EDM measurements – with storage rings –

Gerco Onderwater

VSI, University of Groningen
the Netherlands

Solvay Workshop 'Beyond the Standard model with Neutrinos and Nuclear Physics' 2017

university of groningen

Outline

- Motivation
- EDM landscape
- Current & future limits
- Impact on & of experiments
- Summary & outlook

Motivation

CP/T Violation

Direct measurements

K, B, D

Cosmology (WMAP)

Cosmological matter-antimatter asymmetry

explainable with *e.g.* Sakharov conditions

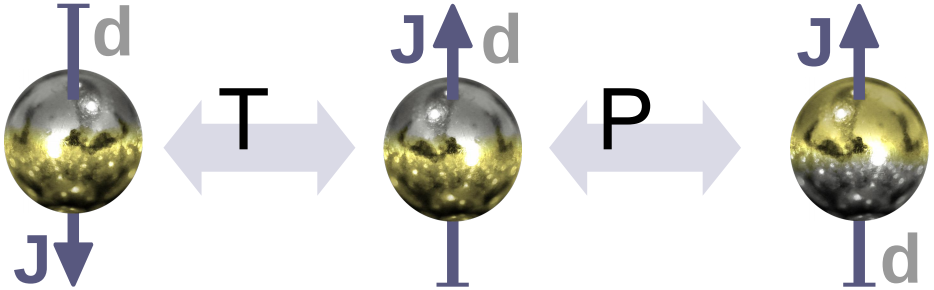
- Baryon number violation
- C & CP violation
- Thermal non-equilibrium

≠

δ_{CKM} from K- and B-physics

Precision Searches

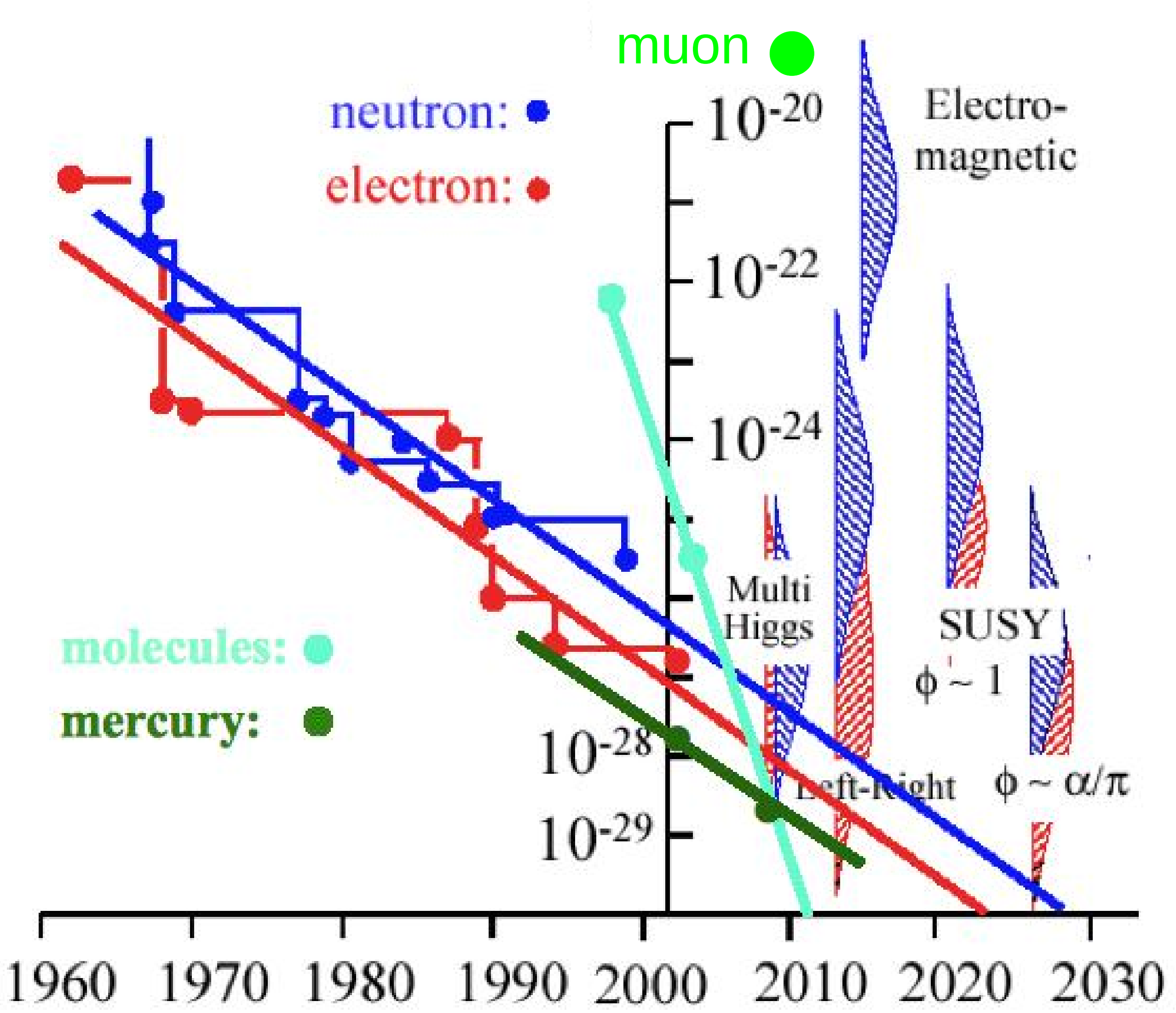
- Correlations in β-decay
- Electric dipole moments



