Head-on beam-beam compensation in a ring-ring electron-ion collider

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Motivation

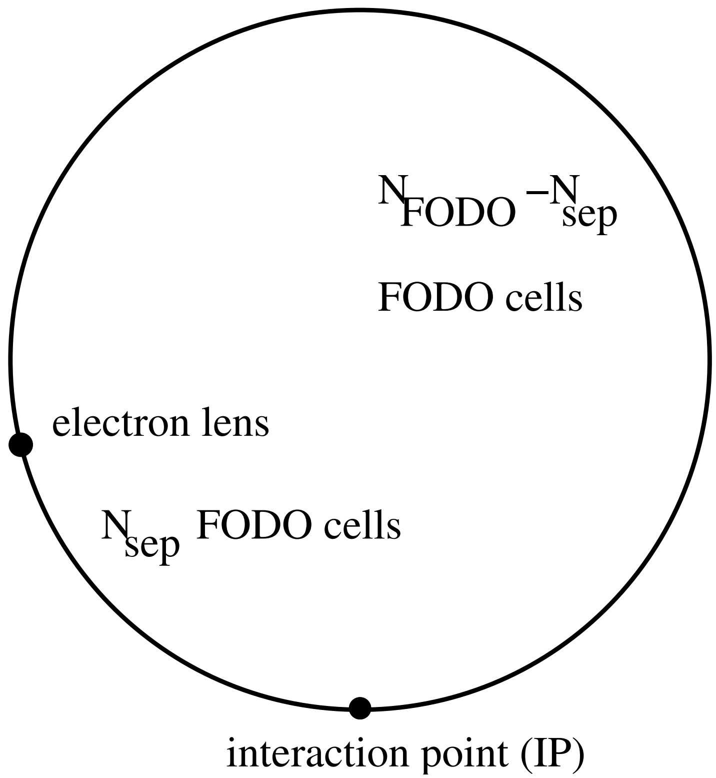
- Installation of electron lenses for head-on beam-beam compensation of proton-proton collisions in RHIC is currently being studied.

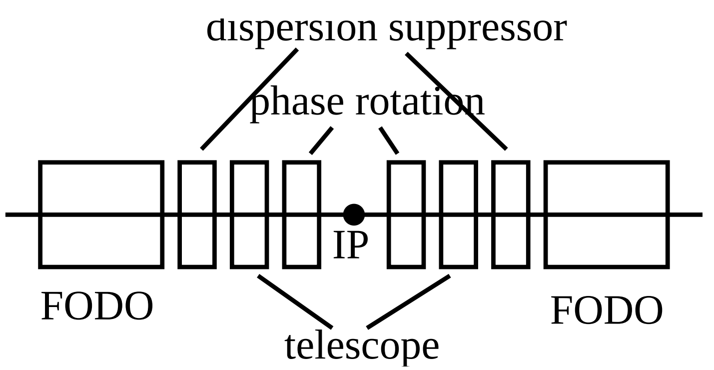
- Realistic simulations with proton beams are very difficult and time consuming.

- Simulations of beam-beam compensation in an electron ring is much easier, and many effects can be studied there.

- As a spin-off, this may be applicable in the eRHIC electron ring.

The electron accelerator model





Parameter table

no. of FODO cells	N_{FODO}	50
no. of cells between IP and electron lens	N_{sep}	10
phase advance/cell (hor./vert.)	$\Delta\Phi_x/\Delta\Phi_y$	79.7°/89.0°
chromaticity (hor./vert.)	$Q'_{x,y} = \Delta Q_{x,y}/\frac{\Delta p}{p}$	+2/+2
telescope chromaticity	$Q'_{\mathsf{telescope}}$	−2.5
synchrotron tune	Q_s	0.015
rms bunch length	σ_s	0.0117 mm
rms momentum spread	σ_p	$9.4 \cdot 10^{-4}$
β-function at IP and electron lens	β_x/β_y	0.19 m, 0.26 m
no. of positive charges/bunch	N_p	$4 \cdot 10^{11}$
electron lens intensity/bunch	N_e	$4 \cdot 10^{11}$
rms proton beam size at IP	$\sigma_{x,p}/\sigma_{y,p}$	101 μm/50.5 μm
rms electron lens beam size	$\sigma_{x,e}/\sigma_{y,e}$	101 μm/50.5 μm
Lorentz factor	γ	19560
electron beam-beam parameter	ξ_x/ξ_y	0.11/0.32
damping times	$\tau_x/\tau_y/\tau_z$	1740/1740/870 turns

