Active Space Charge Compensation with Electron Lenses

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Mitigation Approaches for Storage Rings and Synchrotrons

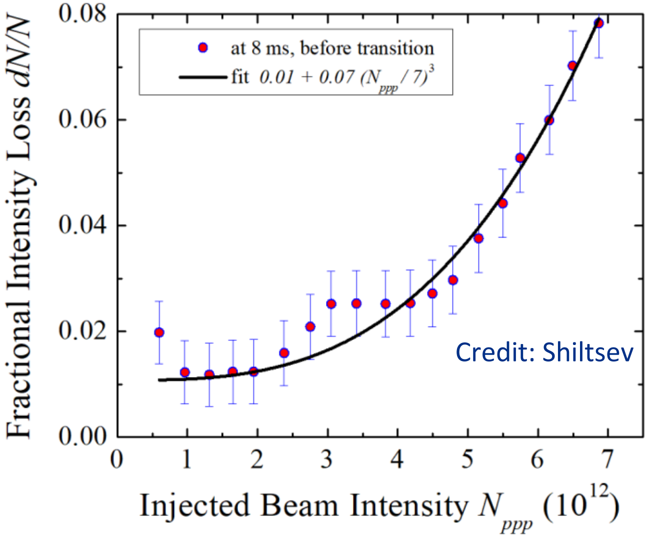
30 June 2020

Outline

- Motivation for Compensation
- Evaluation Plan
- Simulation Code
- Compensation Results Ideal Lens
- Compensation Results Current Driven Lens
- Summary and Future Plans

Why active compensation?

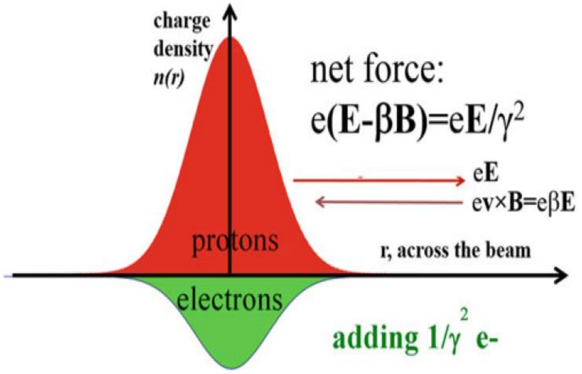
- Proton drivers and RCS machines need to increase the number of accelerated protons/cycle to meet the needs of neutrino experiments and spallation neutron sources.
- Beam losses required to stay < 1W/m.
- Experience shows that fractional losses scale as a power of number of protons in the machine.

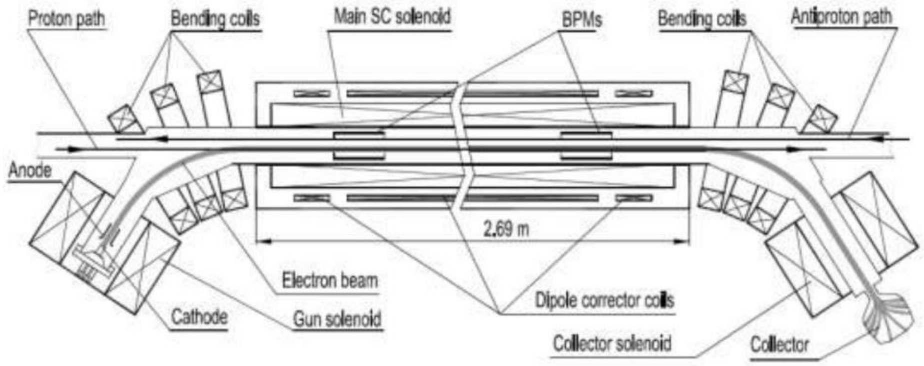


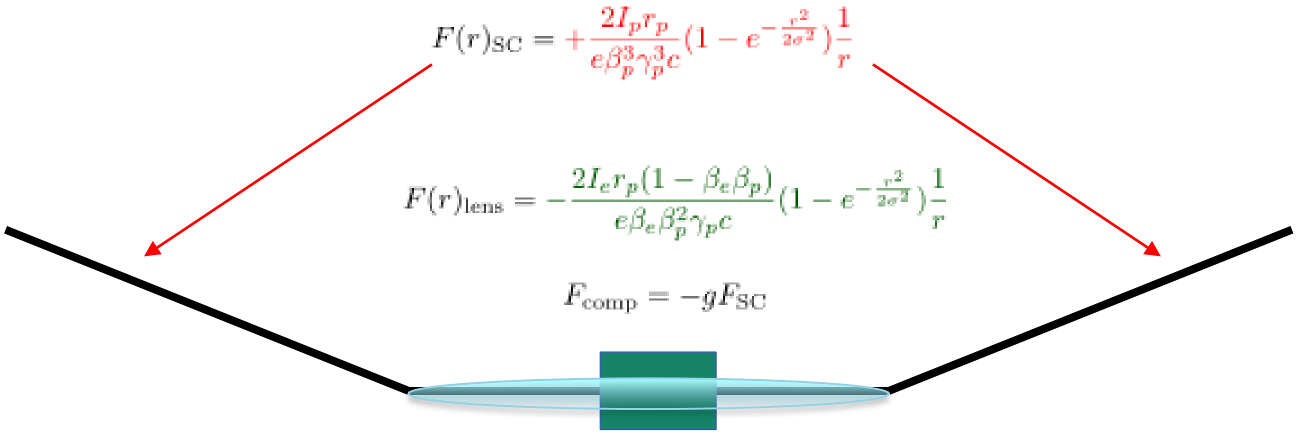
Credit: Shiltsev

- Active compensation may be needed to supplement other mitigation techniques.
- Controlling space charge may be key to limiting halo generation.

How does active compensation work







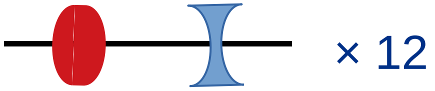
$$F(r)_{\mathrm{SC}} = +\frac{2 I_p r_p}{e \beta_p^3 \gamma_p^3 c}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)\frac{1}{r}$$

$$F(r)_{\mathrm{lens}} = -\frac{2 I_e r_p (1 - \beta_e \beta_p)}{e \beta_e \beta_p^2 \gamma_p c}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)\frac{1}{r}$$

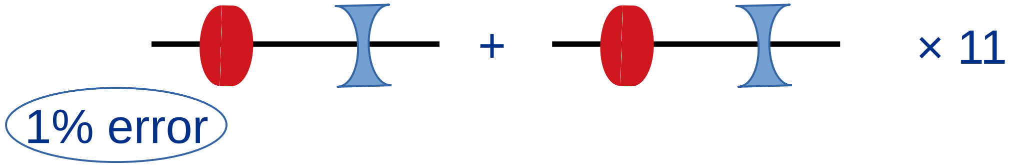
$$F_{\mathrm{comp}} = -g F_{\mathrm{SC}}$$

Evaluation plan

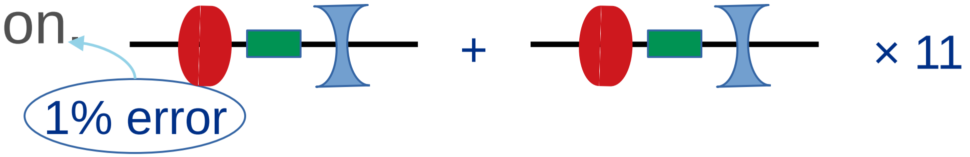
- Run space charge simulations of Gaussian bunches with ΔQ_{SC} = -0.9 in three lattice configurations:
  - 12-fold symmetry FODO* cells



  - Broken symmetry FODO* cells 1% focusing error



  - Broken symmetry FODO* cells 1% focusing error, ideal electron lens compensation.



- Examine RMS emittance growth for different strength ideal compensation
- Examine particle loss with a 4% aperture

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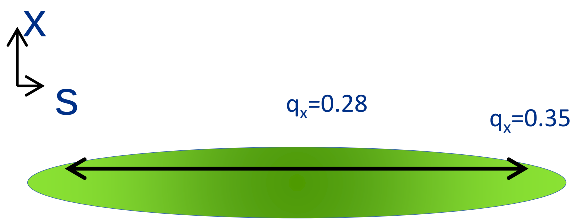
* includes RF cavity

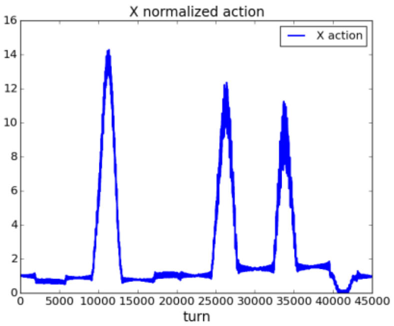
Synergia space charge simulations

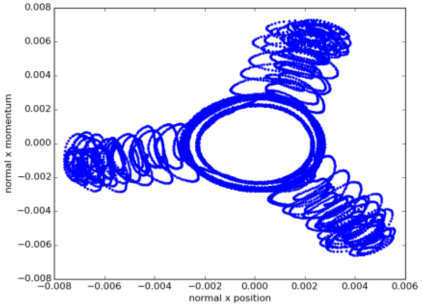
- Fermilab developed PIC accelerator modeling framework combining beam optics, symplectic tracking, 2.5D/3D self-consistent space charge, impedance, and now electron lens. Space charge is combined with tracking using split-operator formalism.