SM predicts EMDs beyond experimental reach

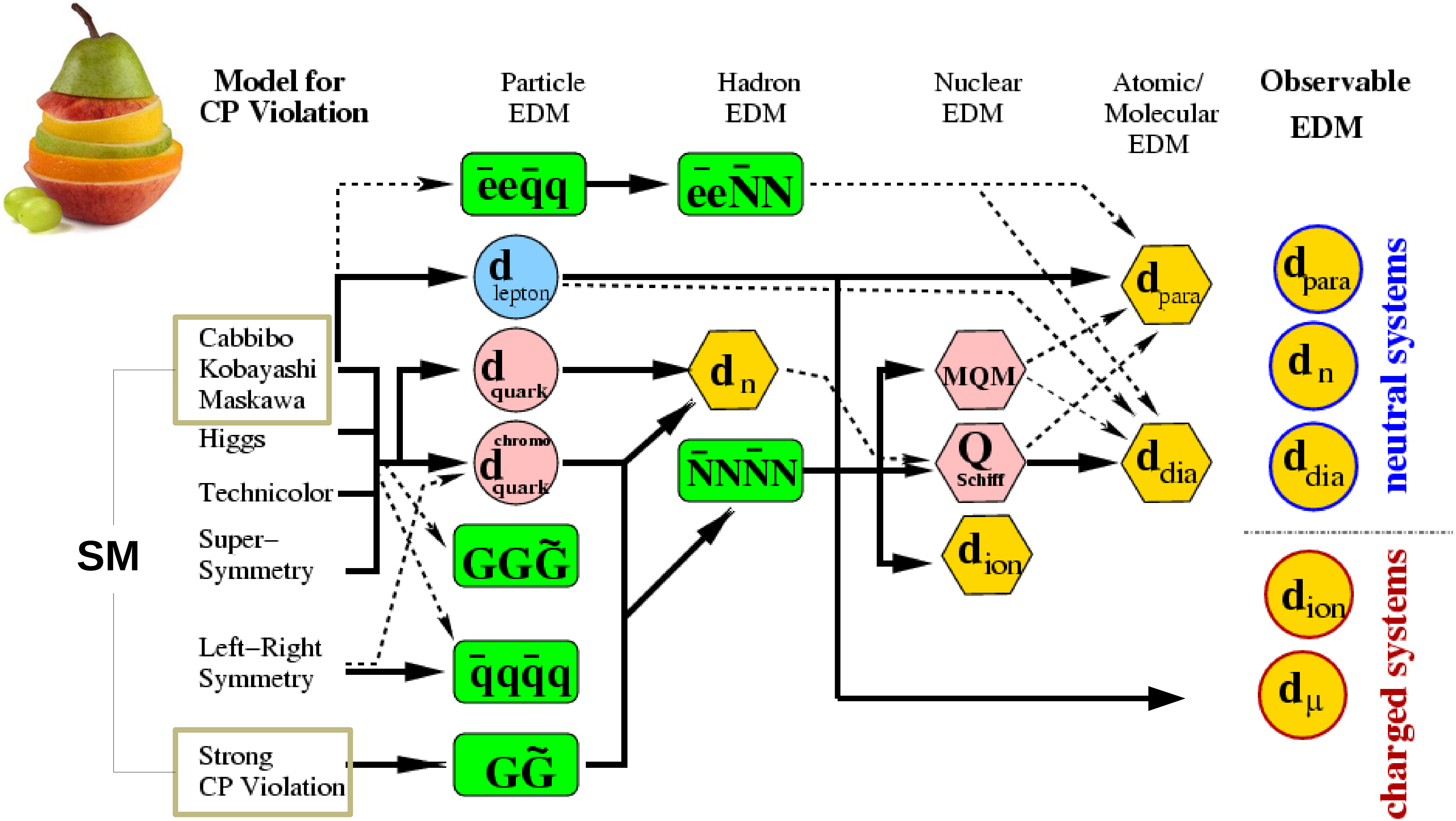
↳ **EDMs are sensitive probe for new physics**

EDM limits



First non-zero EDM is a major discovery!!!

From theory to observable ... and back



Picture from K. Jungmann

Current EDM limits

	Limit [e·cm] 90%CL	**System**
n	**2.9x10^{-26}**	UCN
^{199}Hg	**6.3x10^{-30}**	vapor
↳ p	2.0x10^{-25}	**Assuming all others zero**
↳ n	1.2x10^{-26}	
↳ e	6.0x10^{-28}	
TlF	**5.5x10^{-23}**	molecular beam
↳ p	1.2x10^{-22}	
↳ e	6.7x10^{-25}	
^{129}Xe	**5.5x10^{-27}**	maser (adj. χ^2=1.35)
^{205}Tl	**9.4x10^{-25}**	atomic beam
↳ e	1.6x10^{-27}	
YbF	**???**	molecular beam
↳ e	1.1x10^{-27}	
μ	**1.8x10^{-19}**	rest frame E-field
D	**~10^{-15}**	Deuterium 1S-2S

Why probe (light) nuclei?

Nuclear EDMs from constituents and CPV NN-interaction

$$d_{nucl} = d_n \oplus d_p \oplus d_{\pi NN}$$

n, p, ^{2}H ,^{3}H, ^{3}He, … , ^{129}Xe, ..., ^{199}Hg, ...

CPV one boson exchange

Liu, Timmermans, et al.

EDM operator long range
↓
one-pion exchange
dominates

- EDM in terms of P-odd/T-odd NN interaction:

$$d_{nucl}=g_{\pi NN}\left[a_0 g_{\cancel{C}P}^{I=0}+a_1 g_{\cancel{C}P}^{I=1}+a_2 g_{\cancel{C}P}^{I=2}\right]\cancel{+[\eta]+[\rho]+[\omega]}$$

~14

nuclear structure

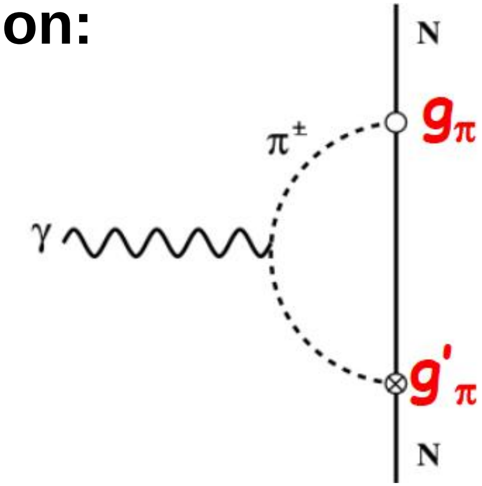
- Schiff moment in terms of P-odd/T-odd NN interaction:

$$S_{nucl}=g_{\pi NN}\left[a_0 g_{\cancel{C}P}^{I=0}+a_1 g_{\cancel{C}P}^{I=1}+a_2 g_{\cancel{C}P}^{I=2}\right]$$

$$d_{atom}=\kappa_S S_{nucl}\cancel{+\eta_e d_e+(k_T C_T+k_S C_S)}$$

atomic structure

diamagnetic



Complementarity

- **Coefficients for light nuclei & heavy atoms**

		$g_{\pi NN} a_0$	$g_{\pi NN} a_1$	$g_{\pi NN} a_2$
	n	0.14	0.00	-0.14
nuclei	**p**	-0.05	0.03	0.14
	D	0.09	0.23	0.00
	^{3}He	0.34	0.32	0.38
atoms	**^{129}Xe(*)**	6×10^{-5}	6×10^{-5}	12×10^{-5}
	^{199}Hg(*)	-21×10^{-5}	11×10^{-5}	-22×10^{-5}
	^{225}Ra(*)	-0.06	-0.12	0.11

Liu & Timmermans 2004
Stetcu et al. 2008
Ban et al. 2010
Ginges & Flambaum 2004
Dzuba et al. 2002
Dzuba et al. 2009

(*) Use Schiff moments :
$d(^{129}\mathrm{Xe}) = +0.38 \times 10^{-17}\ (S/e{\cdot}\mathrm{fm}^3)\ e{\cdot}\mathrm{cm}$
$d(^{199}\mathrm{Hg}) = -2.6 \times 10^{-17}\ (S/e{\cdot}\mathrm{fm}^3)\ e{\cdot}\mathrm{cm}$
$d(^{225}\mathrm{Ra}) = -8.8 \times 10^{-17}\ (S/e{\cdot}\mathrm{fm}^3)\ e{\cdot}\mathrm{cm}$

$$\measuredangle(\vec{a}\,,\vec{b})$$

	p	*d*	*He*	*Xe*	*Hg*	*Ra*
n	152	75	93	108	89	134
p		86	60	46	110	56
d			45	58	85	140
He				16	128	100
Xe					133	85
Hg						116

pairwise ~orthogonal!

