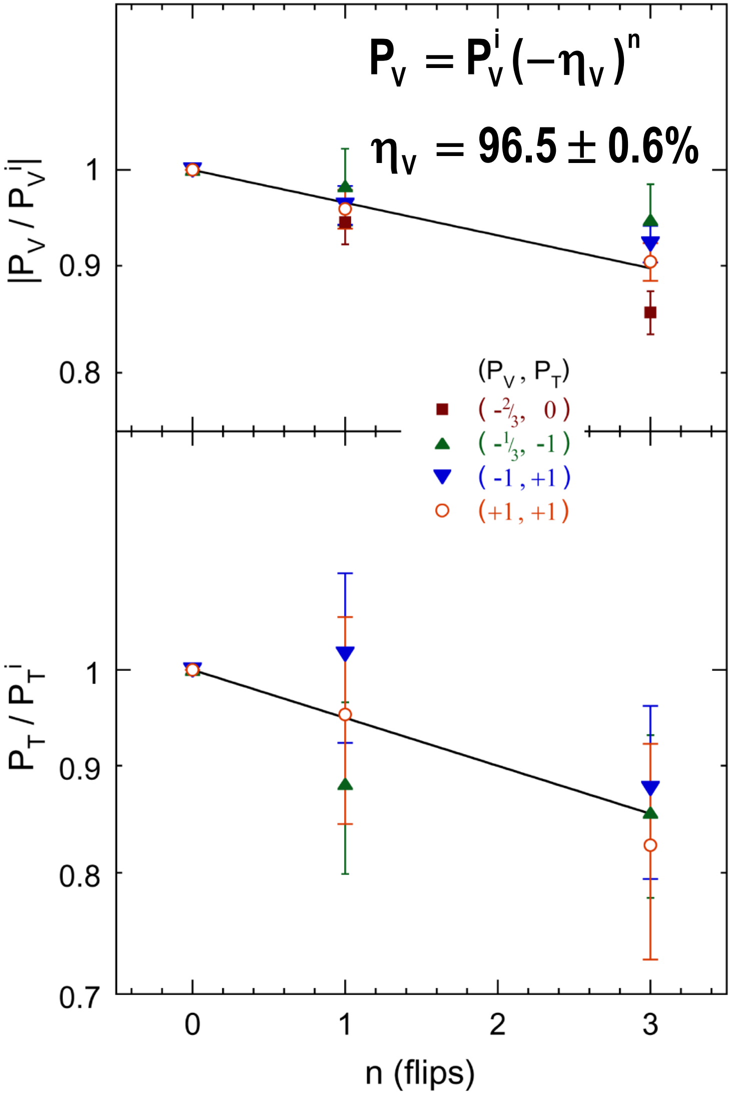
Varying Frequency Range (Dec 03)

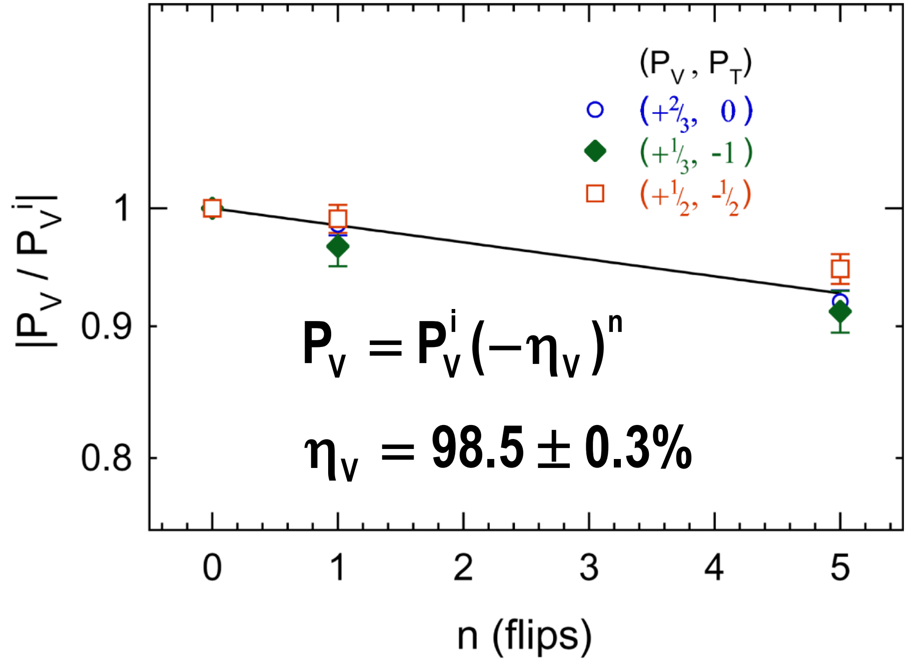
V.S. Morozov *et al.*, Phys. Rev. ST-AB 8, 061001 (2005)



Multiple Spin Flipping (Dec 03)

V.S. Morozov *et al.*, Phys. Rev. ST-AB 8, 061001 (2005)





$$P_T = P_T^i \left[\frac{3}{2} (-\eta_T)^2 - \frac{1}{2} \right]^n$$

$$\eta_T = 98.3 \pm 1.0\%$$

Chao Matrix Formalism

A.W. Chao, Phys. Rev. ST-AB 8, 104001 (2005)

- Particle's spin state described by two-component complex spinor Ψ
- Spinor equation of motion near single spin resonance

$$\frac{d\Psi}{d\theta} = -\frac{i}{2}\begin{bmatrix} -G\gamma(\theta) & \varepsilon\, e^{i\nu_r\theta} \\ \varepsilon^* e^{-i\nu_r\theta} & G\gamma(\theta) \end{bmatrix}\Psi$$

