

# Unexpected reduction of rf spin resonance strength for stored deuteron beams

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Stored beams of polarized protons, electrons, or deuterons can be spin flipped by sweeping an rf dipole's or solenoid's frequency through an rf spin resonance. Fitting such data to the modified Froissart-Stora equation's spin resonance strength  $\mathcal{E}_{FS}$  gave very large deviations from the  $\mathcal{E}_{Bdl}$  obtained from each rf magnet's  $\int B_{rms} dl$ . We recently varied an rf dipole's frequency sweep range  $\Delta f$ , and the momentum spread  $\Delta p/p$  and betatron tune  $\nu_y$  of stored 1.85 GeV/c polarized deuterons. We found a sharp constructive interference when  $\nu_y$  was near an intrinsic spin resonance. Moreover, over large  $\Delta f$  and  $\Delta p/p$  ranges,  $\mathcal{E}_{FS}$  was about 7 times smaller than the predicted  $\mathcal{E}_{Bdl}$ .

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A recent paper [1] analyzed all available data on spin-flipping stored beams of polarized protons, electrons, and deuterons. The polarization was typically manipulated by sweeping the frequency of an rf dipole or rf solenoid through an rf-induced spin resonance; spin-flip efficiencies of up to 99.9% were obtained. Fitting the modified [2,3] Froissart-Stora [4] equation to the measured polarization data after crossing an rf-induced spin resonance gave very large deviations from the widely used resonance strength equations. We recently measured the deuteron's resonance strength deviations by varying an rf dipole's frequency sweep range  $\Delta f$ , and the momentum spread  $\Delta p/p$  and betatron tune  $\nu_y$  of a 1.85 GeV/c polarized deuteron beam stored in COSY.

In any flat storage ring or circular accelerator with no horizontal magnetic fields, each beam particle's spin precesses around the vertical fields of the ring's dipole magnets. The spin tune  $\nu_s$ , which is the number of spin precessions during one turn around the ring, is proportional to the particle's energy

$$\nu_s = G\gamma, \quad (1)$$

where  $G = (g - 2)/2$  is the particle's gyromagnetic anomaly ( $G_d = -0.142987$ ) and  $\gamma$  is its Lorentz energy factor. The vertical polarization can be perturbed by an rf magnet's horizontal rf magnetic field. This perturbation can induce an rf depolarizing resonance [4–6], which can flip the spin direction of stored polarized particles [1–3,7–18]; the resonance's frequency is

$$f_r = f_c(k \pm \nu_s), \quad (2)$$

where  $f_c$  is the circulation frequency and  $k$  is an integer.

Ramping an rf magnet's frequency through  $f_r$  can flip each particle's spin. The modified [2,3] Froissart-Stora

(FS) equation [4] relates the beam's initial polarization  $P_i$  to its final polarization  $P_f$  after crossing the resonance,

$$P_f = P_i \left\{ (1 + \hat{\eta}) \exp \left[ \frac{-(\pi \mathcal{E}_{FS} f_c)^2}{\Delta f / \Delta t} \right] - \hat{\eta} \right\}; \quad (3)$$

the parameter  $\hat{\eta}$  is the limiting spin-flip efficiency and the ratio  $\Delta f / \Delta t$  is the resonance crossing rate, where  $\Delta f$  is the ramp's frequency range during the ramp time  $\Delta t$ , and  $\mathcal{E}_{FS}$  is the resonance strength obtained by fitting measured data to Eq. (3). Equation (3) should be valid if  $\Delta f$  is larger than the spin resonance's width.

For an ideal flat circular accelerator, with no horizontal  $B$ -fields, the resonance strength  $\mathcal{E}_{Bdl}$  due to a short rf solenoid's longitudinal  $B$ -field or a short rf dipole's transverse  $B$ -field is thought to be given by [19–25]

$$\text{Solenoid: } \mathcal{E}_{Bdl} = \frac{1}{\pi 2\sqrt{2}} \frac{e(1+G)}{p} \int B_{rms} dl, \quad (4)$$

$$\text{Dipole: } \mathcal{E}_{Bdl} = \frac{1}{\pi 2\sqrt{2}} \frac{e(1+G\gamma)}{p} \int B_{rms} dl, \quad (5)$$

where  $e$  is the particle's charge,  $p$  is its momentum, and  $\int B_{rms} dl$  is the rf magnet's rms magnetic field integral in its rest frame. There has been some theoretical disagreement about a factor of 2 in both Eqs. (4) and (5). While our experimental data cannot confirm either factor of 2, we now use the [24,25] factor of 2; thus, we changed the resonance strength symbol to  $\mathcal{E}_{Bdl}$ .

