# Investigation of the Spin Coherence Time for measuring the Electric Dipole Moment of protons in the COSY COoler SYnchrotron

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DAONING GU on behalf of the JEDI collaboration

RWTH AACHEN UNIVERSITY JÜLICH Forschungszentrum GSI

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# MOTIVATION

## Matter-antimatter asymmetry

- Predominance of matter over antimatter in the Universe

- Sakharov conditions (1967):

1. Baryon number violation
2. Non thermal equilibrium
3. Violation of $\mathcal{C}$ and $\mathcal{CP}$ symmetry

- Baryon-to-photon ratio: $\frac{n_B - n_{\bar{B}}}{n_\gamma}$

| Baryon-to-photon ratio | |
|---|---|
| Observation | $\approx 6\times10^{-10}$ |
| Theory (SMC) | $\leq 10^{-18}$ |

# MOTIVATION

## ELECTRIC DIPOLE MOMENT (EDM)

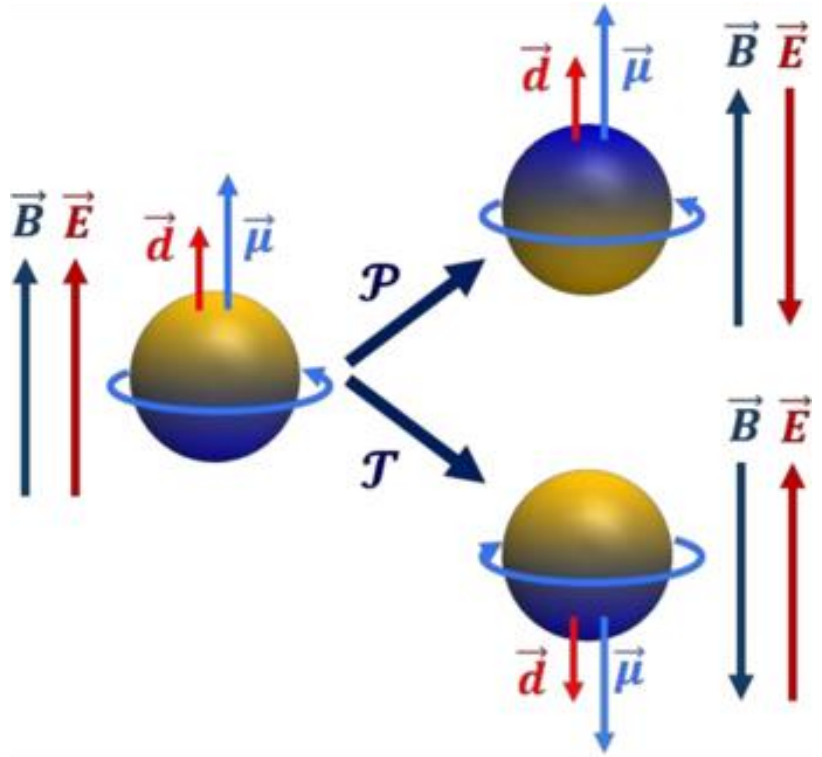
- EDM: Permanent separation of positive and negative charge

- non-zero EDM violates both parity $\mathcal{P}$ and time reversal $\mathcal{T}$ symmetry ($\mathcal{CP}$ violation)

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$$\mathcal{P}: \ \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

$$\mathcal{T}: \ \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$



# SPIN DYNAMICS

## Spin Precession

- Storage ring EDM experiments
- Longitudinally polarized beam: $\vec{S} \parallel \vec{p}$
- Interaction of a particles' spin with electromagnetic fields
- non-zero EDM results in a vertical polarization build up

- Thomas-BMT Equation:

  (pure magnetic field)

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\Omega = \frac{q}{m}\left[G\vec{B} + \underbrace{\frac{\eta}{2}\vec{\beta} \times \vec{B}}_{\text{EDM}}\right]$$

$\Omega$: angular precession frequency

G: anomalous magnetic moment

# SPIN COHERENCE TIME (SCT)

- Spin tune $\nu_s = G\gamma$ :

number of spin precessions per turn

Critical parameter:

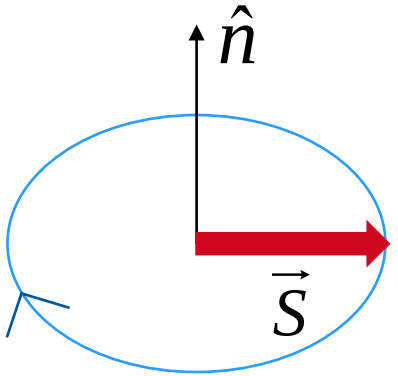
- Spin Coherence Time (SCT):

time after which polarization drops to 1/e of initial value.