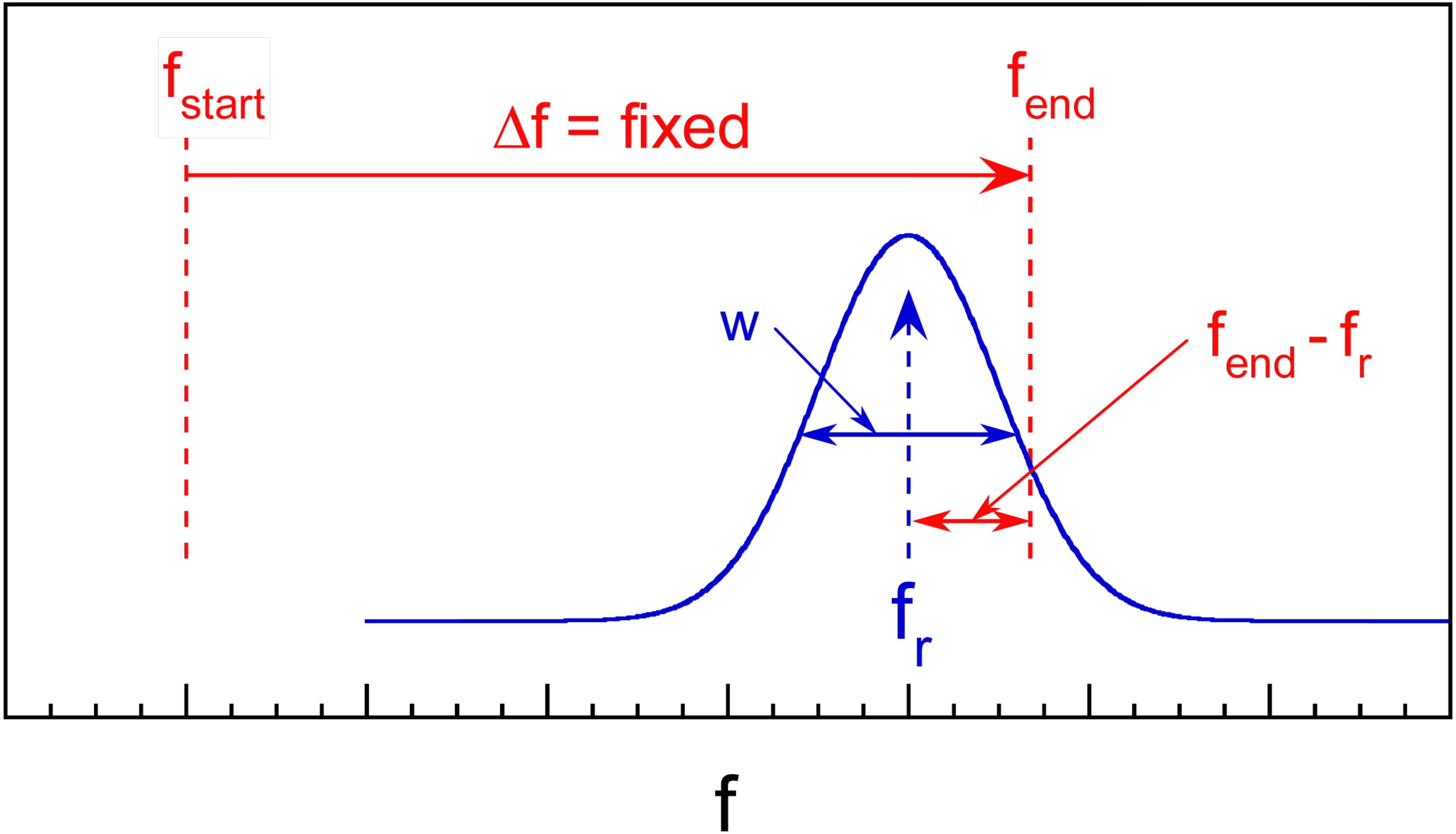
$\theta = 2\pi f_c t$ = time variable

ν_r = the spin resonance tune

- Equation solved analytically for
  - constant distance between $G\gamma$ and ν_r
  - linearly changing distance between $G\gamma$ and ν_r
- Spinor evolution described by time-dependent matrix
- Matrices multiplied sequentially for piece-wise linear crossing pattern
- Resulting matrix determines final spinor state and polarization

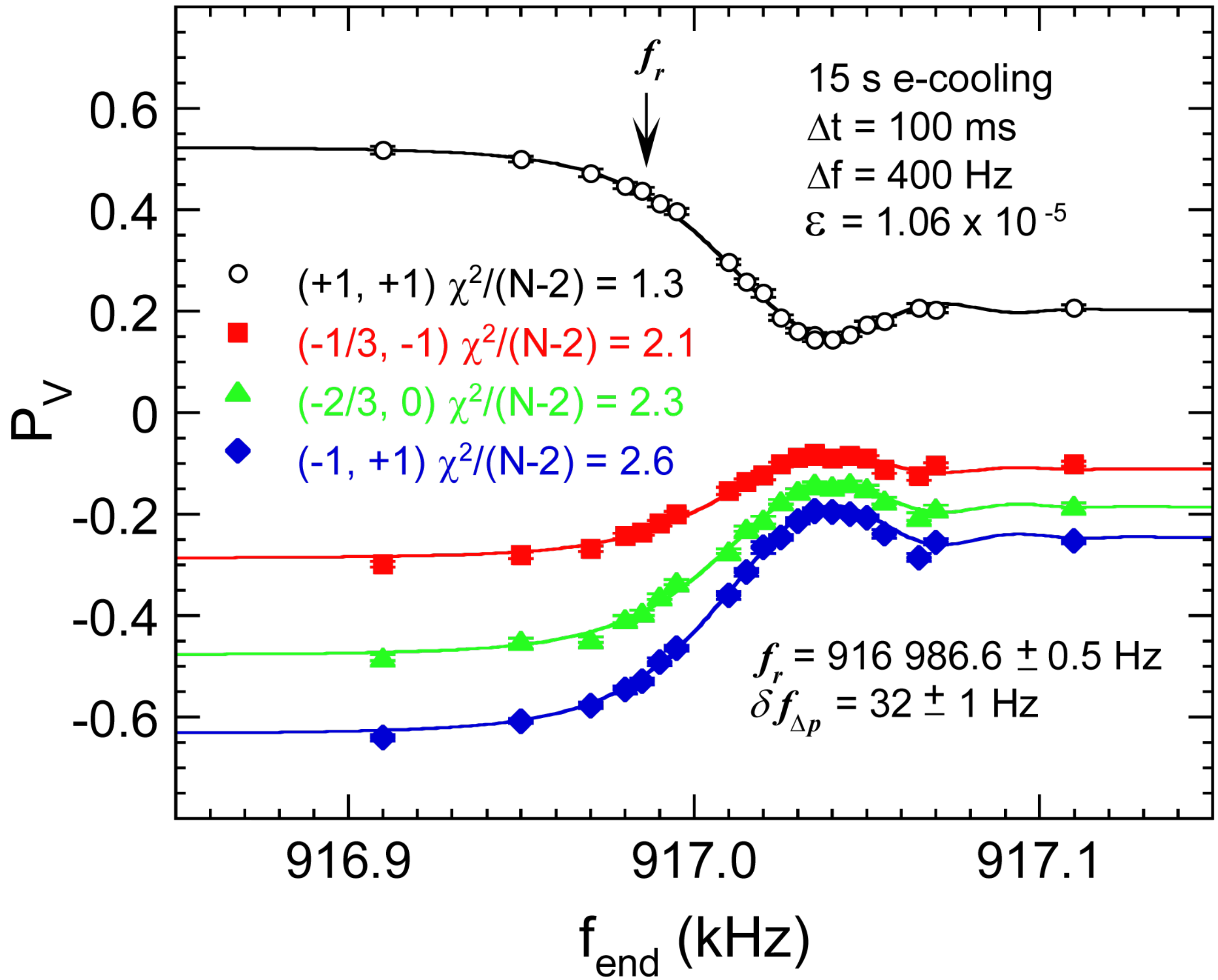
Chao Test Schematic (May 07)

V.S. Morozov *et al.*, Phys. Rev. Lett. 100, 054801 (2008)



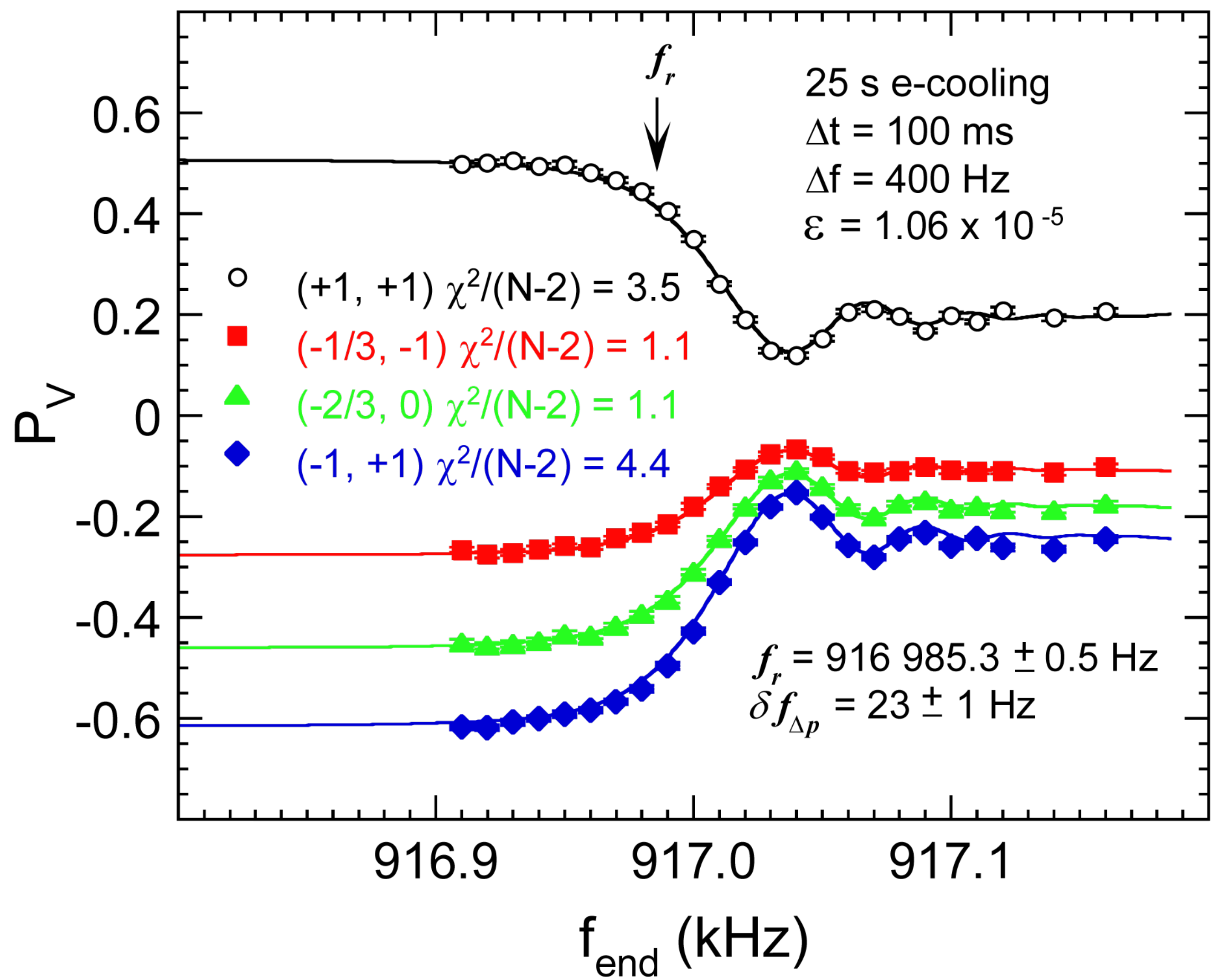
Chao Test with Partially Cooled Beam (May 07)