The recent compilation [1] of all available experimental data [1–3,7,10,11,13–18] allowed a simultaneous evaluation of the spin resonance strength  $\mathcal{E}_{Bdl}$ , obtained from Eqs. (4) and (5), and the spin resonance strength  $\mathcal{E}_{FS}$  obtained from Eq. (3). This compilation indicated that

for many experiments the  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  ratio disagrees with the predictions [19–25] by factors of 0.1, 10, or more. For protons  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  was often much larger than 1; this was explained by a recent experiment [1], which demonstrated that much of this enhancement was due to constructive interference of the rf resonance with a strong intrinsic resonance. However for deuterons,  $\mathcal{E}_{\text{FS}}$  was typically 7 times smaller than  $\mathcal{E}_{\text{Bdl}}$ . The proton experiment [1] was done with the same rf dipole at COSY; thus, these large strength deviations could not be due to an incorrect calibration of  $\int Bdl$ , which was known to  $\pm 5\%$ .

To better understand this unexpected deuteron behavior, we recently measured the dependence of a deuteron rf resonance's strength on various parameters, such as the proximity to a deuteron intrinsic resonance, the beam's momentum spread, and the rf dipole's frequency sweep range  $\Delta f$ . This experiment used a 1.85 GeV/c polarized deuteron beam stored in COSY.

The experimental apparatus (see Fig. 4 in [1]), included the COSY storage ring [26–29], the EDDA detector [30], the electron cooler [31], the low energy polarimeter, the injector cyclotron, and the polarized ion source [32–34]. The beam emerging from the polarized  $\text{D}^-$  ion source was accelerated by the cyclotron to COSY's injection energy of about 75.7 MeV. Then the low energy polarimeter measured the beam's polarization before injection into COSY to monitor the stable operation and polarization of the ion source.

The EDDA detector [30] measured the beam's polarization in COSY; we reduced its systematic errors by cycling the polarized source between the 4 different vector and tensor vertical polarization states:

$$(P_V, P_T) = (0, 0), (+1, +1), (\frac{1}{3}, -1), (-\frac{2}{3}, 0).$$

The rf acceleration cavity was turned off and shorted during COSY's flattop. The measured  $(+1, +1)$  vector polarization, before spin manipulation, was about 63%.

We first determined the resonance's position by measuring the polarization with the rf dipole set at different fixed frequencies. These data are shown in Fig. 1 with the electron cooling both on and off. Note that the deuteron resonance frequency changed slightly due to the slightly different accelerator parameters used when the electron cooling was on or off. The electron cooler reduced the beam's size and momentum spread at injection energy. A 20.6 keV electron beam cooled the deuteron beam to its equilibrium emittances in both the longitudinal and transverse dimensions. As shown in Fig. 1, the electron cooling decreased the resonance's total width  $w$  from  $42 \pm 2$  to  $23 \pm 2$  Hz FWHM. Since the resonance's natural width of  $2\mathcal{E}_{\text{FS}}f_c$  is only 3 Hz, when it is unfolded from these measured  $w$  values, then the width values due to the beam's  $\Delta p/p$  are essentially unchanged.

