UNEXPECTED ENHANCEMENTS AND REDUCTIONS OF RF RESONANCE STRENGTHS*

M.A. Leonova, A.D. Krisch, V.S. Morozov, R.S. Raymond, D.W. Sivers, V.K. Wong
Spin Physics Center, University of Michigan, Ann Arbor, MI 48109-1120, USA

R. Gebel, A. Lehrach, B. Lorentz, R. Maier, D. Prasuhn, A. Schnase, H. Stockhorst
Forschungszentrum Jülich, Inst. für Kernphysik, Postfach 1913, D-52425 Jülich, Germany

F. Hinterberger, K. Ulbrich
Helmholtz Inst. für Strahlen- Kernphysik, Univ. Bonn, Nussallee 14-16, D-53115 Bonn, Germany

SPIN 2006
Kyoto, Japan
2 October 2006

* This research was supported by grants from the German BMBF Science Ministry.

SPIN MOTION AND SPIN RESONANCES.

- Unperturbed spin motion can be seen as precession of the polarization vector around vertical fields of the ring's dipoles.

- Number of such precessions during one turn around the ring is given by

$$\nu_s = G\gamma,$$

  where G is the particle's gyromagnetic anomaly and γ is its Lorentz energy factor.

- Horizontal rf magnetic fields can cause a spin resonance whenever the rf field's frequency f_r is correlated with the spin precession frequency as:

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

  where f_c is the particle's circulation frequency and k is an integer.

USING AN RF-INDUCED RESONANCE TO SPIN-FLIP THE BEAM'S POLARIZATION.

- Sweeping an rf magnet's frequency through f_r can flip the beam's polarization direction. The Froissart-Stora equation relates the beam's polarization after crossing the resonance P_f to its initial polarization P_i

$$P_f = P_i \left\{ 2\exp\left[-\frac{(\pi\, \varepsilon_{FS}\, f_c)^2}{\Delta f / \Delta t} \right] - 1 \right\},$$

where ε_{FS} is the resonance strength and Δf is the frequency range during the ramp time Δt.

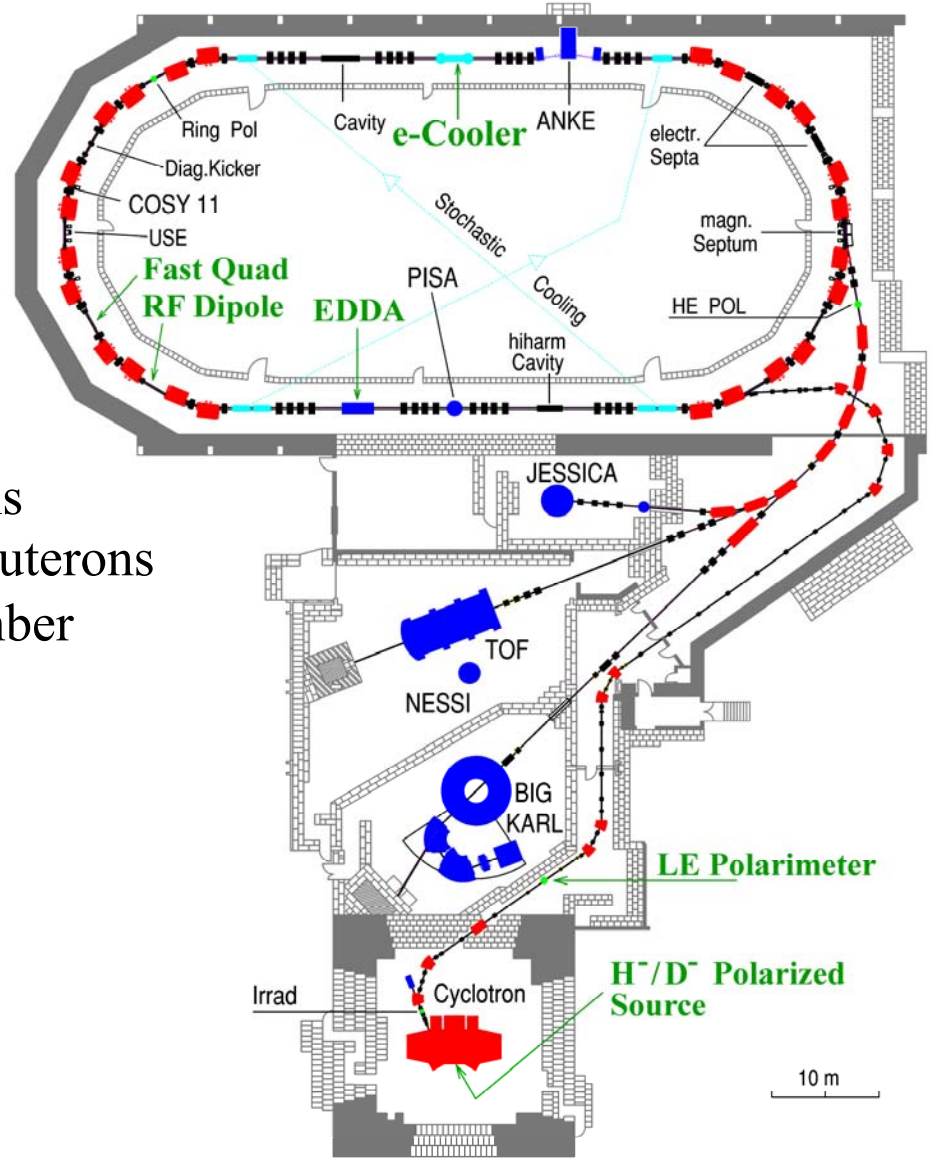
Spin-flip efficiency is then $\eta = \dfrac{-P_f}{P_i}$

