Jefferson Lab, Newport News, VA
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Spin-Manipulating Polarized Deuterons*

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OUTLINE

- Motivation
- Experimental apparatus at Forschungszentrum Jülich
- Manipulation of deuteron vector and tensor polarizations
- Chao's new 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

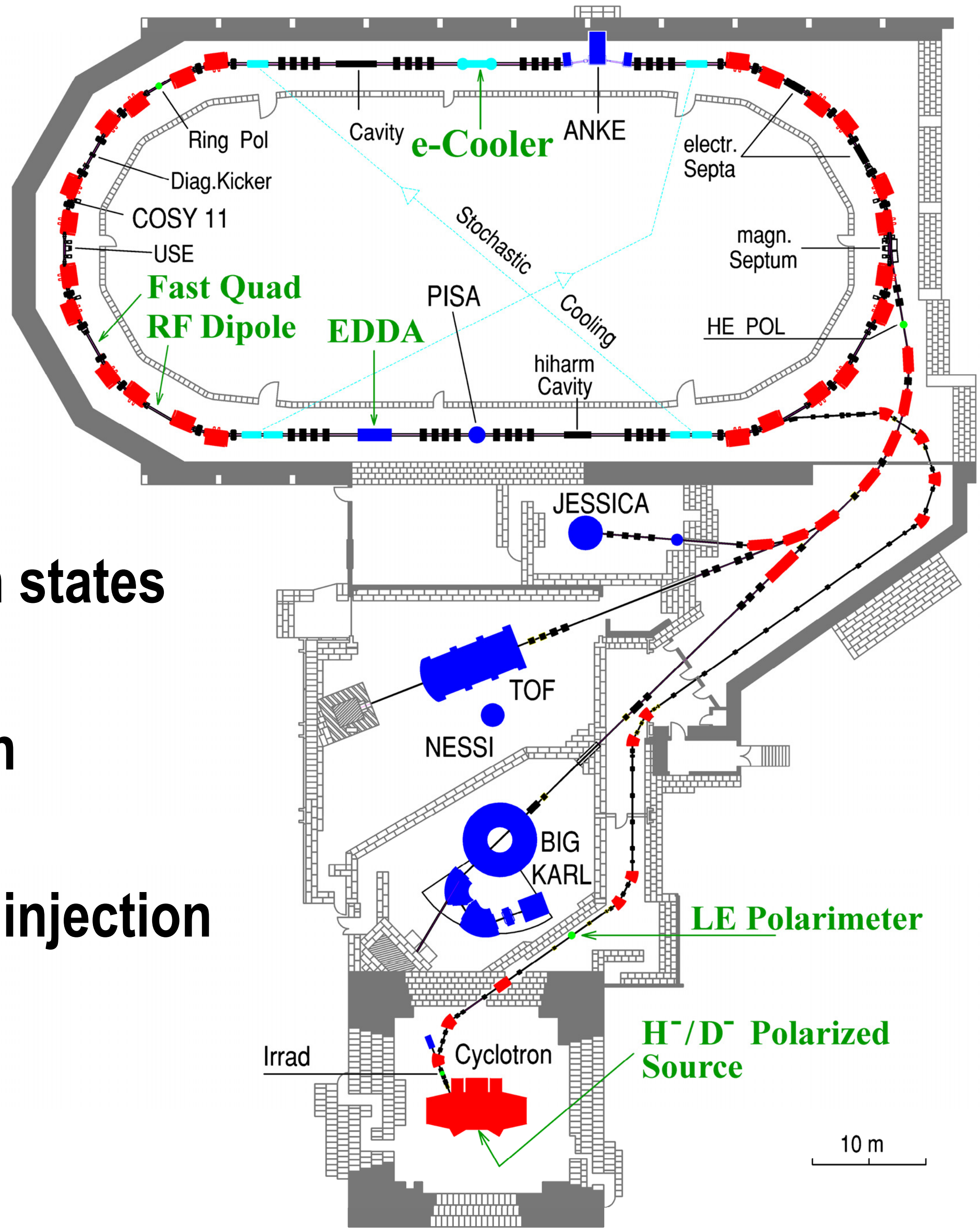
- **Chao's new matrix formalism for describing spin dynamics:**
  analytic calculation of polarization at any time during piecewise-linear spin resonance crossing

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

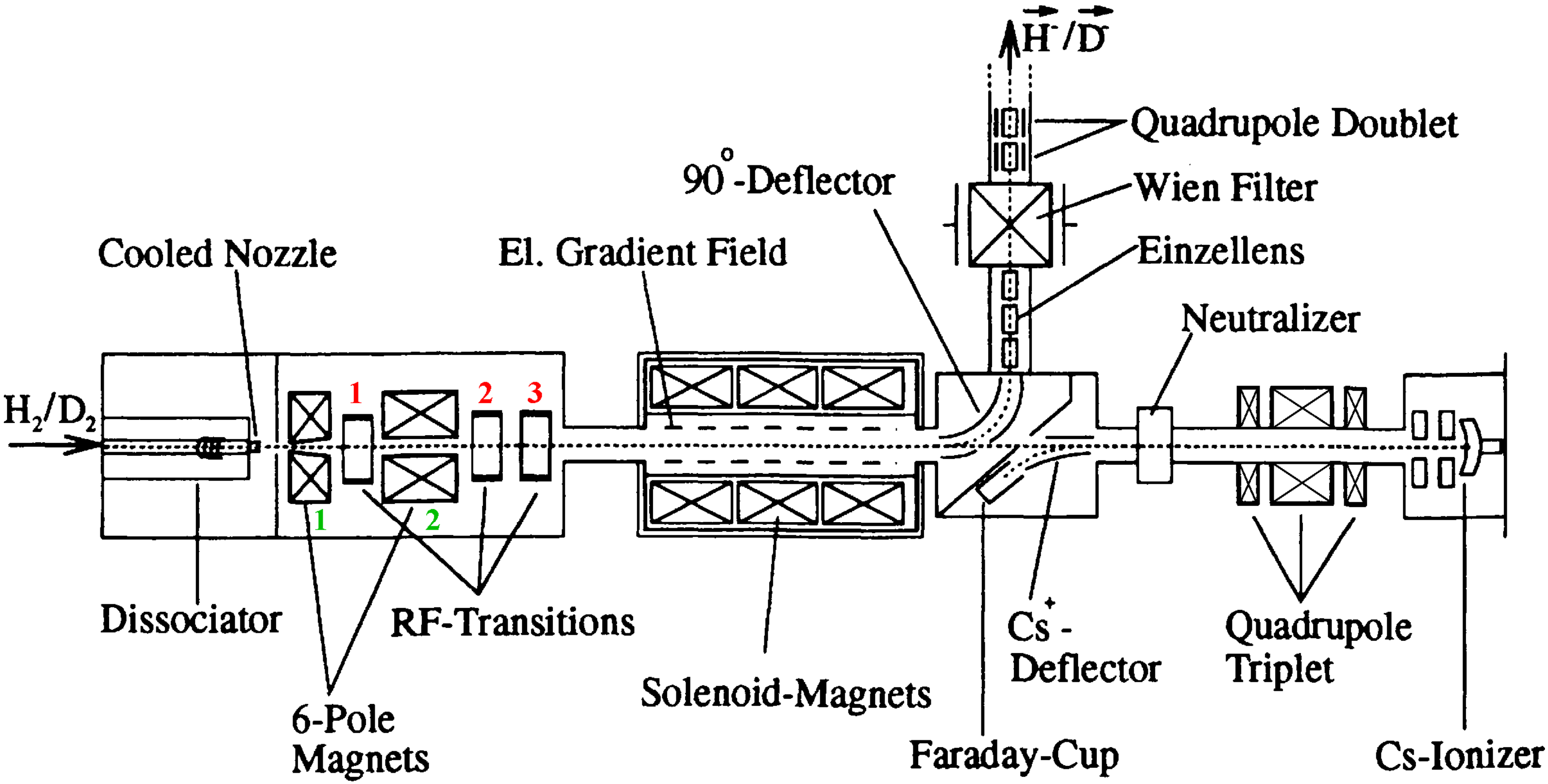
- **Possible improvement of Kondratenko Crossing:**
  easier practical implementation,
  possibly less sensitive to beam's momentum spread

COSY COoler SYnchrotron

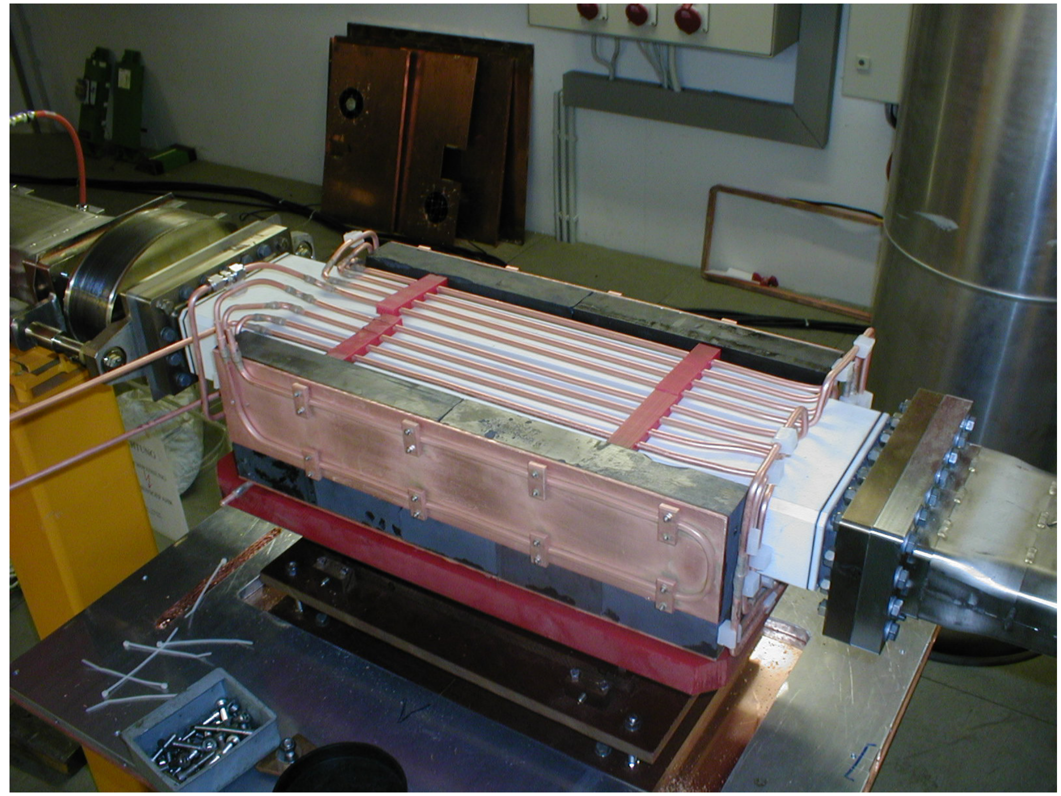
- **Deuterons: 1.85 GeV/c**
- **D⁻ source**
  cycled through 5 (P_V, P_T) spin states
- **LE Polarimeter**
  monitored injected polarization
- **e-Cooler**
  reduced momentum spread at injection
- **RF Dipole or RF Solenoid**
- **EDDA detector as polarimeter**