Looking (a little) deeper

- QCD CPV :

$$g_0 \approx 0.027\bar{\theta} \qquad g_1 = g_2 = 0$$

- quark-chromo-EDMs:

$$g_0 \approx 4(\tilde{d}_u+\tilde{d}_d)\, g_1 \approx 20(\tilde{d}_u-\tilde{d}_d) \qquad g_2 = 0$$

	$d/\tilde{d}_d$ [e·fm]	$d/\tilde{d}_u$ [e·fm]
n	0.56	0.56
p	-0.80	0.40
D	-4.2	5.0
^{3}He	-5.0	7.8
^{129}Xe(*)	$-1.0\text{x}10^{-3}$	$1.4\text{x}10^{-3}$
^{199}Hg(*)	$-3.0\text{x}10^{-3}$	$1.4\text{x}10^{-3}$
^{225}Ra(*)	2.2	-2.6

	$d/\bar{\theta}$ [e·zm]
n	3780
p	-1350
D	2430
^{3}He	9180
^{129}Xe(*)	1.6
^{199}Hg(*)	-5.7
^{225}Ra(*)	-1620

Neutron ~orthogonal to ~everything

Reason : $a_1 = 0$

Others : $|a_0| \sim |a_1|$

See refs. prev. page

Limit on $g_{0,1,2}$

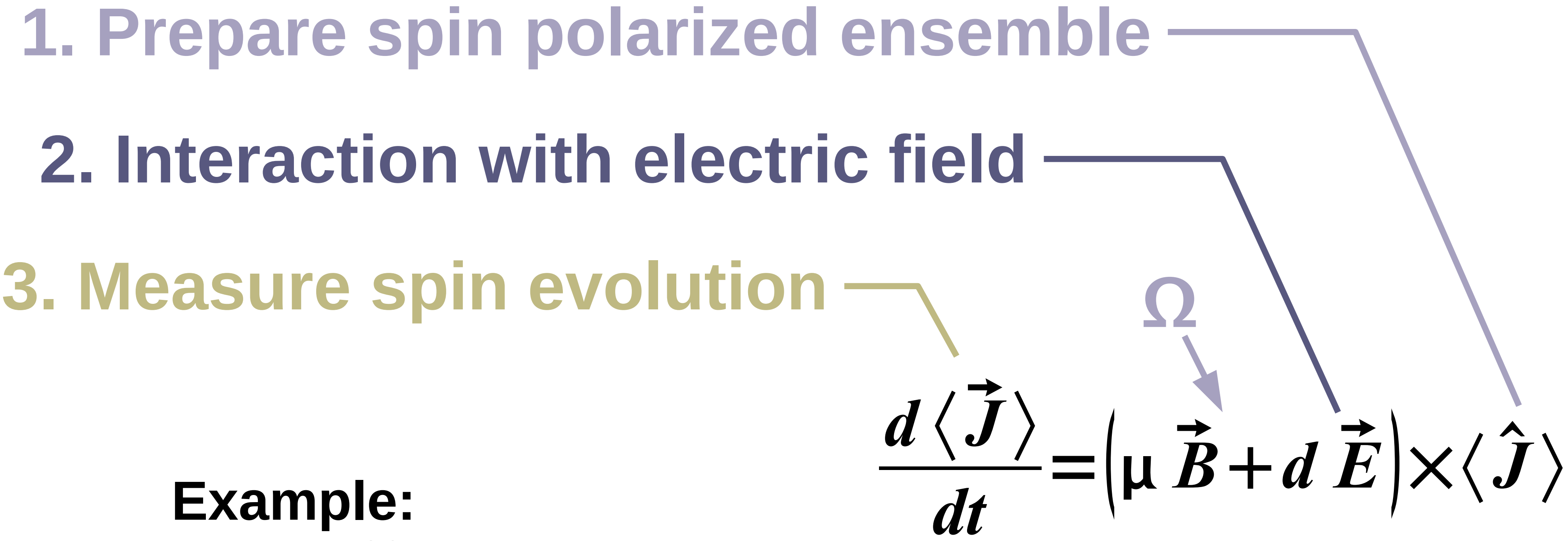
- Obtain $\mathbf{g_{0,1,2}}$ limits from best EDM limits: **n**, ^{129}**Xe** & ^{199}**Hg**
- Assuming no further constraints, **g**'s are of the order of $\mathbf{10^{-10}}$ (and of course strongly correlated)
- Resulting EDMs limits for **p**, **D**, ^{3}**He** of the order of 10^{-23} $e\cdot$cm
- This is dominated by the “poor” **Xe** limit

Enormous window to have impact already with precursor experiments; p, D & ^{3}He all good!

Just measure any one!

Rob Timmermans

Generic EDM experiment



1. Prepare spin polarized ensemble
2. Interaction with electric field
3. Measure spin evolution

Ω

$$\frac{d\langle\vec{J}\rangle}{dt} = \left(\mu\,\vec{B} + d\,\vec{E}\right)\times\langle\hat{J}\rangle$$

Example:

d = 10^{-26} e · cm
E = 100 kV/cm
J = ½
Ω = 150 μHz
(ΔB ~ 5pT)

Sensitivity

General expression for the uncertainty of an EDM experiment

$$\sigma_d \propto \frac{1}{P E \sqrt{N} T A}$$

N: number of particles in full experiment

P: initial polarization of sample

A: analyzing power of polarimeter

E: electric field strength in particle rest frame

T: characteristic time of single measurement

Work on:

- Strong source
- High polarization
- Efficient polarimeter
- High electric field strength
- Spin coherence, efficient storage