Parameters are taken from eRHIC ring-ring ZDR

Electron beam-beam parameter is increased by increased N_p here; cooling of the proton beam would have the same effect

Definitions

Geometric luminosity factor (used in contour plots):

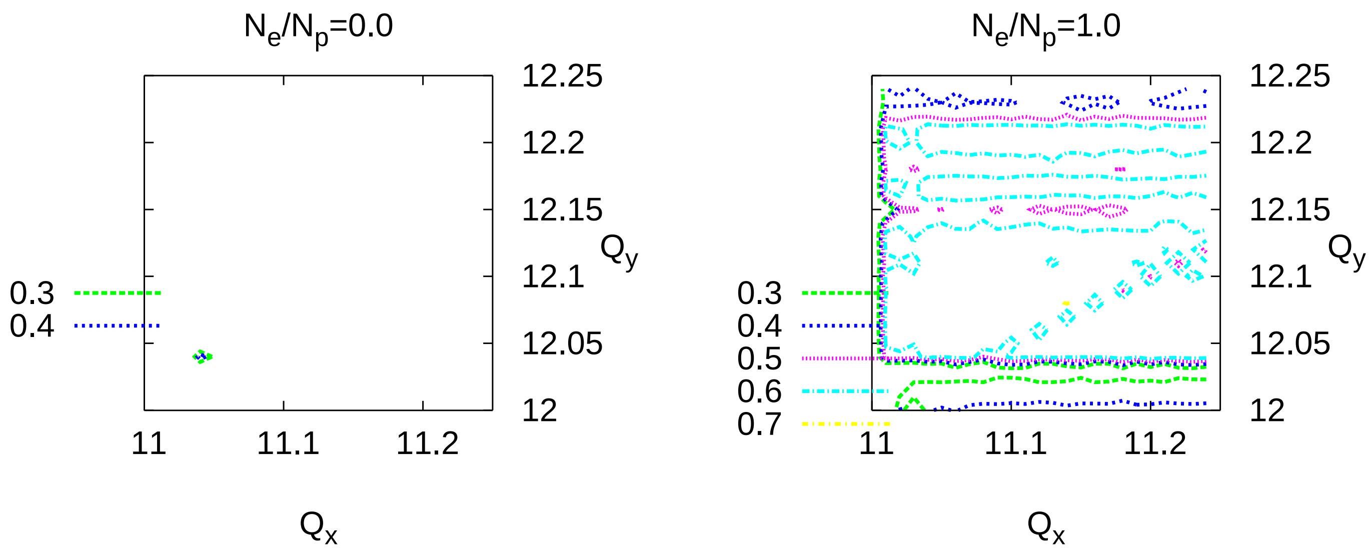
$$F_{\text{geom}} = \frac{L}{L_0} = \frac{2\sigma_{x,p}\sigma_{y,p}}{\sqrt{(\sigma_{x,p}^2 + \sigma_{x,e}^2)(\sigma_{y,p}^2 + \sigma_{y,e}^2)}}$$