GSI Space Charge benchmarking

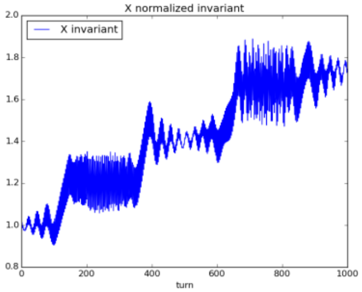


Resonance trapping

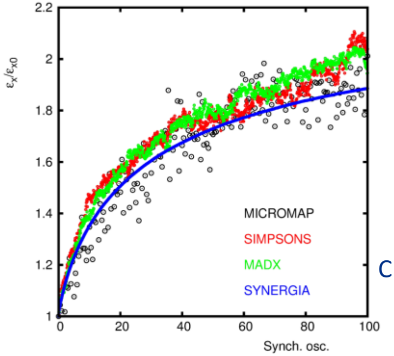




Resonance scattering

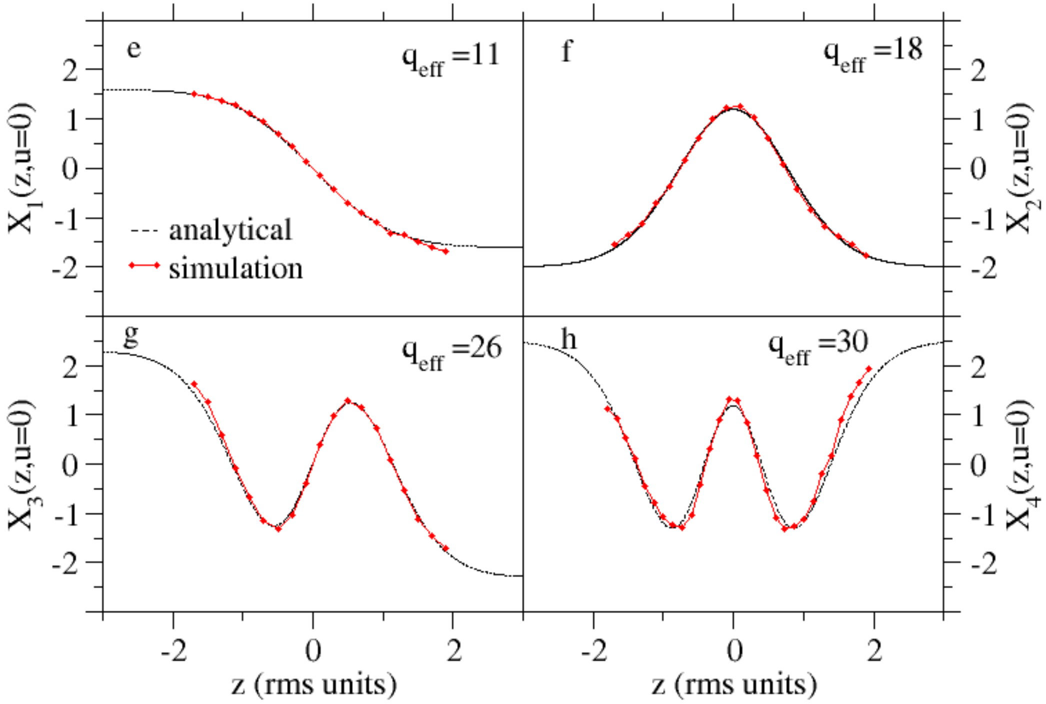


Long-term emittance growth



Credit: Schmidt

Strong Space Charge Modes

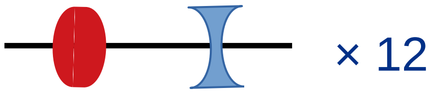


Macridin, et al, Simulation of Transverse Modes with Their Intrinsic Landau Damping for Bunched Beams in the Presence of Space Charge, PRST-AB 18 (2015) no.7, 074401

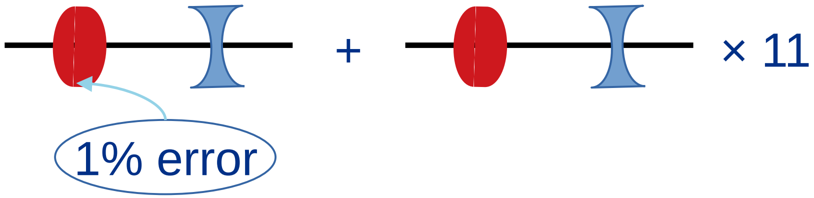
A. Burov, Head-tail Modes for Strong Space Charge, PRST-AB 12, 044202 (2009), PRST-AB 12, 109901, (2009)

Evaluation Plan

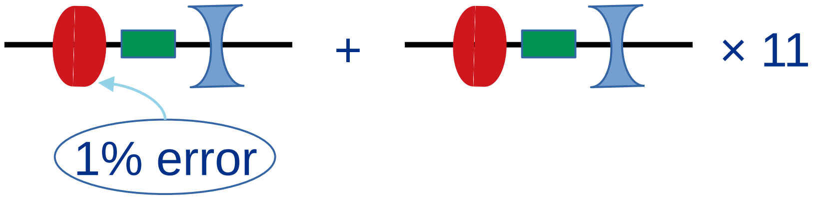
Ideal FODO

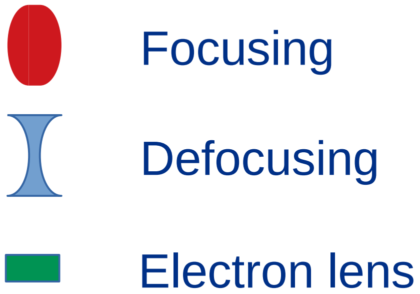


FODO with lattice error



FODO with lattice error and 12 lenses





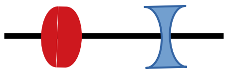
$$\Delta Q_{SC} = -0.9$$

Initially, avoid complications: no bends, all magnets, RF cavities treated linearly

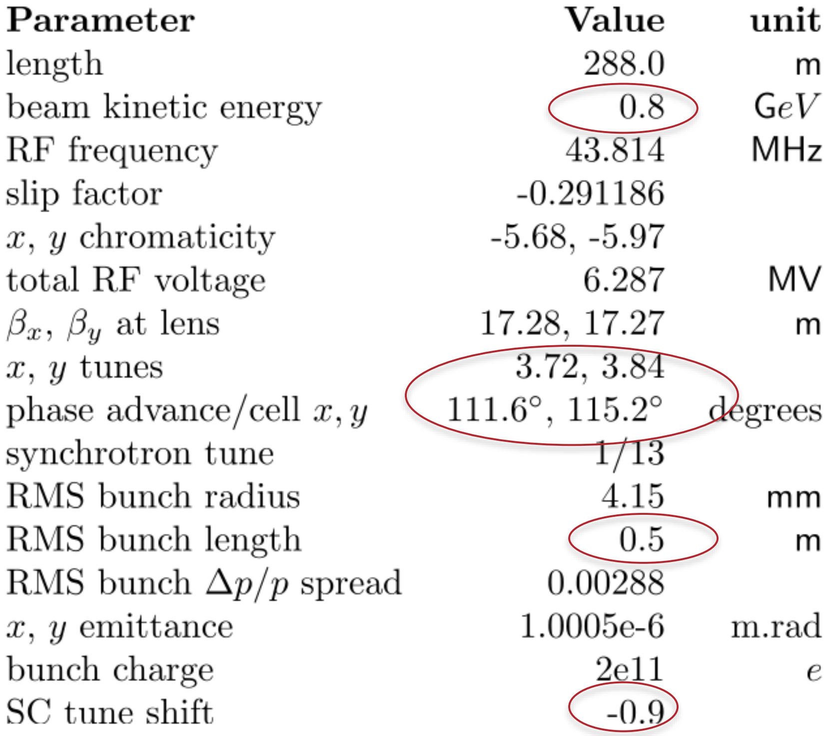
Case #1

How bad is Space Charge by Itself?

