Space Charge Compensation Studies with Electron Lenses

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2021 IOTA/FAST Collaboration Meeting

29 October 2021

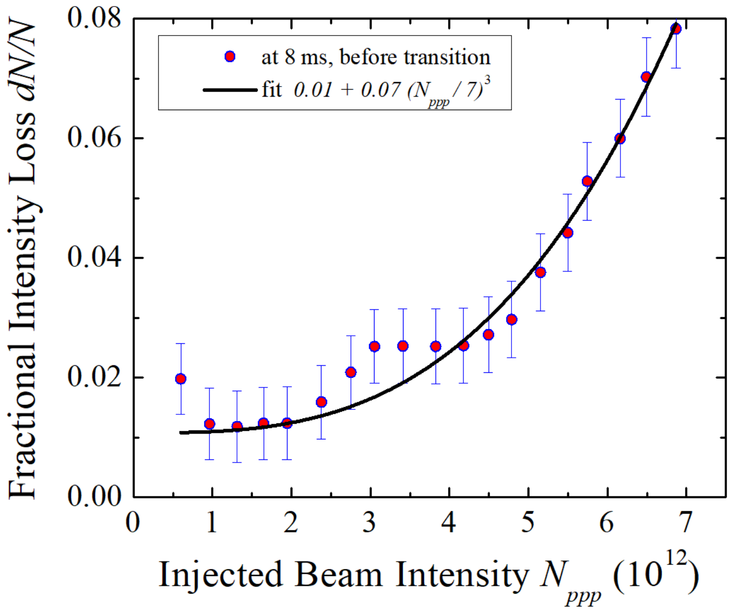
Outline

- Motivation for electron lenses
- Simulation results
  - Perfect electron lenses
  - Gaussian electron lenses
- Physics motivated explanation
- Implications for IOTA experiments
- Summary

Space Charge Problems in Low Energy Injectors

- Experience shows that space charge induces losses in accelerators.
- Progress in science requires higher intensity beams.
- Maximum acceptable loss ~1 W/m.
- Options to increase maximum intensity:
  - Collimation
  - Enlarging apertures
  - Phase space shaping to reduce charge density
  - Increasing injector energy
  - Active compensation with electron lenses

Eldred, et al, Intensity effects in the Fermilab Booster, PRAB 2021



Electron lens active compensation

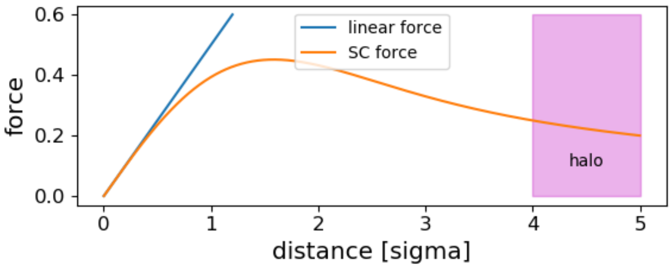
Gaussian proton beam

$$\Delta p_{\mathrm{SC}}(r) = +\frac{2\lambda_p C r_p m_p c}{\beta_p \gamma_p^2}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)\frac{1}{r},$$

Gaussian electron beam

$$\Delta p_{\mathrm{lens}}(r) = -\frac{2 I_e(t) L r_p m_p (1 \mp \beta_e \beta_p)}{e \beta_e \beta_p}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)\frac{1}{r}$$

$$\propto \frac{r}{2\sigma^2} \text{ for } r/\sigma < 0.4$$



N_p	Total charge
λ_p	proton linear charge density
I_e	electron current
m_p	proton mass
σ	RMS electron radius
β_e	electron v/c
β_p	proton v/c
C	machine circumference
L	electron lens length
γ_p	proton relativistic factor
r_p	classical proton radius

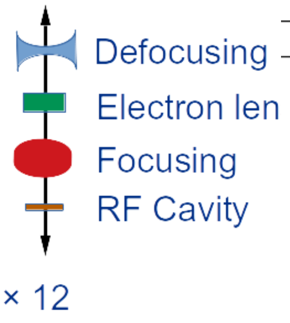
- Space charge strength $\lambda_p C$ balanced by electron lens strength $\sum I_e L$
- Electron beam may be modulated in time
- – sign for *e* beam propagating in the same direction as the *p* beam
  - Electron lens compensation more effective for non-relativistic or coasting beams

Particle simulations of SC and e-lens

- Simulations with Synergia, PIC code for collective effects developed at Fermilab
- 3D fully self-consistent space charge solver
- 16M or 4M macro particles (no significant difference observed)
- Simulations with 12-fold symmetry, then with single quadrupole errors of 0.5%, 1.0%, 2.0%, 3.0%.
- Simulate RMS emittance and 99.9% emittance to characterize halo development over 1000 turns.
- For the same cases, calculate particle loss at 4σ aperture.

