Challenges for EDM Storage Ring

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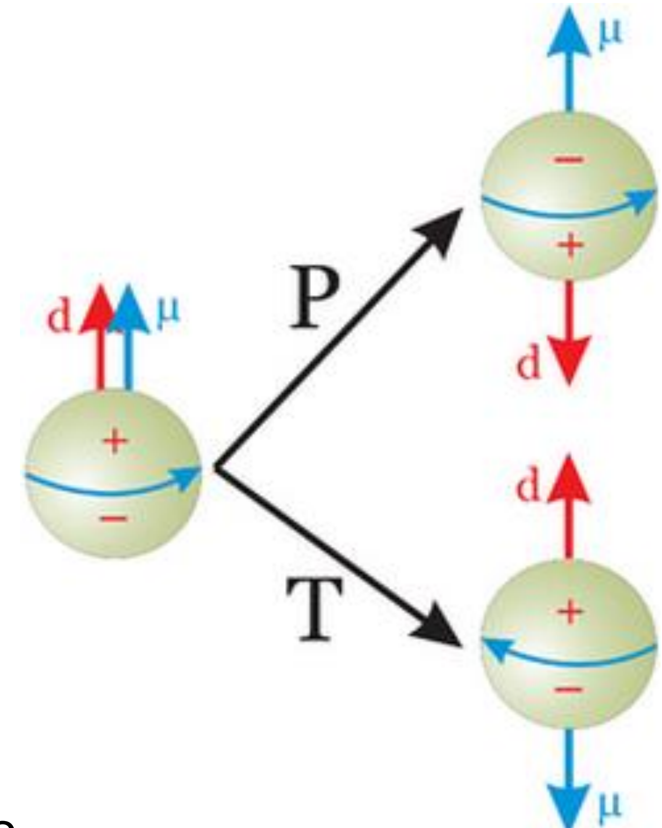
IKP-4, Forschungszentrum, Juelich

Outline

- Introduction
- Challenges
    - *Accelerator options*
    - *Beam instrumentation*
- Landscape of R&D efforts and status
- Summary and outlook
- Acknowledges

Motivation

- Like the MDM, EDM is a vector-like intrinsic property of particles aligning along the spin axis. Non-EDM violates both Parity and Time reversal, an excellent probe for CP-violation
  - SM expects EDM on the order of 10^{-38} e-cm, too weak to explain the asymmetry between matter and anti-matter
  - New physics is needed!

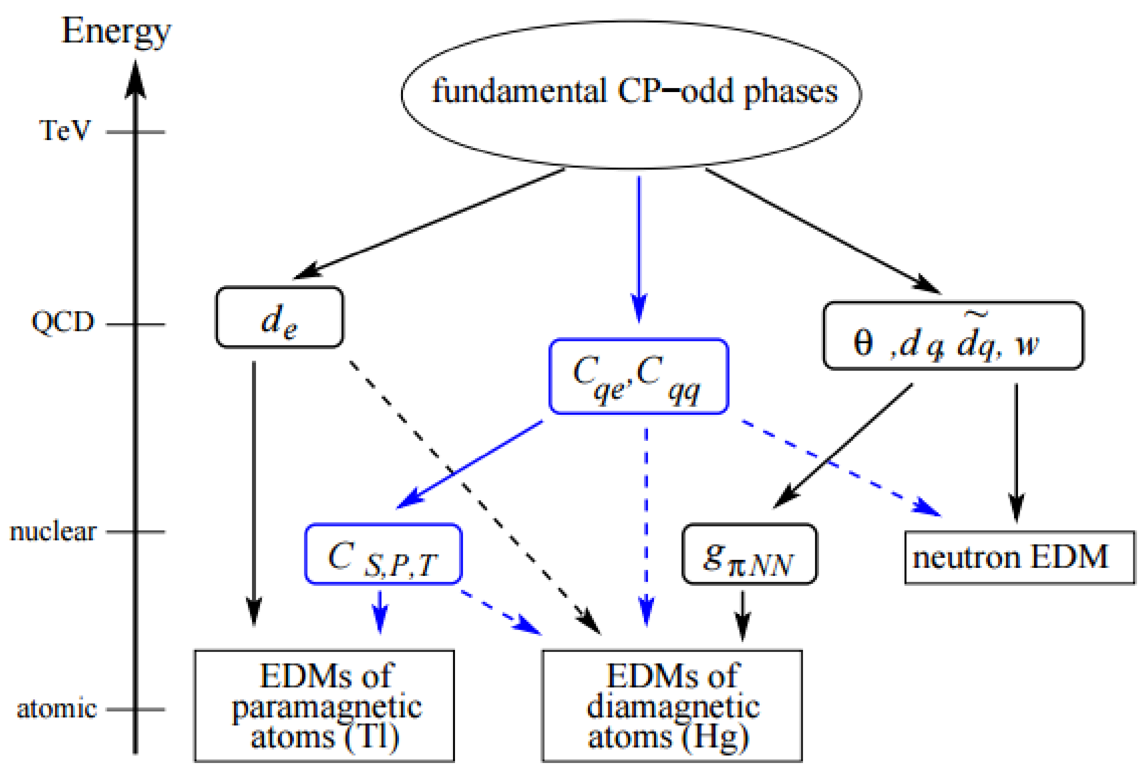


- 1st EDM search of neutron started in 1951 by Smith, Purcell and Ramsey

- Currently, direct charged ion EDM hasn't yet been performed

Motivation

- EDM is one of the few low energy measurements sensitive to fundamental particle physics at a scale of TeV and above
- Schematic plot of the hierarchy of scales between the CP-odd sources and three generic classes of observable EDMs [*M. Pospelov, A. Ritz, arXiv:hep-ph/0504231, 2005*]



Motivation

Current Experimental Limits

"paramagnetic EDM", Berkeley experiment

$$|d_{\mathrm{Tl}}| < 9 \times 10^{-25} e\,\mathrm{cm}$$

"diamagnetic EDM", U of Washington experiment

$$|d_{\mathrm{Hg}}| < \sout{2 \times 10^{-28} e\,\mathrm{cm}} \qquad 7.4 \times 10^{-30}$$

factor of 7 improvement in 2009!