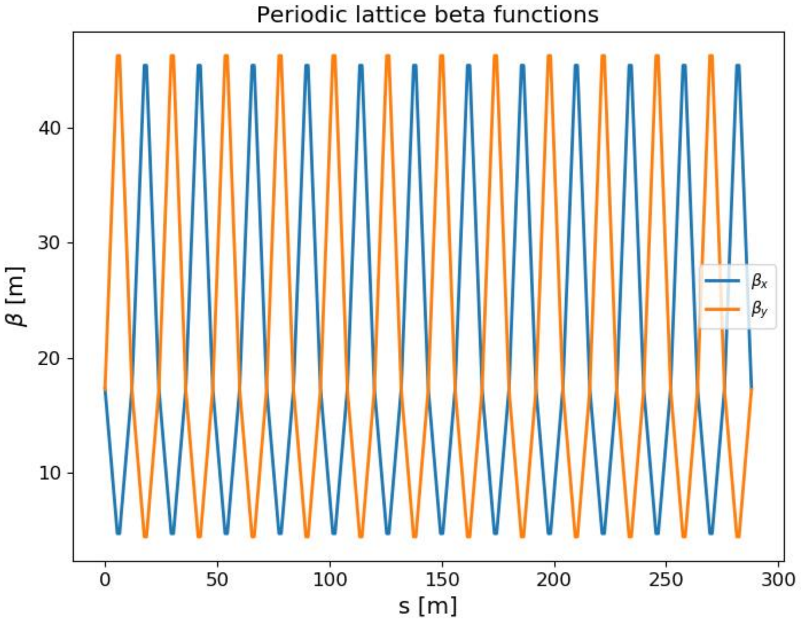
Case #1 lattice model



× 12



Parameter	Value	unit
length	288.0	m
beam kinetic energy	0.8	GeV
RF frequency	43.814	MHz
slip factor	-0.291186	
x, y chromaticity	-5.68, -5.97	
total RF voltage	6.287	MV
β_x, β_y at lens	17.28, 17.27	m
x, y tunes	3.72, 3.84	
phase advance/cell x, y	111.6°, 115.2°	degrees
synchrotron tune	1/13	
RMS bunch radius	4.15	mm
RMS bunch length	0.5	m
RMS bunch $\Delta p/p$ spread	0.00288	
x, y emittance	1.0005e-6	m.rad
bunch charge	2e11	e
SC tune shift	-0.9	



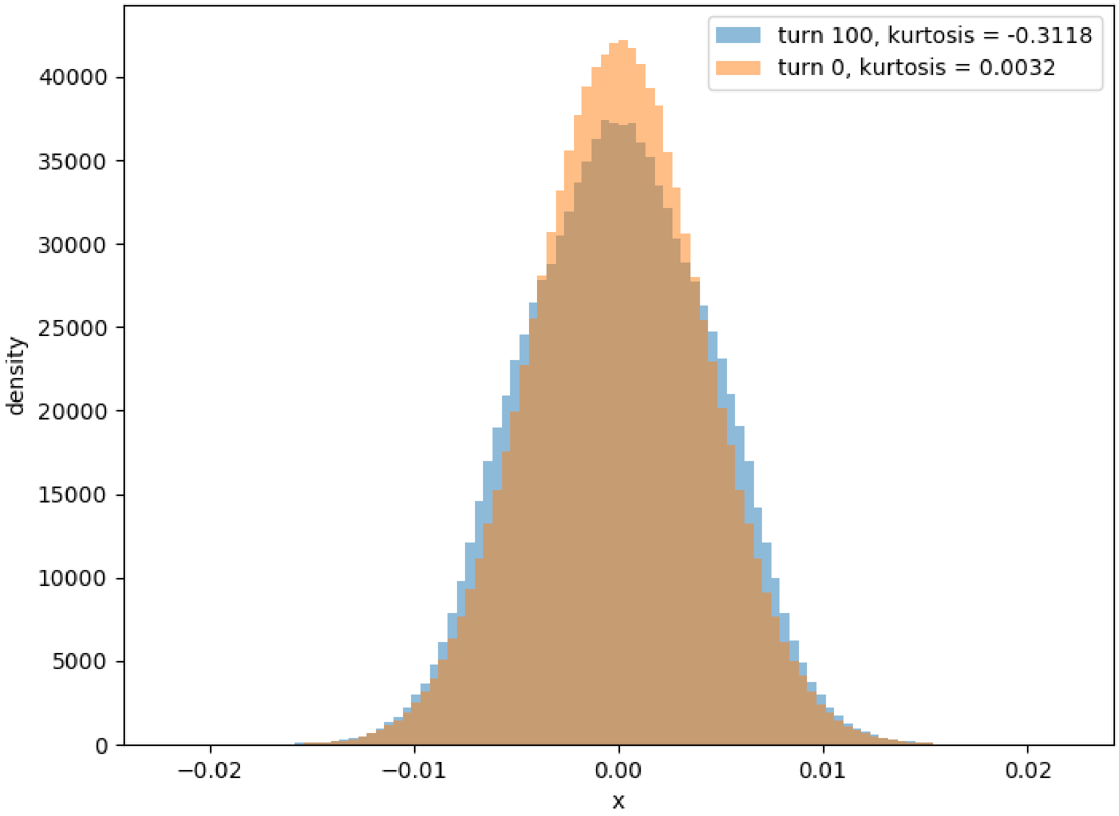
72 SC kicks/turn (6 SC kicks/FODO cell)

Quadrupoles, drifts, RF cavities are linear

Space charge is highly nonlinear

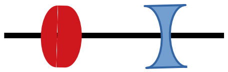
One electron lens/period located at equal beta function location

