BEAM AND SPIN TRACKING

STATUS AND PERSPECTIVE

MARCH 31, 2021 I A. LEHRACH, RWTH AACHEN & FZ JÜLICH

Need for Spin Tracking

- Precursor experiment for Deuterons at COSY
- Spin Coherence Times (SCT) Studies for Protons at COSY
- Search for Axions / Axion-like Particles COSY
- Prototype EDM Ring
- Final EDM Ring

Utilized Simulation Programs

COSY Infinity by M. Berz and K. Makino (MSU)

- based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle, including higher-order nonlinearities, normal form analysis, and symplectic tracking

PTC (Polymorphic Tracking Code) by E. Forest (KEK)

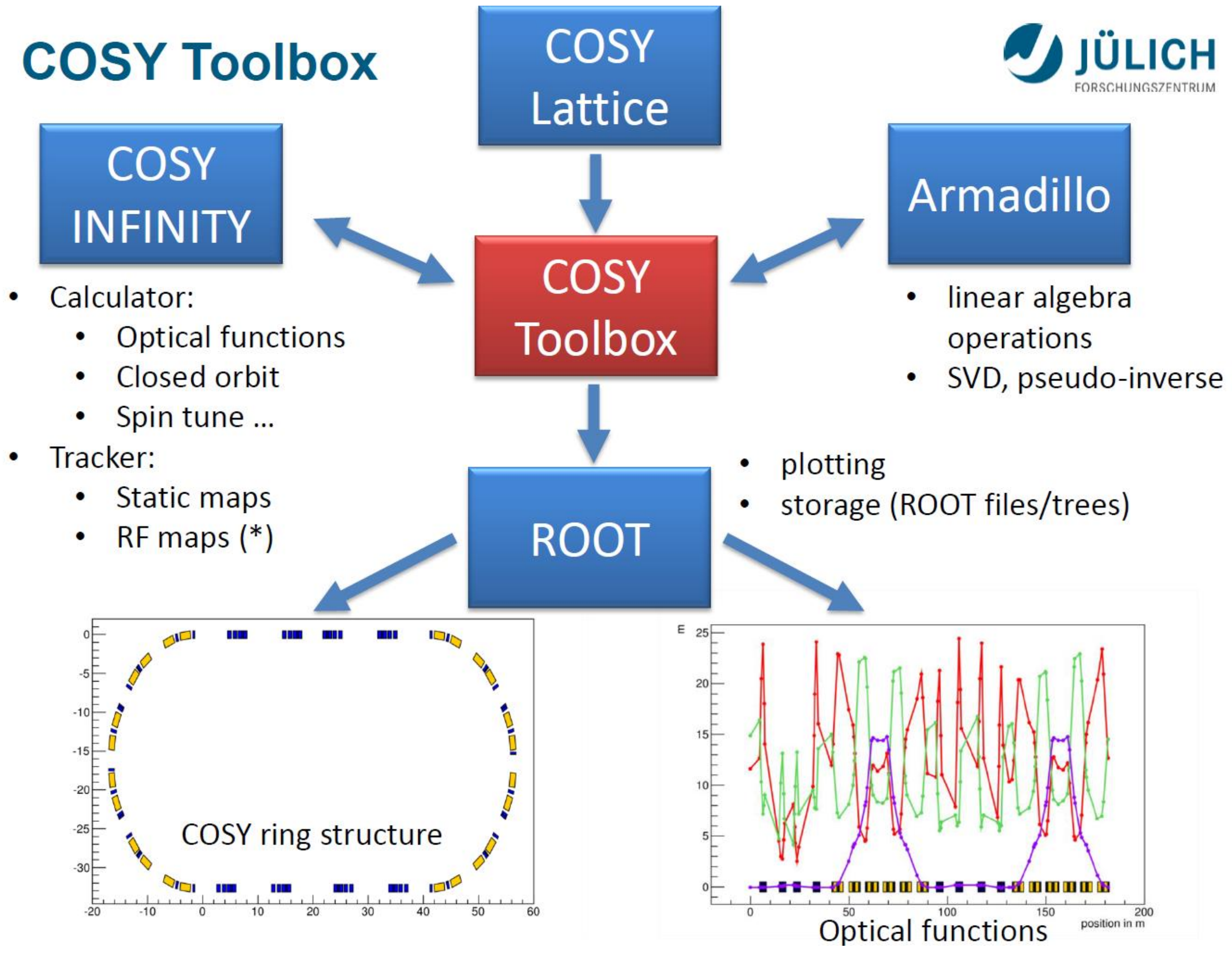
- TPSA maps (truncated power series algebra by Taylor expansion)

Bmad by D. Sagan (Cornell)

- PTC tracking and Runge-Kutta integration

Bench marking with “analog computer” Cooler Synchrotron COSY and other simulation codes

Simulation Setup for COSY Infinity

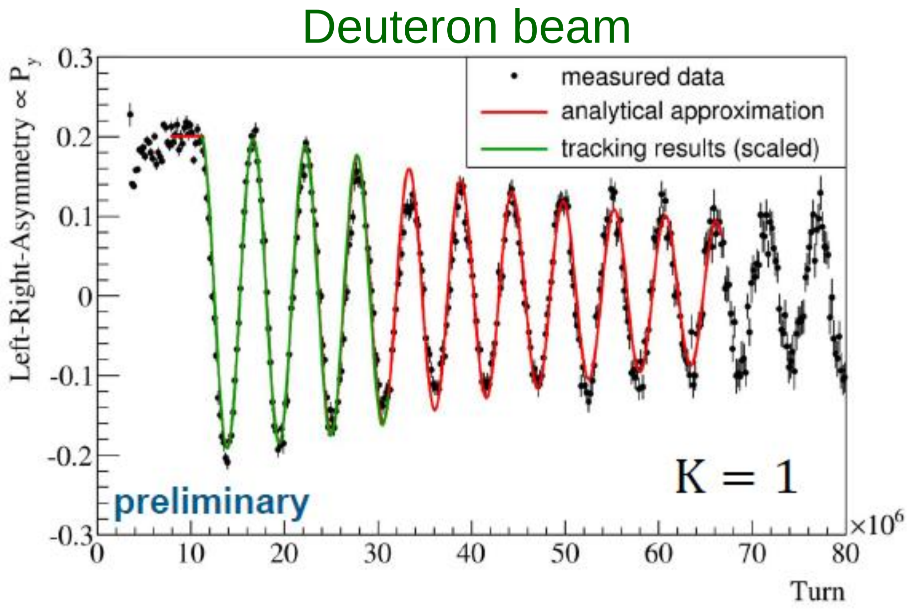


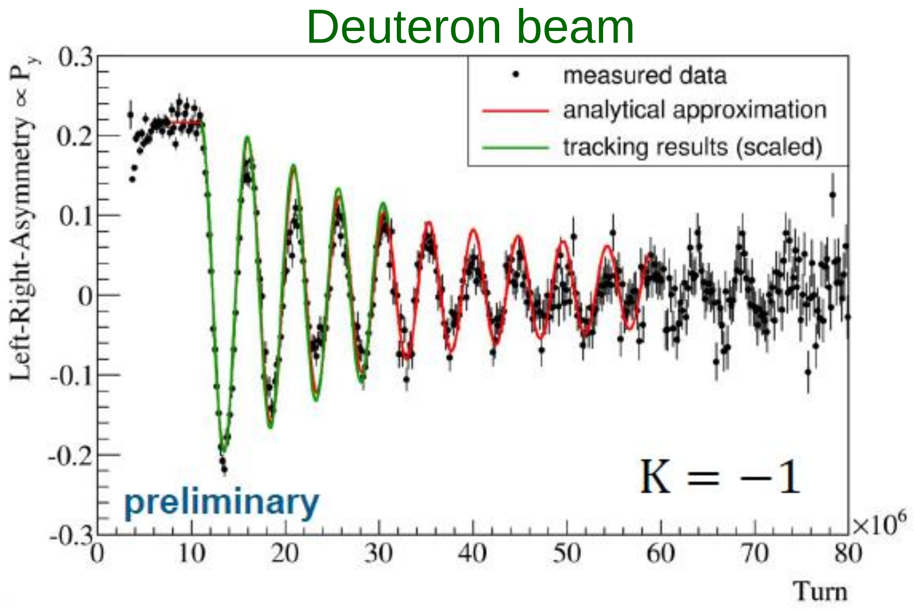
Benchmarking for COSY Infinity

RF spin manipulation elements implemented.