V.S. Morozov *et al.*, Phys. Rev. Lett. 100, 054801 (2008)



Chao Test with Fully Cooled Beam (May 07)

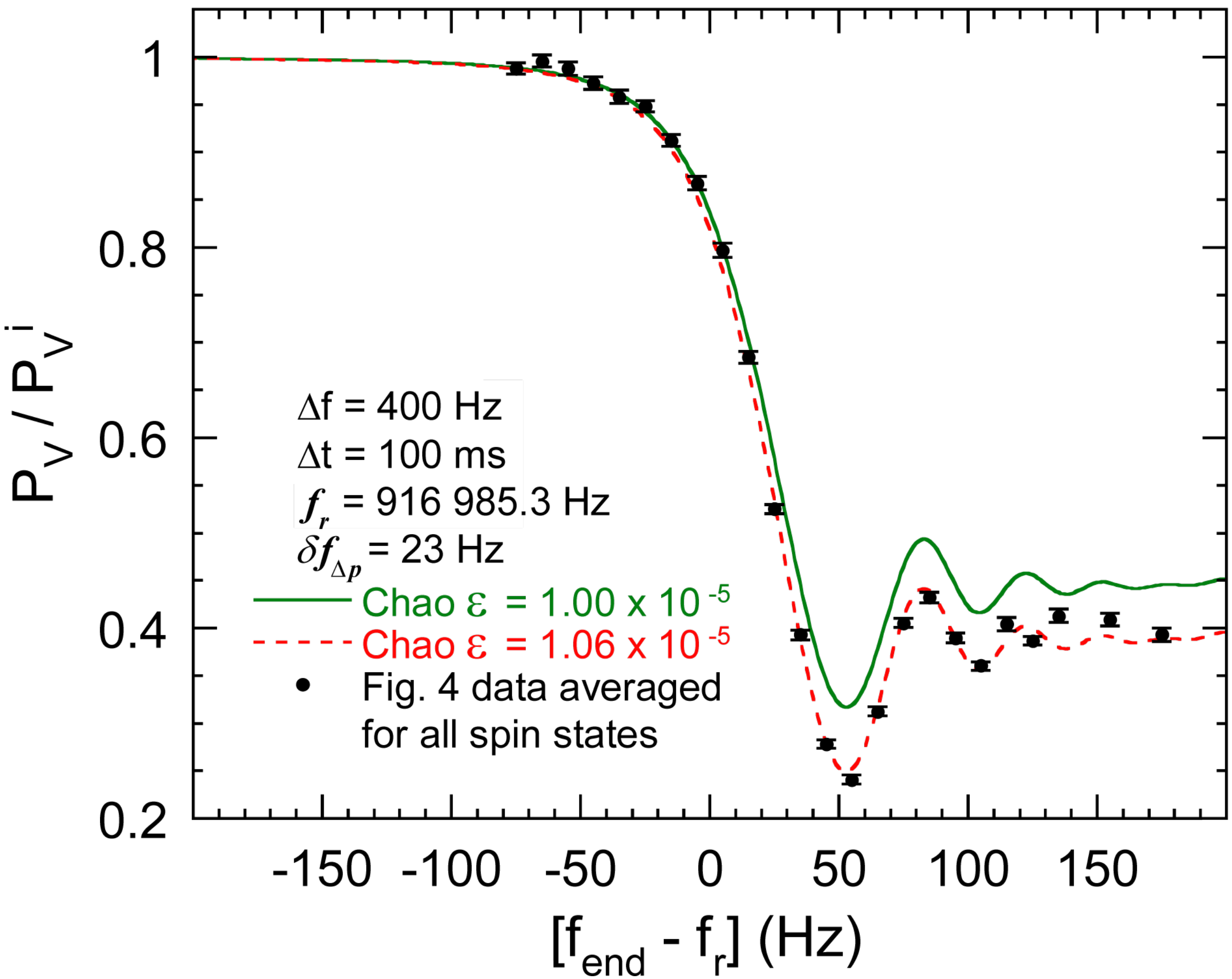
V.S. Morozov *et al.*, Phys. Rev. Lett. 100, 054801 (2008)



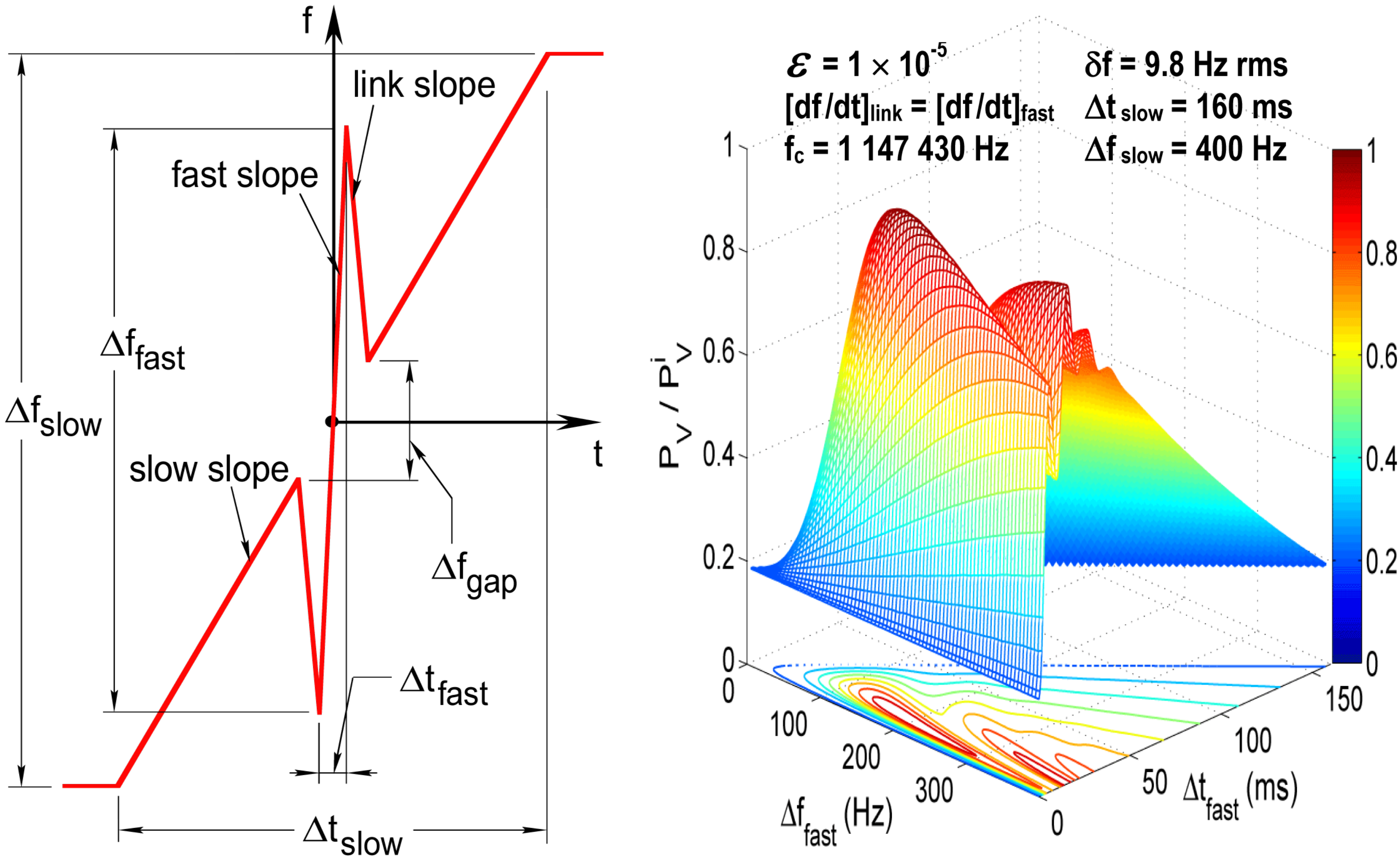
Chao Test with Fully Cooled Beam (May 07)

