# Measuring Electron and Proton Electrical Dipole Moments

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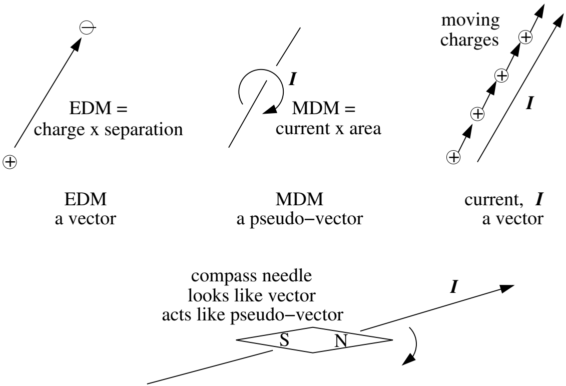
# Outline

Force Field Symmetries
Why Measure EDM?
Resonant Polarimeter
Conceptual EDM Measurement Ring
Why “Rolling Polarization”? and Why the EDM Signal Survives
Frequency Domain Treatment of Helical Resonator Response
Achievable Precision
Long Term EDM Program
BNL “AGS Analogue” Ring as EDM Prototype
Proposed Resonant Polarimetry Test Using COSY Deuteron Beam
Conclusions

Most of this talk is extracted from the following papers:

- R. and J. Talman, *Symplectic orbit and spin tracking code for all-electric storage rings,* Phys. Rev. ST Accel Beams **18**, ZD10091, 2015
- R. and J. Talman, *Electric dipole moment planning with a resurrected BNL Alternating Gradient Synchrotron electron analog ring,* Phys. Rev. ST Accel Beams **18**, ZD10092, 2015
- R. Talman, *Frequency domain storage ring method for Electric Dipole Moment measurement,* arXiv:1508.04366 [physics.acc-ph], 18 Aug 2015

# 4 Force Field Symmetries: Vectors and Pseudovectors

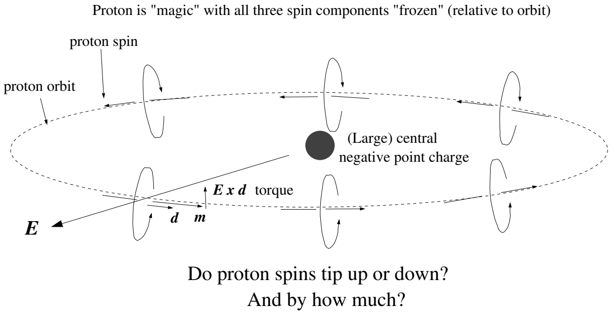



- An electric dipole moment (EDM) points from plus charge toward minus charge—the “orientation” of a true **vector**.
- The axis of a magnetic dipole moment (MDM) is perpendicular to a current loop, whose direction gives a different “orientation”. The MDM is a **pseudo-vector**.
- Ampère: how does the compass needle know which way to turn?

## 5 Capsule history of force field symmetries

- Newton: Gravitational field, (inverse square law) central force
- Coulomb: By analogy, electric force is the same (i.e. central)
- Ampere: How can compass needle near a current figure out which way to turn? Magnetic field is **pseudo-vector**. A **right hand rule** is somehow built into E&M and into the compass needle.
- The upshot: By introducing **pseudo-vector** magnetic field, E&M respects reflection symmetry, but compound objects need not exhibit the symmetry.
- Lee, Yang, etc: A particle with spin (**pseudo-vector**), say "up", can decay more up than down (**vector**);
  - i.e. the decay vector is parallel (not anti-parallel) to the spin pseudo-vector,
  - viewed in a mirror, this statement is reversed.
  - i.e. weak decay force violates reflection symmetry (P).
- Fitch, Cronin, etc: protons, etc. have both MDM and EDM. This violates both parity (P) and time reversal (T).
- Current task: How to exploit the implied symmetry violation to measure the EDM of proton, electron, etc?

# 6 EDM Sensitive Configuration




Two issues:

- Can the tipping angle be measurably large for plausibly large EDM, such as $10^{-30}$ e-cm? With modern, frequency domain, technology, yes
- Can the symmetry be adequately preserved when the idealized configuration above is approximated in the laboratory? This is the main issue

# 7 Why Measure EDM?

- Violations of parity (P) and time reversal (T) in the standard model are insufficient to account for excess of particles over anti-particles in the present day universe.
- Any non-zero EDM of electron or proton would represent a violation of both P and T, and therefore also CP.

Comments:

- Beam direction reversal is possible in all-electric storage ring, with all parameters except injection direction held fixed. This is crucial for reducing systematic errors.
- "Frozen spin" operation in all-electric storage ring is only possible with electrons or protons—by chance their anomalous magnetic moment values are appropriate. The "magic" kinetic energies are 14.5 MeV for e, 235 MeV for p.