Benchmarking experiment at COSY using driven oscillations induced by the RF solenoid

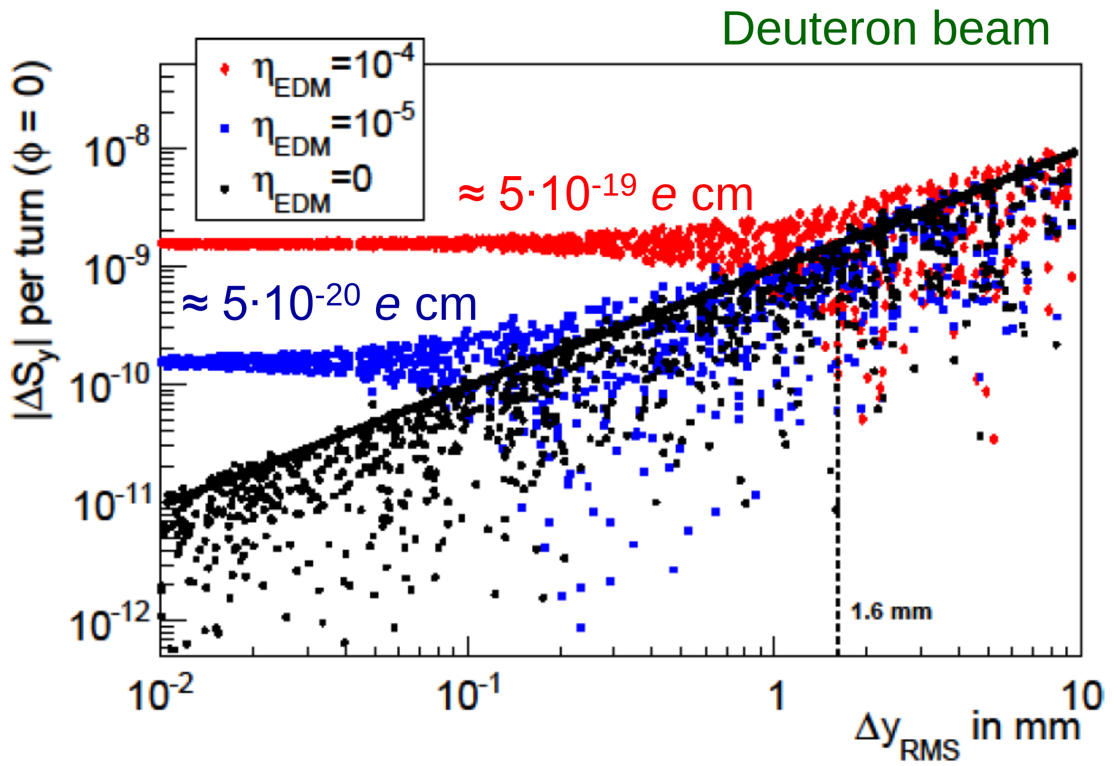
RF field: $B_{sol} = B_0 \cdot \cos(2\pi \cdot \nu_{sol} \cdot n + \Phi_{sol})$, *resonance condition* $\nu_{sol} = \gamma G \pm k$





M.S. Rosenthal, A. Lehrach, Proceedings of IPAC2015, THPF032, Richmond, VA, US

Systematic Limitations for EDM Measurements at COSY

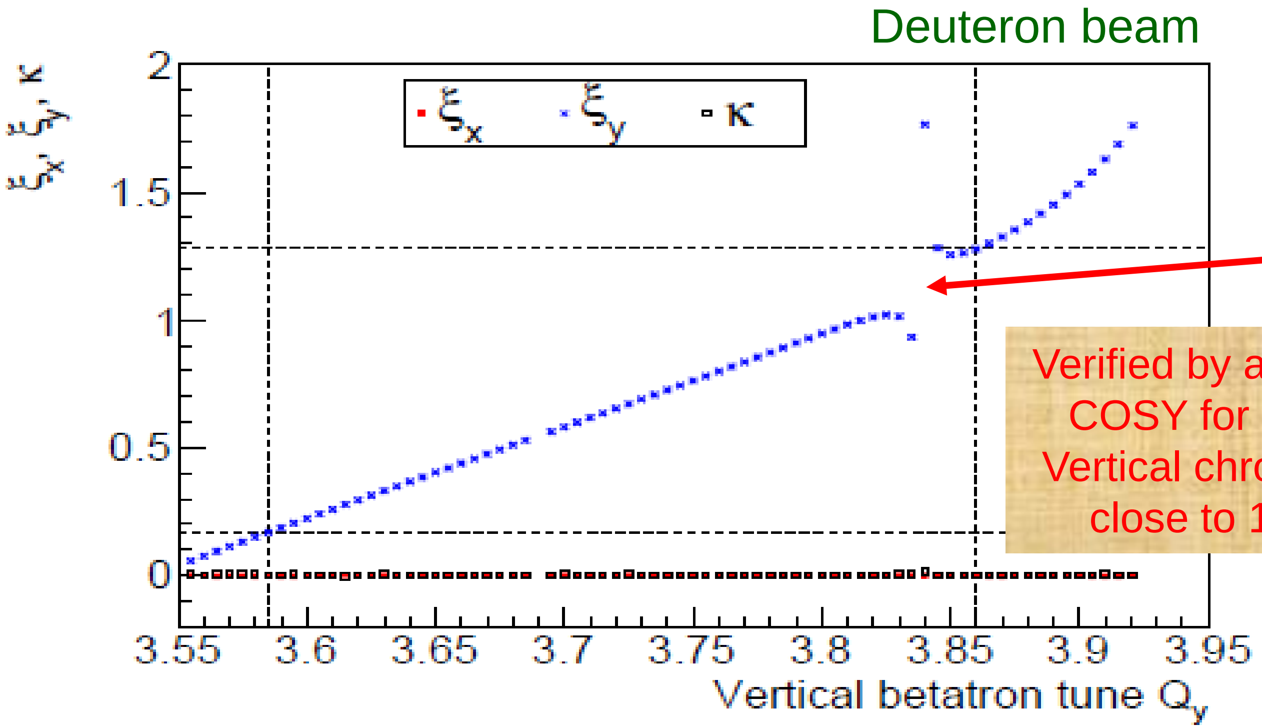


Absolute average change of the vertical spin component ΔS_y per turn for different Δy_{RMS} and an initial Wien filter phase 0°. Wien filter magnetic field 10^{-4} mT (0.8 m length) and corresponding electric field. Different Δy_{RMS} generated by randomized vertical quadrupole shifts assuming Gaussian distributed misalignment errors.

- Solid line shows the 90% upper confidence limit for pure misalignments.
- Dashed line refers to the location for which the false signal by misalignments is equal to an EDM signal corresponding to $\eta_{EDM} = 10^{-4}$.

