Storage Ring Based EDM Search Accelerator Options

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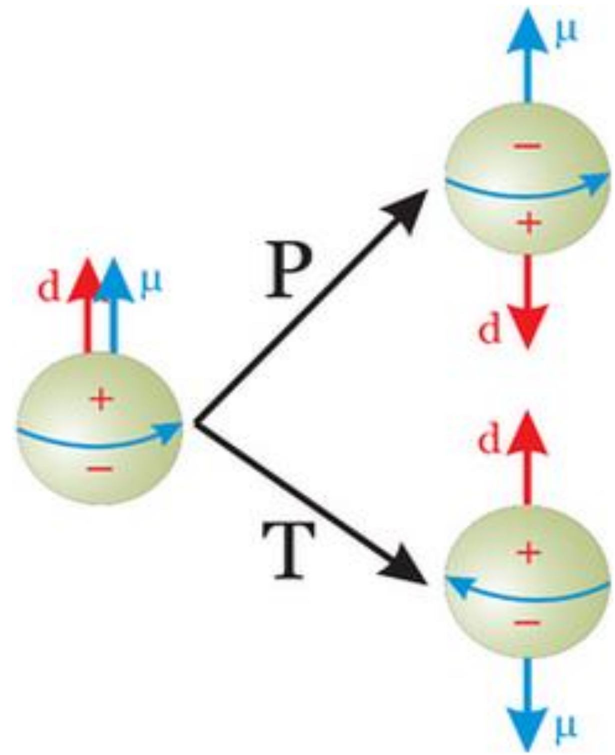
IKP-4, Forschungszentrum, Juelich

Outline

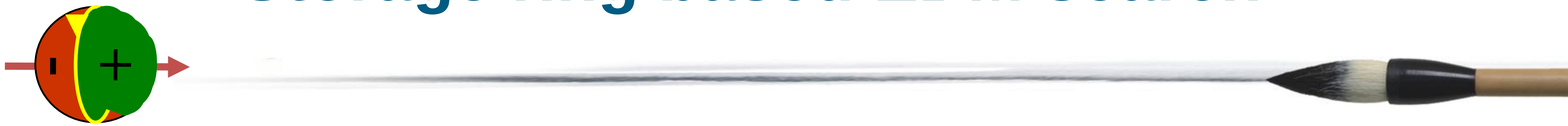
- Introduction
- Accelerator options
  - Injection
  - Storage ring
- Landscape of R&D efforts and status
- Summary
- Acknowledges

Motivation

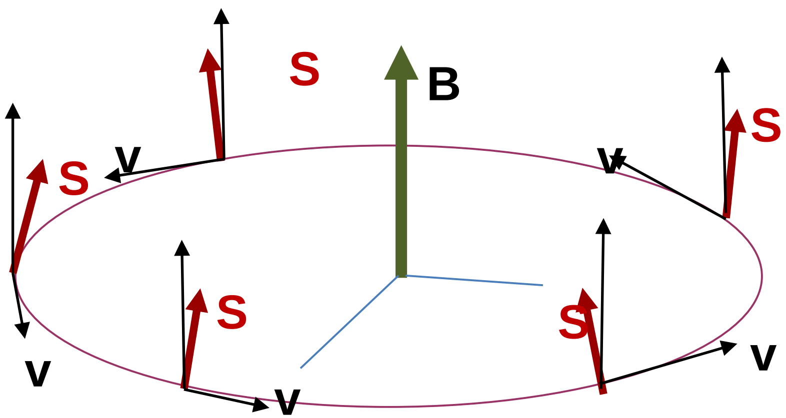
- EDM describes the positive and negative charge distribution inside a particle. It aligns along the spin axis of the particle, and violates both Parity and Time Reversal
- Typically, EDM measurement requires trapping the particle/atom for a long time
- Currently, EDM of neutron has been measured, and direct charged ion EDM hasn't yet been performed
- **For more details, please see the presentation of M. Pospelov on the EDM and precision g-2 leading to new physics morning session of Sept. 6 2016, and the presentation by T. Bowcock and Y. Semertzidis on pEDM, morning session, Sept 7, 2016**



Storage ring based EDM search



- One way to trap charged ions is storage ring
- In the absence of EDM, spin motion in a planar-circular accelerator is governed by Thomas-BMT equation
  - In a perfect case, spin vector precesses around the guiding magnet field direction, i.e. vertical
  - Spin precession frequency $f_{spin} = Q_s f_{orbit}$ and spin tune $Q_s = G\gamma$ for the ideal case, i.e. particle on closed orbit in an error free accelerator



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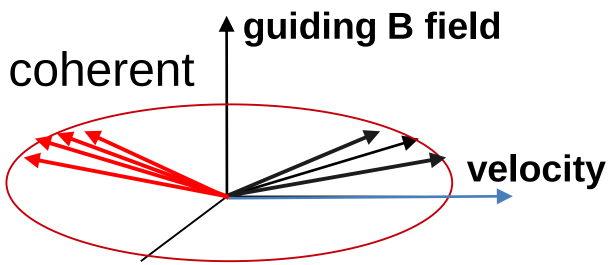
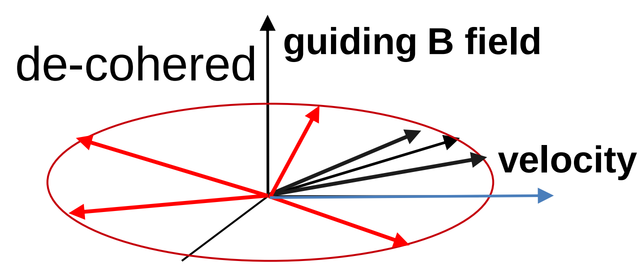
$$f_{spin} = Q_s f_{orbit} \qquad Q_s = G\gamma$$

  - The spin precession frequency can be different for different particles due to the spread of trajectories and momentum
    - ➢ **spin de-coherence**