# 8 Resonant (Longitudinal) Polarimeter

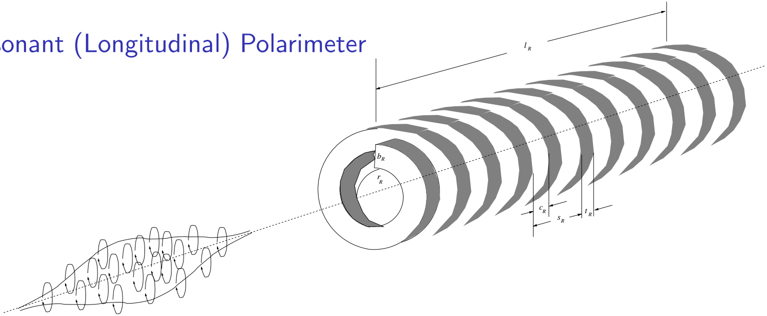



Figure: Longitudinally polarized beam approaching a superconducting helical resonator. Beam polarization is due to the more or less parallel alignment of the individual particle spins, indicated here as tiny current loops. The helix is the inner conductor of a helical transmission line, open at both ends. The cylindrical outer conductor is not shown. High Q, (transverse) polarimetry was first proposed by Derbenev in 1993. But it has not yet been successfully demonstrated.

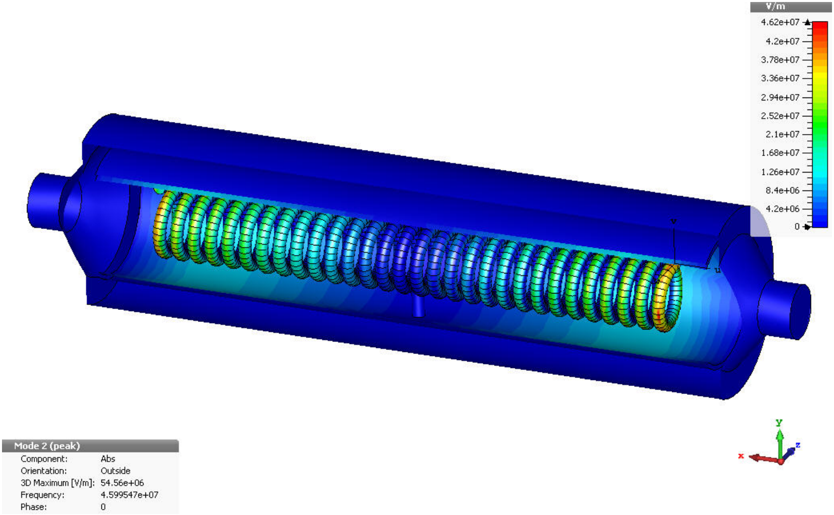



Figure: Evgeny Zaplatin (Jülich) CAD drawing for resonant polarimeter roughly matched for particle speed $\beta_p \approx 0.2$, wave speed $\beta_r \approx 0.1$.

## Resonant (Longitudinal) Polarimeter Response

- The Faraday's law E.M.F. induced in the resonator has one sign on input and the opposite sign on output.
- At high enough resonator frequency these inputs no longer cancel.
- The key parameters are particle speed $v_p$ and (transmission line) wave speed $v_r$.
- The lowest frequency standing wave for a line of length $l_r$, open at both ends, has $\lambda_r = 2l_r$;

$$B_z(z,t) \approx B_0 \sin\frac{\pi z}{l_r}\,\sin\frac{\pi v_r t}{l_r}, \quad 0 < z < l_r. \tag{1}$$

- The (Stern-Gerlach) force on a dipole moment $\mathbf{m}$ is given by

$$\mathbf{F} = \nabla(\mathbf{B}\cdot\mathbf{m}). \tag{2}$$

- The force on a magnetic dipole on the axis of the resonator is

$$F_z(z,t) = m_z\frac{\partial B_z}{\partial z} = \frac{\pi m_z B_0}{l_r}\cos\frac{\pi z}{l_r}\,\sin\frac{\pi v_r t}{l_r}. \tag{3}$$

11 At position $z = v_p t$ a magnetic dipole traveling at velocity $v_p$ is subject to force

$$F_z(z) = \frac{\pi m_z B_0}{l_r} \cos\frac{\pi z}{l_r} \sin\frac{\pi (v_r/v_p) z}{l_r}. \tag{4}$$

Integrating over the resonator length, the work done on the particle, as it passes through the resonator, is

$$\Delta U(v_r/v_p) = m_z B_0 \left[\frac{\pi}{l_r} \int_{z=0}^{l_r} \cos\frac{\pi z}{l_r} \sin\frac{\pi (v_r/v_p) z}{l_r}\, dz\right]. \tag{5}$$

- See plot.