M.S. Rosenthal, A. Lehrach, Proceedings of IPAC2015
M.S. Rosenthal, PhD Thesis, RWTH Aachen, 2016

Spin Coherence Time for Deuterons at COSY



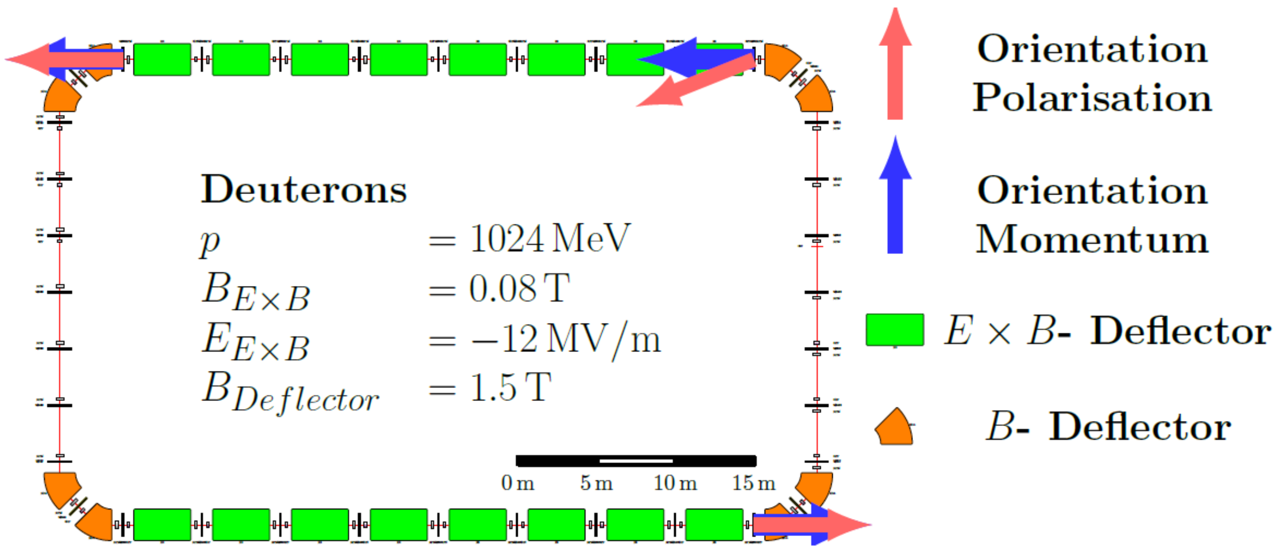
Verified by a measurement at COSY for Q_y close to 3.8. Vertical chromaticity was set close to 1 for long SCT.

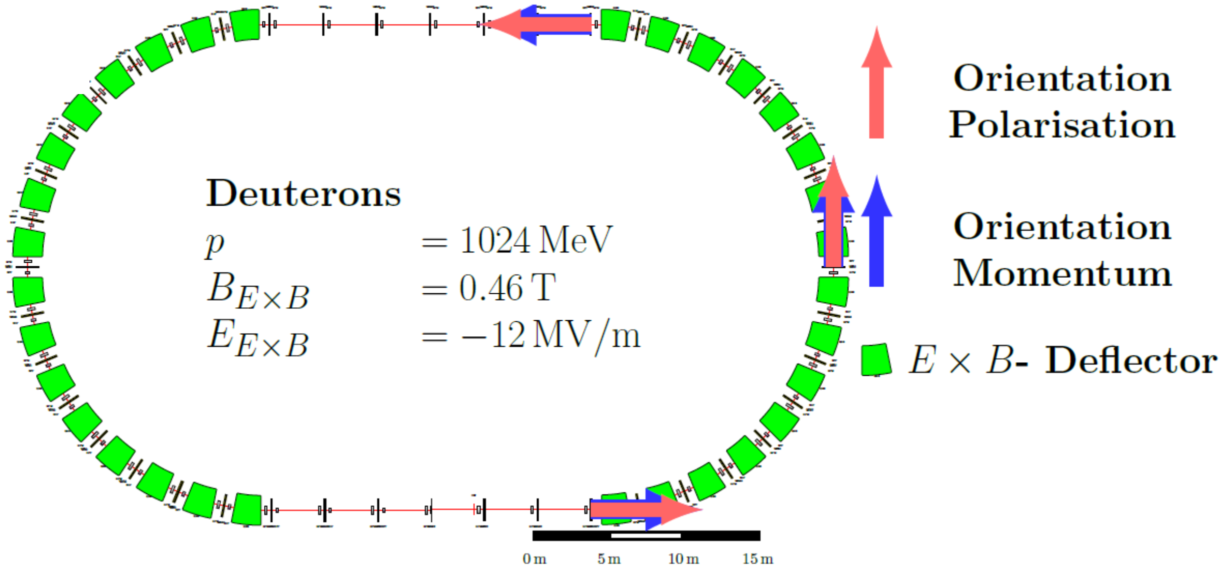
Simulated optimum settings of the chromaticities ξ_x and ξ_y and the second-order momentum compaction factor κ for a minimized spin tune spread as function of the vertical betatron tune Q_y. A lattice setup with minimized dispersion in the straights and a deuteron reference momentum of p = 970 MeV/c has been used.

$$\kappa \equiv \left(\alpha_1 + \frac{3}{2\gamma_0^2}\left[\beta_0^2 + \eta\right]\right), \alpha_1\text{: second order momentum compaction}, \eta\text{: slip factor}$$

M.S. Rosenthal, PhD Thesis, RWTH Aachen, 2016

Quasi-Frozen and Frozen Deuteron EDM Ring

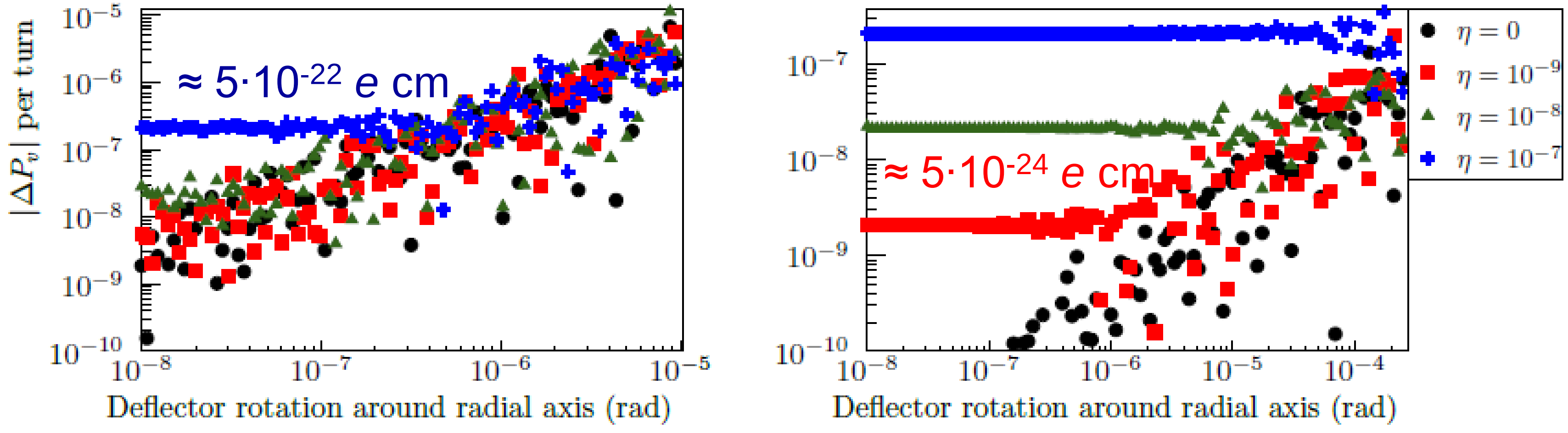




Yu.Senichev et al., Proceedings of IPAC2017, TUPVA084, Copenhagen, Denmark

Deflector Rotation around Radial Axis

Deuteron beam



Quasi-Frozen Spin (left) – Frozen Spin (right)