Initial space charge tuneshift

$$\Delta Q_{\mathrm{SC}} = -\frac{N_p r_p}{4\pi\epsilon\beta_p^2\gamma_p^3}\frac{C}{\sqrt{2\pi}\sigma_s}R \approx -1.25$$

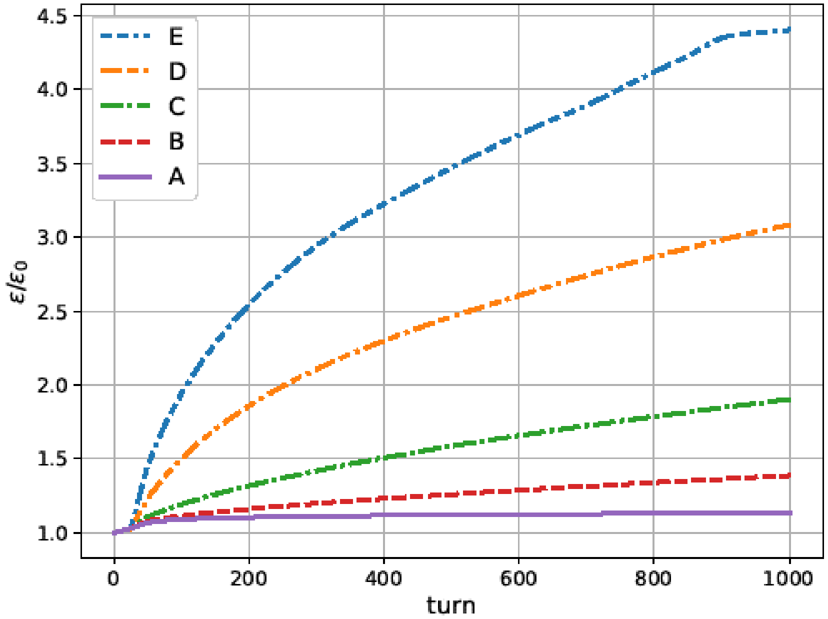


Parameter	Value	Unit
Total length C	288.0	m
Periodicity	12	FODO
Beam kinetic energy	0.8	GeV
Lorentz factors β_p, γ_p	0.84, 1.85	
RF frequency	43.814	MHz
Phase advance between compensators	111.6°	
Total RF voltage	6.287	MV
Proton bunch charge	2e11	e

Parameter	Value	Unit
RMS bunch length σ_s	0.5	m
RMS bunch $\Delta p/p$ spread	0.00288	
RMS geometric x, y emittance ϵ	1.0e-6	m.rad
Beta-functions at el. lens β_x, β_y	17.28, 17.27	m
x, y tunes Q_x, Q_y	3.72, 3.84	
x, y chromaticity Q'_x, Q'_y	-5.68, -5.97	
Slip factor	-0.291186	
Synchrotron tune Q_s	1/13	

