E-field correction

D. Rubin

USPAS January 2019

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{m^2}{p^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$\omega_a = -\frac{q}{m}a_\mu\left[\mathbf{B} - \left(1 - \frac{m^2}{a_\mu p^2}\right)\frac{\beta\times\mathbf{E}}{c}\right] \sim -\frac{q}{m}a_\mu\left[\mathbf{B} - \left(1 - \frac{m^2}{a_\mu p_0^2}(1 - 2\frac{\Delta p}{p})\right)\frac{\beta\times\mathbf{E}}{c}\right] =$$

$$C_e = \frac{\Delta\omega_a}{\omega_a} = -2\frac{\Delta p}{p}\frac{\beta\times\mathbf{E}}{Bc}$$

$$E_{radial} = kx = k\eta\frac{\Delta p}{p}$$

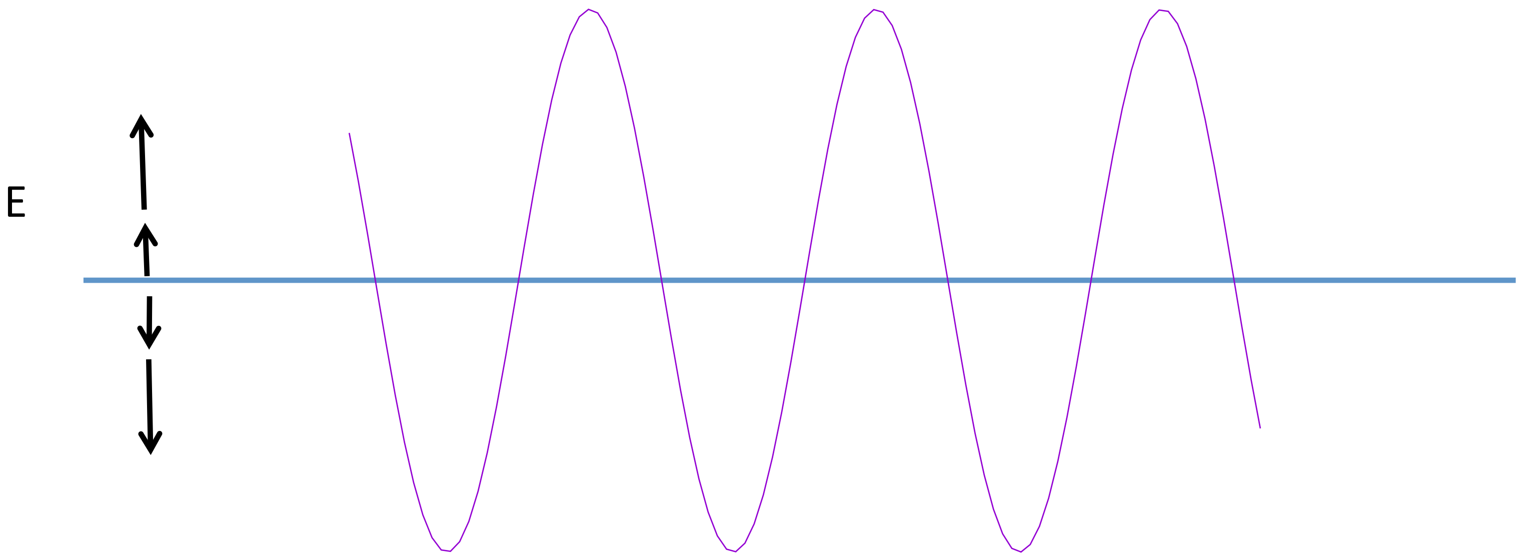
$$C_e = -2\frac{k\beta}{cB}\eta\left(\frac{\Delta p}{p}\right)^2 \qquad \eta = \frac{r_0}{1-n}, n = \frac{kr_0}{vB}$$

$$C_e = -2\beta^2 n(1-n)\frac{\langle x_e\rangle}{r_0^2}$$

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{m^2}{p^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

E-field contribution

In an ideal cartesian geometry and quad field where the radial field is antisymmetric about the magic radius, the E-field correction is independent of betatron amplitude

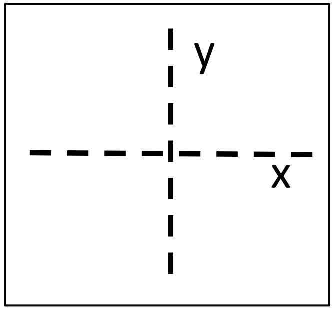


In a curved geometry, the integrated E-field along the trajectory depends on betatron amplitude in two ways

1. Sextupole component of the quads (This component is symmetric about magic radius)
2. Path length (asymmetric about magic radius)

Consider the Laplacian in 2 dimensions and cartesian coordinates

$$\nabla^2 V = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) V(x,y)$$



A solution that corresponds to the perfect quadrupole is

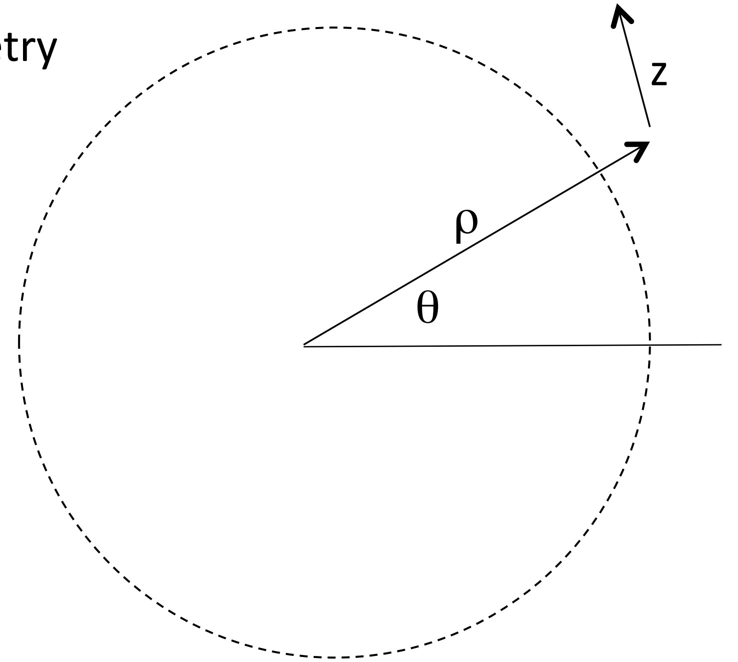
$$V(x,y) = \frac{1}{2} k(x^2 - y^2)$$

Then the divergence gives the E-field, linear in x and y.
and anti symmetric about x,y=0