- SCT > 1000 s

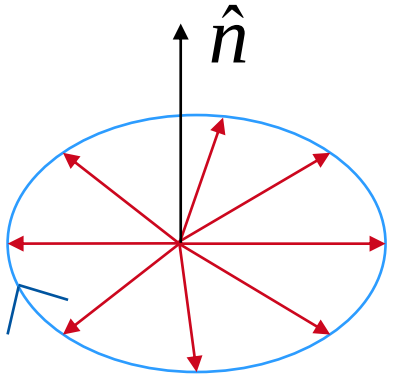
(Achieved at COSY for deuterons, 2016)

Horizontally polarized




At injection

unpolarized




After some time

# SPIN TUNE DECOHERENCE

- Spin tune spread $\Delta\nu_s = G\Delta\gamma$
- First order effect: momentum spread $\frac{\Delta p}{p_0}$.
- Second order effects: path length change & intrinsic resonances.
- The path length change due to:
  1. betatron motion: $\left(\frac{\Delta L}{L}\right)_\beta = \frac{2\pi}{L}\left(\varepsilon_x\xi_x + \varepsilon_y\xi_y\right)$
  2. momentum deviation: $\left(\frac{\Delta L}{L}\right)_\alpha = \alpha_0\left(\frac{\Delta p}{p_0}\right) + \alpha_1\left(\frac{\Delta p}{P_0}\right)^2 + \cdots$
- Path length changes ΔL → 0.
- Two optimization approaches.

# COSY COoler SYnchrotron

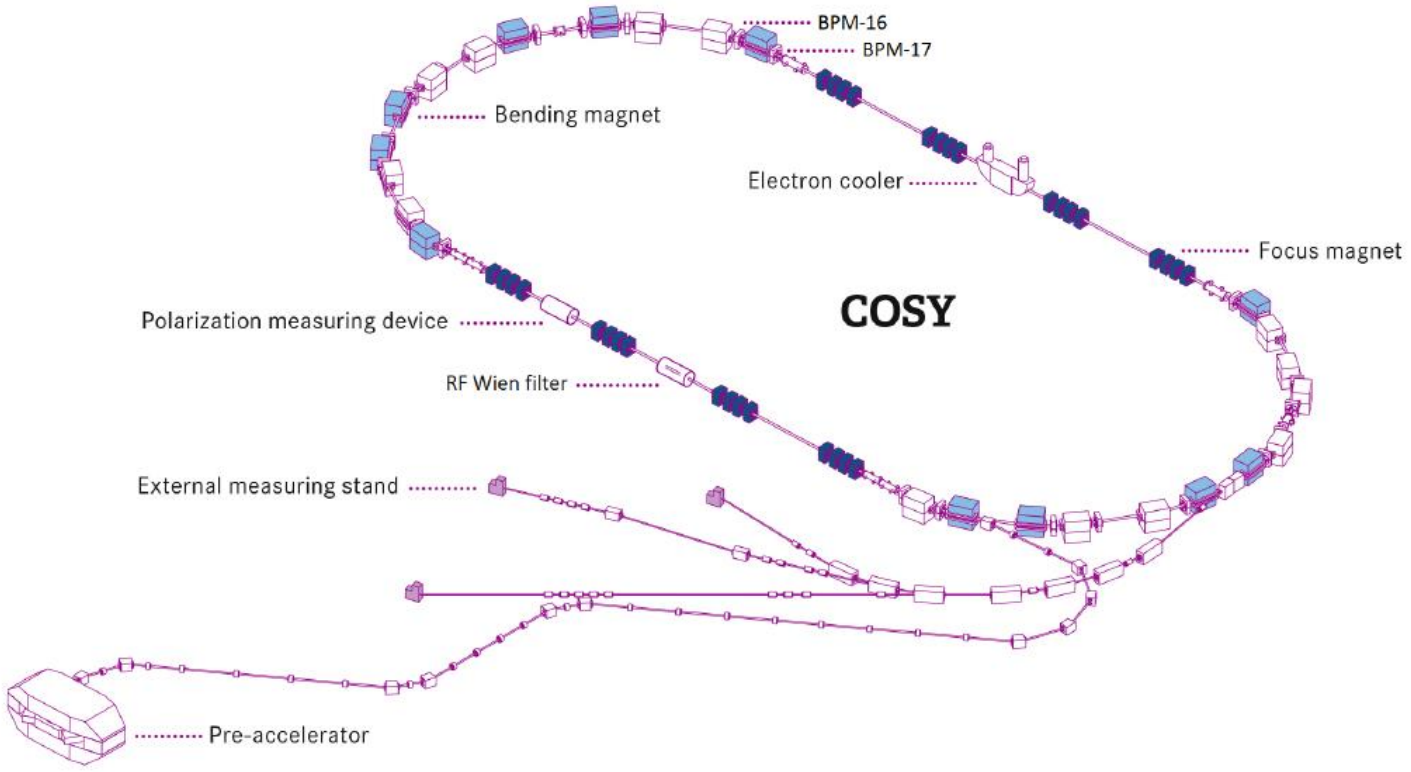
- Circumference: 184 m
- Polarized protons and deuterons
- Current experiment uses protons :

