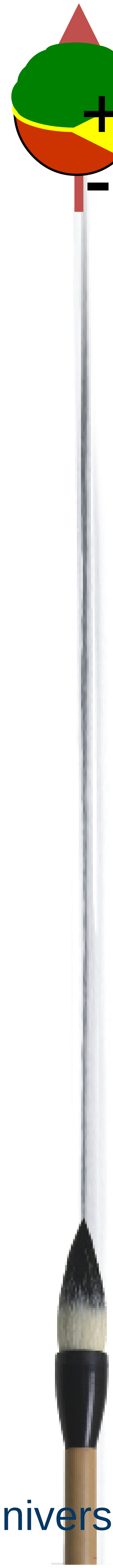


Accelerator Challenges of a Storage Ring based EDM Search

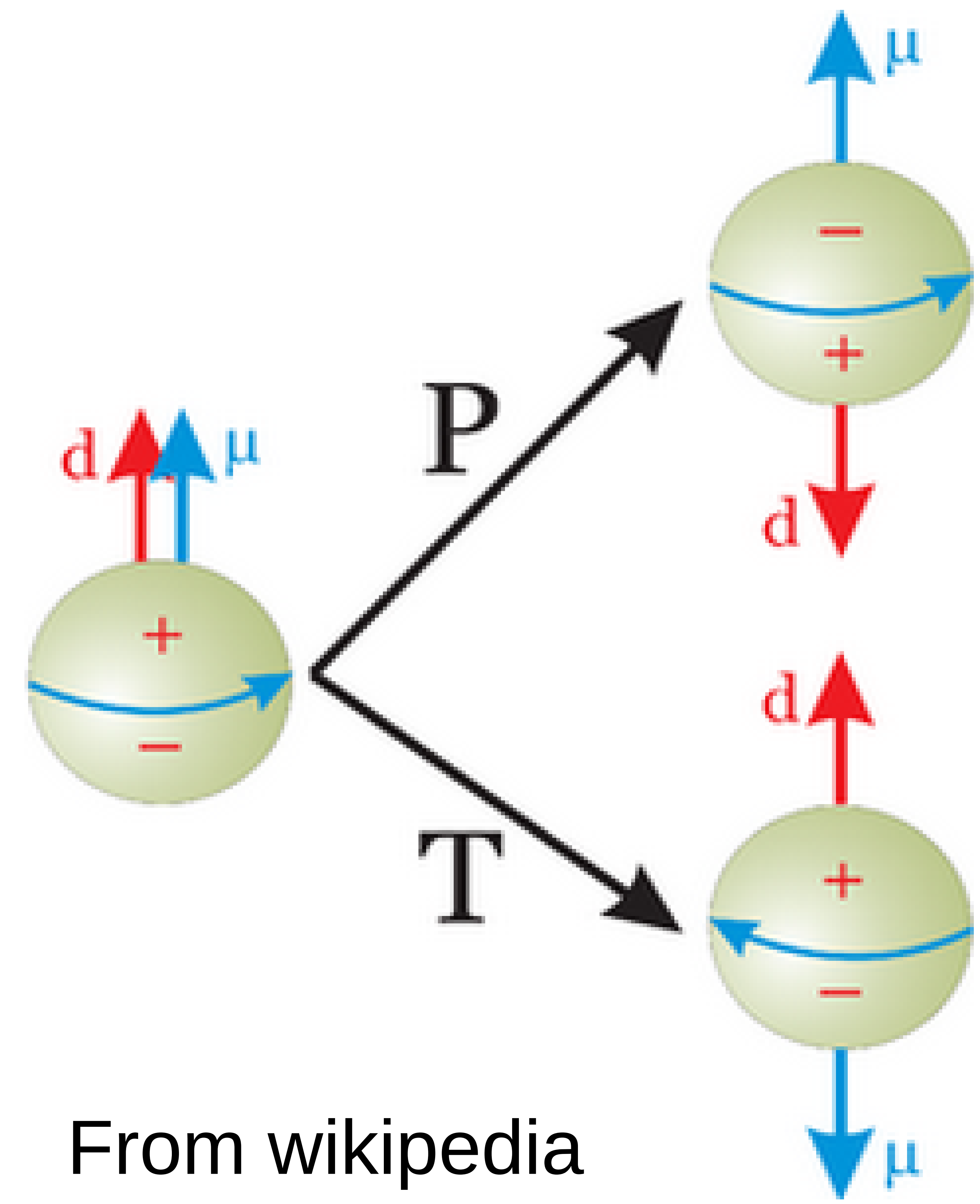
M. Bai

IKP-4, Forschungszentrum, Juelich

EPS-HEP 2015, University of Vienna, July 22-29, 2015

What's an Electric Dipole Moment?

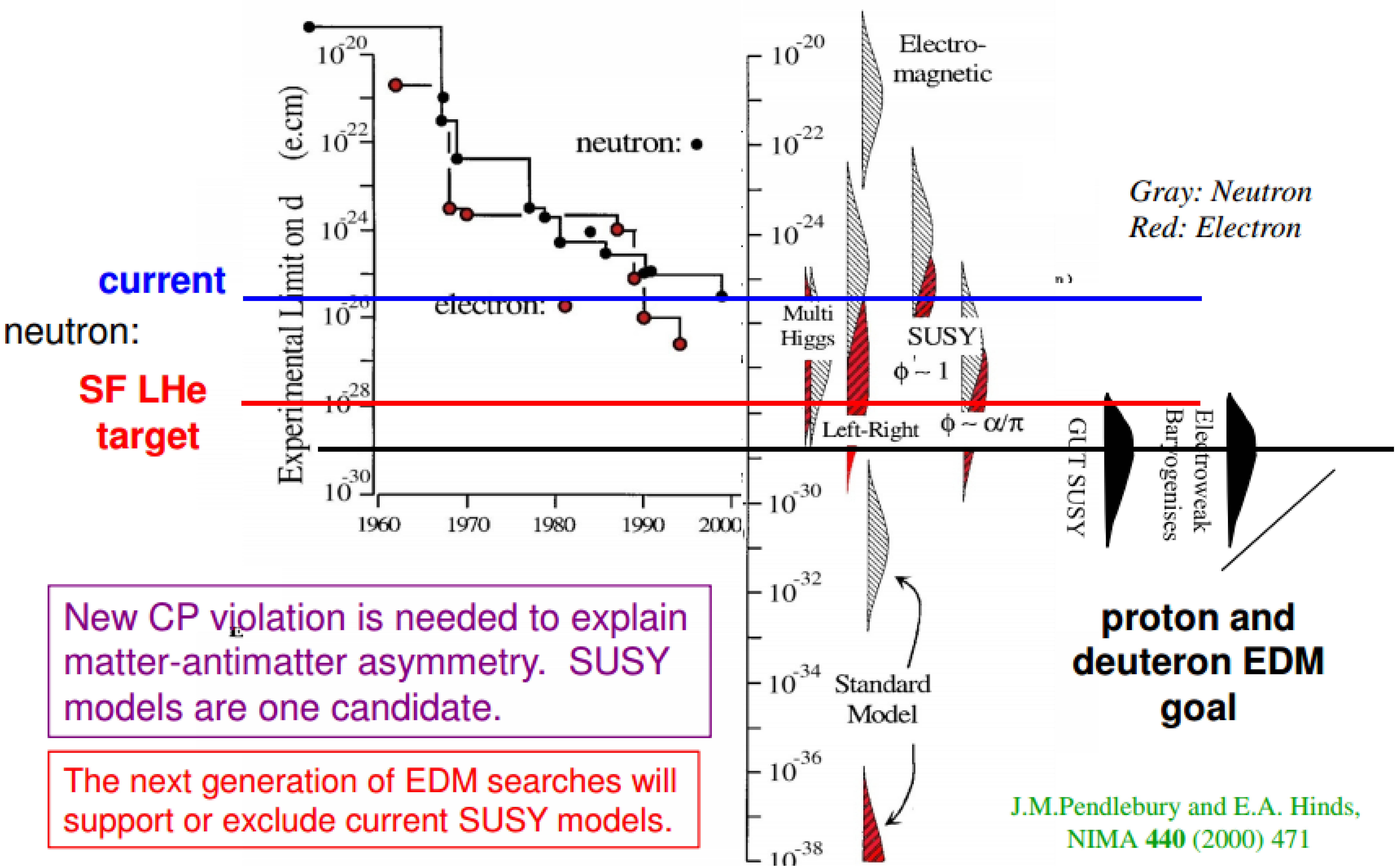
- Permanent separation of positive and negative charge distribution inside a particle
- It aligns along the spin axis of the particle, and violates both Parity and Time Reversal. Hence, an effective probe of CP-violation
- could be the key to explain the baryon asymmetry of the universe



From wikipedia

For more details, please see H. Stroeher's presentation "Electric Dipole Moment – A window for New Physics", Session HS41, July 25, 2015

Status of EDM Search

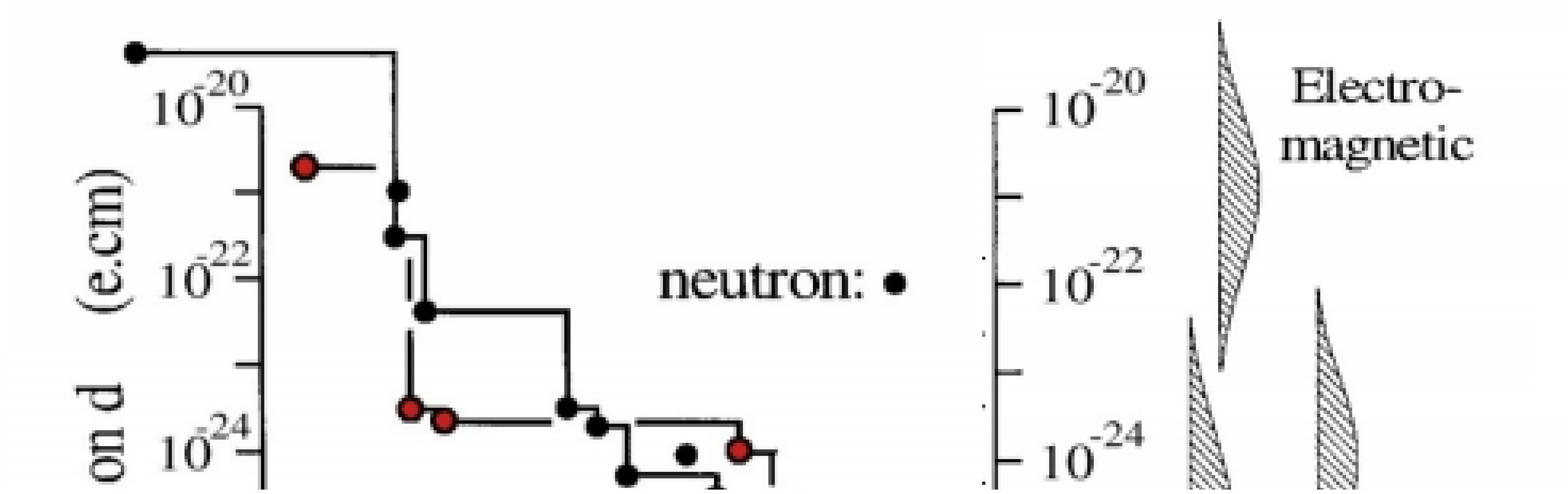


New CP violation is needed to explain matter-antimatter asymmetry. SUSY models are one candidate.