Equally important: understand systematic effects

Charged particles in an electric field

Bare nuclei

Charged particle accelerate and escape due to electric field

$$T \sim \sqrt{\frac{\mathrm{2mL}}{qE}} \sim ns$$

Atomic nuclei

Charged constituent of a neutral system rearrange themselves to balance forces

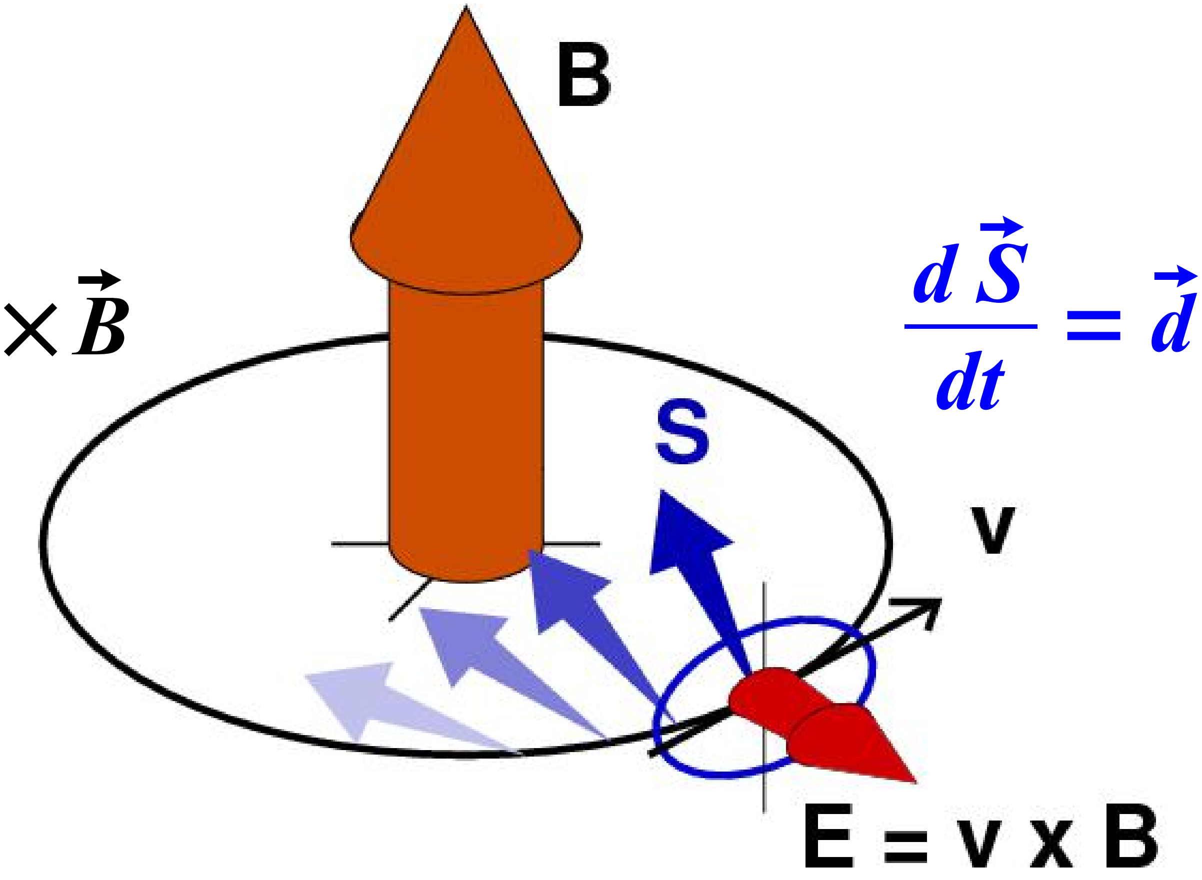
$$d_{\mathrm{2H}} \sim 10^{-7} d_D$$

Established techniques inadequate for charged particles

Solution: store relativistic particles in magnetic field
EDM interacts with motional electric field

Fast charged particles in a magnetic field

$$\frac{d\vec{p}}{dt} = q\vec{v}\times\vec{B}$$



$$\frac{d\vec{S}}{dt} = \vec{d}\times\left[\vec{v}\times\vec{B}\right]$$

$\vec{E}^{cm} = \vec{v}\times\vec{B}$ **can be very large (GV/m)**

Spins in an electromagnetic field

$$\vec{\Omega} = \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B} \right) \right]$$

magnetic moment anomaly

EDM

parasitic

$E=0$, $B=B_y$

(1) $\omega = \sqrt{a^2 + (\eta\beta)^2/4}\, B$

(2) $\hat{\omega} \times \hat{B} = \eta\beta / 2a$

electrostatic

$B=0$, E_r, $1/(\gamma^2-1)=a$

(1) $\langle \omega_\eta \rangle = \eta E/2$

(2) $\hat{\omega}_\eta = \hat{E}$

resonance

$E_z \approx E\cos(\Omega t)$

(1) $\langle \omega_\eta \rangle = \eta \Delta\beta B/4$

(2) $\langle \hat{\omega}_\eta \times \hat{B} \rangle = 1$

frozens spin

$E_r \approx aBc\beta\gamma^2$

(1) $\omega = \eta\beta B/2$

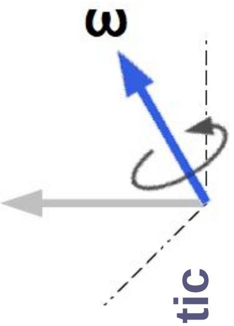
(2) $\hat{\omega} \times \hat{B} = 1$

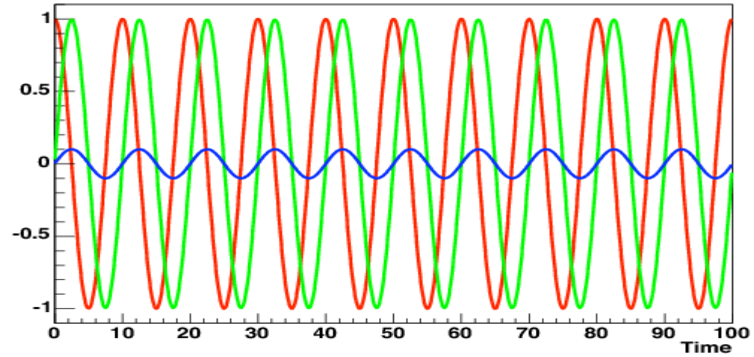
Spins in an electromagnetic field

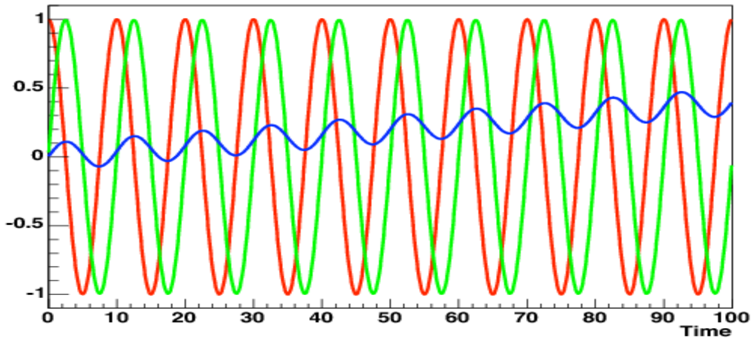
$$\vec{\Omega} = \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{v}\times\vec{E} + \frac{\eta}{2}\left(\vec{E} + \vec{v}\times\vec{B}\right)\right]$$