Initial mismatch from large space charge

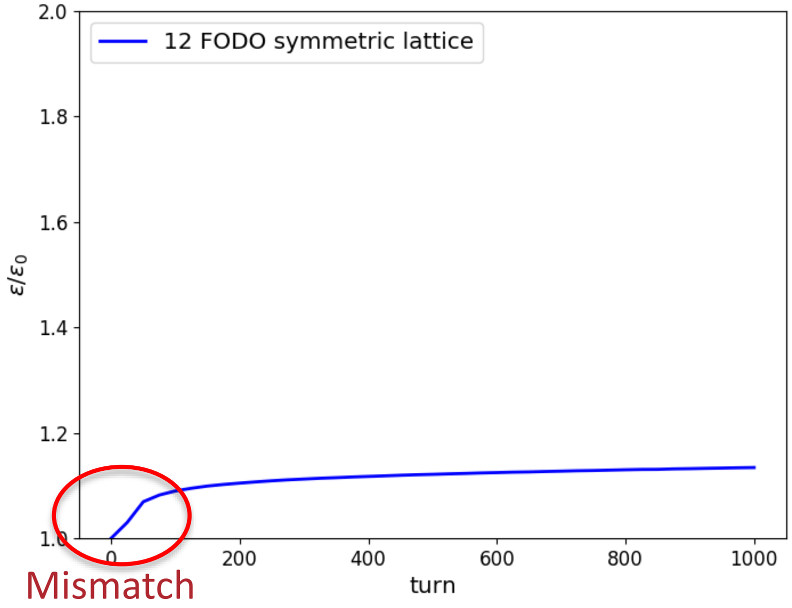


Very large space charge pushes particles out of the core of the Gaussian bunch

Case #1

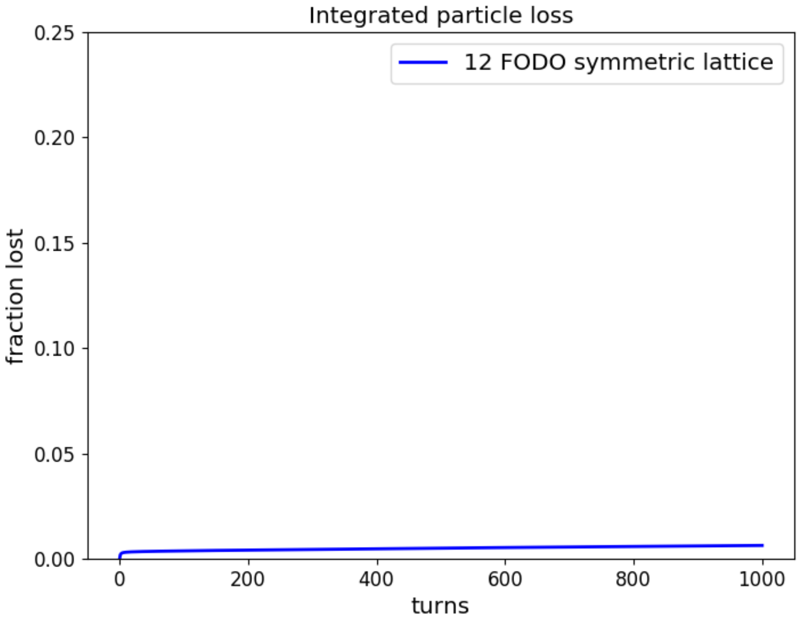

× 12

RMS x emittance growth



13% emittance growth

4 sigma aperture loss



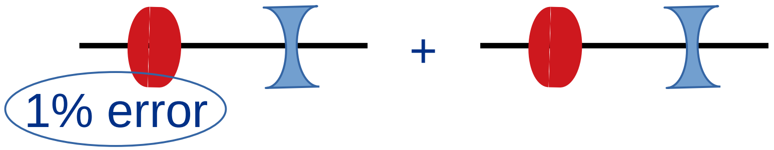
0.6% particle loss

No large growth after initial mismatch

Case #2

Add Lattice Error to Single Element

Case #2 1% focusing error



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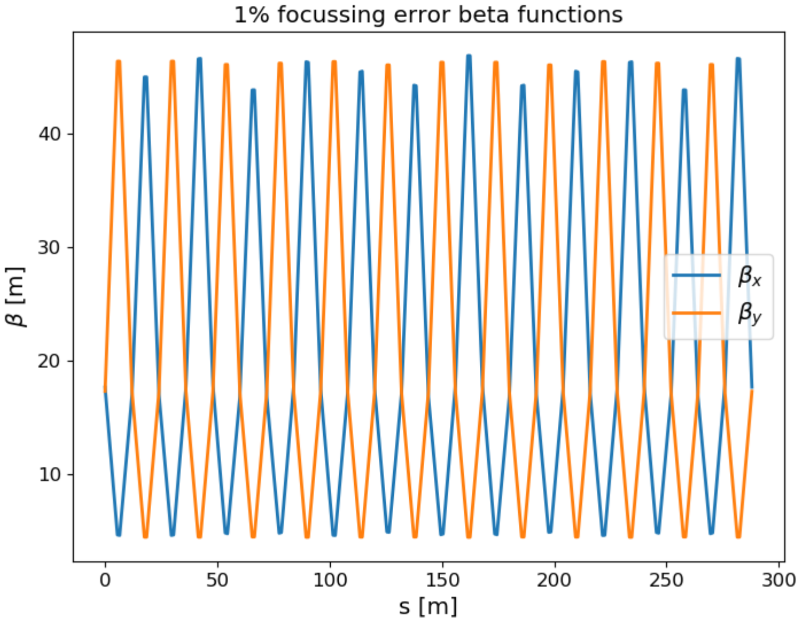
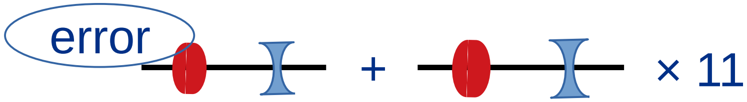
SC tune shift	-0.9	



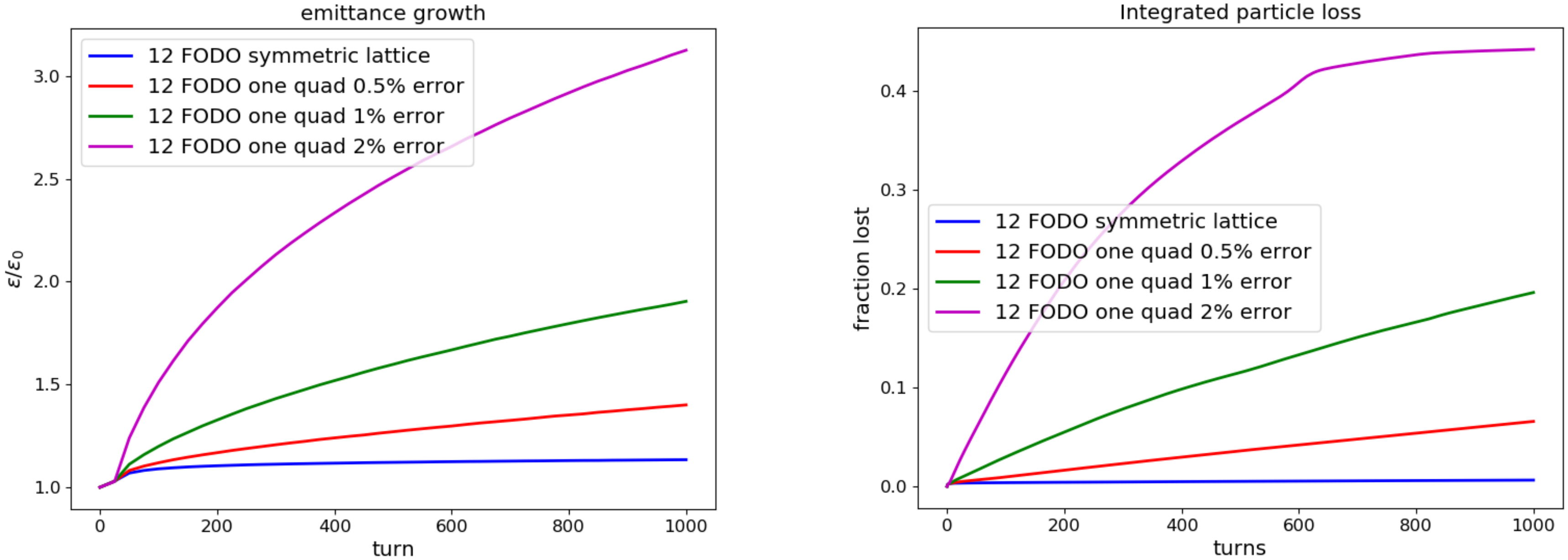
Beta beating is less than 4% but…

Case #2 element errors



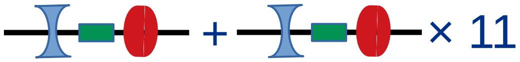
RMS x emittance growth

4 sigma aperture loss



Lattice error (%)	Emittance growth (%)	4 sigma loss
0	13	0.6
0.5	41	6.7
1.0	91	19.7
2.0	210	44.5

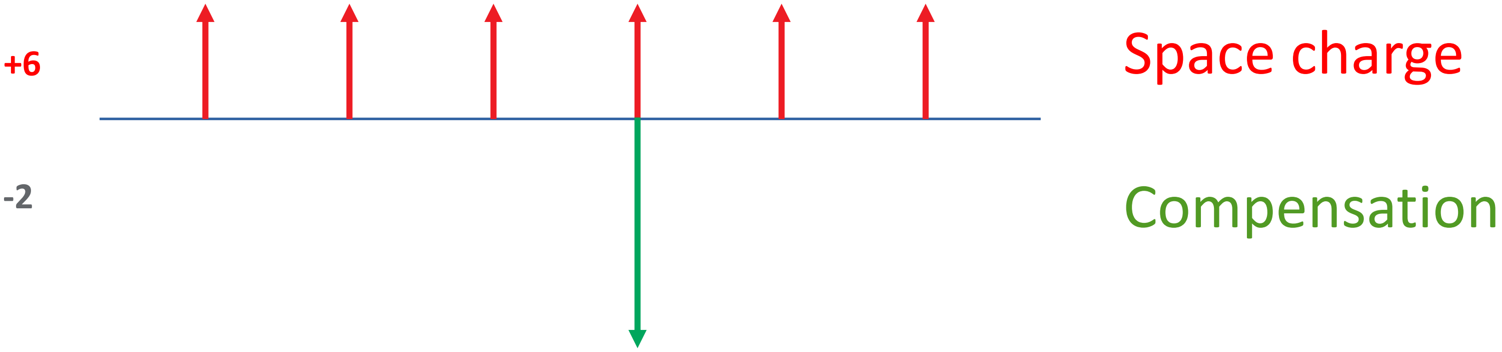
Case #3



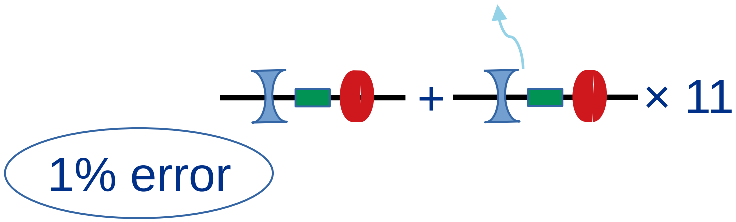
1% error

Add 12 “ideal” compensating lenses

The simulation adds space charge kicks at 72 locations. We simulate a mathematically perfect compensating lens by adding the same space charge kick particle-by-particle multiplied by a negative factor at 12 locations 111° phase advance separation. “Maxwell’s Daemon”