The next generation of EDM searches will support or exclude current SUSY models.

J.M.Pendlebury and E.A. Hinds, NIMA **440** (2000) 471

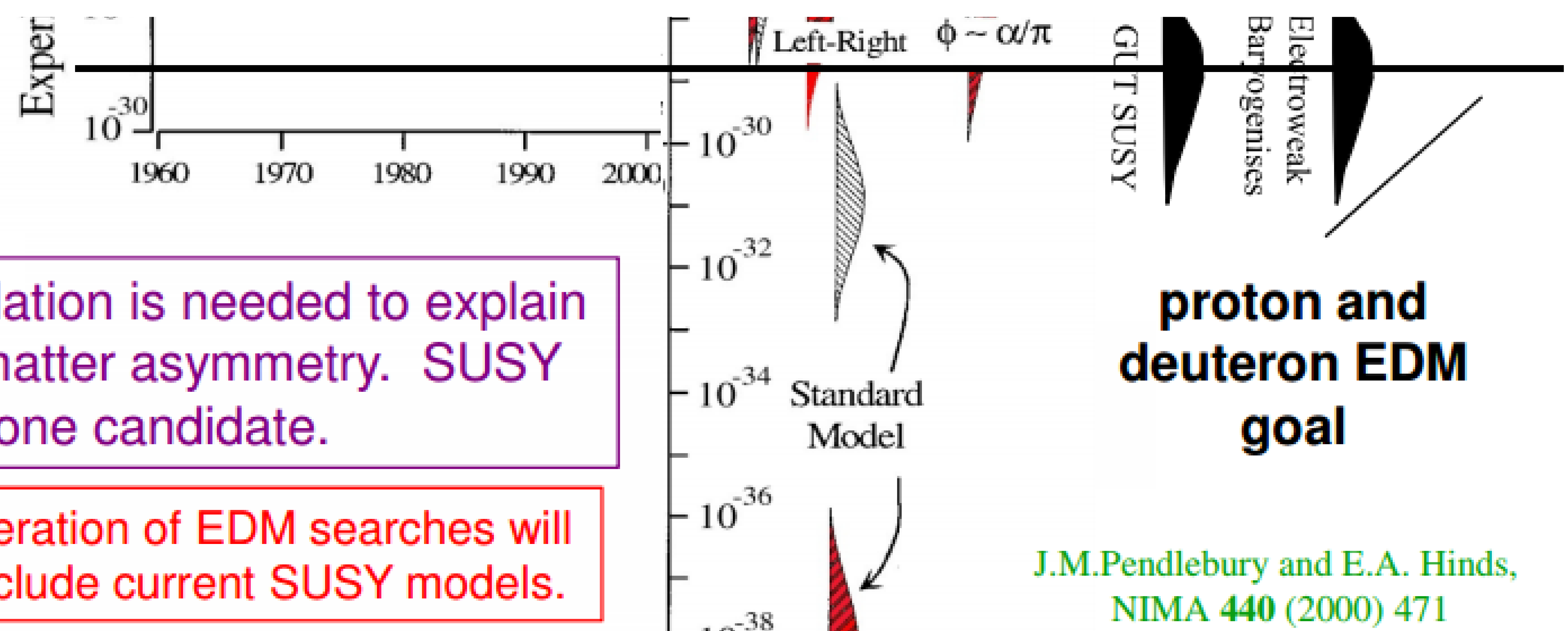
Status of EDM Search



Gray: Neutron
Red: Electron

For more details, please see H. Stroeher's presentation "Electric Dipole Moment – A window for New Physics", Session HS41

target



New CP violation is needed to explain matter-antimatter asymmetry. SUSY models are one candidate.

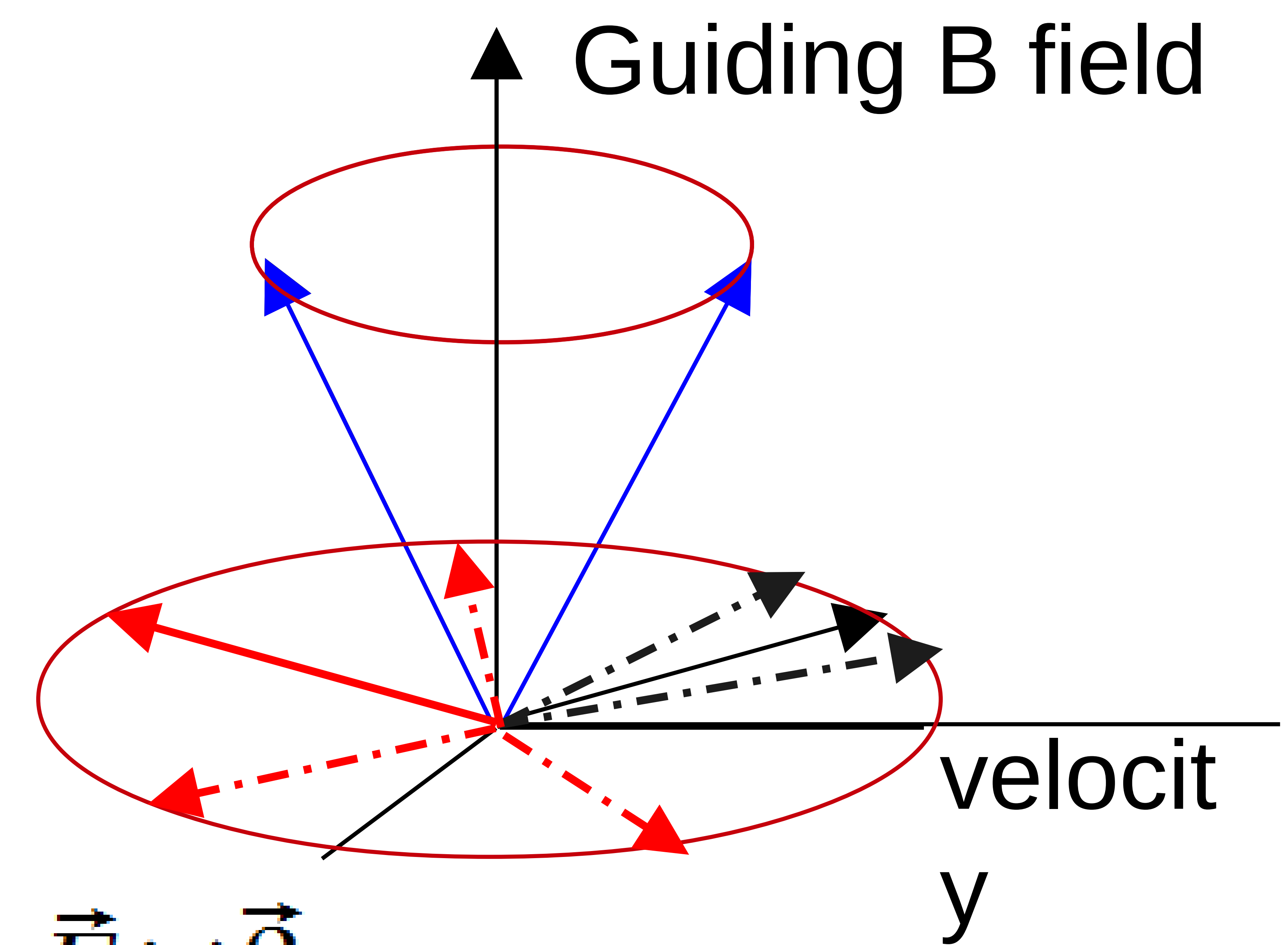
The next generation of EDM searches will support or exclude current SUSY models.

proton and deuteron EDM goal

J.M.Pendlebury and E.A. Hinds, NIMA **440** (2000) 471

Storage Ring based EDM Search

Spin motion in a storage ring



$$\frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_m + \vec{\Omega}_e)$$

with

$$\vec{\Omega}_m = \frac{e}{\gamma m}\left[G\gamma\vec{B}_T + (1+G)\vec{B}_L + \left(G - \frac{\gamma}{\gamma^2 - 1}\right)\frac{\vec{E}\times\vec{\beta}}{c}\right]$$

and

$$\vec{\Omega}_e = \frac{e}{m}\left[\frac{\eta}{2}(\vec{E} + \vec{\beta}\times\vec{B})\right]$$

where G=1.7928474 for proton, G=-0.143 for deuteron is the anomalous g-factor, and $d = \eta\frac{e}{2mc}S$ is the electric dipole moment