Storage ring based EDM search

- In the presence of EDM,

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times \left[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} + \left(G - \frac{\gamma}{\gamma^2 - 1}\right)\frac{\vec{E}\times\vec{\beta}}{c} + \boldsymbol{d}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}}) \right]$$

- **Null to remove the MDM contribution to spin motion. And glue the spin vector along the particle's velocity in the horizontal plane**

Storage ring based EDM search

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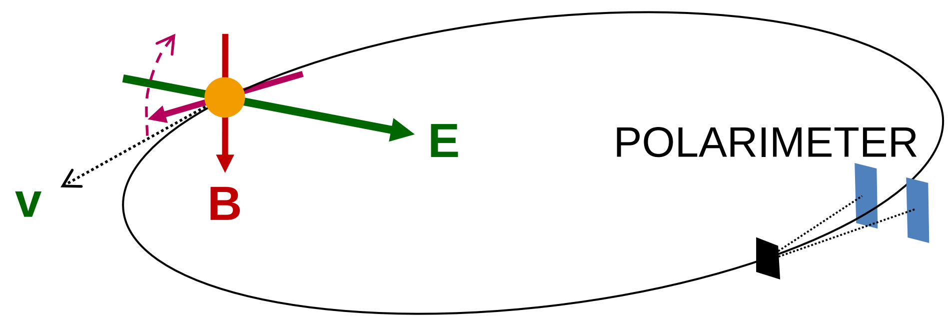
- **Null to remove the MDM contribution to spin motion. And glue the spin vector along the particle's velocity in the horizontal plane**
  - **Non-zero EDM results in the vertical polarization buildup**

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [\boldsymbol{d}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}})]$$



courtesy of E. Stephenson

⇩

Full Spin Frozen storage ring is the most effective way!

Storage Ring EDM search main challenges

- Spin frozen condition
- Long spin coherence time
- Fast polarimeter with high efficiency
  - Measure the spin buildup due to EDM signal
  - Spin manipulation
- Monitor/mitigate systematic fake EDM signals due to various sources of un-wanted fields
  - a radial magnetic field of $B_r = \frac{d}{\mu} E_r$ produces the same signal through MDM as radial E_r on EDM
    - **Can be mitigated by CW-CCW rotating beams**
  - Requires high quality control of the magnetic/electric fields, and high precision beam monitoring/control

To Freeze Spin

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times \left[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} + \left(G - \frac{\gamma}{\gamma^2 - 1}\right)\frac{\vec{E}\times\vec{\beta}}{c} + \boldsymbol{d}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}})\right]$$

For positive G factor particles, spin frozen with p= $m/\sqrt{G}$ in a ring with out B field

For negative G factor particles, spin frozen with $E = \frac{G\gamma c p}{1 + G\beta^2\gamma^2} B$

To Freeze Spin

For proton, G=1.793 and a electrostatic storage ring at magic momentum

$$p = m/\sqrt{G} = 0.7007\ GeV/c$$

For deuteron G=-0.143, a storage ring with ExB combined deflectors that fulfill

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

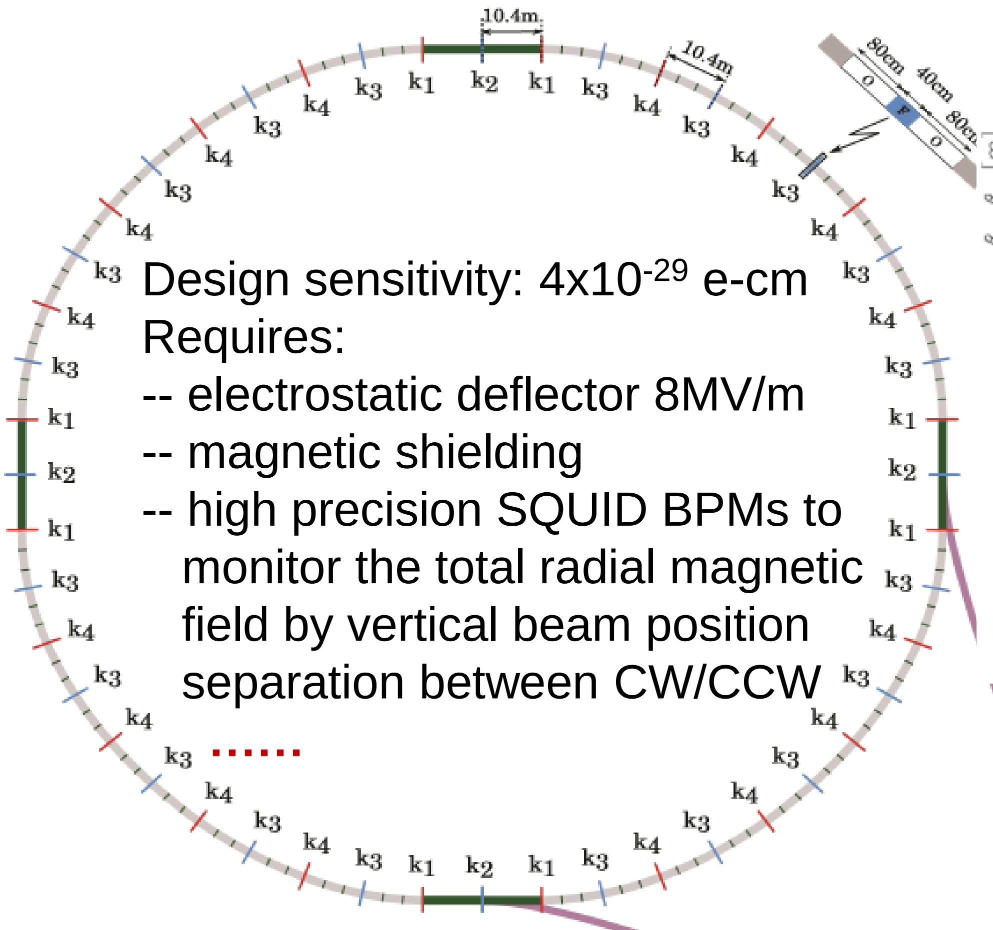
	Bending radius[m]	Deflector E field strength	Deflector B field strength	CW/CCW same orbit/time
pEDM	52.3	8.017 MV/m	--	yes
dEDM	52.3	2.3 MV/m	0.07 Tesla	no
dEDM	26.4	4.54 MV/m	0.153 Tesla	no
pEDM	26.4	15 MV/m	--	yes

