Spin wheel - a new method of suppression of spin decoherence in the EDM storage rings

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Outline

- Introduction. What is EDM? Some numbers.
- Frozen spin method (Yannis Semertzidis, BNL)

- All electric storage ring. Magic gamma: $\gamma = \sqrt{\mu/\mu'} = \sqrt{(1+a)/a} \; > \; 1$

  $a_e = 0.00116$, $a_p = 1.793$, $a_{H3} = 7.937$, $a_{C13} = 0.51$ - is OK!

  $a_d = -0.143$, $a_{He3} = -4.191$ - to freeze need magnetic field too!

- Synchrotron oscillations in all electric storage ring. Monochromatization effect.
- Use counter rotating beam as co-magnetometer. SQUID-based pickups (Dave Kawall).
- “Spin wheel” method to increase SCT.
- Asymmetric energy EDM collider.
- Conclusion and discussion.

What is EDM? Some numbers.

- Natural magnetic moment units - Nuclear and Bohr magnetons:
  $\mu_N = e\hbar/2m_pc = e \cdot \lambda\!\!\!^{-}_p/2 = 3.152 \cdot 10^{-14}\, MeV/T = 1.05 \cdot 10^{-14} e \cdot cm$
  $\mu_B = e\hbar/2m_ec = e \cdot \lambda\!\!\!^{-}_e/2 = 5.788 \cdot 10^{-11}\, MeV/T = 1.93 \cdot 10^{-11} e \cdot cm$

- Proton magnet moment: $\mu_p = (1 + a)\mu_N = 2.793\mu_N \quad \rightarrow \quad a = 1.793$

- Proton EDM (goal): $d_p = \eta\mu_N = 10^{-29} e \cdot cm \quad \rightarrow \quad \eta = 10^{-15}$!!!

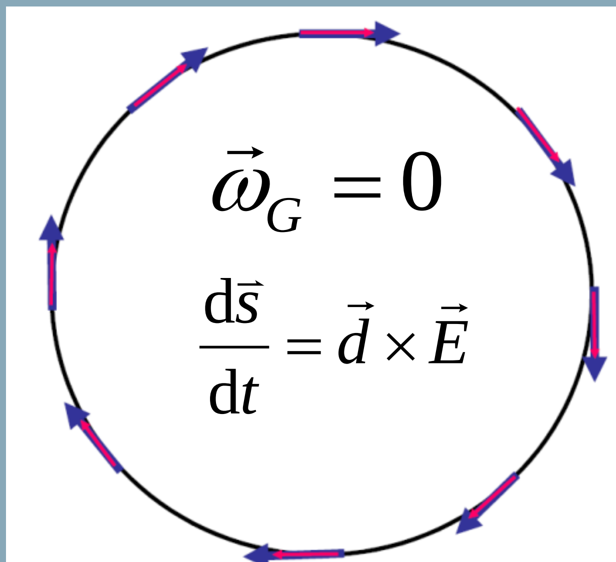
- Magnetic and EDM precessions: $\hbar\omega_m = \mu_p B \qquad \hbar\omega_{EDM} = d_p E$

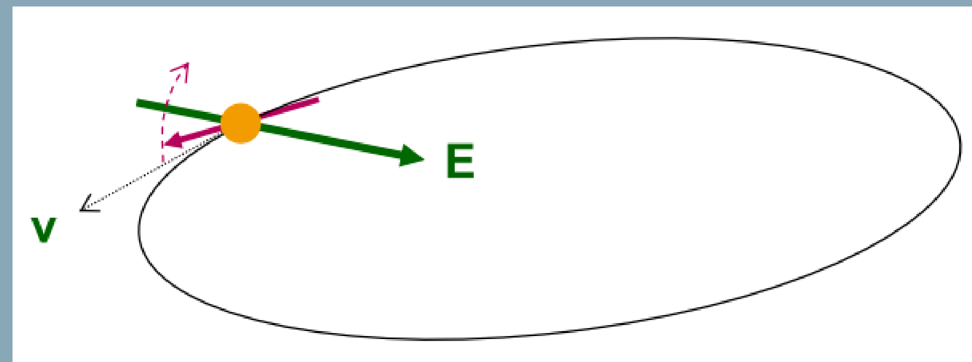
- pEDM relative precession frequency: $\gamma = 1.25, \quad \beta = 0.6$
  $$\nu_{pEDM} = \frac{\omega_{pEDM}}{\omega_0} = \eta\gamma\beta \approx 10^{-15}$$