$$\mathbf{E} = k(x\hat{\mathbf{i}} - y\hat{\mathbf{j}})$$

But the quad plates are curved.
We assumed in the above that there is no z-dependence.
And that is true only in the limit of $\rho \rightarrow \infty$

Cylindrical coordinates are a better match to our geometry
ρ – radial, z – vertical, θ - azimuthal



Laplacian in cylindrical coordinates

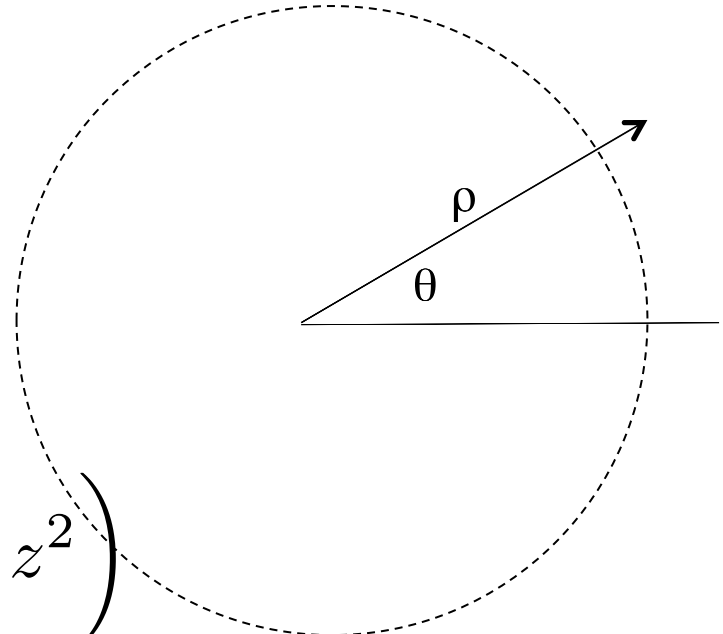
$$\nabla^2 V = \left(\frac{1}{\rho} \frac{\partial}{\partial \rho} \left(\rho \frac{\partial}{\partial \rho} \right) + \frac{1}{\rho^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2} \right) V$$

Define x $$\rho = \rho_0 + x$$

The simple symmetric quadratic potential is **not** a solution to the this Laplacian

$$V(x, z) \neq \frac{1}{2} k(x^2 - z^2)$$

The simplest (lowest order) solution to the 2 D cylindrical Laplacian is



$$V(\rho, z) = k\left(\frac{1}{2}(\rho^2 - 1) - \rho_0 \ln\frac{\rho}{\rho_0} - z^2\right)$$

Then with the substitution

$$\rho = \rho_0 + x$$

And expanding in the limit where $x \ll \rho_0$

$$\nabla V = \mathbf{E} \sim k\left((x - \frac{x^2}{\rho_0} + \ldots)\hat{\rho} - z\hat{\mathbf{z}}\right)$$

$$\nabla V = \mathbf{E} \sim k \left((x - \frac{x^2}{\rho_0} + \ldots)\hat{\rho} - z\hat{\mathbf{z}} \right)$$

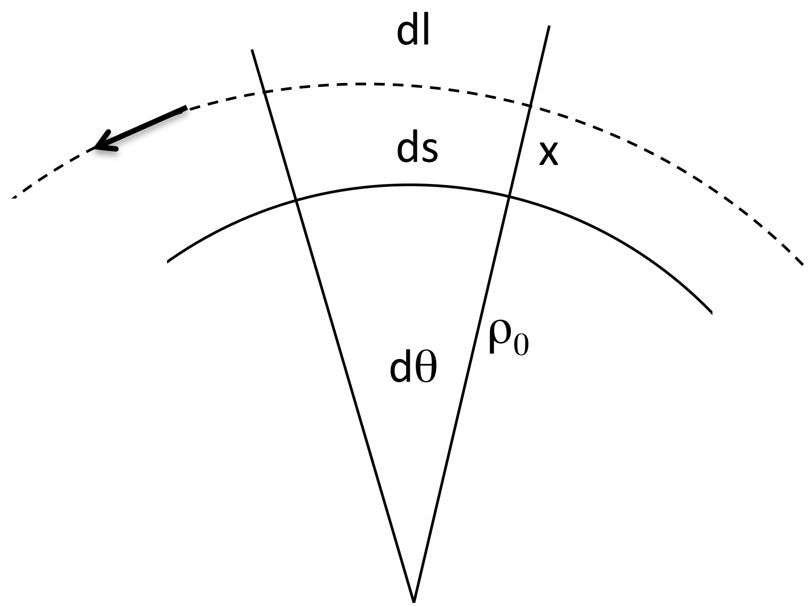
Linear term

Sextupole

The solution is not unique.
It is possible to find a solution that is linear in x,
but then it is necessarily nonlinear in z (vertical)

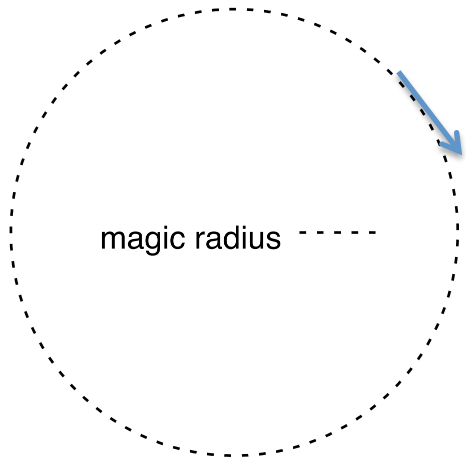
There is inevitably a sextupole component with curved plates independent of the plate shape details and alignment.