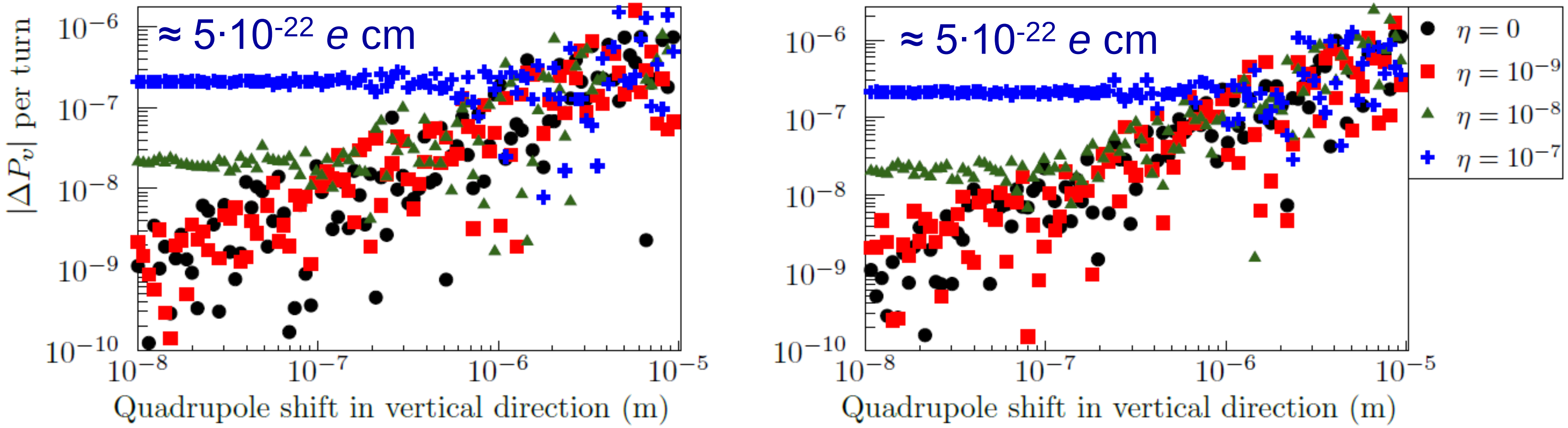
Vertical spin build up for different magnitudes of EDM and Gaussian distributed rotations of ExB deflectors (RMS values) around the radial axis.
Each simulation has different randomly generated misalignments.

Artificial spin buildup roughly two orders of magnitude weaker for QS compared to QFS

A.A. Skawran, A. Lehrach, Proceedings of IPAC2017, TUPVA082, Copenhagen, Denmark

Quadrupole Shift in Vertical Direction

Deuteron beam



Quasi-Frozen Spin (left) – Frozen Spin (right)

Vertical spin build up for different magnitudes of EDM and Gaussian distributed quadrupole shifts (RMS values) around the vertical axis.
Each simulation has different randomly generated misalignments.

Effect of QFS and FS is roughly the same

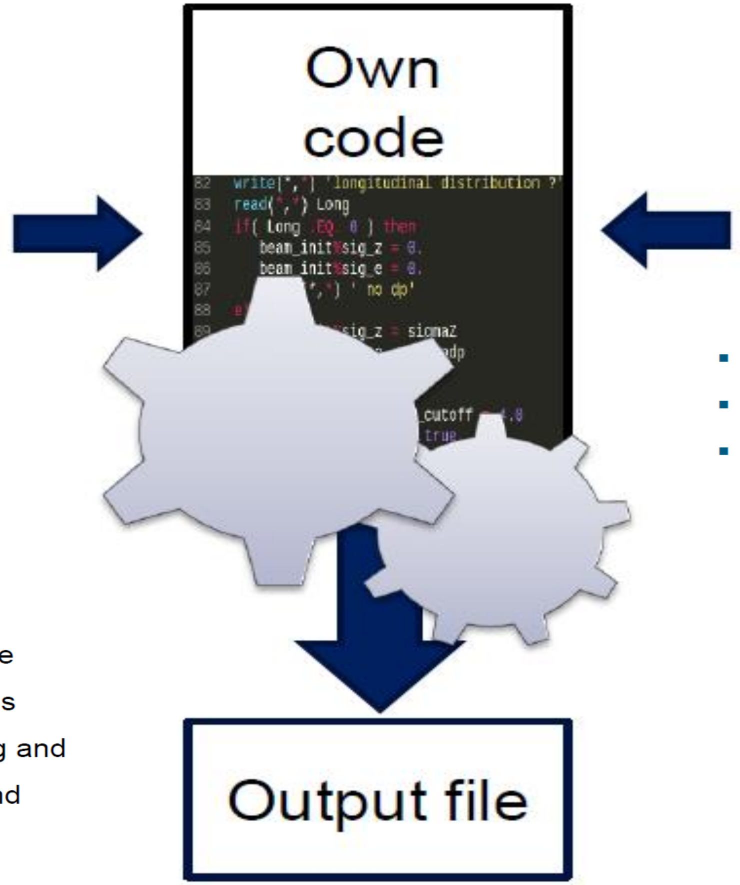
A.A. Skawran, A. Lehrach, Proceedings of IPAC2017, TUPVA082, Copenhagen, Denmark

Bmad

Tao

- Open source subroutine library
- Object orientated
- Written in Fortran with C++ interface
- routines for calculating transfer matrices, emittances, Twiss parameters, dispersion, coupling, etc.

- Tool for Accelerator Optics program
- view lattices, do Twiss and orbit calculations, nonlinear optimization on lattices, etc.



- MAD like syntax
- Many predefined element types
- Custom elements possible

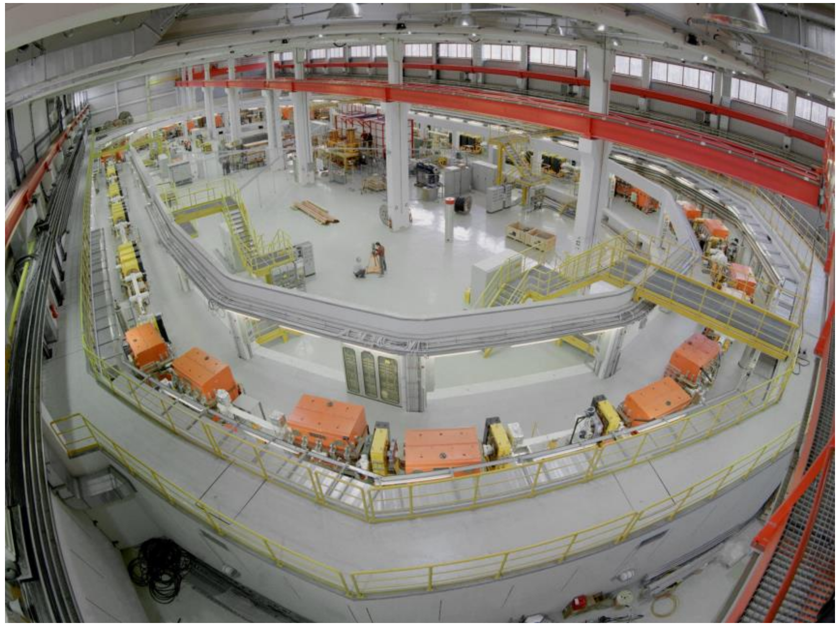
PTC

- Software library
- Taylor maps and Lie algebraic operations
- Used for integrating and analysing orbital and spin motion