V.S. Morozov *et al.*, Phys. Rev. Lett. 100, 054801 (2008)

Green line: original prediction from V.S. Morozov *et al.*, PRST-AB 10, 041001 (2007)

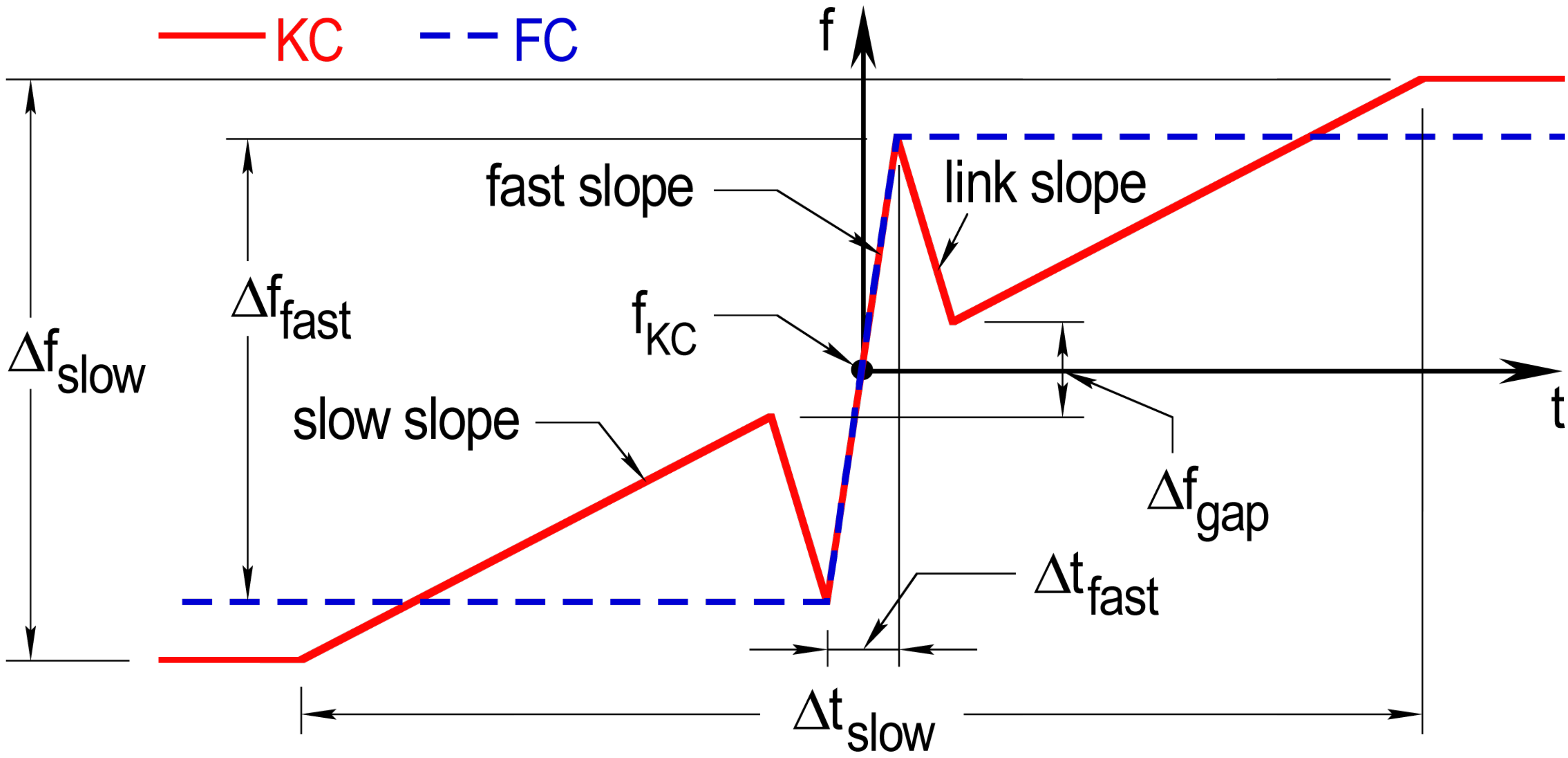


Application to Kondratenko Crossing



Kondratenko Crossing (KC) and Fast Crossing (FC) Shapes

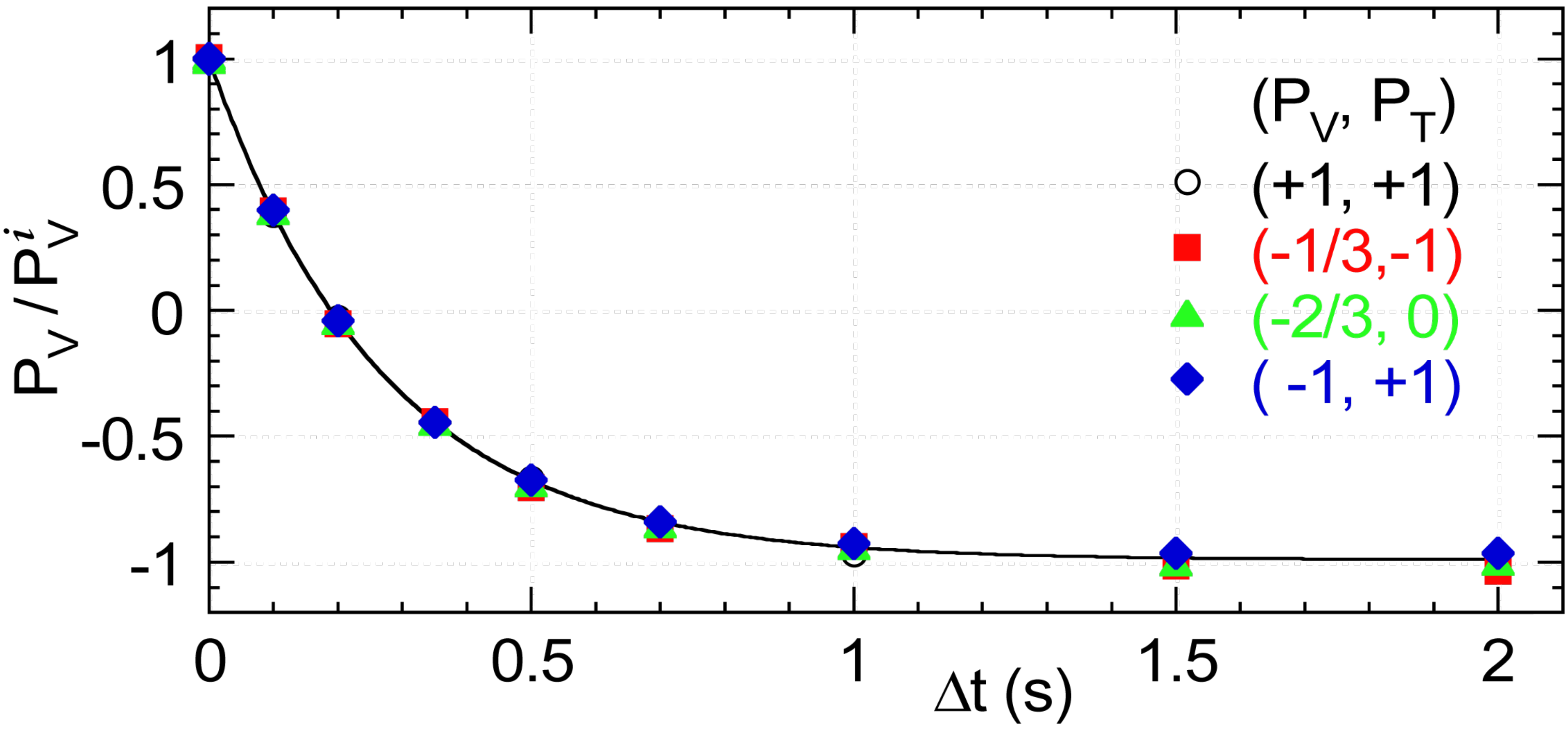
Shape defined by Δt_{slow}, Δf_{slow}, Δt_{fast}, Δf_{fast}, and $[df/dt]_{fast}$ / $[df/dt]_{link}$ ratio