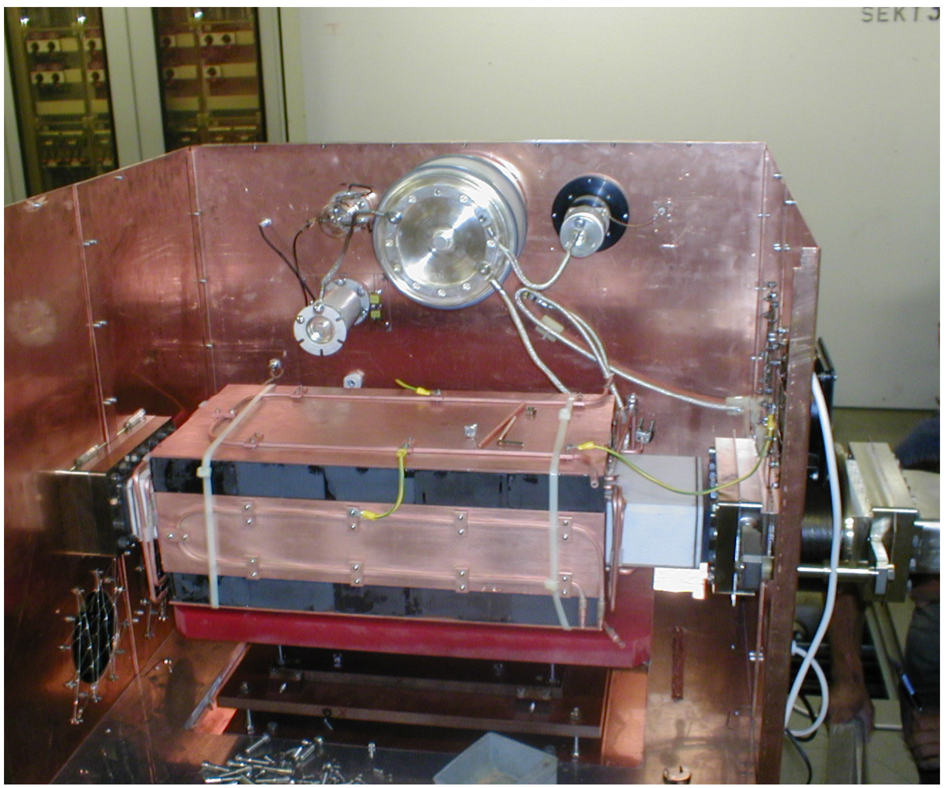


POLARIZED H$^-$/D$^-$ ION SOURCE



FERRITE RF DIPOLE

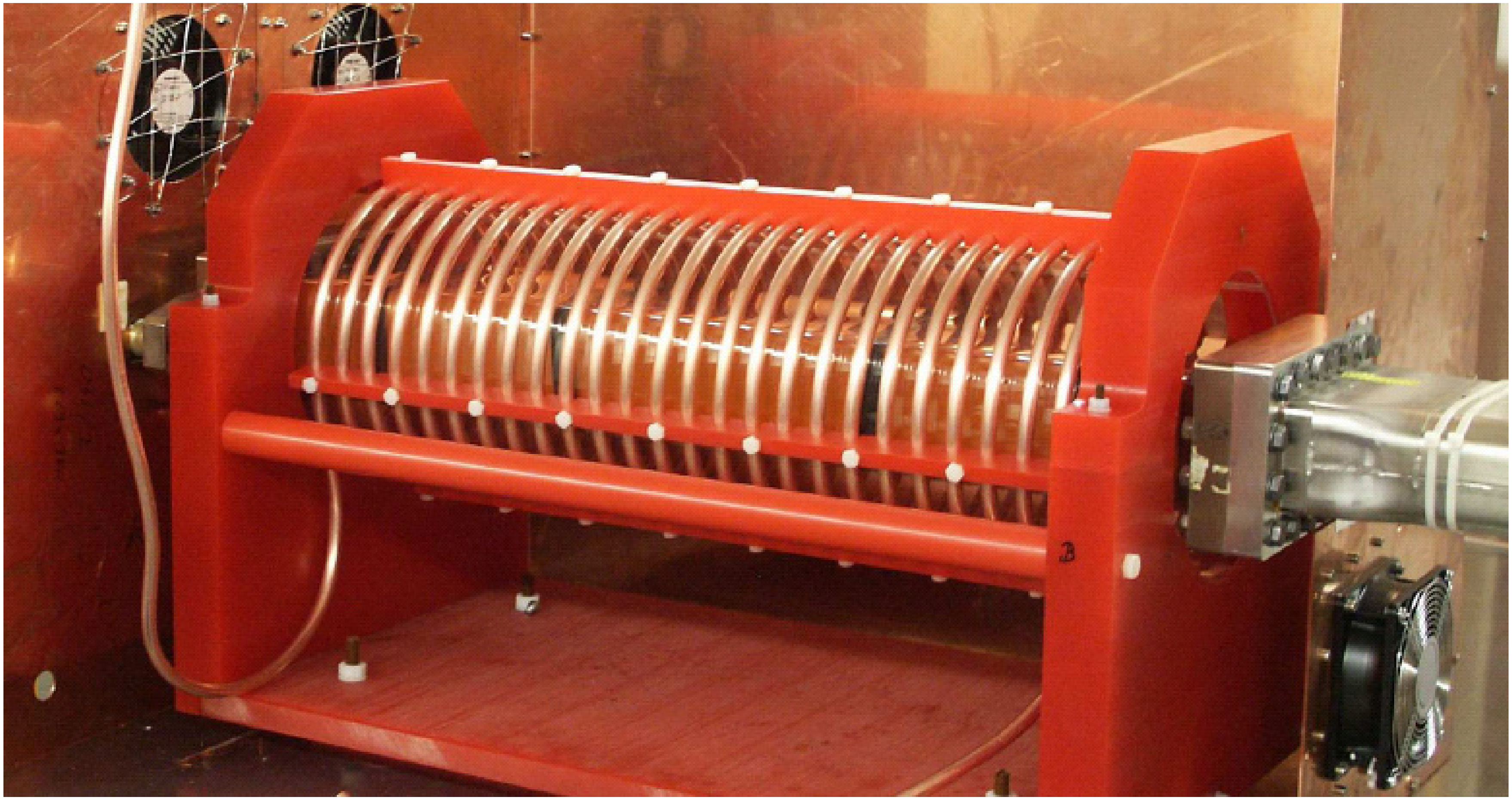




Ceramic vacuum pipe

$\int B_{rms} \cdot dl$ **= 0.54 T·mm at ~917 kHz**

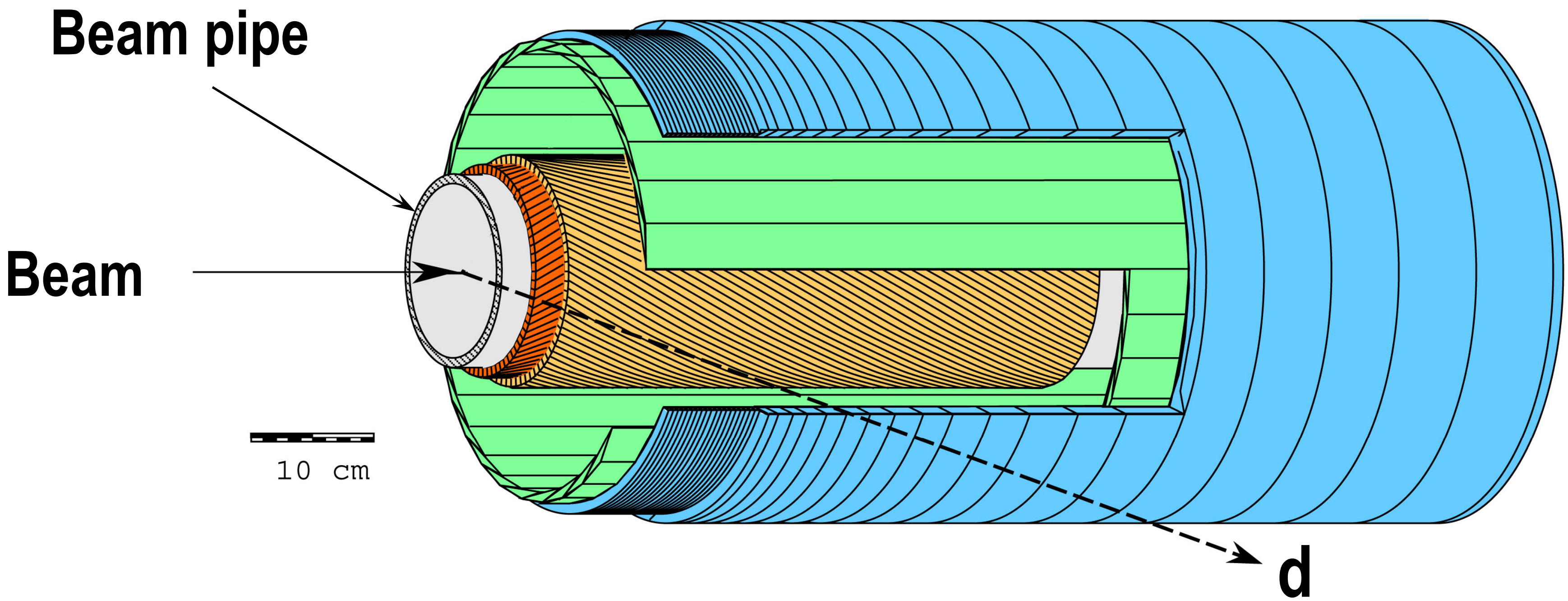
RF SOLENOID



Ceramic vacuum pipe

$\int B_{rms} \cdot dl$ **= 0.67 T·mm at ~917 kHz**

EDDA DETECTOR as deuteron polarimeter



- 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

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

- 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

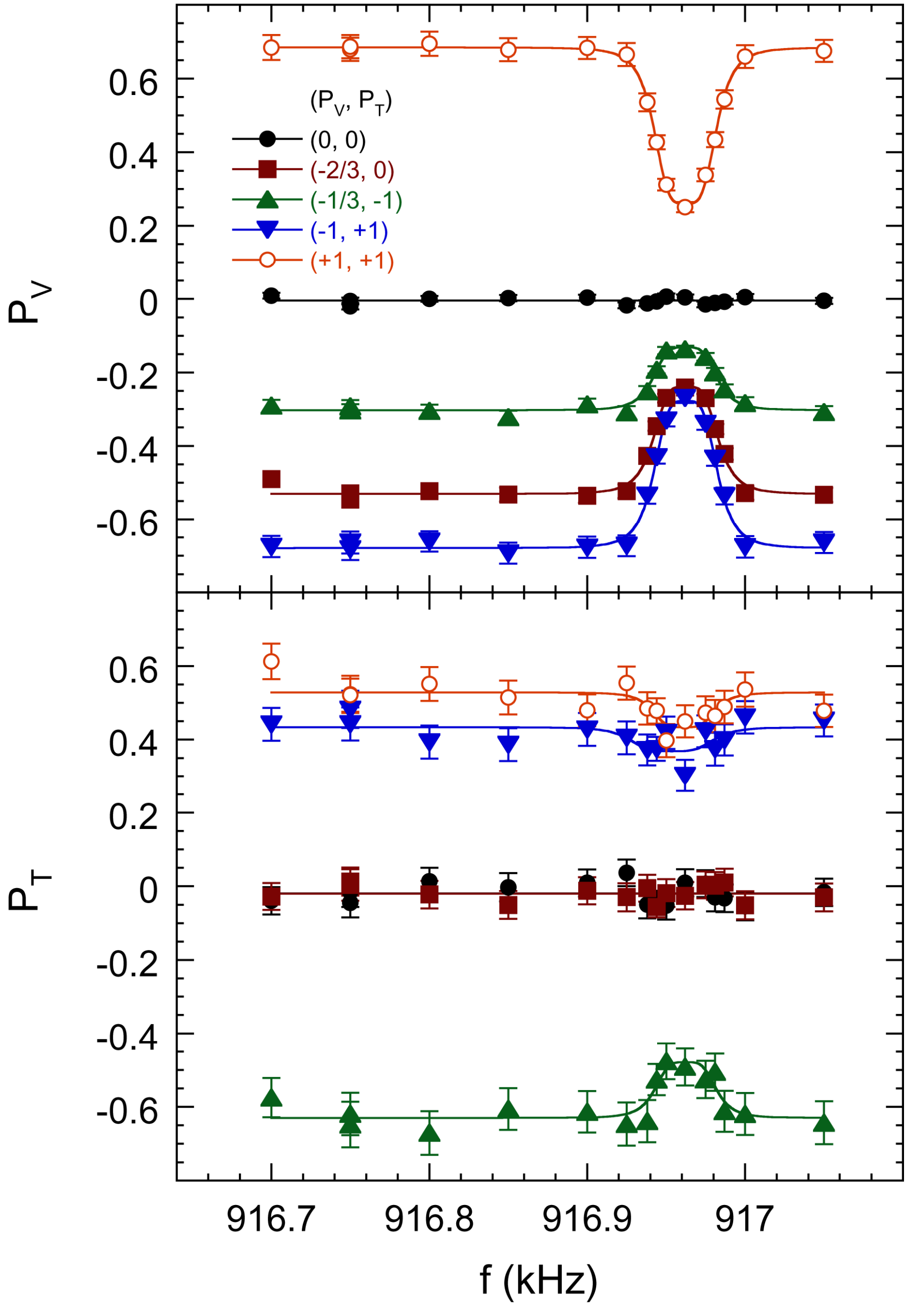
$$\frac{P_T}{P_T^i} = \frac{3}{2}\left(\frac{P_V}{P_V^i}\right)^2 - \frac{1}{2} = \frac{3}{2}\left\{(1+\hat{\eta})\exp\left[\frac{(\pi\ |\mathcal{E}|\ f_c)^2}{\Delta f/\Delta t}\right] - \hat{\eta}\right\}^2 - \frac{1}{2}$$

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

RESONANCE MAP at fixed frequency

December 03

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



Measured Resonance Frequency and Width

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

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

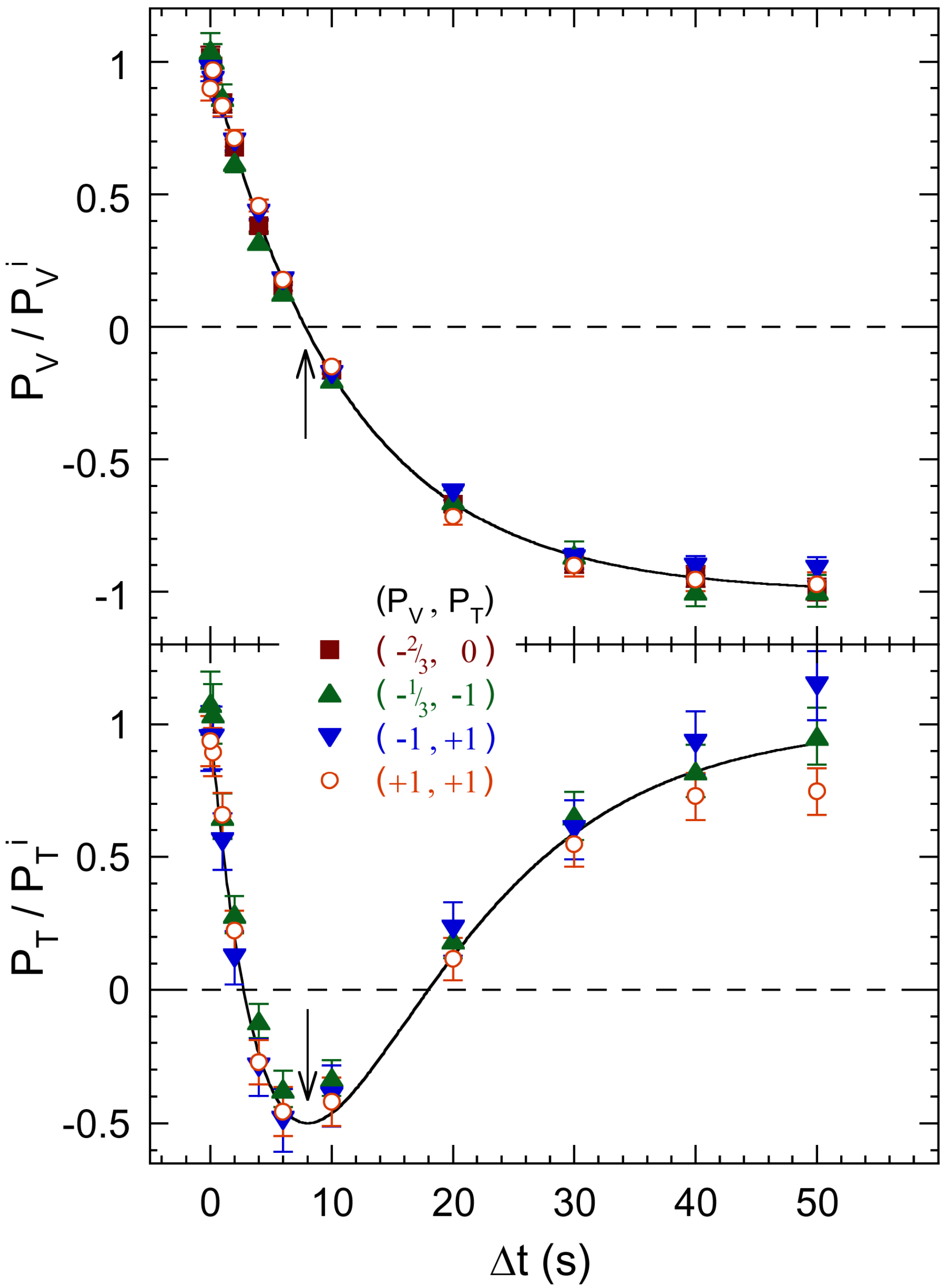
$$f_T = 916.961 \pm 0.003 \ \text{kHz}$$