Normalized luminosity (all other plots and tables):

$$L_{\text{norm}} = F_{\text{geom}} \cdot N_p.$$

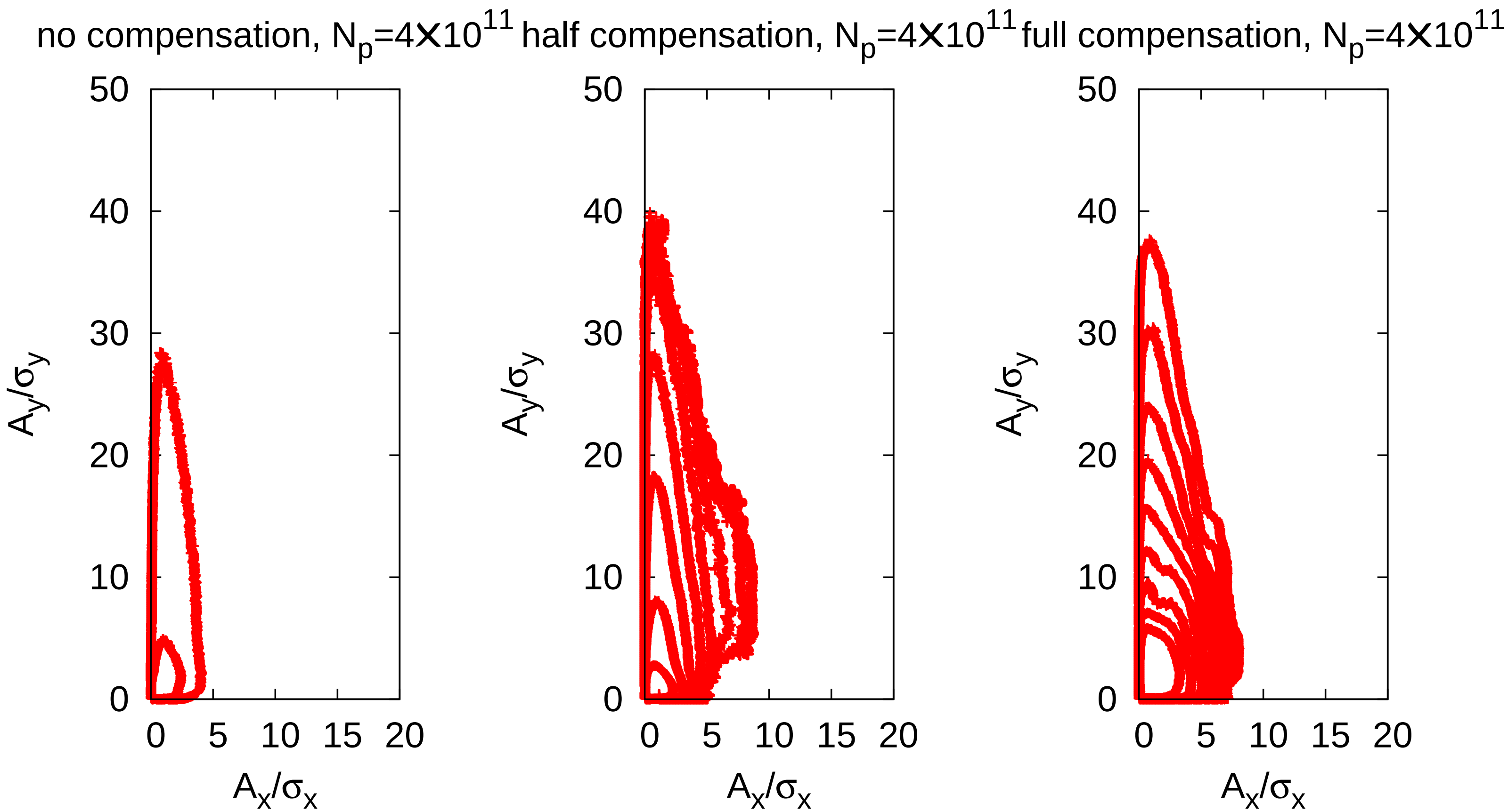
Both F_{geom} and L_{norm} are proportional to the collider luminosity.

Contours of geometric luminosity F_{norm}, $N_p = 4 \cdot 10^{11}$



Electron lens nearly doubles geometric luminosity F_{norm}, over a large tune space.

Transverse tails for $N_p = 4 \cdot 10^{11}$



Contour lines spaced by factor 10.
Electron lens significantly reduces transverse tails.