Path length

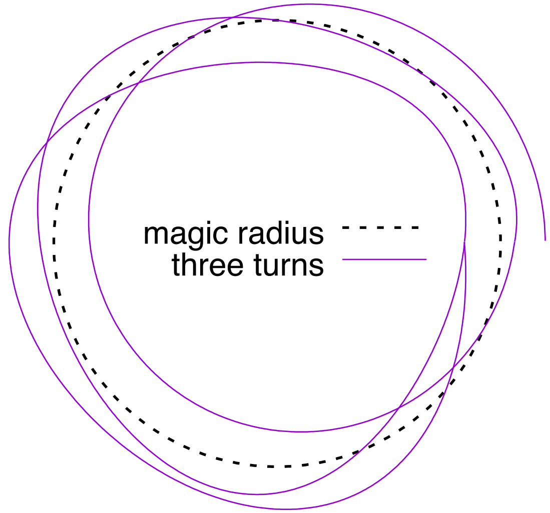


A particle oscillating about the magic radius (ρ_0) spends more time at x>0 than x<0

$$dl = (\rho_0 + x)d\theta$$



The E-field along the trajectory at the magic radius (momentum = p_0) is zero.



But what about the muon with momentum p_0 that oscillates about the magic radius with some betatron amplitude x_β ?

Or the muon with momentum $p_0 + \Delta p$ and betatron amplitude x_β?

$$x = \eta\delta + x_\beta \qquad \delta = \Delta p/p_0$$

$$\nabla V = \mathbf{E} \sim k\left((x - \frac{x^2}{\rho_0} + \ldots)\hat{\rho} - z\hat{\mathbf{z}}\right)$$

$$\begin{aligned}
\langle E_r(s)\rangle &= k\langle\left(\eta\delta + x_\beta - \frac{1}{2\rho_0}(\eta\delta + x_\beta)^2\right)\rangle \\
&= \frac{k}{L}\int_0 \left(\eta\delta + x_\beta - \frac{1}{2\rho_0}(\eta\delta + x_\beta)^2\right) dl \\
&= \frac{k}{L}\int_0 \left(\eta\delta + x_\beta - \frac{1}{2\rho_0}(\eta\delta + x_\beta)^2\right)(1 + x_\beta/\rho_0)ds
\end{aligned}$$

sextupole

Path length

The average E-field for a muon with momentum $p_0 + \Delta p$ and betatron amplitude x_β is

$$\langle E_r \rangle = k \left(\eta\delta + \frac{1}{2\rho_0}((\eta\delta)^2 + \frac{1}{2}x_{\beta 0}^2) + \ldots \right)$$

$$(x_e = \eta\delta)$$

E-field correction

$$C_e = \left(1 - \frac{1}{a_\mu}\frac{m^2}{p^2}\right)\frac{\beta E_r}{cB} \sim \left(1 - \frac{m^2}{a_\mu p_0^2}(1 - 2\frac{\Delta p}{p})\right)\frac{\beta E_r}{cB} \qquad (1)$$

Magic momentum $m^2/p_0^2 = a_\mu$

$$x_e = \eta\delta$$

$$C_e(\delta, x_{\beta 0}) \approx 2\frac{\beta k}{cB}\left(\frac{x_e^2}{\eta} + \frac{1}{2\rho_0}(\frac{x_e^3}{\eta} + \frac{1}{2}x_{\beta 0}^2\frac{x_e}{\eta})\right)$$

If $\langle x_e\rangle = \langle\delta\rangle\eta = 0$ then correction is independent of x_β

$$\langle C_e(\delta, x_{\beta 0})\rangle = 2\frac{\beta k}{cB}\eta\langle\delta^2\rangle$$

If $\langle x_e \rangle = \langle \delta \rangle \eta \neq 0$ then according to the Miller/Nguyen rule

To minimize the E-field correction choose p_0 so that

$$2a_\mu \langle \frac{p - p_0}{p_0} \rangle = \frac{m^2}{p_0^2} - a_\mu$$

Then

$$\langle C_e \rangle \sim 2 \left[-\eta (\langle \delta \rangle^2 - \langle \delta^2 \rangle) + \frac{1}{4\rho_0} (\langle \delta \rangle^2 \langle x_{\beta 0}^2 \rangle \right] \frac{\beta k}{cB}$$

Contribution from betatron amplitude

$$\nabla V = \mathbf{E} \sim k\left((x - \frac{x^2}{\rho_0} + \ldots)\hat{\rho} - z\hat{\mathbf{z}}\right)$$

$$\begin{aligned}
\langle E_r(s)\rangle &= k\langle\left(\eta\delta + x_\beta - \frac{1}{2\rho_0}(\eta\delta + x_\beta)^2\right)\rangle \\
&= \frac{k}{L}\int_0 \left(\eta\delta + x_\beta - \frac{1}{2\rho_0}(\eta\delta + x_\beta)^2\right) dl \\
&= \frac{k}{L}\int_0 \left(\eta\delta + x_\beta - \frac{1}{2\rho_0}(\eta\delta + x_\beta)^2\right)(1 + x_\beta/\rho_0)ds
\end{aligned}$$

sextupole

Path length

The average E-field for a muon with momentum $p_0 + \Delta p$ and betatron amplitude x_β is

$$\langle E_r \rangle \quad = \quad k\left(\eta\delta + \frac{1}{2\rho_0}((\eta\delta)^2 + \frac{1}{2}x_{\beta 0}^2) + \dots\right)$$