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

VARYING RAMP TIME

December 03

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



Measured Resonance Strength

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

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

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

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

$$\varepsilon \neq \frac{1}{\pi 2\sqrt{2}} \frac{e(1+G\gamma)}{p} \int B_{rms} dl$$

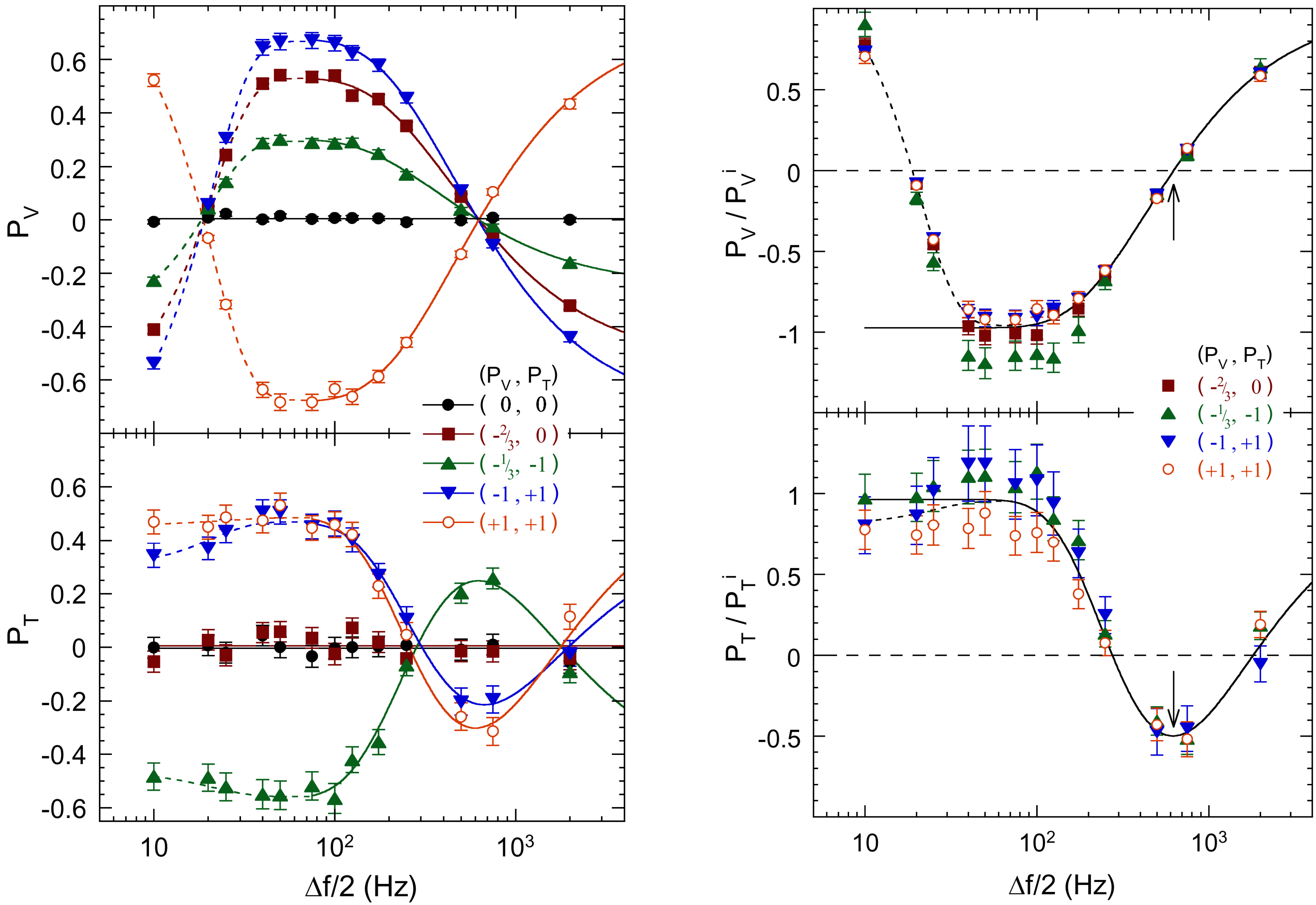
$$\Downarrow$$

$\sim 7\times$ too large!

VARYING FREQUENCY RANGE

December 03

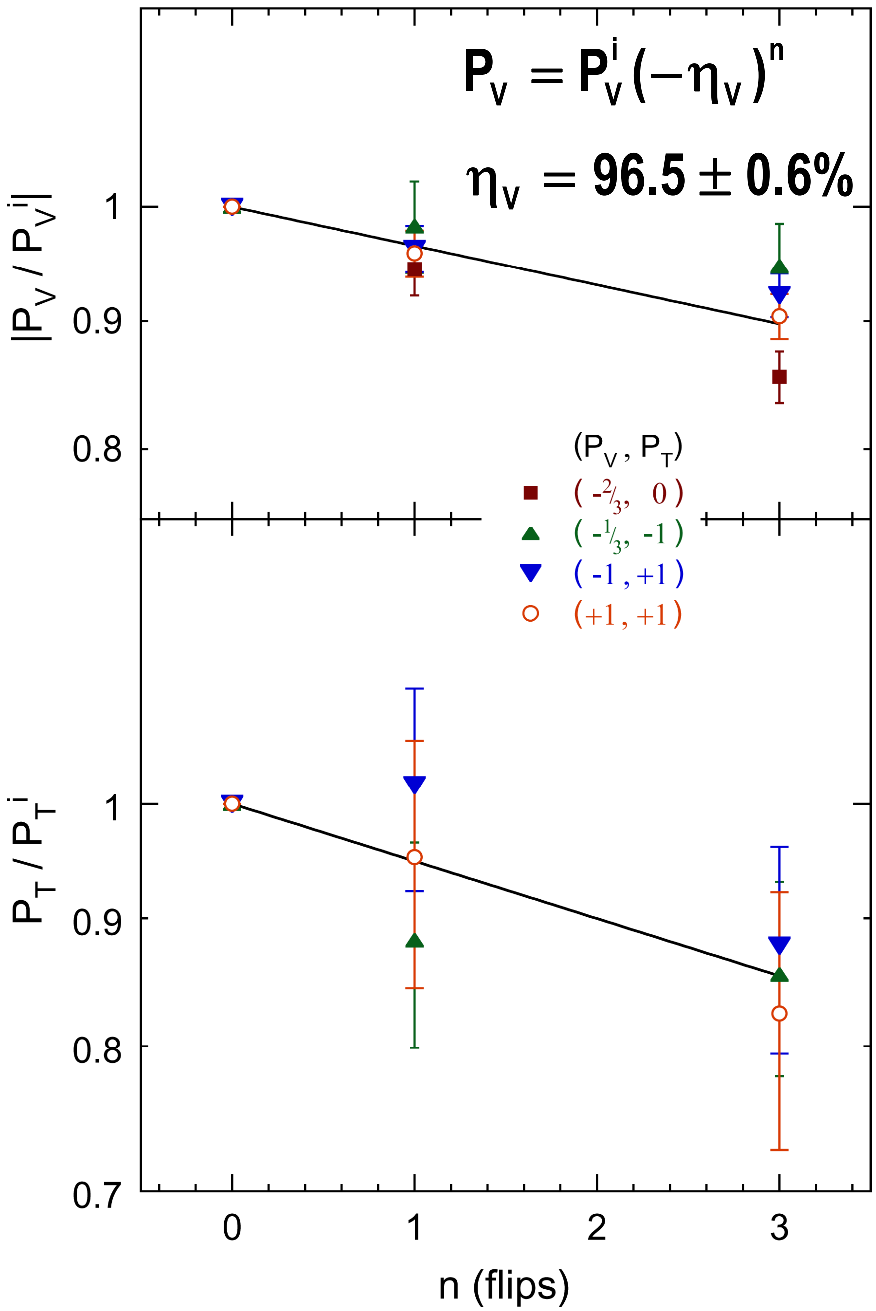
V.S. Morozov *et al.*, Phys. Rev. ST-AB 8, 061001 (2005)

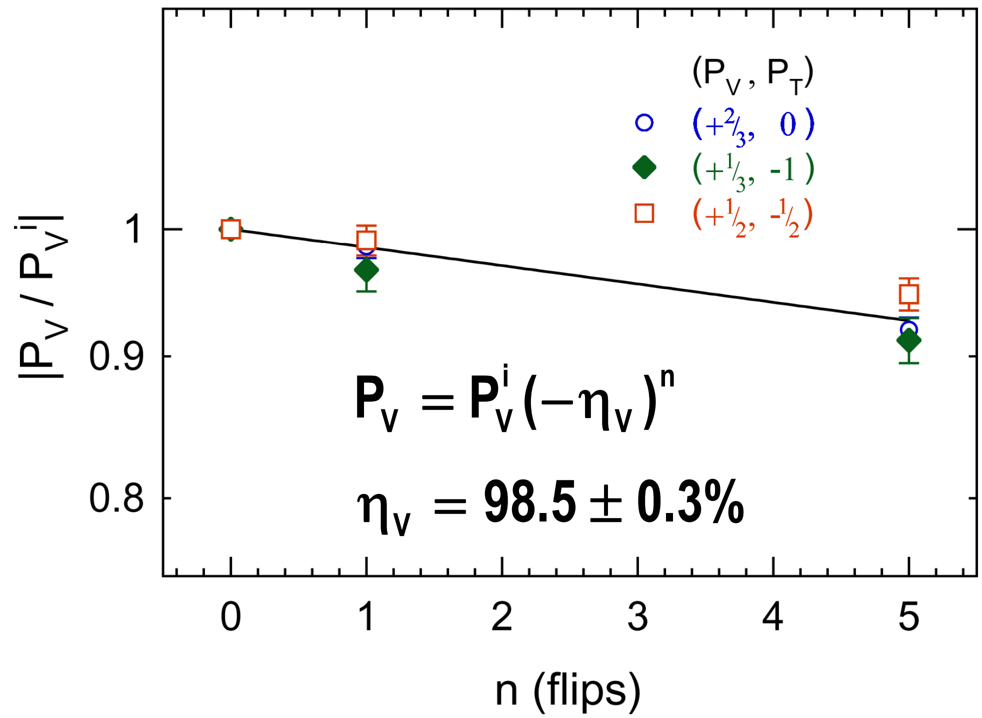


MULTIPLE SPIN FLIPPING

December 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

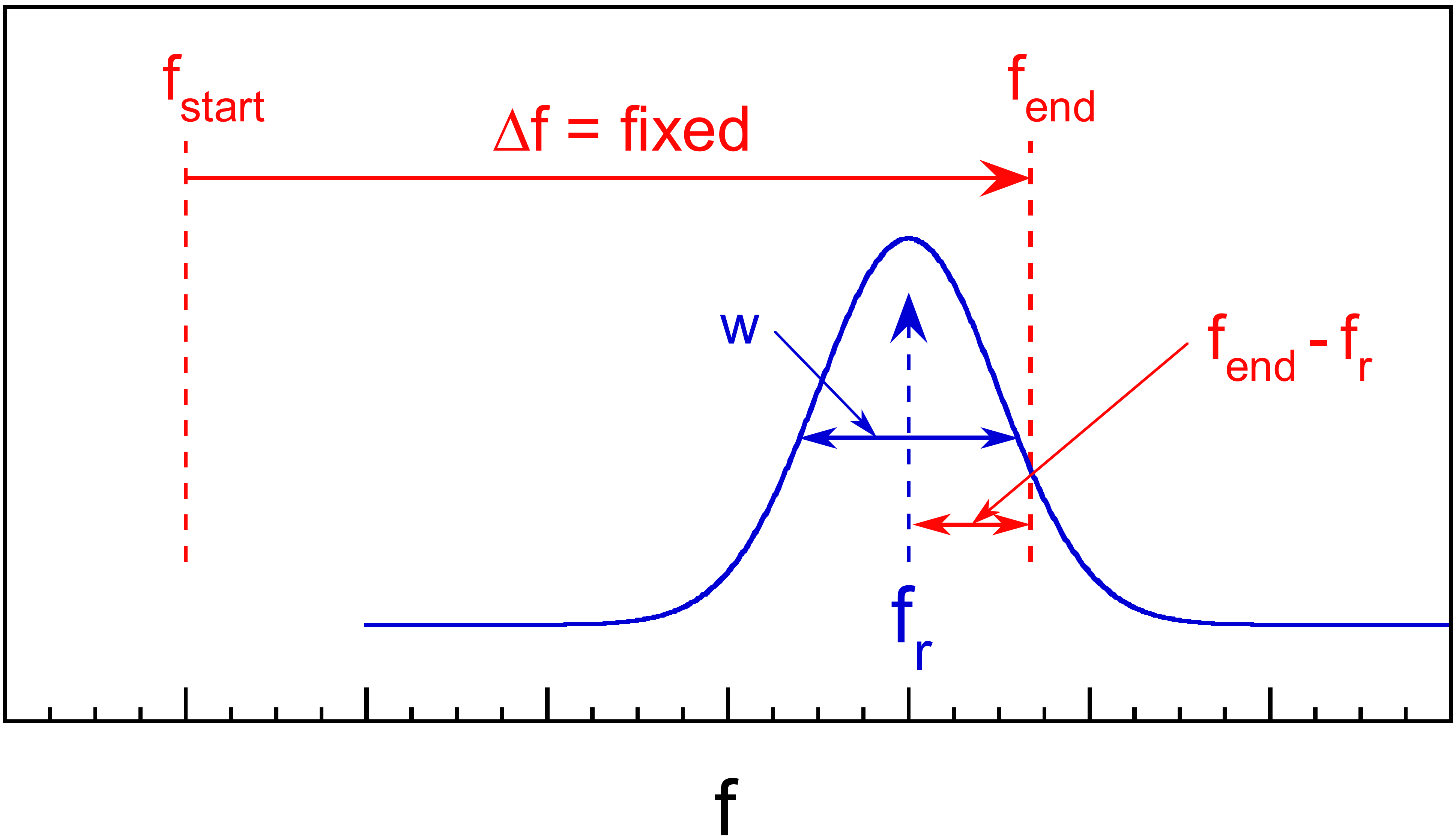
$$\frac{d\Psi}{d\theta} = -\frac{i}{2}\begin{bmatrix} -G\gamma(\theta) & \mathcal{E}\, e^{i\nu_r\theta} \\ \mathcal{E}^* e^{-i\nu_r\theta} & G\gamma(\theta) \end{bmatrix}\Psi$$