$$|d_{\mathrm{Hg}}| < 3 \times 10^{-29} e\,\mathrm{cm}$$

neutron EDM, ILL experiment

$$|d_n| < 3 \times 10^{-26} e\,\mathrm{cm}$$

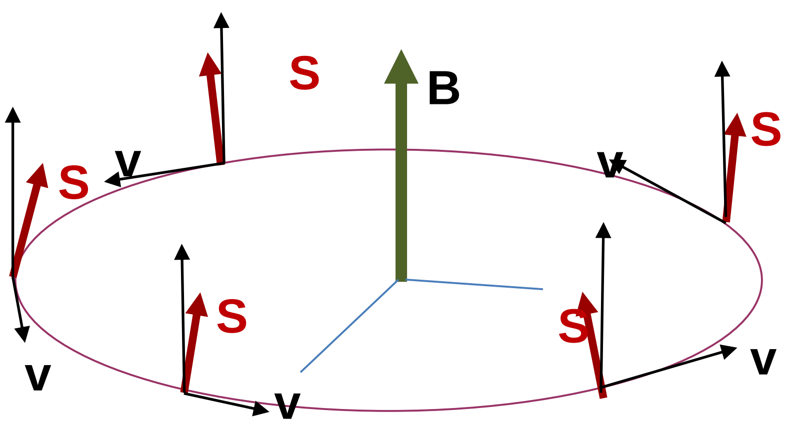
Notice that Thallium EDM is usually quoted as $d_e < 1.6\ 10^{-27}$ cm bound, and in 2011 it was improved to $1.0\ 10^{-27}$ cm.

2013 ThO result by Harvard-Yale collaboration: $|d_e| < 8.7 \times 10^{-29}$

M. Pospelov, physics Beyond Colliders, CERN, Sept. 2016 https://indico.cern.ch/event/523655/contributions/2246441/attachments/1331946/2002069/CERN2016_pospelov.pdf

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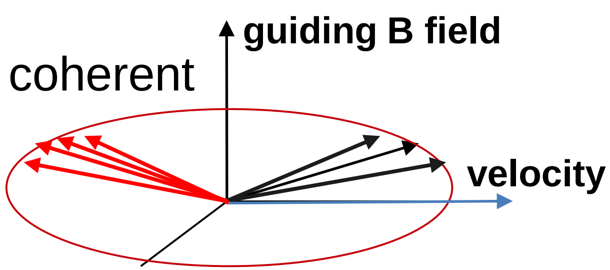
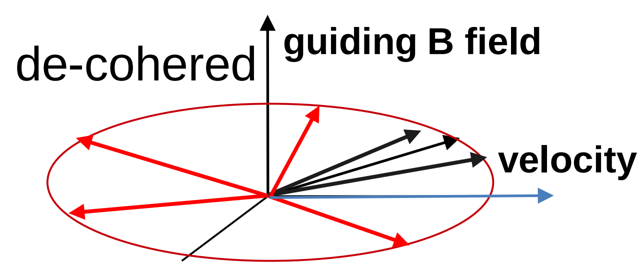
$$f_{spin} = Q_s f_{orbit} \qquad Q_s = G\gamma$$

  - 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,

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

Storage ring based EDM search

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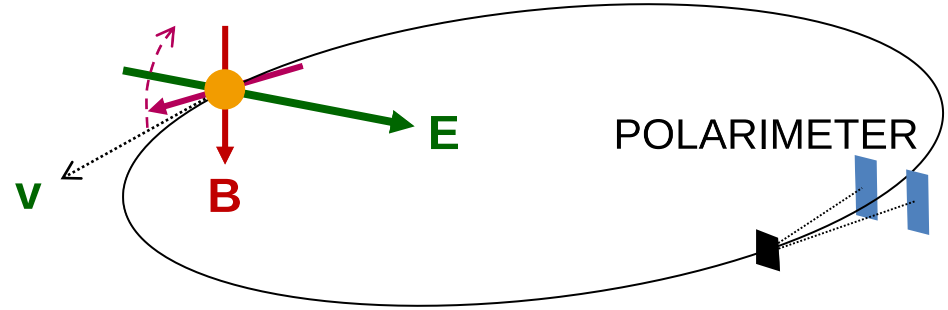
- **Null to remove the MDM contribution to spin motion. And glue the spin vector along the particle's velocity in the horizontal plane**
  - **Non-zero EDM results in the vertical polarization buildup**

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



courtesy of E. Stephenson

⇓

Full Spin Frozen storage ring is the most effective way!