- Magnetic moment frequency in the magnetic field: $\nu_m = \gamma a > 1.793$

- Electrons in all electric ring: $\gamma = 30, \quad a = 0.00116$
  $\nu_m = \gamma a = 0.0342$ – less sensitive to stray magnetic field!
  $d_e = 10^{-29} e \cdot cm \qquad \eta = 0.5 \cdot 10^{-18} \qquad \nu_{eEDM} = \eta\gamma\beta = 1.5 \cdot 10^{-17}$

NEW: EDM search in time development of spin in a storage ring:





"Freeze" horizontal spin precession; watch for development of a vertical component !

A *magic* storage ring for protons (electrostatic), deuterons, …

particle	p (GeV/c)	E (MV/m)	B (T)
proton	0.701	16.789	0.000
deuteron	1.000	−3.983	0.160
^{3}He	1.285	17.158	−0.051

One machine with $r \sim 30$ m

All electric EDM storage ring.

- Radial electric field:

$$E = 10\,\frac{MV}{m} = 334\,Gs \qquad E = E_0\,\frac{r_0}{r} \qquad or \qquad E = E_0\left(\frac{r_0}{r}\;\right)^{1+m}$$

- Circular orbit $r = const$:

$$\left|\frac{d\vec{p}}{dt}\right| = p\omega \equiv p\,\frac{v}{r} = -eE_0\,\frac{r_0}{r} \qquad \rightarrow \qquad pv \equiv p_0 v_0 = -eE_0 r_0$$

- All circular orbits have the same momentum!!! (For field index m=0)