$\theta = 2\pi f_c t$ = 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

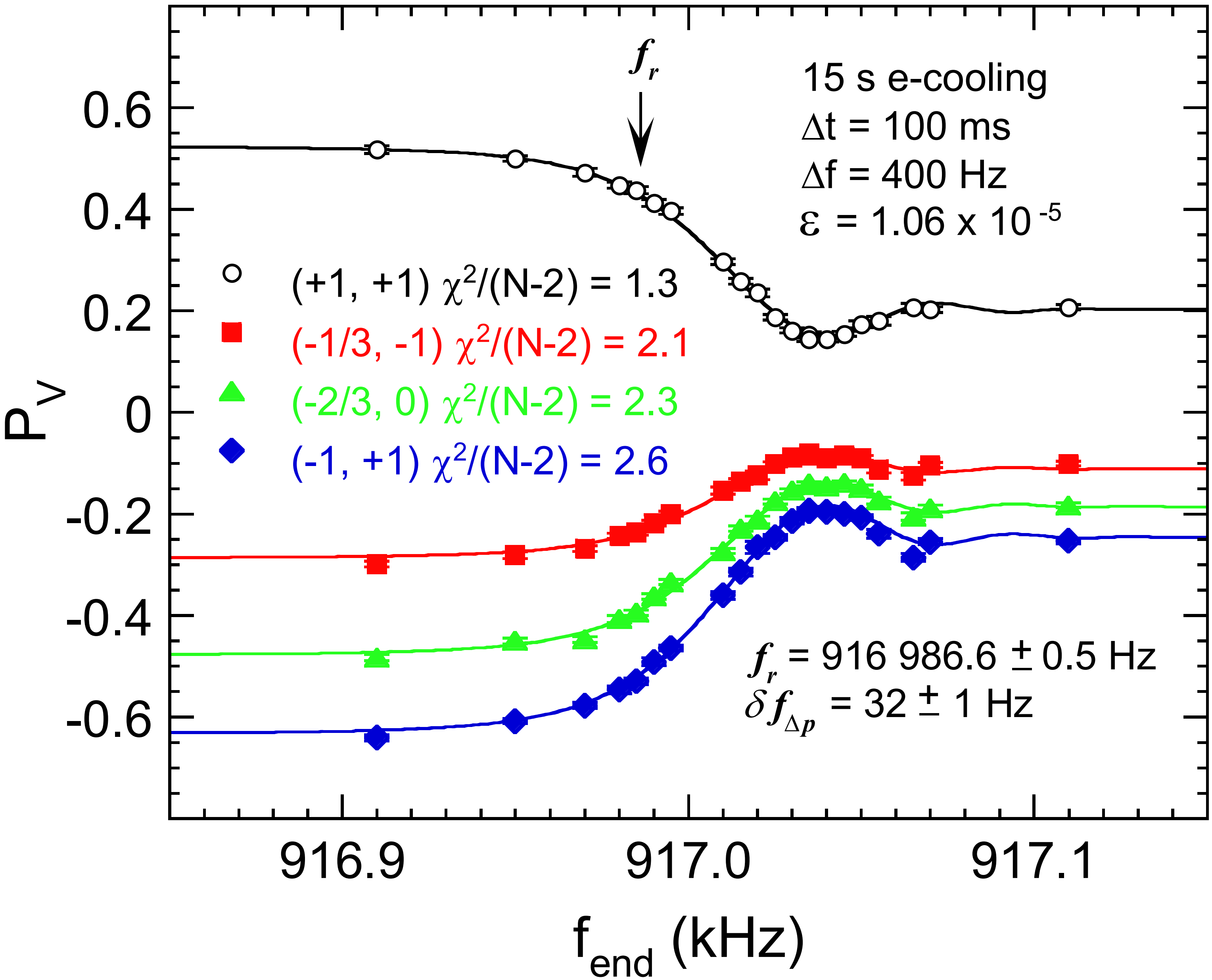
CHAO TEST SCHEMATIC



CHAO TEST WITH PARTIALLY COOLED BEAM

May 07

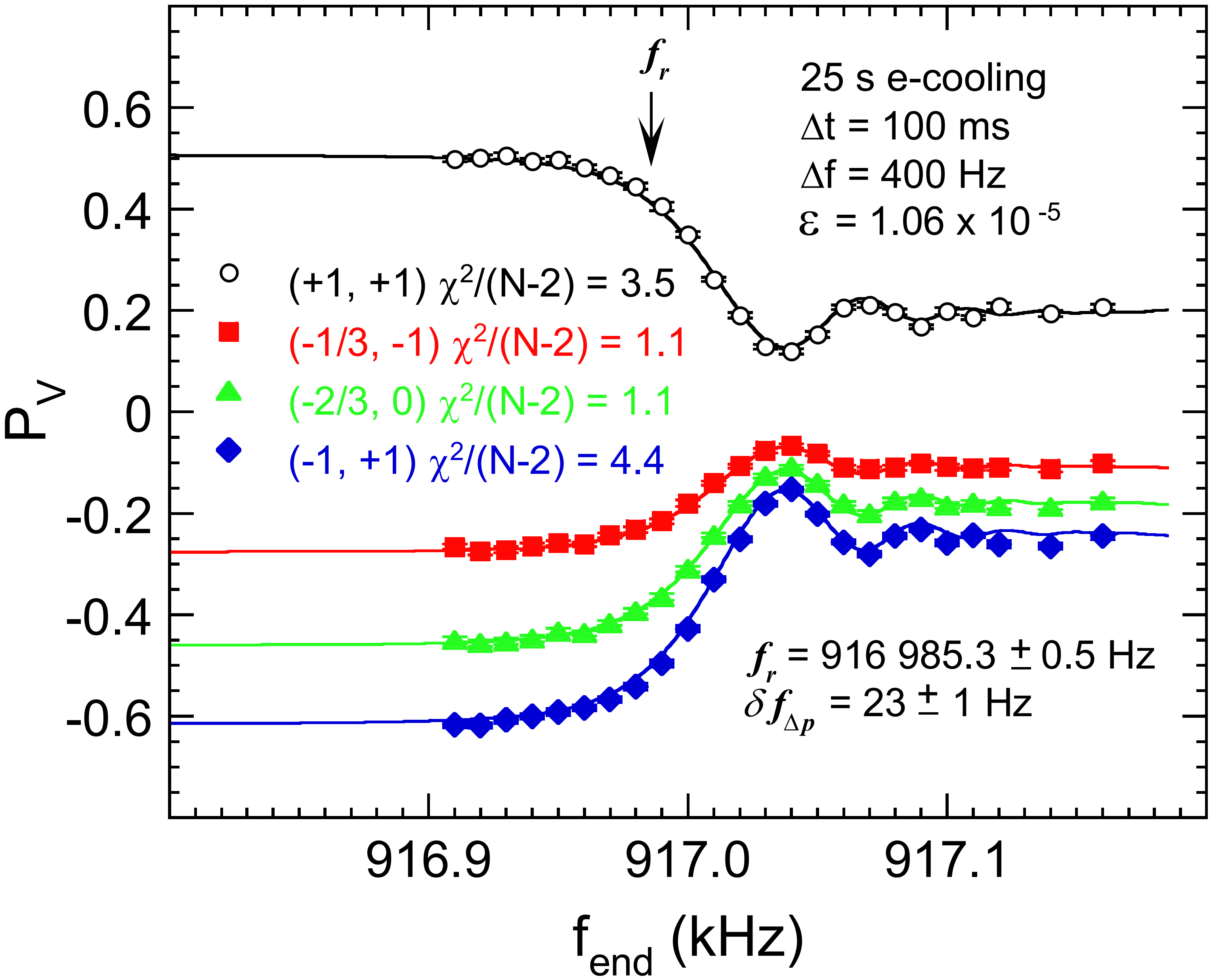
V.S. Morozov *et al.*, Phys. Rev. Lett. 100, 054801 (2008)