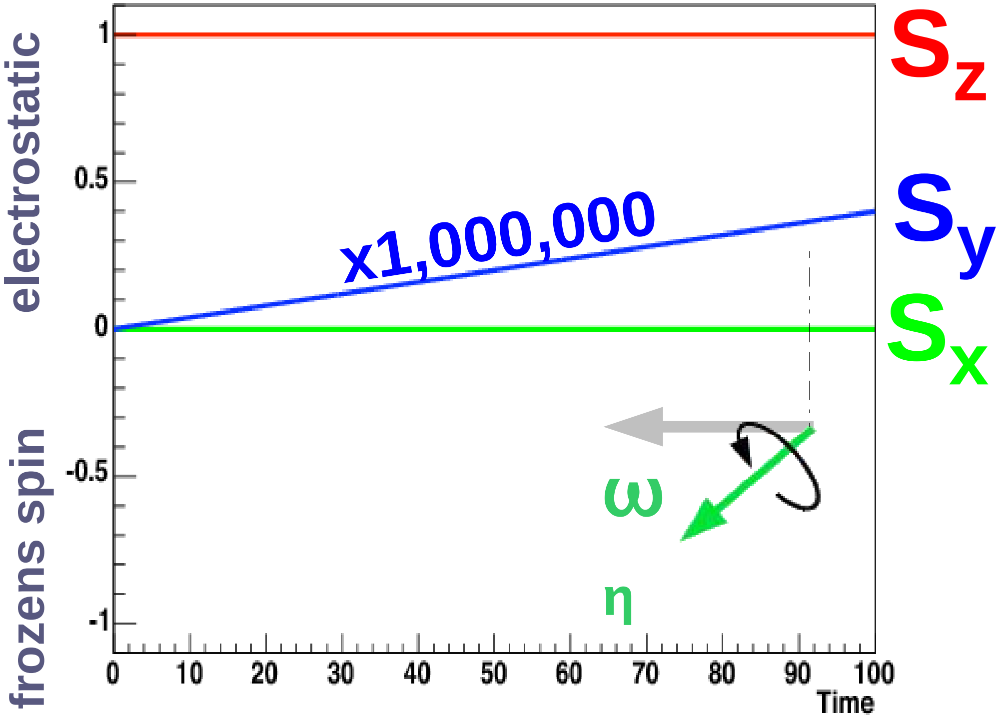
magnetic moment anomaly

EDM









In all cases : EDM in S_y, MDM in $S_{x,z}$

Frozen spin sensitivity

$$\xi = \frac{E + v \times B}{E} = \frac{a+1}{a\gamma^2}$$

particle	μ/μ_N	a	$\xi\gamma^2$
μ	-8.891	0.001166	858
n	-1.913	-2.910	–
p	2.793	1.793	1.56
D	0.857	-0.143	-5.99
^{3}H	2.979	7.918	1.13
^{3}He	-2.128	-4.184	0.76

Additional requirements

- Polarizability
- Polarimetry
- Lifetime
- Intensity
- Competitive

Experiments In Preparation

Parasitic : muon g-2 @ FNAL

FNAL E969:

The New (g-2) Experiment: Measure the Muon Anomalous Magnetic Moment to 0.14 ppm Precision

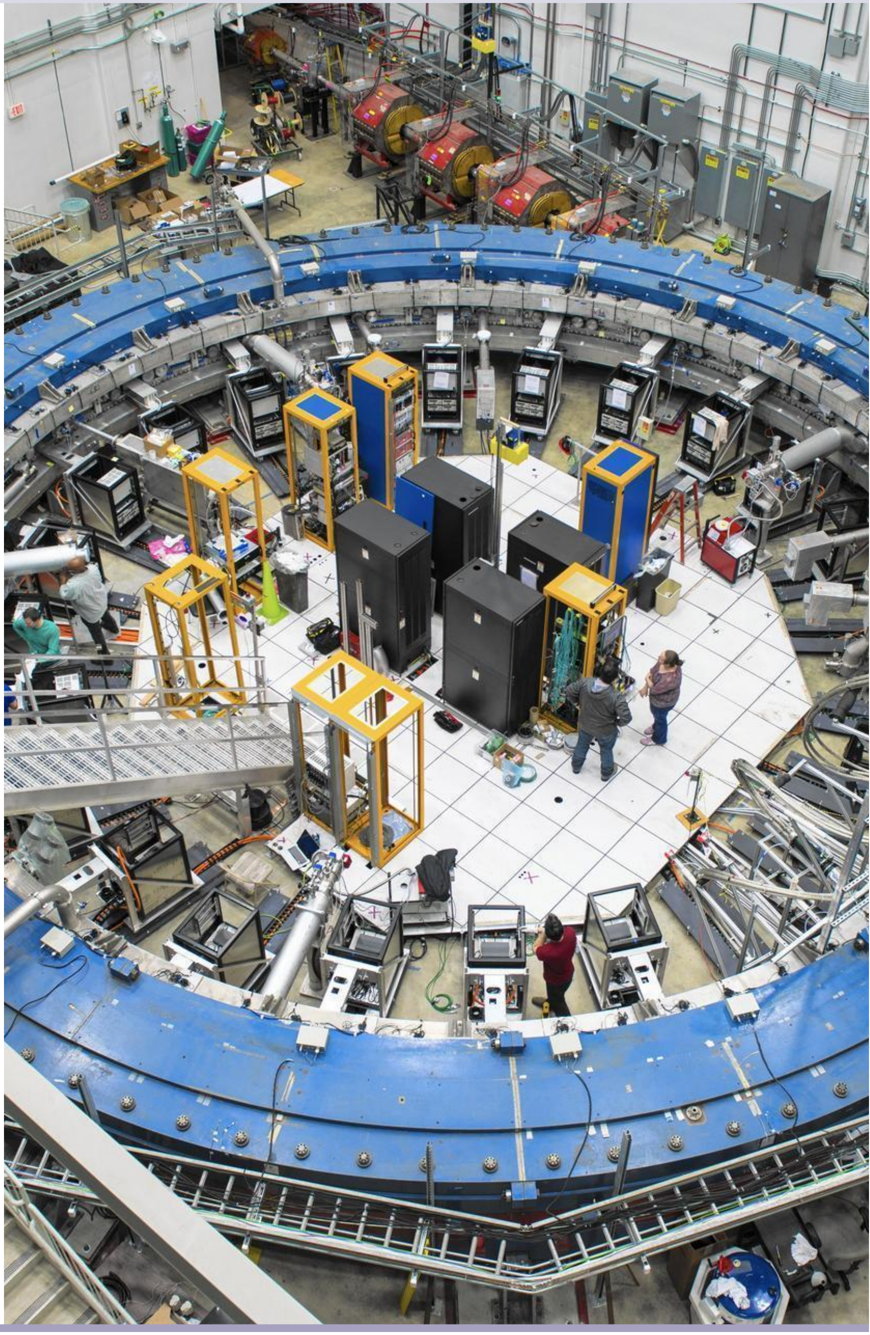
Design:

- p = 3.1GeV/*c*
- B = 1.45T,
- R = 7m

Estimated EDM Sensitivity

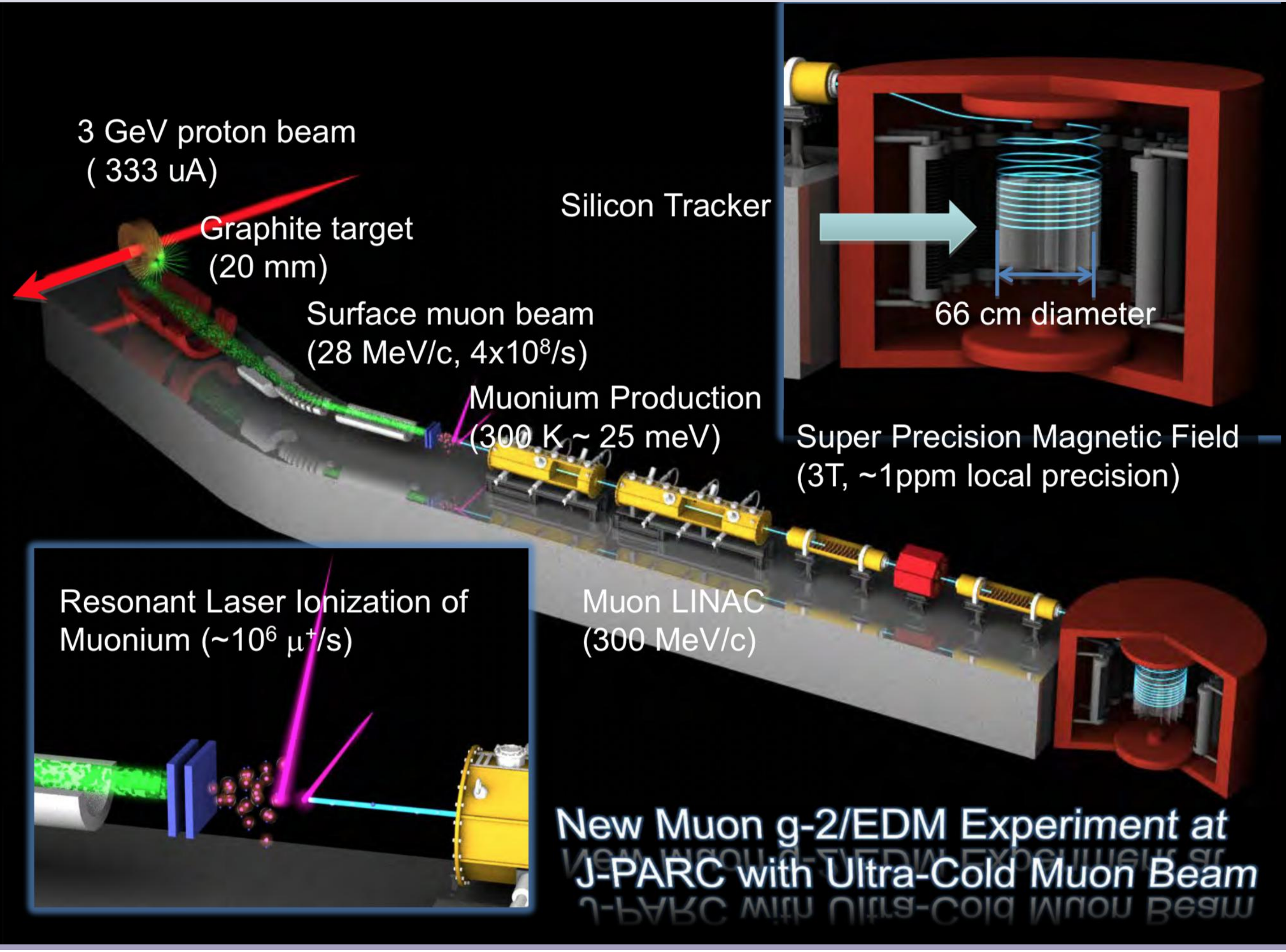
around 10^{-21} e·cm

two orders below current limit



Ultra-cold muons @ J-PARC

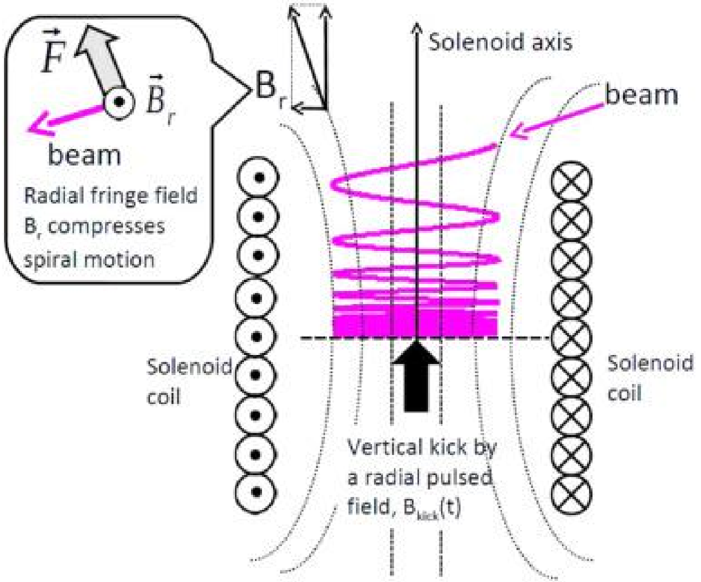
K. Ishida, NuFact'17



Recent achievements & activities

Spiral Injection Scheme for $\eta_{injection}$ ≥80% (vs. 3.5%)

NIMA 832, 51 (2016)



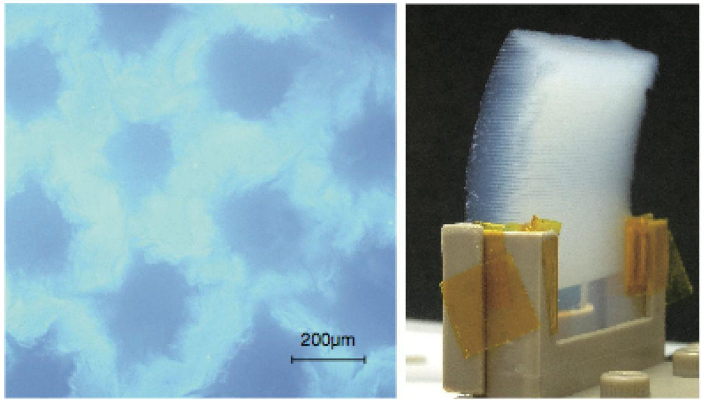
High-Acceptance Muon Re-Acceleration

Phys. Rev. Accel. Beams 19, 040101 (2016)

J. Phys.: Conf. Ser. 874 012055 (2017)

Muonium Production @ 20% of 10^6/s

Prog. Theor. Exp. Phys. 091C01 (2014)



Progress in many essential areas

Status

K. Ishida, NuFact'17

Muon g-2/EDM@J-PARC : Status

J-PARC PAC
- Letter of Intent (July, 2009)
- Conceptual Design Report at J-PARC PAC (Jan 2012)
- Stage 1 approval as E34 (21 Sep 2012)
- Technical Design Report (TDR) (May 2015)
  - Focused Review on TDR (Nov 15-16, 2016)