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 without B field

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

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 = -0.14

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

	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

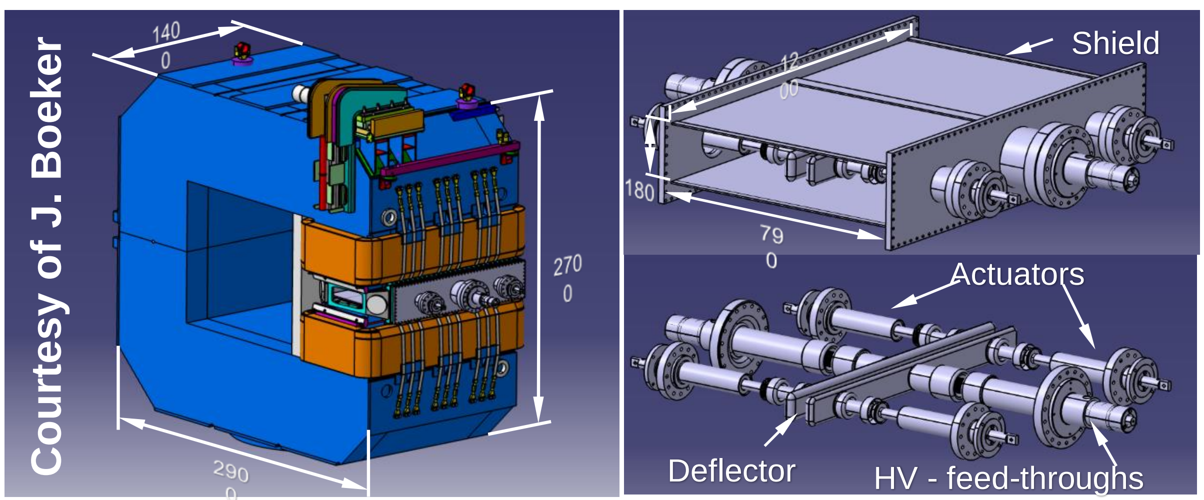
Key: ExB deflector

Spin Frozen Bending Elements R&D

ExB deflector R&D@COSY

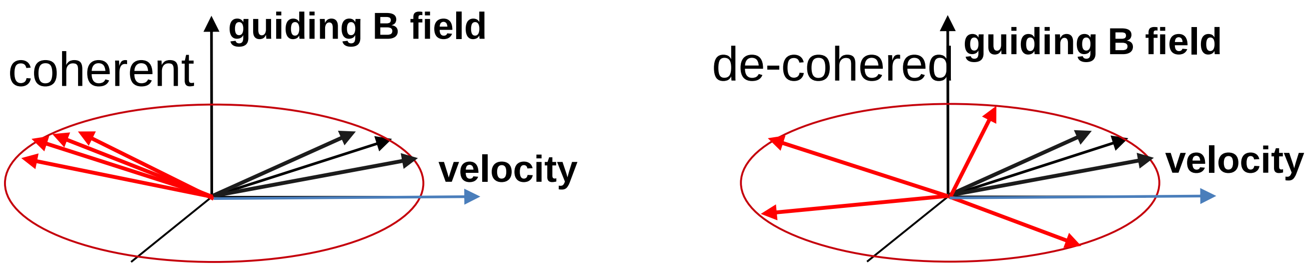
- Test setup using existing ANKE-D2 magnet together with electrostatic plates to study the effect of magnetic field on the E field strength to investigate the feasibility of ExB deflector for spin frozen storage ring with E up to 8MV/m and B up to 0.3 Tesla

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



Storage Ring EDM search main challenges

- Spin frozen condition
- Long spin coherence time: To reach 10^{-29} e-cm, >1000 sec spin coherence time is required



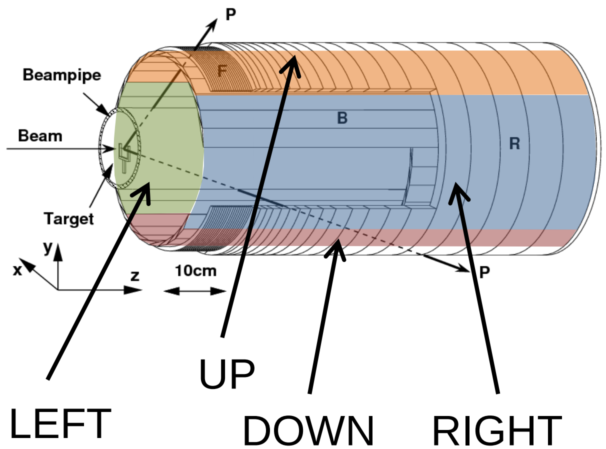
- Requires careful design of lattice design, as well as tuning/beam control
  - Control spin tune spread by chromaticity 1st achieved in VEPP-2M
  - **With pre-cooled polarized deuteron beam, >1000s spin coherence time was experimentally achieved at COSY:** PRL **117**, 054801 ('16)
  - In the absence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

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

Fast polarimeter@COSY

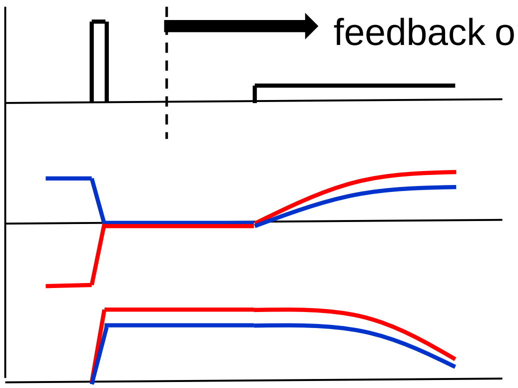
EDDA detector



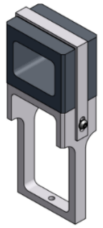
Azimuthal angles yield two asymmetries:

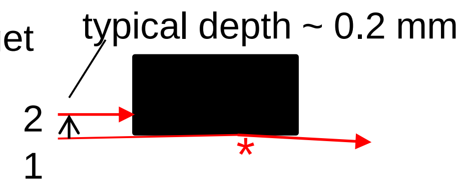
$$\varepsilon_{EDM}=\frac{L-R}{L+R} \qquad \varepsilon_{g-2}=\frac{D-U}{D+U}$$