Courtesy: Vera Poncza

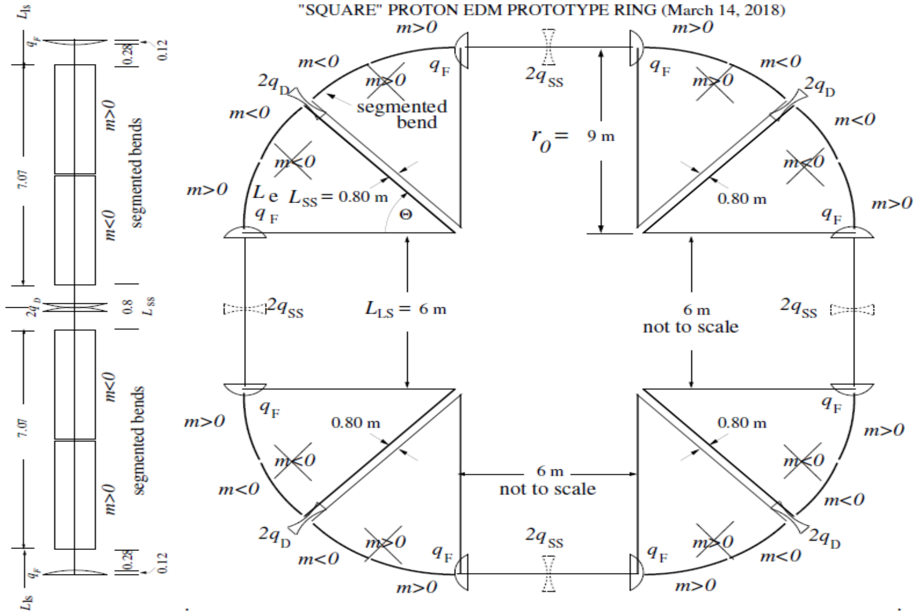
From COSY to A Prototype EDM Storage RING

Cooler Synchrotron COSY



- Ideal starting point for R&D work
- Deliver first direct EDM measurement for deuterons

Prototype EDM Ring



- Prototype EDM ring
- Energy 35 - 45 MeV, CW-CCW beams
- Pure electric and combined E/B
- Length roughly 120m

→ Design of a final EDM storage ring

Misalignments of Main COSY Magnets

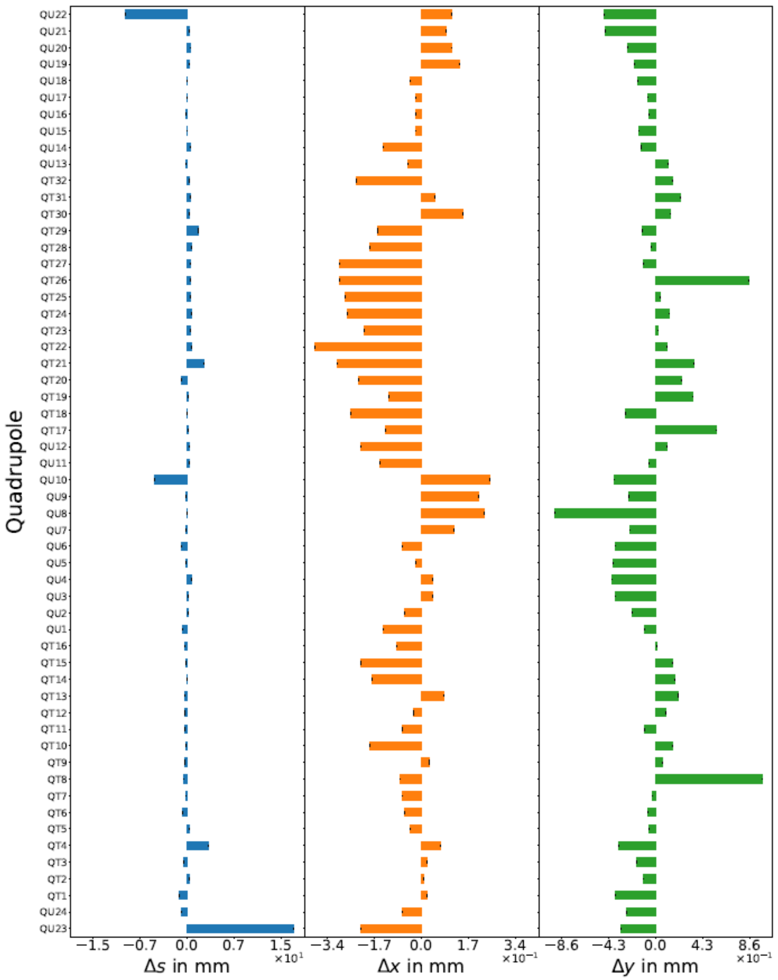


Figure A.3: Measured misalignments of all quadrupoles including the measurement uncertainties. QT1, ..., QT16 are the quadrupoles in the straight sections and QU1, ..., QU12 the quadrupoles in the arc sections of COSY. The measurements were performed in January 2020.

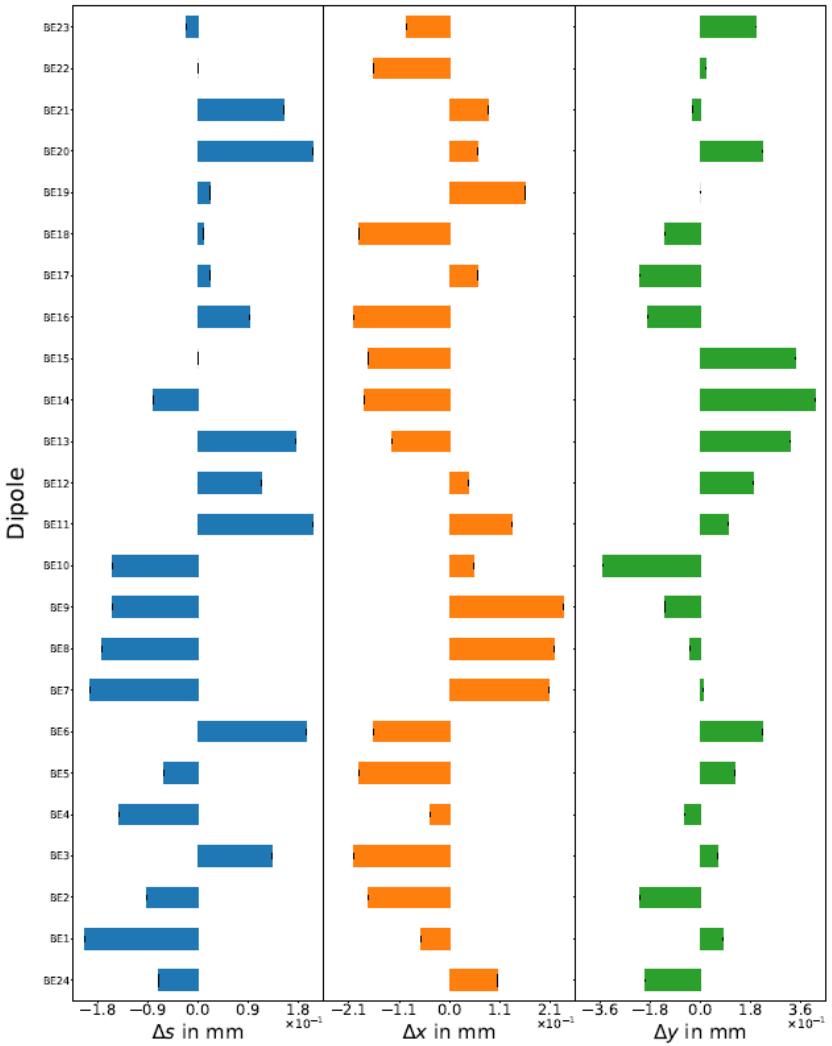


Figure 6.2: Measured misalignments of all dipoles including the measurement uncertainties. The individual 24 dipole magnets of COSY are denoted with B1, ..., B24. The measurements were performed in January 2020.