  p = 531 MeV/c

- Electron cooling system:

1. Reducing momentum spread
2. Reducing emittance

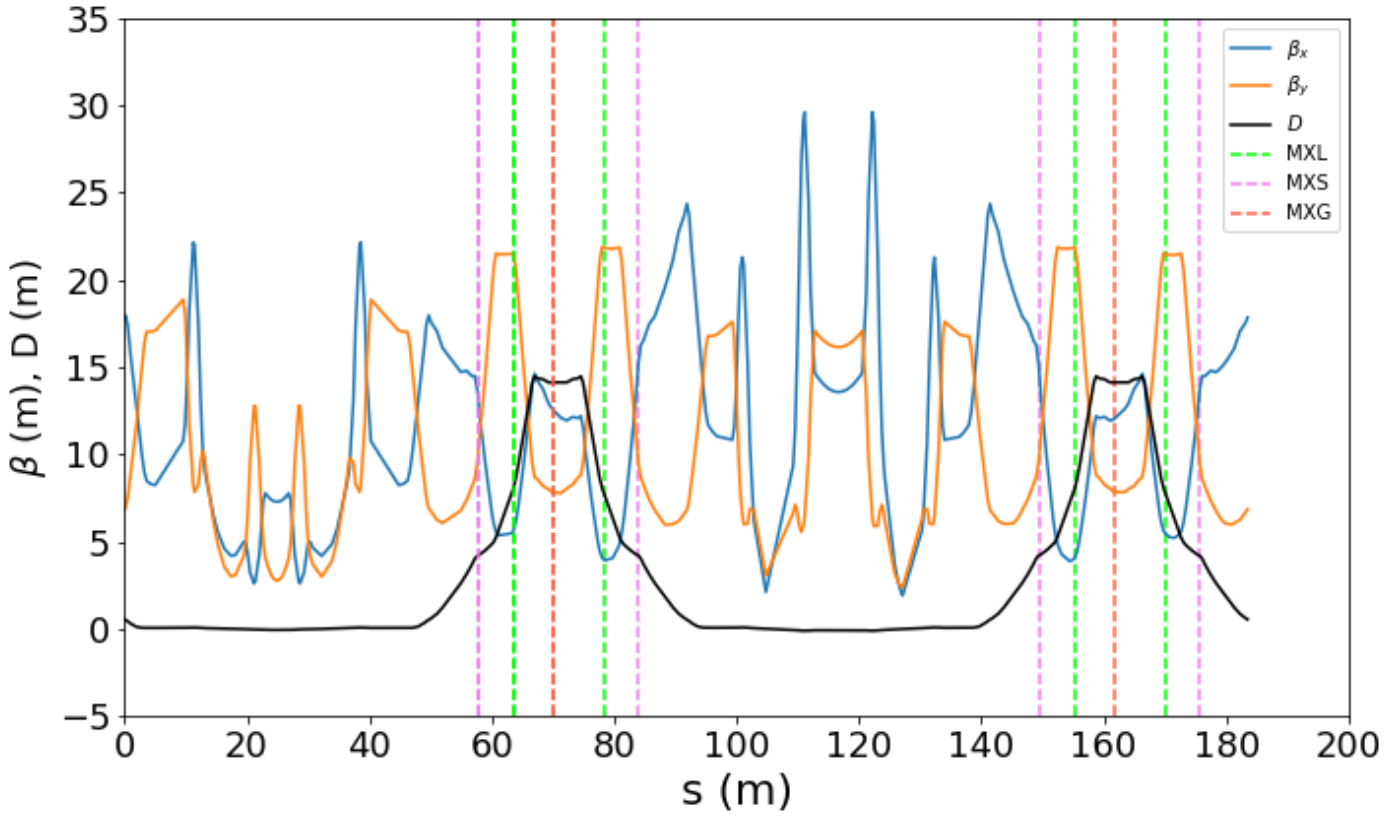
Improve SCT !