Key: high field electrostatic deflector

Key: ExB deflector

pEDM Storage Ring

Pure Electrostatic Storage Ring for proton EDM



Design sensitivity: 4×10^{-29} e-cm

Requires:

-- electrostatic deflector 8MV/m

-- magnetic shielding

-- high precision SQUID BPMs to monitor the total radial magnetic field by vertical beam position separation between CW/CCW

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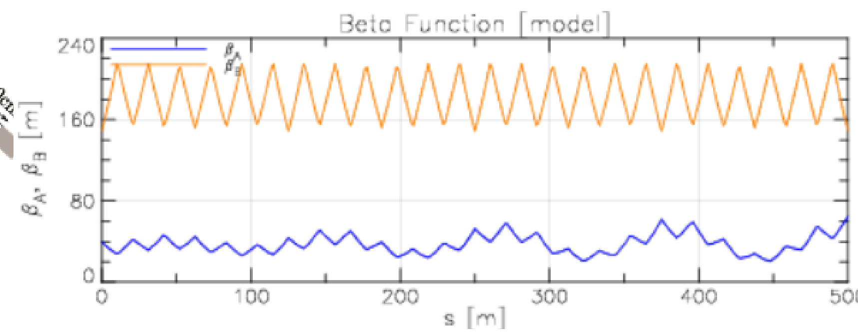
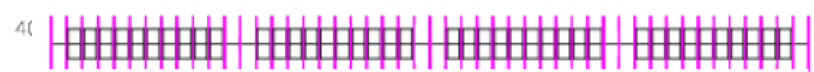




Bending radius	52.3 m
circumference	500 m
Electrode spacing	3 cm
Deflector shape	cylindrical
Harmonic, RF[MHz]	100, 35.878
Q_x, Q_y	2.42, 0.44
ε_x , ε_y [mm-mrad]	17, 3.2
maximum $\frac{dp}{p}$	4.6×10^{-4}
Dispersion, max [m]	30 m

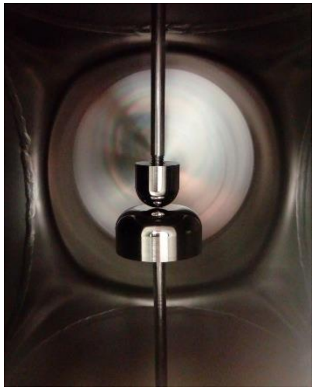
V. Anastassopulos et al, https://arxiv.org/abs/1502.04317

Spin Frozen Bending Elements R&D

High Field Electrostatic Deflector

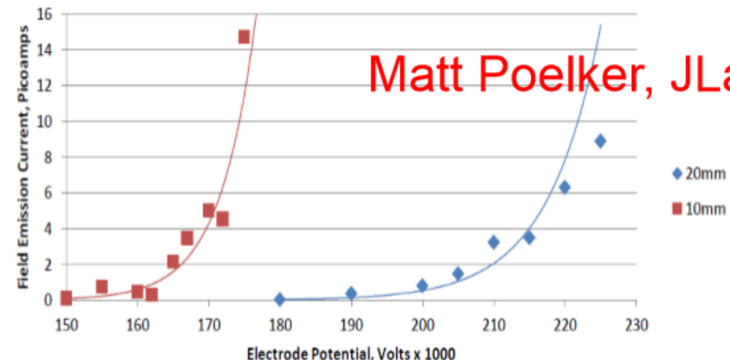
- 10 MV/m at a gap of 40mm was achieved at JLab HV electrode for electron source
- Large scale full prototype is in working progress
- ~17MV/m over 1 mm gap was also achieved at RWTH Aachen