Robustness against imperfections

- Betatron phase advance errors between IP and electron lens

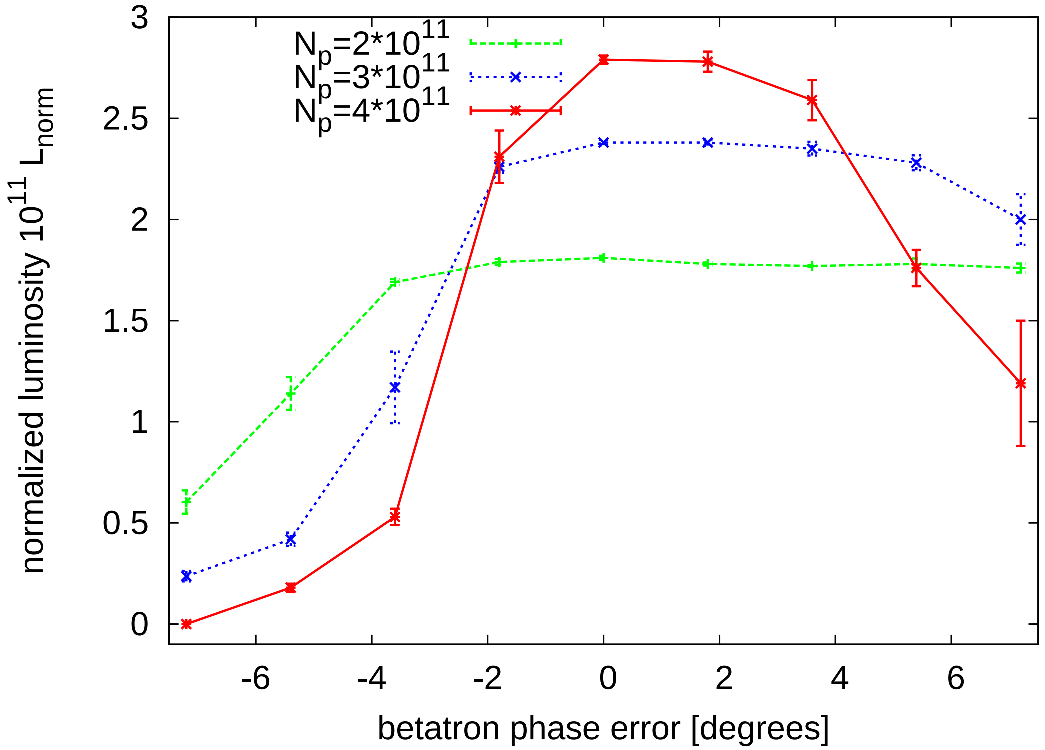
- Intensity mismatch between electron lens and corresponding proton bunch

- Nonlinearities (= number of FODO cells with sextupoles) between IP and electron lens

- Shape mismatch (ellipticity) between electron lens and corresponding proton bunch

- Beam size and intensity mismatch between electron lens and corresponding proton bunch