CHAO TEST WITH FULLY COOLED BEAM

May 07

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

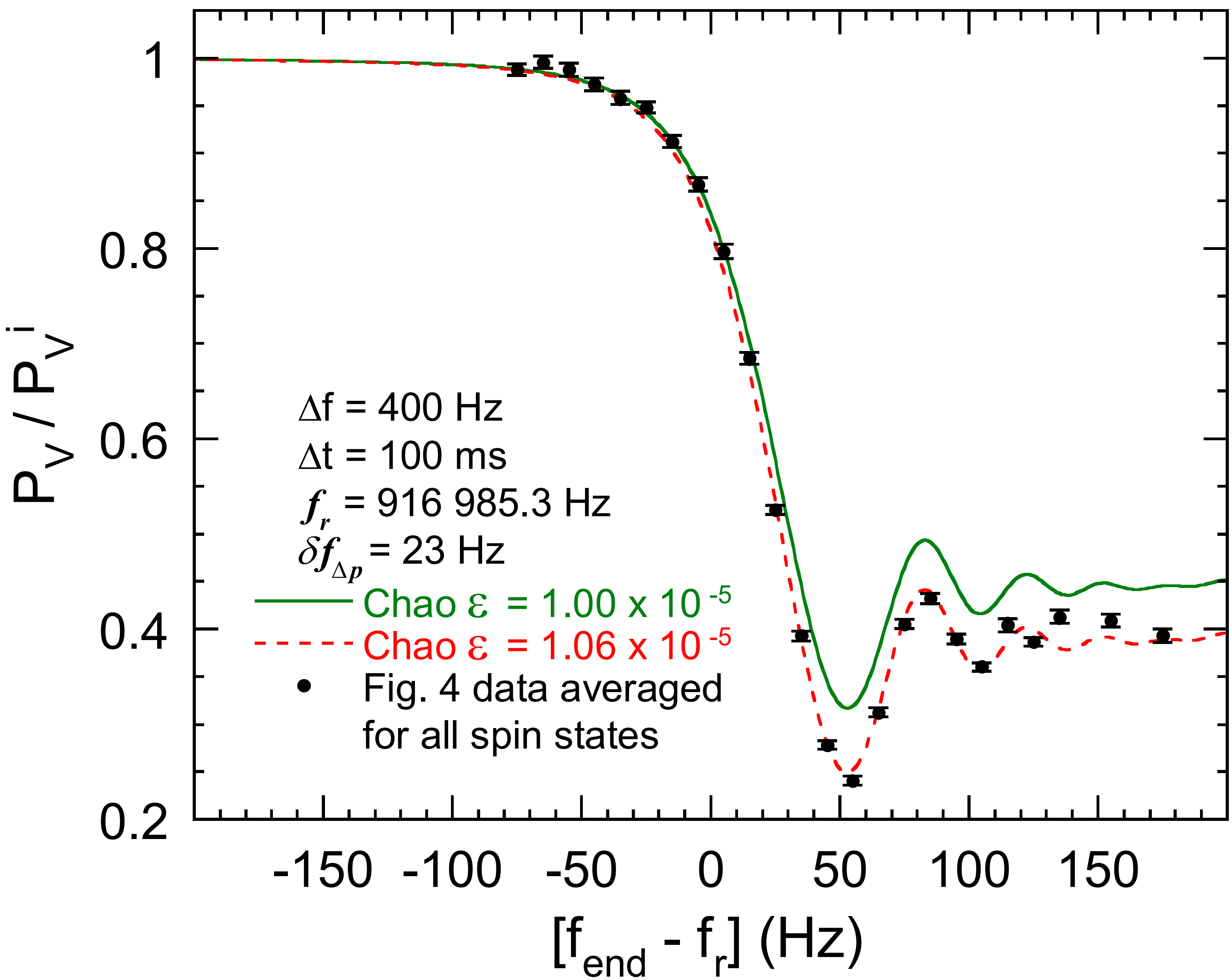


CHAO TEST WITH FULLY COOLED BEAM

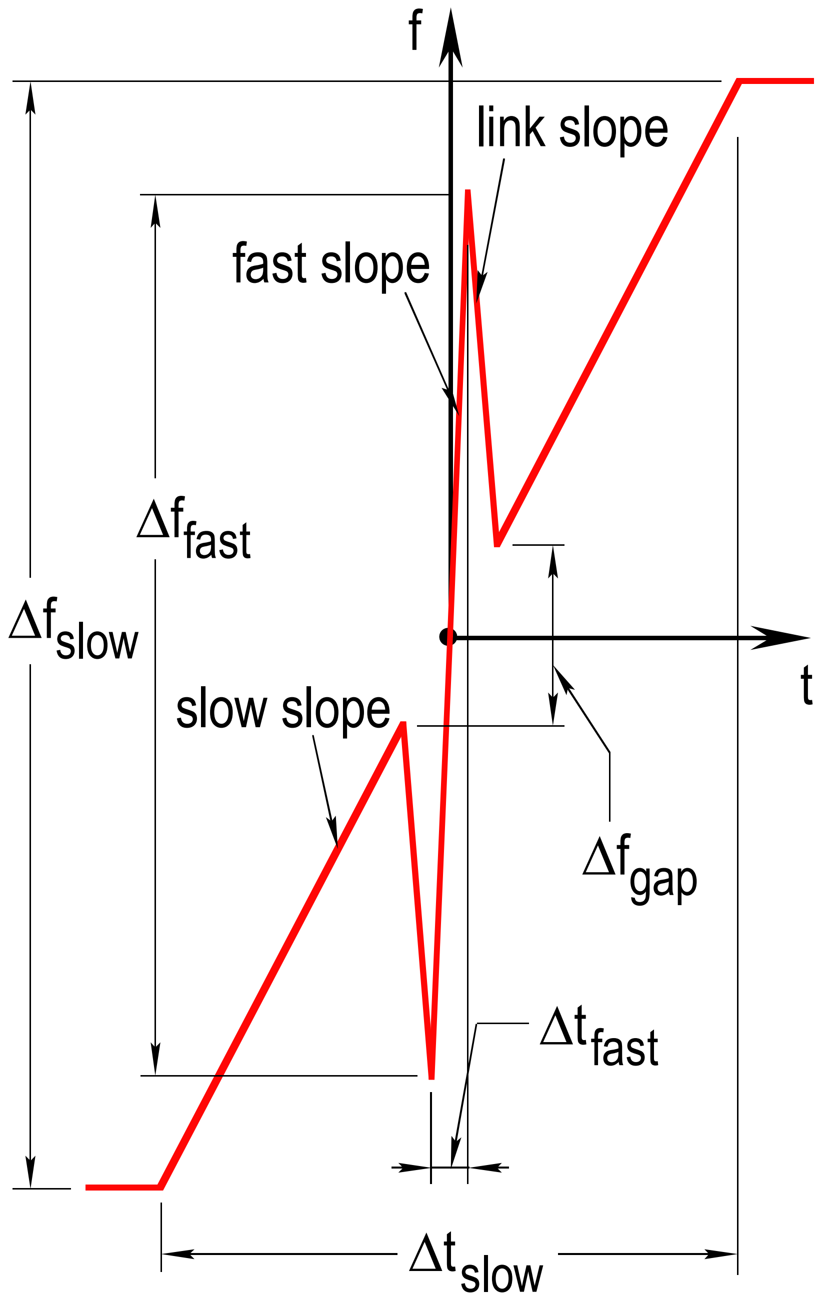
May 07

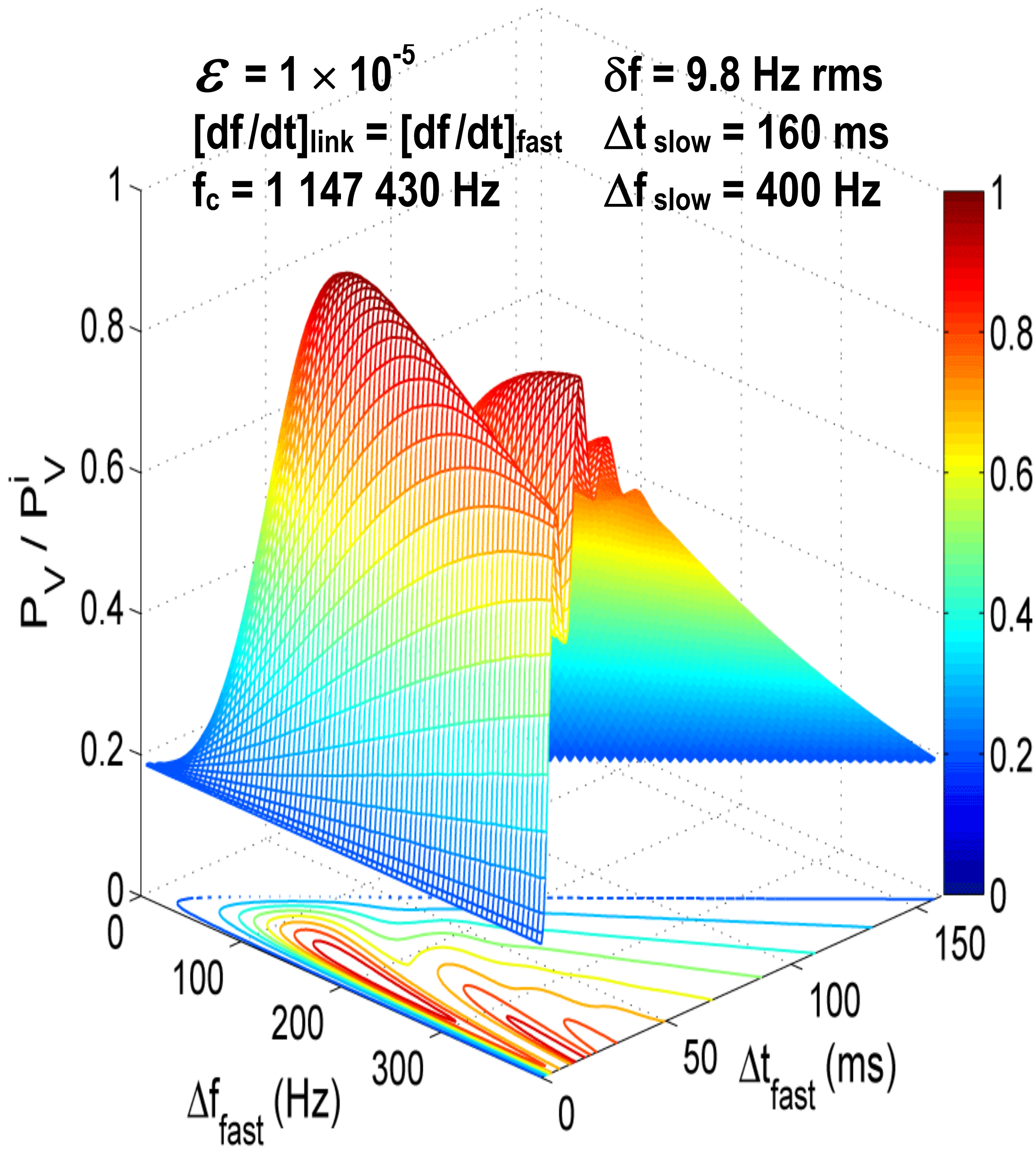
V.S. Morozov *et al.*, Phys. Rev. Lett. 100, 054801 (2008)

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

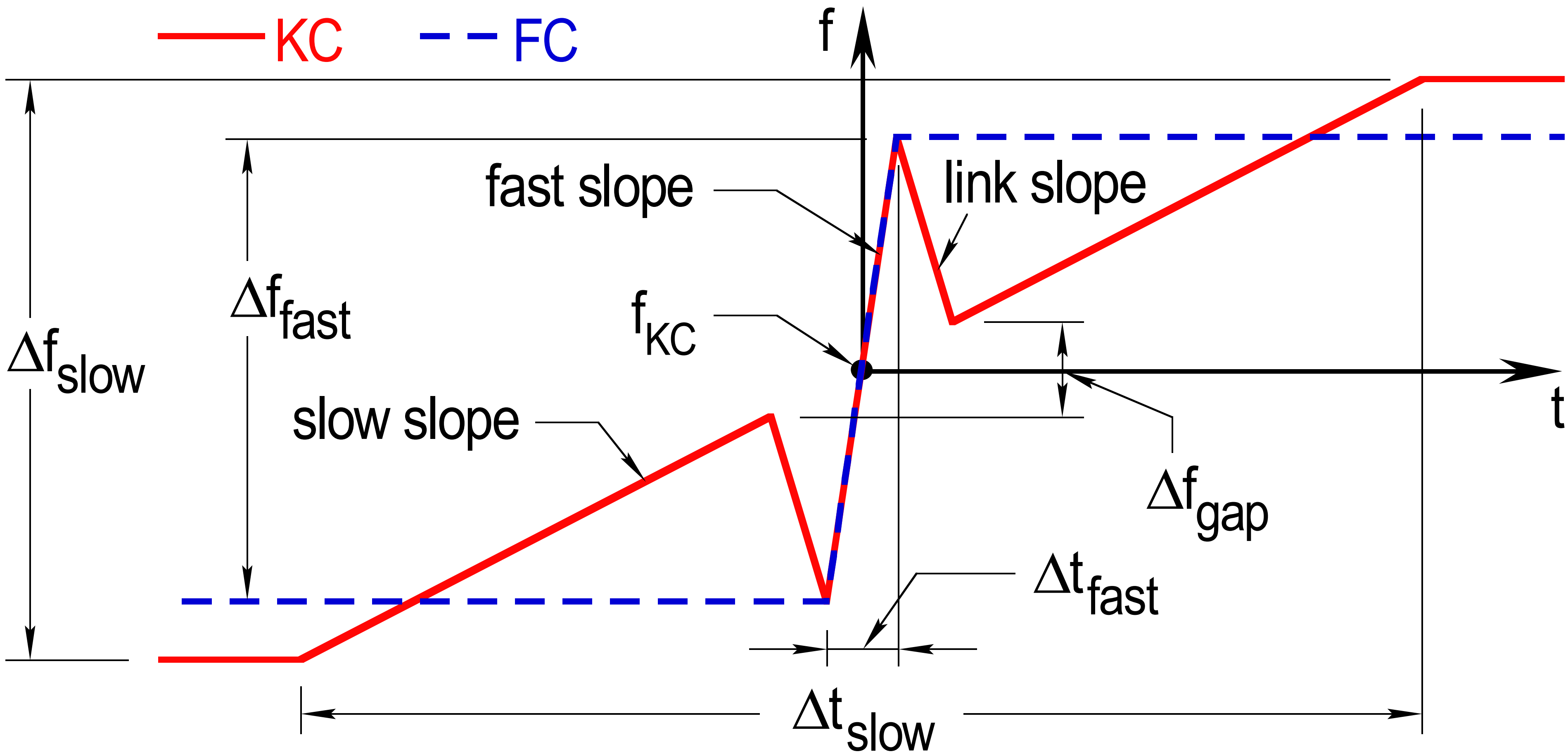


APPLICATION TO KONDRATENKO CROSSING





KONDRATENKO CROSSING SHAPE



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

CHOOSING CROSSING PARAMETERS

A.M. Kondratenko, SPIN@COSY Internal Report, 17 November 2006.

Suppose $[df/dt]_{link} = [df/dt]_{fast}$

then to overcome spin resonance strength ε
with rms spin resonance frequency spread δf
$[df/dt]_{fast}$ must satisfy:

$$[df/dt]_{fast} \geq 83\,(\varepsilon f_c)^2$$

$$[df/dt]_{fast} \geq 156\,(\delta f)^2$$

[$f_c \equiv$ circulation frequency]

and the crossing parameters should be chosen as

$$\Delta f_{slow} \geq ([df/dt]_{fast})^{1/2}$$

$$\Delta t_{slow} = 6.03\,\Delta f_{slow} / [df/dt]_{fast}$$

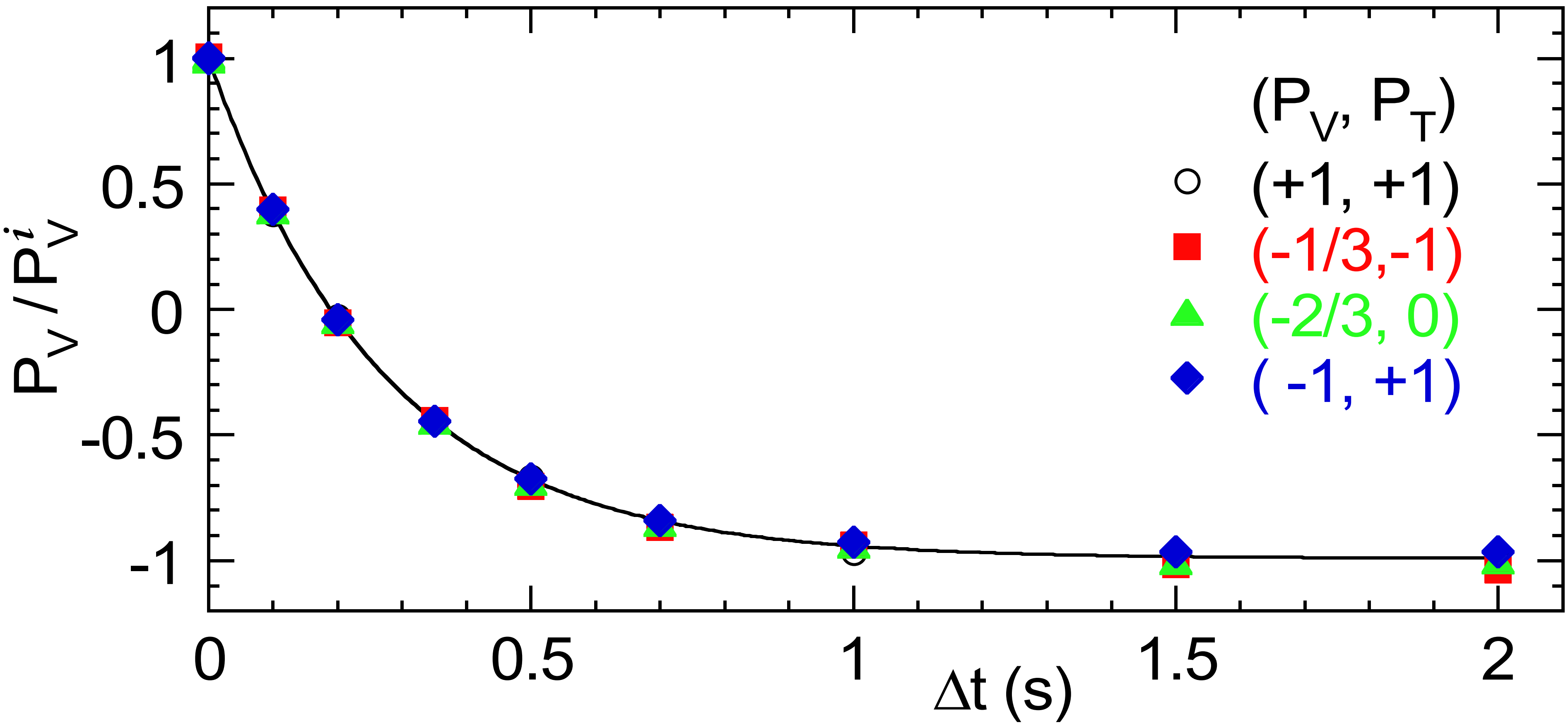
$$\Delta f_{fast} = 1.43\,([df/dt]_{fast})^{1/2}$$

$$\Delta t_{fast} = 1.43 / ([df/dt]_{fast})^{1/2}$$

1.85 GeV/c DEUTERONS AT COSY

May 08

V.S. Morozov *et al.*, accepted for publication in Phys. Rev. Lett.



