

SPIN MANIPULATING 2 GeV/c POLARIZED PROTONS AND DEUTERONS STORED IN COSY*

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POLARIZATION OF A BEAM OF SPIN-1 DEUTERONS

- A spin-1 particle has three possible **vector** spin states $|P\rangle$ along the vertical axis: $|+1\rangle$, $|0\rangle$, $|-1\rangle$.

- The **vector** polarization is

$$\mathbf{P}_V = \frac{N_+ - N_-}{N_+ + N_0 + N_-}.$$

- The **tensor** polarization is

$$\mathbf{P}_T = 1 - \frac{3N_0}{N_+ + N_0 + N_-},$$

where N_+ , N_0 , and N_- are the number of particles in the $|+1\rangle$, $|0\rangle$, and $|-1\rangle$ states.

SPIN MOTION AND SPIN FLIPPING IN AN ACCELERATOR RING

- Unperturbed spin motion
 - precession of spin-polarization vector around ring's vertical dipole fields.
- Horizontal rf magnetic fields can cause a spin resonance
 - whenever rf field's frequency is correlated with spin precession frequency.
- Sweeping rf magnet's frequency through a spin resonance's frequency
 - can flip the beam's polarization direction.
 - Froissart-Stora formula relates beam's final \mathbf{P}_V^f and initial \mathbf{P}_V^i vector polarizations when crossing resonance

$$\mathbf{P}_V^f = \mathbf{P}_V^i \left\{ 2 \exp \left[- \frac{(\pi \varepsilon f_c)^2}{\Delta f / \Delta t} \right] - 1 \right\}$$

- ε is the resonance strength.
 - f_c is the circulation frequency around the ring.
 - $\Delta f / \Delta t$ is the resonance crossing rate.
 - Δf is the frequency range during the ramp time Δt .
- The spin-flip efficiency is defined as:

$$\eta = \frac{-\mathbf{P}_V^f}{\mathbf{P}_V^i}$$

SPIN-FLIPPING SPIN-1 DEUTERONS

Sweeping rf magnet's frequency through a spin resonance's frequency

- rotates polarization by an angle θ .
- vector and tensor polarizations transform as

$$\mathbf{P}_V(\theta) = \mathbf{P}_V^i \cos \theta, \quad \mathbf{P}_T(\theta) = \mathbf{P}_T^i \left[\frac{3}{2} \cos^2 \theta - \frac{1}{2} \right].$$

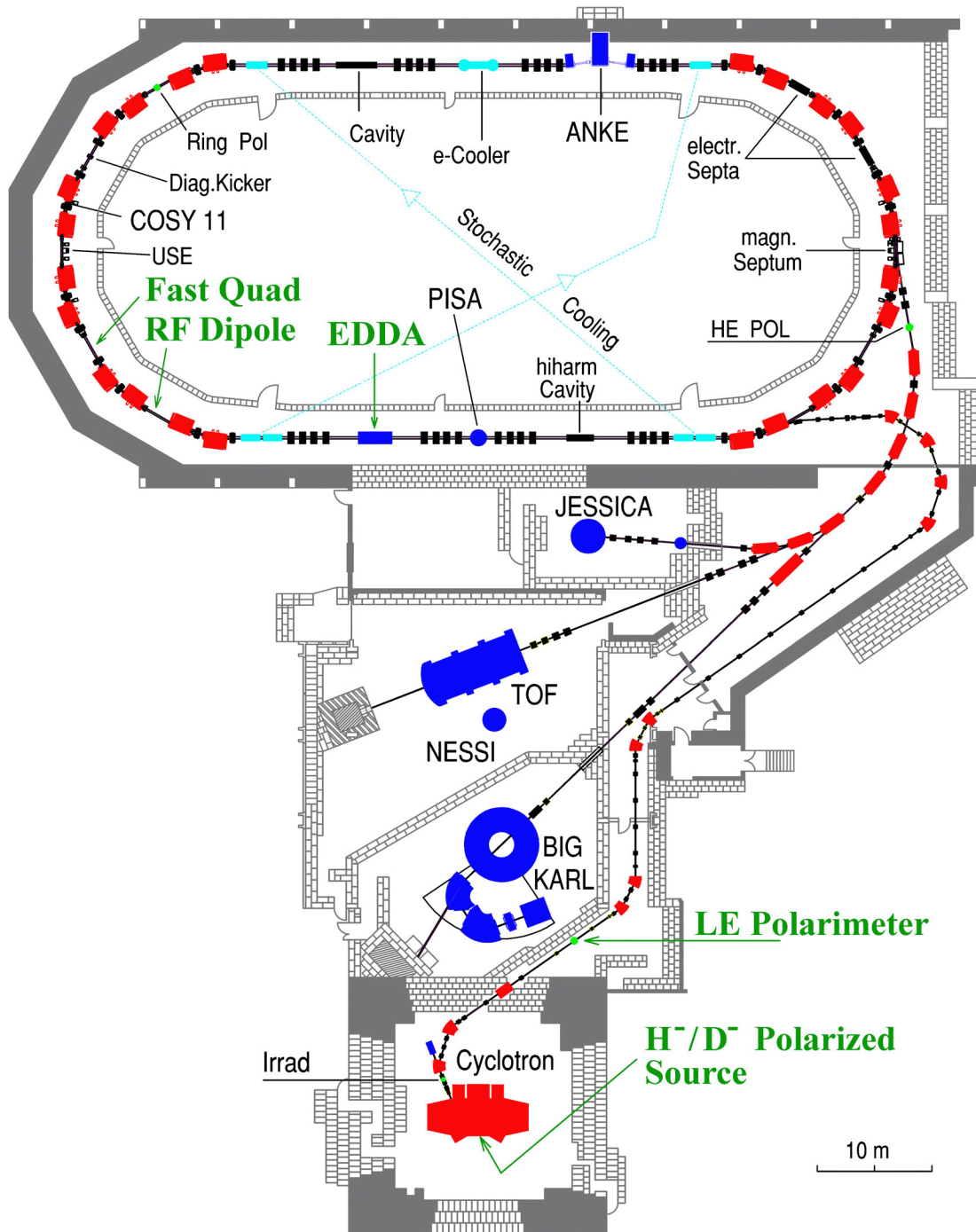
- modified Froissart-Stora formula for vector polarization:

$$\frac{\mathbf{P}_V}{\mathbf{P}_V^i} = (1 + \eta) \exp \left[- \frac{(\pi \epsilon f_c)^2}{\Delta f / \Delta t} \right] - \eta$$

- formula for tensor polarization:

$$\frac{\mathbf{P}_T}{\mathbf{P}_T^i} = \frac{3}{2} \left(\frac{\mathbf{P}_V}{\mathbf{P}_V^i} \right)^2 - \frac{1}{2} = \frac{3}{2} \left\{ (1 + \eta) \exp \left[- \frac{(\pi \epsilon f_c)^2}{\Delta f / \Delta t} \right] - \eta \right\}^2 - \frac{1}{2}$$