We manipulated the deuteron's polarization using a ferrite-yoke rf dipole, with an 8-turn copper coil, which

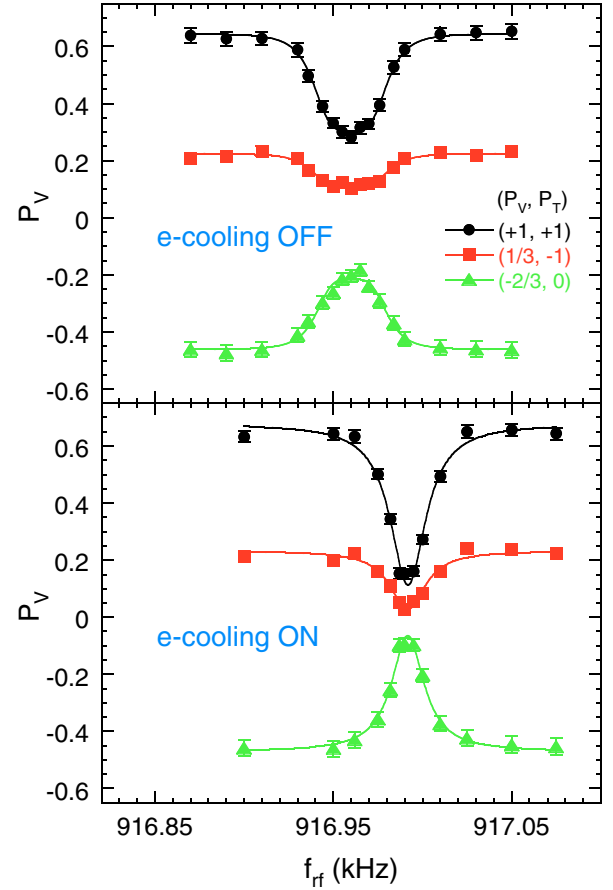


FIG. 1. (Color) Measured vector deuteron polarizations at 1.85 GeV/c are plotted vs rf-dipole frequency  $f_{\text{rf}}$ . Fits to a 2nd-order Lorentzian give a resonance frequency  $f_r$  of  $916960 \pm 10$  Hz and a resonance width  $w$  of  $42 \pm 2$  Hz for the uncooled beam. Fits to a 1st-order Lorentzian give  $f_r$  of  $916992 \pm 10$  Hz and  $w$  of  $23 \pm 2$  Hz with electron cooling.

produced a uniform radial magnetic field. The rf dipole was part of an LC resonant circuit, which operated near  $f_r = 917$  kHz, typically at an rf voltage of 3.1 kV rms giving an rf  $\int B_{\text{rms}} dl$  of  $0.60 \pm 0.03$  T mm.

As shown in Fig. 2, the resonance strength  $\mathcal{E}_{\text{FS}}$  was obtained by first measuring the final beam polarization  $P_f$  after ramping an rf magnet's frequency by a range  $\Delta f$  during a time  $\Delta t$  through a spin resonance. The measured dependence of  $P_f$  on  $\Delta t$  was then fit to Eq. (3). Thus, we obtained  $\mathcal{E}_{\text{FS}}$  for two different frequency ranges,  $\Delta f$  of 100 and 300 Hz; and for two different momentum spreads by using electron cooling to reduce the beam's  $\Delta p/p$ .

The resonance strengths  $\mathcal{E}_{\text{FS}}$  and their  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  ratios were all obtained by fitting these data to Eq. (3) as explained in the Fig. 2 caption. The  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  ratios at  $\Delta f$  of 100 and 300 Hz, for both the cooled and uncooled beams, are shown in Fig. 3 along with other data. Recall that Fig. 1 indicated that the cooling reduced  $\Delta p/p$  by a factor of 2 while the  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  ratios for the cooled and uncooled beams only differ by about 7%. Thus, any small  $\Delta p/p$