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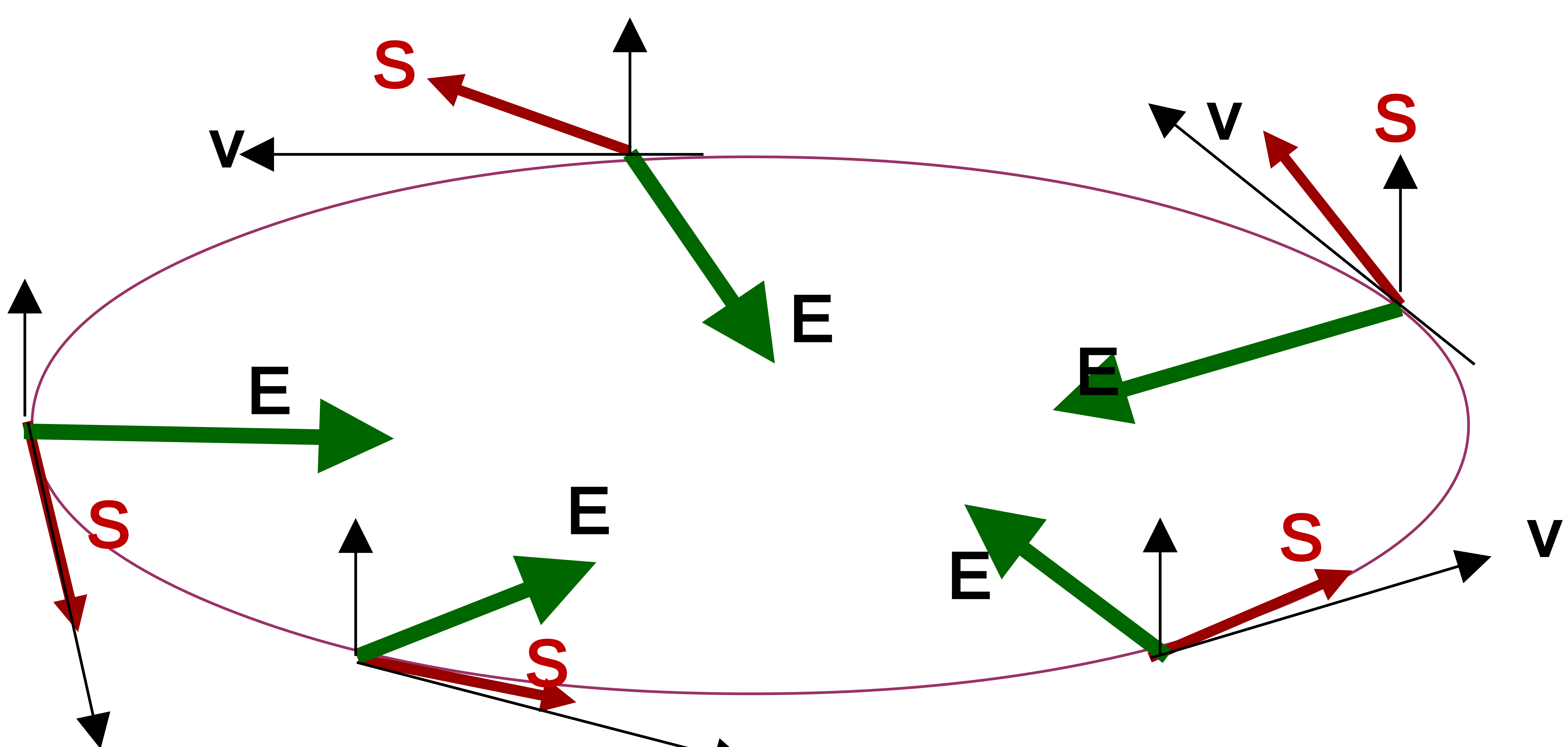
Storage Ring based EDM Search

- ❖ Frozen spin method
  - ➢ Freeze the spin motion so that polarization remains parallel to the velocity, i.e. no g-2 precession
  - ➢ Non-zero EDM results in slow vertical polarization build up in the presence of radial electric field
  - ➢ For a fixed momentum, the smaller the bending radius, the larger the EDM signal. However, the required electric and magnetic fields need to go up.



To Freeze Spin

- For the proton, one can use all electrostatic ring at a magic momentum of p= $m/\sqrt{G} = 0.701\ GeV/c$
  - This allows one to have two polarized proton beams circulating at opposite direction simultaneously
- For the deuteron, frozen spin condition can only be achieved with a hybrid of B and E bending fields

$$E = \frac{G\gamma cp}{1 + G\beta^2\gamma^2} B$$

for a ring with a bending radius of ~33m, a bender with a B field of ~0.15 T-m and E field of ~ 5MV/m is required

Key Technical Requirements

Long spin coherence time

- statistical precision for protons

$$\sigma_p = \frac{3\hbar}{P_{beam} A E \sqrt{N_{beam} f T_{spin} T_{tot}}}$$

Beam polarization

Analyzing power

Electric field

Beam intensity

Polarimeter efficiency

Spin coherence time [s]

Measurement time [s]

To reach 10^{-29} e-cm measurement within a year $T_{tot}=10^7$ sec, T_{spin} >= 1000 sec is required

Proton EDM proposal http://www.bnl.gov/edm/files/pdf/Proton_EDM_proposal_20111027_final.pdf
Deuteron EDM proposal http://www.bnl.gov/edm/files/pdf/deuteron_proposal_080423_final.pdf

Key Technical Requirements

- **Long spin coherence time**
  - **In a planar circular accelerator, spin tune spread due to momentum spread as well as betatron amplitude dependence can result in quick de-coherence**
  - **efforts required to minimize spin tune spread to maintain spin coherent precession in the horizontal plane**
- **Fast polarimeter with high efficiency**
  - one of the key constraints to desirable energy for ExB EDM storage ring
- **Investigate measures to monitor/mitigate systematic fake EDM signals**

Systematics

There are various source of unwanted fields that can induce vertical spin buildup independent of the vertical spin buildup due to EDM. The precision limit critically relies on how to mitigate/compensate these fake EDM signals

EDM Ring type	Radial magnetic field	Vertical electric field	Non-commutative spin rotation	others
Electro-static	dipole non zero $\langle B_r \rangle$ 1st order effect	Non-EDM signal cancels w. counter rotating beams	N/A	• Geometrical phase: from imperfection of E plates • fringe fields • Image current • E and B fields in RF cavity • polarimeter
ExB hybrid	Sensitive to both localized and distributed	1st order effect, and can't be perfectly mitigated with CW/CCW beams	Yes, requires ExB combined deflector to minimize the effect	• Geometrical phase • Fringe field • E and B fields in RF cavity • Stern-gerlach effect • Gravity • polarimeter

Systematics

- For electrostatic EDM storage ring with radial E field of E_r, a radial dipole field of $B_r=(d/\mu)E_r$ produces the same signal as the radial E field. For pEDM ring with E_r=10MV/m, B_r~0.13pG!
  - can be mitigated by having counter rotating beams, which split by ~2×10^{-12} m due to radial magnetic field
    - require high precision magnetometers
    - requires high precision optics measurement of the ring
  - critical to have extremely good magnetic shielding from earth magnetic field by a factor of 10^9 or better.

Systematics

- For storage ring with hybrid ExB bender,
  - noncommutative spin rotation
    - Can be minimized by using combined ExB deflectors
  - vertical electric field
    - g-2 precession rate $\omega_{Ev} = \dfrac{ge\langle E_v \rangle}{2mc\beta\gamma^2}$
    - to mitigate the effect
      - requires CW/CCW beams
      - high precision monitoring of E plates to minimize the mechanical influence on E plates from B fields
      - high reproducibility of magnetic and electric field with the reversal of magnet polarity
  - Distributed radial magnetic field or local spin rotation tilts stable spin direction away from vertical direction
    - Requires high precision orbit control to mitigate the effect

EDM@ Juelich: status and plan

- **J**uelich **E**lectric **D**ipole moment **I**nvestigation
  - Collaboration establish at the end of 2011, http://collaborations.fz-juelich.de/ikp/jedi/about/introduction.shtml
  - About 110 collaborators, from Juelich, BNL, as well as other European universities

- Has been carrying out relevant R&Ds for key technologies as well as investigating the option of dedicated EDM storage ring
  - deuteron polarimeter development at COSY
  - deuteron long spin coherence time at COSY
  - bender development for dEDM as well as pEDM
  - precursor EDM experiment at COSY

Precursor EDM measurement@CoSY

- Proposed by F. Rathmann. Partial frozen spin using an RF Wien-Filter, a device that produces transverse RF E and B fields

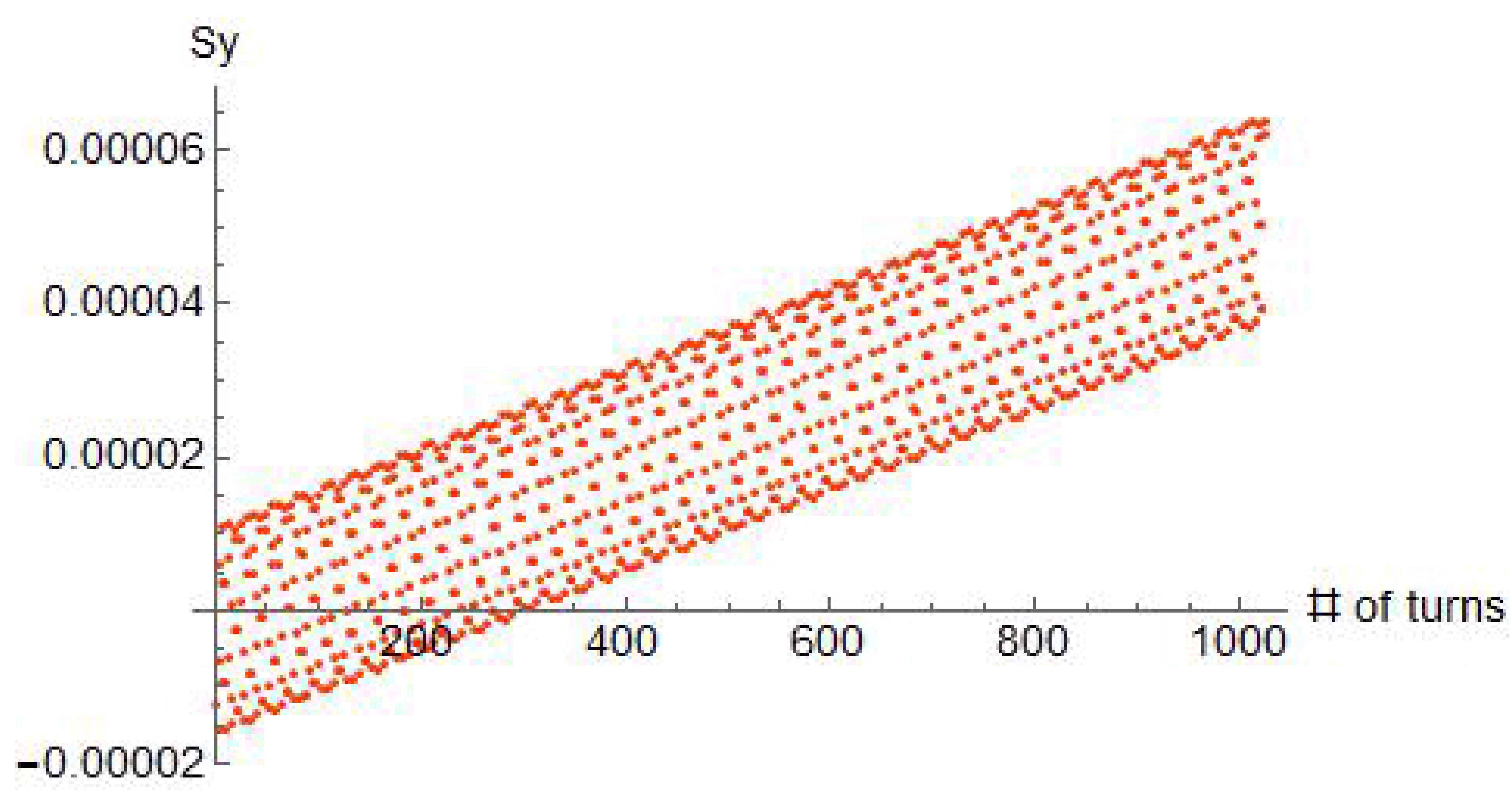
$$\vec{E} + \vec{V} \times \vec{B} = 0$$