$$(x_e = \eta\delta)$$

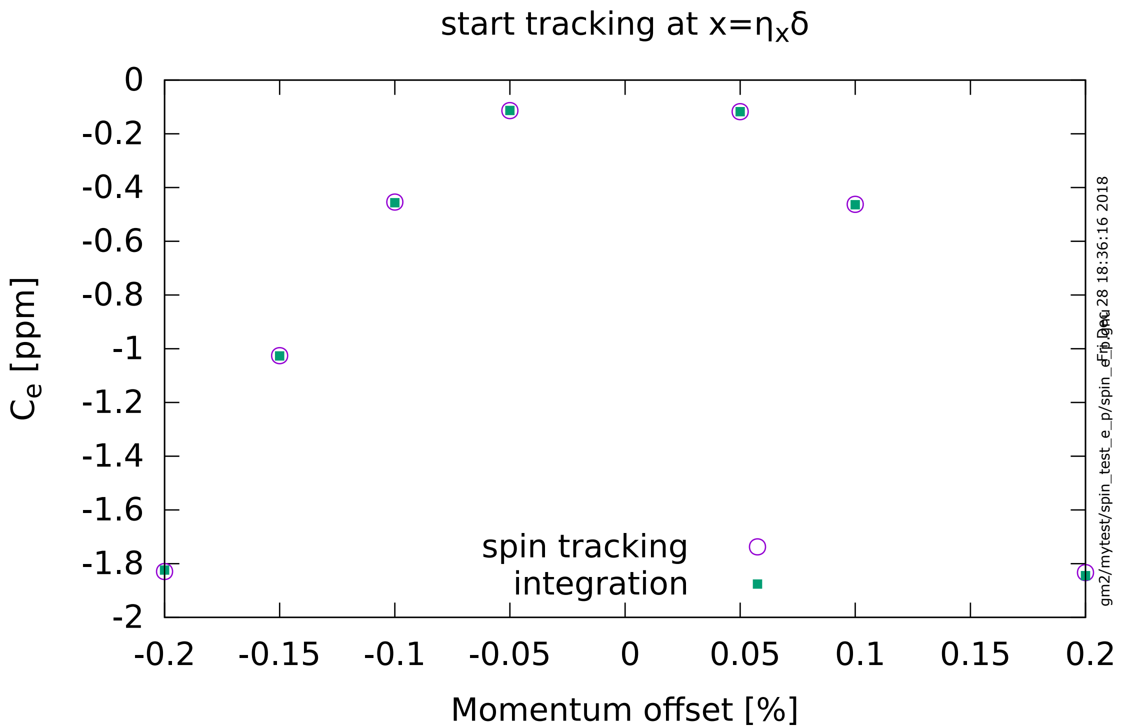
For positive momentum offset correction *increases* with betatron amplitude