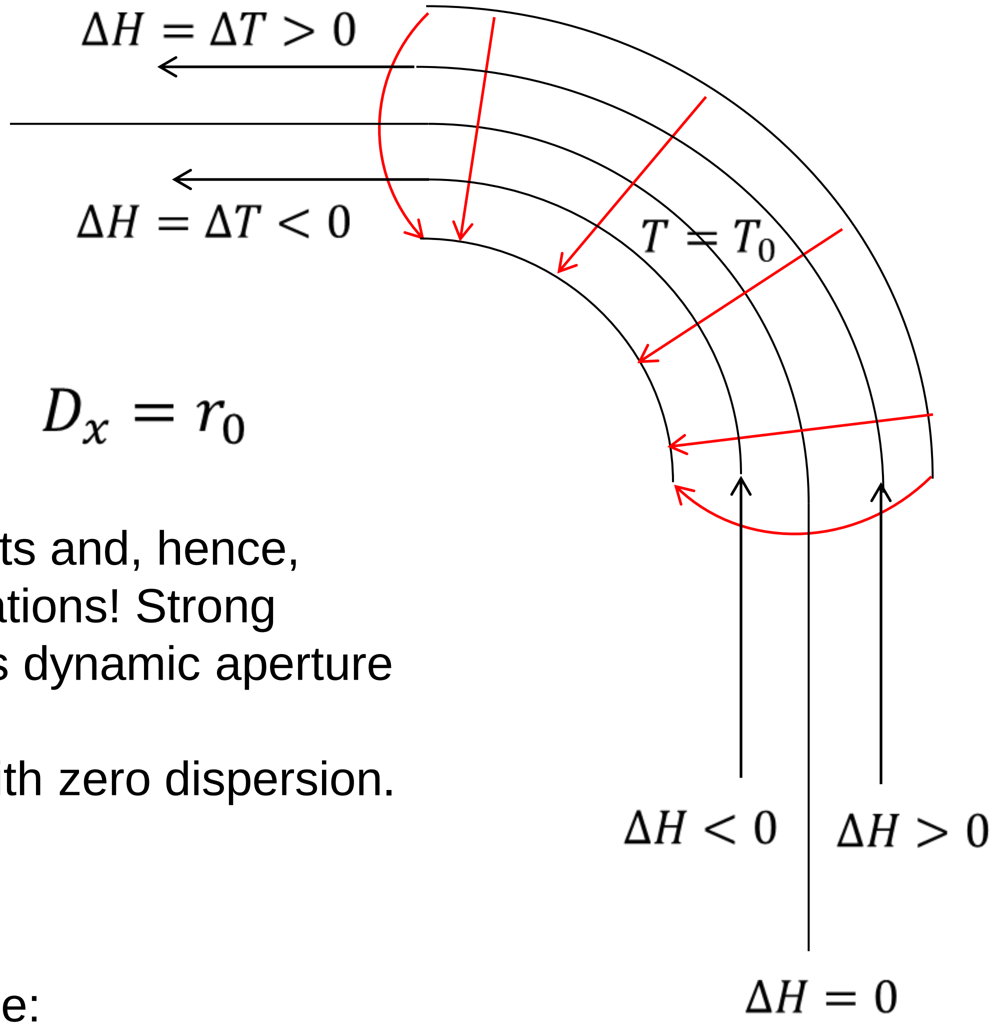
- Horizontal betatron motion: is conserved the sum of the potential $U(r)$ and the kinetic $T(p)$ energies, but $U(r)$ and $T(p)$ oscillate:

$$H = U(r) + T(p) = \text{const}$$

- Synchrotron (RF) motion: $T(p) = const$, but H and $U(r)$ are oscillating

Electric sector bend + drift. Dispersion.

Acceleration/deceleration by the longitudinal component of the edge electric field:



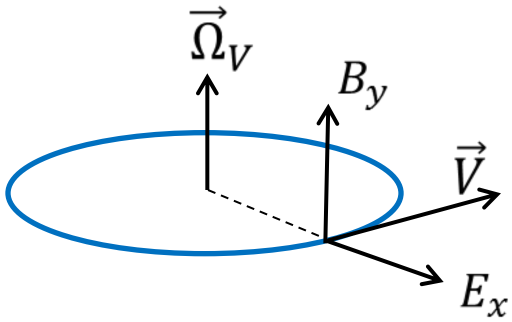
For $E = E_0 \frac{r_0}{r}$ x=$r_0 \frac{\Delta H}{H}$ $\rightarrow$ $D_x = r_0$

RF changes the kinetic energy in drifts and, hence, excites the horizontal betatron oscillations! Strong synchro-betatron coupling. It reduces dynamic aperture

It is desirable to place RF in a drift with zero dispersion.

For complete spin/orbit description see:
S.R.Mane, NIMA-D-12-00433

Orbital and spin motions. Basic formulae.



$$B\rho = pc/Ze$$

$$\vec{\Omega}_V = -\frac{Ze}{\gamma mc}\left(\vec{B} - \frac{\vec{\beta}\times\vec{E}}{\beta^2}\right)$$

$$(\Omega_V)_y = -\frac{c}{B\rho}\left(B_y + \frac{E_x}{\beta}\right) = \frac{\beta c}{r}$$

$$(\Omega_m - \Omega_V)_y =$$
$$= -\frac{\gamma c}{B\rho}\left(aB_y - \left(\frac{1}{\gamma^2\beta^2} - a\right)\beta E_x\right) \to 0$$