# COSY LATTICE

- Software library BMAD
- Idealized COSY lattice
- $Q_x = 3.63$, $Q_y = 3.72$

- Three groups of sextupole:
  1. MXS: large βx
  2. MXL: large βy
  3. MXG: large dispersion D

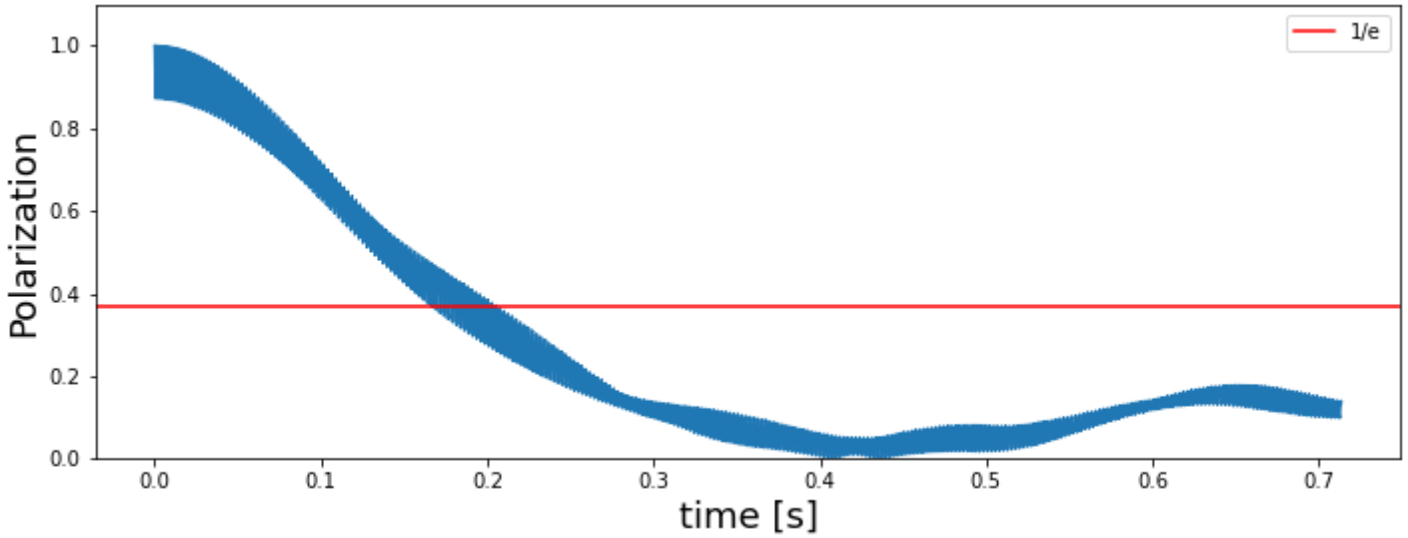


# ZERO CHROMATICITIES

$(\xi_x, \xi_y) = (\mathbf{0}, \mathbf{0})$

