Polarimetry for Measuring the Electron EDM at Wilson Lab

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2 Outline

3 Long Term Plan for Measuring Electron and Proton EDM's

- Design and build resonant polarimeter and circuitry
- Develop rolling-polarization 15 MeV electron beam (e.g at Wilson Lab or Jefferson Lab.)
- Confirm resonant polarimetry using polarized electron beam
- Build 50 m circumference, 14.5 MeV electron ring (e.g. at Wilson Lab)
- Measure electron EDM crudely
- Attack electron EDM systematic errors (Relative to this, everything before else will have been easy)
- Repeat above for 230 MeV protons in 300 m circumference, all electric ring (e.g. at BNL or FNAL)

4 Conceptual EDM Measurement Ring

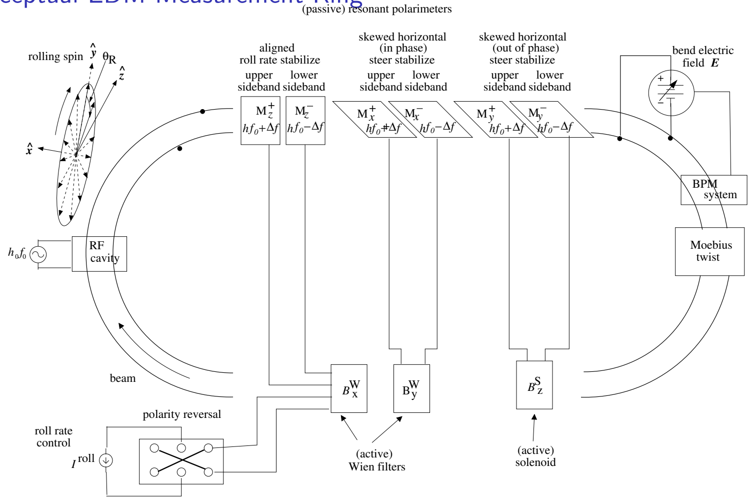

Figure: Cartoon schematic of the ring and its instrumentation. The boxes in the lower straight section respond to polarimeters in the upper straigt and apply torques to steer the wheel and keep it upright. The switch reverses the roll. EDM causes forward and backward roll rates to differ.

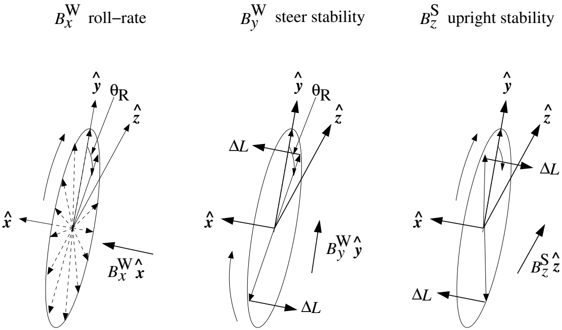

Figure: Roll-plane stabilizers: Wien filter $B_x^W\hat{\mathbf{x}}$ adjusts the "wheel" roll rate, Wien filter $B_y^W\hat{\mathbf{y}}$ steers the wheel left-right, Solenoid $B_z^S\hat{\mathbf{z}}$ keeps the wheel upright.

 ## Why "Rolling Polarization"? and Why EDM Signal Survives

- Polarized "wheel" was proposed by Koop (for different reason).
- 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).**

- 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.

8 Resonant Polarimetry

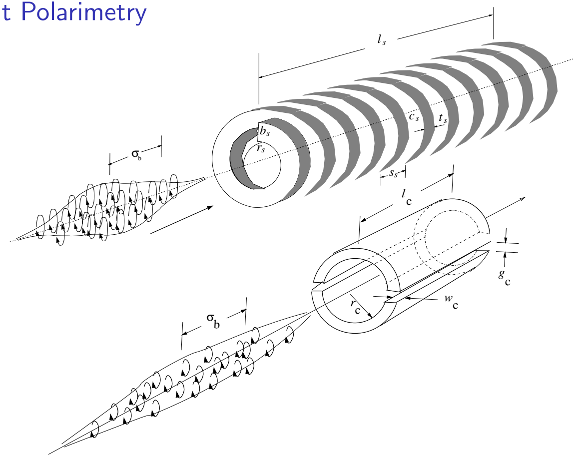

Figure: Polarized beam bunch approaching a helical resonator (above) or a split-cylinder (below). Splitting the cylinder symmetrically on both sides suppresses a direct e.m.f. induced in the loop by a vertically-displaced beam bunch. Individual particle magnetic moments are cartooned as tiny current loops. In NMR a cavity field "rings up" the particle spins. Here particle spins "ring up" the cavity field.