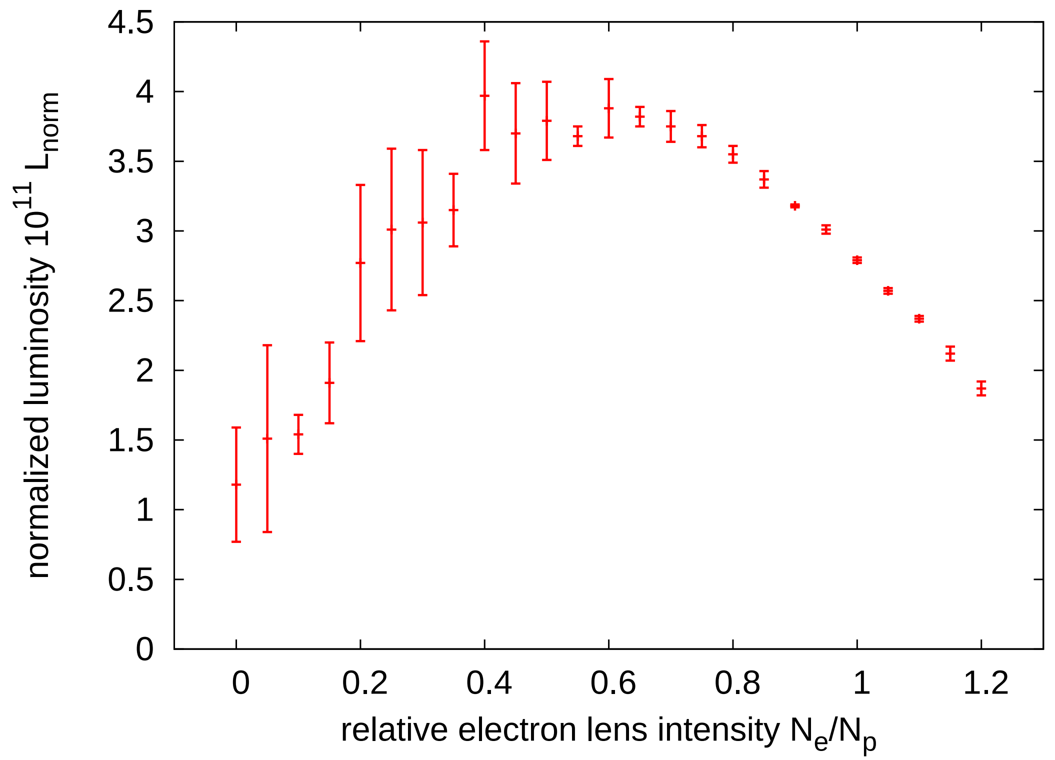
Normalized luminosity L_{norm} vs. phase error



Sensitivity to phase errors is reduced for reduced beam-beam parameters.

Based on complete tune scans between integer and quarter resonance.

Normalized luminosity L_{norm} vs. compensation degree

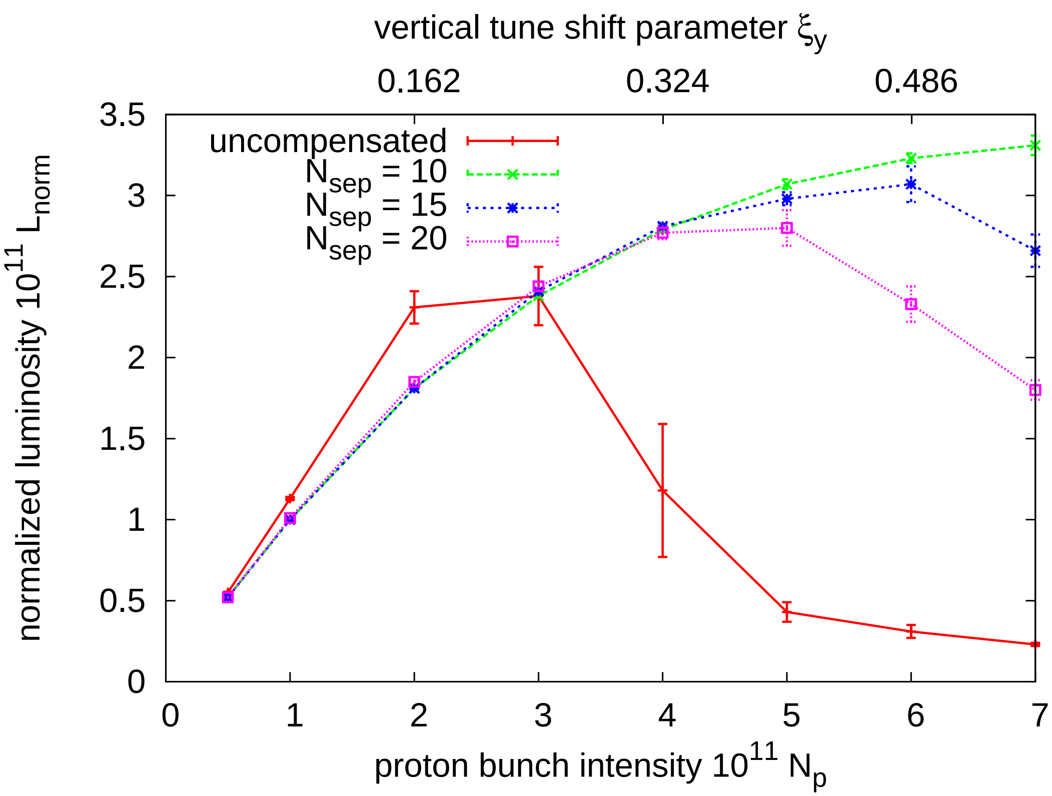


Balance between emittance blow-up and dynamic focusing.