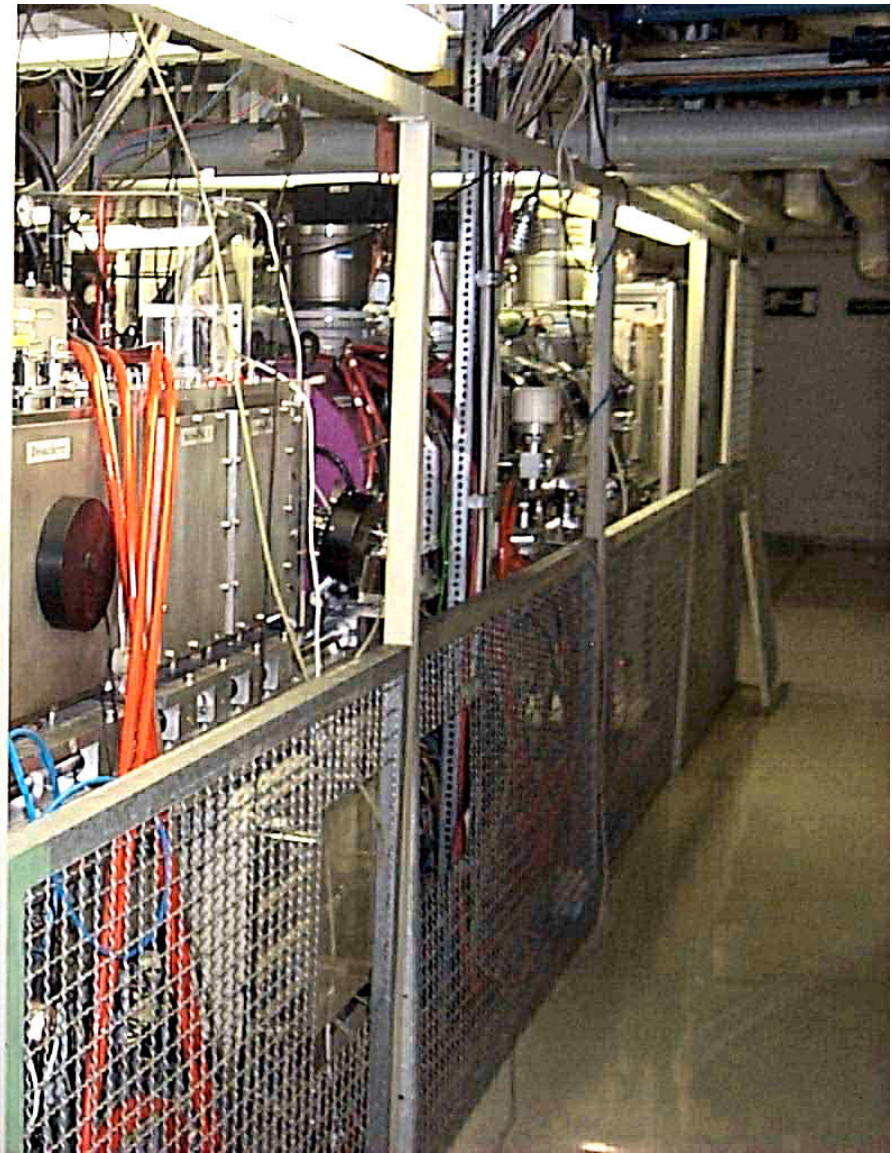
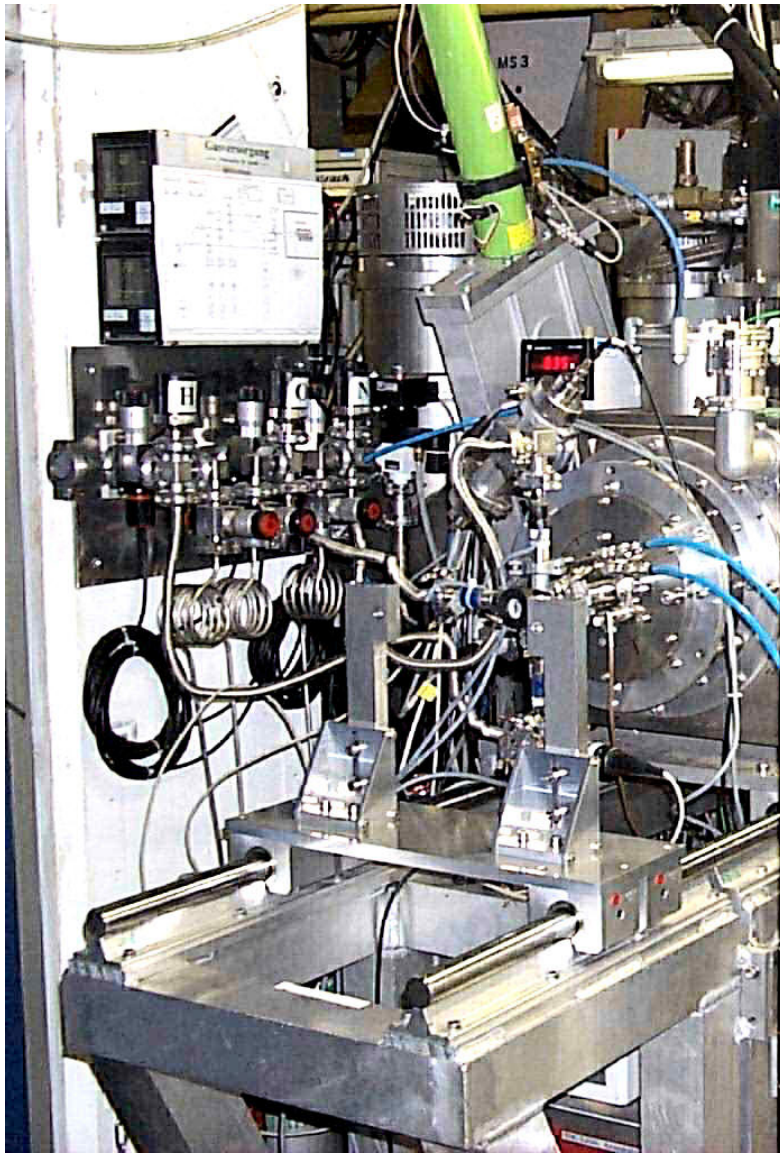
COSY



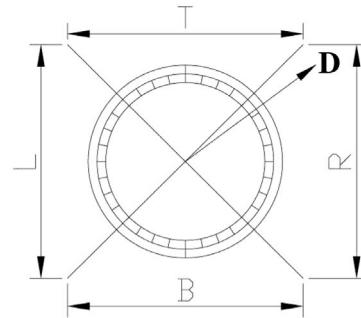
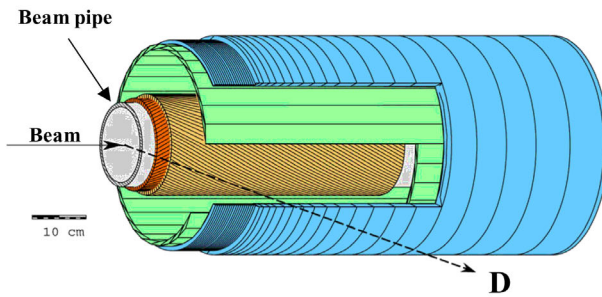
COoler-SYnchrotron COSY