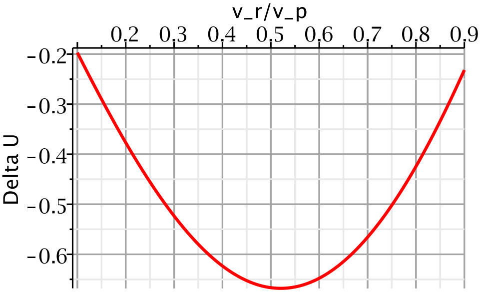



Figure: Plot of energy lost in resonator $\Delta U(v_r/v_p)$ as given by the bracketed expression in Eq. (5).

- For $v_r = 0.51\, v_p$, the energy transfer from particle to resonator is maximized.
- **With particle speed twice wave speed, during half cycle of resonator, $B_z$ reverses phase as particle proceeds from entry to exit.**

# 13 EDM Measurement Ring

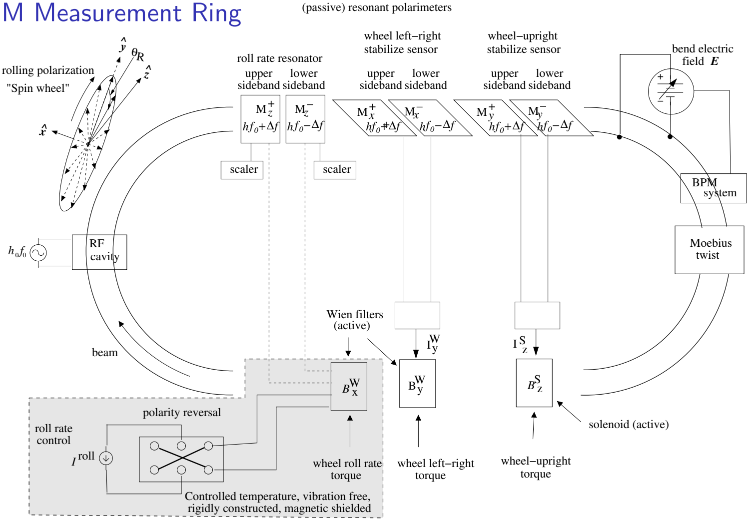



Figure: Cartoon of the EDM ring and its spin control. The Koop polarization “spin wheel” in the upper left corner “rolls” along the ring, always upright, and aligned with the orbit. The boxes at the bottom apply torques to the magnetic moments without altering the design orbit.

- Because of the rolling polarization the resonator excitation appears as upper and lower sidebands of the revolution frequency (and its harmonics).
- Elements with superscript “W” are Wien filters; superscript “S” indicates solenoid.
- **The frequency domain EDM signal is the difference between forward and backward spin wheel rotation frequencies, when the $B_x^W$ Wien filter polarity is reversed.**
- EDM measurement accuracy (as contrasted with precision) is limited by the reversal accuracy occurring in the shaded region.
- Precision is governed by scaler precision. This is a benefit obtained by moving the EDM sensitivity from polarimeter intensity to polarimeter frequency response.

# 15 Spin wheel stabilizing torques

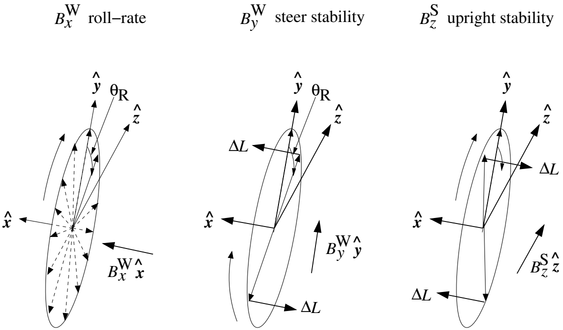



Figure: Roll-plane stabilizers: Wien filter $B_x^W \hat{\mathbf{x}}$ adjusts the "wheel" roll rate, Wien filter $B_y^W \hat{\mathbf{y}}$ steers the wheel left-right, Solenoid $B_z^S \hat{\mathbf{z}}$ keeps the wheel upright.

- A Wien filter does not affect the particle orbit (because the crossed electric and magnetic forces cancel) but it acts on the particle magnetic moment (because there is a non-zero magnetic field in the particle's rest frame).
- A Wien torque
$$\hat{\mathbf{x}} \times (\hat{\mathbf{y}}, \hat{\mathbf{z}})\, S = (\hat{\mathbf{z}}, -\hat{\mathbf{y}})\, S$$
changes the roll-rate.
- A Wien torque
$$\hat{\mathbf{y}} \times (\hat{\mathbf{z}}, \hat{\mathbf{x}})\, S = (\hat{\mathbf{x}}, -\hat{\mathbf{z}})\, S$$
steers the wheel left-right.
- (Without affecting the orbit) a solenoid torque
$$\hat{\mathbf{z}} \times (\hat{\mathbf{x}}, \hat{\mathbf{y}})\, S = (\hat{\mathbf{y}}, -\hat{\mathbf{x}})\, S$$
can keep the wheel upright.