Emittance growth over 1000 turns

X RMS emittance growth

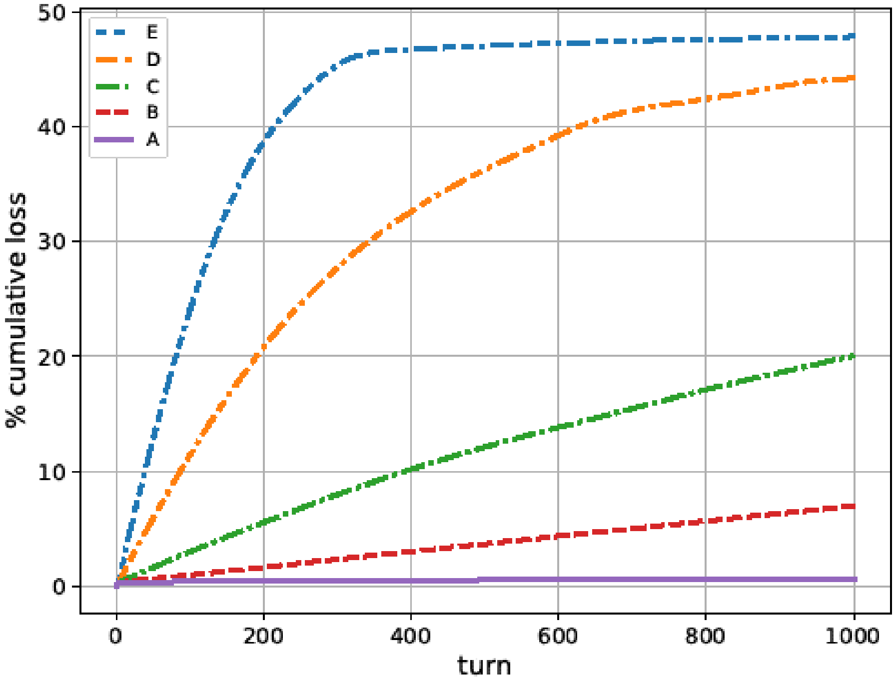


Emittance growth

Key	**quad error**	RMS $(\epsilon - \epsilon_0)/\epsilon_0$
E	3%	3.40
D	2%	2.0
C	1%	0.90
B	0.5%	0.39
A	0%	0.13

Losses over 1000 turns

4σ cum. loss

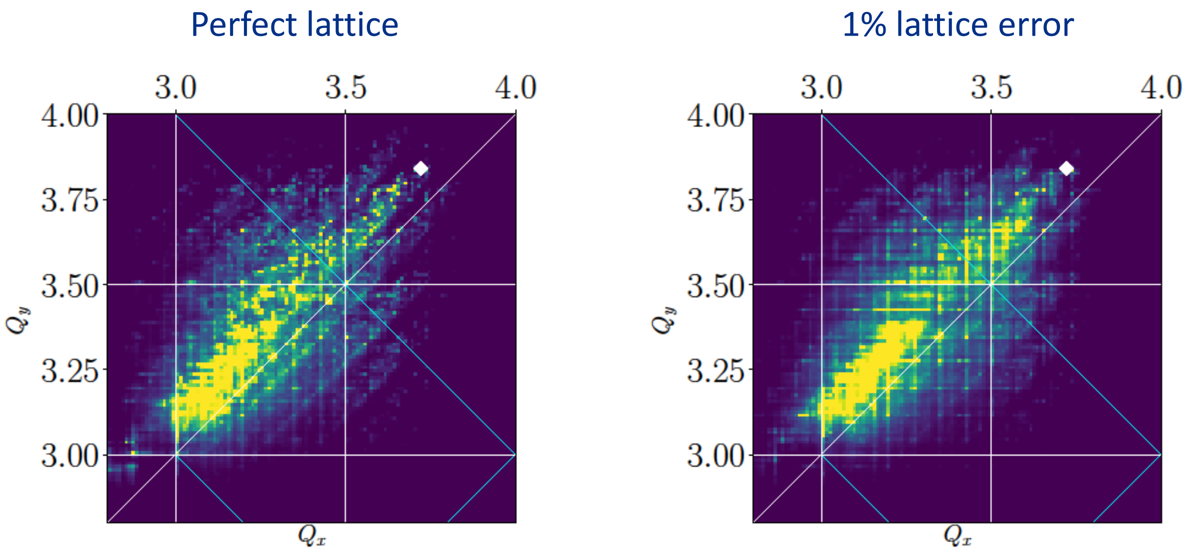


losses

Key	**quad error**	$(\Delta N_p/N_p)_{4\sigma}$
E	3%	0.48
D	2%	0.44
C	1%	0.20
B	0.5%	0.07
A	0%	0.007

The tune footprint does not obviously show the difference

Tune spectral densities



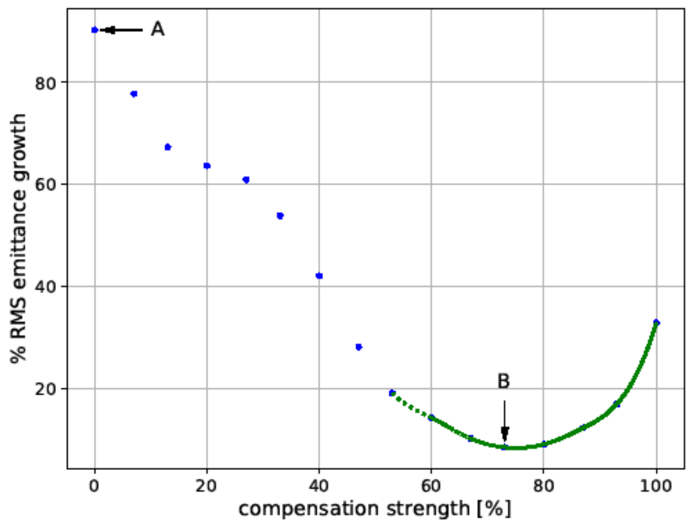
Enable perfect compensators

Electron lens compensators 1/cell (111º phase advance)