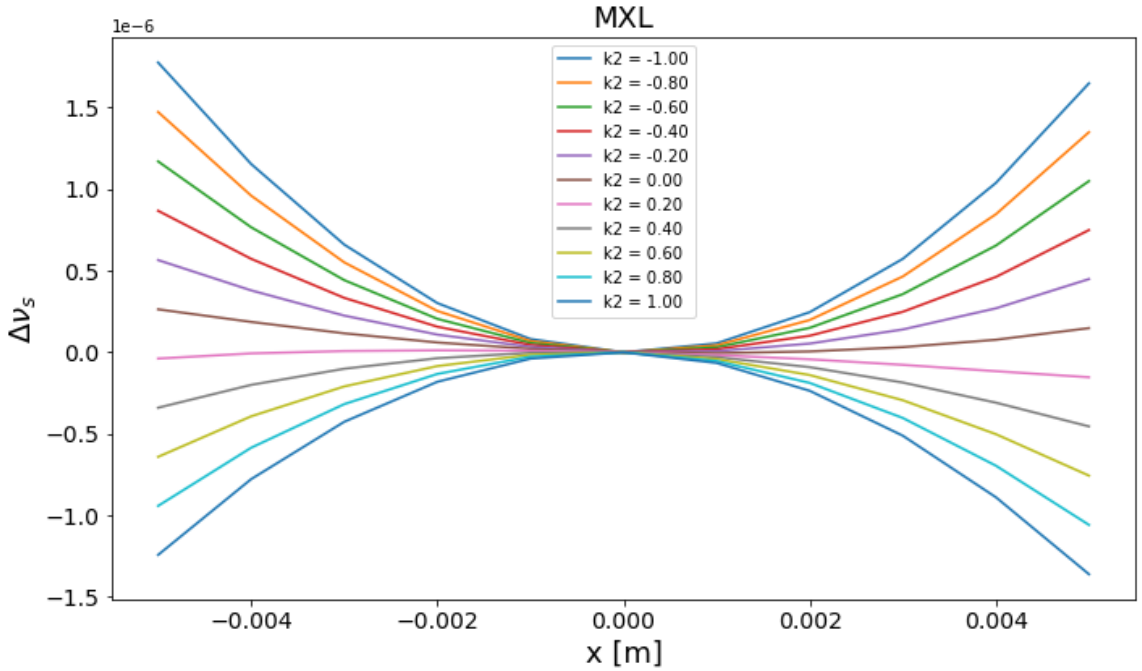
- 3 dimensional BMAD scanning routine : MXL x MXG x MXS
- Rough scan with 121 x 101 x 101 grid:

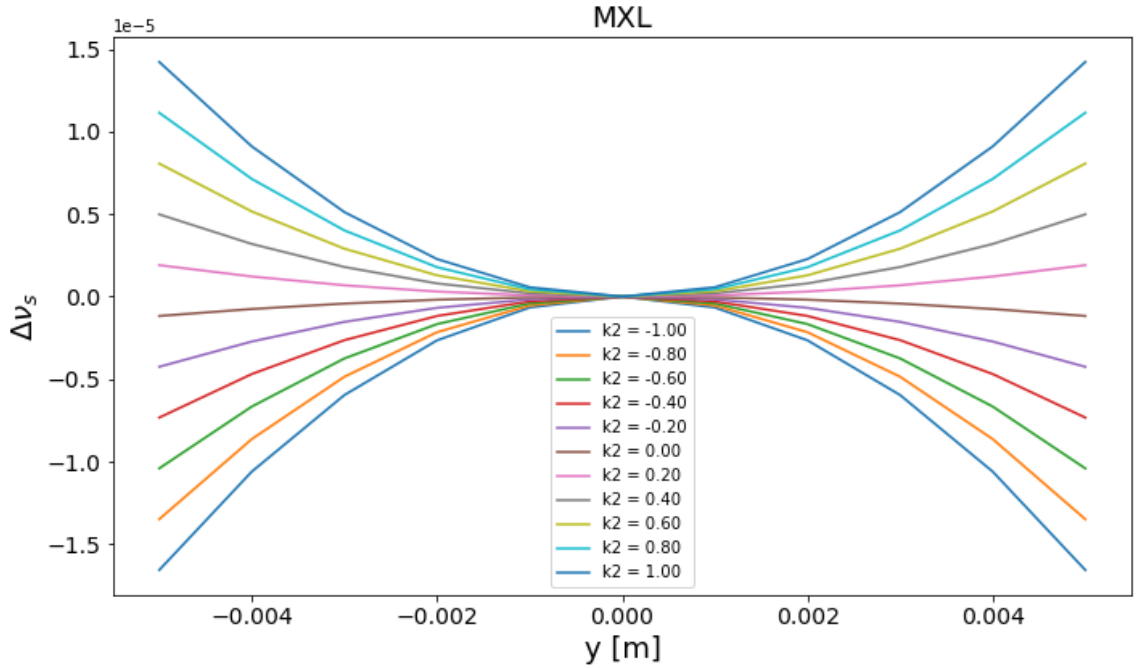
  (0,0) points are at nearly fixed MXL: $k_2 \approx -0.5\, m^{-3}$
- Finer scan with 121 x 101 x 401 grid.
- SCT = 0.185 s