- Resonance strength due to dipole $\varepsilon^*_{Bdl} = \dfrac{1}{\pi 2\sqrt{2}} \dfrac{e(1+G\gamma)}{p} \int B_{rms} dl \xrightarrow{\gamma\to\infty} \sim \dfrac{1}{\beta}$

Resonance strength due to solenoid $\varepsilon^*_{Bdl} = \dfrac{1}{\pi 2\sqrt{2}} \dfrac{e(1+G)}{p} \int B_{rms} dl \xrightarrow{\gamma\to\infty} \sim \dfrac{1}{\gamma}$

where e and p are the particle's charge and momentum.

COSY LAYOUT



- 2.1 GeV/c vertically polarized protons or 1.85 GeV/c vertically polarized deuterons
- RF dipole magnet with ceramic chamber
- EDDA detector as a polarimeter
- LE Polarimeter monitoring injection polarization
- H^- source cycled through two polarization states or D^- source cycled through four polarization states

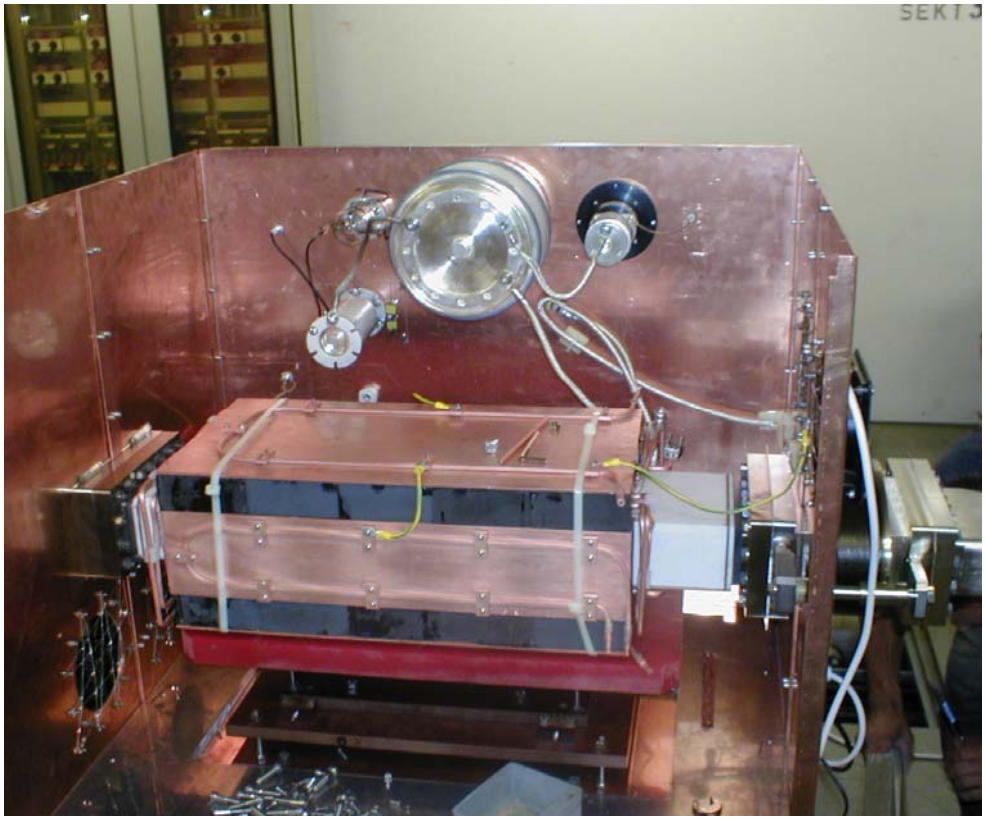
FERRITE RF DIPOLE

It gave

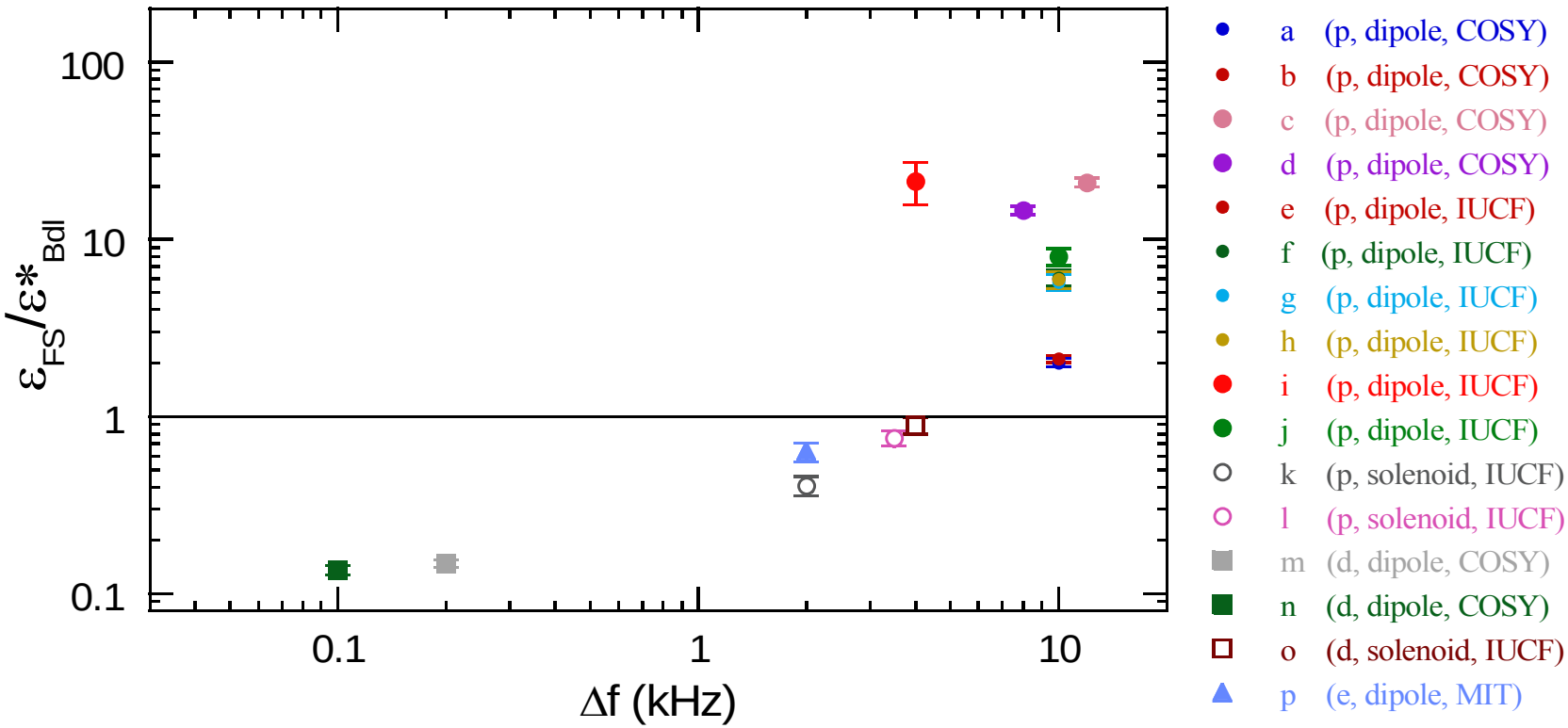
$\int B \cdot dl \sim 0.6$ T·mm r.m.s.

For protons we ran it
near 906 kHz

For deuterons we ran it
near 917 kHz



RESONANCE STRENGTH STUDY
as of November 2004



Ratios of ε_{FS} to ε^*_{Bdl} vs. frequency range Δf used in the Δt curves.