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

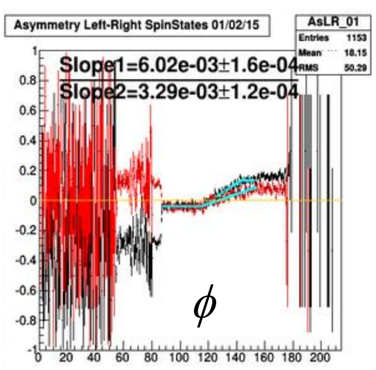


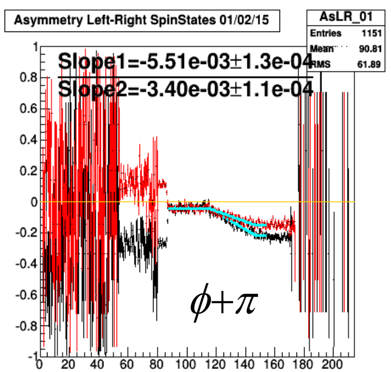
17 mm Carbon target





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





Courtesy of E. Stephenson

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

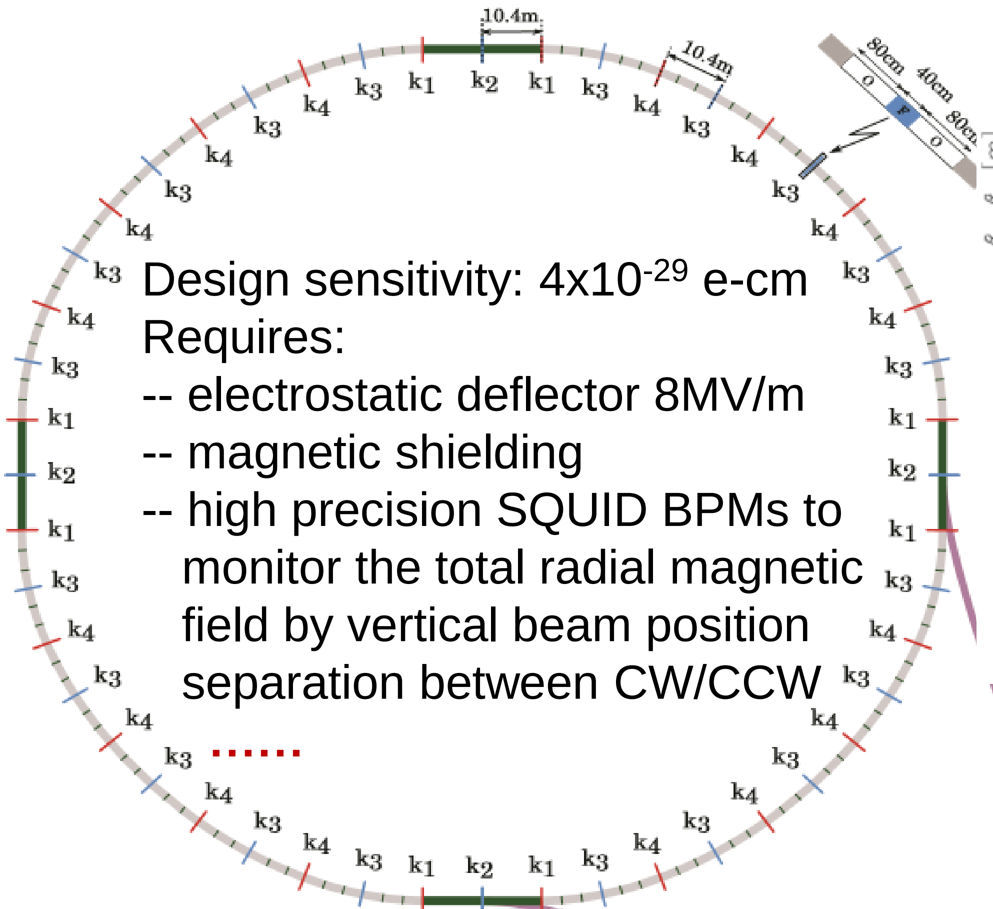
Main Systematic Errors

pEDM ring, all electrostatic	dEDM ring, EB elements
Off-center vertical closed orbit through quadrupoles, which is mitigated by simultaneous CW/CCW beams	Off-center vertical closed orbit through quadrupoles, which is mitigated by CW/CCW beams assuming **the reversal of the fields** is perfect
Non zero $< B_r >$, that can be monitored by measuring the vertical split of the CW/CCW beams. High sensitive beam position monitor	Non zero $< E_y >$, can be mitigated by CW/CCW beams assuming **the reversal of the fields** is perfect
Polarimeter, mitigated by consecutive bunches of opposite helicity.	Polarimeter, various methods of mitigation.
fringe fields, E and B fields in RF cavity,Gravity	
Image current	Stern-Gerlach effect

[1] A Proposal to Measure the Proton Electric Dipole Moment with 10^{-29} e.cm Sensitivity, V. Anastassopoulos et al., October 2011.
[2] AGS Proposal: Search for a permanent electric dipole moment of the deuteron nucleus at the 10^{-29} e.cm level, D. Anastassopoulos et al., April 2008

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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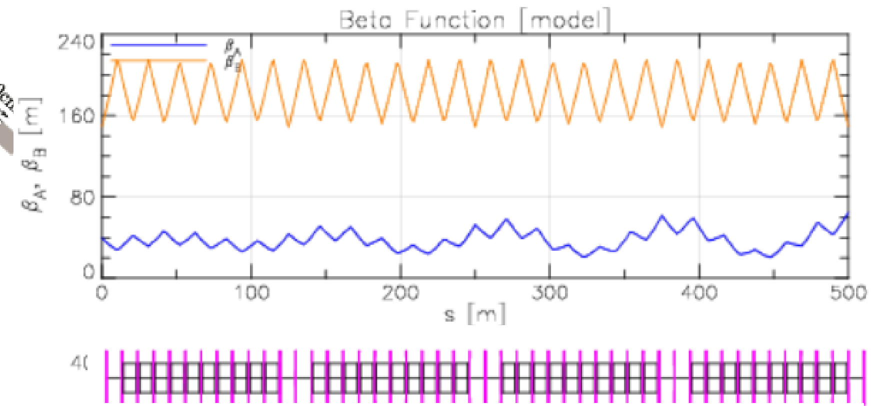

Bending radius	52.3 m
circumference	500 m
Electrode spacing	3 cm
Deflector shape	cylindrical
Harmonic, RF[MHz]	100, 35.878
Q_x, Q_y	2.42, 0.44
ε_x , ε_y [mm-mrad]	17, 3.2
maximum $\frac{dp}{p}$	4.6×10^{-4}
Dispersion, max [m]	30 m