at frequency ~750kHz. Designed amplitude of the Bx = 0.0237T-mm*

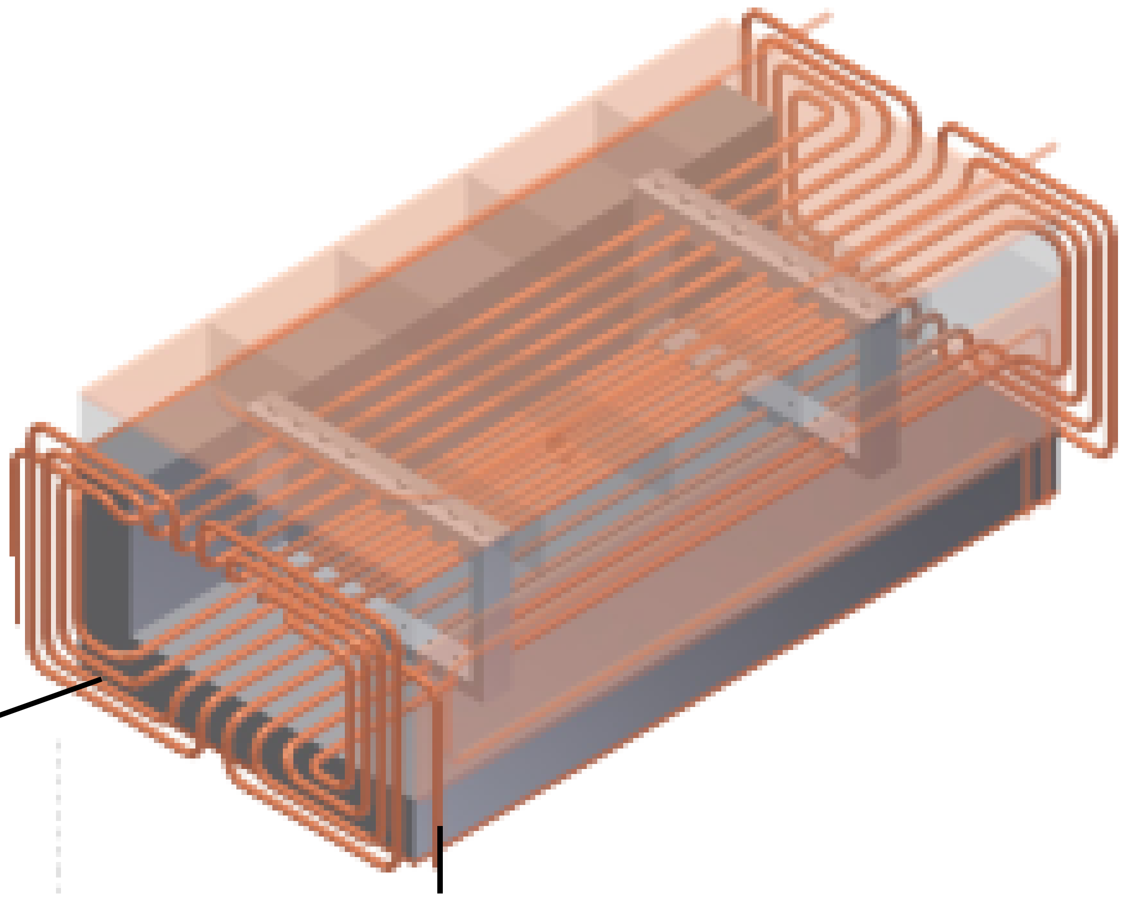
* from J. Slim, "RF Wien Filter, Effects of the support structure", JEDI collaboration meeting, March 2015

- The net effect on spin motion induces a non-zero component of spin vector along the direction of velocity, which allows the EDM build up by the B fields from all main dipoles [Y. Semertzidis, W. Morse, Y. Orlov, PRST AB 16, 114001 (2013)]

$$\frac{dS_v}{dt} = \eta \frac{e\beta b_v}{4mc} \frac{1+G}{G}$$

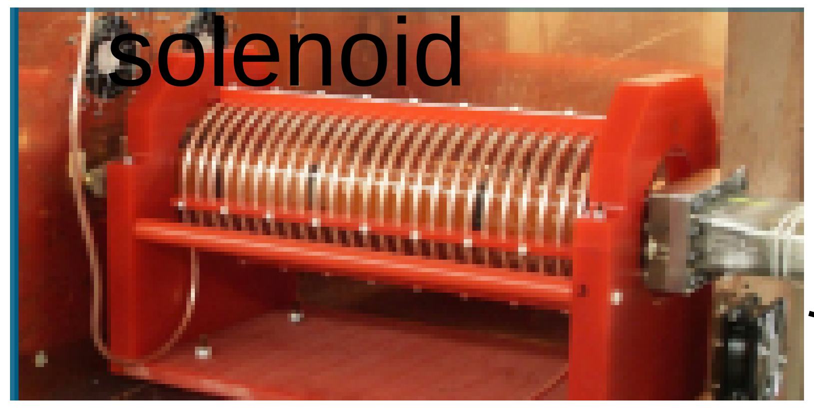


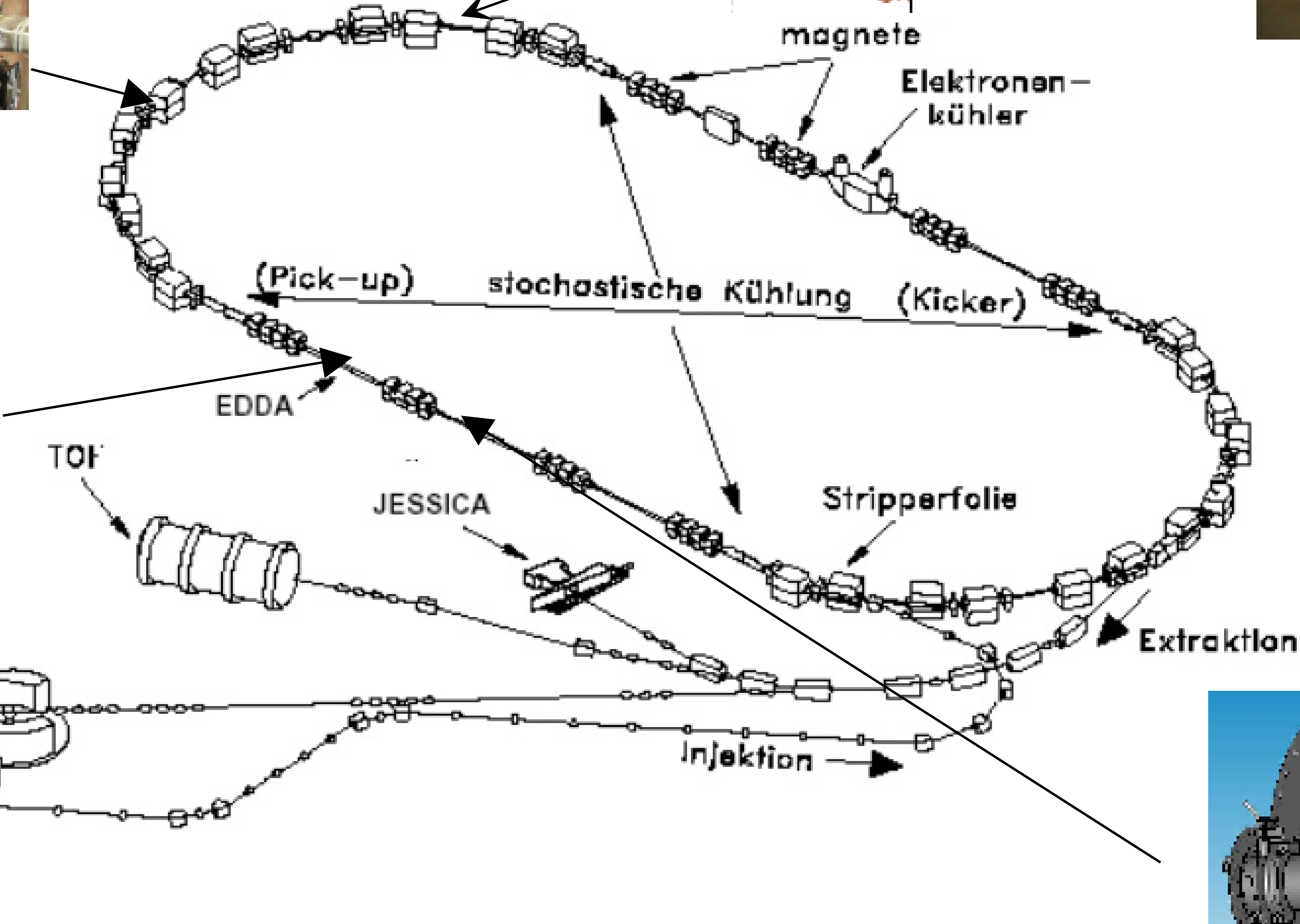
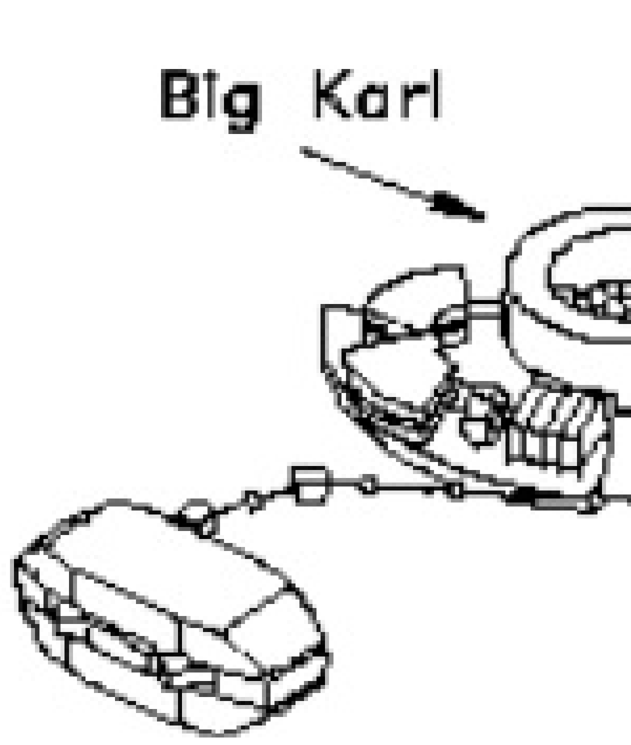
Precursor EDM measurement@CoSY