9 Resonator 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

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

 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.

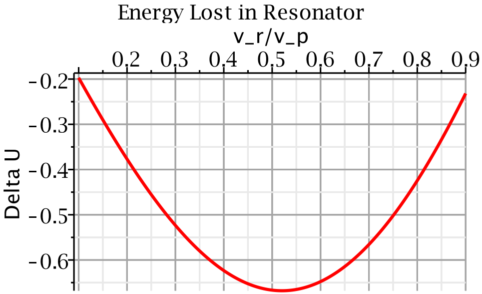

Figure: Plot of energy lost in resonator $\Delta U(v_r/v_p)$ as given by the bracketed expression in Eq. (5).

- 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.**

Resonator Test Rig

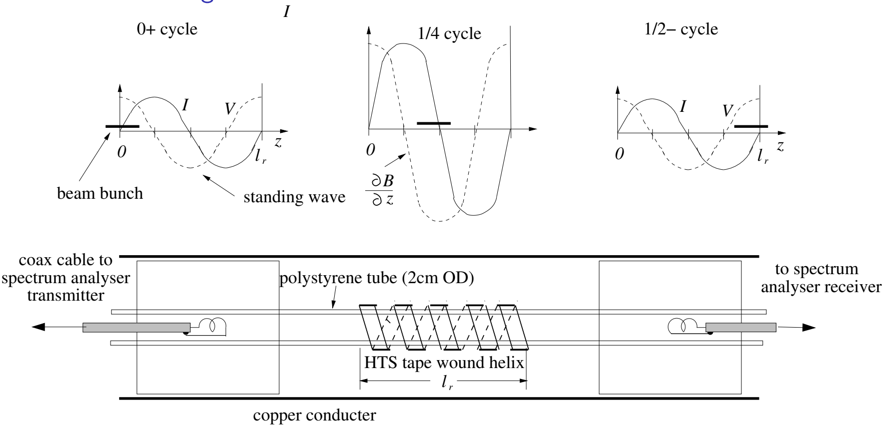

Figure: Test set-up for investigating the self-resonant helical coil resonator, using high temperature superconductor, for example. The inset graph shows instantaneous voltage and current standing-wave patterns for the lowest oscillation mode. Treated as a transmission line open at both ends, the lowest standing wave oscillation mode has coil length l_r equal to line half wavelength $\lambda_r/2$.

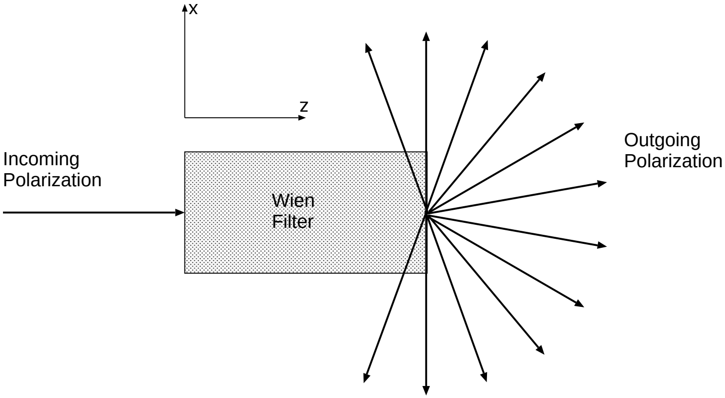

Figure: Figure (copied from Grames's thesis), showing the front end of the CEBAF injector. The 100 KeV electron beam entering the DC Wien filter is longitudinally polarized. The superimposed transverse electric and magnetic forces exactly cancel, therefore causing no beam deflection. But the net torque acting on the electron MDM rotate the polarization vector angle to the positions depending on their strength.