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

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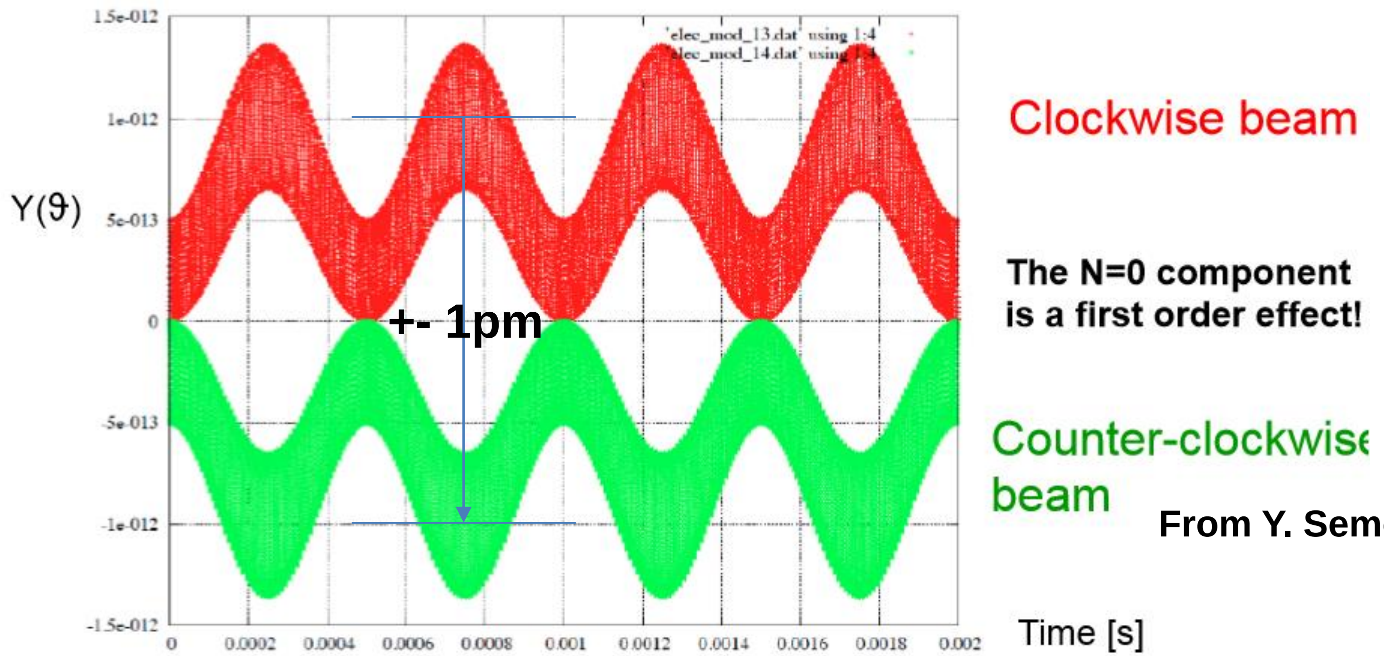
Residual Magnetic Field

- 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

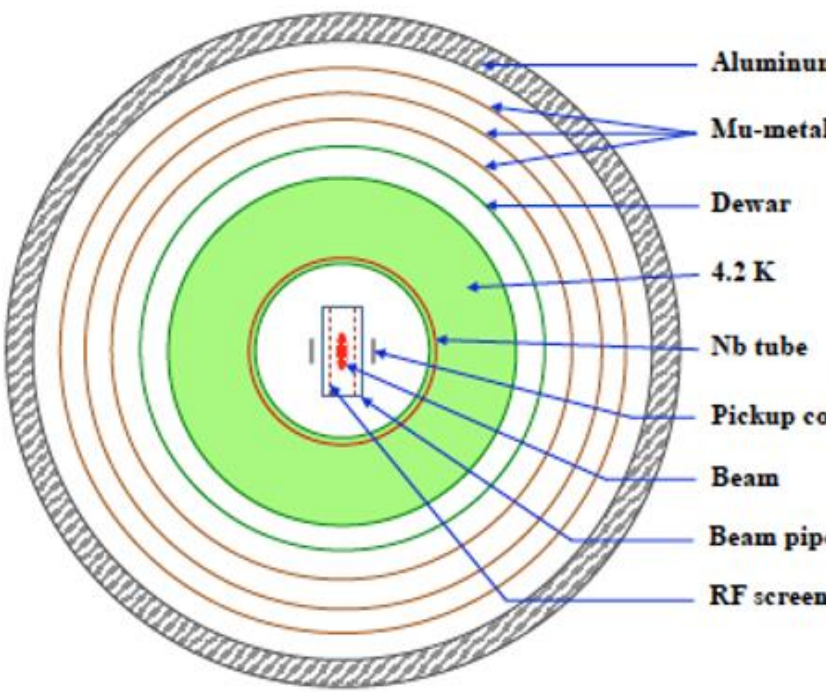
$$y(\vartheta) = \sum_{N=0}^{\infty} \frac{\beta R_0 B_{rN}}{E_0 \left(Q_y^2 - N^2\right)} \cos\left(N\vartheta + \varphi_N\right)$$