RF wien filter by
S. Mey and R. Gebel

RF
solenoid



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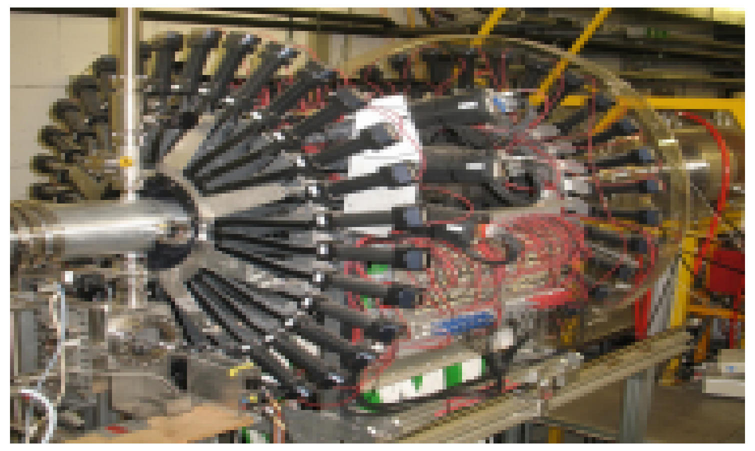
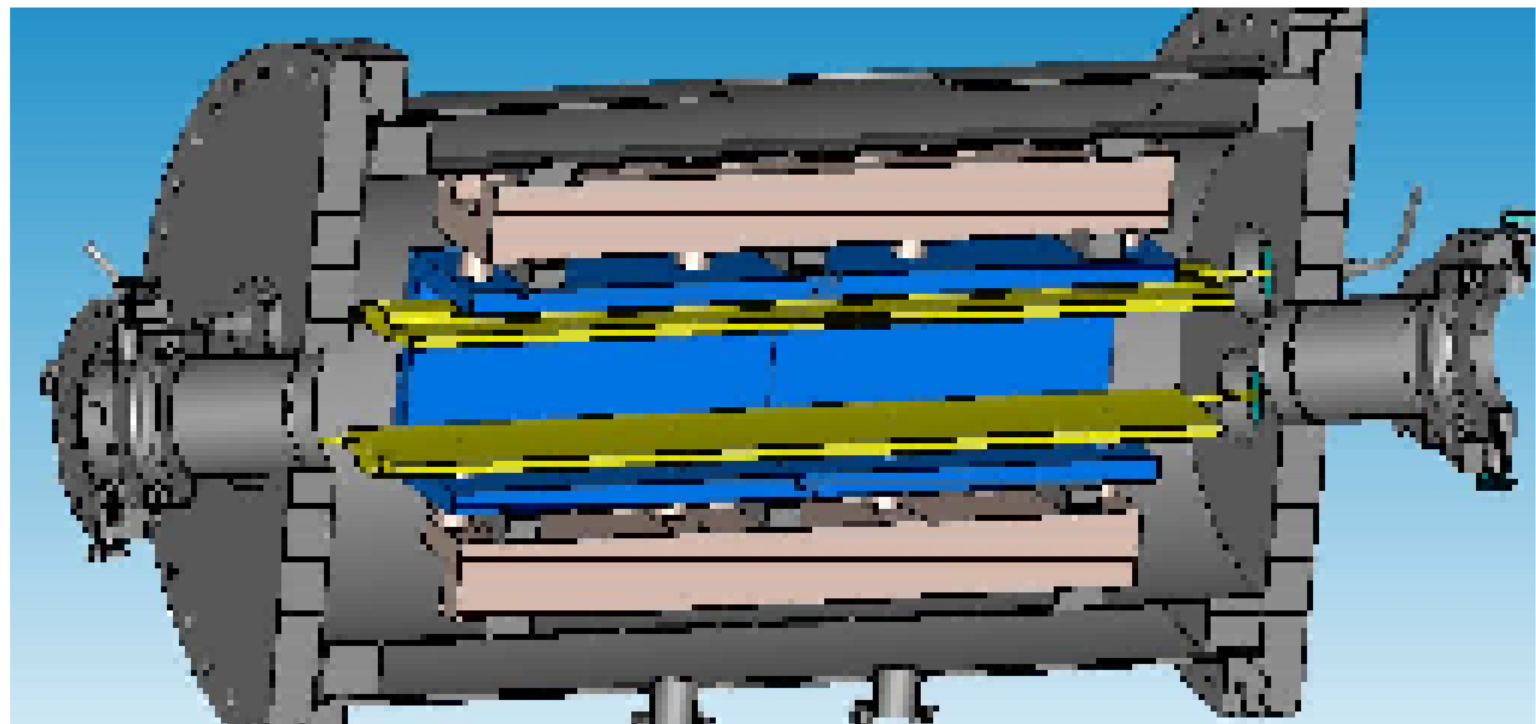
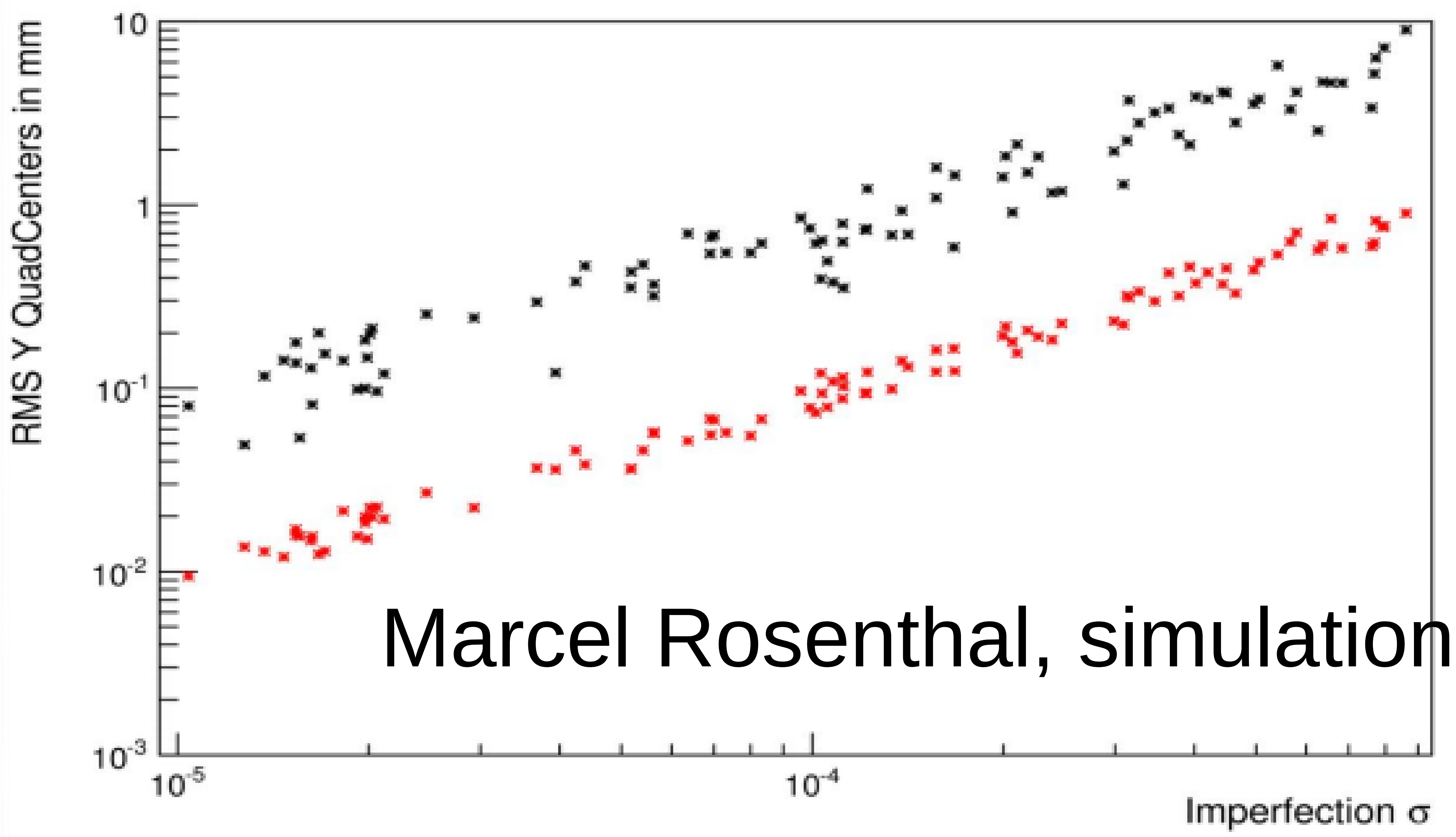