COSY's POLARIZED H⁺/D⁻ ION SOURCE

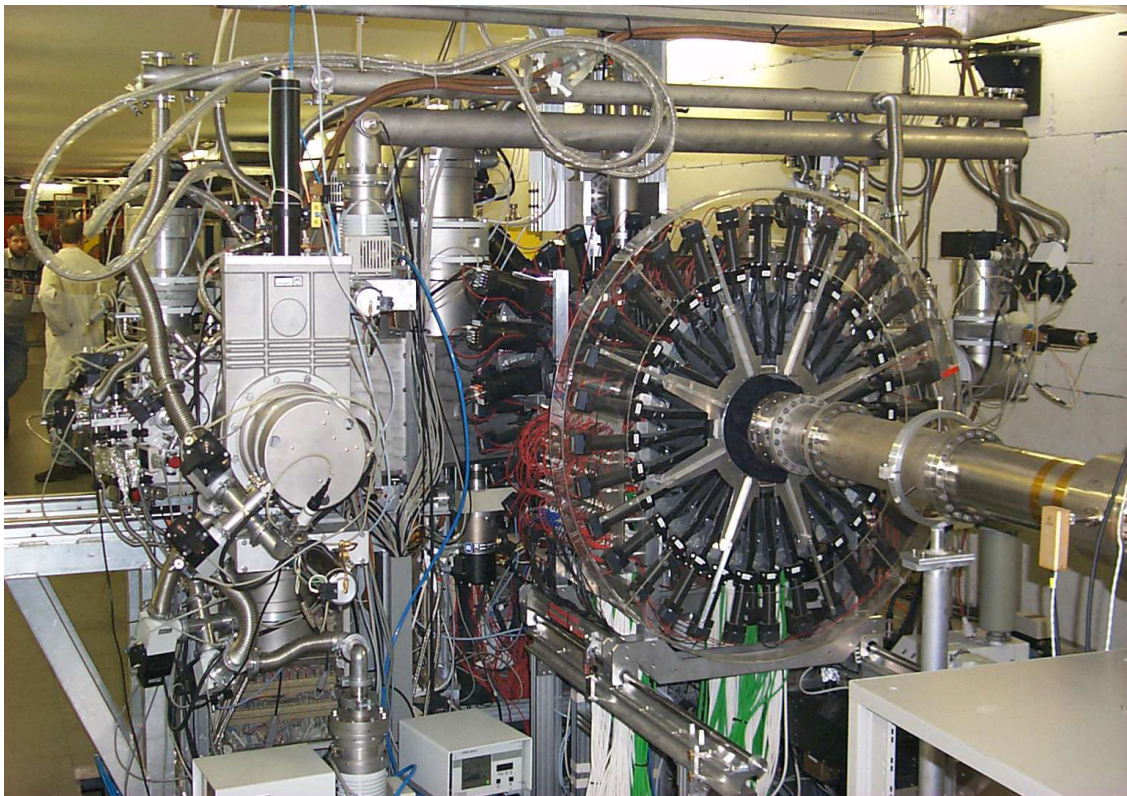


EDDA DETECTOR

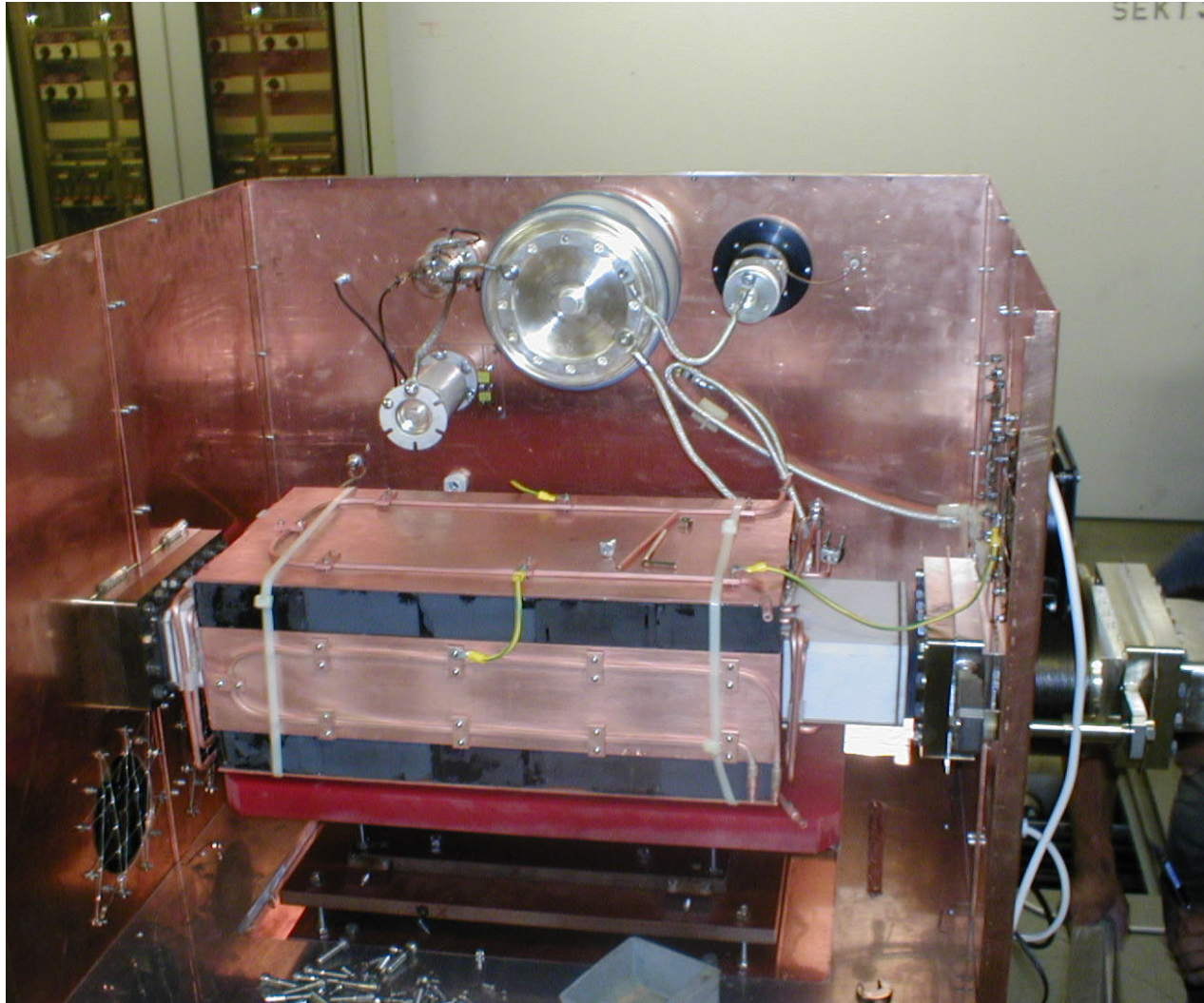


Cross-sectional view of Outer Layer

- two-layered cylindrical scintillator structure
 - Outer Layer (→ trigger!)
 - D**: 32 overlapping slabs of triangular cross-section ($\Delta\phi = 11.25^\circ$)
 - F,R**: 2x29 semirings ($\Delta\theta_{lab} = 2.5^\circ$)
 - left semirings $\phi \in [-90^\circ, 90^\circ]$
 - right semirings $\phi \in [90^\circ, 270^\circ]$
 - Inner Layer (H): 640 scintillating fibers
 - vertex reconstruction ($\sigma \approx 1\text{mm}$)
- Acceptance: $\theta_{lab} \in [10^\circ, 72^\circ]$
- Targets: CH₂ and C fiber targets, polarized H and D atomic beam target.