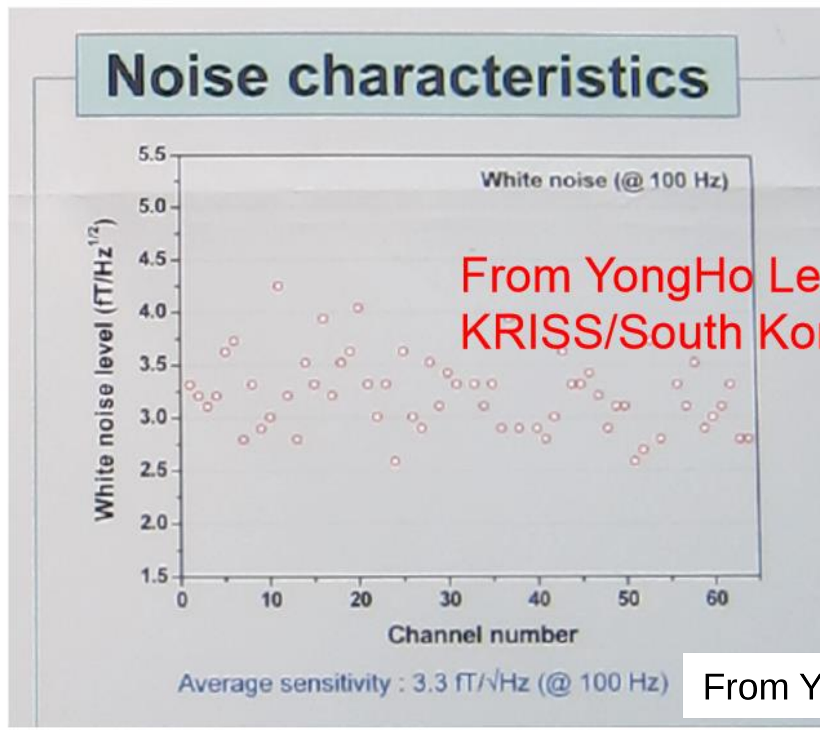


From Y. Semertzidis

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 YongHo Lee's group
KRISS/South Korea

From Y. Semertzidis

A MDM spin transparent Quadrupole

- Similar to the condition for freezing spin in a dipole, it is possible to make the MDM part of the spin motion to be transparent in a quadrupole.

- It is necessary that electric and magnetic fields remain perpendicular,

$$\vec{B} \cdot \vec{E} = 0.$$

- For a quadrupole with fields

$$B_x + iB_x = b_1(x + iy) \text{ and } E_x - iE_y = \frac{b_{e1}}{r_0}(x + iy)$$

the MDM spin transparent condition is

$$B_x = -\left[1 - \frac{1}{(\gamma+1)(1+G\gamma)}\right]\frac{\beta E_y}{c} \quad B_y = \left[1 - \frac{1}{(\gamma+1)(1+G\gamma)}\right]\frac{\beta E_x}{c}.$$

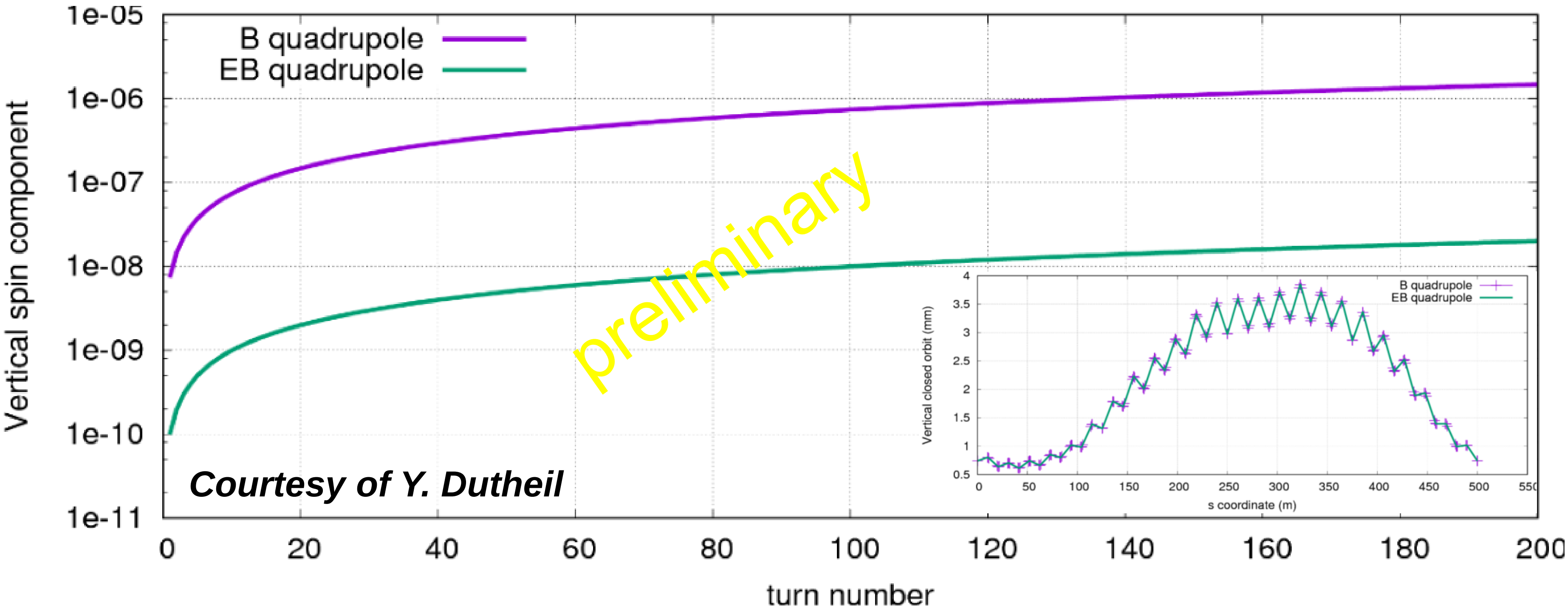
- The equivalent field gradient of such a quadrupole is

$$k_1 = \left[\left[1 - \frac{1}{(\gamma+1)(1+G\gamma)}\right]\frac{\beta}{c} + \frac{1}{\beta c}\right]\frac{b_{e1}}{r_0}$$

***M. Bai, Y. Dutheil, D. Sagan,* arXiv:1611.04992, 2016**

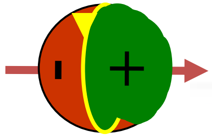
Full spin transparent storage ring

- Such an MDM spin transparent element reduces the systematic error due to vertical closed orbit by an order of magnitude