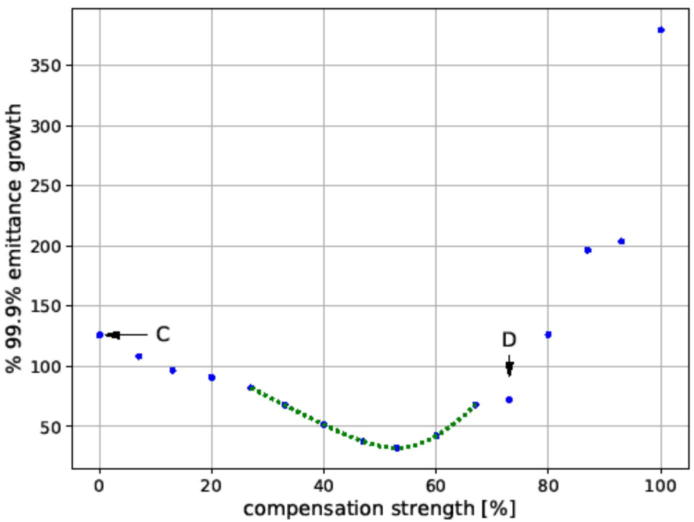
At 73% compensation strength, RMS emittance growth reduced 91% → 8.5%.

99.9% emittance growth not significantly improved.

RMS emittance growth



99.9% emittance growth



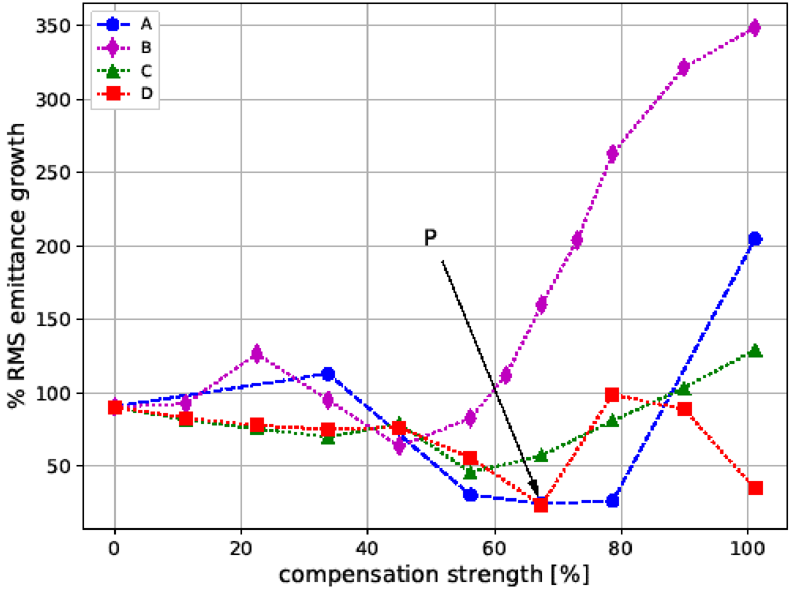
Enable Gaussian compensators

Longitudinal	Transverse: Static Gaussian	Transverse: Gaussian tracks p-bunch
static (DC)	B	C
Gaussian	A	D

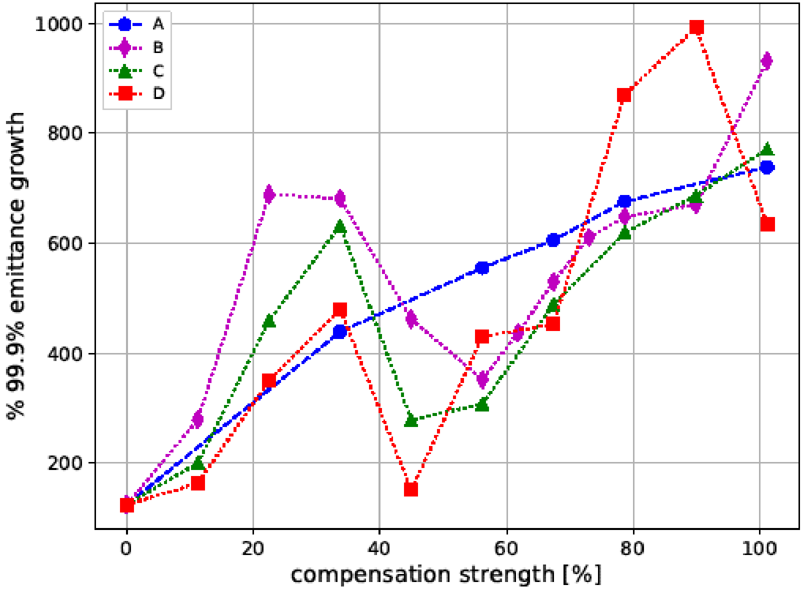
Best curve if A (blue), static transverse, pulsed longitudinally. No amount of compensation improves the halo.