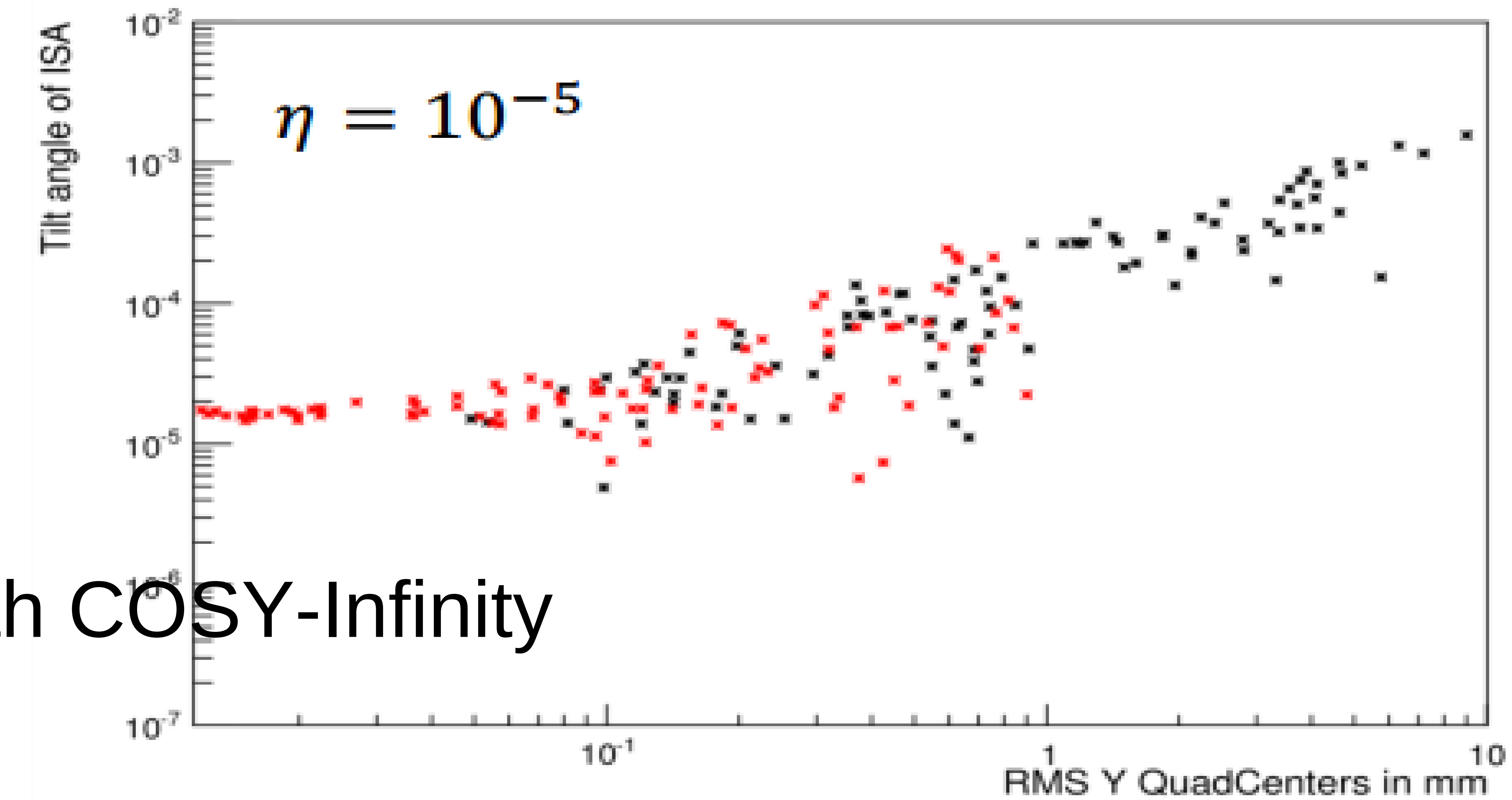
RF wien filter by
J. Slim (RWTH)



Machine Imperfection on Precursor precision

Imperfections of the machine tilts stable spin direction away from vertical.
Excluding other systematics, rms c.o ~ 100um puts the precision limit ~ 5x10^-18 e-



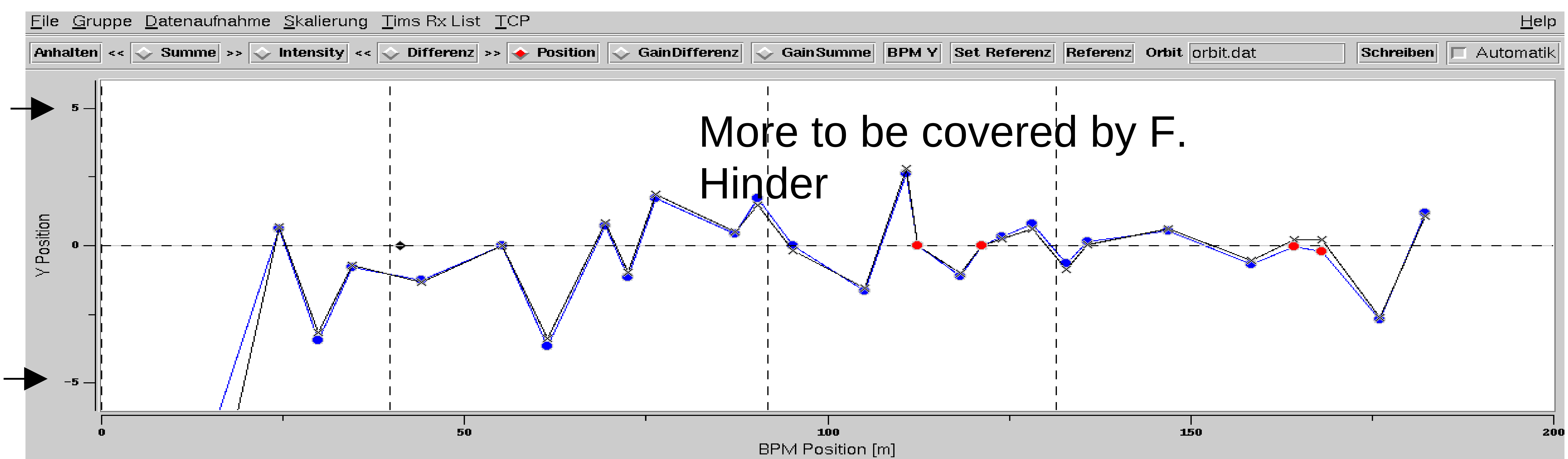


Marcel Rosenthal, simulation with COSY-Infinity

Current COSY orbit

5mm

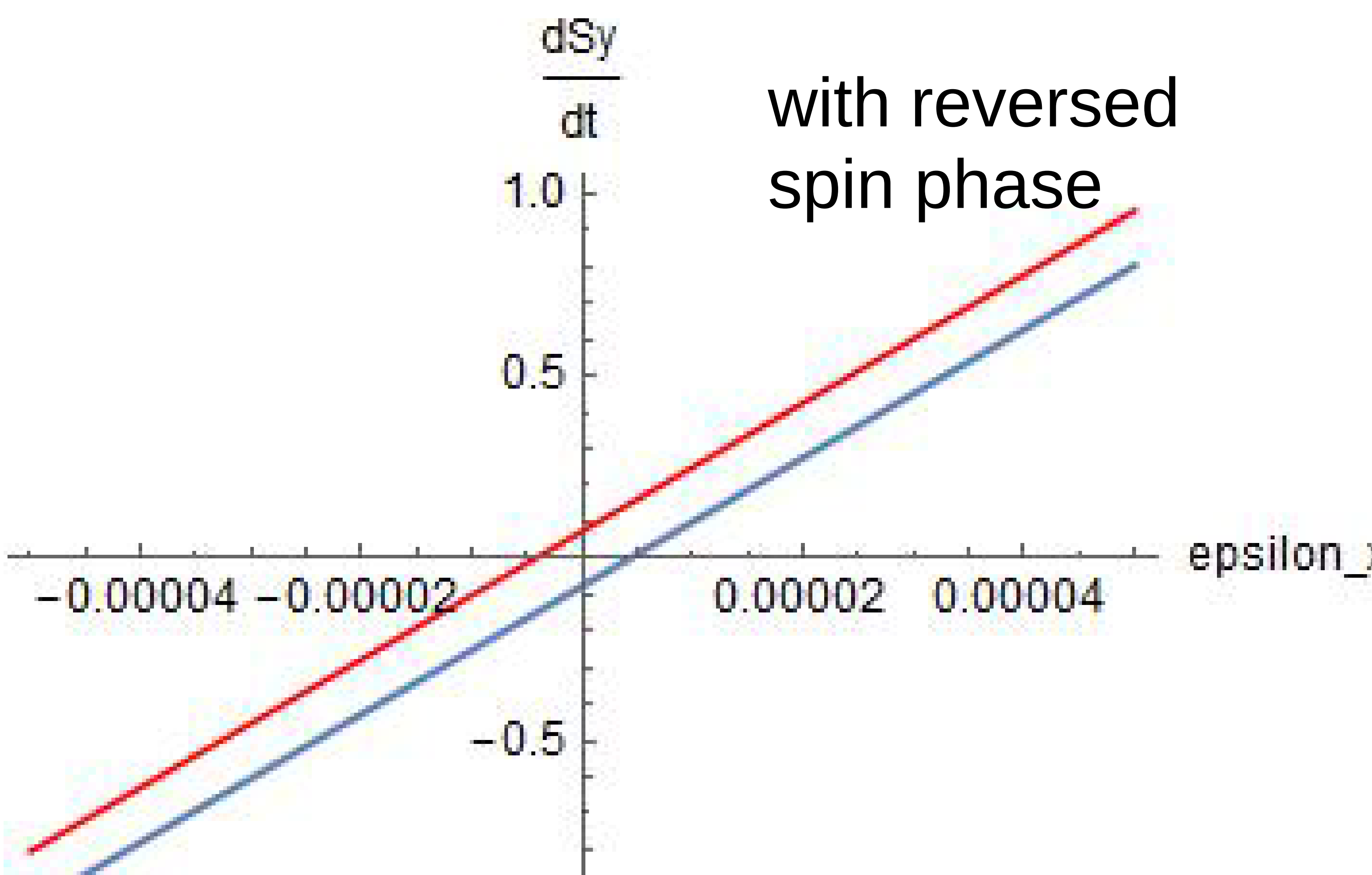
-5mm



More to be covered by F. Hinder

Mitigation

- Improve COSY beam control
  - closed orbit: F. Hinder/Trinkel, together w. COSY experts
    - Evaluate current BPM electronics
    - Determine # of bpms needed
    - Precise optics measurements
  - direct measurement of stable spin direction at RF wien filter:
    - Developed by A. Saleev, N. Nikolaev, S. Mey
- Systematic scan of closed orbit and spin phase at RF wien filter
  - Precise control of the orbit
    - reproducibility of orbit as well as other beam parameters
  - RF feedback with online polarimeter measurement