K. Grigorey, Aachen electrostatic deflector development, JEDI Collaboration Meeting, Sept. 2016

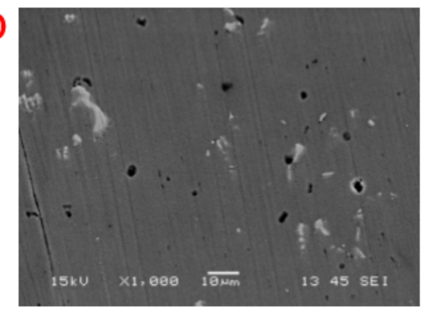


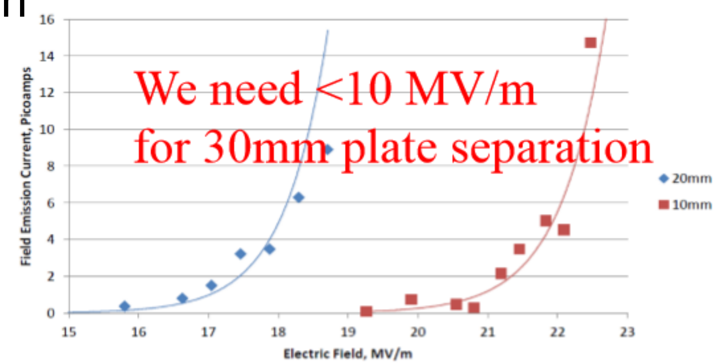
JLab results with TiN-coated Aluminum

No measureable field emission at 225 kV for gaps > 40 mm, happy at high gradient



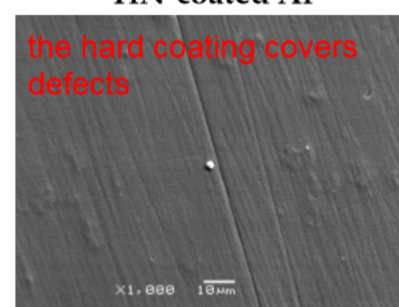
Bare Al





15 MV/m 20 MV/m

TiN-coated Al



Work of Md. A. Mamun and E. Forman

From Y. Semertzdis

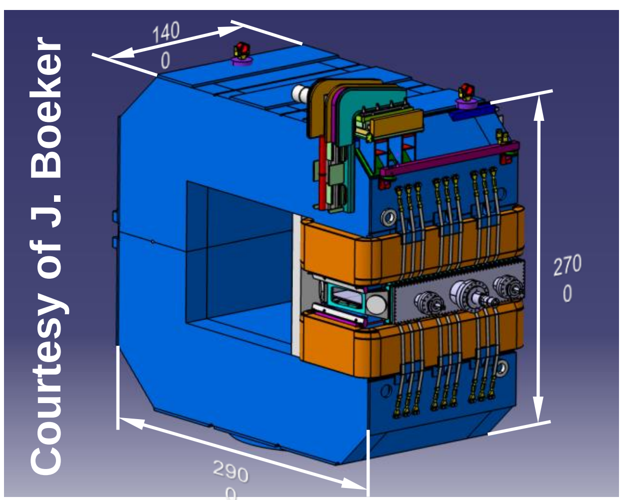
JÜLICH FORSCHUNGSZENTRUM

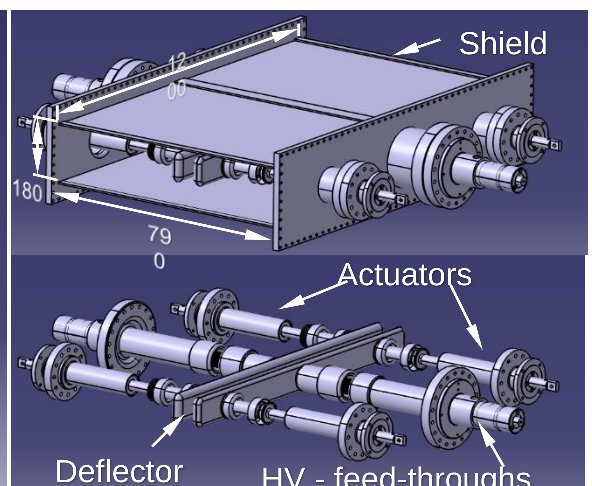
Spin Frozen Bending Elements R&D

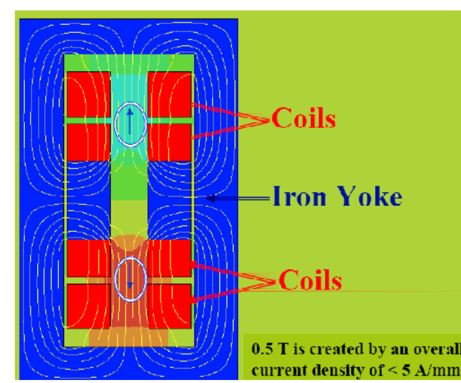
ExB deflector R&D@COSY

- Test setup using existing ANKE-D2 magnet together with electrostatic plates to study the effect of magnetic field on the E field strength to investigate the feasibility of ExB deflector for spin frozen storage ring with E up to 8MV/m and B up to 0.3 Tesla

- **If feasible, develop a prototype with dual B fields over common vacuum pipe and electrostatic plates**