Best compensation reduces x emittance growth from 91% → 24%

X RMS emittance growth

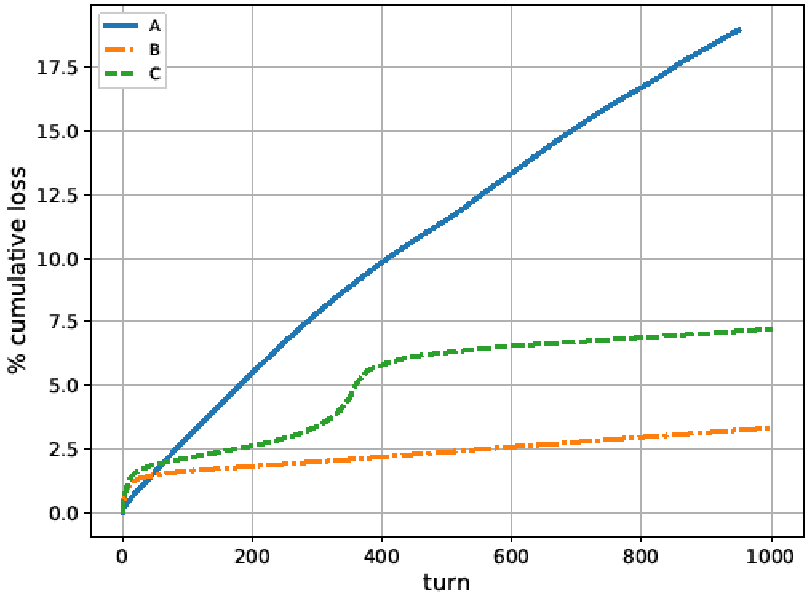


X 99.9% emittance growth



Improved losses at 4 sigma aperture

Cum loss over 1000 turns



uncompensated

Gaussian longitudinally with adaptive transverse

Gaussian longitudinally, static Gaussian transverse

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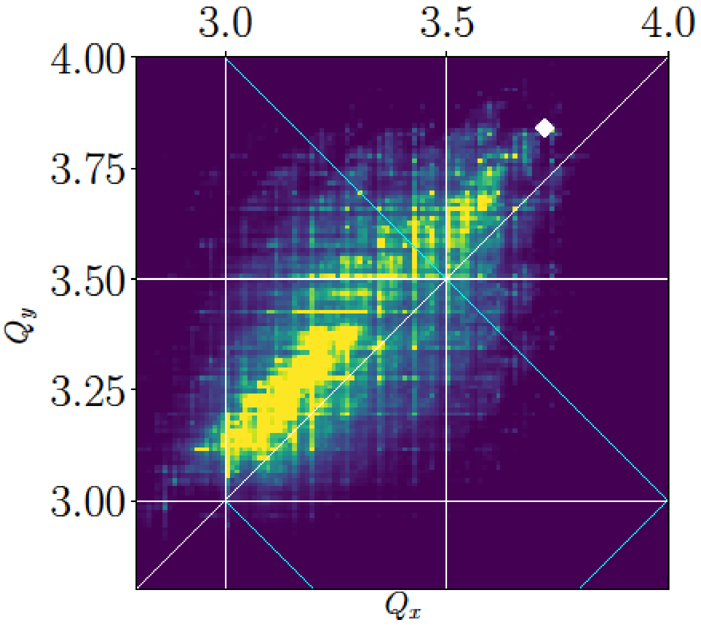
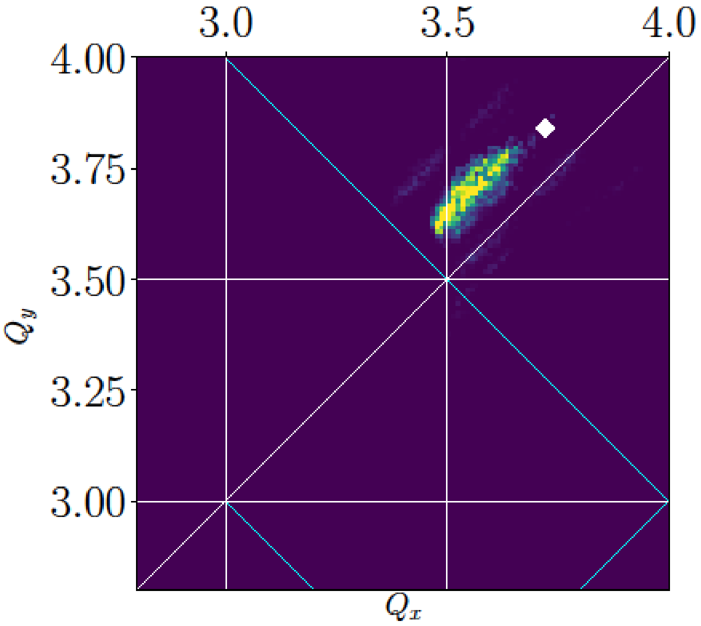
Tune footprint is compressed with working compensation