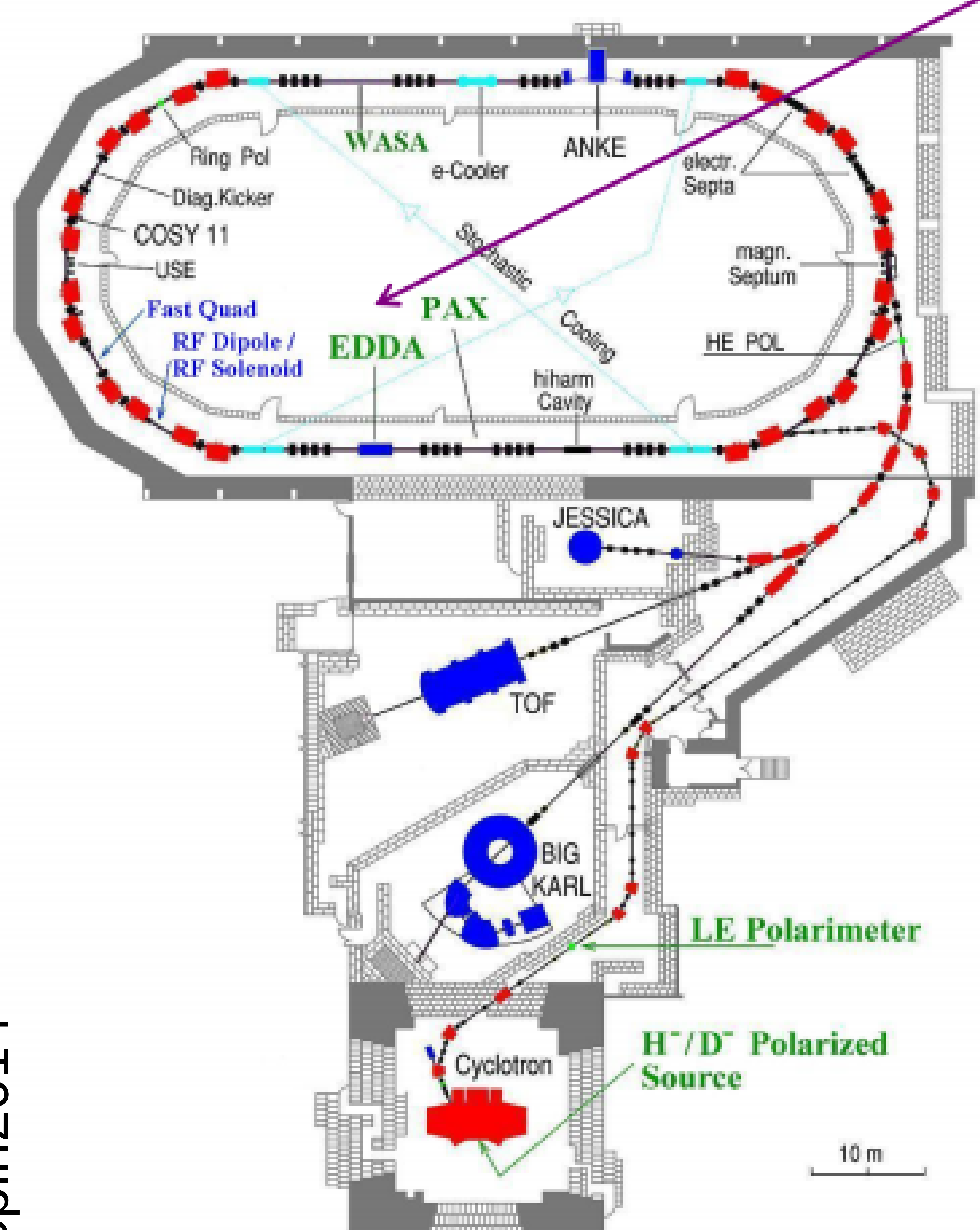


What has been achieved?

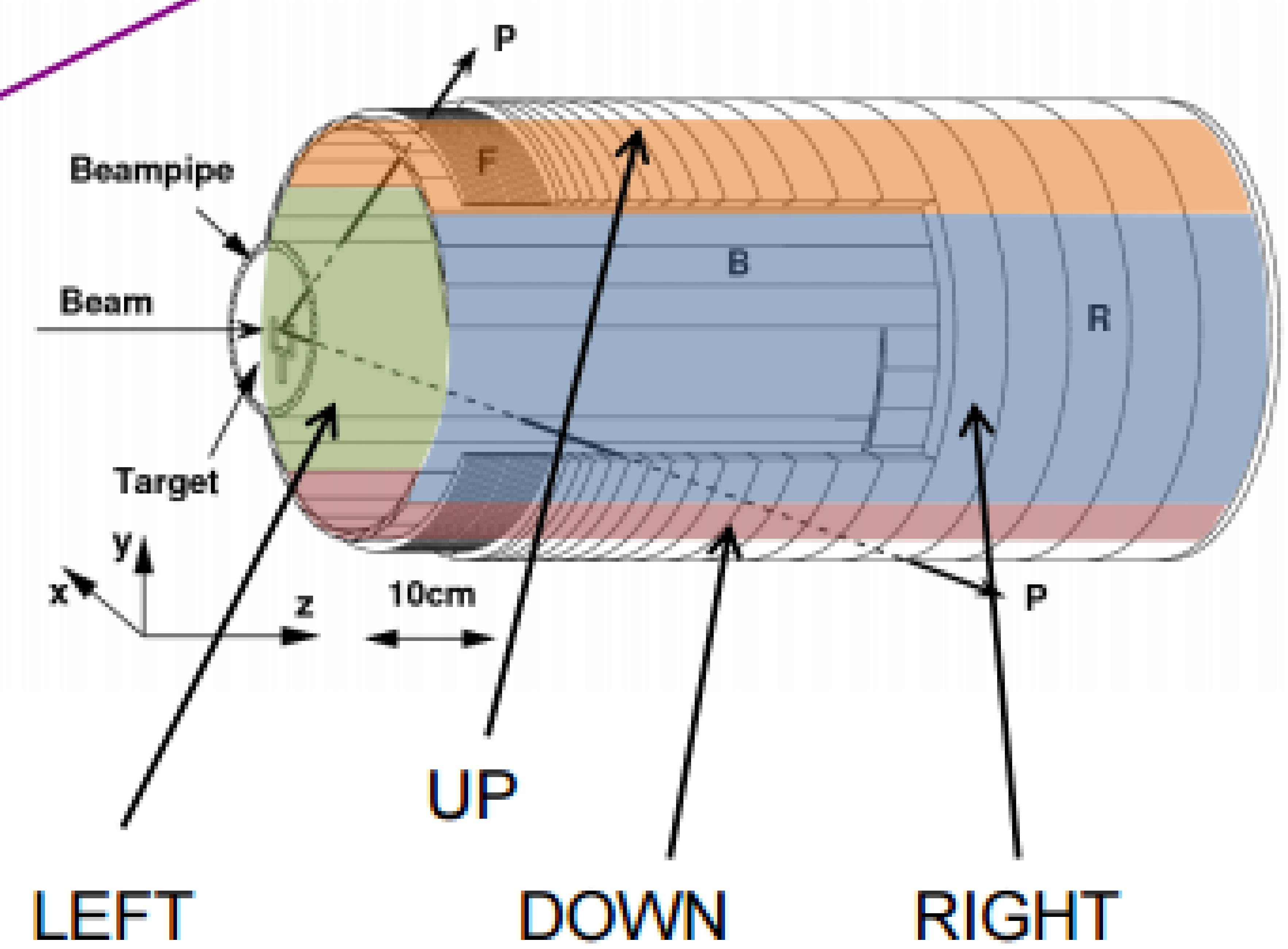
Fast polarimeter that enabled spin coherence time investigation

COSY storage ring

polarized deuterons, 0.97 GeV/c



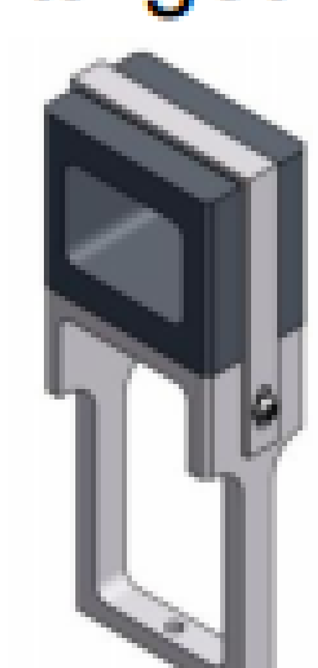
EDDA detector



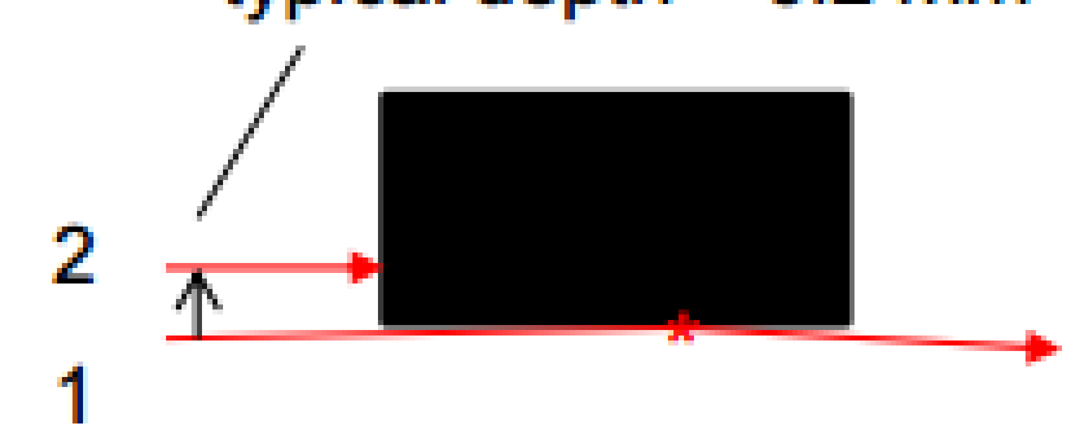
Azimuthal angles yield two asymmetries:

$$\varepsilon_{EDM} = \frac{L-R}{L+R} \qquad \varepsilon_{g-2} = \frac{D-U}{D+U}$$