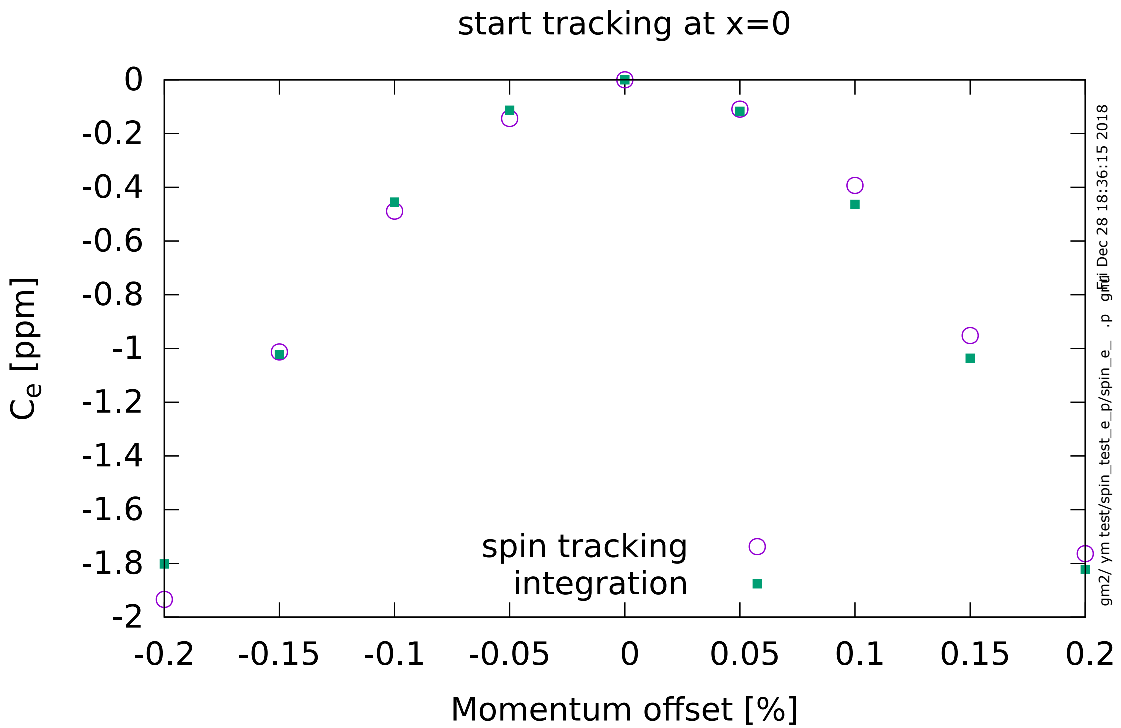
E-field correction

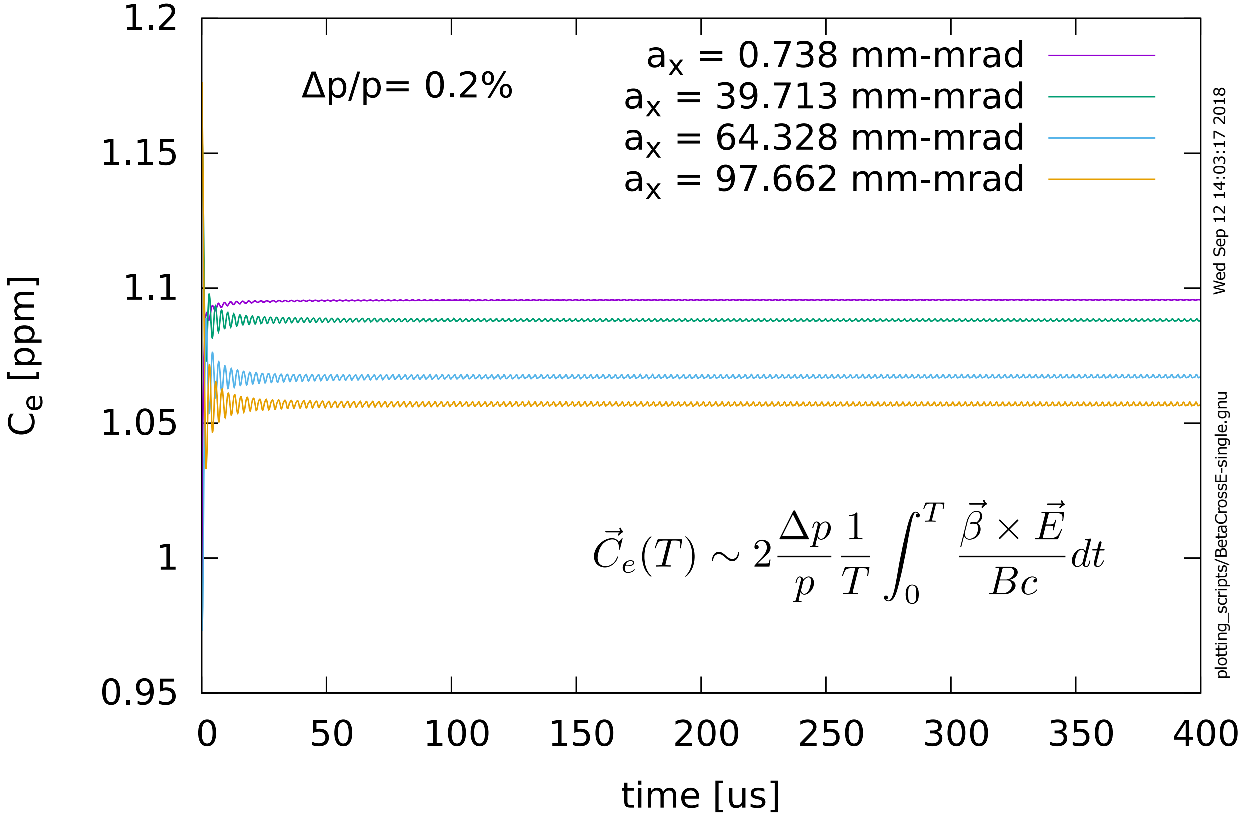
$$\vec{C}_e(T) \sim 2\frac{\Delta p}{p}\frac{1}{T}\int_0^T \frac{\vec{\beta} \times \vec{E}}{Bc} dt$$

To compute correction in simulation integrate $\langle \vec{\beta} \times \vec{E} \rangle$ along the trajectory of the muon