1% lattice error uncompensated



Best compensation case A



How does remote compensation work?

$$F_{\mathrm{SC}} \sim \frac{x}{\sigma^2} \text{ for } x < 0.4\sigma$$

SC kick at A

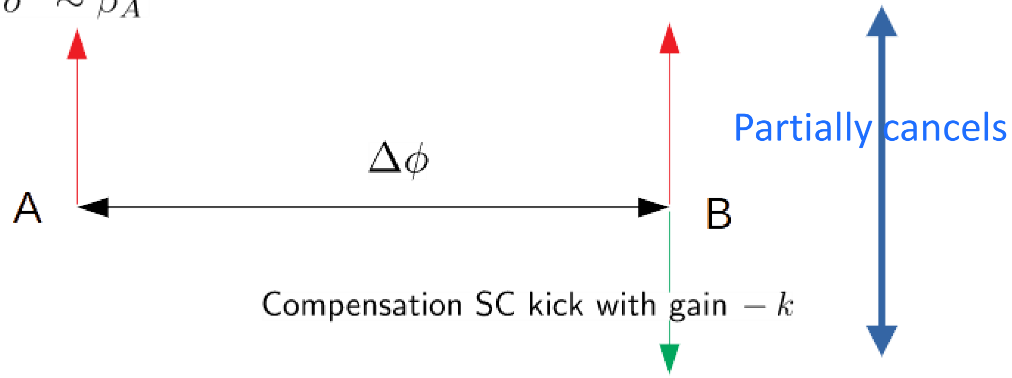
$$F_{\mathrm{A}} \sim \frac{x}{\sigma^2} \sim \frac{1}{\sqrt{\beta_A}}$$

$$x \sim \sqrt{\beta_A}$$

$$\sigma^2 \sim \beta_A$$

kick A contribution at B

$$\sqrt{\frac{\beta_A}{\beta_B}} F_{\mathrm{A}} \cos\Delta\phi \sim \frac{1}{\sqrt{\beta_B}} \cos\Delta\phi$$

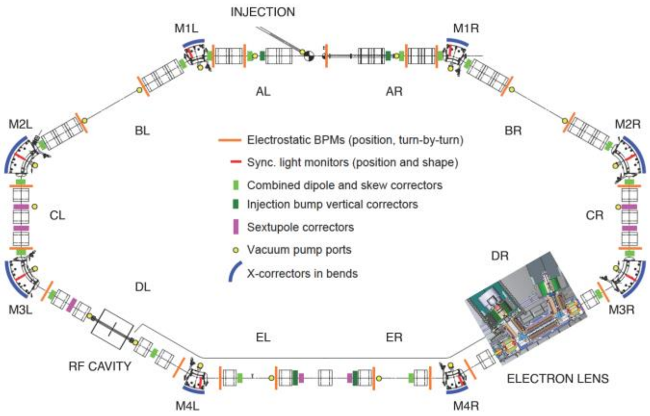


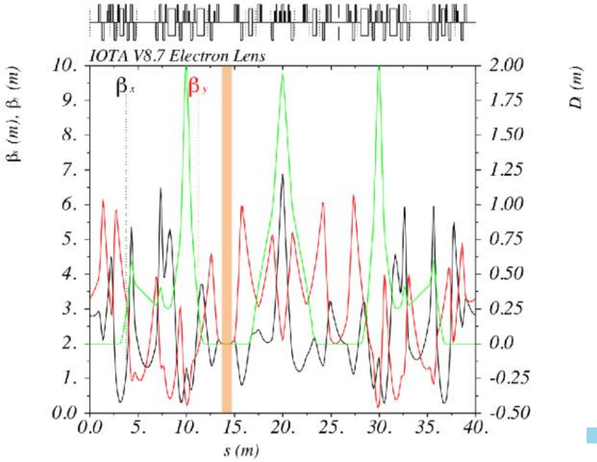
$$F_{\mathrm{B}} \sim -k\frac{x}{\sigma^2} \sim -k\frac{1}{\sqrt{\beta_B}}$$

Compensation works for core particles when the phase advance is not too large.