1.85 GeV/c Deuterons at COSY (May 08)

V.S. Morozov *et al.*, Phys. Rev. Lett. 102, 244801 (2009)

Fit to Froissart-Stora formula $\Rightarrow$ $\mathcal{E}$ = (1.067 ± 0.003) 10^{-5}

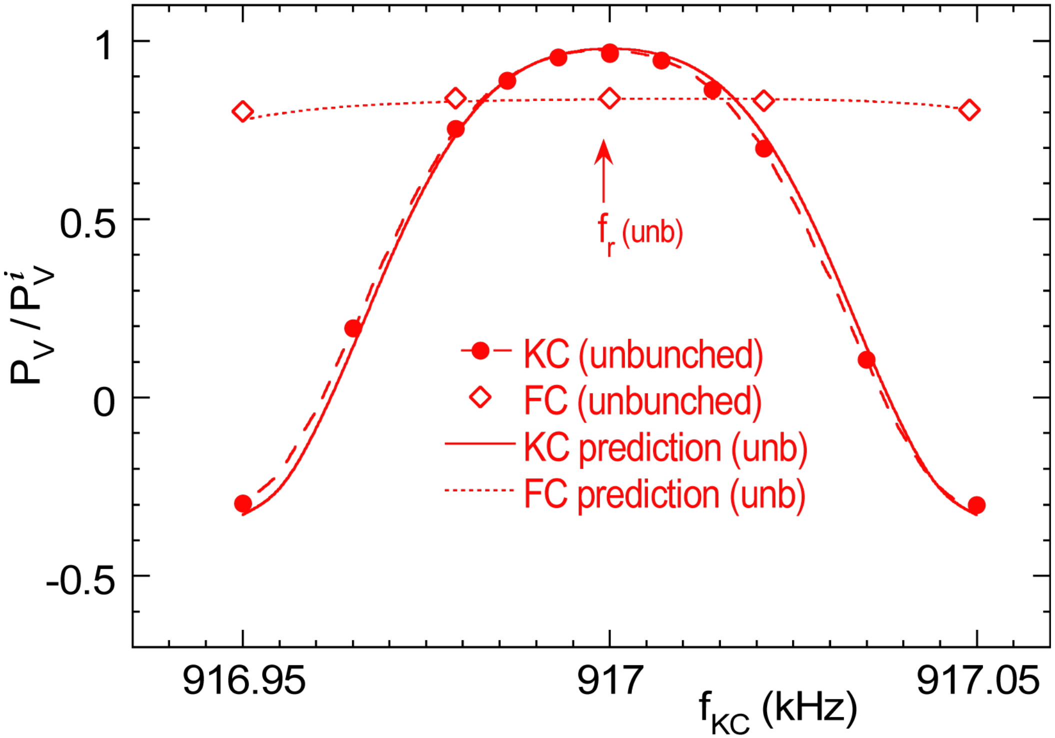


KC & FC by Varying f_{KC} (May 08)

V.S. Morozov *et al.*, Phys. Rev. Lett. 102, 244801 (2009)

- $f_r \equiv$ spin resonance center frequency, $f_{KC} \equiv$ KC shape center frequency
- Parameters at COSY:

  ε = 1.067 10^{-5}, Δf_{slow} = 400 Hz, Δt_{slow} = 160 ms, Δf_{fast} = 185 Hz, Δt_{fast} = 12 ms
- KC fit using Chao formalism $\Rightarrow$ fr = 916 999.1 $\pm$ 0.1 Hz, δf = 24.4 $\pm$ 0.2 Hz fwhm