## 17 Why “Rolling Polarization”? and Why the EDM Signal Survives

- Polarized “spin wheel” was proposed by Koop for different (but important) reason—to cancel $\Delta\gamma$ spin decoherence.
- Here the primary purpose of the rolling polarization is to shift the resonator response frequency *away from* harmonic of revolution frequency.
- This is essential to protect the polarization response from being overwhelmed by direct response to beam charge or beam current.
- Since the EDM torque is always in the plane of the wheel its effect is to alter the roll rate.
- Reversing the roll direction (with beam direction fixed) does not change the EDM contribution to the roll.
- **The difference between forward and backward roll-rates measures the EDM (as a frequency difference).**

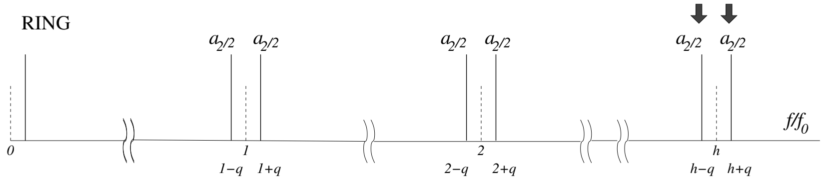



Figure: Frequency spectra of the beam polarization drive signal to the resonant polarimeter. The operative polarimetry sideband lines are indicated by dark arrows.

# 19 Polarimeter room temperature bench test

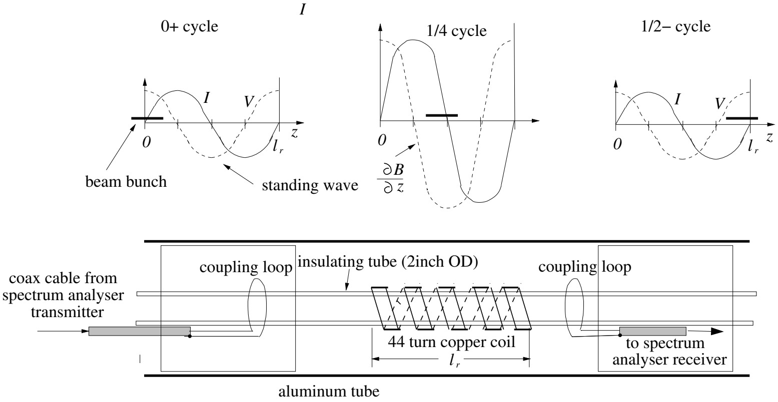



Figure: . Room temperaure bench test set-up of prototype resonant polarimeter, with results shown in next figure. The coil length is $l_r$=11 inches. Beam magnetization is emulated by the spectrum analyser transmitter.

- Resonator excitation is detected by a single turn loop connected to the spectrum analyser receiver.
- This would be an appropriate pick-up in the true polarimetry application though, like the resonator, the preamplifier would have to be at cryogenic temperature to maximize the signal to noise ratio.
- The figures above the apparatus are intended to complete the analogy to a situation in which the transmitter is replaced by the passage of a beam bunch.
- The particle and wave speeds are arranged to maximize the energy transfer from beam to resonator.

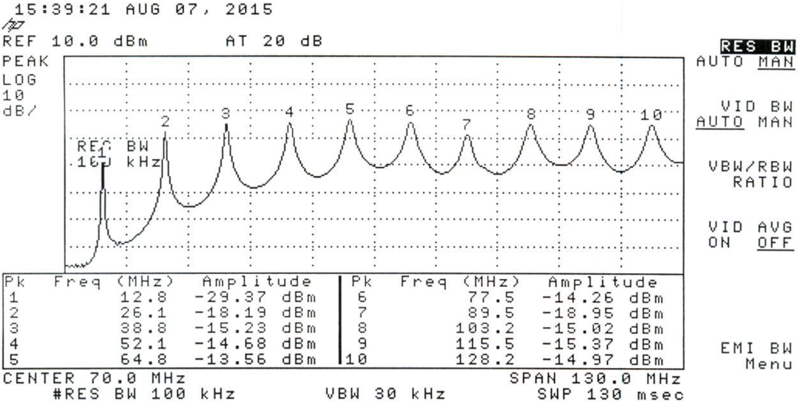



Figure: Frequency spectrum observed using the bench test shown in previous figure. Ten normal modes of the helical transmission line are visible.

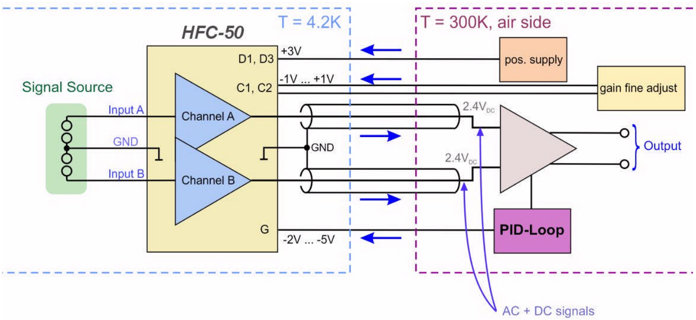



Figure: Commercial, cryogenic, low noise, high gain, dual pre-amp for transmission line signal extraction from cryogenic to room temperature environments.