$$(\Omega_V)_x = -\frac{c}{B\rho}\left(B_x - \frac{E_y}{\beta}\right) = 0!$$

$$(\Omega_m - \Omega_V)_x =$$
$$= -\frac{\gamma c}{B\rho}\left(aB_x + \left(\frac{1}{\gamma^2\beta^2} - a\right)\beta E_y\right) =$$
$$= -\frac{cB_x}{B\rho}\frac{1+a}{\gamma}$$

$$(\Omega_{EDM})_x = -\eta\frac{1}{B\rho}(E_x + \beta B_y)$$

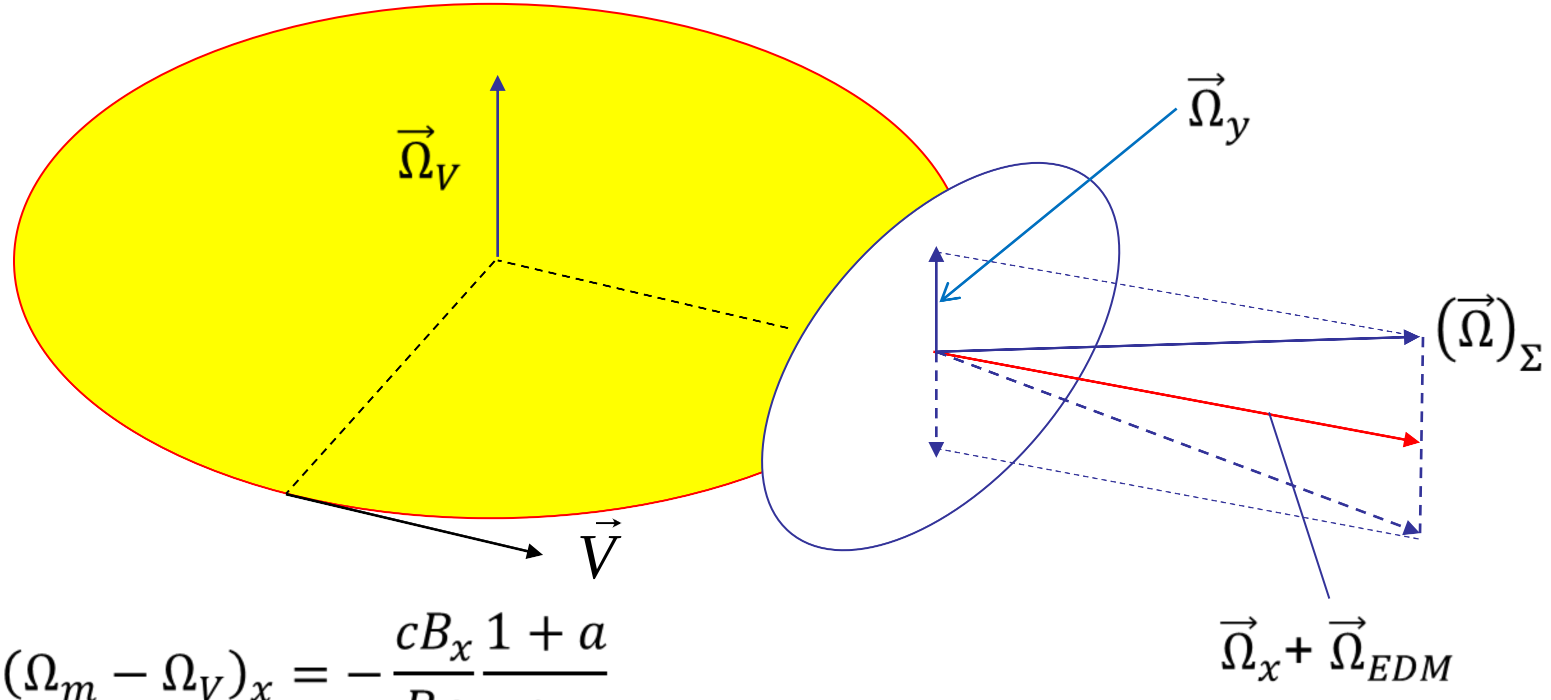
$$\to \quad (\Omega_{EDM})_x = -\eta\frac{E_x}{B\rho}\frac{1+a}{\gamma a}$$