Half compensation results in highest luminosity.

Based on complete tune scans between integer and quarter resonance.

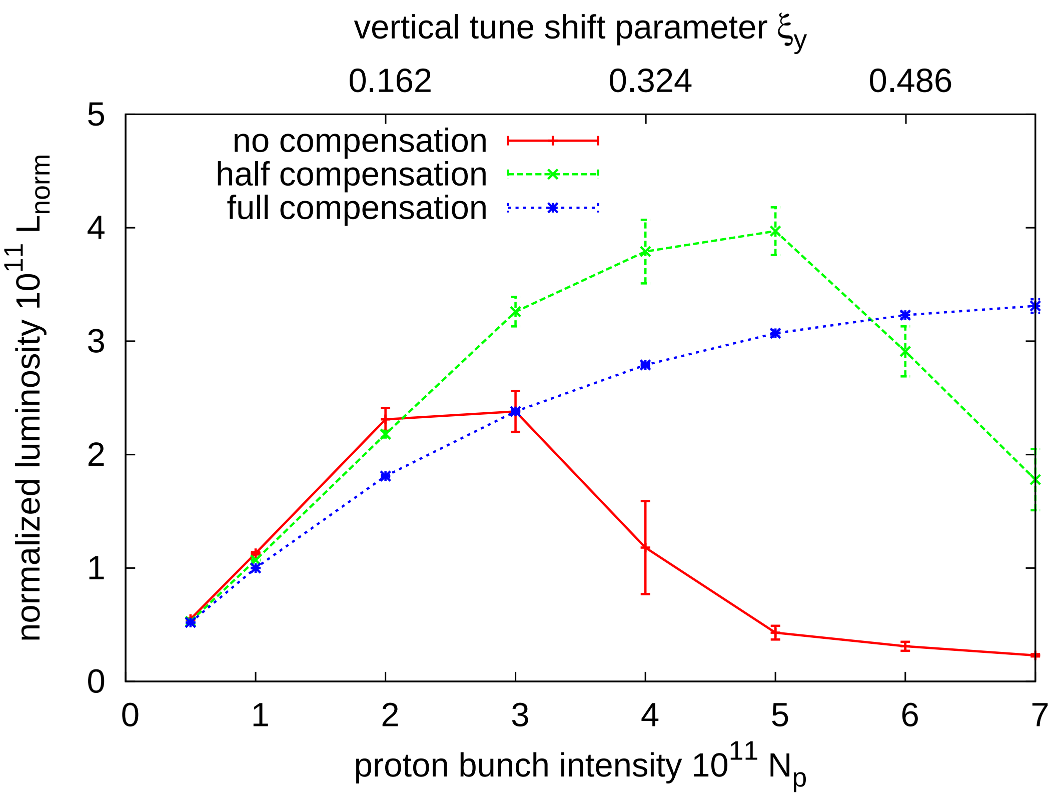
L_{norm} vs. number of FODO cells (=nonlinearity)



Maximum luminosity affected only at very high beam-beam parameters; available tune space shrinks with larger N_{sep}.

Based on complete tune scans between integer and quarter resonance.

Normalized luminosity L_{norm} vs. compensation degree



Half compensation maximizes luminosity for $N_p < 5.5{\cdot}10^{11}$.

Based on complete tune scans between integer and quarter resonance.

Summary

- E-lens in an electron beam opens up huge tune space; nonlinearities between IP and e-lens reduce this space.

- Transverse tails significantly reduced by e-lens.