Courtesy: Vera Poncza

Measured and Simulated Closed-Orbit of COSY

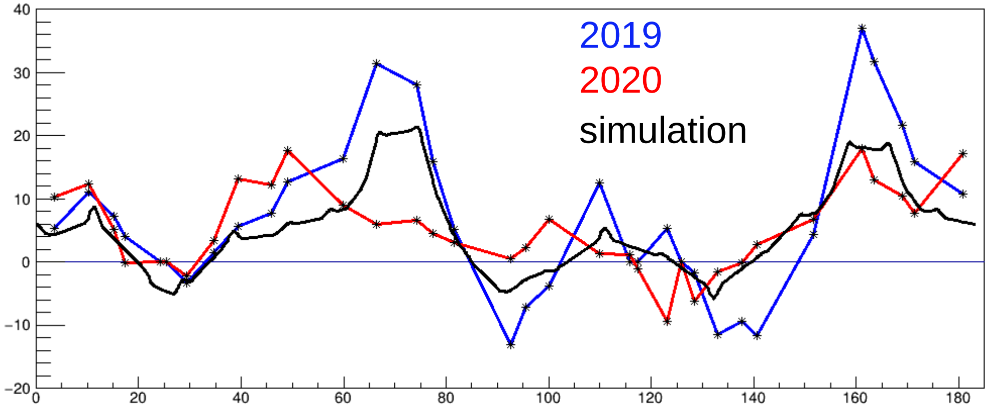
without COSY correctors

Two COSY orbit-measurements
2019 2020
with almost identical setup:

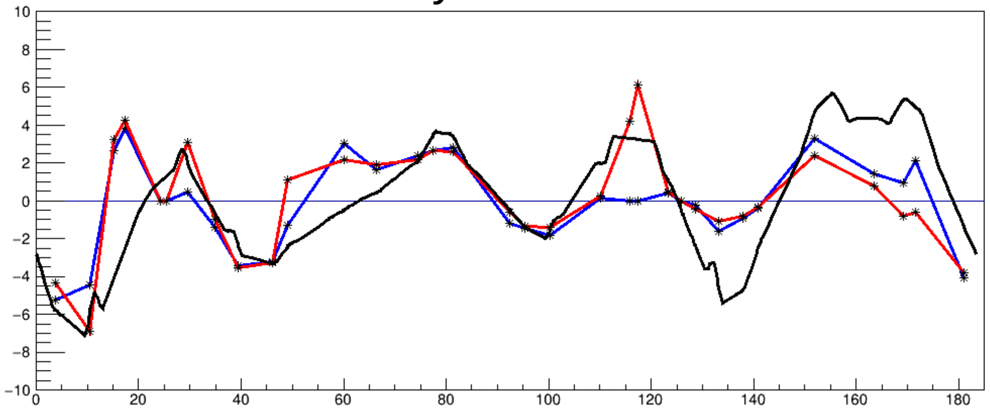
Close-orbit model-calculations including possible shortening effects of the arc dipoles

see next slide ….

x orbit



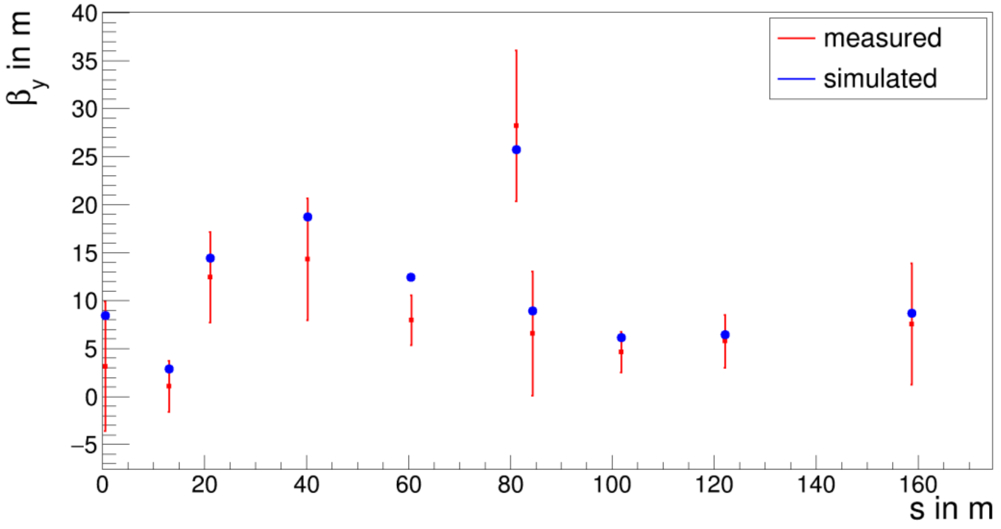
y orbit

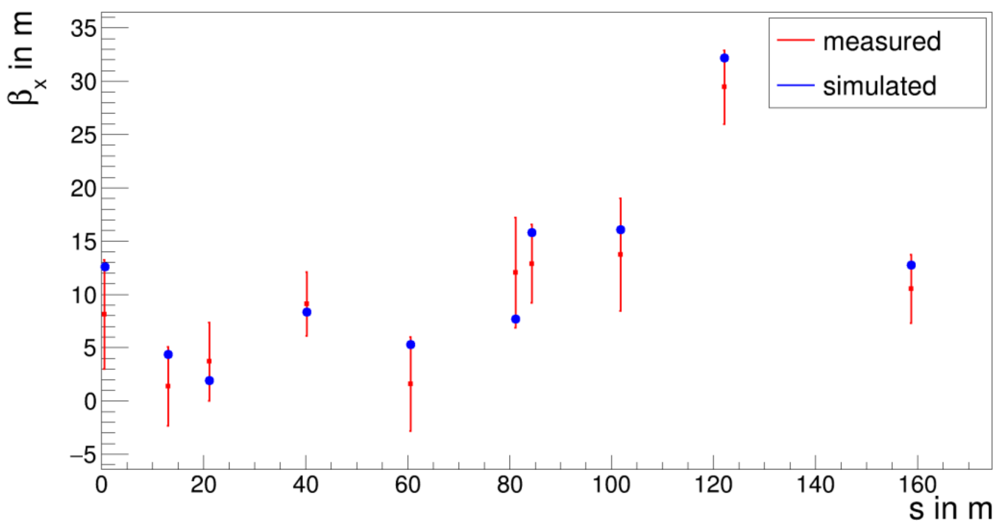


Courtesy: Michael Hartmann

Final Model VS. Measurement with LOCO

Deuteron beam

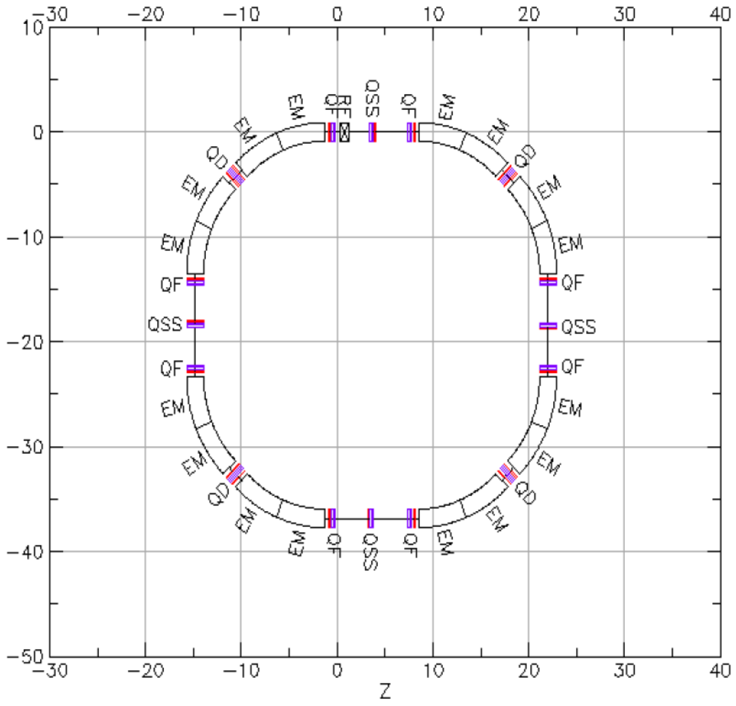




	Simulation	Measurement
Q_x	3.58210	3.57119
Q_y	3.59430	3.58641
n_x	-0.003122	-0.00348
n_s	0.0009970	0.00557