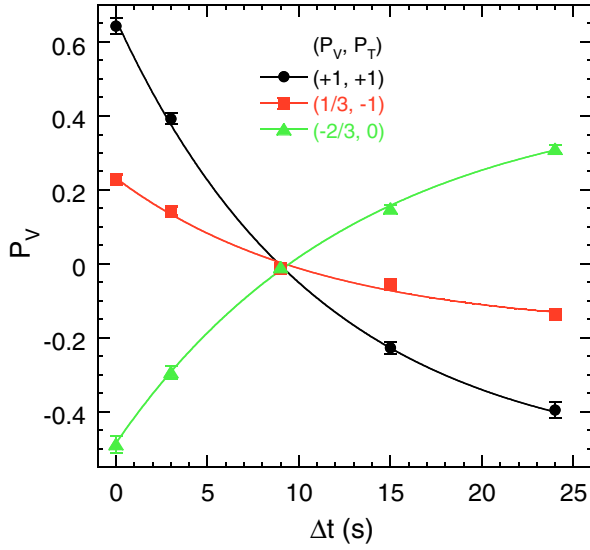


FIG. 2. (Color) Measured vector deuteron polarizations at 1.85 GeV/c are plotted vs rf-dipole ramp time  $\Delta t$  for 3 different spin states with electron cooling off. The rf dipole's frequency range  $\Delta f$  was 300 Hz; its  $\int B dl$  was  $0.60 \pm 0.03$  T mm; thus, Eq. (5) gives  $^*\mathcal{E}_{Bdl}$  of  $(8.8 \pm 0.4) \times 10^{-6}$ . The fit to Eq. (3) gives  $\mathcal{E}_{FS}$  of  $(1.39 \pm 0.04) \times 10^{-6}$ .

fluctuations cannot explain the observed sevenfold reduction of the resonance strength for experiments with both cooled and uncooled beams.

All earlier anomalous deuteron data [1] were at small  $\Delta f$  values of 100–200 Hz; thus, we increased  $\Delta f$  in four

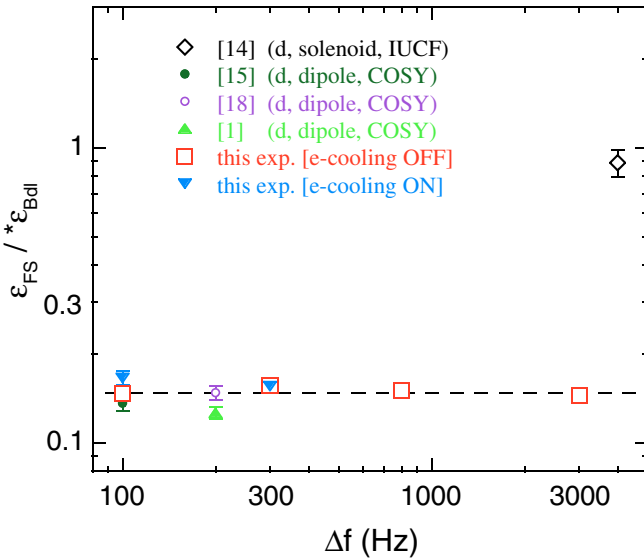


FIG. 3. (Color) Ratio of  $\mathcal{E}_{FS}$  to  $^*\mathcal{E}_{Bdl}$  for deuterons is plotted vs rf dipole's frequency sweep range  $\Delta f$ . The  $\nu_y$  values at COSY were all 3.60, and  $\nu_y$  was 4.80 at IUCF.  $\mathcal{E}_{FS}$  is the resonance strength obtained by fitting the  $\Delta t$  curve for each data point to Eq. (3);  $^*\mathcal{E}_{Bdl}$  was obtained using each data point's  $\int B dl$  in Eq. (4) or Eq. (5). The fit to all rf-dipole points gives a resonance strength ratio of  $0.15 \pm 0.01$ .

steps from 100 to 3000 Hz. The resulting  $\mathcal{E}_{FS}/^*\mathcal{E}_{Bdl}$  ratios at  $\nu_y = 3.60$ , along with all earlier deuteron data, are plotted vs  $\Delta f$  in Fig. 3, which shows no dependence of  $\mathcal{E}_{FS}/^*\mathcal{E}_{Bdl}$  on  $\Delta f$ . The fit to all rf-dipole points gives a resonance strength ratio of  $0.15 \pm 0.01$  for deuterons, which certainly disagrees with Eq. (5). However, note that the Indiana University Cyclotron Facility (IUCF) cooler ring rf solenoid point [14] is quite near to 1.