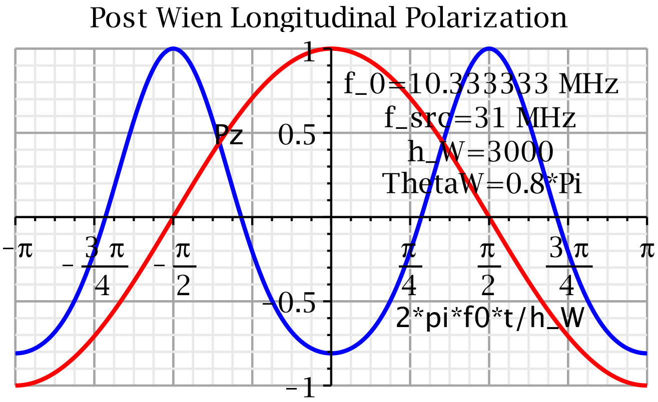

Figure: Time dependences of the Wien filter drive voltage and the resulting longitudinal polarization component for linac beam following the Wien filter polarization rotater. The range of the output is less than ± 1 because $\Theta_{\max} = 0.8\pi$ is less than π. Note the frequency doubling of the output signal relative to the drive signal and the not-quite-sinusoidal time dependence of the output.

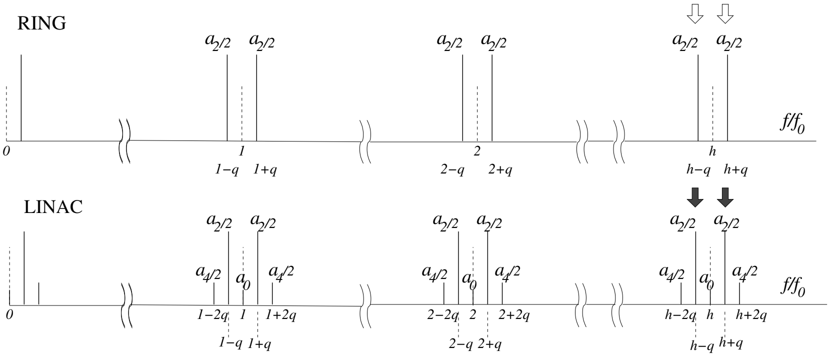

Figure: Frequency spectra of the beam polarization drive to the resonant polarimeter. The ring drive modulation (above) is purely sinusoidal. The linac drive (below) is distorted, but can be approximately sinusoidal, giving the same two dominant sideband signals. The operative polarimetry sideband lines are indicated by dark arrows.

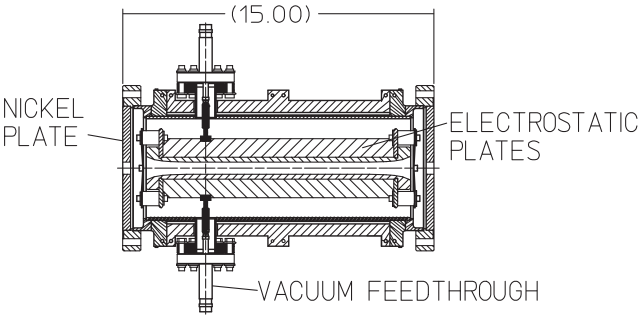

Figure: The Wien filter spin manipulator used with CEBAF's second and third polarized electron sources. (Figure copied from Sinclair et al. paper.) The maximum field integrals are approximately $\int \hat{B}_x ds \approx 0.003\,\mathrm{T\,m}$ and $\int \hat{E}_y ds \approx 500\,\mathrm{KV}$

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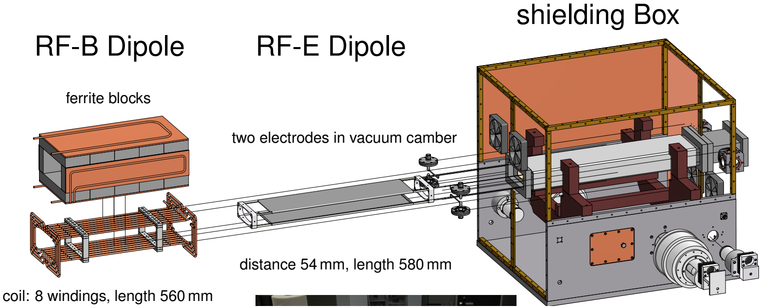


Figure: RF Wien filter currently in use at the COSY ring in Juelich Germany. (Copied and cropped from a poster presentation by Sebastian Mey.) For RF frequencies near 1 MHz the maximum field integrals are $\int \hat{B}_x ds$=0.000175 T m and $\int \hat{E}_y ds$=24 KV. These limits are about 20 times weaker than the CEBAF Wien filter. But the COSY frequency is unnecessarily high by a factor of $10^6/3 \times 10^3 \approx 300$. This suggests that the required Wien filter, oscillating for example at 3 KHz, should be feasible.