=> E-field correction as a function of time, $C_e(t)$

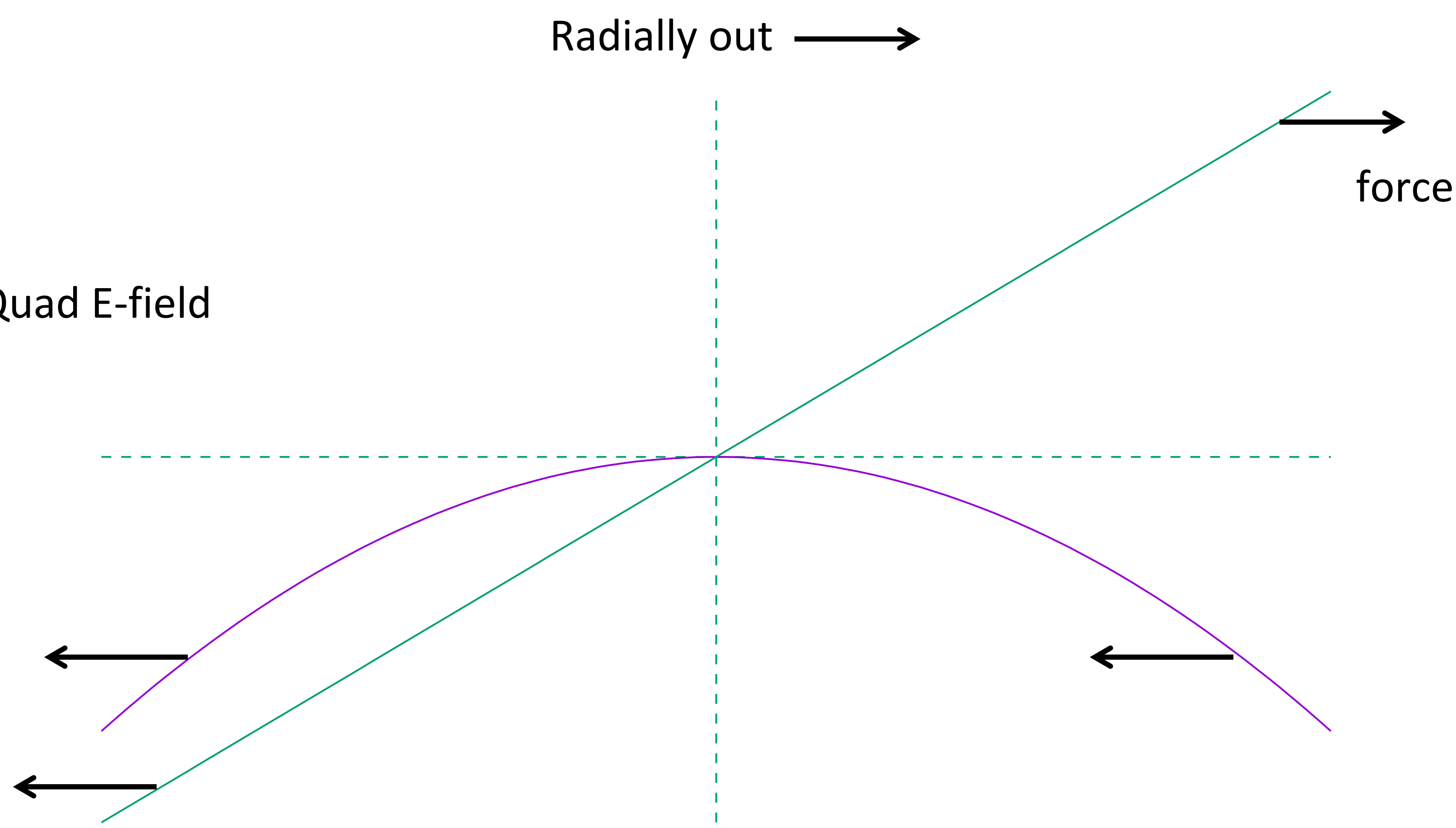

start tracking at x=ηxδ
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
Ce [ppm]
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
Momentum offset [%]
spin tracking
integration
gm2/mytest/spin_test_e_p/spin_e_p.gnu
Fri Dec 28 18:36:16 2018


start tracking at x=0
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
C_e [ppm]
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
Momentum offset [%]
spin tracking
integration



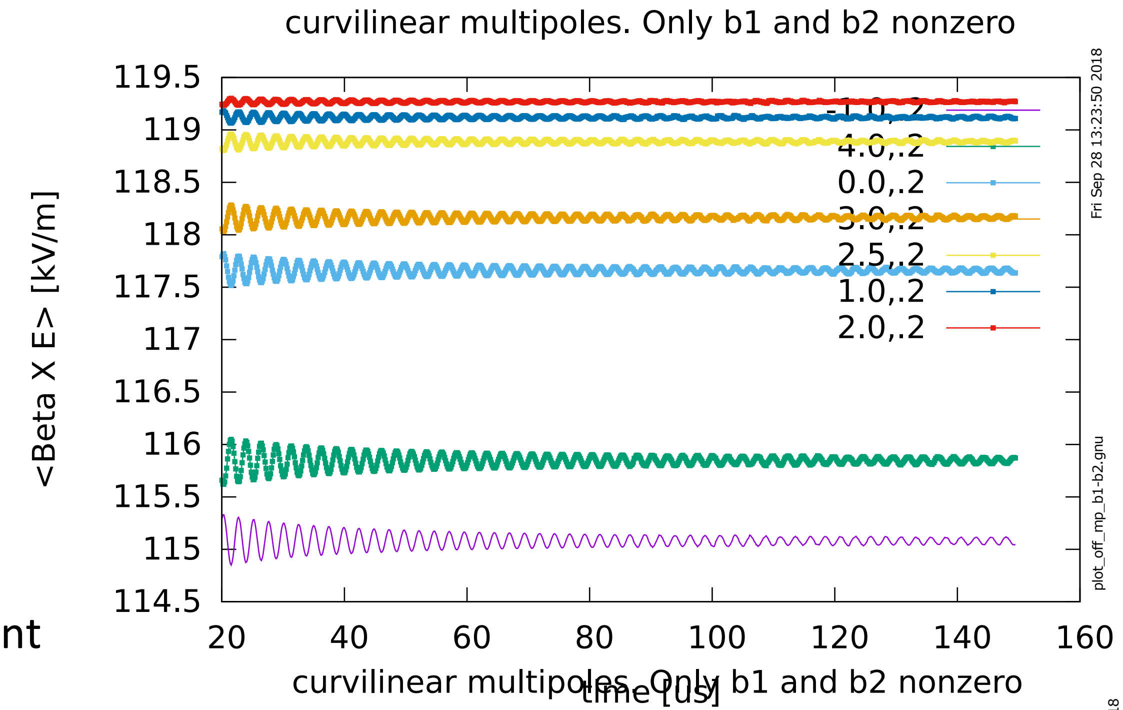
- $C_e(t)$ oscillates with betatron frequency at early time
- $C_e(t)$ decreases with increasing betatron amplitude
- Contribution from betatron amplitude < 40 ppb

Correction *decreases* with amplitude



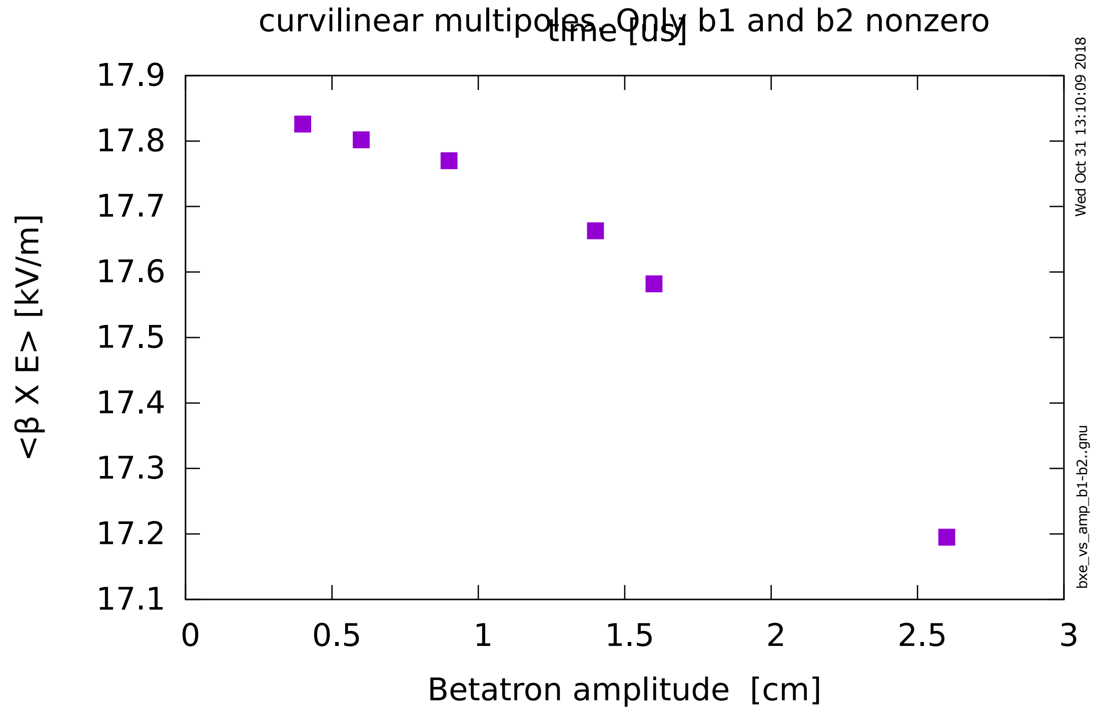
Sextupole component shifts <x> radially inward by