Case #3



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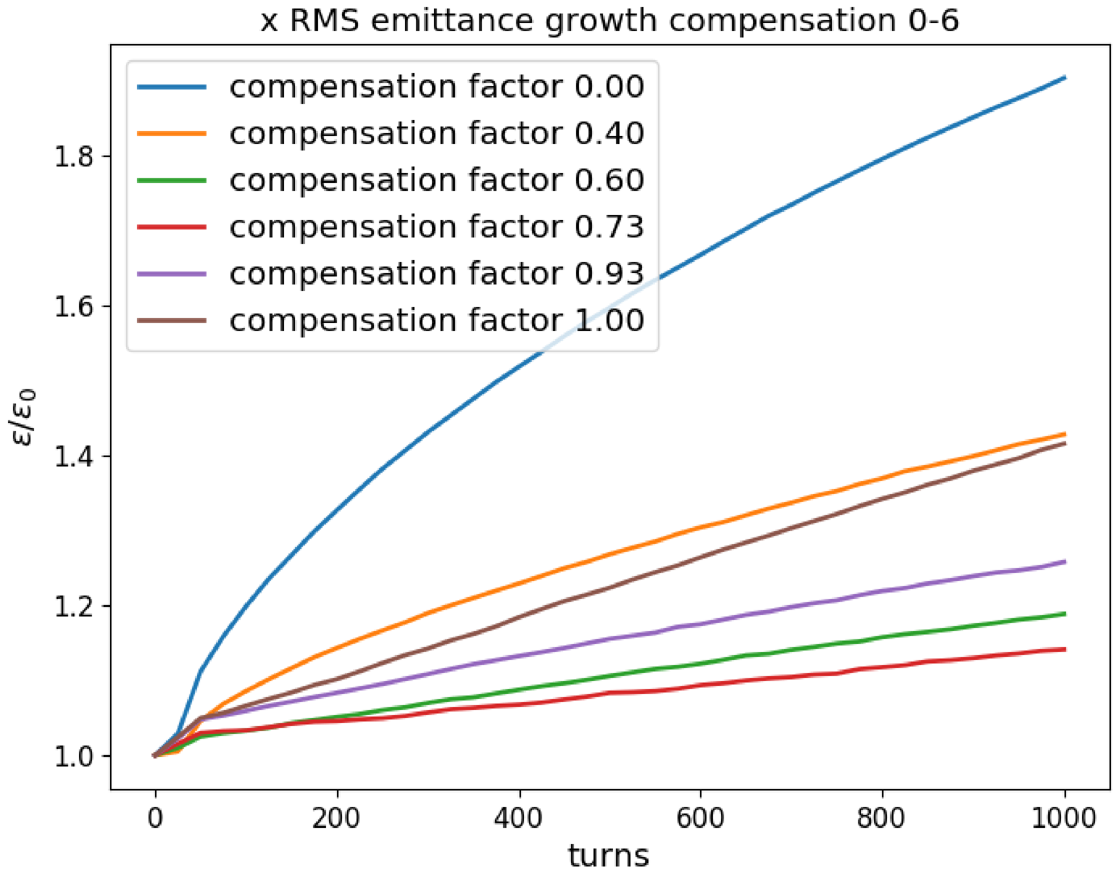
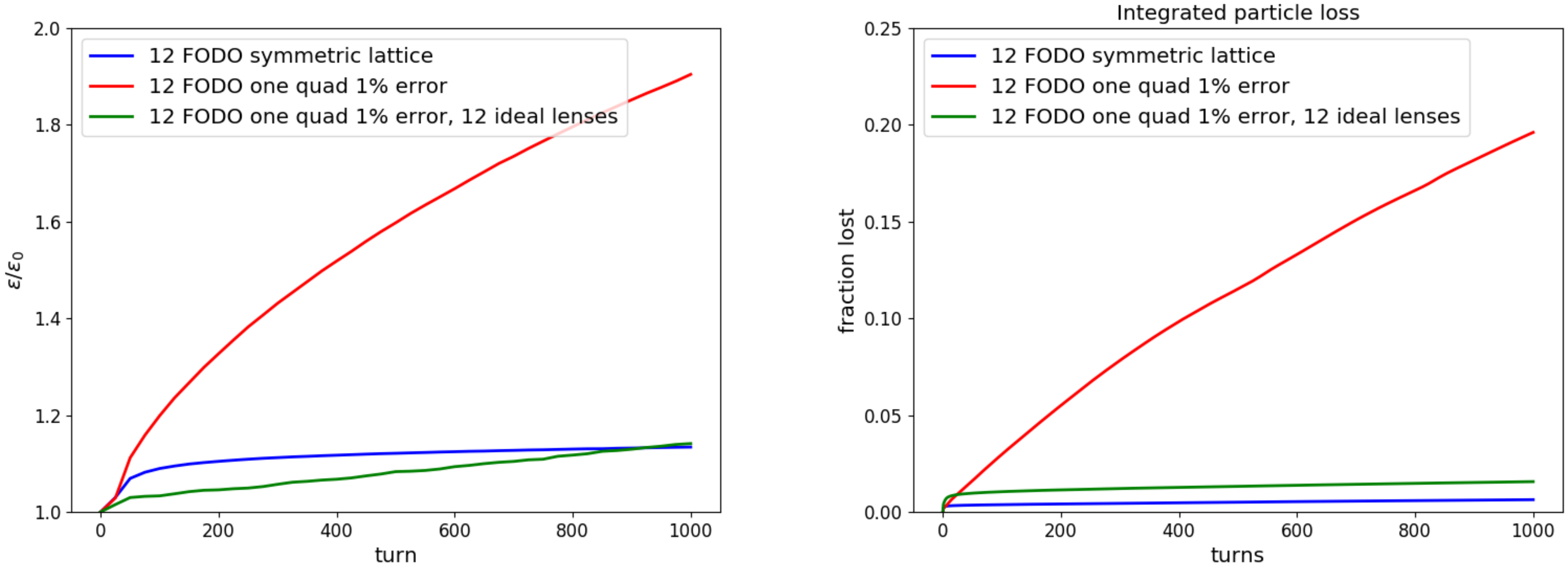


Best compensation occurs at a factor of 0.73 resulting in emittance growth of 14%