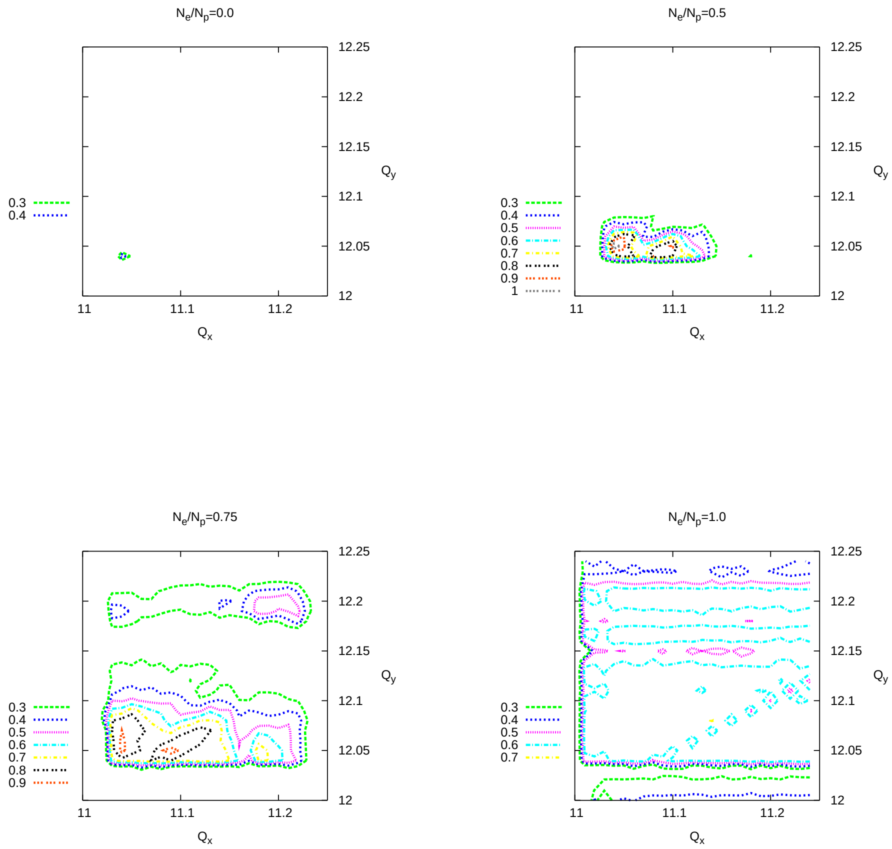
- Rather insensitive to size, shape (ellipticity) and intensity errors.

- Phase advance error between IP and e-lens most critical; needs to be better than a few degrees. Tolerance depends on beam-beam parameter.