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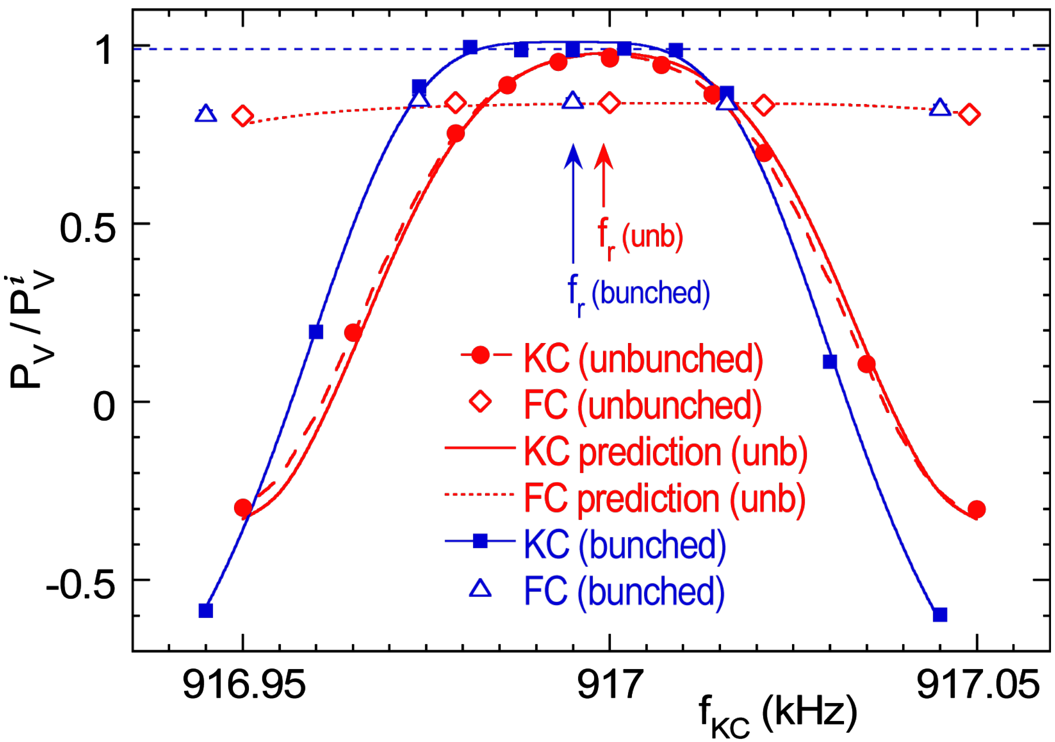
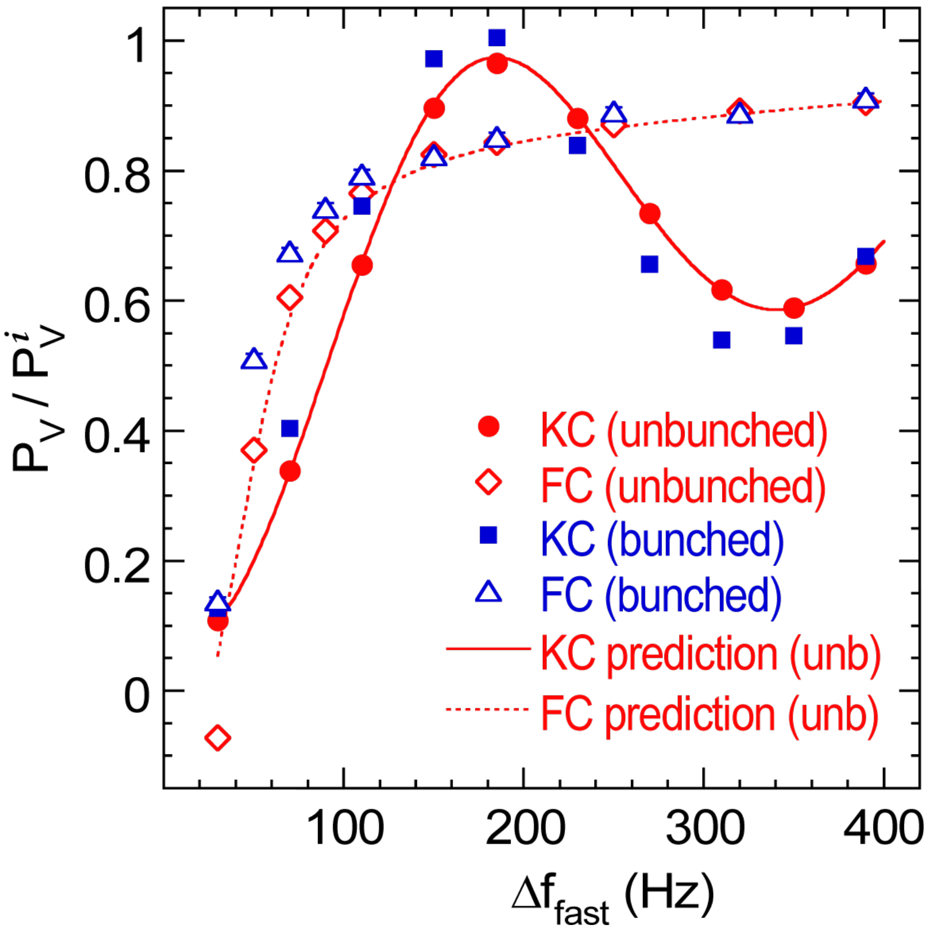
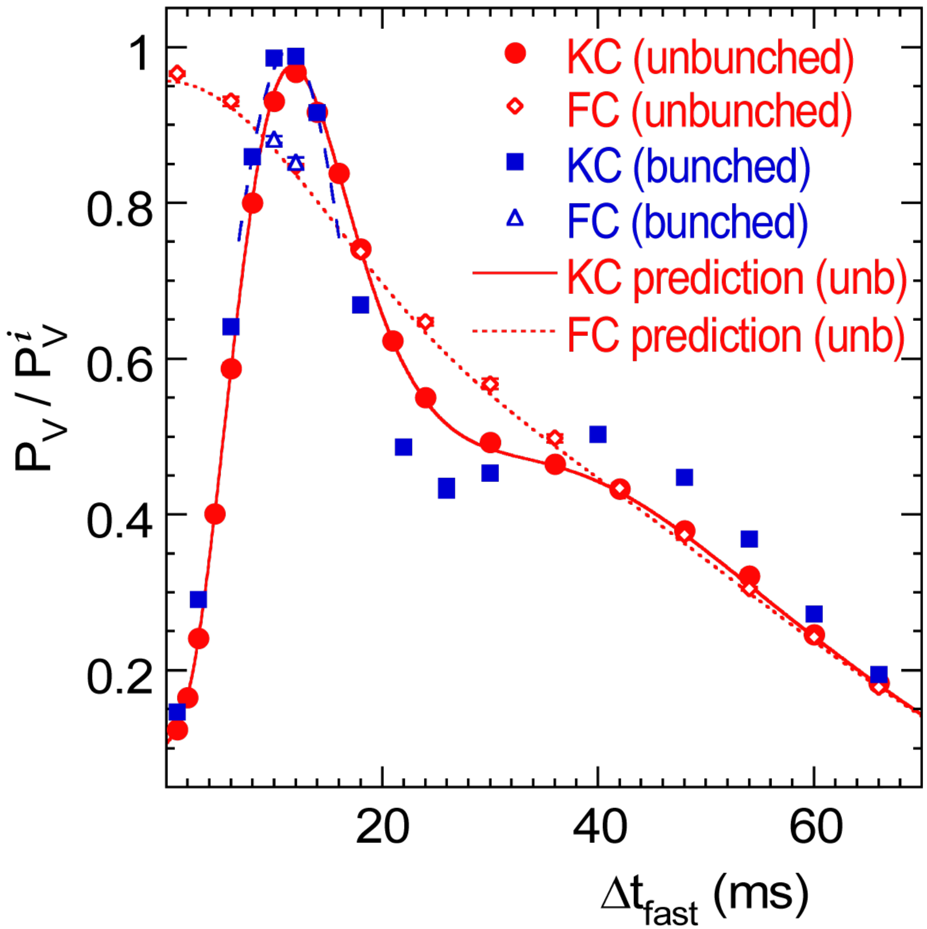


KC & FC by Varying Δf_{fast} & Δt_{fast} (May 08)

V.S. Morozov *et al.*, Phys. Rev. Lett. 102, 244801 (2009)

$\mathcal{E}$ = 1.067 10^{-5}, f_r = 916 999.1 ± 0.1 Hz, δf = 24.4 ± 0.2 Hz fwhm

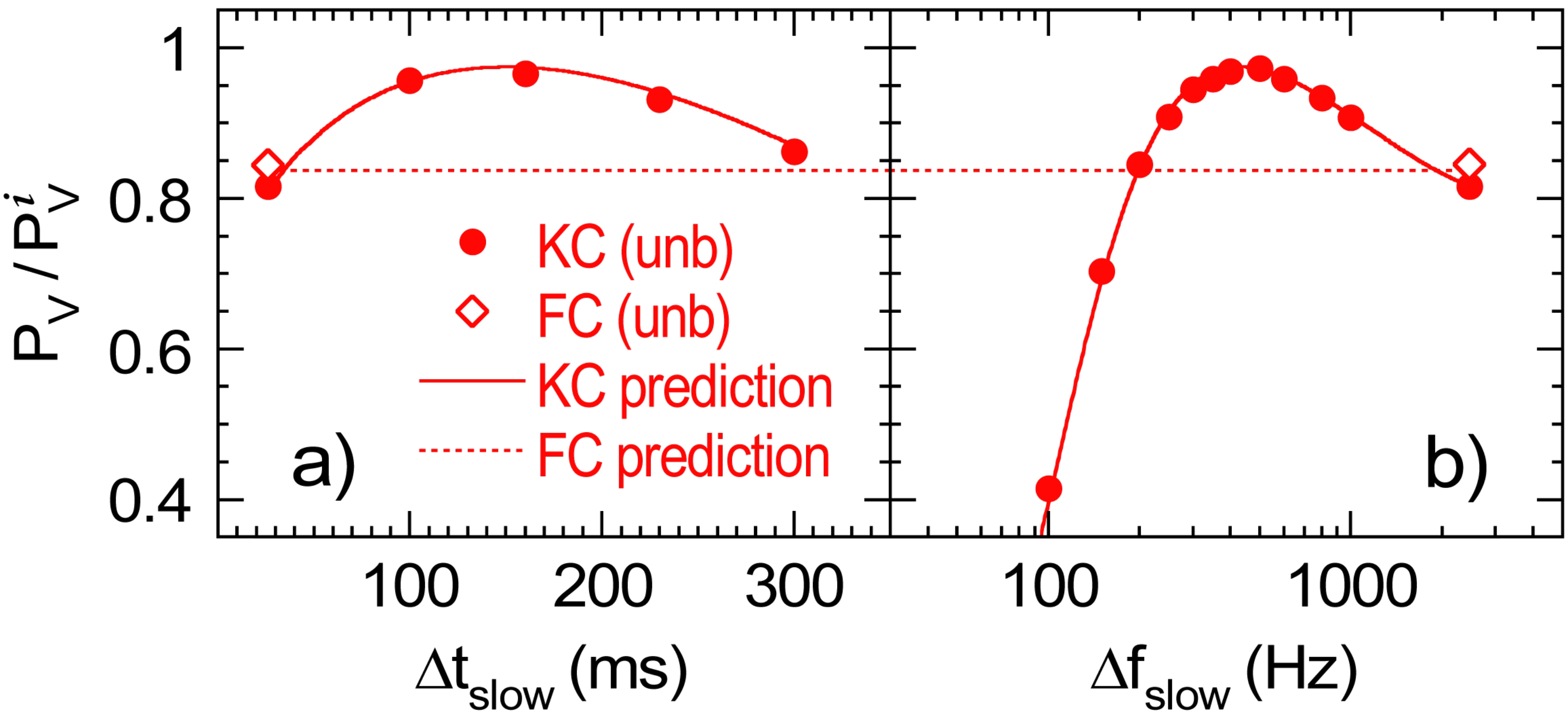




KC & FC by Varying Δt_{slow} & Δf_{slow} (May 08)