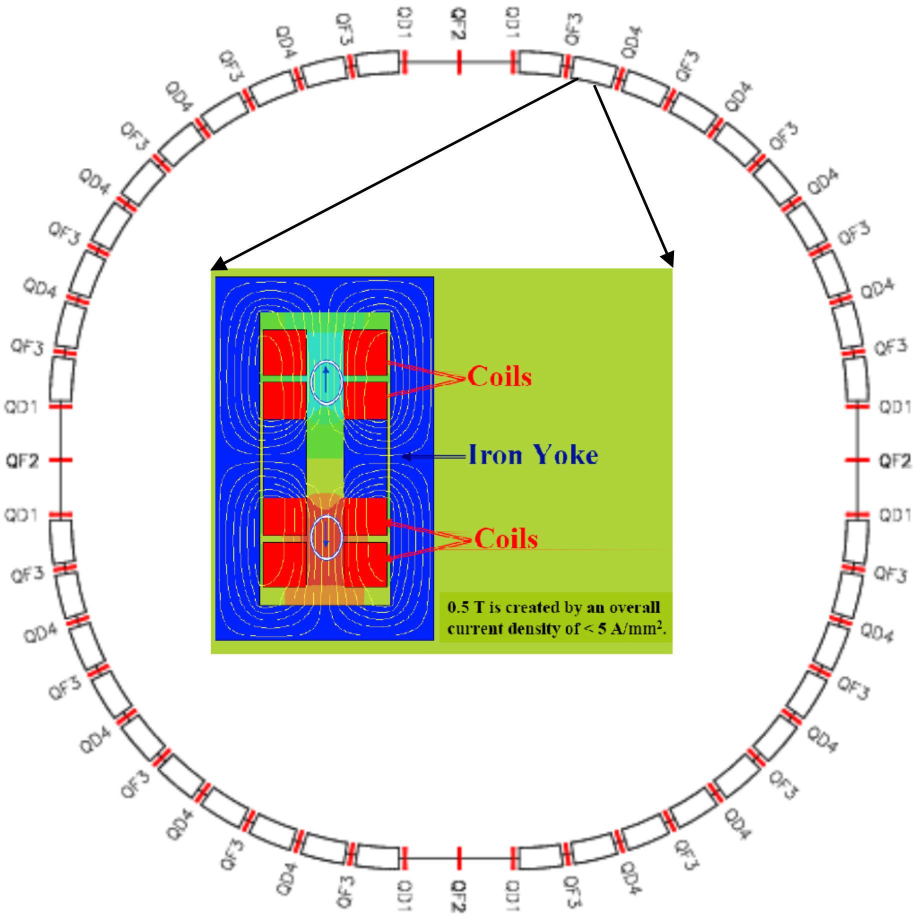




Design by Gupta, BNL

EDM Storage Ring

Deuteron EDM storage ring



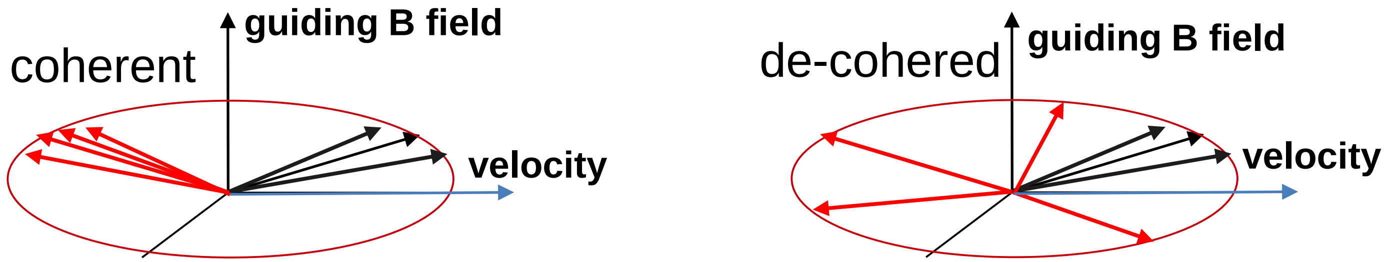
dEDM Uniqueness

- Also needed for solving the mystery of CP violation
- The spin coherence time has been experimentally achieved
- The tensor polarization effect needs to be mitigated, and maybe a tool for additional polarization monitoring/measurement(?)
- Could be a intermediate step towards the holy grail of 10^{-29}e-cm

With ExB components, this storage ring can also be run in pure electrostatic mode with B=0 for proton

Spin Coherence Time

- To reach 10^{-29} e-cm, >1000 sec spin coherence time is required



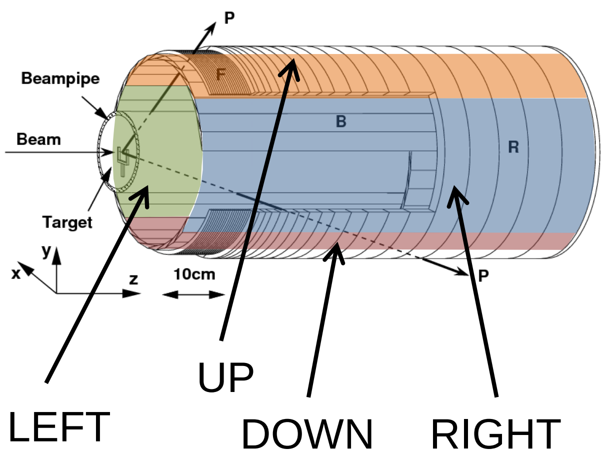
  – More details see T. Bowock's talk

- Requires careful design of lattice design, as well as tuning/beam control
  - Control spin tune spread by chromaticity 1st achieved in VEPP-2M
  - **With pre-cooled polarized deuteron beam, >1000s spin coherence time was experimentally achieved at COSY:** PRL **117**, 054801 ('16)
  - In the absence of beam cooling, one can also minimize spin tune spread by scraping the beam at injection
    - Requires high current polarized ion source
    - Demonstrated at the AGS of BNL

What have been achieved?

Fast polarimeter@COSY that enabled spin coherence time investigation

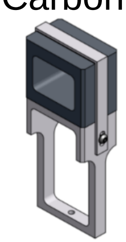
EDDA detector

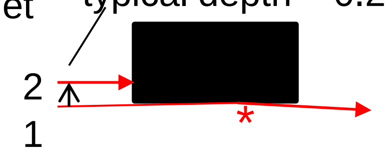


Azimuthal angles yield two asymmetries:

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

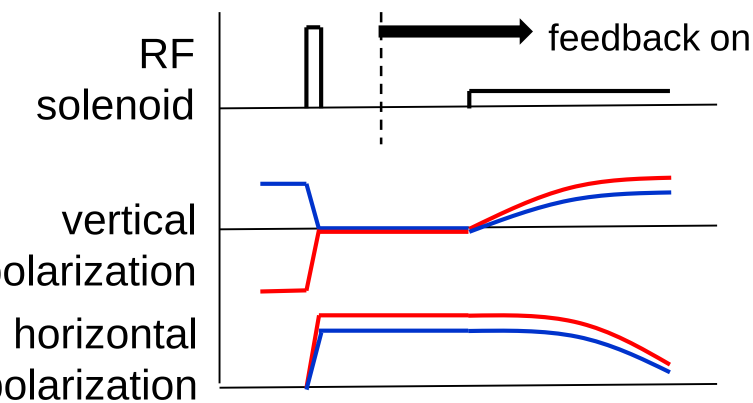
17 mm Carbon target

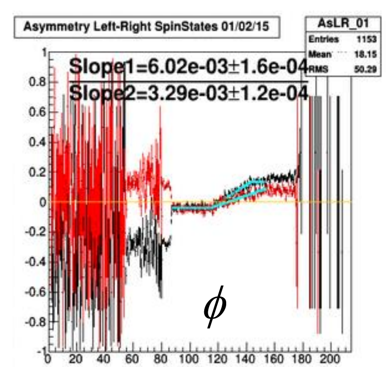


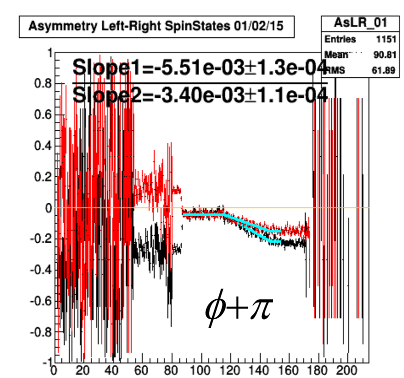


double-hit extraction?:
deflect at (1), then oscillate to (2)