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

Kondratenko Crossing (KC) & Fast Crossing (FC) by Varying f_{KC}

May 08

V.S. Morozov *et al.*, accepted for publication in Phys. Rev. Lett.

$f_r \equiv$ spin resonance center frequency $\quad f_{KC} \equiv$ KC shape center frequency

Parameters at COSY:

$\varepsilon = 1.067\ 10^{-5}$

$\delta f \cong 10$ Hz rms

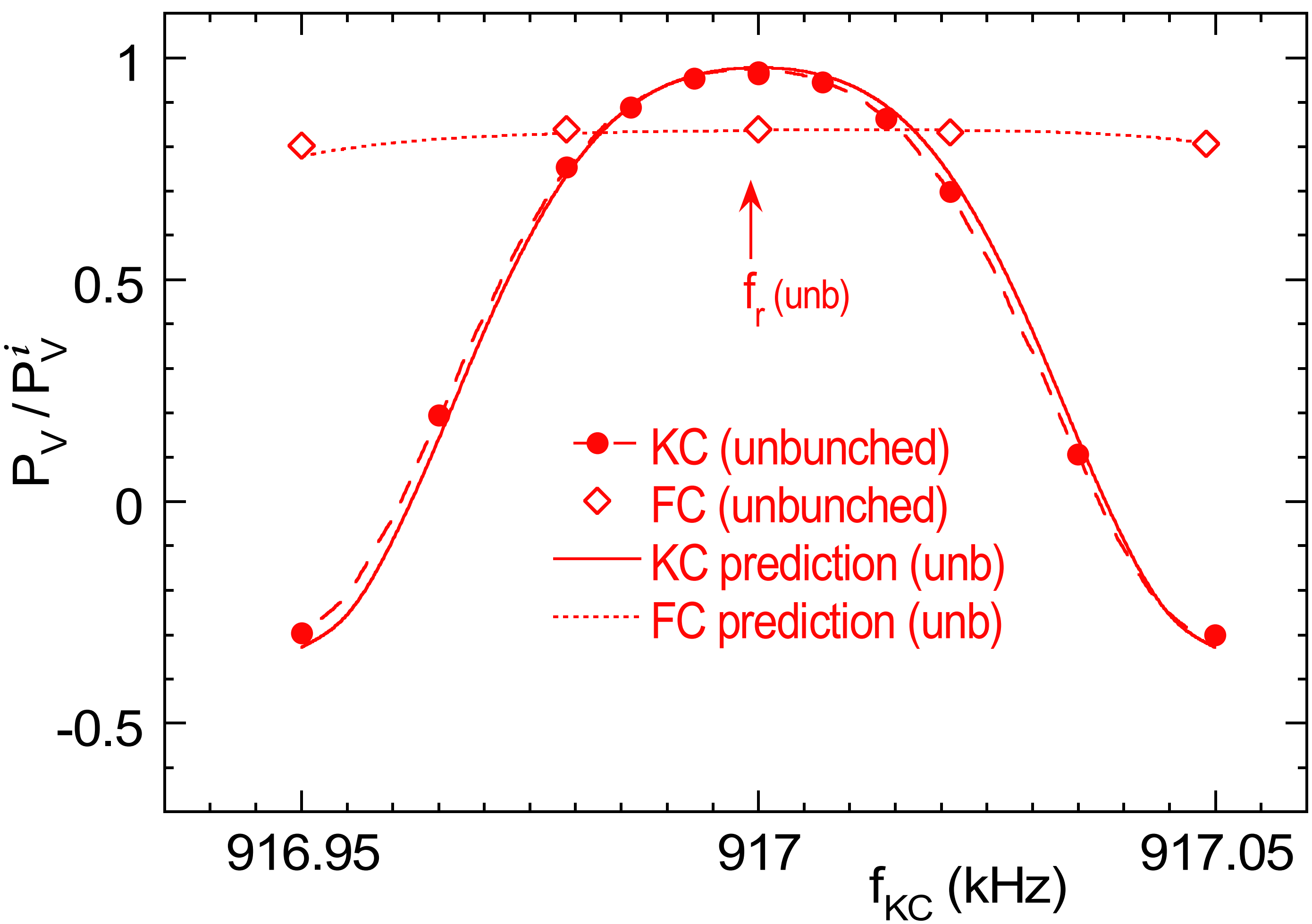
$\Downarrow$

$\Delta f_{slow} = 400$ Hz

$\Delta t_{slow} = 160$ ms

$\Delta f_{fast} = 185$ Hz

$\Delta t_{fast} = 12$ ms



– – KC fit using Chao formalism $\Rightarrow f_r = 916\ 999.1 \pm 0.1$ Hz

$\delta f = 24.4 \pm 0.2$ Hz fwhm

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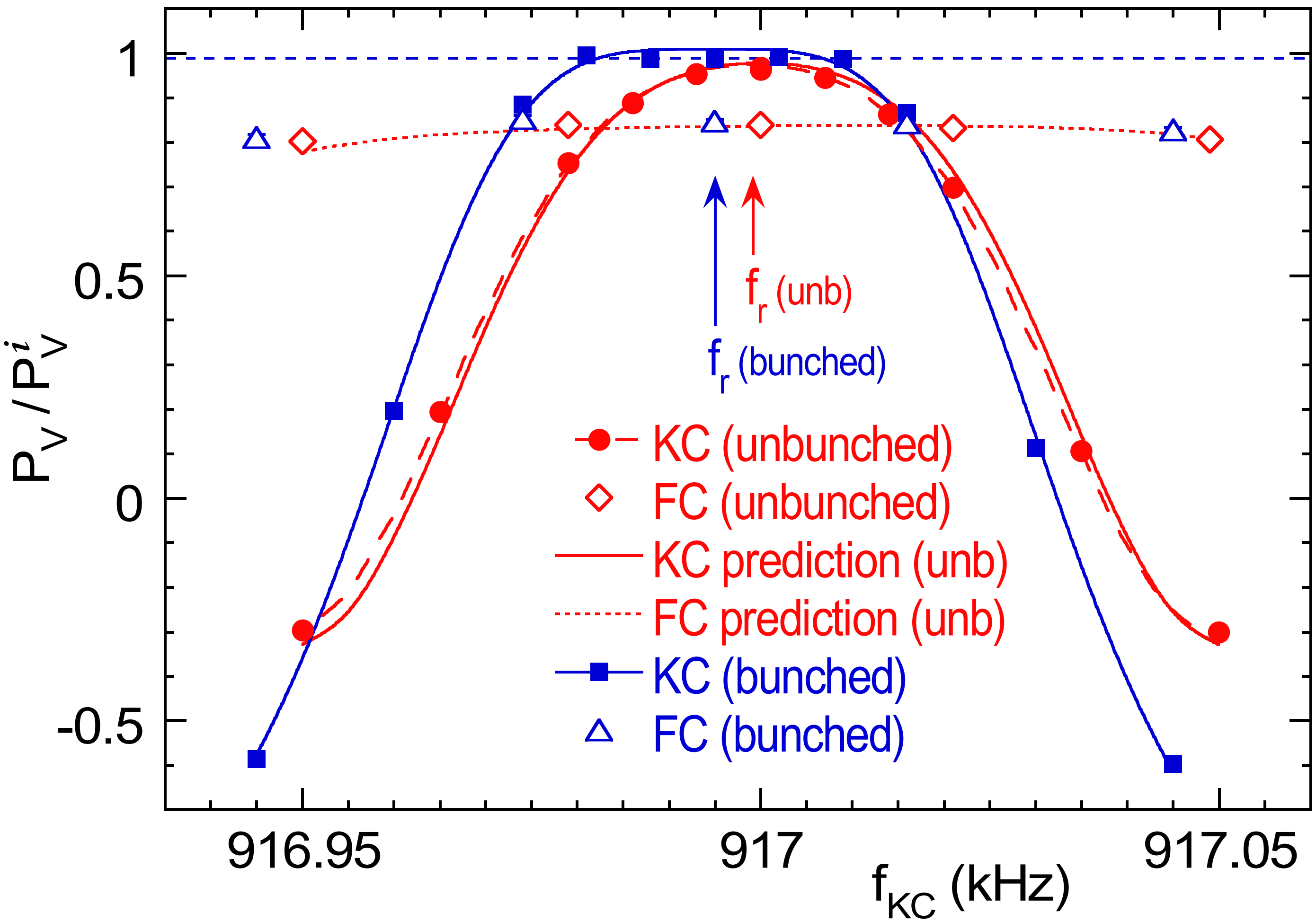