We next measured  $\mathcal{E}_{FS}$ , as in Fig. 2, for different values of the vertical betatron tune  $\nu_y$ ;  $^*\mathcal{E}_{Bdl}$  was again obtained using each data point's  $\int B dl$  in Eq. (5). The  $\mathcal{E}_{FS}/^*\mathcal{E}_{Bdl}$  ratios are plotted against  $\nu_y$  in Fig. 4(a). Notice the nearby  $\nu_s = \nu_y - 4$  first-order intrinsic spin resonance for deuterons [also see Fig. 4(b)]. We fit the observed asymmetric dependence of  $\mathcal{E}_{FS}/^*\mathcal{E}_{Bdl}$  on the distance between  $\nu_y$  and the rf spin resonance's tune  $\nu_r \equiv k \pm f_r/f_c$  ( $k$  is an integer) by empirically modifying the earlier-derived hyperbola [1,21] into an asymmetric hyperbola [35]

$$\mathcal{E}_{FS}/^*\mathcal{E}_{Bdl} = \left| A + \frac{B}{\nu_r - \nu_y} \right|. \quad (6)$$

Fitting the deuteron data in Fig. 4(a) to Eq. (6) gave  $A$  of  $0.06 \pm 0.04$ ,  $B$  of  $0.010 \pm 0.002$ , and  $\nu_r$  of  $3.798 \pm 0.001$ . This  $\nu_r$  value was near the  $\nu_r$  value of  $3.799\,23 \pm 0.000\,01$ , calculated from

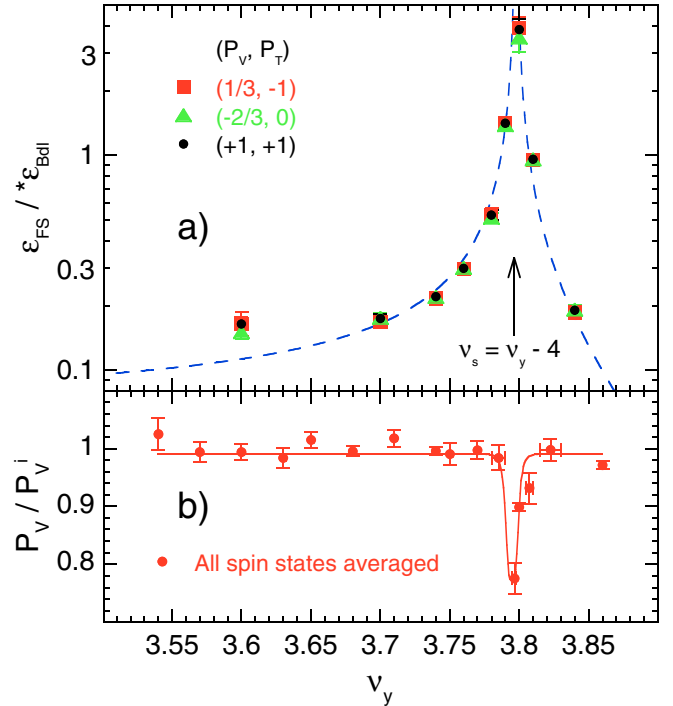


FIG. 4. (Color) (a) Ratio of  $\mathcal{E}_{FS}$  to  $^*\mathcal{E}_{Bdl}$  is plotted vs the vertical betatron tune  $\nu_y$ ;  $\Delta f$  was 300 Hz; the cooling was off. The dashed blue curve is a fit to Eq. (6). (b) Measured deuteron vector polarization ratio at 1.85 GeV/c is plotted vs  $\nu_y$ ; the rf dipole was off; the cooling was on. The red curve is a fit to a 2nd-order Lorentzian.

$$\nu_r = 3 + f_r/f_c \quad (7)$$

using COSY's measured  $f_c$  of 1 147 306 Hz and the measured  $f_r$  of  $916\,960 \pm 10$  Hz from Fig. 1. The parameter  $B$  depends on many details of the ring. The parameter  $A$  should give the predicted [20–25] ratio  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  far from any intrinsic spin resonances.

Figure 4(b) shows the measured ratio of the final to initial vector polarization plotted against various values of  $\nu_y$  with the rf dipole off. Fitting the sharp and narrow dip to a 2nd-order Lorentzian gave  $\nu_r$  of  $3.795 \pm 0.002$ , exactly as in Fig. 4(a); and gave a width of  $(10 \pm 3) \times 10^{-3}$  FWHM. Figures 4(a) and 4(b) may be the first detailed study of a deuteron intrinsic resonance.