Valued as independent approach that should be done ASAP

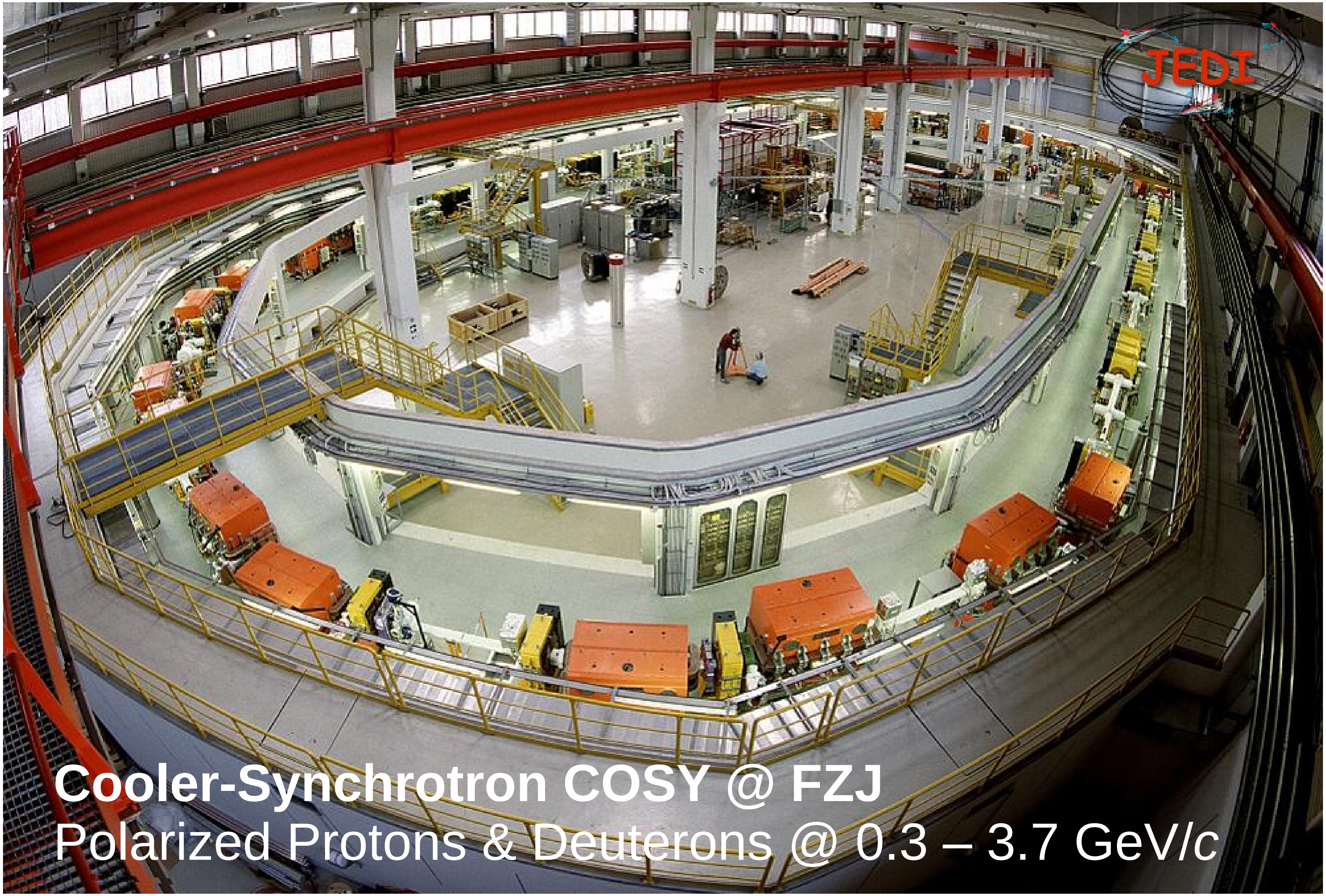
Many follow-up works done to respond recommendations

Selected as one of priority project in KEK Project Implementation Plan (PIP)
Selected as one of 28 in "Master Plan 2017" by Science Council of Japan
("Origin of Matter" with COMET and Hadron extension)

Several grants obtained for each development.
Overall budget is still a issue.

Goal: 10^{-21} e·cm

JEDI : Jülich EDM Investigations

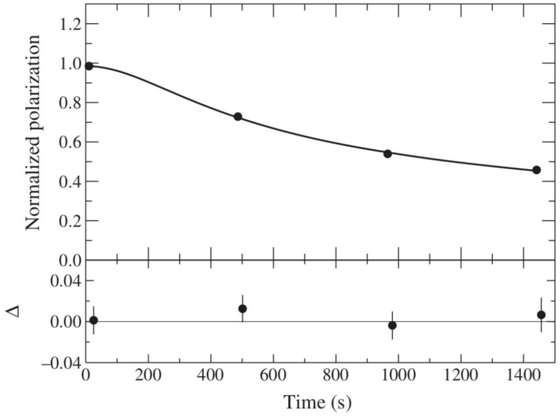


Cooler-Synchrotron COSY @ FZJ

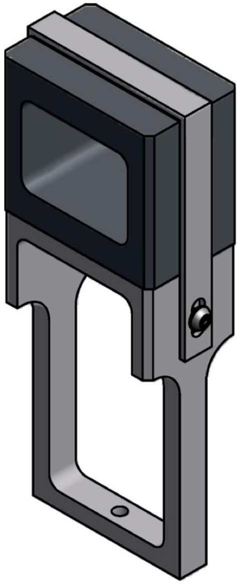
Polarized Protons & Deuterons @ 0.3 – 3.7 GeV/*c*

Recent achievements & activities w/ Deuterons

- **Spin feedback: sync polarization @ field w/ 12°**
  PRL 119, 014801 (2017)