Real time feedback to control the spin phase at the polarimeter was demonstrated in the latest JEDI beam time at COSY





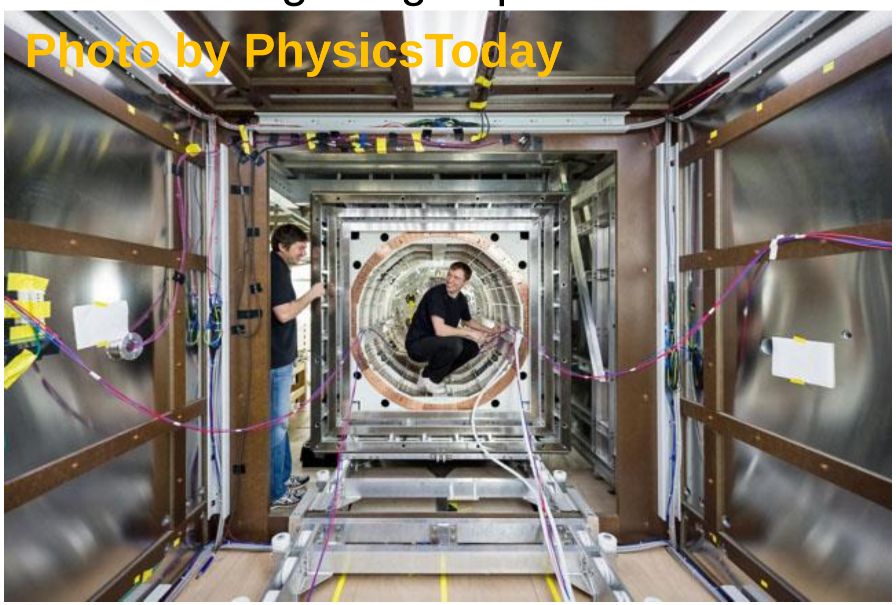


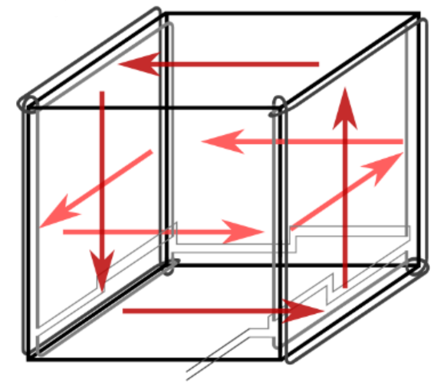
Courtesy of E. Stephenson

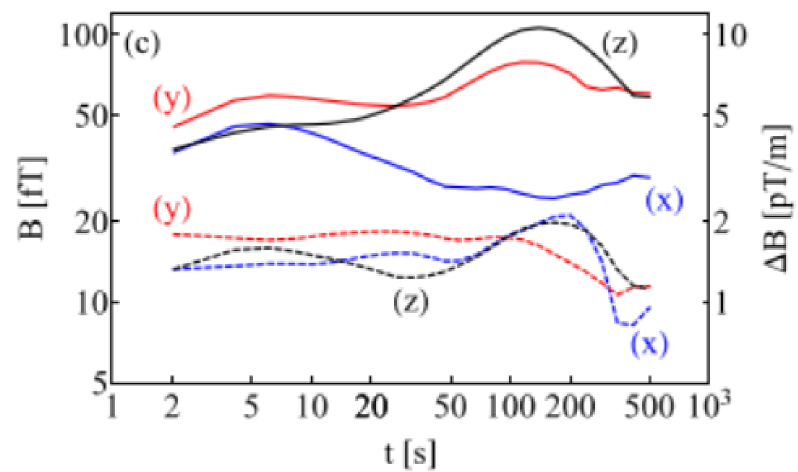
Magnetic Shielding

< 1 nT large scale magnetic shielding has been achieved in a 4 m^3 space!

- Two layers of MSRs that can be individually equilibrated
- Each MSR consists with multi-layer of Permalloy and high conductive material
- Additional equilibration coils to provide simultaneous flux path in both directions
- R&D at CAPP in Korea to achieve below 0.5 nT, 0.1nT/m in a volume of ~3m long cylinder w. 80cm diameter is in working-progress led by Dr. Semertzidis and Dr. Haciomeroglu in collaboration with Dr. Fierlinger's group







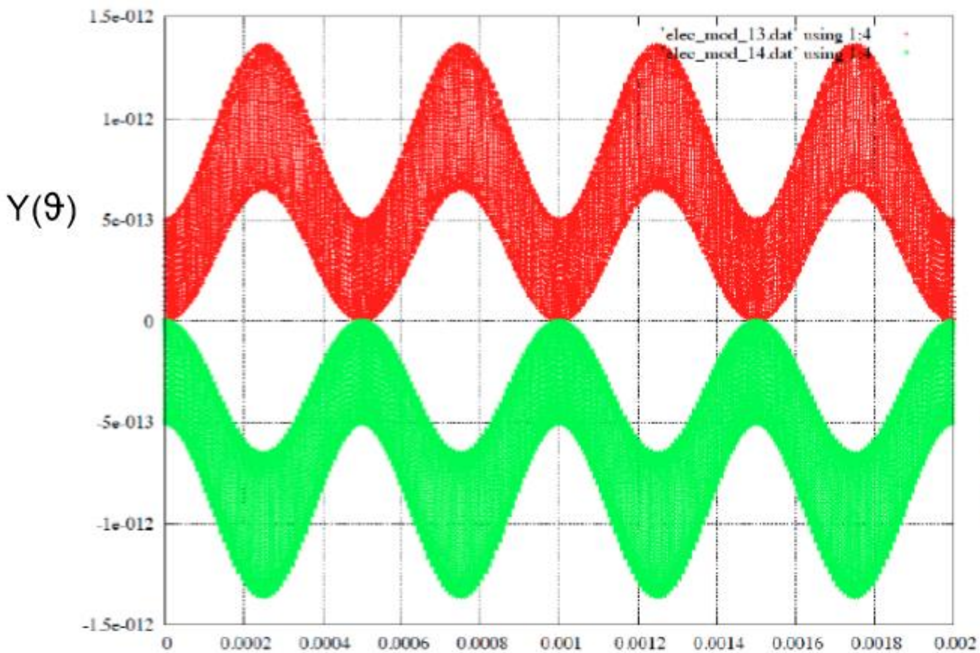
I. Altarev et al.,*J. Appl. Phys.* 117, 183903, 2015, Fierlinger's group@TUM