# 23 Wien Filter

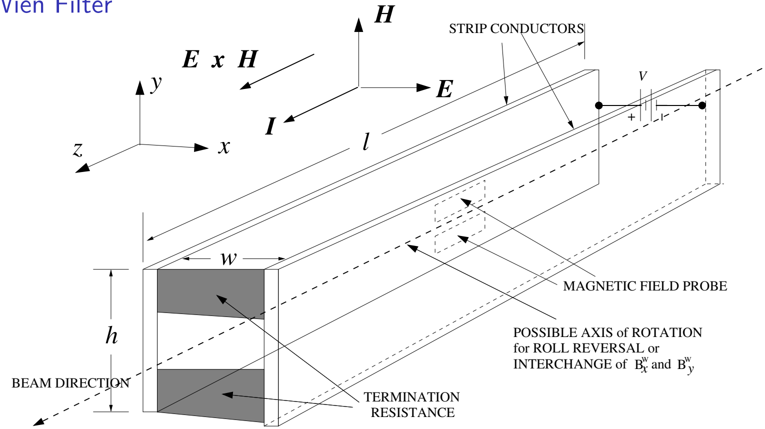



Figure: Stripline Wien filter dimensions. With electromagnetic power and beam traveling in the same direction, the electric and magnetic forces tend to cancel. Termination resistance $R$ is adjusted for exact cancelation. For rolling polarization reversal, the Wien filter current to be reversed will be a conveniently low value, such as 5 A.

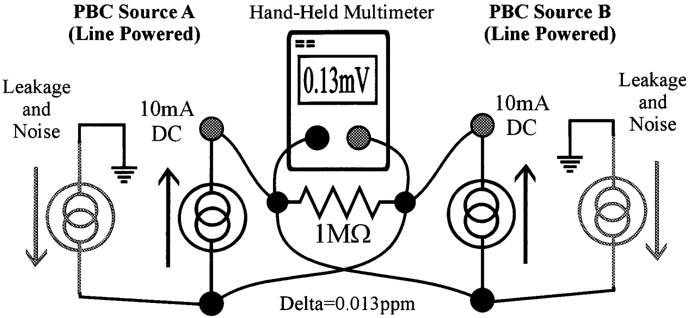



Figure: Current bridge used for high precision current monitoring. Copied from CERN, PBC reference. One current is the active current, the other a highly stable reference current. Even hand-held, 1 part in $10^8$ precision is obtained. Wien current reversal precision will be monitored every run by recording the potentiometer voltage with Wien current in one arm and standard current in the other.

# (Almost) Phase-Locked Spin Deuteron Beam, COSY Lab. Juelich

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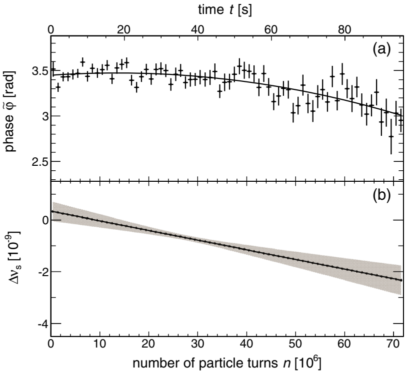


FIG. 3 (color online). (a) Phase $\tilde{\varphi}$ as a function of turn number $n$ for all 72 turn intervals of a single measurement cycle for $|\nu_s^{\mathrm{fix}}| = 0.160\,975\,407$, together with a parabolic fit. (b) Deviation $\Delta\nu_s$ of the spin tune from $\nu_s^{\mathrm{fix}}$ as a function of turn number in the cycle. At $t \approx 38$ s, the interpolated spin tune amounts to $|\nu_s| = (16\,097\,540\,628.3 \pm 9.7) \times 10^{-11}$. The error band shows the statistical error obtained from the parabolic fit, shown in panel (a).