# OPTIMIZATION METHOD

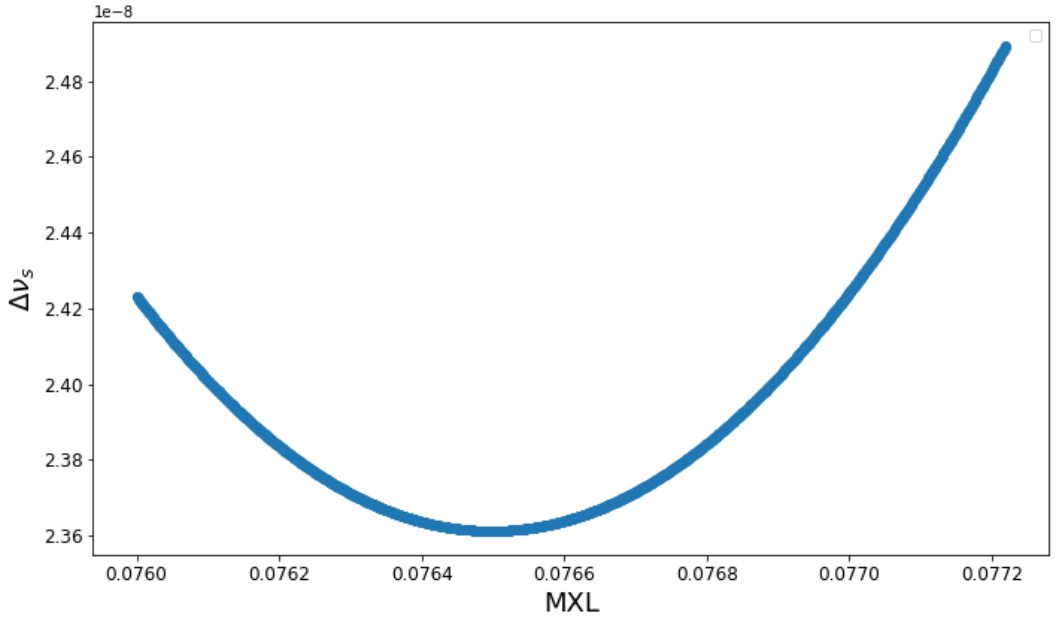
- Spin-tune shift for horizontal or vertical offset particles at different sextupole settings.
- The minimum $\Delta\nu_s$ can be obtained by flattening these parabolas.
- Spin tune spread $\Delta\nu_s$ in MXL-y plane is 1 order of magnitude larger than others.