$$\langle F_x \rangle \sim k \frac{x_\beta^2}{2\rho}$$



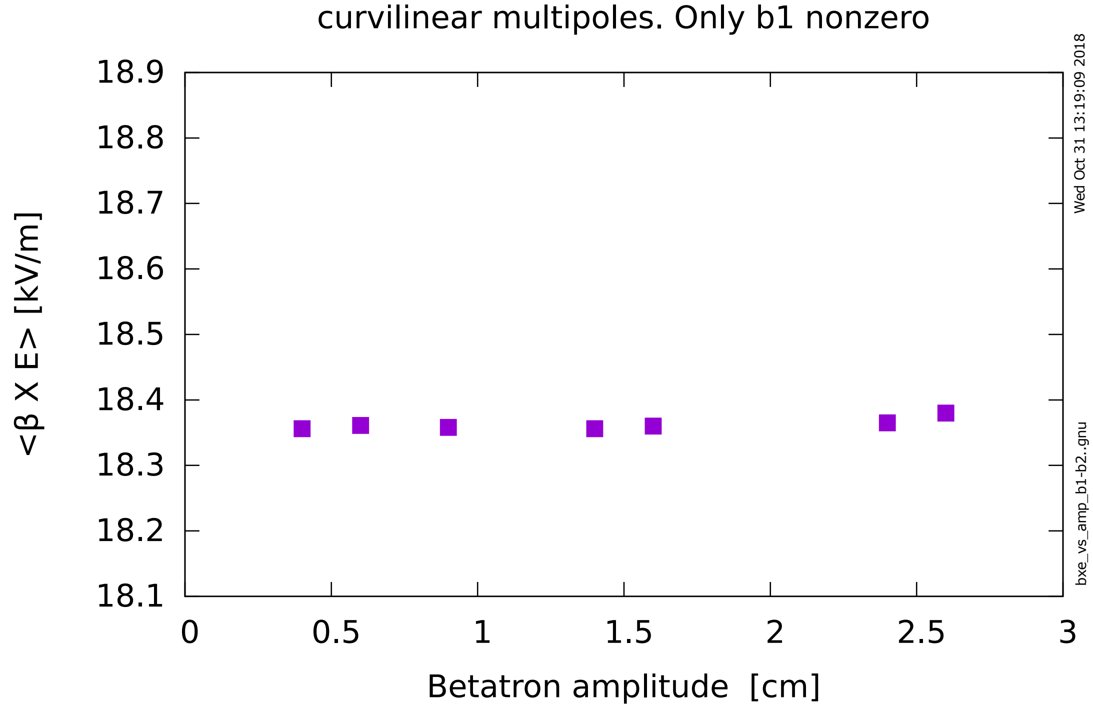
Restore sextupole component

Correction *decreases* with amplitude (average orbit shifted radially inward)



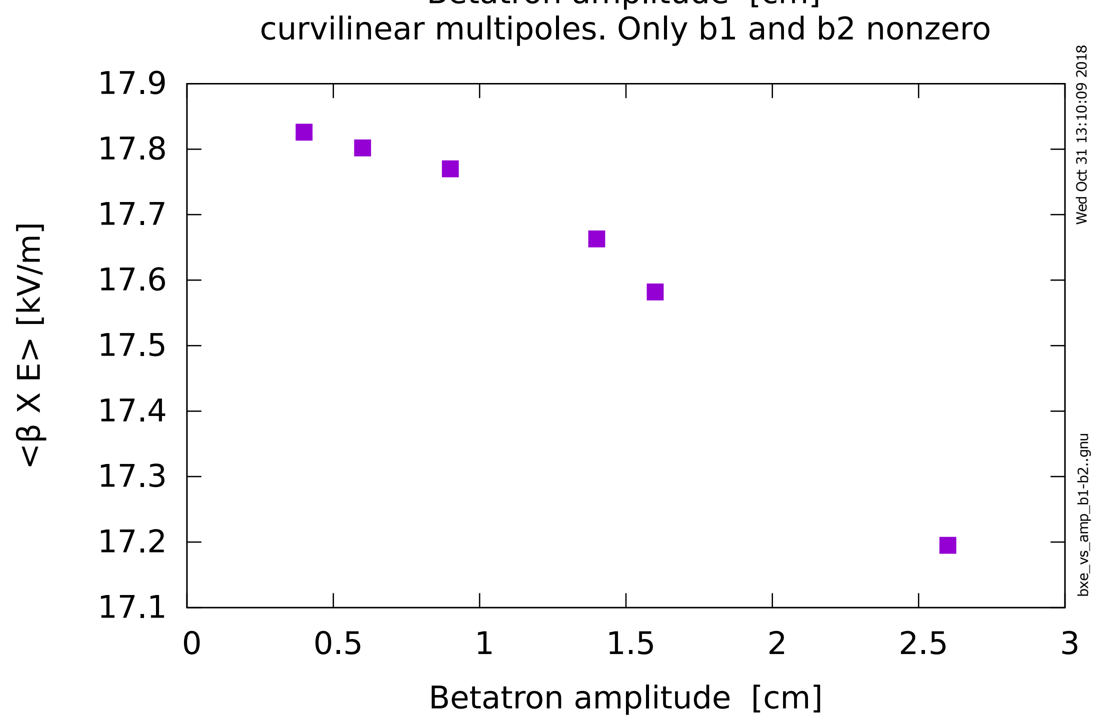
Dependence of E-field correction on Betatron amplitude with and without sextupole-like