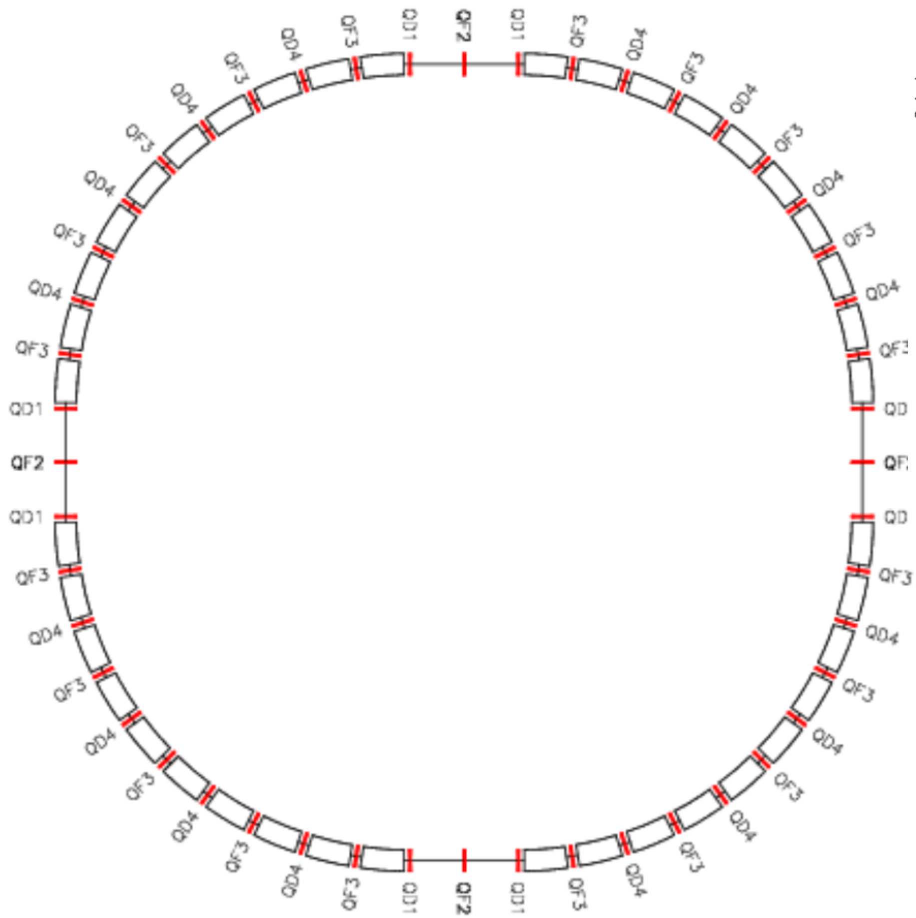


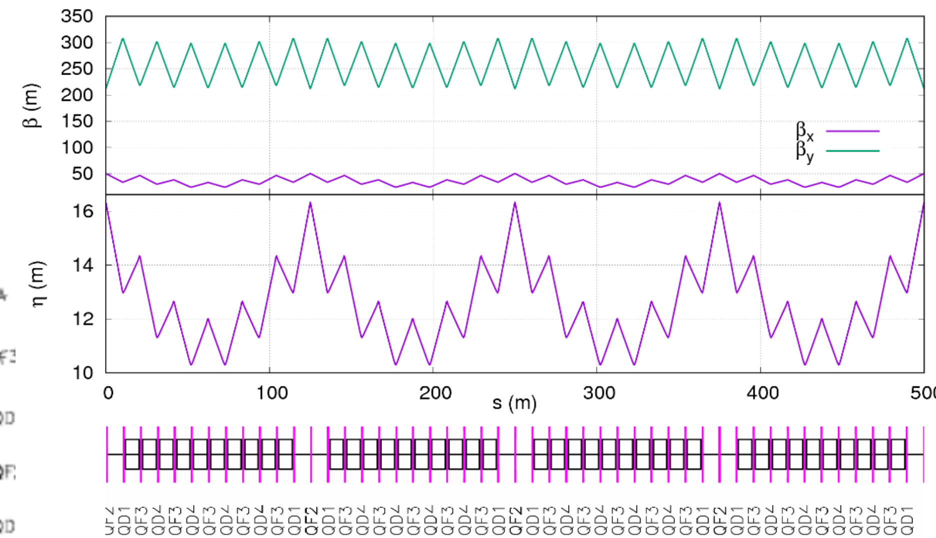
- Detailed investigation on other systematics in the presence of such an element is working progress

EDM Storage Ring



Deuteron EDM storage ring





Bending radius	52.3 m
circumference	500 m
Q_x, Q_y	2.31, 0.312
Dispersion, max [m]	16 m

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

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Summary

- Storage ring based EDM search offers discovery physics at a scale compatible to TeV particle 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 …

- Nevertheless, there are still a lot of challenges ahead of us
  - Key technologies demonstration
  - Beyond the state-of-art high precision beam control and monitoring
  - Full understanding of various systematics
    - High precision, long term numerical simulation including spin

Outlook

Physics Beyond Colliders Kickoff Workshop

6-7 September 2016
CERN
Europe/Zurich timezone
There is a live webcast for this event.

Search...

EDM kick-off meeting

13-14 March 2017
CERN
Europe/Zurich timezone

Search...

- Overview
- Timetable
- Contribution List

The physics potential of a precision measurement of the EDM of the proton, anti-proton, or deuteron is well motivated. Considerable work has gone into the storage ring approach and the aim is to bring together active participants in ongoing EDM measurement research to explore the potential of CERN to contribute to progress in this domain.