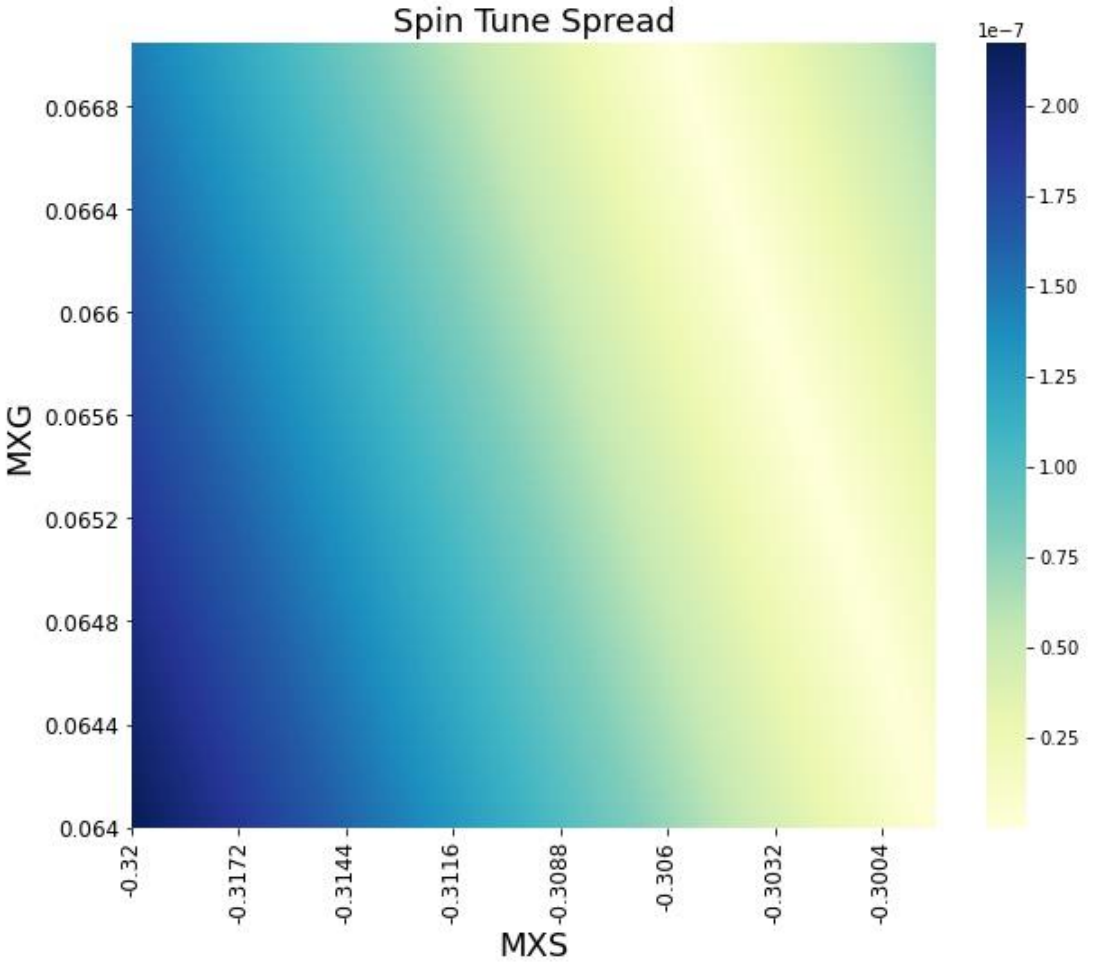


# OPTIMIZATION PROCEDURE

- BMAD scanning routine + spin tracking
- 1D: MXL + MXS + MXG
- 1D + 2D: MXL + MXS x MXG
- Find the minimum $\Delta\nu_s$ point

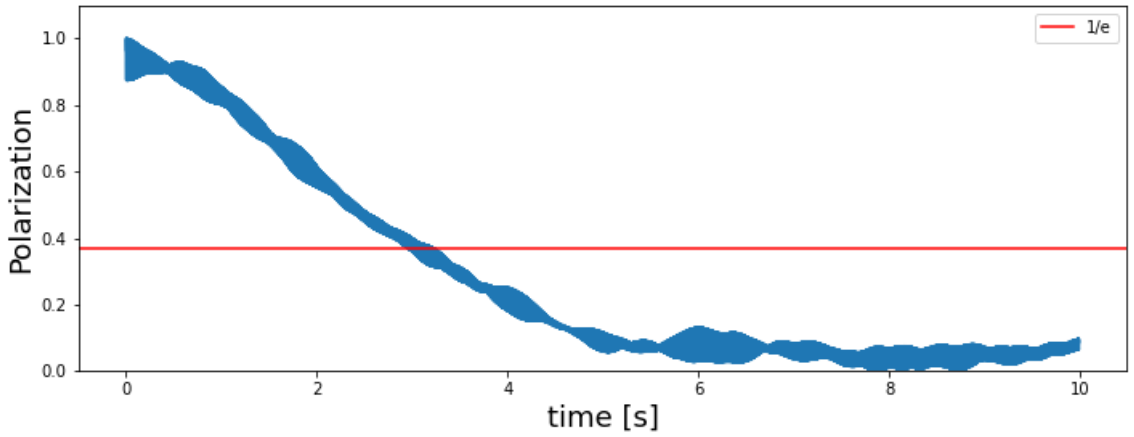


# OPTIMIZATION RESULTS

- $\Delta\nu_s$ are reduced by 3 orders of magnitude: ($10^{-5}$~ $10^{-6}$ to $10^{-8}$~ $10^{-9}$)
- After optimization with horizontal and vertical planes, the SCT reaches 3 s.
- Optimal chromaticities are all negative and far from zero.
- The smaller the $\alpha_1$ the longer the SCT.