ε_{FS} is resonance strength obtained by fitting data on Δt curves to Froissart-Stora equation,

ε^*_{Bdl} is resonance strengths obtained using rf-magnet's ∫B·dl

The total strength:

$$\varepsilon = \varepsilon_{\beta} + \varepsilon_{\text{dipole}} + \varepsilon_{\text{coh}} = \mathrm{C} + \int \hat{\mathrm{B}} \cdot \mathrm{dl} \left(\mathrm{A} + \frac{\mathrm{D}}{|\nu_{\mathrm{y}} - \nu_{\text{res}} + \mathrm{k}|} \right),$$

where ε_{β} is due to the fields seen during betatron oscillations,

$\varepsilon_{\text{dipole}}$ is due to the rf dipole's field,

ε_{coh} is due to the fields seen during coherent oscillations,

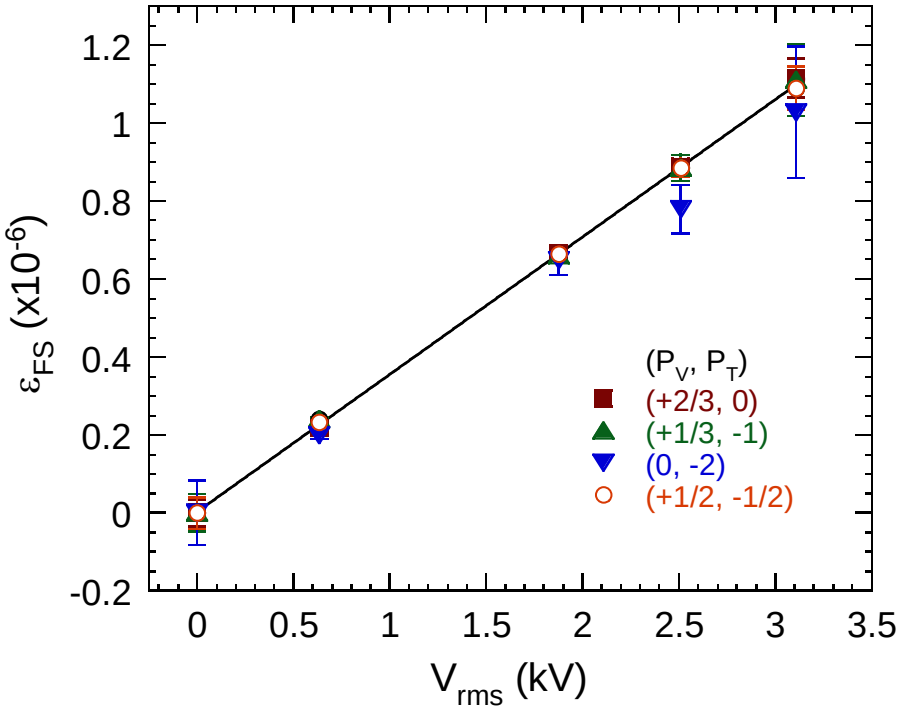
A, C and D are complex constants,

ν_{y} is the vertical betatron tune and ν_{res} is the spin resonance tune

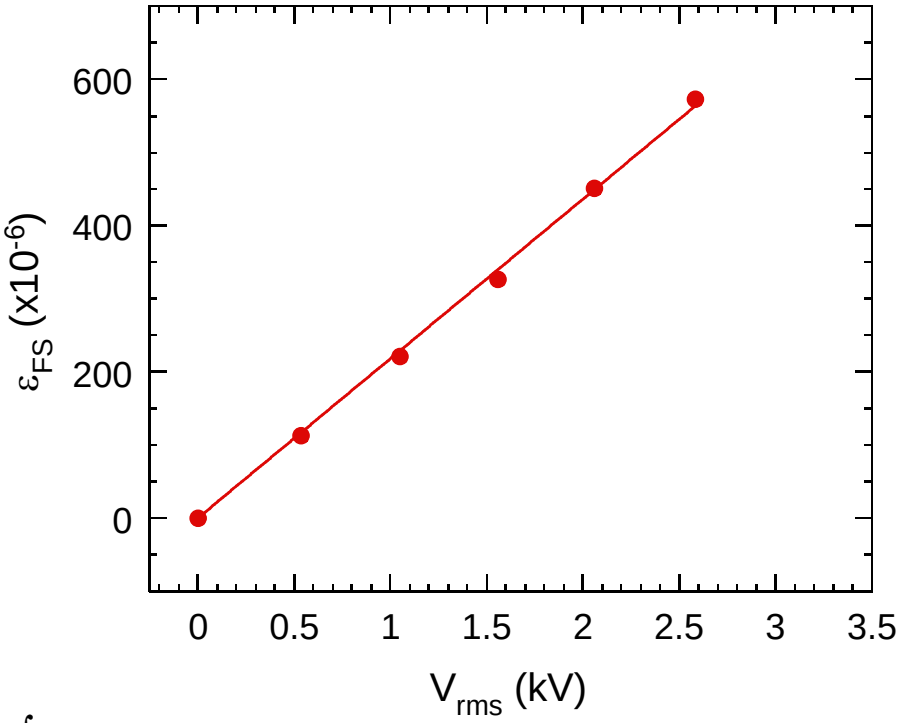
- dependence on dipole strength
- dependence on distance to 1st order spin resonance
- dependence on beam's size
- dependence on beam's momentum spread
- dependence on frequency sweep range Δf for deuterons