– – KC fit using Chao formalism $\Rightarrow f_r = 916\ 999.1 \pm 0.1$ Hz

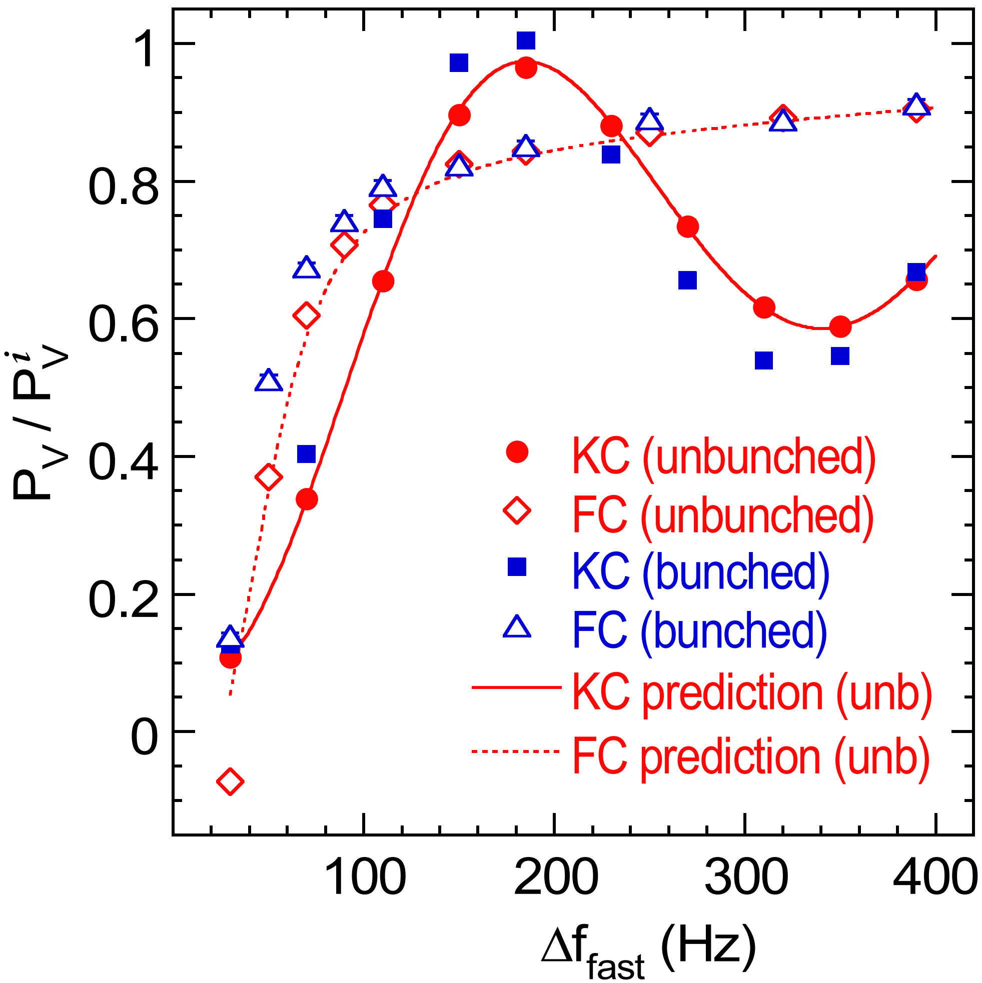
$\delta f = 24.4 \pm 0.2$ Hz fwhm

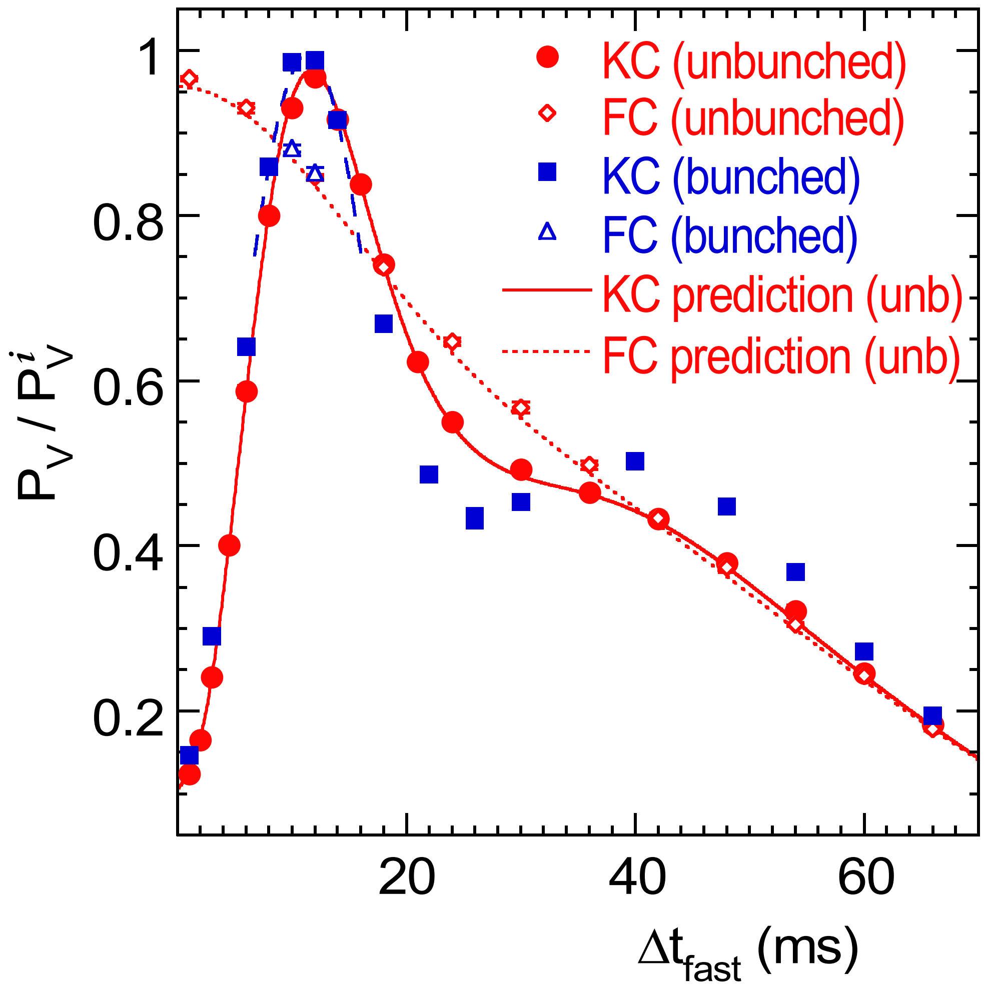
KC and FC by Varying Δf_{fast} and Δt_{fast}

May 08

V.S. Morozov *et al.*, accepted for publication in Phys. Rev. Lett.

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





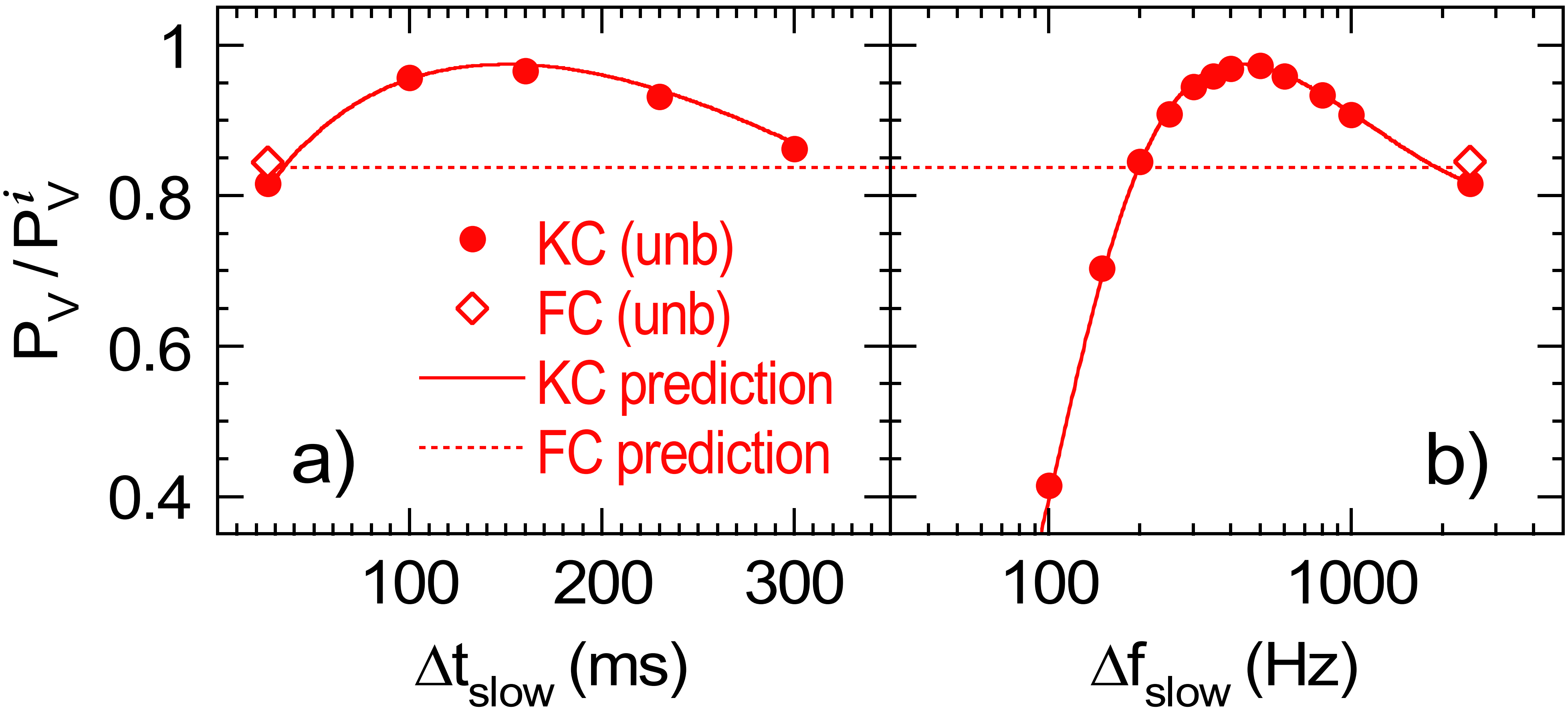
KC and FC by Varying Δt_{slow} and Δf_{slow}

May 08

V.S. Morozov *et al.*, accepted for publication in Phys. Rev. Lett.

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

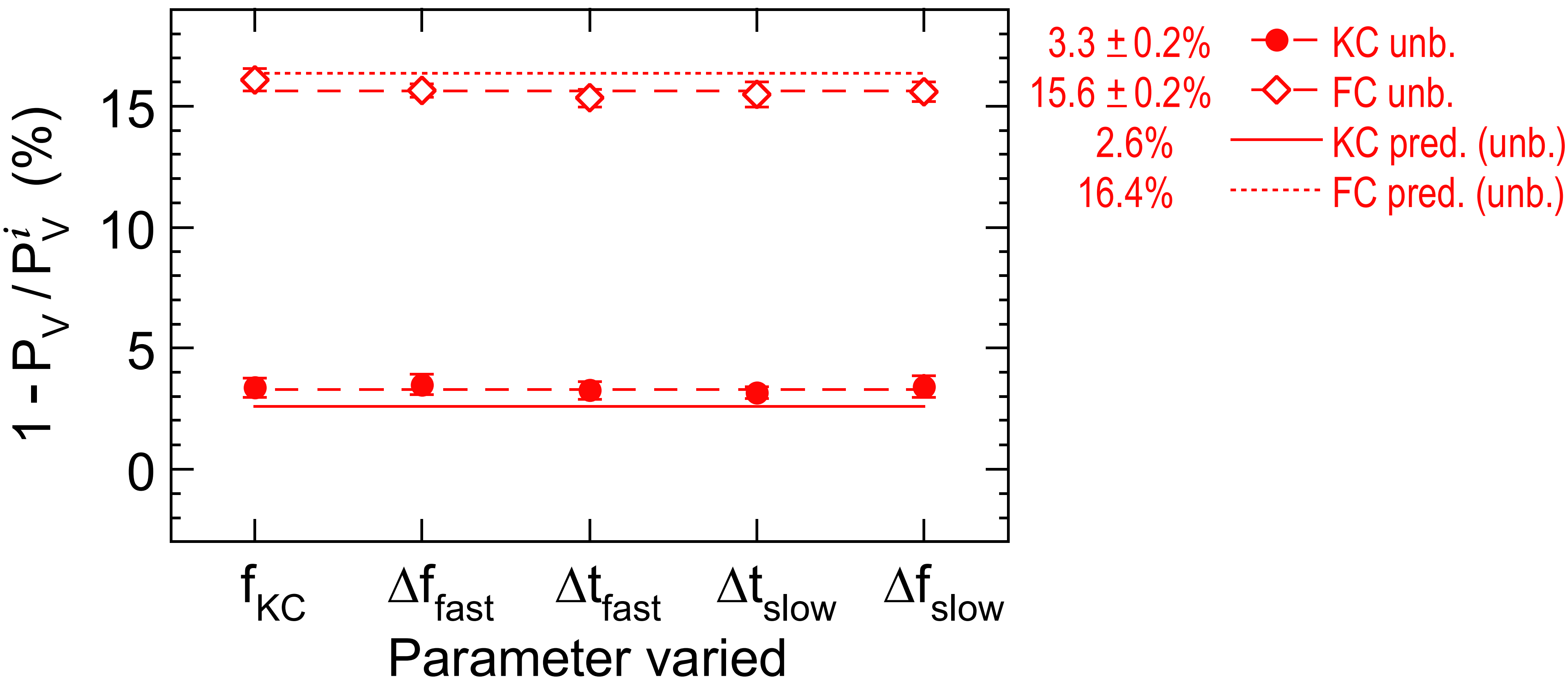
Unbunched



Depolarization Summary at KC Peak

May 08

V.S. Morozov *et al.*, accepted for publication in Phys. Rev. Lett.