Idea of the “Spin Wheel” approach

- Let introduce the background precession around the X-axis, which is, say, 10 times larger than the spread of spin tunes (averaged over the phases of all three types of oscillations).
- Now injected spins, being aligned vertically or longitudinally, will rotate coherently around the X-axis in the vertical plane with the about 20 times less dispersed frequencies.
- In this respect there is a full analogy with the spin echo technique.
- The needed precession frequency Ω_X could be achieved by excitation of very small radial magnetic field B_X which, of course, is accompanied by vertical component of the electric field $E_Y = \beta B_X$.
- The radial magnetic field will split orbits vertically for CW and CCW beams. SQUID based BPMs will detect this splitting at picometer level.
- EDM signal, in this method, is in fact asymmetry of the precession frequency measured for positive and negative orbit splitting.

A "spin wheel" approach

$$\Omega_y = \langle(\Omega_m - \Omega_V)_y\rangle = c1 \cdot {a_x}^2 + c2 \cdot {a_y}^2 + c3 \cdot (\Delta p/p)^2$$



$$\Omega_x = (\Omega_m - \Omega_V)_x = -\frac{cB_x}{B\rho}\frac{1+a}{\gamma}$$

$$\Omega_\Sigma = \sqrt{{\Omega_x}^2 + {\Omega_y}^2} \approx \Omega_y + \Omega_y \frac{\Omega_y}{2\Omega_x}$$ But $\frac{\Omega_y}{2\Omega_x} \leq \frac{1}{20}$ for $\Omega_x \geq 10\Omega_y$

Numerical example

$f_0 \simeq 10^6$ Hz - revolution frequency

$$\Delta p / p \simeq 2.5 \cdot 10^{-4} \quad \rightarrow \quad f_y / f_0 \simeq 10^{-8} \quad \rightarrow \quad f_y = .01\,\text{Hz}$$

$$f_x = .1\,\text{Hz} \qquad f = \sqrt{f_x{}^2 + f_y{}^2} \simeq f_x + \frac{f_y{}^2}{2 f_x}$$

$$\Delta f = f_y \frac{f_y}{2 f_x} = 10^{-2} \frac{10^{-2}}{2 \cdot 0.1} = 0.5 \cdot 10^{-3}\ \text{Hz}$$ -frequency spread

SCT=$(\Delta f)^{-1}$=2000 s! instead of 100 s in case of $f_x = 0$

Second (CCW) beam as co-magnetometer

Radial electric field: Ex=100 (kV/cm)=0.033333 (T)

β1, proton	β2, proton	ρ (m)	B(T)	E(T)/β1	β2/β1
0.302846	-0.181708	6.248995	0.045666	0.110066	-0.6
0.400031	-0.266687	12.529028	0.025705	0.083326	-0.666666
0.474505	-0.355879	19.897105	0.014544	0.070248	-0.75
0.598379	-0.598379	41.960283	0	0.055705	-1.0

β1, He3	β2, He3	ρ (m)	B(T)	E(T)/β1	β2/β1
0.230633	-0.307511	10.7507	-0.040335	0.144528	-1.333333

β1, H2	β2, proton	ρ (m)	B(T)	E(T)/β1	β2/β1
0.29695	0.395932	-3.171489	-0.725713	0.112251	1.33333
0.460592	0.57574	-9.5	-0.414107	0.07237	1.25

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Conclusion

- The strong enough driving field ($\Omega_X = 10^8 \cdot \Omega_{EDM} = 10^{-7} \cdot \Omega_0$), directed along the X-axis, prolongs SCT by one order of magnitude, at least (by factor 20 in our numerical example).

- At first glance idea of spin wheel looks promising!