## 26 Achievable Precision (i.e. not including systematic error) say for electron

EDM in units of (nominal value) $10^{-29}$ e-cm $= \tilde{d}$
2 x EDM(nominal)/MDM precession rate ratio:
$2\eta^{(e)} = 0.92 \times 10^{-15} \approx 10^{-15}$
duration of each one of a pair of runs $= T_{\rm run}$
smallest detectable fraction of a cycle $= \eta_{\rm fringe} = 0.001$

$$N_{FF} = \text{EDM induced fractional fringe shift per pair of runs}$$
$$= \frac{(2\eta^{(e)})\tilde{d}}{\eta_{\rm fringe}}\, h_r f_0 T_{\rm run} \quad \Big( \overset{\rm e.g.}{\approx}\ \tilde{d}\, \frac{10^{-15}\cdot 10\cdot 10^{7}\cdot 10^{3}}{10^{-3}} = 0.1\tilde{d} \Big),$$

Assumed roll rate reversal error $: \pm\eta^{\rm rev.} \overset{\rm e.g.}{=} 10^{-10}$

$$\sigma_{FF}^{\rm rev.} = \ \text{roll reversal error measured in fractional fringes}$$
$$= \pm\, \frac{f^{\rm roll}\eta^{\rm rev.}\, T_{\rm run}}{\eta_{\rm fringe}} \quad \Big( \overset{\rm e.g.}{\approx}\ \pm \frac{10^{2}\cdot 10^{-10}\cdot 10^{3}}{10^{-3}} = 10^{-2} \Big).$$

| particle | $\lvert d_{\rm elec}\rvert$ current upper limit e-cm | excess fractional cycles per pair of 1000 s runs | error after $10^4$ pairs of runs e-cm | roll reversal error e-cm |
|---|---|---|---|---|
| neutron | $3 \times 10^{-26}$ | | | |
| proton | $8 \times 10^{-25}$ | $\pm 8 \times 10^{3}$ | $\pm 10^{-30}$ | $\pm 10^{-30}$ |
| electron | $10^{-28}$ | $\pm 1$ | $\pm 10^{-30}$ | $\pm 10^{-30}$ |

# 27 Long Term EDM Program

- Design and build resonant polarimeter and circuitry
- Confirm (longitudinal, helical) resonant polarimetry using polarized electron or proton beam, or (currently most promising) the same polarized deuteron beam at COSY, Jülich, shown in earlier slide.
- Develop rolling-polarization 15 MeV electron beam (e.g at Wilson Lab or Jefferson Lab or Mainz)
- Confirm (transverse, TE101) resonant polarimetry using polarized electron or proton beam
- Build 5 m diameter, 14.5 MeV electron ring (e.g. at Wilson Lab, J-Lab, Mainz, etc.)
- Measure electron EDM
- Attack electron EDM systematic errors
- Meanwhile, same program as above for 235 MeV protons in 40 m radius, all electric ring (e.g. at BNL, FNAL, or COSY)

# BNL "AGS Analogue" Ring as EDM Prototype

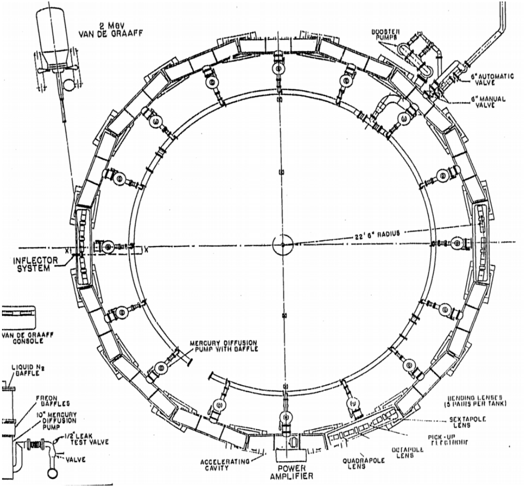


Figure: The 1955 AGS-Analogue lattice as reverse engineered from available documentation—mainly the 1953 BNL-AEC proposal letter. Except for insufficient straight section length, and the 10 MeV rather than 14.5 Mev energy, this ring could be used to measure the electron EDM.

| | |
|---|---|
| Field strength (magnetic type) | |
| at injection | 10.5 gauss |
| at 10 MeV | 74 gauss |
| Field strength (electrostatic type) | |
| at injection | 3 kV/cm |
| at 10 MeV | 22 kV/cm |
| Rise time | .01 sec |
| Phase transition energy | 2.8 MeV |
| Frequency (final) | 7 mc |
| Frequency change | 5½ % |
| Volts/turn | 150 V |
| RF power | about 1 kw |
| No. of betatron wavelengths | about 6.2 |
| aperture | 1 X 1 in. |
| Betatron amplitude for $10^{-3}$ rad. error | 0.07 in. |
| Maximum stable amplitude, synchrotron osc. | -0.16 in. |
| Radial spacing of betatron resonances | about 0.4 in. |
| Vacuum requirement | about $10^{-6}$ mm Hg |

Total power requirements will be small and available with existing installations. The test shack seems to be a suitable location since the ring will be erected inside a thin magnetic shield which can be thermally insulated and heated economically.