Acknowledge

Thanks the workshop organizer for the invitation

Many thanks for the fruitful discussions with many colleagues
E. Stephenson, Y. Semertzidis, U. Meißner, H. Stroeher, and many others

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

Spin Frozen Bending Elements R&D

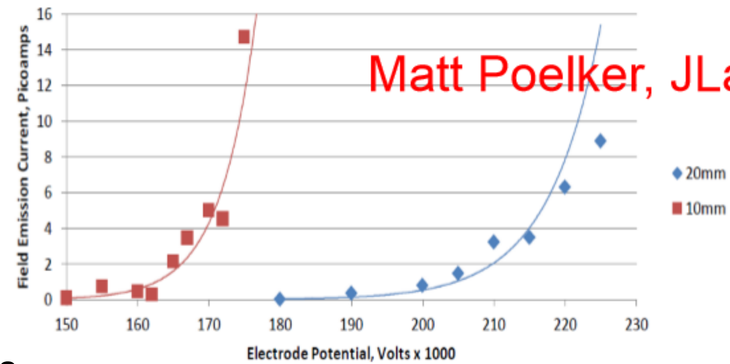
High Field Electrostatic Deflector

- 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

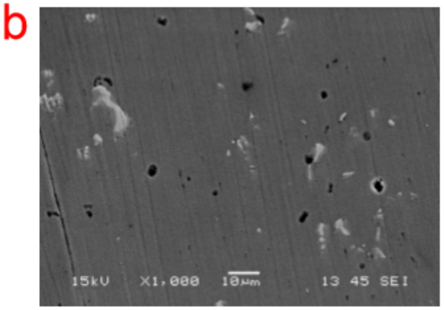
K. Grigorey, Aachen electrostatic deflector development, JEDI Collaboration Meeting, Sept. 2016

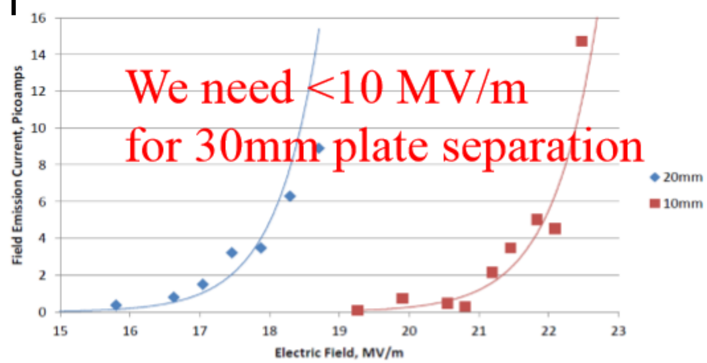
JLab results with TiN-coated Aluminum

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



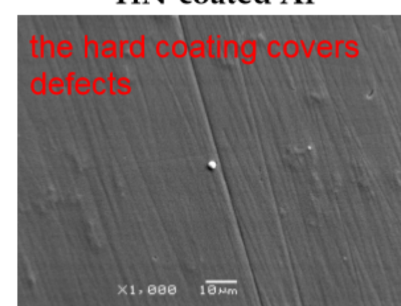
Bare Al





15 MV/m 20 MV/m

TiN-coated Al



From Y. Semertzdis

Work of Md. A. Mamun and E. Forman

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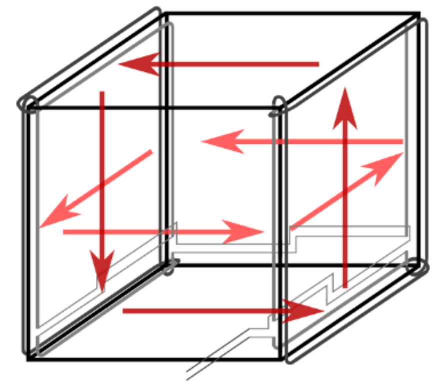
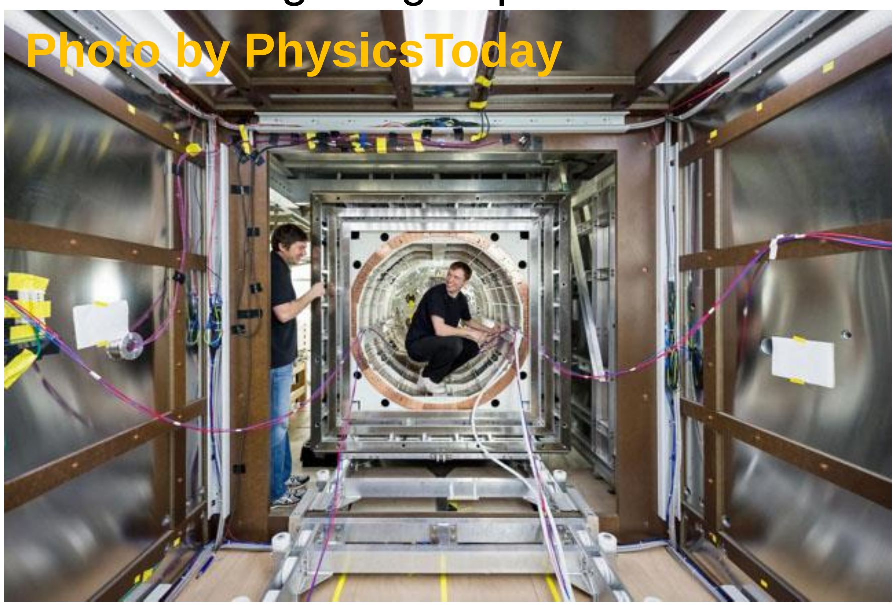
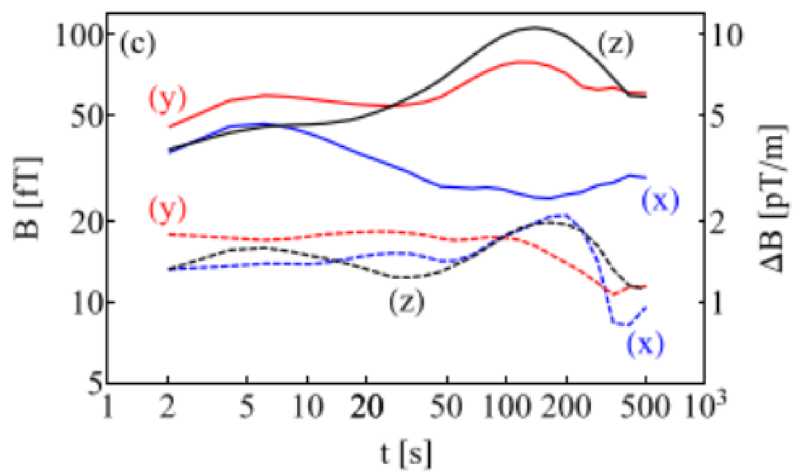
Magnetic Shielding

< 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