Courtesy: Vera Poncza

Spin Tracking for the PT EDM Ring



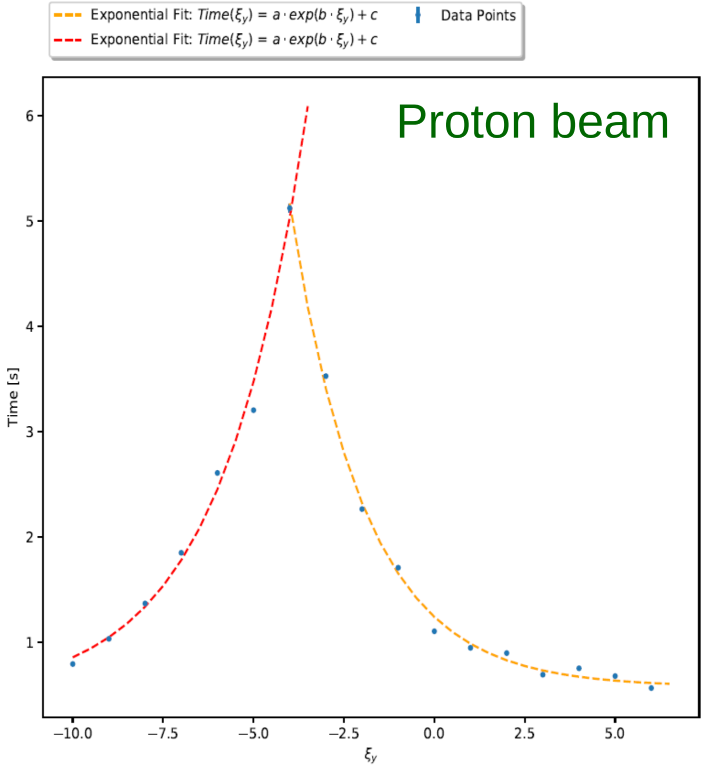
- Perfectly aligned lattice
- Circumference: 123. 358 m
- Width: 36. 252 m
- Dipole Length: 4.810 m
- Dipole E-Field: 5.061 kV/m
- Dipole B-Field: 0.023 T
- Frozen Spin for Proton Beam

- WP: $Q_x = 1.823,\, Q_y = 1.123$
- Beam Properties:

$$N = 100$$
$$\epsilon_x = 5 \cdot 10^{-7} m \cdot rad$$
$$\epsilon_y = 5 \cdot 10^{-7} m \cdot rad$$
$$\sigma_z = 1 \cdot 10^{-3}$$
$$\sigma_{pz} = 1 \cdot 10^{-4}$$

Spin Decoherence:

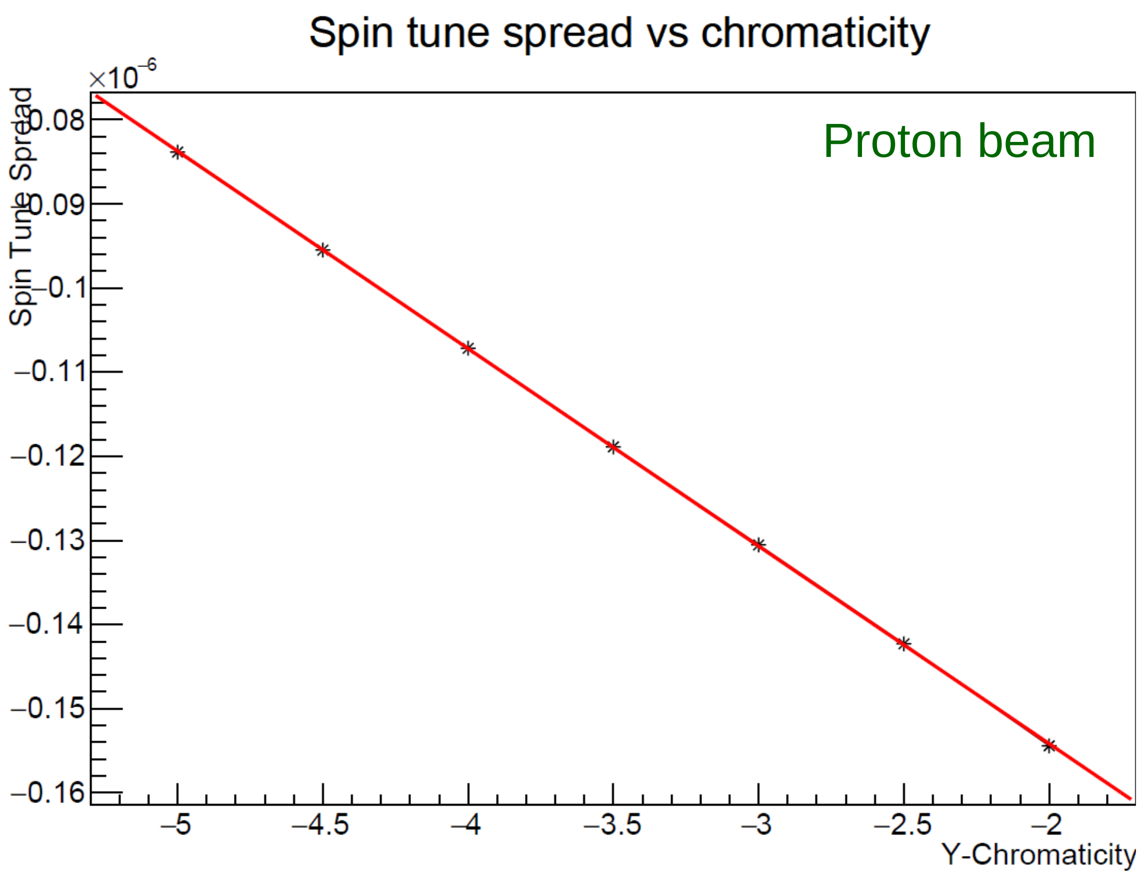
- Crossing Point at $\xi_y = -3.99$
- max. Spin Coherence Time: 5.05 s

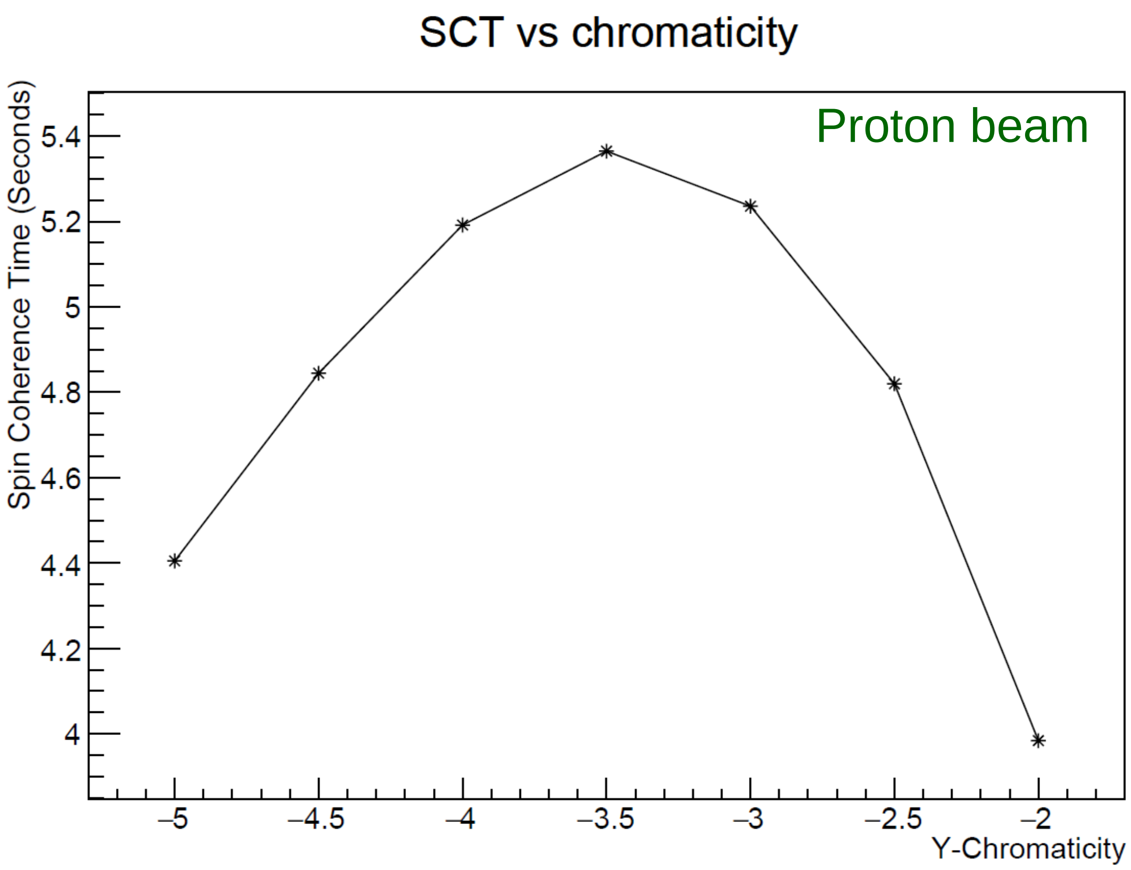


S, Martin, A. Lehrach R. Talman, Design of a Prototype EDM Storage Ring, *PoS* SPIN2018 (2019) 144