Residual Magnetic Field

- The residual radial magnetic field can be monitored by measuring the vertical separation of the beam

Closed orbit distortion due to N^{th}-- harmonic of the radial magnetic field

$$y(\vartheta) = \sum_{N=0}^{\infty} \frac{\beta R_0 B_{rN}}{E_0 \left(Q_y^2 - N^2\right)} \cos\left(N\vartheta + \varphi_N\right)$$



Clockwise beam

The N=0 component is a first order effect!

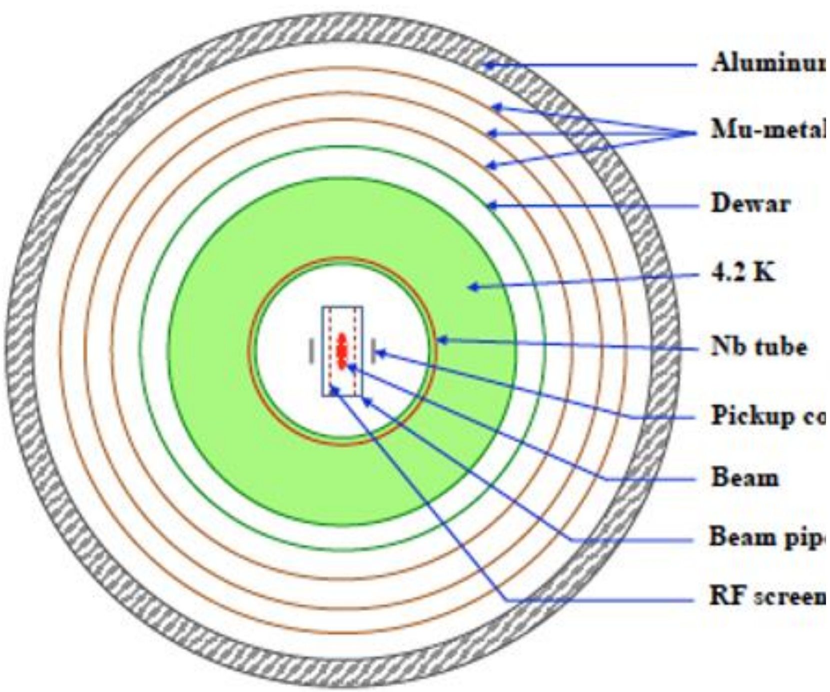
Counter-clockwise beam

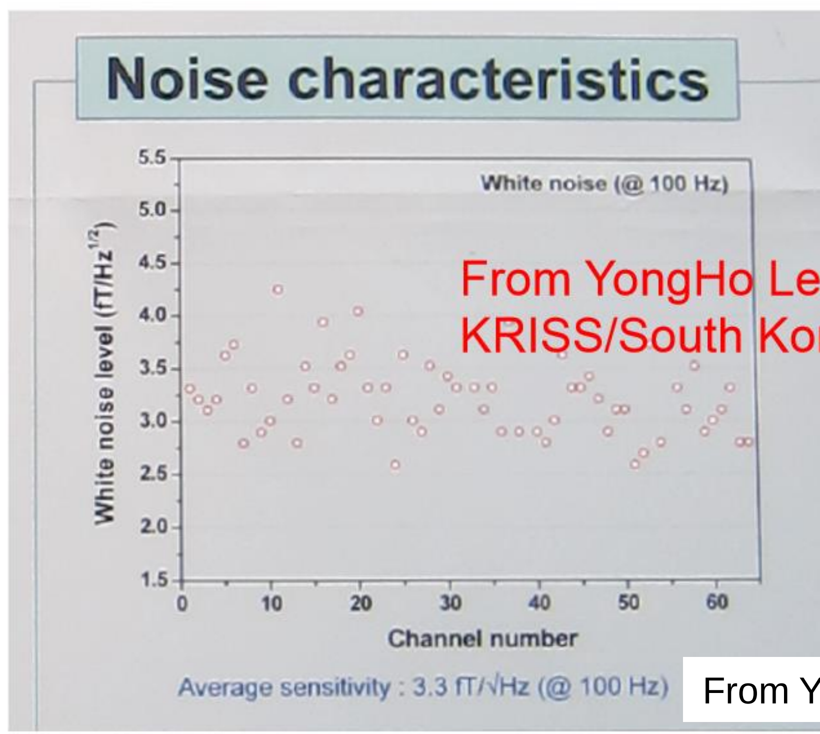
From Y. Semertzidis

More details in T. Bowcock's presentation Sept. 7, 2016

High precision beam position monitor

- SQUID to detect the vertical separation at 1-10kHz
- Sufficient # of SQUID bpm distributed around the ring
- Currently under development at CAPP in Korea
  - Commercially available low noise SQUID (KRISS)
- Very close to the target
- Can be further improved