17 mm C target



typical depth ~ 0.2 mm



double-hit extraction?: deflect at (1), then oscillate to (2)

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Courtesy of E. Stephenson, "Storage Ring Polarimetry", Spin2014

World-record spin coherence time

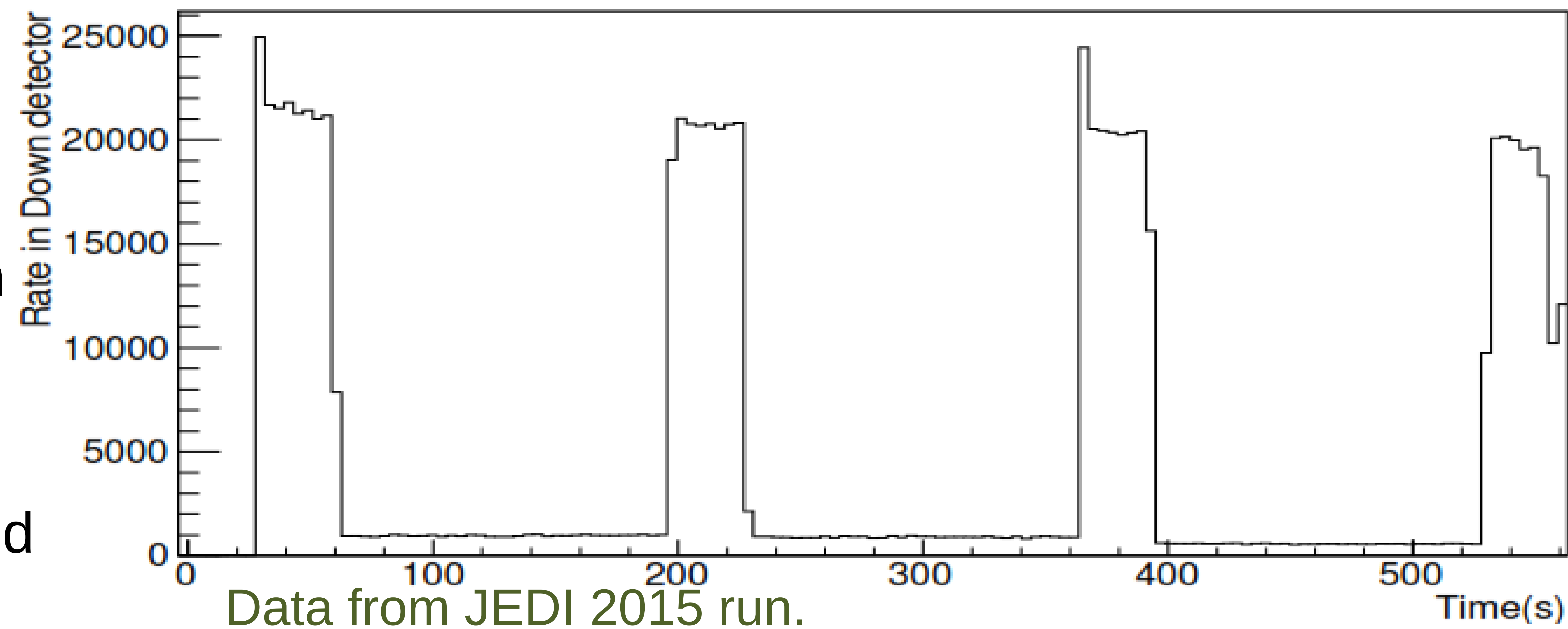
For this data set,

Beam was pre-cooled for 25sec, estimate momentum spread ~10^-5

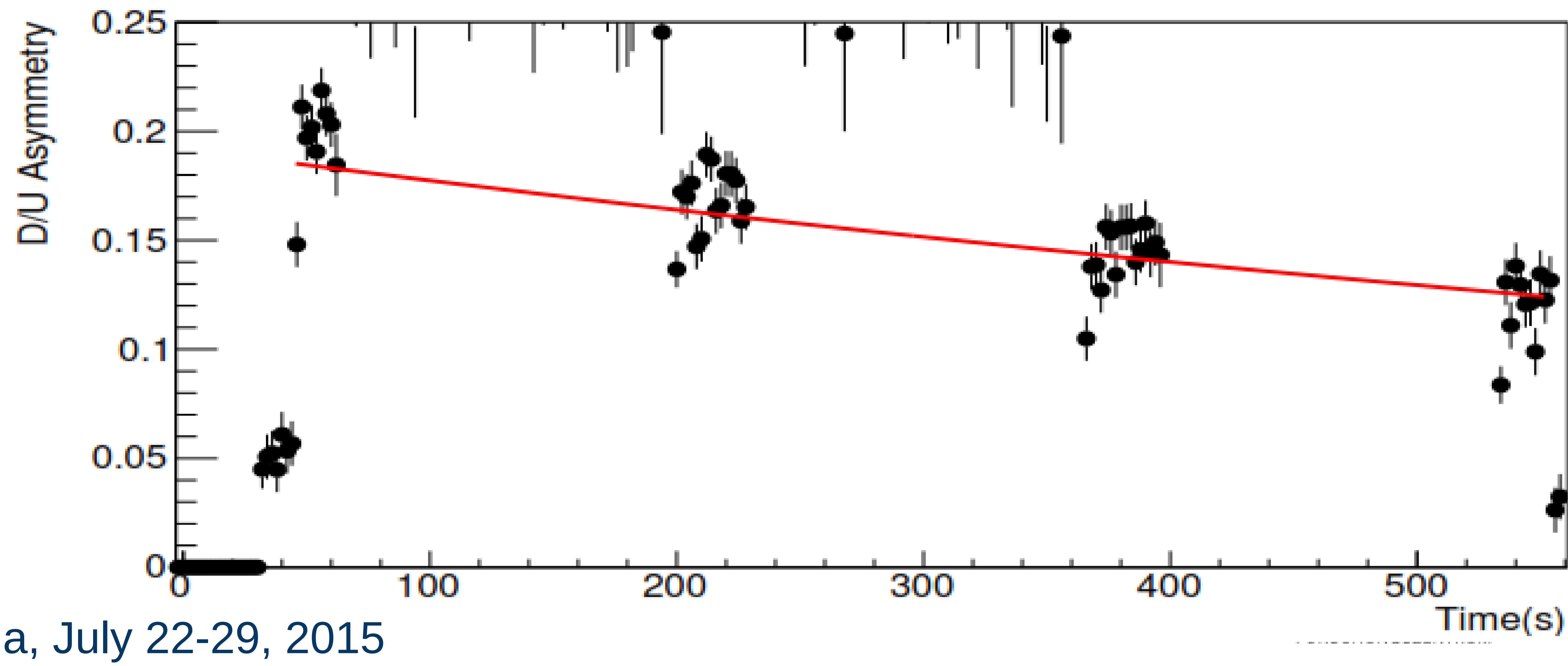
All sextupole (3 families) were optimized, and resulted in very small chromaticity in both planes

Spin coherence time reached 1268 sec

Later data with continuous cooling, ~4000 sec spin coherence was also measured



Data from JEDI 2015 run.
Plot prepared by E. Stephenson and G. Guidoboni



List of Accelerator Challenges

- ❖ Lattice design
  - ➢ Long lasting spin coherence time
  - ➢ Beam dynamics

- ❖ High precision beam control
  - ➢ Minimize absolute closed orbit
  - ➢ High precision control of reproducible orbit for monitoring and mitigation of systematics
  - ➢ High precision optics measurements to minimize the impact of blind spot due to limited # of bpms

- ❖ High precision numerical tracking tools to study systematic effects
  - ➢ Accurate description of all ring elements including fringe fields.
  - ➢ Allowing various error inputs for systematics investigation.
  - ➢ Accurate implementation of RF spin manipulation elements.
  - ➢ Precise calculation of orbital and spin motion for over 10^9 orbital turns
  - ➢ Allowing multipole particle tracking for IBS as well as beam-beam

for more details: https://indico.cern.ch/event/368912/

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List of Accelerator Challenges

- ExB bender development for dEDM ring
  - BNL 2-in-1 option to allow CW-CCW in the same vacuum
  - high precision electric field of MV/m in the presence of B fields
  - high precision reproducibility of magnetic field with reversal polarity

- High field electrostatic deflector for pEDM ring
  - EDM builtup rate is $2dE_r/\hbar$. The higher the electrostatic deflector, the higher the signal level, and more compact the storage ring
    - bending radius of ~25m corresponds to ~17 MV/m
  - to reach 17 MV/m requires substantial R&D

- Magnetic field shielding for all electrostatic ring
  - current state of the art reached by Peter Fierlinger at TUM [http://physicsworld.com/cws/article/news/2015/may/20/extraordinary-magnetic-shield-could-reveal-neutrons-electric-dipole-moment]
    - 0.5 nT in a 1m^3 volume with ~4m^3 total volume
  - still challenges ahead on how to realize it for a storage ring

Summary

- Storage ring based EDM search offers fantastic physics
- Significant effort and progress made, especially in
  - Demonstration > 1000 sec spin coherence time@CoSY
  - State-of-art deuteron polarimeter development@CoSY
  - Earth magnetic field shielding
- Work in progress
  - Beam control improvement for precursor experiment to measure deuteron EDM at CoSY with 10^-19 e-cm precision
  - Polarimeter development and more
  - High precision bpm investigation for EDM ring
  - Very high field electrostatic deflectors

Summary

❖ EDM storage ring is the ultimate marriage of science and technology between accelerator and Detector

❖ Please come and join us at JEDI@Juelich!