Figure 3 demonstrated that the  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  reduction is not due to the earlier [1] small frequency ramp range,  $\Delta f$ . It also shows that, for deuterons, all ratios are far below 1 for an rf dipole, but near to 1 for the single rf solenoid point. Thus, perhaps the earlier unexpected behavior of spin-1 deuterons only occurs when they are spin-manipulated by an rf dipole. We hope to soon study this possibility using a new rf solenoid in COSY.

Recently there have been some theoretical efforts to understand what causes this large reduction in  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  for deuterons. Two independent approaches [36,37] now challenge the derivation of Eq. (5) [19–21,24,25]; they suggest that its factor  $(1 + G\gamma)$  should instead be proportional to  $G\gamma$ . For high-energy protons, where it was studied earlier, the ratio of  $G\gamma$  to  $(1 + G\gamma)$  is very near 1. However, for our 1.85 GeV/ $c$  deuterons, the ratio's magnitude is  $|-0.201/0.799| \approx 0.25$ . Our measured  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  ratio of  $0.15 \pm 0.01$  is certainly closer to 0.25 than to 1.

In summary, by compiling all available deuteron, electron, and proton data and fitting them to the Froissart-Stora equation, one found deviations of  $\mathcal{E}_{\text{FS}}/\mathcal{E}_{\text{Bdl}}$  in the range of about 0.12 to 170. A recent proton experiment at COSY [1] showed that much of the almost-ubiquitous enhancements for protons were due to the interference of the rf-dipole spin resonance with a nearby intrinsic proton spin resonance. The current deuteron experiment, using an rf dipole, shows that the sevenfold reductions for deuterons are not due to:

- (i) the small  $\Delta f$  sweep used to flip the deuteron spin;
- (ii) the beam's momentum spread;
- (iii) interference with a deuteron intrinsic resonance;
- (iv) a relativistic change in the deuteron's magnetic moment  $\mu_d$  that was precisely measured in Figs. 1 and 4.

We plan to next study this intriguing problem experimentally by using a new rf solenoid to spin-manipulate polarized deuterons.

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- [1] M.A. Leonova *et al.*, Phys. Rev. ST Accel. Beams **9**, 051001 (2006).
  - [2] B.B. Blinov *et al.*, Phys. Rev. Lett. **81**, 2906 (1998); V.A. Anferov *et al.*, in *Proceedings of the 13th International High Energy Spin Physics Symposium, Protvino, 1998*, edited by N.E. Tyurin (World Scientific, Singapore, 1999), p. 503.
  - [3] V.S. Morozov *et al.*, Phys. Rev. ST Accel. Beams **4**, 104002 (2001).
  - [4] M. Froissart and R. Stora, Nucl. Instrum. Methods **7**, 297 (1960).
  - [5] E.D. Courant, Bull. Am. Phys. Soc. **7**, 33 (1962); and Report No. BNL-EDC-45, 1962.
  - [6] B.W. Montague, Phys. Rep. **113**, 35 (1984).
  - [7] D.D. Caussyn *et al.*, Phys. Rev. Lett. **73**, 2857 (1994).
  - [8] D.A. Crandell *et al.*, Phys. Rev. Lett. **77**, 1763 (1996).
  - [9] B. von Przewoski *et al.*, Rev. Sci. Instrum. **67**, 165 (1996).
  - [10] V.A. Anferov *et al.*, Phys. Rev. ST Accel. Beams **3**, 041001 (2000).
  - [11] B.B. Blinov *et al.*, Phys. Rev. ST Accel. Beams **3**, 104001 (2000).
  - [12] A.M.T. Lin *et al.*, in *SPIN 2000: 14th International Spin Physics Symposium*, AIP Conf. Proc. No. 570 (AIP, New York, 2001), p. 736.
  - [13] B.B. Blinov *et al.*, Phys. Rev. Lett. **88**, 014801 (2002); V.S. Morozov *et al.*, in *SPIN 2002: 15th International Spin Physics Symposium and Workshop on Polarized Electron Sources and Polarimeters*, edited by Y.I. Makdisi, A.U. Luccio, and W.W. MacKay, AIP Conf. Proc. No. 675 (AIP, New York, 2003), p. 776.
  - [14] V.S. Morozov *et al.*, Phys. Rev. Lett. **91**, 214801 (2003).
  - [15] K. Yonehara *et al.*, in *Intersections of Particle and Nuclear Physics: 8th Conference; CIPANP2003*, edited by Z. Parsa, AIP Conf. Proc. No. 698 (AIP, New York, 2003), p. 763.
  - [16] M.A. Leonova *et al.*, Phys. Rev. Lett. **93**, 224801 (2004).
  - [17] V.S. Morozov *et al.*, Phys. Rev. ST Accel. Beams **7**, 024002 (2004).
  - [18] V.S. Morozov *et al.*, Phys. Rev. ST Accel. Beams **8**, 061001 (2005).
  - [19] E.D. Courant and R.D. Ruth, BNL Report No. 51270, 1980.
  - [20] S.Y. Lee, *Spin Dynamics and Snakes in Synchrotrons* (World Scientific, Singapore, 1997), p. 79, Eq. (4.85).
  - [21] S.Y. Lee, Phys. Rev. ST Accel. Beams **9**, 074001 (2006).
  - [22] H. Stockhorst and B. Lorentz, COSY Internal Report, 2003.
  - [23] V.S. Morozov *et al.*, Phys. Rev. ST Accel. Beams **8**, 099002 (2005).
  - [24] T. Roser, *Handbook of Accelerator Physics and Engineering*, edited by A. Chao and M. Tigner (World Scientific, Singapore, 2002), p. 153, Eq. (7).