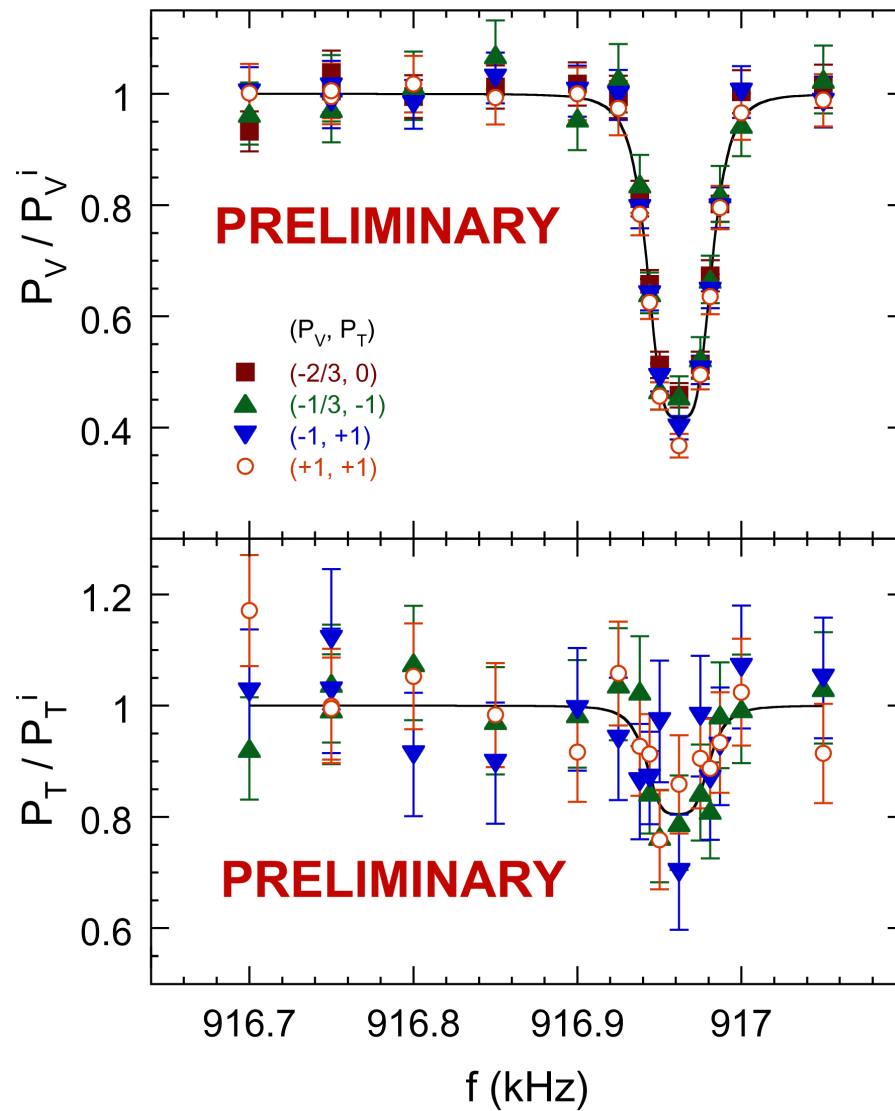


WATER COOLED FERRITE RF DIPOLE



- installed around a ceramic vacuum pipe.
- $\int B_{\text{rms}} \cdot dl = 0.54 \text{ T} \cdot \text{mm}$ at $\sim 916 \text{ kHz}$.

RESONANCE MAP AT FIXED FREQUENCY



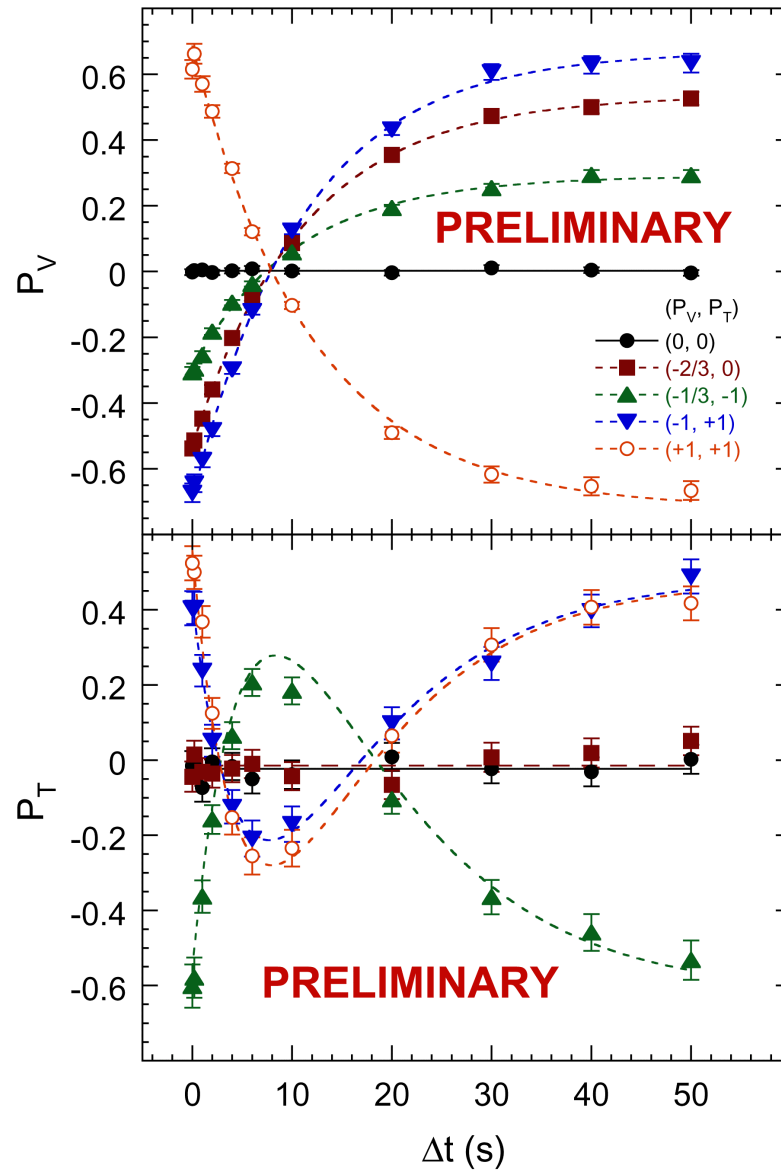
$$f_V = 916.9622 \pm 0.0003 \text{ kHz}$$

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

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

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

SPIN FLIPPING VARYING RAMP TIME



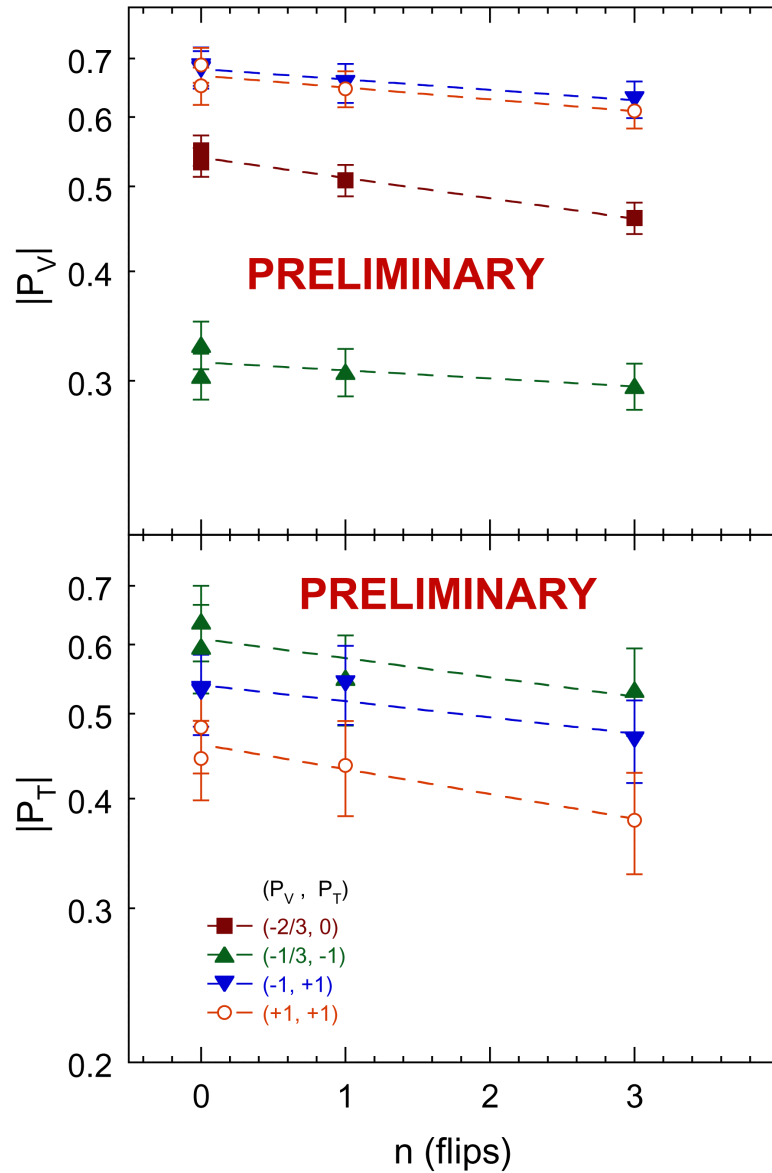
$$\eta_V = 100 \pm 2\%$$

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

$$\eta_T = 100 \pm 2\%$$

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

MULTIPLE SPIN FLIPPING



$$P_V = P_V^i (-\eta)^n$$

$$\eta_V = 96.4 \pm 0.9\%$$

RESULT: $\eta_V = \eta_T \equiv \eta = 97 \pm 1\%$

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

$$\eta_T = 98.3 \pm 0.9\%$$

HIGHER-ORDER SPIN RESONANCES

- **Spin tune** ν_s

- number of spin precessions during one turn around the ring:

$$\nu_s = G\gamma$$

- G is the proton's gyromagnetic anomaly.
- γ is the proton's Lorentz energy factor.