RESONANCE STRENGTH vs DIPOLE STRENGTH STUDY

Deuterons
December 04 Run



Protons
November 05 Run



1 kV r.m.s. corresponds to $\int B \cdot dl \sim 0.2$ T·mm r.m.s.

Conclusions: $\varepsilon_\beta = 0$
linear dependence on dipole strength

RESONANCE STRENGTH vs BEAM SIZE STUDY

Ratios of ε_{FS} to ε^*_{Bdl} vs. vertical beam size (FWHM).

ε_{FS} is resonance strength obtained by fitting data on Δt curves to Froissart-Stora equation,

ε^*_{Bdl} is resonance strength obtained using rf-magnet's $\int B \cdot dl$

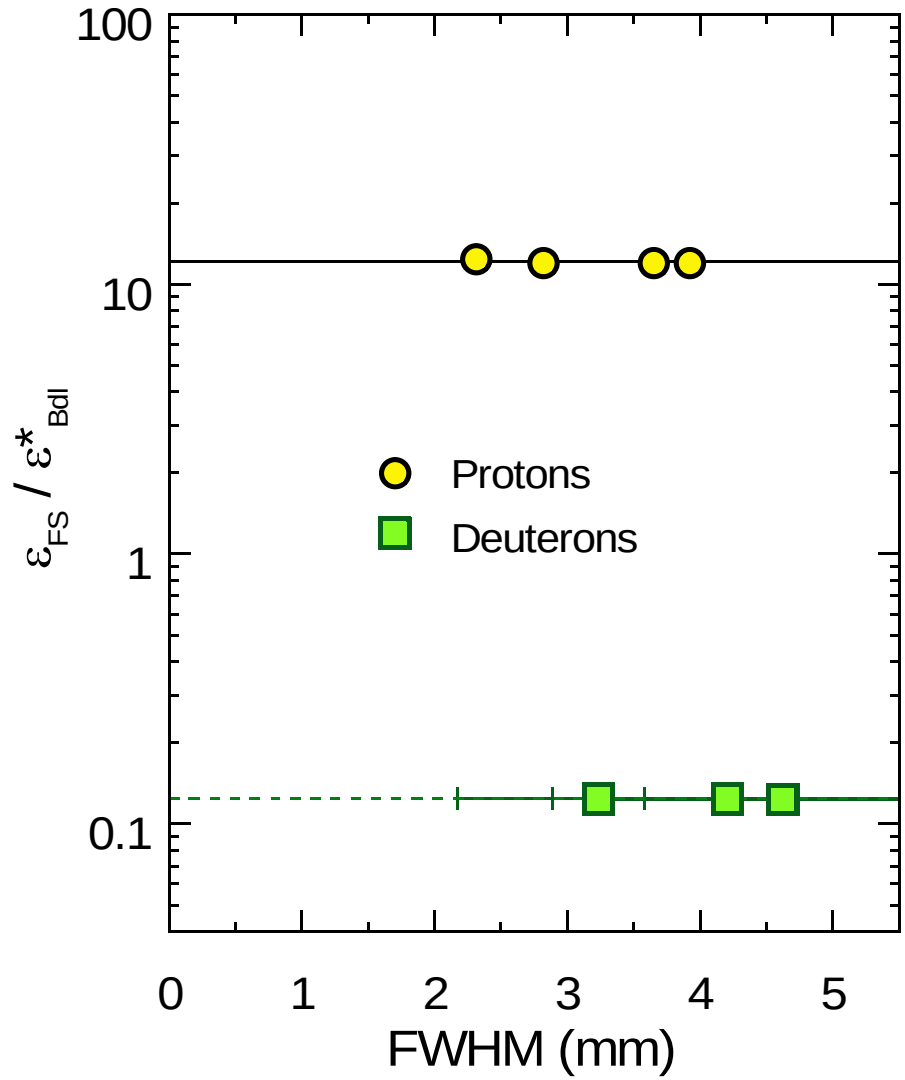
Fit for these data to straight horizontal lines give