Simulations suggest compensation works 60º forwards and backwards from the compensator or one unit of phase advance.

Implications for IOTA electron lens experiments





- It will be interesting to see if the well controlled beam optics in IOTA suppress space charge effects.
- Run unbunched beam.
- Compensation can occur over one unit of phase advance before and after the compensating element.
- Beta function is 2 at the lens so one unit of PA is 2m. Plan to try to compensate 4m / 40m or 10% or the total tune spread.
- Electron lenses in IOTA hugely benefit from low beta. At electron energy of 3 KeV, you only need 0.5 A-m of electron lens coverage to compensate the entire ring at 8 mA (if it were covered in lenses.)
- If you're expecting a tune shift of 0.5, suggest increasing tune above 5.3.
- If possible, increase beta function at the lens to lower phase advance rate of change.

Conclusions

- We performed detailed simulations of extreme space charge shift beams with electron lenses.
- In a perfectly symmetric lattice simulation with no errors, space charge is not as big of a problem as it is in actual operational conditions. We must introduce lattice errors to induce emittance growth that can be compensated.
- Sufficient number of electron lenses positioned at close phase advance separations can compensate for a large fraction of space charge induced emittance growth and losses.
- The most important part of the lens is to match the lens strength to the longitudinal profile of the beam bunch.
- The lens strength should be set to compensate 65-70% of the space charge within one unit of phase advance of its position.
- It should be achievable to observe electron lens effects in IOTA.

I thank my collaborators A. Burov, V. Shiltsev, and late Yu. Alexahin.

Acknowledgements

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Synergia development has been supported by the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research and Office of High Energy Physics, Scientific Discovery through Advanced Computing (SciDAC) program.

This research used resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility located at Lawrence Berkeley National Laboratory, operated under Contract No. DE-AC02-05CH11231.

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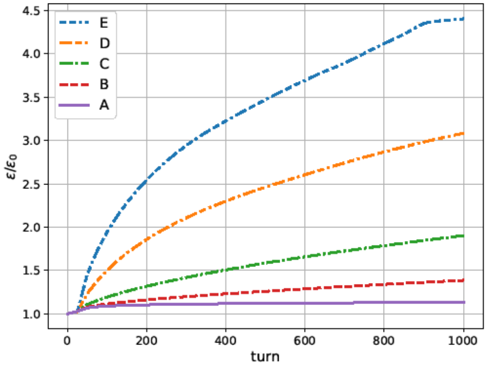
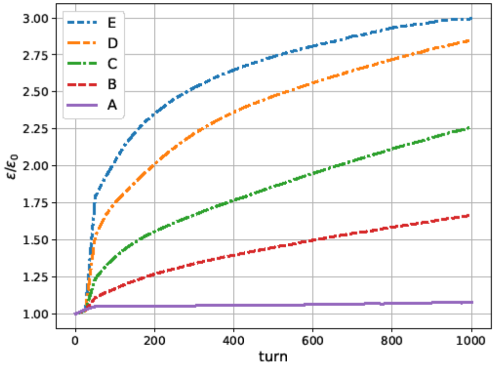
Emittance growth and losses over 1000 turns