Case #3

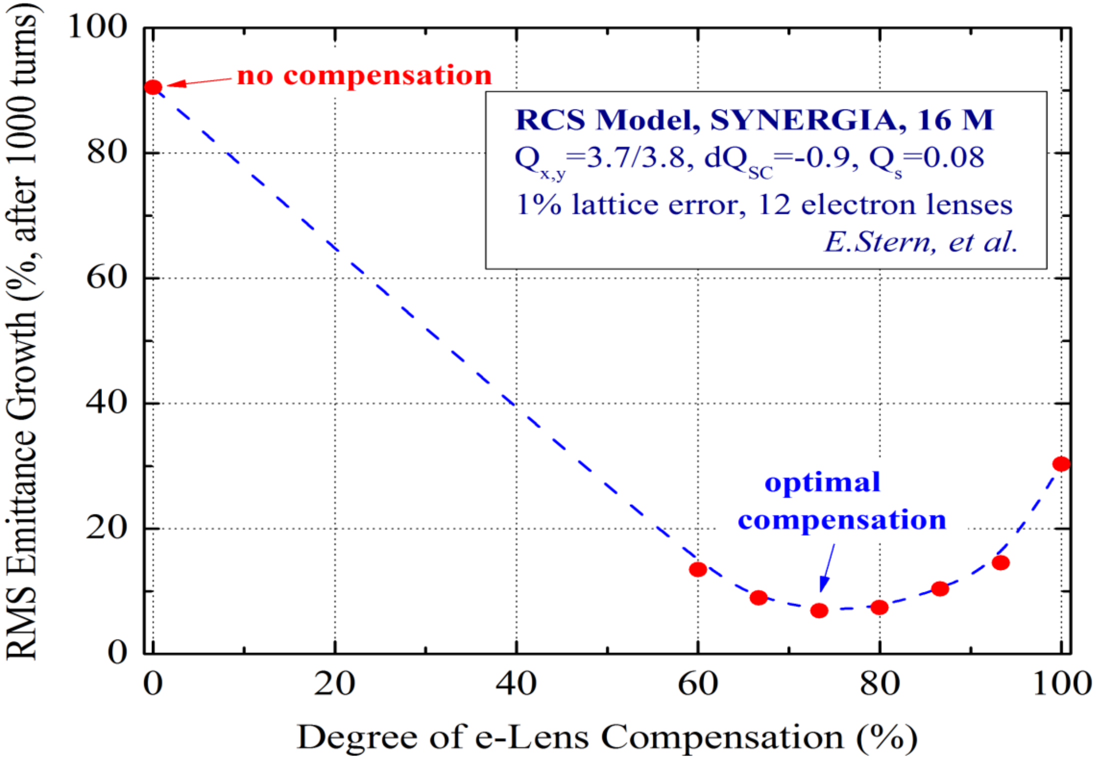
RMS x emittance growth

4 sigma aperture loss

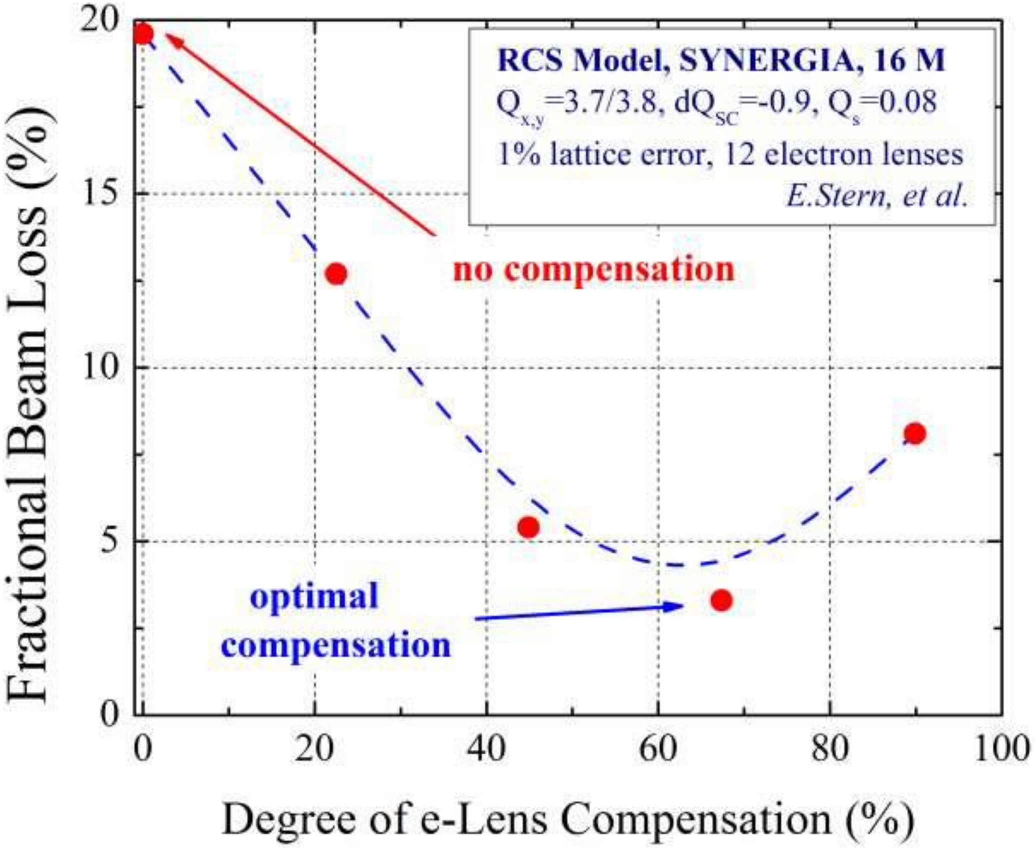


	x emittance growth (%)	4 Sigma loss (%)
Case #1 (symmetric)	13	0.6
Case #2 (1% element error)	91	19.7
Case #3 (compensation .73)	14	1.5

Case #3 dependence on compensation strength



Loss vs. compensation strength

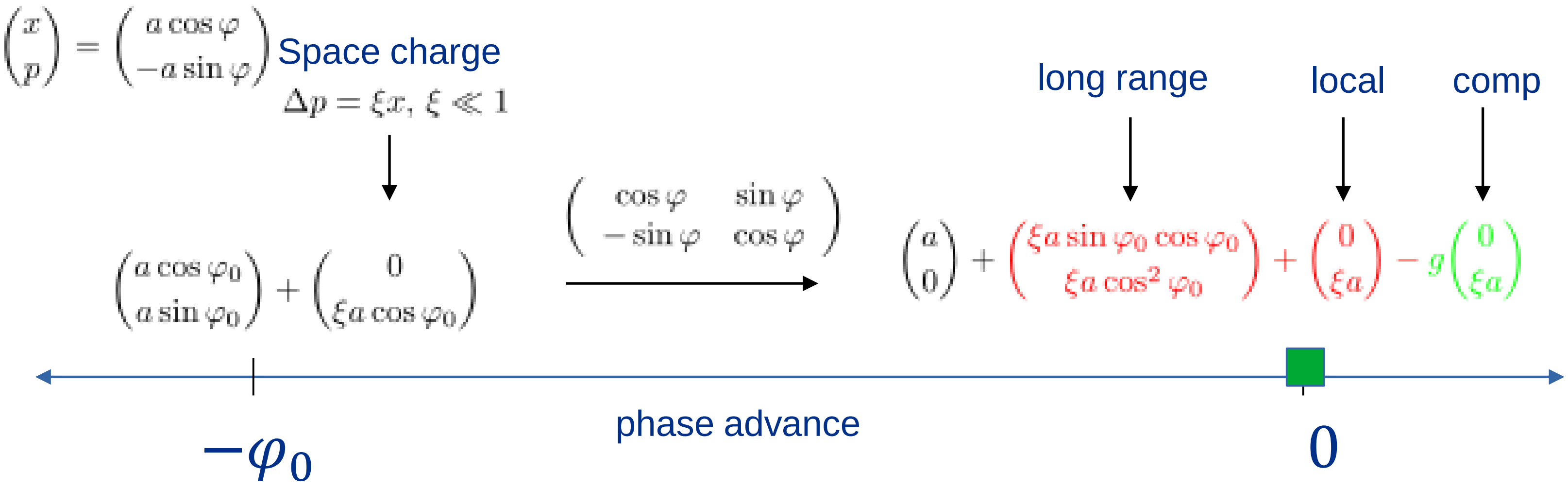


Dependence on number of lenses

#lenses	Phase advance	Best X emittance growth (%)
24	55.8°	6.5
12	116.6°	13
6	223.2°	86

Compensation works best with lenses about 120° apart, or 60° forward, 60° backwards.

Compensation model



$$\begin{pmatrix}x\\ p\end{pmatrix} = \begin{pmatrix}a\cos\varphi\\ -a\sin\varphi\end{pmatrix}$$

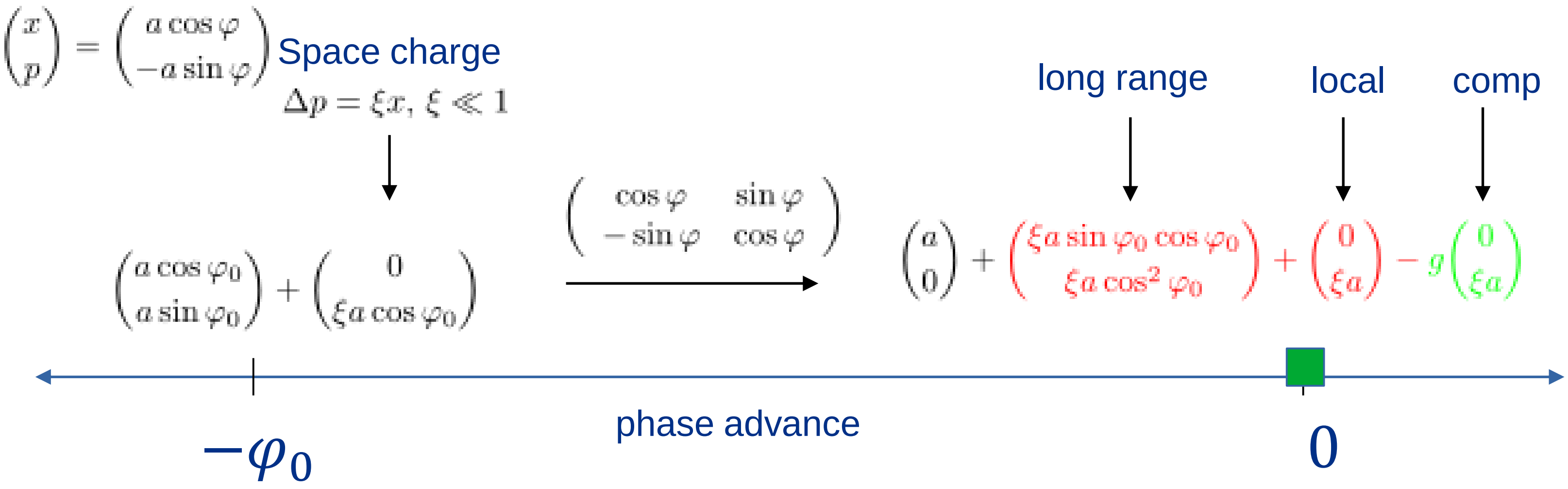
Space charge

$\Delta p = \xi x,\ \xi \ll 1$

$$\begin{pmatrix}a\cos\varphi_0\\ a\sin\varphi_0\end{pmatrix} + \begin{pmatrix}0\\ \xi a\cos\varphi_0\end{pmatrix} \xrightarrow{\begin{pmatrix}\cos\varphi & \sin\varphi\\ -\sin\varphi & \cos\varphi\end{pmatrix}} \begin{pmatrix}a\\ 0\end{pmatrix} + \underbrace{\begin{pmatrix}\xi a\sin\varphi_0\cos\varphi_0\\ \xi a\cos^2\varphi_0\end{pmatrix}}_{\text{long range}} + \underbrace{\begin{pmatrix}0\\ \xi a\end{pmatrix}}_{\text{local}} - \underbrace{g\begin{pmatrix}0\\ \xi a\end{pmatrix}}_{\text{comp}}$$

- Because the space charge is assumed linear, the compensator can in principle completely eliminate the momentum kick up to phase advance π/2.
- There is no compensation power at phase advance of π /2.
- The position coordinate is disturbed by uncorrectable space charge generated displacement with the maximum disturbance occurring at a phase advance of π/4. .
- Compensation works both forwards and backwards in phase advance.