We estimate the cost to be approximately $600,000, distributed as shown in the following table:

| Model | Direct | Overhead | Total | Inflate to 2015 |
|---|---|---|---|---|
| Staff S. & W. | $135,000 | $ 65,000 | $200,000 | $M 1.76 |
| Van de Graaff | 70,000 | - | 70,000 | 0.62 |
| Other E. & S. | 130,000 | - | 130,000 | 1.14 |
| Shops | 135,000 | 65,000 | 200,000 | 1.76 |
| | $470,000 | $130,000 | $600,000 | $M 5.27 |

# 30 Resonant Polarimetry Test Using COSY Deuteron Beam

Table: An earlier slide showed spin phase stability to better than $2\pi$ for about 100 s time duration, long enough for EDM measurement.

| experiment | | | TEST | TEST | TEST(pessimistic) | TEST(optimistic) |
|---|---|---|---|---|---|---|
| parameter | symbol | unit | proton | deuteron | deuteron | deuteron |
| bunches/ring | $N_b$ | | 116 | 1 | 10 | 10 |
| beam | | | COSY | COSY | COSY | COSY |
| conductor | | | SC | SC | SC | SC |
| RF solenoid | | | ✓ | ✓ | ✓ | ✓ |
| magnetization freq. | $F_{\mathrm{roll}}$ | MHz | 0.12 | 0.12 | 0.12 | 0.12 |
| free or driven? | | | free | free | free | free |
| ring frequency | $f_0$ | MHz | 9.804 | 0.75 | | |
| magnetic moment | $\mu$ | eV/T | 0.88e-7 | 0.2703e-8 | | |
| $\beta$ | $\beta$ | | 0.6 | 0.434 | | |
| resonator frequency | $f_r$ | MHz | $116 f_0 \pm 0.12$ | $110 f_0 \pm 0.12$ | | |
| resonator radius | $r_r$ | cm | 1.80 | 2 | | |
| resonator length | $l_r$ | m | 2 | 0.920 | | |
| temperature | $T$ | $^\circ$K | 4 | 10 | 10 | 4 |
| phase velocity/$c$ | $\beta_r$ | | 0.408 | 0.22 | | |
| quality factor | $Q_{\mathrm{res.}}$ | | 1e6 | 1e6 | 1e6 | 1e7 |
| response time | $Q_{\mathrm{res.}}/f_r$ | s | 0.0088 | 0.012 | | 0.12 |
| beam current | $I$ | A | 0.001 | 0.0001 | 0.0001 | 0.001 |
| particles | $N_e$ | | 6.4e9 | 0.832e8 | 0.832e8 | 0.832e9 |
| particles/bunch | $N_e/N_b$ | | 5.5e7 | 0.832e8 | 0.832e7 | 0.832e8 |
| magnetic field | $H_r$ | Henry | 1.15e-8 | 0.90e-9 | | 0.90e-7 |
| resonator current | $I_r$ | A | 2.6e-9 | 0.90e-10 | | 0.90e-8 |
| magnetic induction | $B_r$ | T | 1.4e-14 | 1.13e-15 | | 1.13e-13 |
| max. resonator energy | $U_r$ | J | 3.8e-25 | 1.19e-27 | | 1.19e-23 |
| noise energy | $\overline{U_m}$ | J | 2.8e-23 | 6.9e-23 | | |
| S/N(ampl.) | $\sqrt{U_r/\overline{U_m}}$ | | 0.117 | 0.0042 | 0.0042 | 0.66 |
| S/N(synch.) | $(S/N)\sqrt{f_0}$ | $\mathrm{s}^{-1/2}$ | phase-lock? | phase-lock? | phase-lock? | phase-lock? |
| S/N(lock-in) | $(S/N)\sqrt{f_0}$ | | $1248\sqrt{T[s]}$ | $37.7\sqrt{T[s]}$ | $37.7\sqrt{T[s]}$ | $5960\sqrt{T[s]}$ |
| S/N(2pol-coh.) | $(S/N)\sqrt{f_0}$ | | $>> 1248\sqrt{T[s]}$ | $>> 37.7\sqrt{T[s]}$ | $>> 37.7\sqrt{T[s]}$ | $>> 5960\sqrt{T[s]}$ |

- Successful application of the method depends on two not yet established experimental methods: resonant polarimetry (promising theoretically) and "rolling polarization trap" operation—meaning stable, phase-locked, rolling polarization operation—(promising experimentally, at COSY).
- It is thermal noise in the resonant polarimeter that limits EDM measurement *precision*.
- A successful single beam fill will include at least one forward/backward reversal of the roll (not beam) direction, with roll frequency precisely measured both before and after.
- One (of many) successful single beam EDM measurements will consist of four data sets, roll forward and backward, with EDM effect on (spin wheel vertical) and off (spin wheel horizontal "background" measurement).

- Almost all AC magnetic fields have cancelled. Only pure DC (or rather less than 0.01 Hz) $\Delta B_r$ error field gives a spurious EDM signal.
- Only CW/CCW beam direction reversal (with vanishingly small vertical orbit displacement) can reduce this systematic error. But the beams do not need to be present at the same time.
- Alternate runs with beam direction reversed to "cancel" EDM systematic error due to residual radial magnetic field.
- By running on integer (non-zero) vertical tune $Q_y$ (to magnify BPM sensitivity) local $\Delta B_r$ fields can be cancelled, using CW/CCW beams, with diametrically-opposite pairs of $\Delta B_r$ correctors.
- Expressed as EDM upper limit, measurement *precision* of $10^{-30}$ e-cm after year-long running, for either electrons and protons, can be expected.