| | $\alpha_1$ | $\xi_x$ | $\xi_y$ | SCT(s) |
|---|---|---|---|---|
| $(\xi_x, \xi_y) = (0, 0)$ | -6.284 | +0.0002 | -0.0002 | 0.185 |
| BMAD-1D (x, y) | 0.051 | -3.9770 | -4.9849 | 3.388 |
| BMAD-2D (x, y) | 0.294 | -3.9596 | -4.9446 | 3.094 |
| COSY infinity (x, y, E) | 0.035 | -3.6920 | -5.3711 | 7.899 |

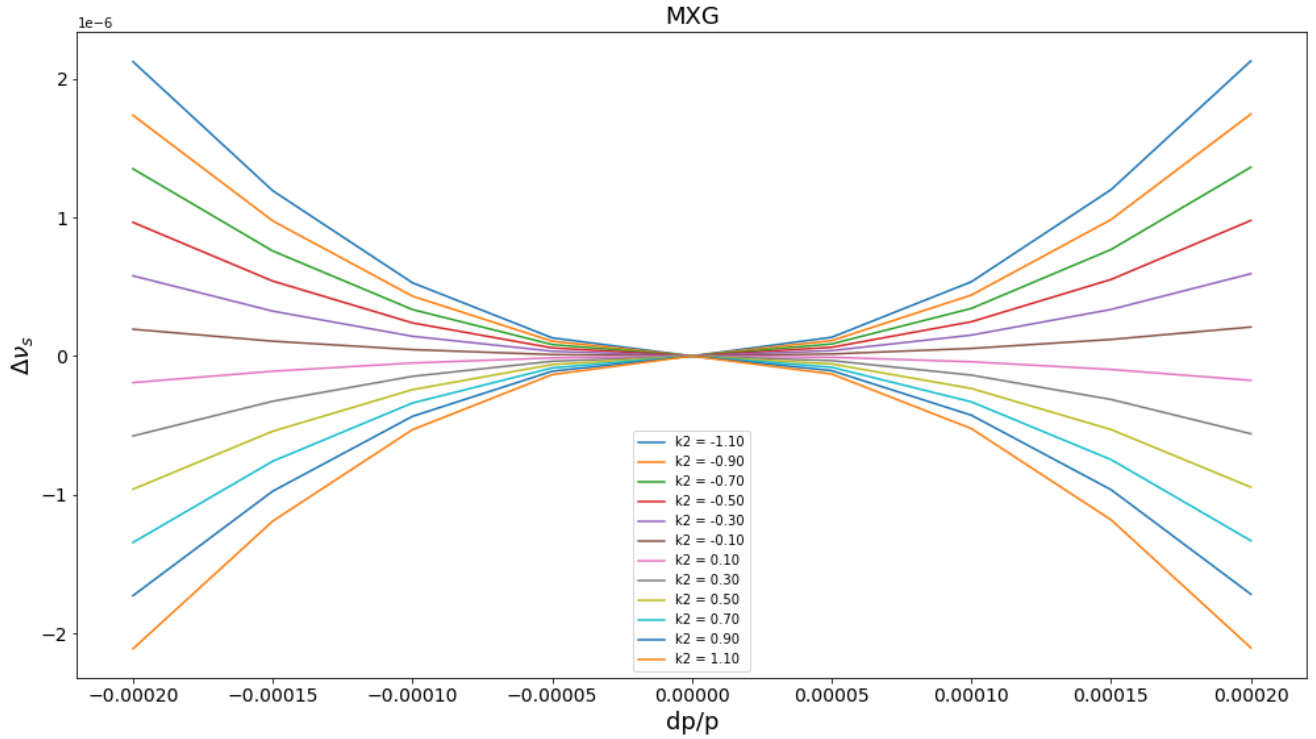


# SUMMARY

- Storage ring EDM experiment requires the SCT > 1000 s.
- Path length change leads to spin tune decoherence.
- The new optimization method significantly improves SCT of protons.

# OUTLOOK

- Implement the momentum deviation to BMAD optimization.
- Investigate the impact of intrinsic resonances for protons.



# Thank You!