Courtesy: Max Vitz

Spin Tracking for the PTEDM Lattice

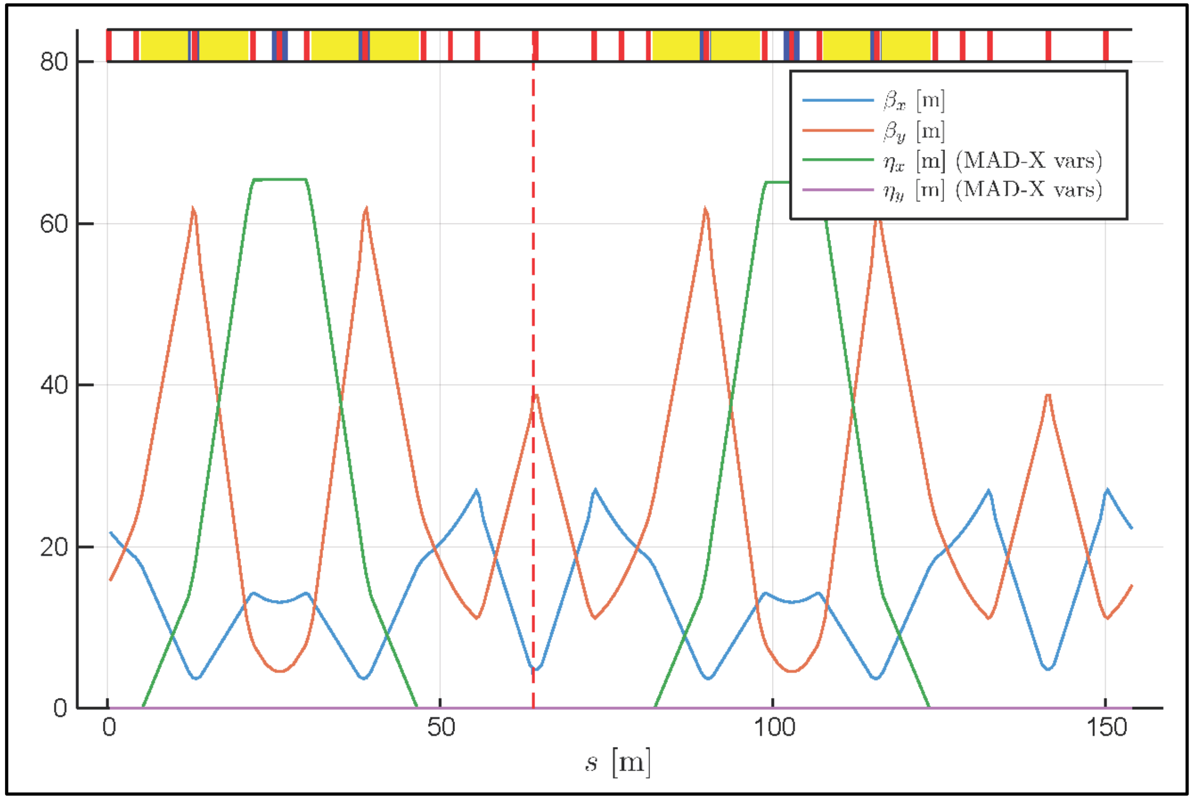




Courtesy: Rahul Shankar

Lattice with Dispersion-Free Straight Sections

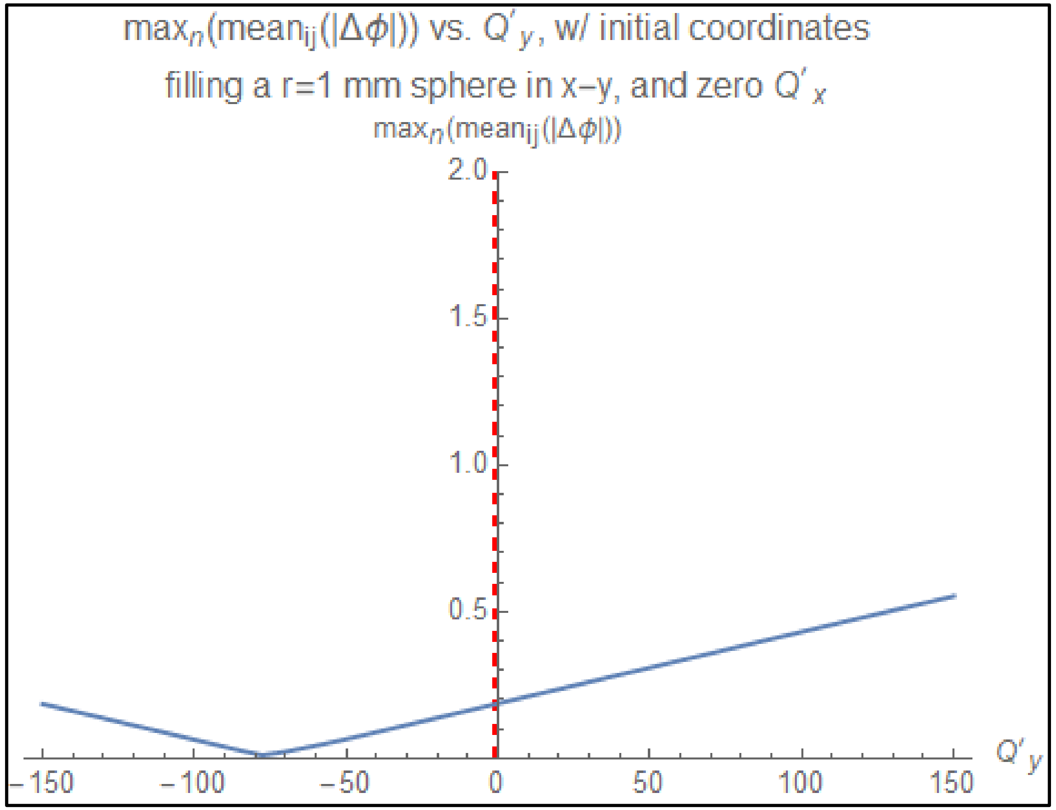
p = 45 MeV, *ExB* elements with B_{field} = 0.0325 T, E_{field} is 7.01 MV/m



$\mu_x = 0.4318$
$\mu_y = 0.4750$
$Q'_x = -4.262$
$Q'_y = -1.397$

- Lattice optimized for the Frozen Spin condition
- RF cavity parameters: $V = 100\ kV,\ f = 6f_{rev}$
- Tracking was performed for 1 million turns

Proton beam



Courtesy: Eremey Valetov

Next Steps

- **Precursor**
  - Deuterons: Comparing simulated and measure optics / orbit to further improve the COSY model
  - Protons: Understand and optimize SCT for protons

- **Prototype EDM ring**
  - Implement more realistic E/B element
  - Optimize lattice for longer SCT
  - Investigate systematic errors