X RMS emittance growth



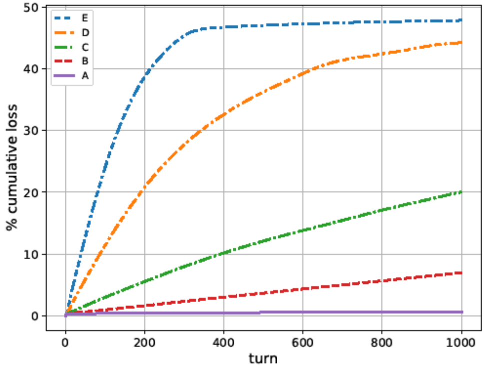
X 99.9% emittance growth



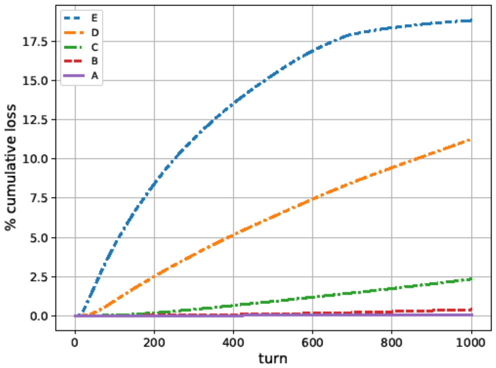
Emittance growth

Key	**quad error**	RMS $(\epsilon - \epsilon_0)/\epsilon_0$	99.9% $(\epsilon - \epsilon_0)/\epsilon_0$
E	3%	3.40	1.99
D	2%	2.08	1.85
C	1%	0.90	1.26
B	0.5%	0.39	0.67
A	0%	0.13	0.08

4σ cum. loss



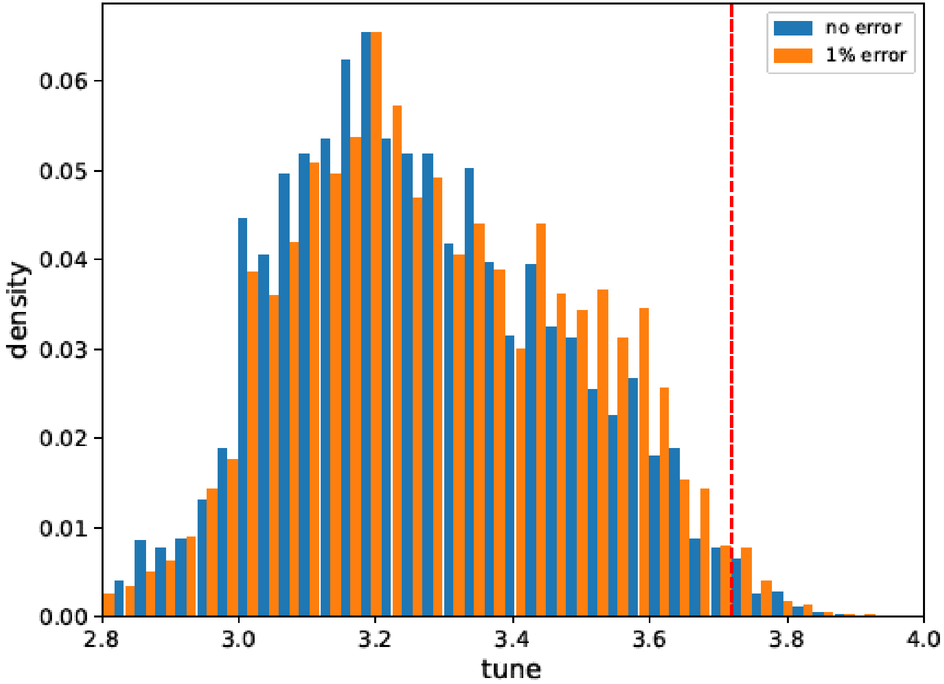
5σ cum. loss



losses

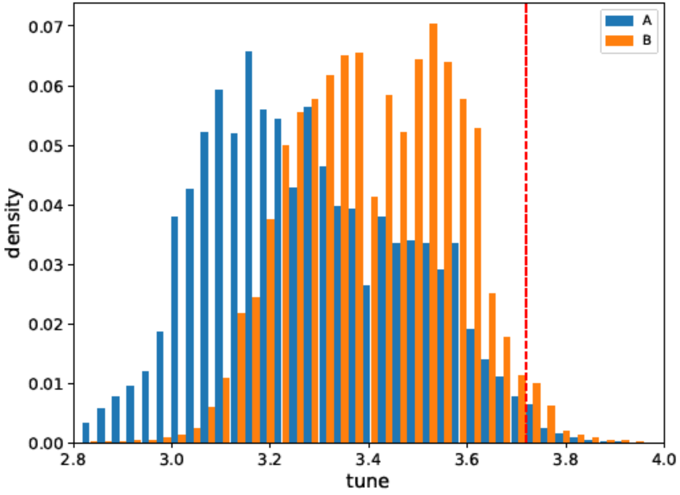
Key	**quad error**	$(\Delta N_p/N_p)_{4\sigma}$	$(\Delta N_p/N_p)_{5\sigma}$
E	3%	0.48	0.19
D	2%	0.44	0.11
C	1%	0.20	0.024
B	0.5%	0.07	0.004
A	0%	0.007	0.0004

Tune densities with and without lattice error



Non-monotonic compensation

A: uncompensated
B: 33% compensated



A: uncompensated
B: 67% compensated