Additional factors in compensation



$$\begin{pmatrix} x \\ p \end{pmatrix} = \begin{pmatrix} a\cos\varphi \\ -a\sin\varphi \end{pmatrix}$$

Space charge

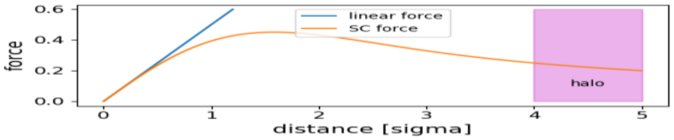
$\Delta p = \xi x,\ \xi \ll 1$

long range local comp

$$\begin{pmatrix} a\cos\varphi_0 \\ a\sin\varphi_0 \end{pmatrix} + \begin{pmatrix} 0 \\ \xi a\cos\varphi_0 \end{pmatrix} \xrightarrow{\begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix}} \begin{pmatrix} a \\ 0 \end{pmatrix} + \begin{pmatrix} \xi a\sin\varphi_0\cos\varphi_0 \\ \xi a\cos^2\varphi_0 \end{pmatrix} + \begin{pmatrix} 0 \\ \xi a \end{pmatrix} - g\begin{pmatrix} 0 \\ \xi a \end{pmatrix}$$

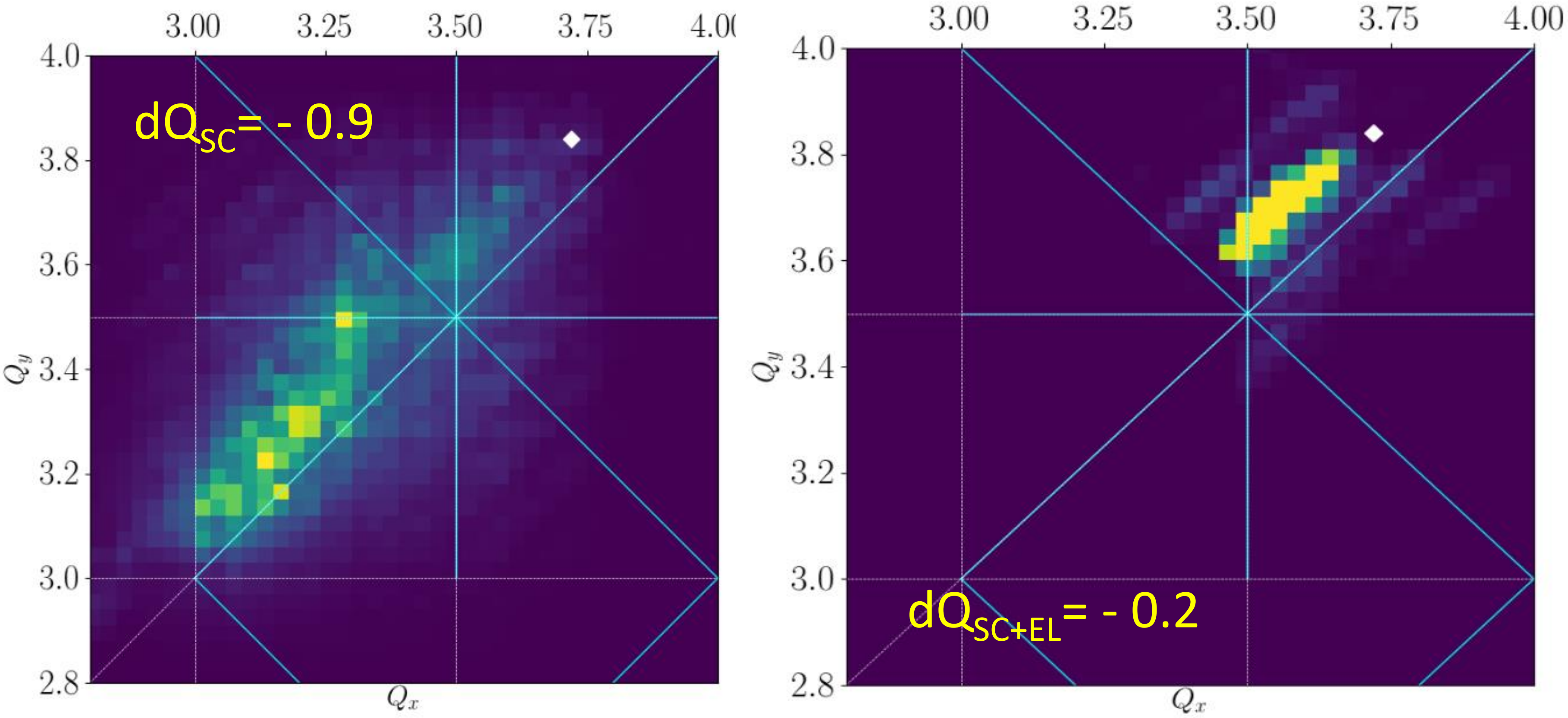
phase advance

$-\varphi_0$ 0



- Compensation at large phase advances may be less effective because the impulse acquired diffuses to neighboring particles.
- Compensation of both core and halo particles is difficult:
  - In Gaussian bunches, the space charge force is only linear within about a radius of 0.4 σ. Outside of that, the compensation subtraction is less good.
  - Compensation is less effective for particles far from the core compared to those in the core because they their phase advance from their space charge kick location is different.
- Compensation gain that is too large acts as a driving term to the motion causing trouble.

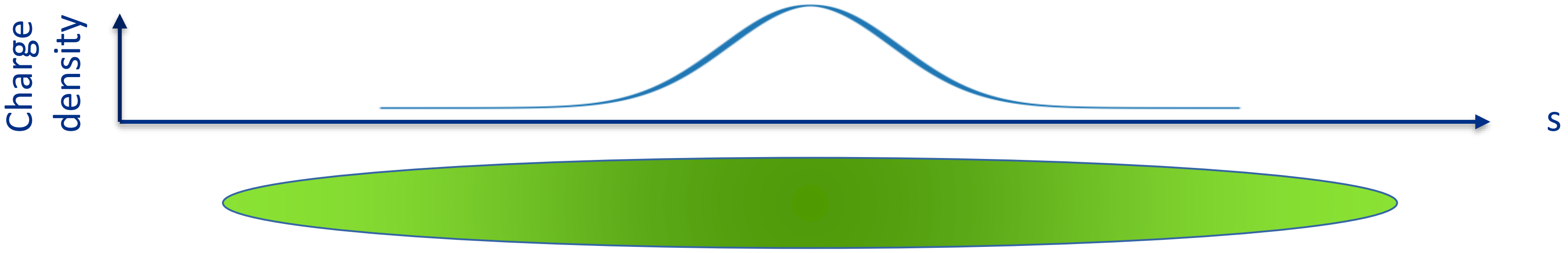
Compensation tune footprints



Stern et al, THPAF075, IPAC18, Beams Document 6790-v1 FNAL (2019)

Compensation with a simulated current distribution

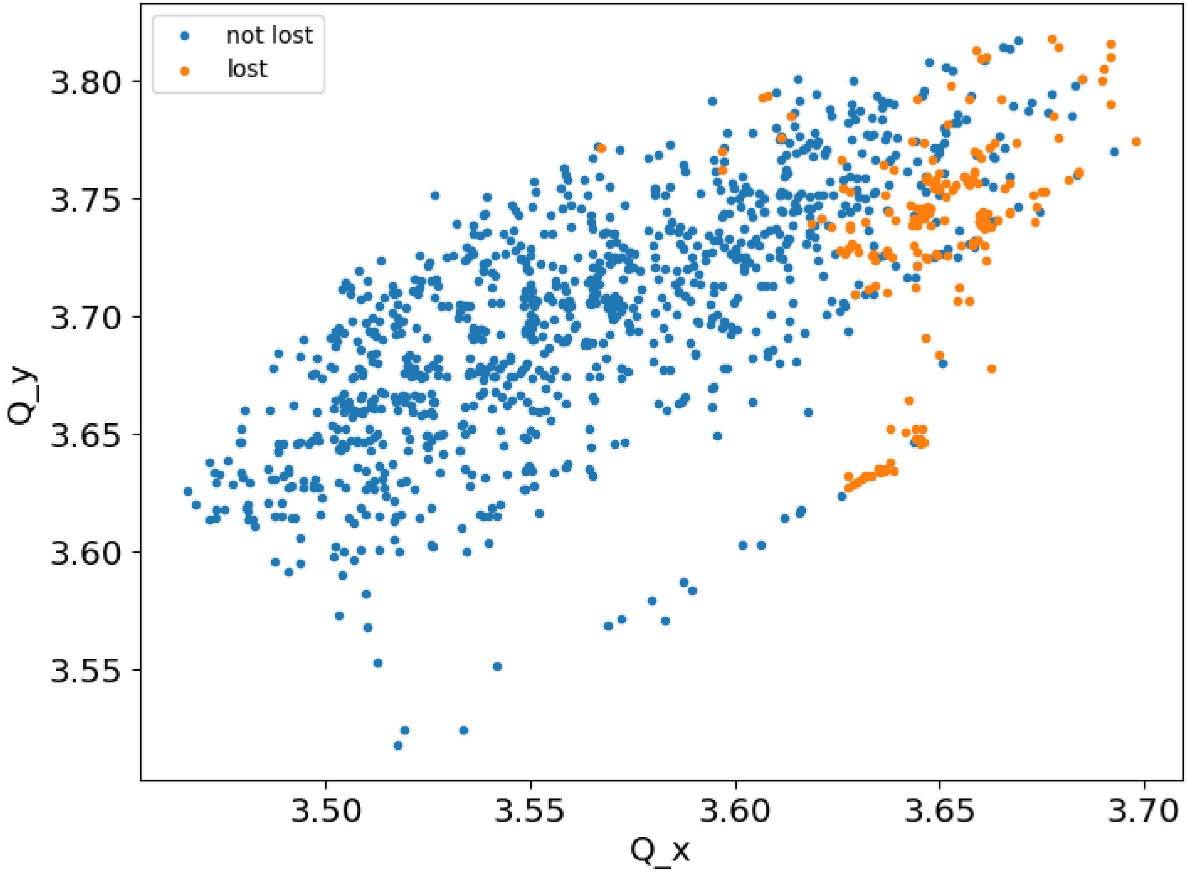
Lens transverse Gaussian profile fixed, σ = 4.15 mm