- [25] M. Bai *et al.*, Phys. Rev. ST Accel. Beams **8**, 099001 (2005).
- [26] R. Maier, Nucl. Instrum. Methods Phys. Res., Sect. A **390**, 1 (1997).
- [27] A. Lehrach *et al.*, *Proceedings of 1999 PAC, New York, NY, 1999*, edited by A. Luccio and W. MacKay (IEEE, Piscataway, NJ, 1999), p. 2292.
- [28] H. Stockhorst *et al.*, *Proceedings of the 8th EPAC, Paris, 2002* (EPS-IGA/CERN, Geneva, 2002), p. 629.
- [29] A. Lehrach *et al.*, in SPIN 2002: 15th International Spin Physics Symposium and Workshop on Polarized Electron Sources and Polarimeters (Ref. [13]), p. 153.
- [30] V. Schwarz *et al.*, in *Proceedings of the 13th International High Energy Spin Physics Symposium, Protvino, 1998* (Ref. [2]), p. 560.
- [31] H. Stein *et al.*, At. Energy (N.Y.) **94**, 24 (2003).
- [32] P.D. Eversheim *et al.*, in *Polarization Phenomena in Nuclear Physics: Eighth International Symposium*, edited by E.J. Stephenson and S.E. Vigdor, AIP Conf. Proc. No. 339 (AIP, New York, 1995), p. 668.
- [33] R. Weidmann *et al.*, Rev. Sci. Instrum. **67**, 1357 (1996).
- [34] O. Felden *et al.*, in *Proceedings of the 9th International PST Workshop, Nashville, IN, 2001*, edited by V.P. Derenchuk and B. von Przewoski (World Scientific, Singapore, 2002), p. 200.
- [35] Above the  $\nu_y \approx 3.80$  intrinsic resonance, one had to first sweep  $\nu_y$  through it, since the beam was accelerated at  $\nu_y = 3.60$ ; then  $f_{rf}$  was swept through the interfering rf/intrinsic resonance. Perhaps this contributed to an asymmetry.
- [36] A. M. Kondratenko, SPIN@COSY Internal Report, 2006; *ibid.* 2007; *Proceedings of the 9th International Symposium on High Energy Spin Physics, Bonn, 1990* (Springer-Verlag, Berlin, 1991), p. 140; *Proceedings of the VI Workshop on High Energy Spin Physics, Protvino, 1995* (Institute for High Energy Physics, Protvino, Russia, 1996), p. 207.
- [37] D. W. Sivers *et al.*, SPIN@COSY Internal Report, 2007.