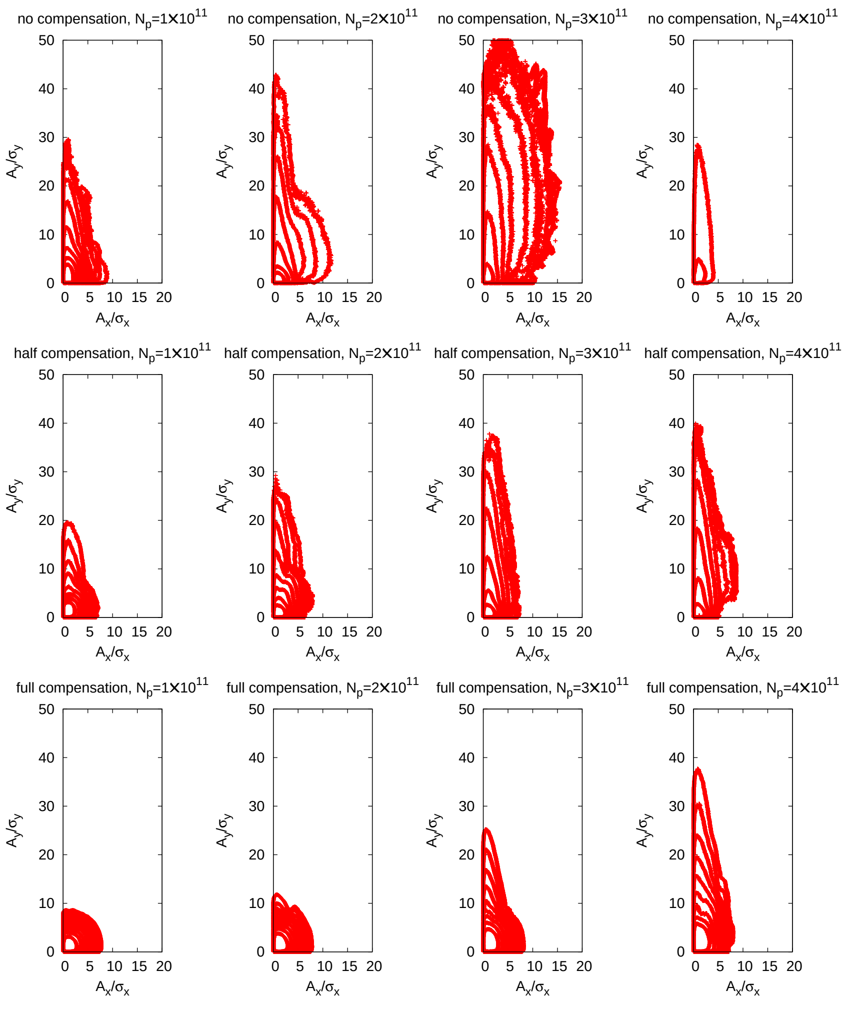
- Under-compensation preferred, but that's largely due to dynamic focussing effects.

Back-up slides

Luminosity contours for various degrees of compensation



Transverse tails



Normalized luminosity L_{norm} vs. shape mismatch

		r_x					
		1.00	1.05	1.10	1.15	1.20	1.25
	1.00	2.79 ± 0.02	2.87 ± 0.02	2.96 ± 0.02	3.04 ± 0.02	3.07 ± 0.02	$3.11 \pm 0.$
	1.05	2.85 ± 0.03	2.95 ± 0.03	3.01 ± 0.01	3.02 ± 0.03	3.09 ± 0.03	$3.12 \pm 0.$
r_y	1.10	2.97 ± 0.02	2.99 ± 0.05	3.03 ± 0.05	3.08 ± 0.05	2.99 ± 0.02	$3.06 \pm 0.$
	1.15	2.97 ± 0.06	3.01 ± 0.06	3.05 ± 0.05	3.05 ± 0.03	3.06 ± 0.07	$3.05 \pm 0.$
	1.20	2.96 ± 0.09	3.00 ± 0.08	2.99 ± 0.08	3.07 ± 0.19	3.00 ± 0.13	$3.04 \pm 0.$
	1.25	2.93 ± 0.10	3.00 ± 0.09	3.02 ± 0.11	2.92 ± 0.14	3.05 ± 0.14	$2.95 \pm 0.$

Normalized luminosity L_{norm} vs. size and intensity mismatc

		N_e/N_p				
		0.80	0.85	0.90	0.95	1.00
	1.00	3.55 ± 0.06	3.37 ± 0.06	3.18 ± 0.01	3.01 ± 0.03	2.79 ± 0.02
	1.05	3.56 ± 0.10	3.42 ± 0.04	3.34 ± 0.07	3.16 ± 0.04	2.95 ± 0.03
r	1.10	3.48 ± 0.16	3.36 ± 0.03	3.36 ± 0.10	3.19 ± 0.09	3.03 ± 0.05
	1.15	3.41 ± 0.23	3.30 ± 0.07	3.31 ± 0.09	3.18 ± 0.18	3.05 ± 0.03
	1.20	3.23 ± 0.16	3.15 ± 0.15	3.15 ± 0.10	3.17 ± 0.24	3.00 ± 0.13
	1.25	3.06 ± 0.24	3.06 ± 0.13	3.00 ± 0.14	2.99 ± 0.07	2.95 ± 0.04