- **Spin resonance**

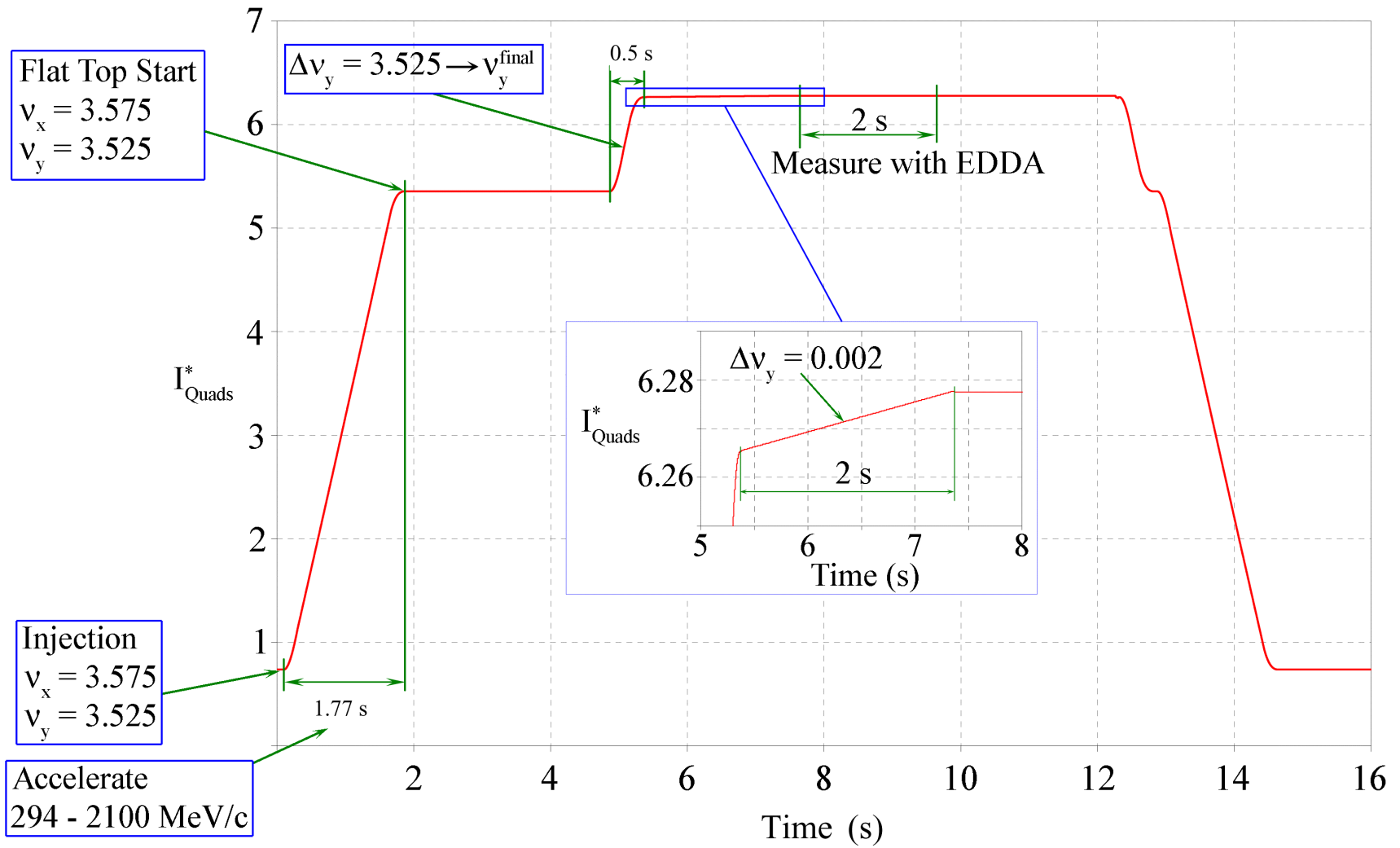
- Occurs when the spin precession frequency is correlated with the betatron oscillation frequency.
- resonance condition

$$\nu_s = k \nu_x + l \nu_y + m$$

- ν_x and ν_y are the horizontal and vertical betatron tunes.
- k , l , and m are integers.

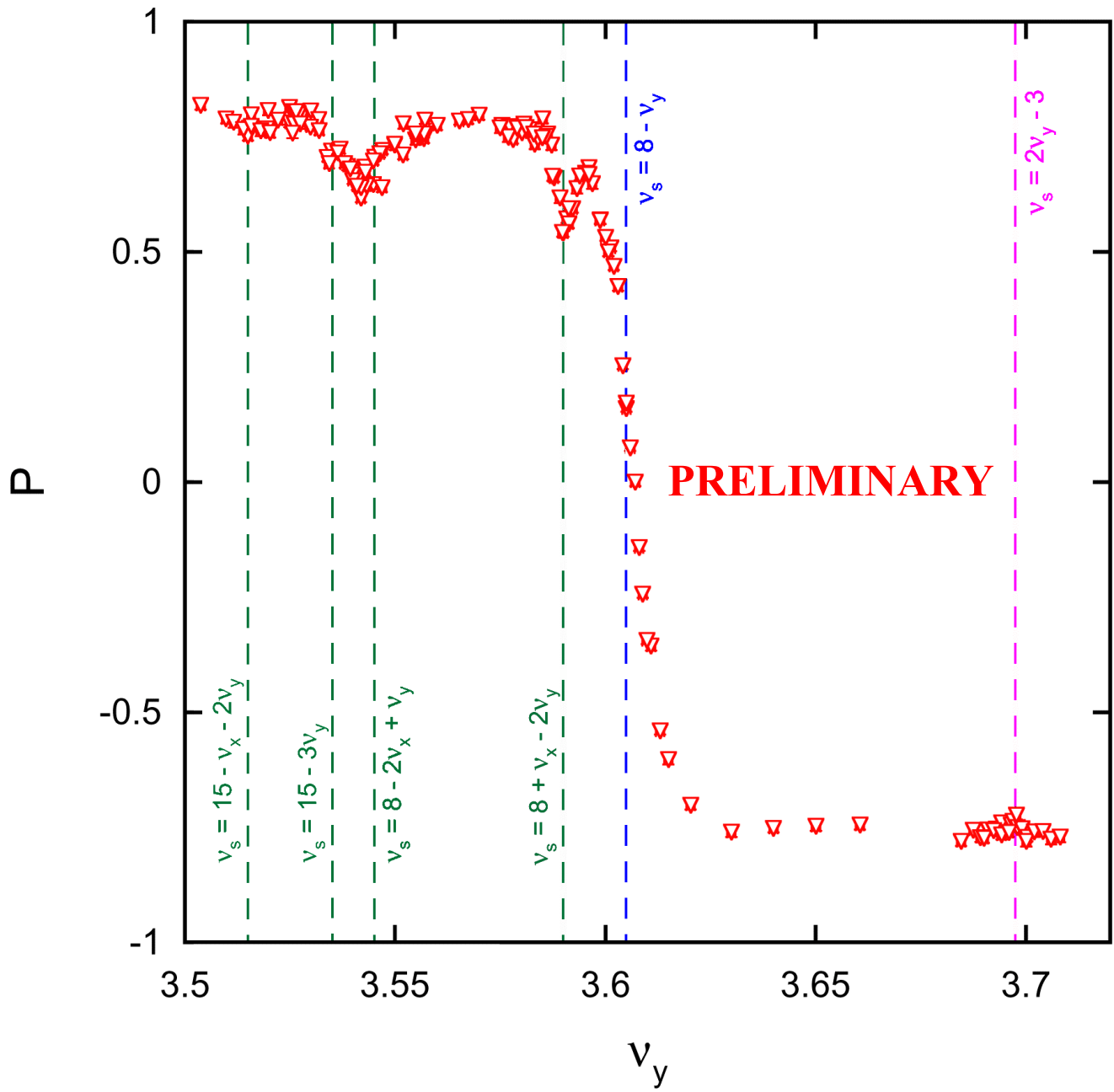
- $|k| + |l| =$ order of the spin resonance.