18 Possible polarimeter tests and applications

parameter beam conductor	symbol	unit	electron linac HTS	electron linac SC	electron ring HTS	electron ring SC	proton ring SC
ring frequency	f_0	MHz			10	10	1
magnetic moment	μ_p	eV/T	0.58e-4	0.58e-4	0.58e-4	0.58e-4	0.88e-7
magic β	β_p		1.0	1.0	1.0	1.0	0.60
resonator freq.	f_r	MHz	190	190	190	190	114
radius	r_r	cm	0.5	0.5	2	2	2
length	l_r	m	1.07	1.07	1.07	1.07	1.80
temperature	T	$^\circ$K	77	1	77	1	1
phase vel./c	β_r		0.68	0.68	0.68	0.68	0.408
quality factor	Q_r		1e6	1e8	1e6	1e8	1e8
response time	Q_r/f_r	s		0.53	0.0052	0.52	0.88
beam current	I	A	0.001	0.001	0.02	0.02	0.002
bunches/ring	N_b				19	19	114
particles	N_e				1.2e10	1.2e10	1.2e10
particles/bunch	N_e/N_b		3.3e7	3.3e7	0.63e9	0.63e9	1.1e8
magnetic field	H_r	Henry	2.6e-7	2.6e-6	1.3e-6	1.3e-4	2.3e-6
resonator current	I_r	A	2.2e-8	2.2e-6	2.2e-7	2.2e-5	0.50e-6
mag. induction	B_r	T	3.3e-13	3.3e-11	1.6e-12	1.6e-10	2.8e-12
maximum energy	U_r	J	2.9e-23	2.9e-19	2.9e-21	2.9e-17	1.5e-20
noise energy	$\overline{U_m}$	J	0.53e-21	0.69e-23	0.53e-21	0.69e-23	0.69e-23
signal/noise	$\sqrt{U_r/\overline{U_m}}$		0.23	205	2.3	2055	45.8
signal/noise (lock-in)	$\times 1000$		230	205,000			

Table: Anticipated rates at current EDM upper limits, assuming resonator frequency $f_r = 100\,\mathrm{MHz}$.

particle	$\lvert d_e \rvert$ upper limit e-cm	resonator cycles per day	excess due to EDM cycles per day
neutron	3×10^{-26}		
proton*	8×10^{-25}	2×10^{13}	± 7600
electron*	2×10^{-27}	2×10^{13}	± 2

* Elementary particle (proton or electron) EDM is corrected down from atomic EDM by factor ~ 1000.

- Proton is ultimately more promising, but electron is cheaper to start with (primarily to gain experience).

Why Measure EDM? Why Electron, then Proton?

- 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.
- In all-electric rings "frozen spin" operation is only possible with electrons or protons.

Some of this presentation is extracted from the following two papers, both of which have been accepted for publication to PRST-AB.

- ArXiv:1503.08468v1 [physics.acc-ph] 29 Mar 2015 , *ETEAPOT: symplectic orbit/spin tracking code for all-electric storage rings*, Richard Talman and John Talman
- ArXiv:1503.08494v1 [physics.acc-ph] 29 Mar 2015, *EDM planning using ETEAPOT with a resurrected AGS Electron Analogue ring* , Richard Talman and John Talman

Alternative EDM Measurement Strategies

- Start with "frozen beam"—as the beam rotates through 2π the polarization rotates by 2π around the same (vertical) axis.
- !4.5 MeV electrons and 230 MeV protons can be frozen in an all-electric ring (which is favorable for measuring EDM)
- There are two possibilities:
  1. If the beam starts polarized forward, the EDM tips the beam up or down out of the plane of the beam. Measure the tip angle.
  2. If the beam is (intentionally) "rolling" in a vertical plane tangent to the orbit the EDM causes the forward and backward roll rates to be different. Measure the roll rate.
- I will concentrate on the latter

23 BNL "AGS Analogue" Ring as EDM Prototype

August 21, 1953

Dr. T.H. Johnson, Director
Division of Research
U.S. Atomic Energy Commission
Washington 25, D.C.

Dear Tom:

This letter concerns certain aspects of our accelerator development program, particularly the proposed electron model.