- *Accuracy* at the same level as the *precision* will require average sign reversal accuracy of Wien filter length/strength product at the level of one part in $10^{11}$, also averaged over one year.
- Apparatus constituting a single Wien filter will all be contained in a single, temperature regulated, limited vibration, magnetically shielded, highly isolated, etc. box.
- Emittance growth due to intrabeam scattering (IBS) has been seen as a serious impediment to EDM measurement. With ultra-low $Q_y$ not required, running "below transition", which tends to suppress beam growth due to IBS, will be possible.
- Spin coherence time SCT is greatly increased by Möbius ring operation.

# 34 Extra Slides

# 35 Possible polarimeter tests and applications

Table: Signal level and signal to noise ratio for various applications. In all cases the polarization is taken to be 1. In spite of the quite high $Q_c$ values achievable with HTS, the economy this promises is overwhelmed by the signal to noise benefit in running at far lower liquid helium temperature. The bottom row is the most important.

| experiment | | | TEST | TEST | e-EDM | e-EDM | p-EDM | TEST |
|---|---|---|---|---|---|---|---|---|
| parameter<br>beam<br>conductor | symbol | unit | electron<br>J-LAB linac<br>HTS | electron<br>J-LAB linac<br>SC | electron<br>ring<br>HTS | electron<br>ring<br>SC | proton<br>ring<br>SC | proton<br>COSY<br>SC |
| ring frequency | $f_0$ | MHz | | | 10 | 10 | 1 | 9.804 |
| magnetic moment | $\mu_p$ | eV/T | 0.58e-4 | 0.58e-4 | 0.58e-4 | 0.58e-4 | 0.88e-7 | 0.88e-7 |
| magic $\beta$ | $\beta_p$ | | 1.0 | 1.0 | 1.0 | 1.0 | 0.60 | 0.6 |
| resonator frequency | $f_r$ | MHz | 190 | 190 | 190 | 190 | 114 | 114 |
| resonator radius | $r_r$ | cm | 0.5 | 0.5 | 2 | 2 | 2 | 2 |
| resonator length | $l_r$ | m | 1.07 | 1.07 | 1.07 | 1.07 | 1.80 | 1.80 |
| temperature | $T$ | °K | 77 | 1 | 77 | 1 | 1 | 4 |
| phase velocity/$c$ | $\beta_r$ | | 0.68 | 0.68 | 0.68 | 0.68 | 0.408 | 0.408 |
| quality factor | $Q_{\rm res.}$ | | 1e6 | 1e8 | 1e6 | 1e8 | 1e8 | 1e6 |
| response time | $Q_{\rm res.}/f_r$ | s | | 0.53 | 0.0052 | 0.52 | 0.88 | 0.0088 |
| beam current | $I$ | A | 0.001 | 0.001 | 0.02 | 0.02 | 0.002 | 0.001 |
| bunches/ring | $N_b$ | | | | 19 | 19 | 114 | 116 |
| particles | $N_e$ | | | | 1.2e10 | 1.2e10 | 1.2e10 | 6.4e9 |
| particles/bunch | $N_e/N_b$ | | 3.3e7 | 3.3e7 | 0.63e9 | 0.63e9 | 1.1e8 | 5.5e7 |
| magnetic field | $H_r$ | Henry | 2.6e-7 | 2.6e-6 | 1.3e-6 | 1.3e-4 | 2.3e-6 | 1.15e-8 |
| resonator current | $I_r$ | A | 2.2e-8 | 2.2e-6 | 2.2e-7 | 2.2e-5 | 0.50e-6 | 2.6e-9 |
| magnetic induction | $B_r$ | T | 3.3e-13 | 3.3e-11 | 1.6e-12 | 1.6e-10 | 2.8e-12 | 1.4e-14 |
| max. resonator energy | $U_r$ | J | 2.9e-23 | 2.9e-19 | 2.9e-21 | 2.9e-17 | 1.5e-20 | 3.8e-25 |
| noise energy | $\overline{U_m}$ | J | 0.53e-21 | 0.69e-23 | 0.53e-21 | 0.69e-23 | 0.69e-23 | 2.8e-23 |
| S/N(ampl.) | $\sqrt{U_r/\overline{U_m}}$ | | 0.23 | 205 | 2.3 | 2055 | 45.8 | 0.117 |
| S/N(ph-lock) | $(S/N)\sqrt{f_0}$ | $\mathrm{s}^{-1/2}$ | 3.2e3 | 2.8e6 | 3.2e4 | 2.8e7 | 4.9e5 | 1248 |