BETATRON TUNE JUMP CYCLE



* Arbitrary units

VARYING v_y



Spin-Flipping 2.1 GeV/c Polarized Protons Stored in COSY*

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Spin Motion in a Circular Accelerator

- Polarization vector precesses around ring's vertical dipole fields.

- Spin tune = precessions per turn around ring

$$\nu_s = G\gamma$$

where G = proton gyromagnetic anomaly = 1.792847,
 $\gamma = E/m$.

- RF induced spin resonance can occur whenever

$$f_{\text{rf}} = f_c(k \pm \nu_s)$$

where f_{rf} = rf field's frequency,

f_c = circulation frequency around ring,

k = integer.

Spin-flipping

- Froissart-Stora formula

$$P_f = P_i (2e^{-\frac{\pi|\varepsilon|^2}{2\alpha}} - 1),$$

where P_f and P_i = final and initial polarizations,

ε = resonance strength,

α = resonance crossing rate.

- Resonance strength

$$\varepsilon = \frac{1}{\pi\sqrt{2}} \frac{e(1 + G\gamma)}{p} \int \mathbf{B}_{\text{rms}} \cdot d\mathbf{l},$$

where $\int \mathbf{B}_{\text{rms}} \cdot d\mathbf{l}$ = rf dipole's rms magnetic field integral.

- Resonance crossing rate

$$\alpha = \frac{1}{2\pi f_c^2} \frac{\Delta f}{\Delta t}$$

where Δf = frequency range,

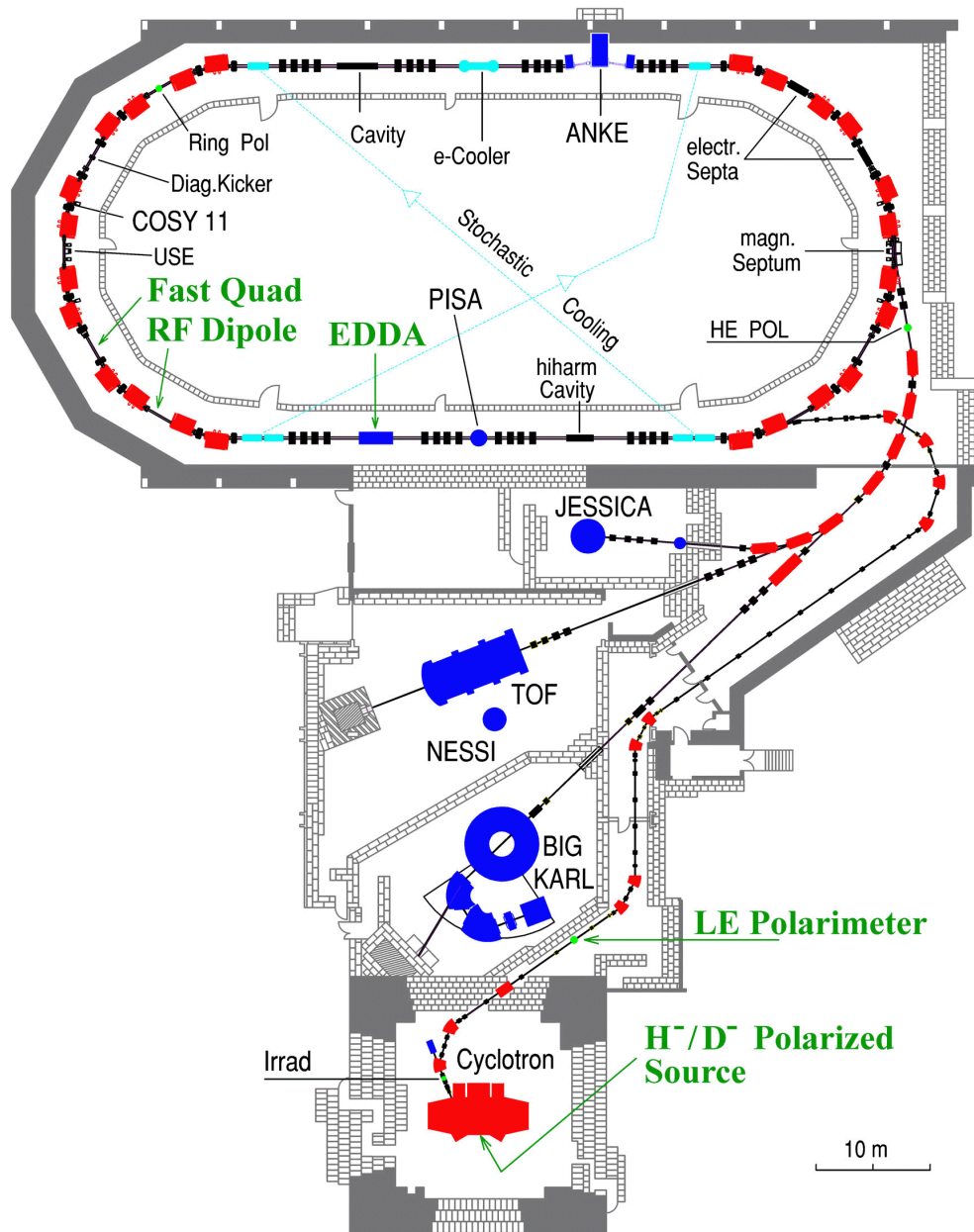
Δt = frequency ramp time.

- If $\frac{\pi|\varepsilon|^2}{2\alpha} \gg 1$ then $P_f \approx -P_i$.