As you know, the general development of a very high energy alternating gradient synchrotron is proceeding actively at Brookhaven, utilizing operating funds allocated to Basic Physics Research. As I explained in my letter of August 12, however, these funds are insufficient to carry forward the development as rapidly as desirable. Also, there are certain steps which should be taken for which the expenditure of operating funds is not appropriate. The first and most important of these is the construction of an electron model intended to provide final assurance of the technical feasibility of the chosen machine and, more importantly, to provide information enabling us to design in the most effective and economical manner. (We have no doubt of the general feasibility of accelerators of this type.)

We have given considerable thought to the requirements for such a model and to the philosophy which should guide us in designing and building it. In the alternating gradient synchrotron, two problems require especially careful exploration by extensive calculation and experimental modelling. These are the close-spaced resonances in the betatron oscillations and the shift of phase stability at intermediate energies. It seems best to study these problems with an electron accelerator which would be essentially an analogue rather than an exact model. This device should, in our opinion, be designed to yield the maximum of orbital data with a minimum of engineering complications, especially those not applicable to a final machine. After considerable thought we have arrived at a tentative description and list of parameters which follow.

The device would consist of an accelerator having an orbital radius of 15 feet and an overall diameter including the straight sections, of approximately 45 feet; the guide and focussing fields would be electrostatic, with electrode shapes as indicated in the sketch (full scale).

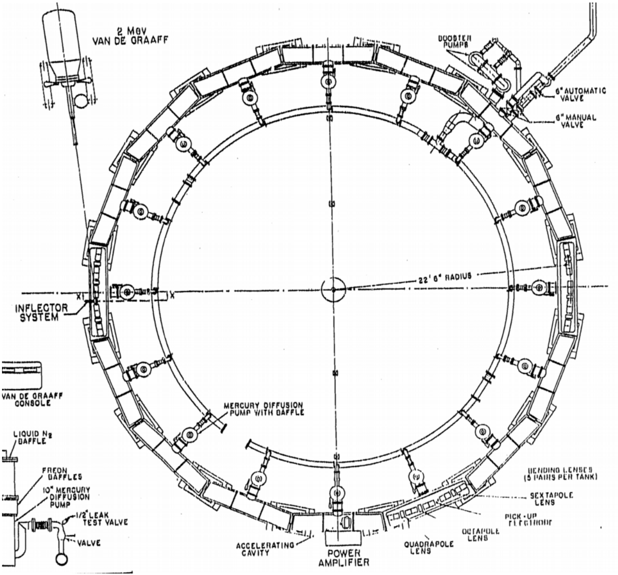
Field strength (magnetic type)	
at injection	10.5 gauss
at 10 MeV	74 gauss
Field strength (electrostatic type)	
at injection	3 kV/cm
at 10 MeV	22 kV/cm
Rise time	.01 sec
Phase transition energy	2.8 MeV
Frequency (final)	7 mc
Frequency change	5½ %
Volts/turn	150 V
RF power	about 1 kw
No. of betatron wavelengths	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

25 The AGS Analogue as Prototype Electron EDM Ring



Proton EDM Ring

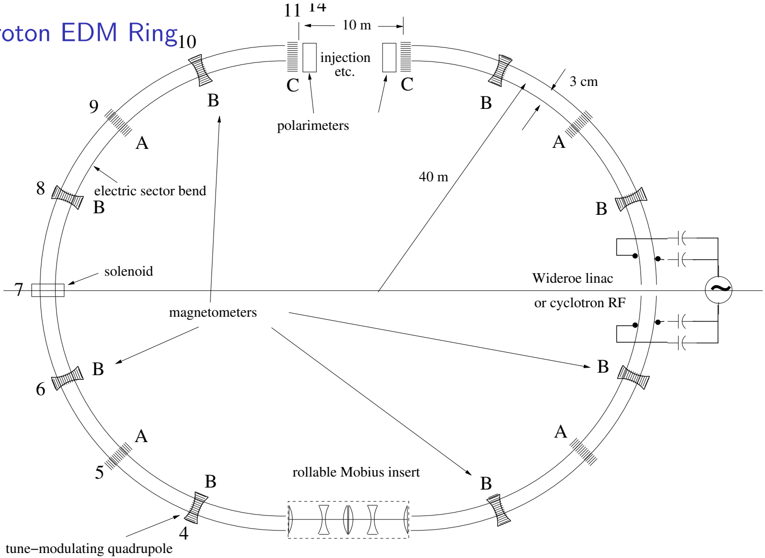


Figure: Proton EDM lattice. With the Möbius insert rolled by 45 degrees, horizontal and vertical betatron oscillations interchange every turn. This provides long spin coherence time (SCT).