$$\Delta p/p = 0.2\%$$

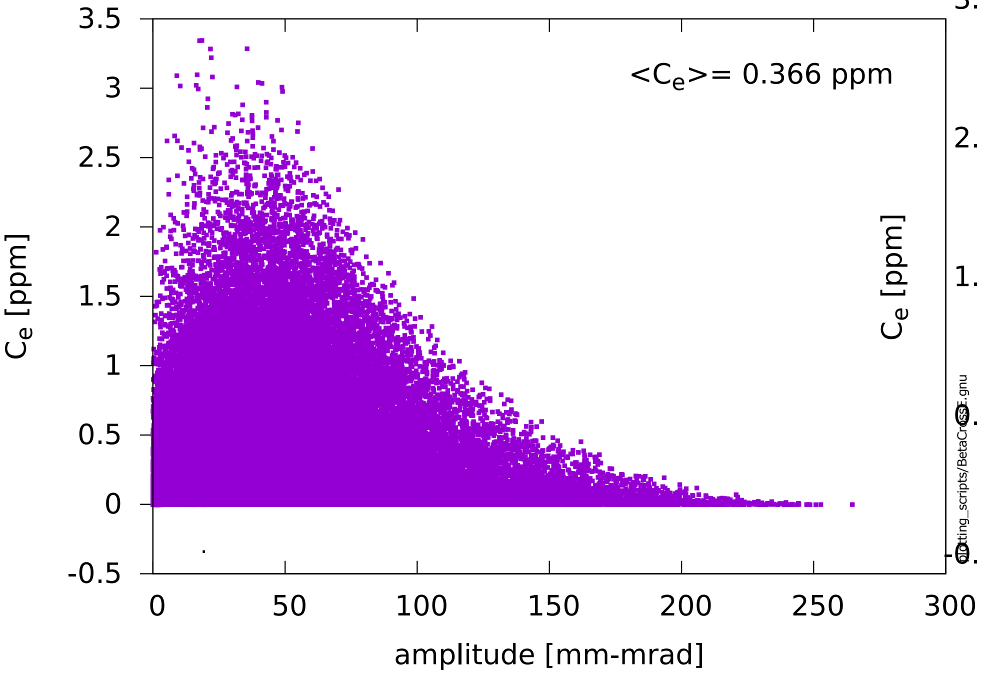


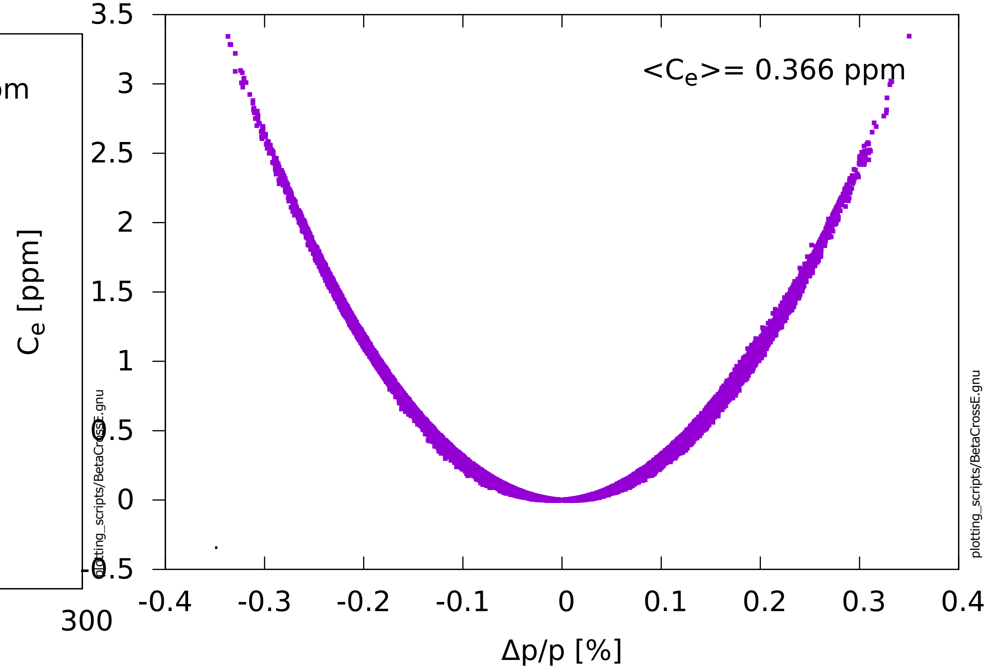
Efield correction decreases with betatron amplitude for $\Delta p/p > 0$

And increases for $\Delta p/p < 0$



1. Generated and track a distribution and compute
   - Momentum and frequency distribution
   - E-field correction for each particle





Summary

- Effect of E-field and pitch is computed in tracking simulation by integrating (summing along the trajectory)

$$\vec{C}_e(T) \sim 2\frac{\Delta p}{p}\frac{1}{T}\int_0^T \frac{\vec{\beta}\times\vec{E}}{Bc}dt$$

- Almost as good as spin tracking