- Spin-flip efficiency

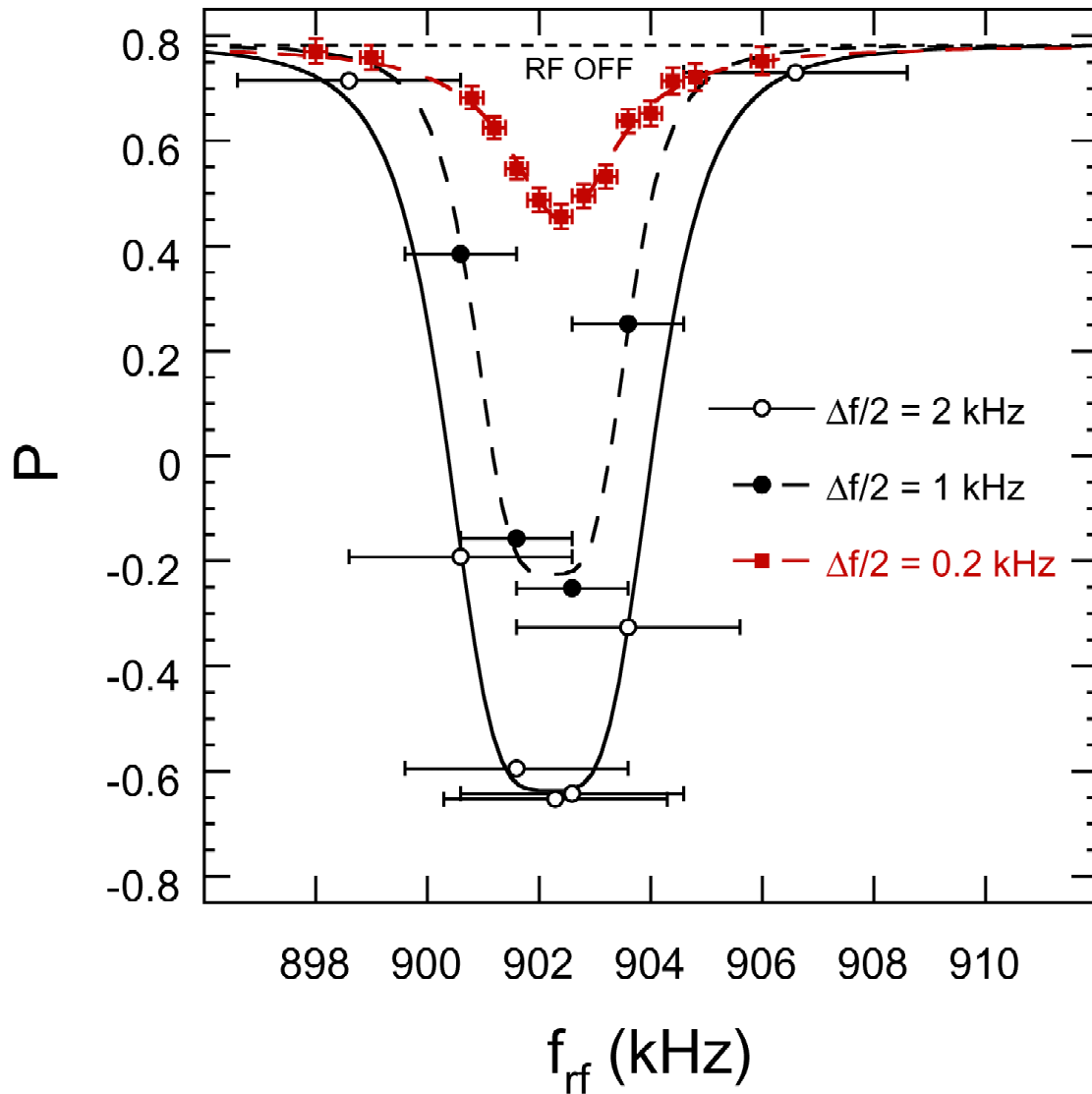
$$\eta = \frac{-P_f}{P_i}.$$

COSY



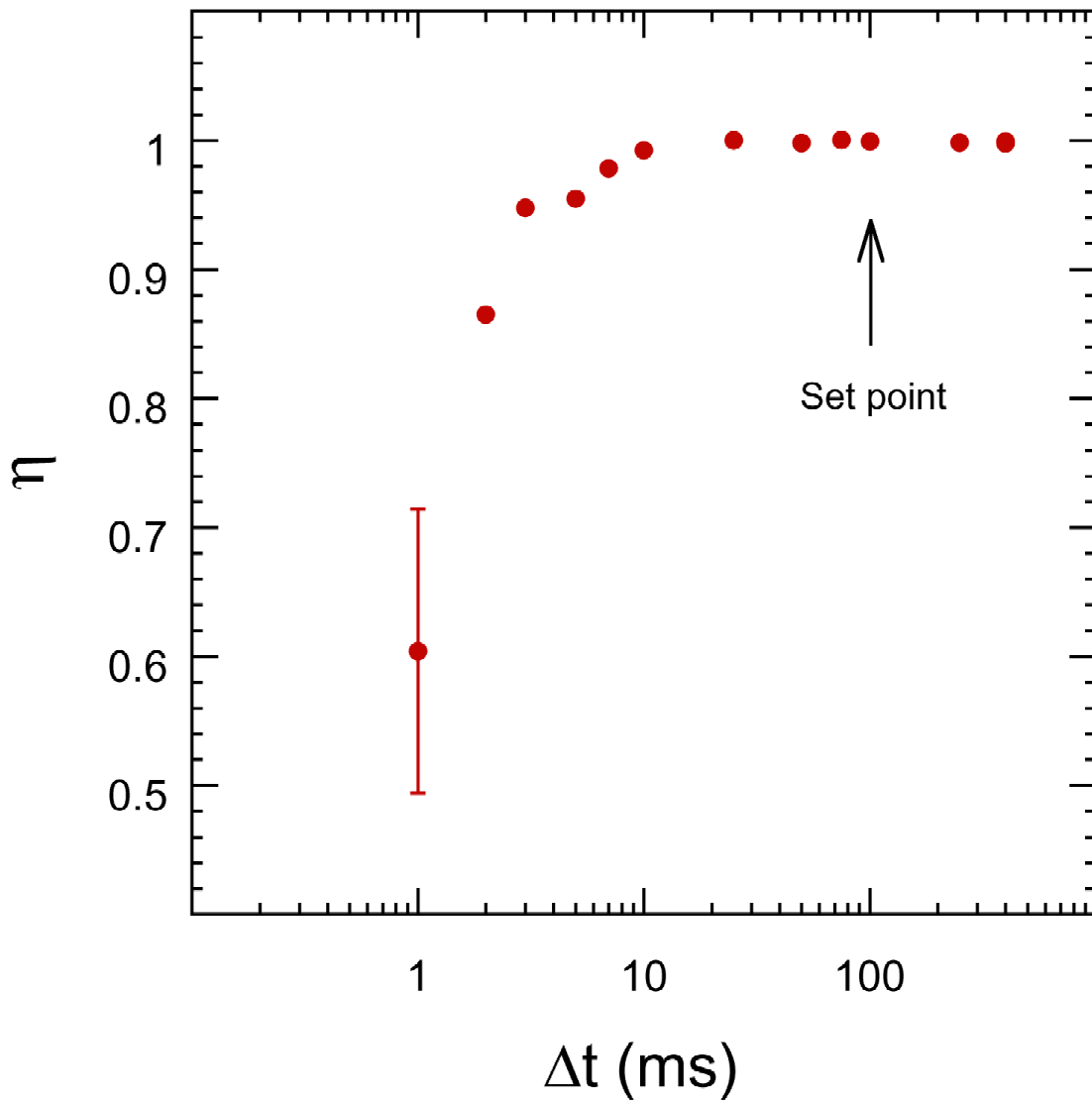
- Proton momentum = 1.94 & 2.1 GeV/c.
- Deuteron momentum = 1.85 GeV/c.
- Ferrite-core rf dipole installed around ceramic pipe.
- EDDA detector as a polarimeter.
- At injection polarization monitored with LE Polarimeter.