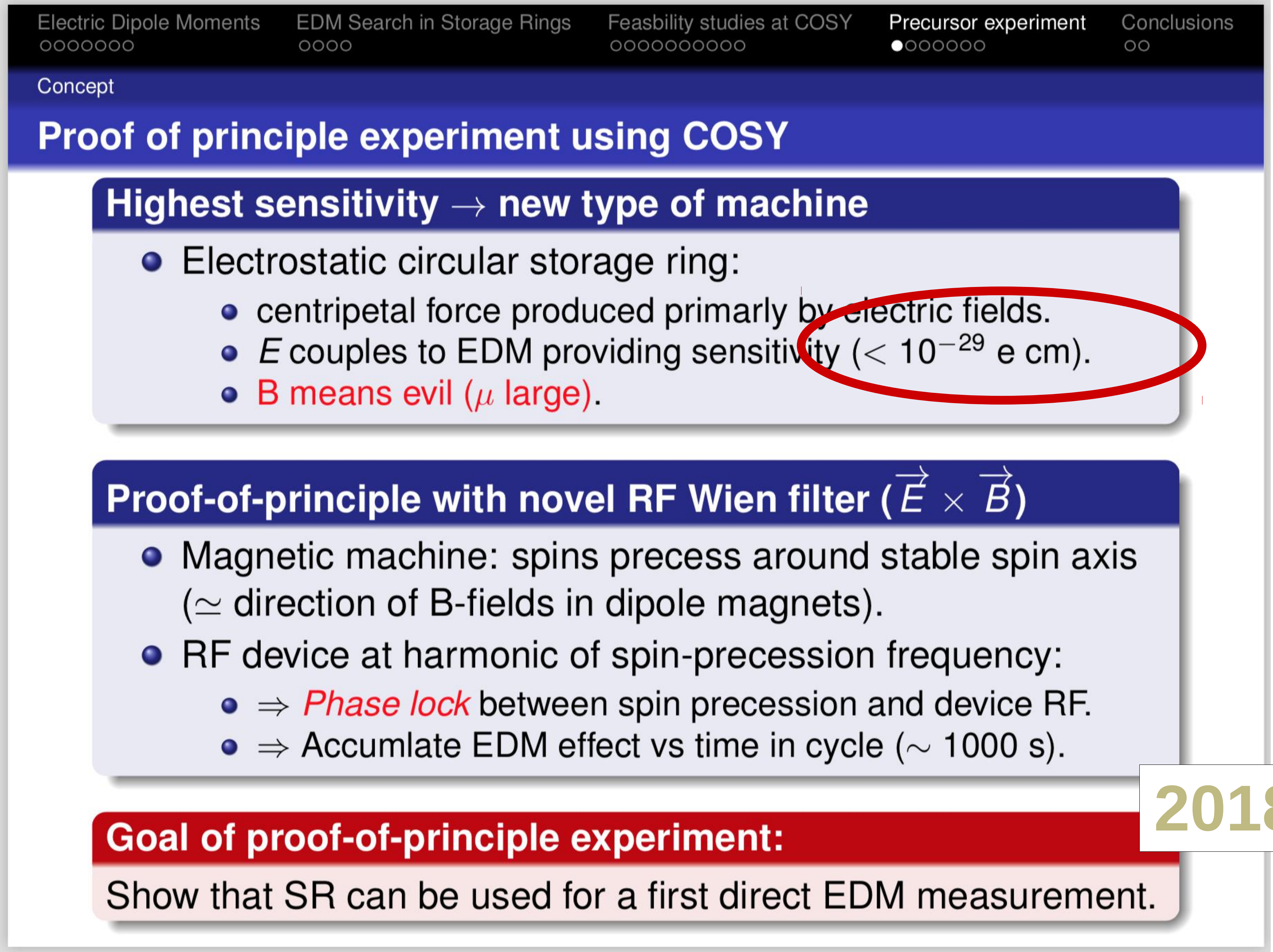


- **Spin tune mapping → field imperfections**
  Phys. Rev. ST Accel. Beams 20, 072801 (2017)
- **Spin Coherence Time: T_2>1000s (~10^8 turns)**
  PRL 117, 054801 (2016)
- **Spin Tune: ν_S = –0.16097…± 10^{-10} in 100s**
  PRL 115, 094801 (2015)
- **High-precision polarimetry**
  NIMA 664 (2012) 49–64



J. Pretz, CERN, *Physics Beyond Colliders*, Nov. 2017

Future (P. Lenisa, STORI2017)



Proof of principle experiment using COSY

Highest sensitivity → new type of machine

- Electrostatic circular storage ring:
  - centripetal force produced primarily by electric fields.
  - E couples to EDM providing sensitivity ($< 10^{-29}$ e cm).
  - B means evil (μ large).

Proof-of-principle with novel RF Wien filter ($\vec{E} \times \vec{B}$)

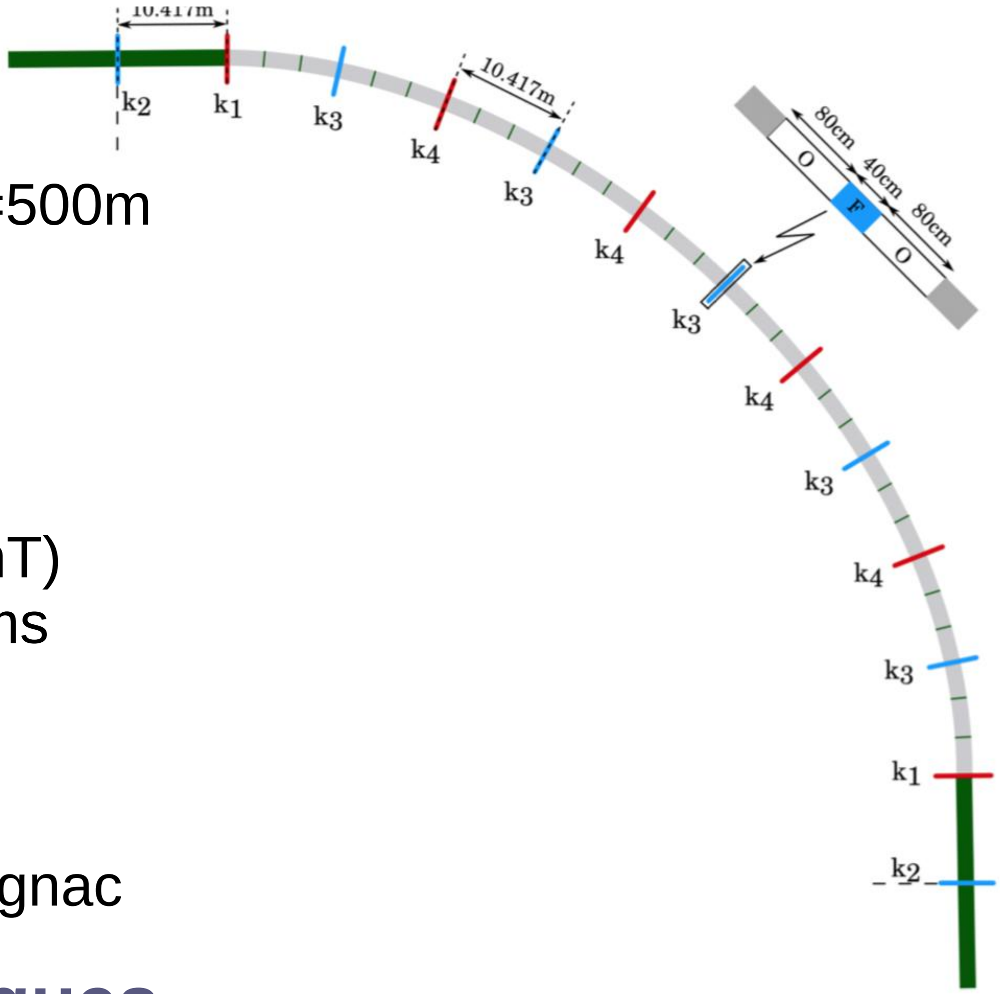
- Magnetic machine: spins precess around stable spin axis ($\simeq$ direction of B-fields in dipole magnets).
- RF device at harmonic of spin-precession frequency:
  - $\Rightarrow$ *Phase lock* between spin precession and device RF.
  - $\Rightarrow$ Accumlate EDM effect vs time in cycle ($\sim$ 1000 s).

Goal of proof-of-principle experiment:

Show that SR can be used for a first direct EDM measurement.

2018?

SREDM : Storage Ring EDM Collaboration



- **All-Electric Storage Ring**
  - Optimized for protons
  - p=0.7GeV/*c*, 8MV/m, ρ=50m, ℓ=500m
  - 1000s storage time
  - Aim 10^{-29} *e*·cm
- **Deal w/ systematic errors**
  - Stray B-field shielding (10–100nT)
  - Simultaneous CW & CCW beams
  - Different helicities
  - Develop & test simulation tools
  - Misalignments
  - Understand gravity, Coriolis, Sagnac
- **Develop detection techniques**
  - Squid magnetometers
  - High-precision BPMs (pm @ 10^7s)

Rev. Sc. Inst. 87, 115116 (2016)
ArXiv:1709.01208
“The Electric Dipole Moment Challenge”,
Richard Talman, IOPScience (2017)

Summary
&
Outlook

Summary & Outlook

- **Strong Motivation for Light Ion EDM Search**
  - Protons, deuterons, … complementary to heavy nuclei
  - Muons only second generation particle

- **Storage Rings open new EDM territory**
  - Loads of experience
  - Intense Effort to Overcome Experimental Challenges
  - Intense Effort to Study Systematic Errors

- **Future**
  - FNAL muon g-2/EDM : commissioning
  - KEK muon g-2/EDM : applying for funding
  - JEDI deuteron EDM : preparing proof-of-principle
  - srEDM proton EDM : pioneering all-E concept