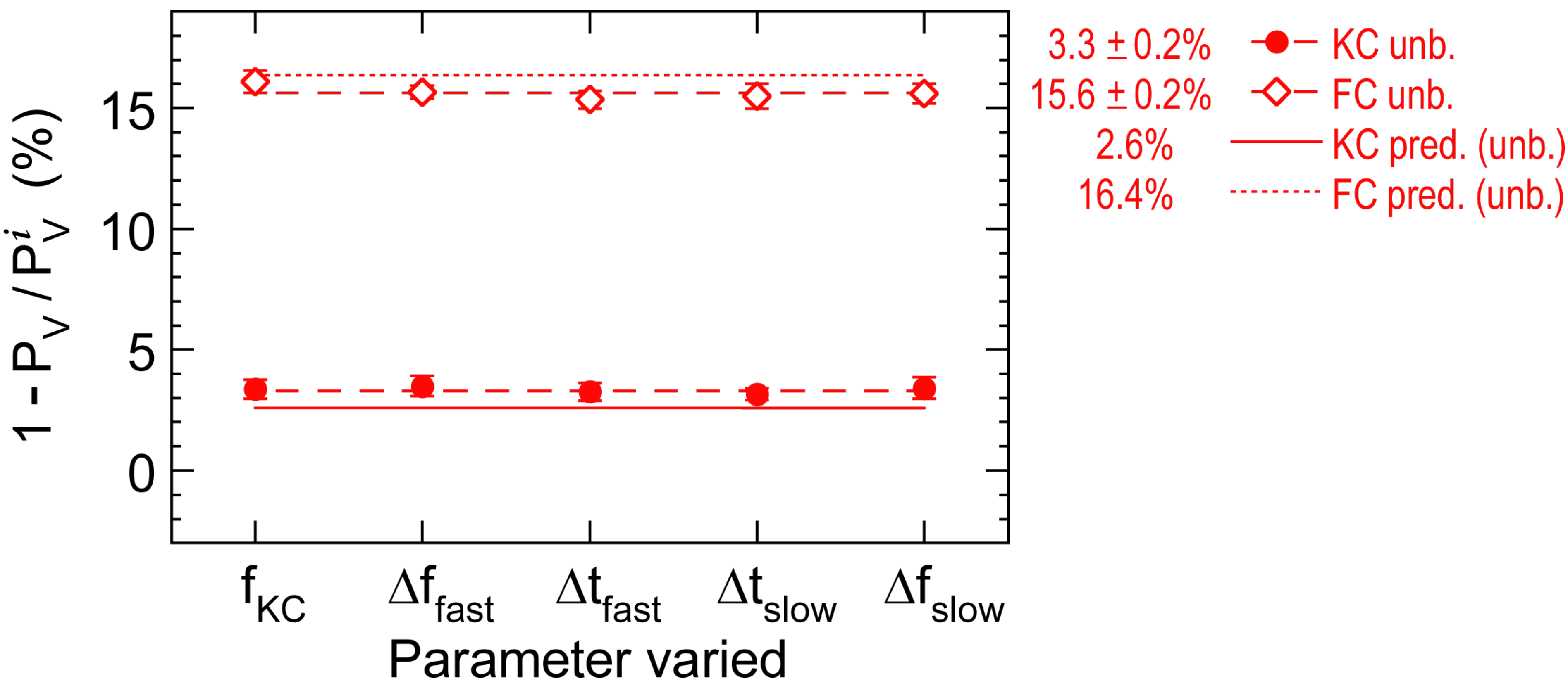
V.S. Morozov *et al.*, Phys. Rev. Lett. 102, 244801 (2009)

$\mathcal{E}$ = 1.067 10^{-5}, f_r = 916 999.1 ± 0.1 Hz, δf = 24.4 ± 0.2 Hz fwhm



Depolarization Summary at KC Peak (May 08)

V.S. Morozov *et al.*, Phys. Rev. Lett. 102, 244801 (2009)