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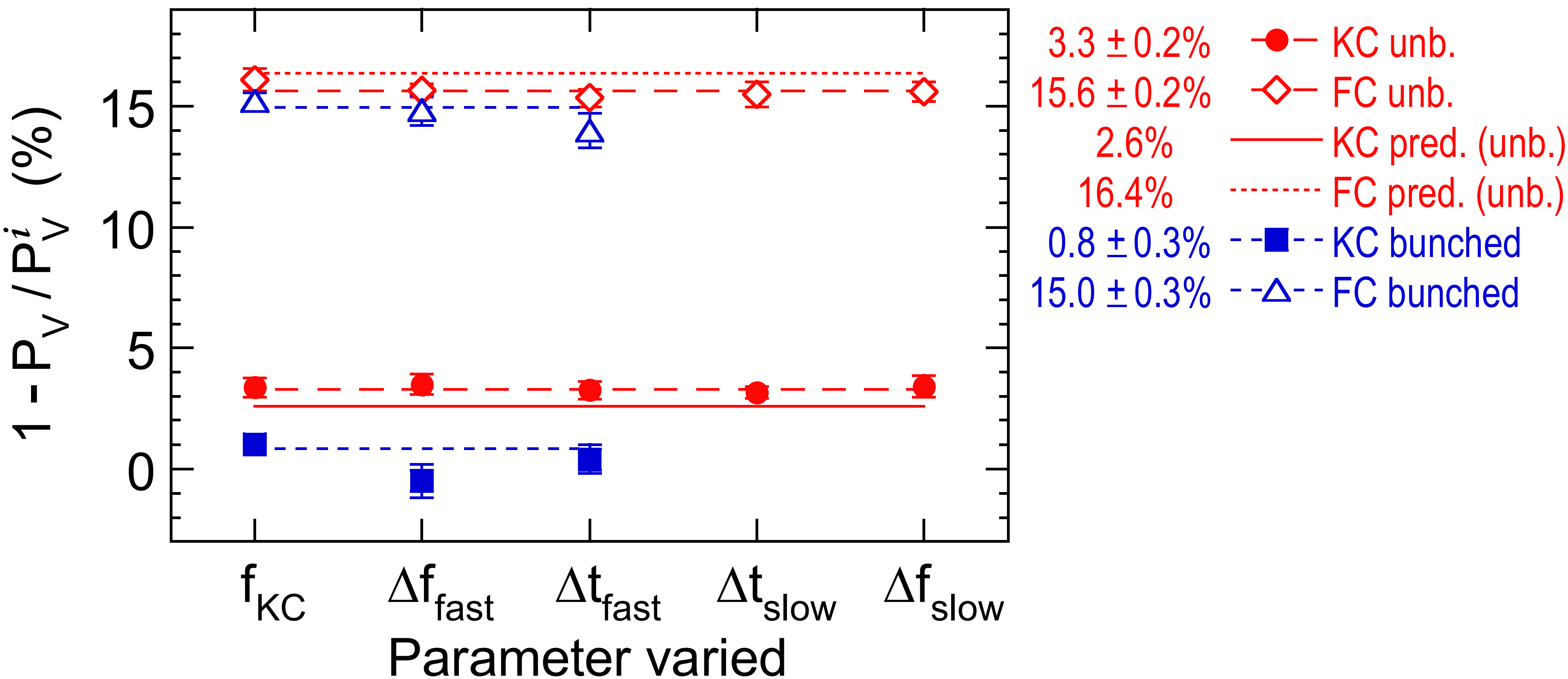
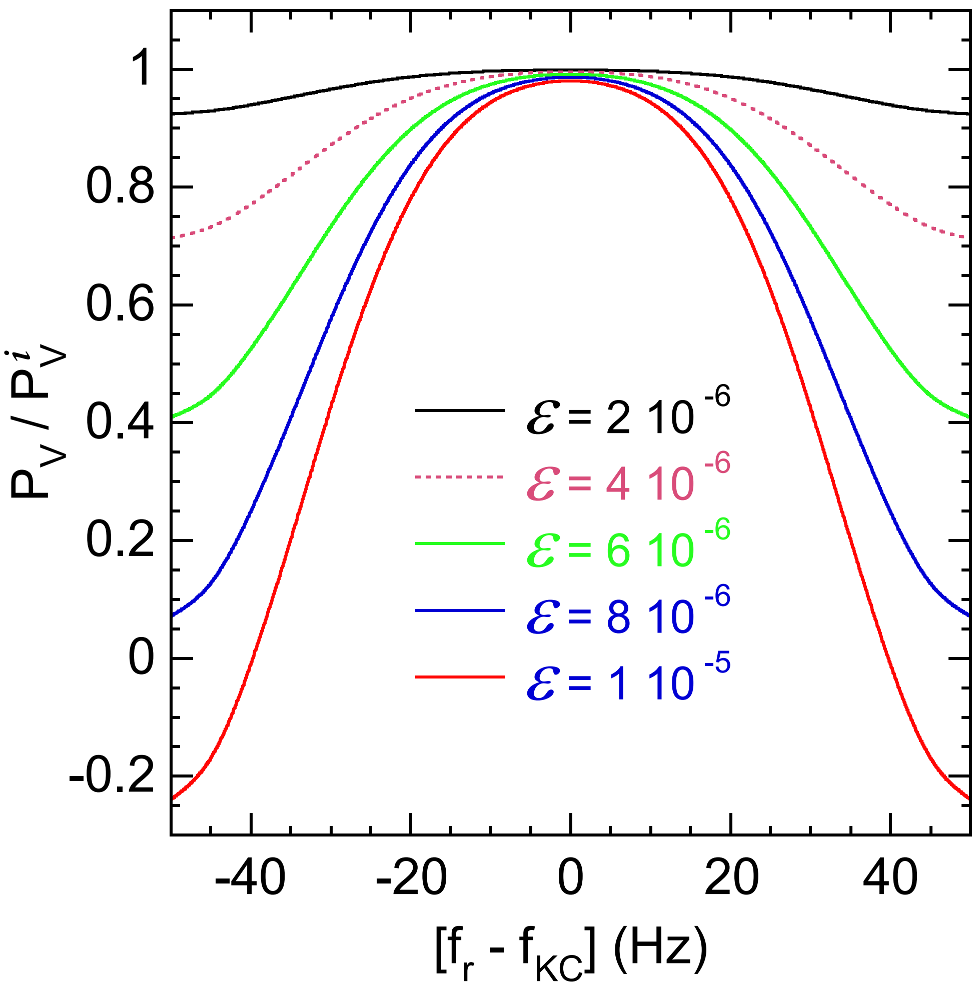
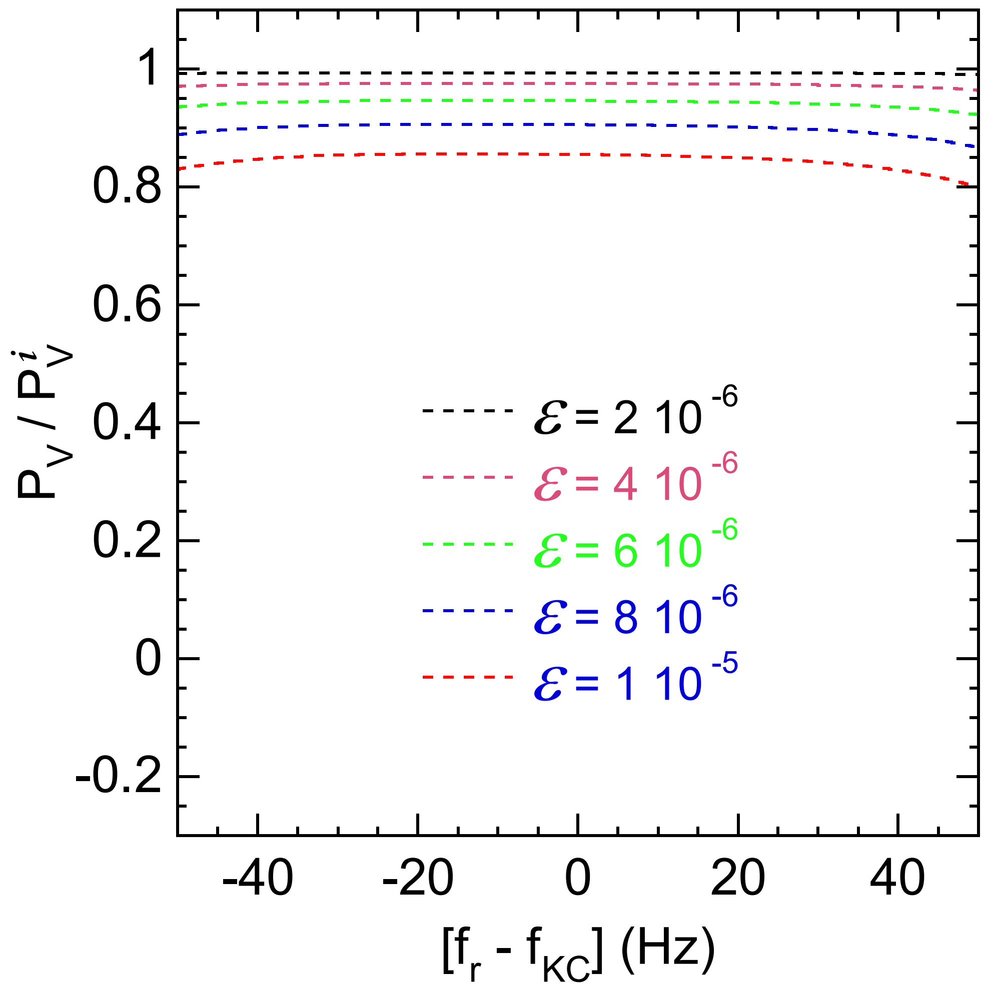


KC and FC for Different $\mathcal{E}$

Kondratenko Crossing



Fast Crossing



Kondratenko Triple Crossing

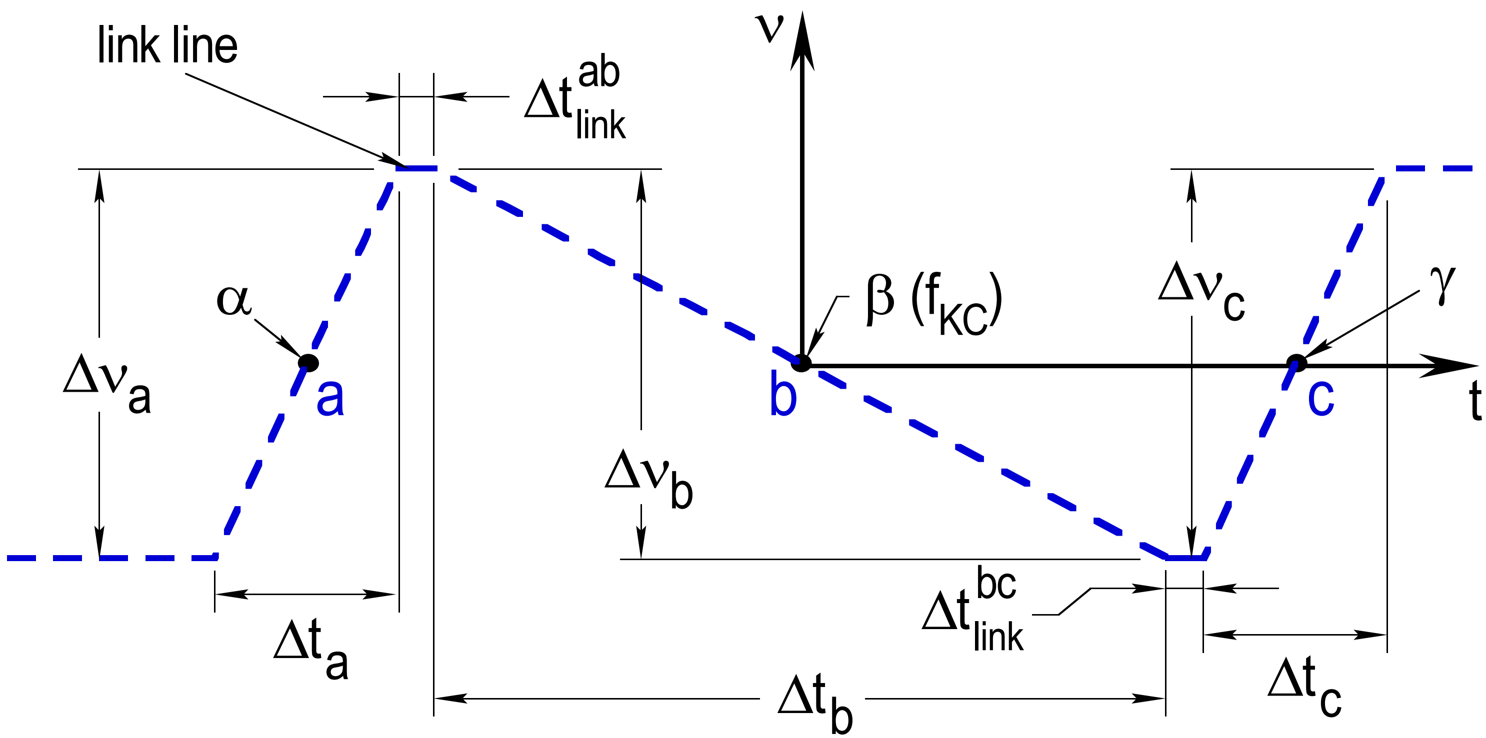
$$\nu \equiv G\gamma - \nu_r \qquad \nu_r \equiv m \quad \text{or} \quad m \pm \nu_y$$

Requirements:

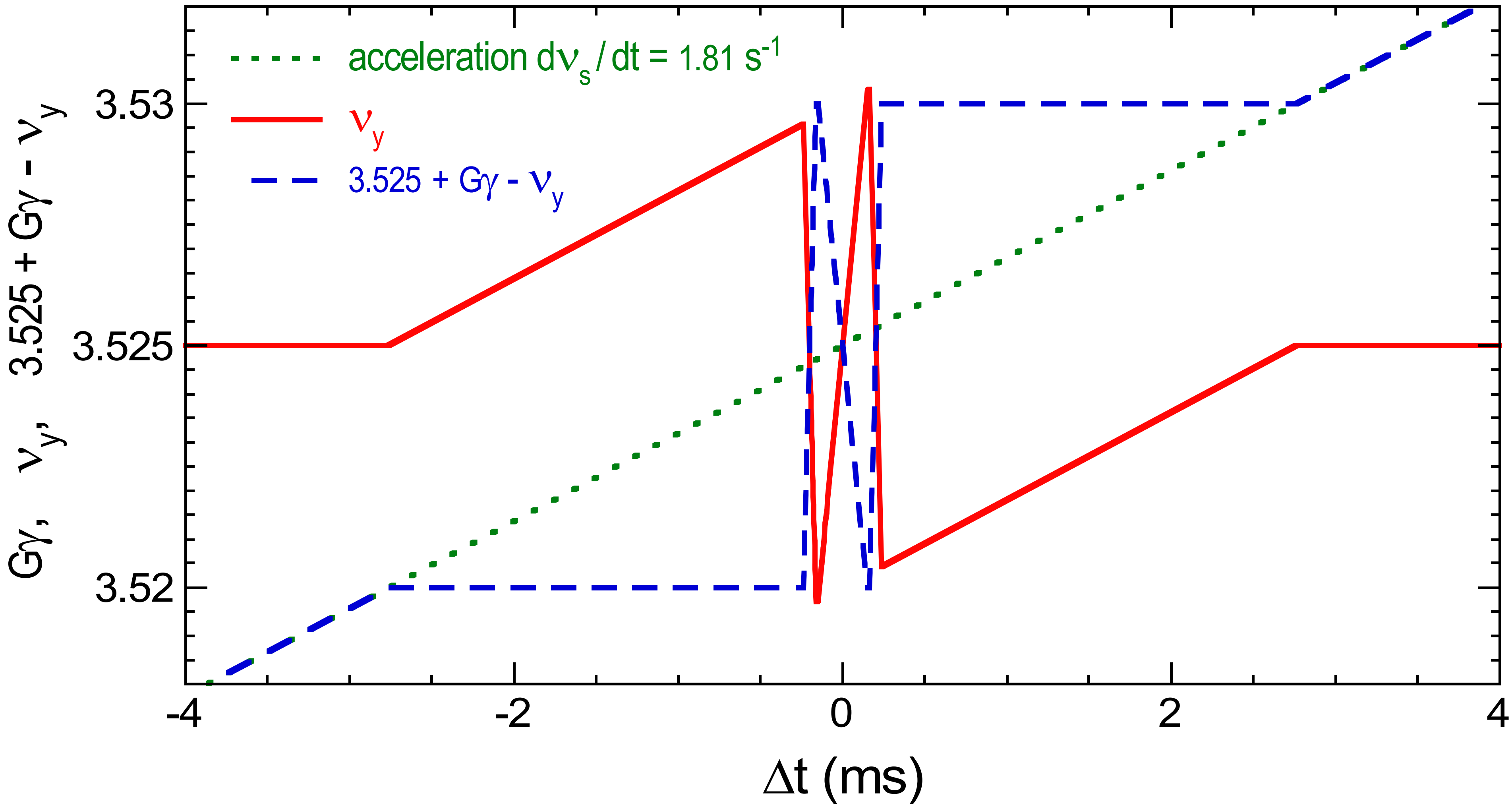
- Spin rotation about vertical axis between crossings $\Psi_{\alpha\beta} = \Psi_{\beta\gamma} = 2\pi m$
- Spin rotation about horizontal axis

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

- 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



Kondratenko Triple Crossing by Ramping ν_y



SUMMARY

- **Achieved 97 $\pm$ 1% vector polarization 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
- **Developing KC test with proton intrinsic & imperfection resonances**