December 04 Run

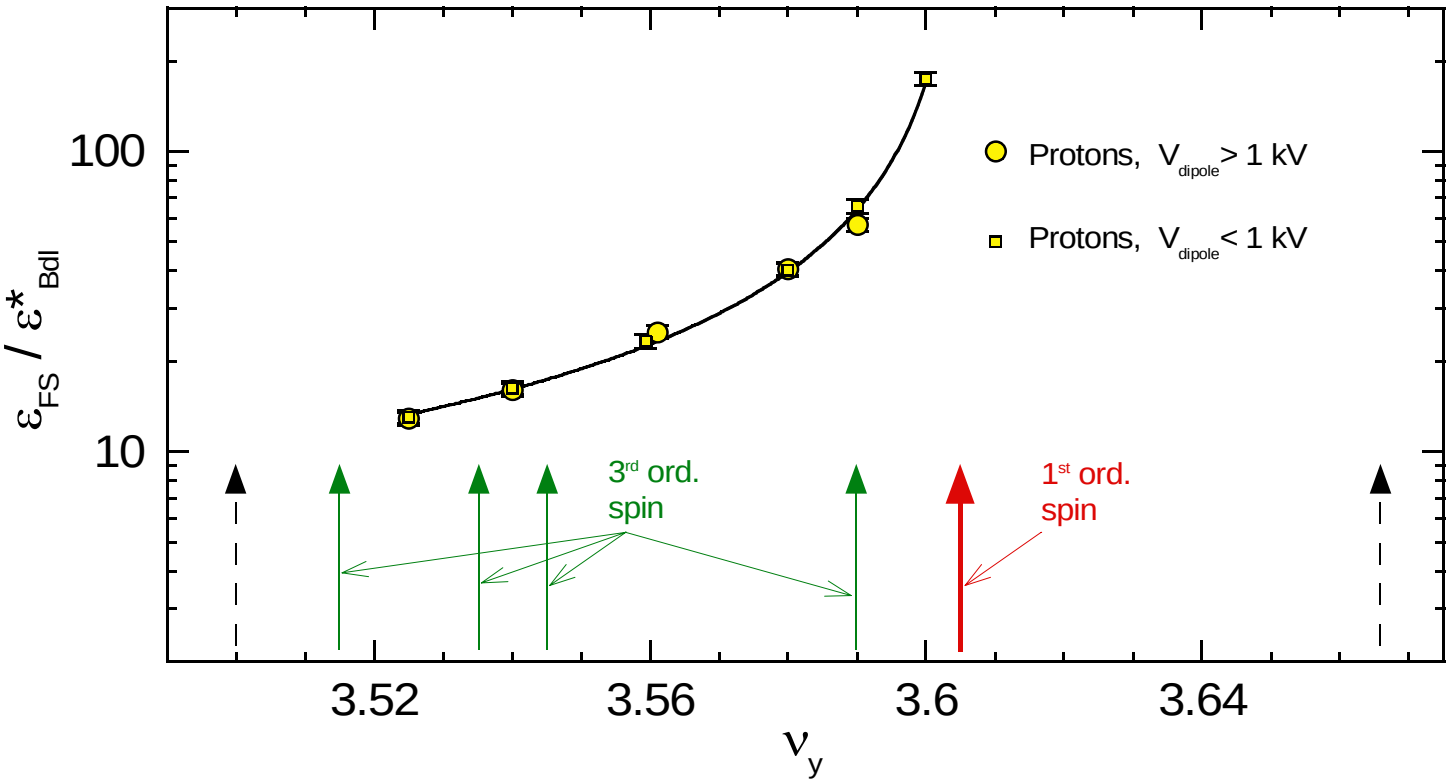
Deuterons $\varepsilon_{FS}/\varepsilon^*_{Bdl} = 0.124 \pm 0.001$

November 05 Run

Protons $\varepsilon_{FS}/\varepsilon^*_{Bdl} = 12.1 \pm 0.1$



PROTON RESONANCE STRENGTH vs ν_y STUDY



November 05 Run

Fit for proton data to a hyperbola

$$\frac{\varepsilon_{FS}}{\varepsilon^*_{Bdl}} = A + \frac{B}{|\nu_y - \nu_{res}|}$$ gives:

$\nu_{res} = 3.6060 \pm 0.0005$ (calculated $\nu_{res} = 3.605$)

$A = 0.9 \pm 0.9$

$B = 1.01 \pm 0.06$

DEUTERON RESONANCE STRENGTH vs ν_y STUDY

May 06 Run

Fit for deuteron data
to an asymmetric hyperbola

$$\frac{\varepsilon_{FS}}{\varepsilon^*_{Bdl}} = \begin{cases} \nu_y < \nu_{res}, & A_L + \dfrac{B_L}{|\nu_y - \nu_{res}|} \\ \nu_y > \nu_{res}, & A_H + \dfrac{B_H}{|\nu_y - \nu_{res}|} \end{cases}$$

gives:

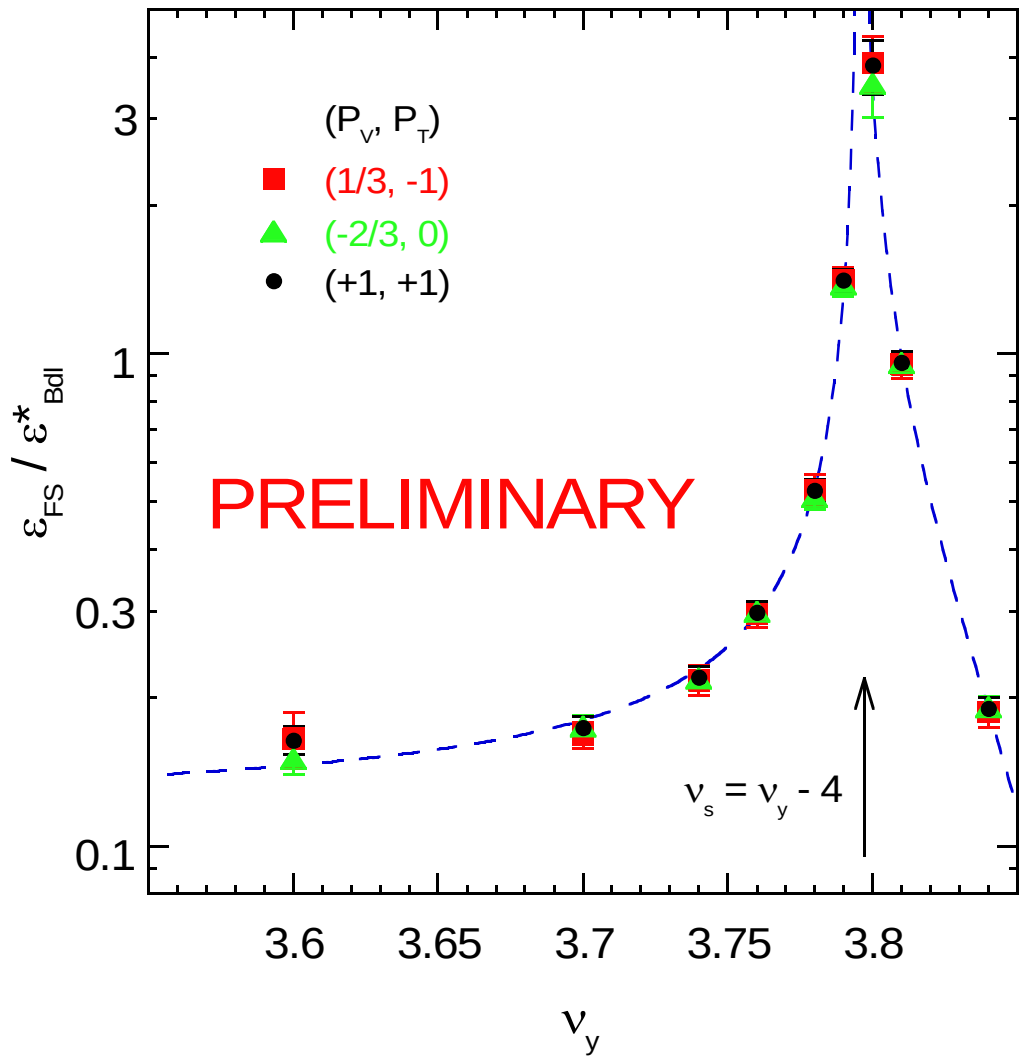
$\nu_{res} = 3.795 \pm 0.002$

for the lower side

$A_L = 0.11 \pm 0.01$
$B_L = 0.006 \pm 0.001$

for the higher side

$A_H = -0.20 \pm 0.04$
$B_H = 0.018 \pm 0.002$



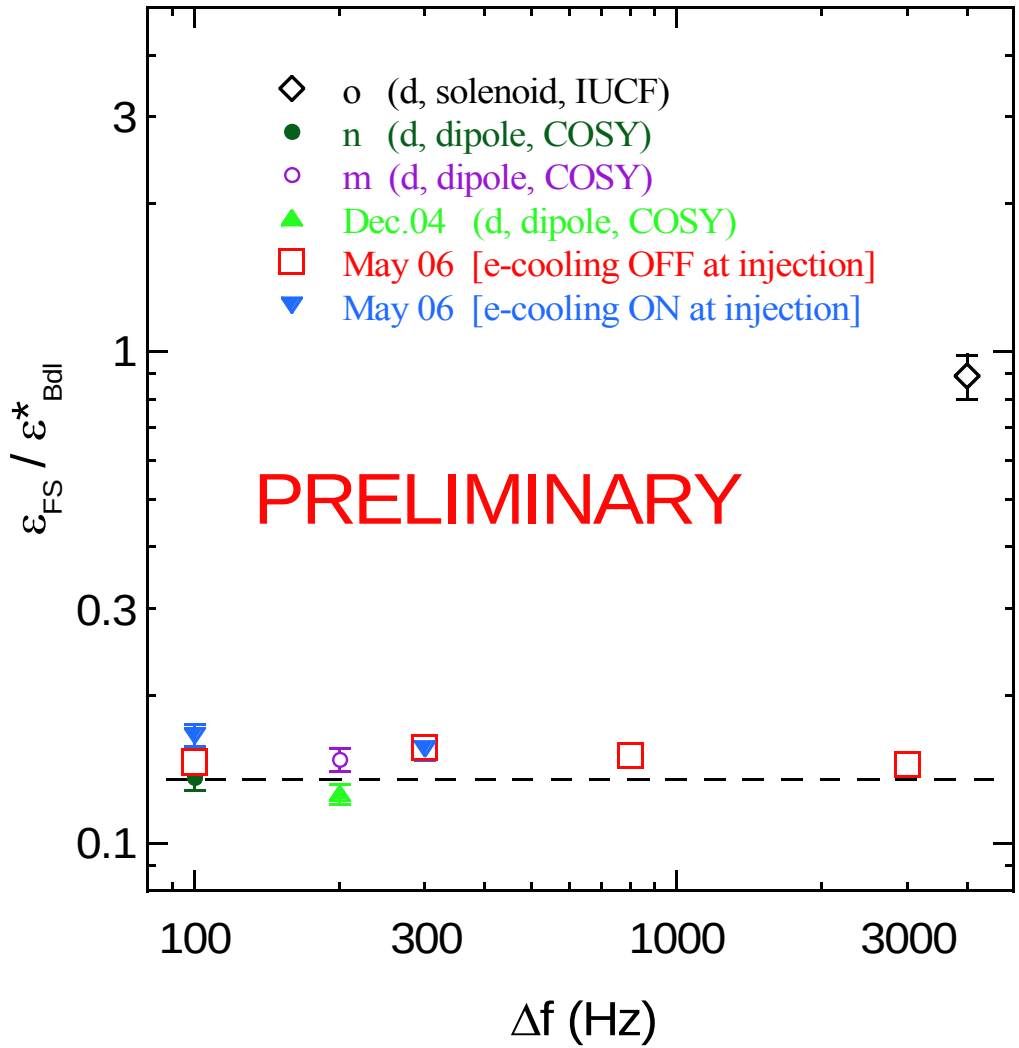
DEUTERON RESONANCE STRENGTH vs FREQUENCY SWEEP RANGE Δf and BEAM'S MOMENTUM SPREAD STUDY

May 06 Run

Fit for dipole data
to a horizontal line

gives

$$\varepsilon_{FS}/\varepsilon^*_{Bdl} = 0.135 \pm 0.008$$



CONCLUSIONS

- We found large deviations of measured rf-induced spin resonance strength from the resonance strength calculated using rf magnet's $\int B \cdot dl$.
- We studied rf spin resonance strength enhancements and reductions for both protons and deuterons using an rf dipole and observed
  - ✓ linear dependence on dipole strength
  - ✓ no dependence on beam's size
  - ✓ no dependence on beam's momentum spread
  - ✓ no dependence on frequency sweep range Δf for deuterons
  - ✓ hyperbolic dependence on distance to 1st order spin resonance
    - ➢ explains strength enhancements for the protons
    - ➢ does not explain strength reductions for deuterons
- We plan to further study the resonance strength to better understand it.