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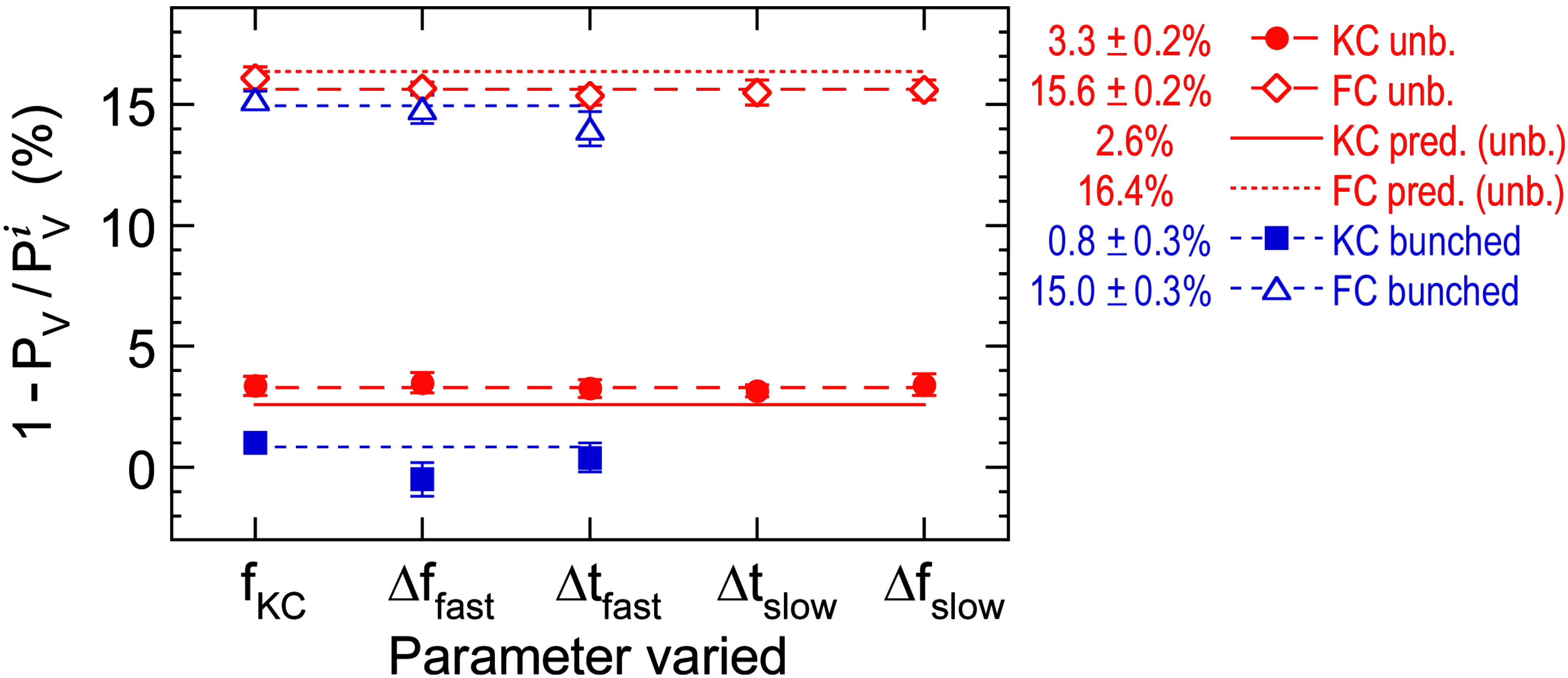
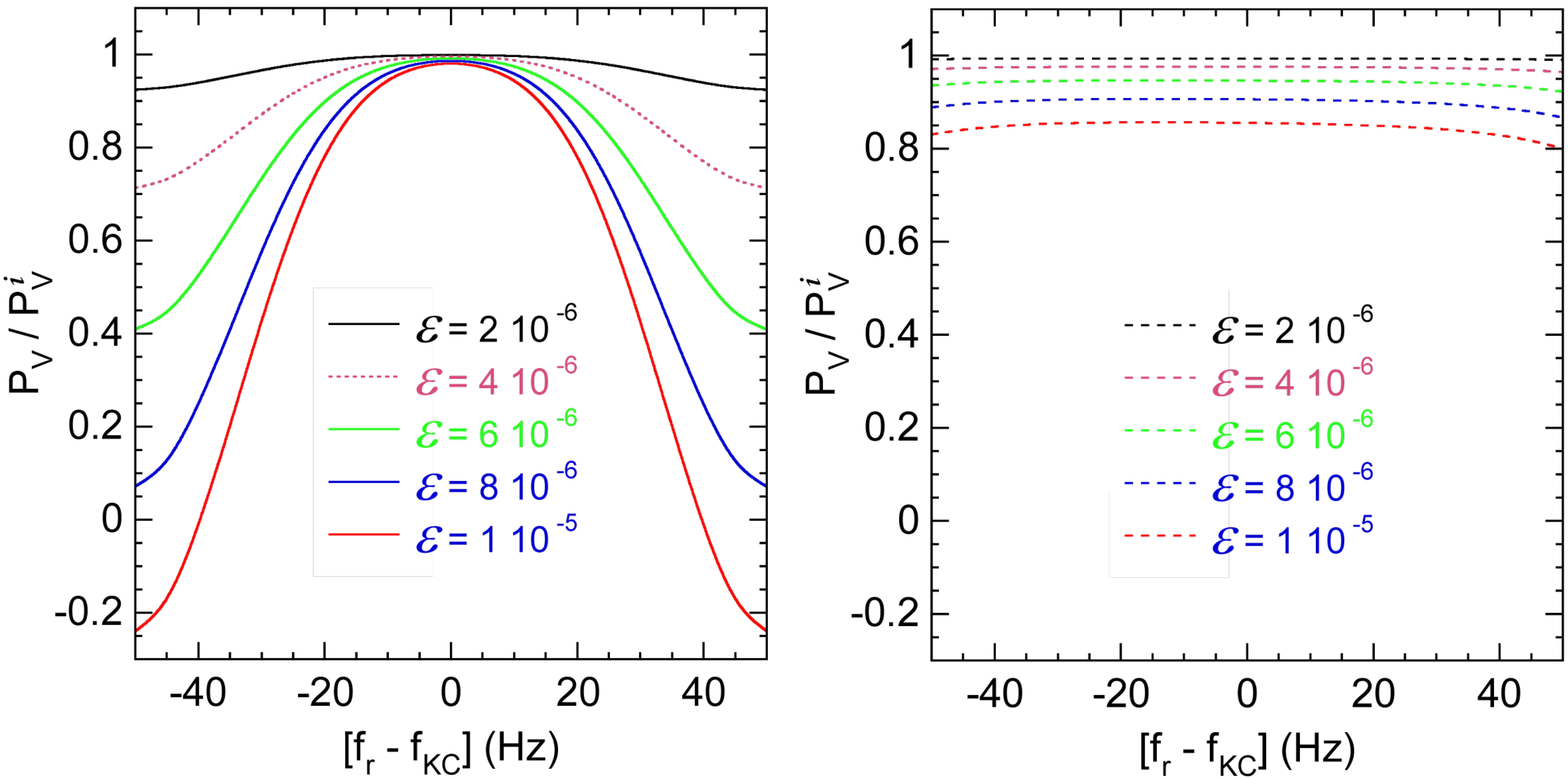


KC & FC Sensitivity to ε & $[f_r - f_{KC}]$

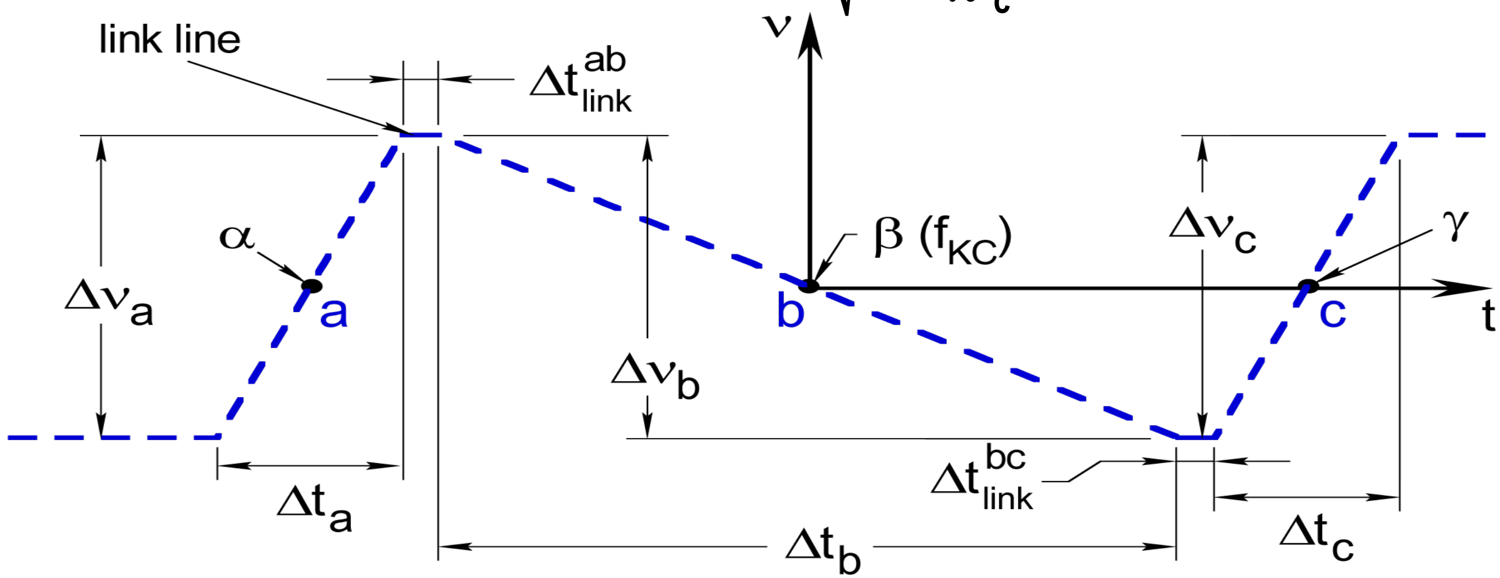


Kondratenko Triple Crossing

- $\nu \equiv G\gamma - \nu_r$, $\nu_r \equiv m$ or $m \pm \nu_y$
- **Requirements:**
  - Spin rotation about vertical axis between crossings $\Psi_{\alpha\beta} = \Psi_{\beta\gamma} = 2\pi m$
  - Spin rotation about horizontal axis

$$\theta_a = \theta_c = \frac{\theta_b}{2} + \frac{\pi}{4}, \quad \text{where} \quad \sin\theta = \exp\left\{ -\frac{(\pi\mathcal{E})^2 f_c}{2\Delta\nu / \Delta t} \right\}$$

  - Tune change ranges $\Delta\nu_i > \Delta\nu_i^{na} \equiv \sqrt{\frac{\Delta\nu_i / \Delta t_i}{2\pi f_c}}$ = non-adiabatic zone size



Summary

- Demonstrated 98 $\pm$ 1% vector and tensor spin-flip efficiency
- Observed and explained tensor polarization's behavior:
  - transformation of tensor component under rotation
- Experimentally demonstrated Chao formalism's validity:
  - excellent agreement of observed polarization oscillations with Chao formalism prediction
- Successfully tested KC concept:
  - ~ 4.7 x reduction in depolarization with unbunched beam
  - ~ 14-31 x reduction in depolarization with bunched beam
- Possible improvement of KC with triple resonance crossing
  - reduced sensitivity to beam's momentum spread
  - applicable to preserving polarization as well as spin flip