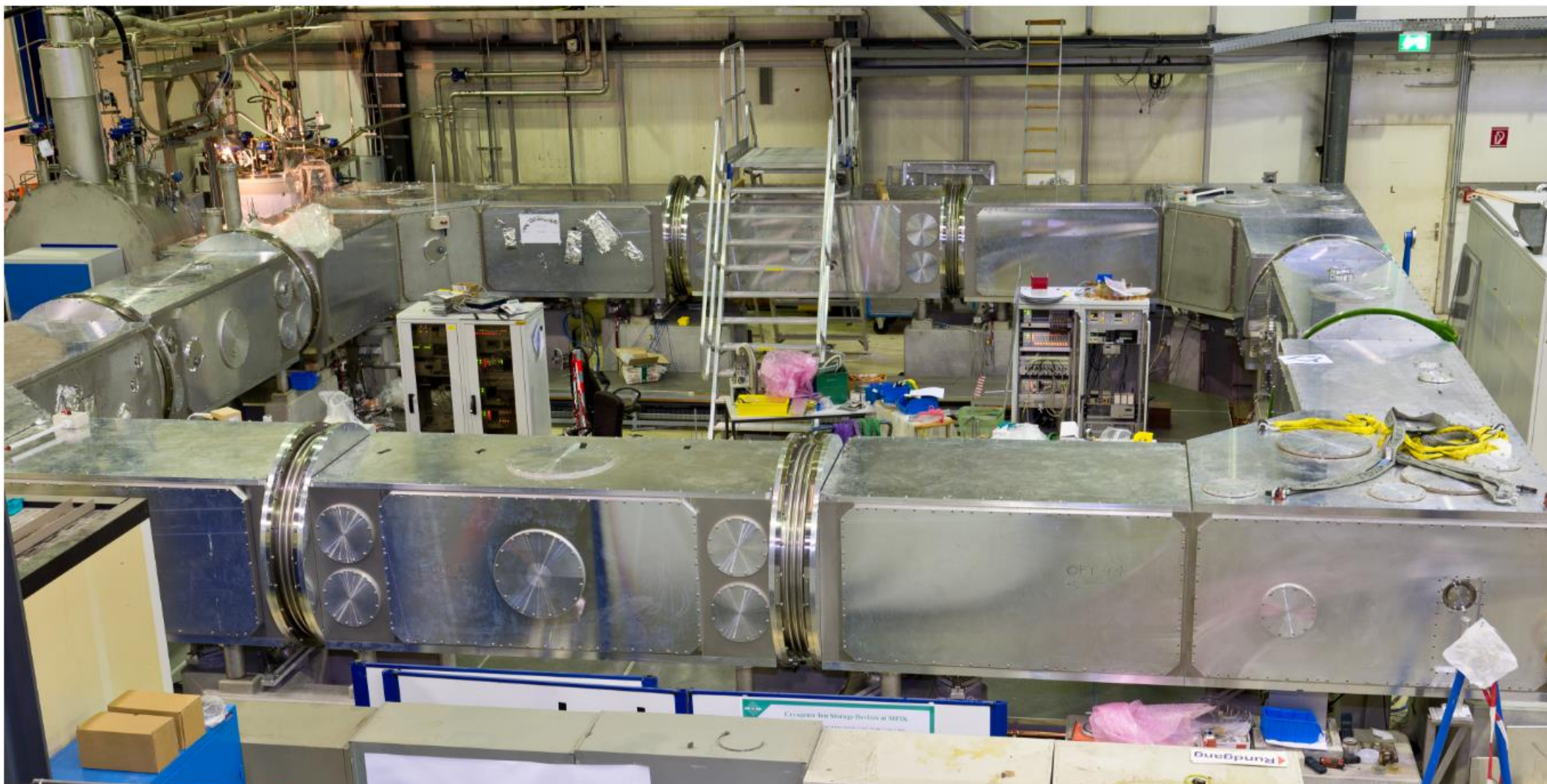




From Y. Semertzidis

A fully Shielded Storage Ring

- Will be one of a kind for scale of a storage ring
- The Cryogenic Storage Ring (CSR) at Heidelberg is fully enclosed in a cryogenic vacuum system of 35 m circumference



Polarized Beams for EDM Storage Ring

- Polarized ion source and injector
  - Polarized ion source
    - BNL OPPIS: high intensity high polarization polarized H-
    - Atomic beam based ion source
      - polarized deuterium is also available
      - mA current can also be reachable
  - Injector
    - option A: LINAC-4 160 MeV proton to Booster and accelerates to ~245 MeV
      - Pro: no intrinsic spin resonance
      - Con: injection energy close to $G\gamma=2$
    - alternatives:
      - 50 MeV proton from LINAC to Booster
      - LINAC-4 deliver 245MeV proton beam to pEDM ring?
    - for deuterons, LEIR could be an option?

Thanks to CERN colleagues for the lattice and and Y. Dutheil for the depol calculation

Summary

- Storage ring based EDM search offers fantastic physics
- Significant effort and progress are made worldwide
  - Experimental demonstration of long spin coherence time
  - The new low magnetic field shielding
  - High efficient polarimeter for deuteron beam that enabled key spin manipulations
  - Many others …
- For the implementation of the EDM ring, things to consider
  - the progress of the ongoing R&D efforts worldwide
  - scenarios that allow the search of EDM of multiple ion species for fully understand the CP violation
  - and with this in mind, a staged approach for reaching the holy grail of 10^{-29} e-cm or better sensitivity may benefit the community, both physics and accelerator, in the long run

Acknowledge

Thanks the workshop organizer for the invitation

Many thanks for the fruitful discussions with many colleagues
E. Stephenson, Y. Semertzidis, T. Bowcock, F. Rathmann, H. Stroeher, etc

Special thanks to D. Sagan(Cornell) and Y. Dutheil(FZJ) for their meticulously strong support on BMad, a tool for lattice modeling as well as numerical tracking including spin with both MDM and EDM