Lens Longitudinal profile	X emittance growth (%)	4 sigma particle loss (%)
DC	60	76
Gaussian, σ = 0.5 m	27	3.4

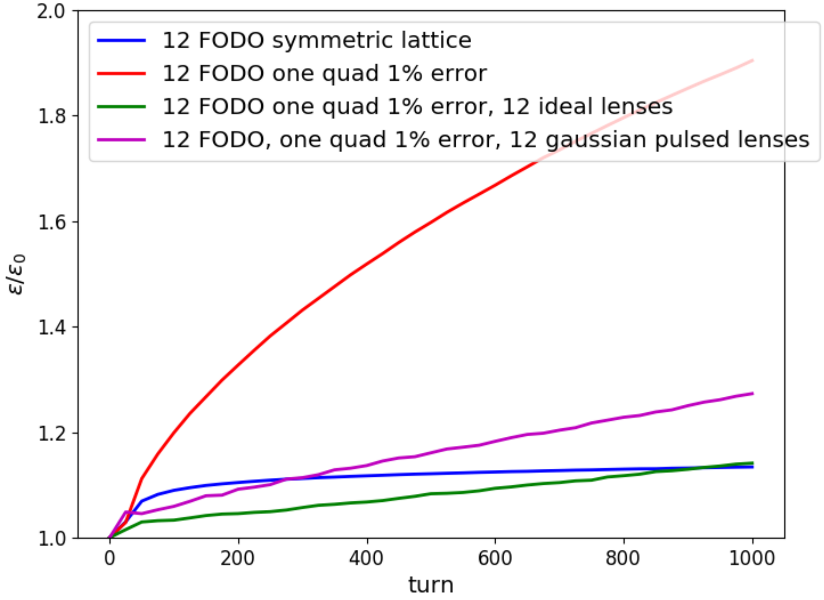
Can the lost particles tell us anything

Tunes of the lost and (1000 of) kept particles

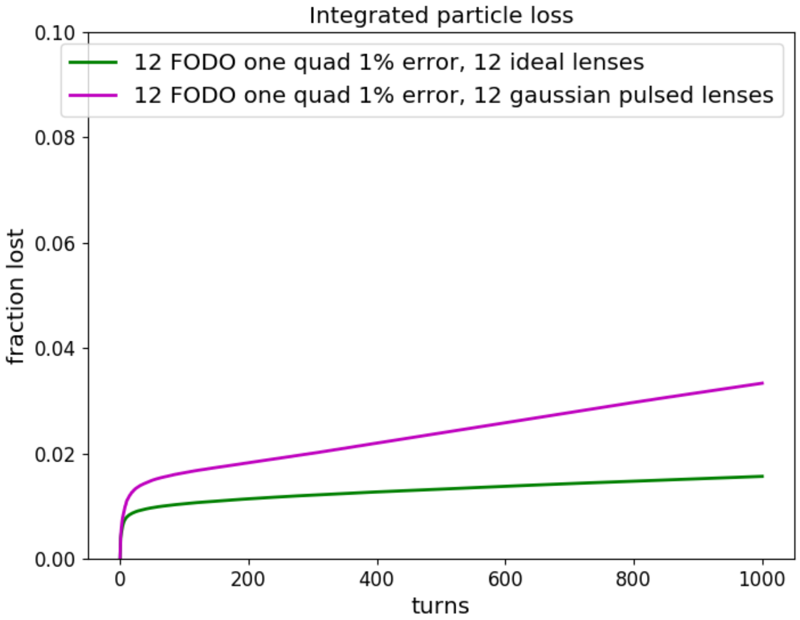


All lens comparison

RMS x emittance growth



4 sigma aperture loss



Conditions	X emittance growth (%)	4 sigma particle loss (%)
12 FODO symmetric	13	0.6
12 FODO one quad 1% error	91	19.7
previous plus 12 ideal lenses	14	1.6
12 DC lenses	60	76
12 Gaussian longitudinal lenses	27	3.4

Summary

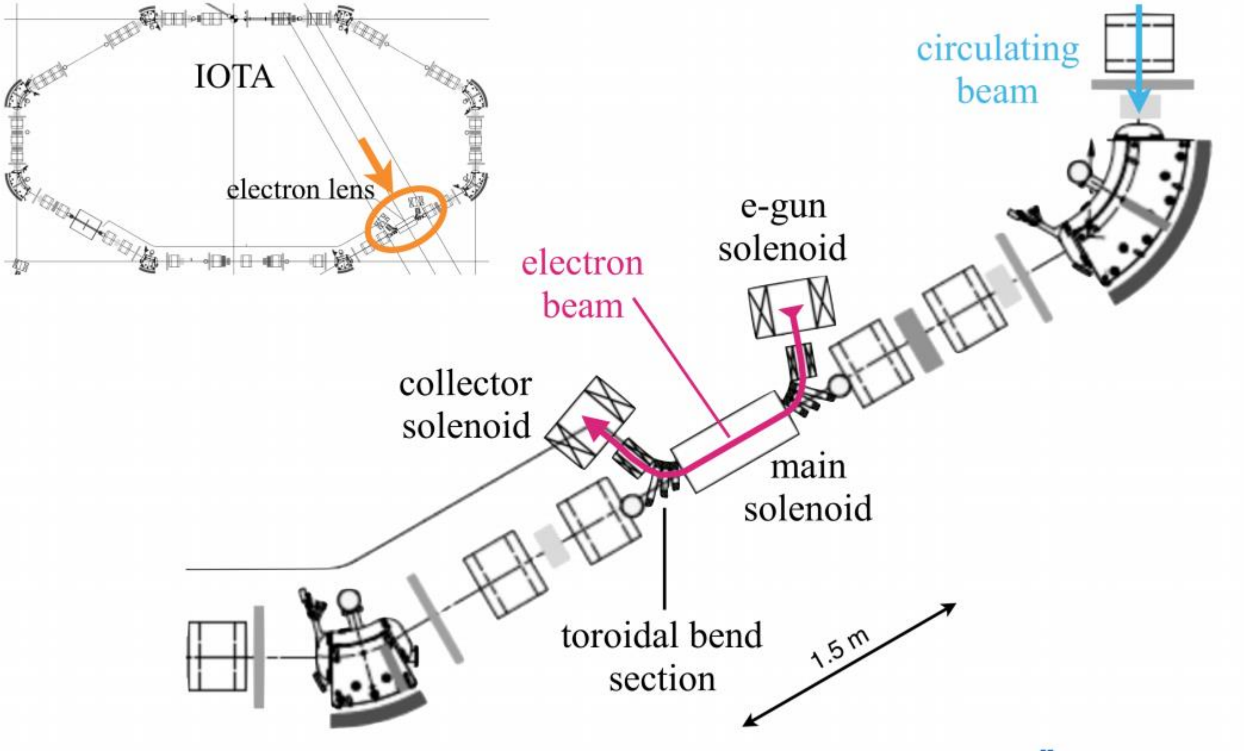
- We have run Synergia’s space charge simulation at the ultimate space charge tune shift of close to 1 with various compensation schemes.
- Synergia validated by GSI Benchmarking suite and successful simulation of Space Charge modes.
- 16M particles tracked for statistical noise reduction in calculations of emittance growth and losses.
- Extremely high tune spread simulated.
- Lattice errors are a major contributor to space charge generated beam effects.
- We have demonstrated for the first time in detailed simulations that placement of a sufficient number of electron lenses can substantially ameliorate space charge effects and reduce losses.
- Compensation of the bunch core is more successful than the halo but that is what is needed to suppress halo generation and reduce losses.

Future plans

- Longitudinally flat proton bunch distributions may be more beneficial to compensation to allow DC lens current
- Incorporate more realistic lattice including dipoles, sextupoles, dispersion, chromaticity, etc.
- Explore interplay between impedance and space charge
- Participate in the design and analysis of IOTA electron lens experiments

Electron lens experiment at IOTA

- Simulations will be part of the experiment planning and analysis
- Design underway with CERN and U. Lapland
- Construction planned for 2020–2021



Thanks for listening!

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