Fast Resonance Search



- Fitting $\Delta f / 2 = 0.2$ kHz data to first-order Lorentzian gave:
 $f_{rf} = 902.4 \pm 0.1$ kHz
 $w = 2.4 \pm 0.3$ kHz FWHM

Spin-Flipping by Varying Ramp Time



- rf dipole parameters:
 $V_{\text{rms}} = 2.4 \text{ kV}$
 $\Delta f/2 = 6 \text{ kHz}$

April 2003 Run Result at 1.94 GeV/c

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Spin manipulation of 1.94 GeV/c polarized protons stored in the COSY cooler synchrotron

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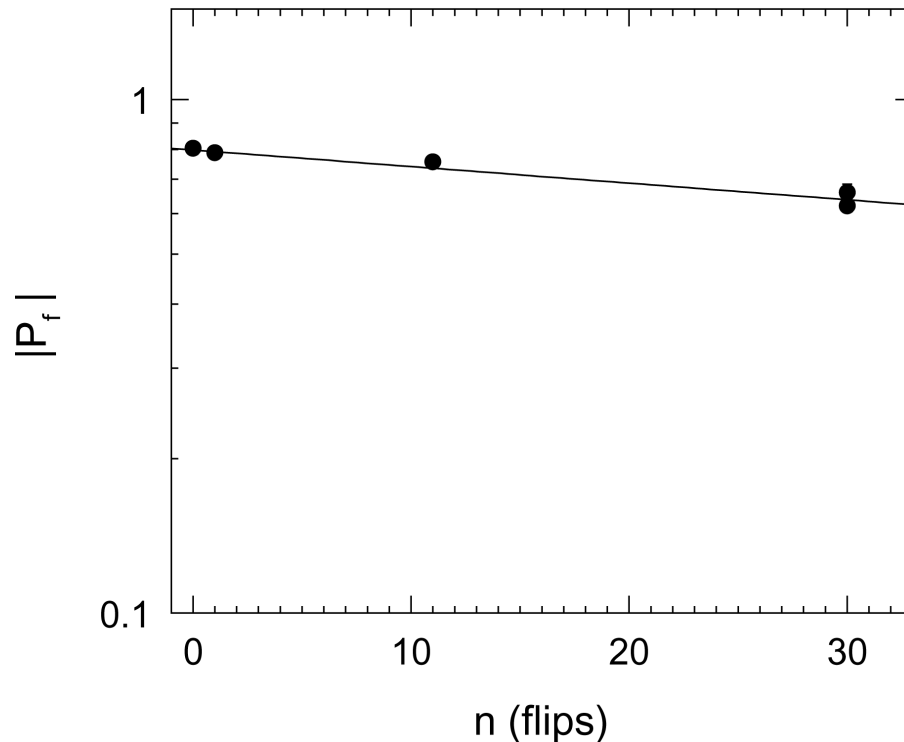
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We recently studied spin flipping of a 1.94 GeV/c vertically polarized proton beam at COSY in Jülich, Germany. We swept an rf-dipole's frequency through an rf-induced spin resonance to flip the beam's polarization direction. After determining the resonance's frequency, we varied the dipole's strength, frequency range, and frequency ramp time. At the rf-dipole's maximum strength, and optimum frequency range and ramp time, we measured a spin-flip efficiency of $99.3\% \pm 0.1\%$. This result indicates that an rf dipole may allow efficient spin flipping in high energy proton rings.

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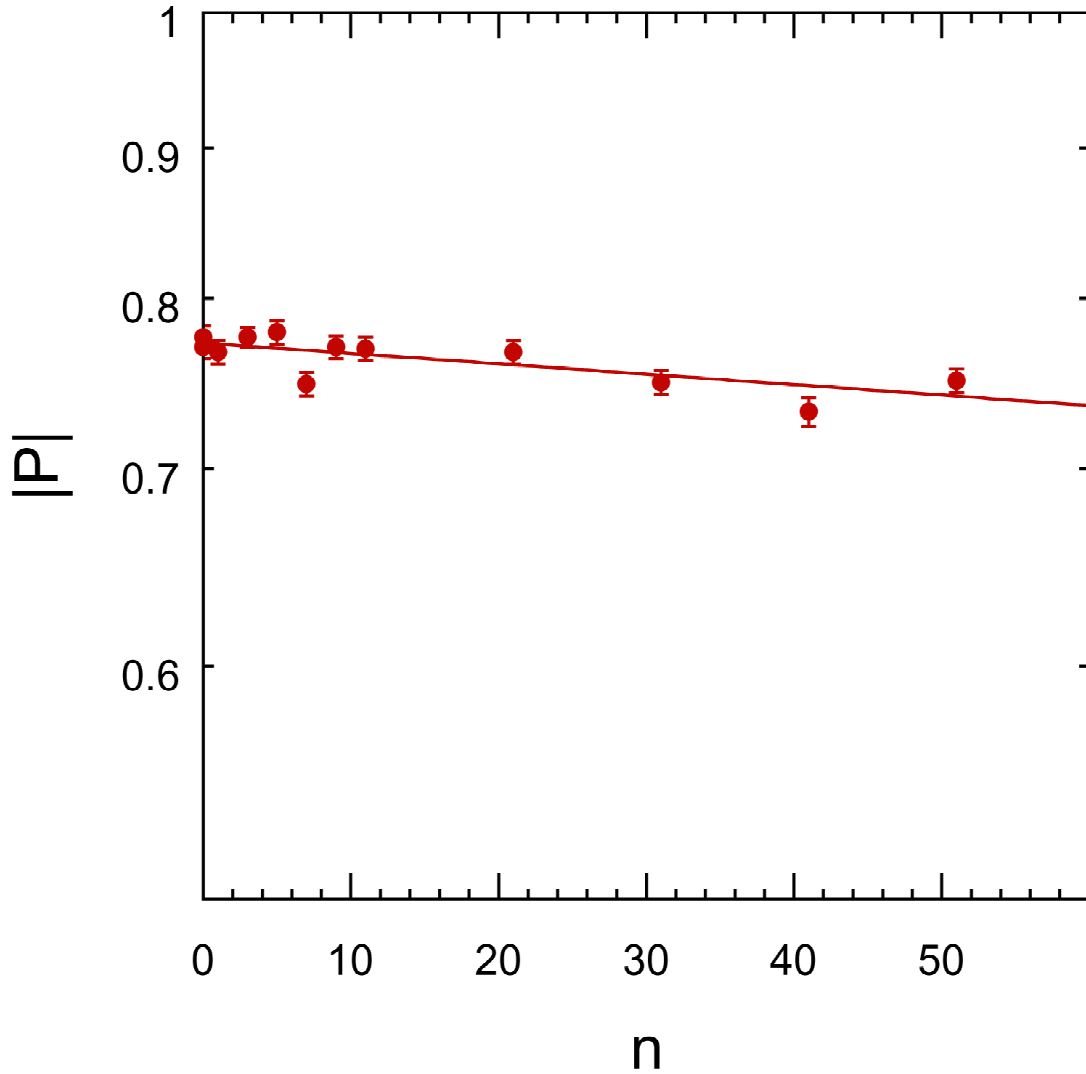
PACS numbers: 29.27.Bd, 29.27.Hj, 41.75.Ak



- Frequency sweep parameters:
 $\Delta f/2 = 4 \text{ kHz}$
 $\Delta t = 10 \text{ sec}$
- Fit to $P_f = P_i(-\eta)^n$ gives $\eta = 99.3 \pm 0.1\%$.

Spin-Flipping by Varying Number of Flips

(accepted by PRL)



- Frequency sweep parameters:
 $\Delta f/2 = 6 \text{ kHz}$
 $\Delta t = 0.1 \text{ sec}$
- Fit to $P_f = P_i(-\eta)^n$ gives $\eta = \mathbf{99.92 \pm 0.04\%}$.

Conclusions

- We used an rf-induced spin resonance to flip the polarization of a stored proton beam.
- With a stronger water-cooled ferrite-core rf dipole we achieved higher spin-flip efficiency with a faster ramp time.
- We flipped the polarization 51 times with most of the polarization preserved.
- We measured a spin-flip efficiency of $\eta = 99.92 \pm 0.04\%$.
- Our small rf dipole's $\int B dl$ may only need to be increased by **35%** for more than **99%** proton spin-flip efficiency at **100 GeV RHIC** or even **7 TeV LHC**.