Beam-Beam Simulations for the LHeC Project

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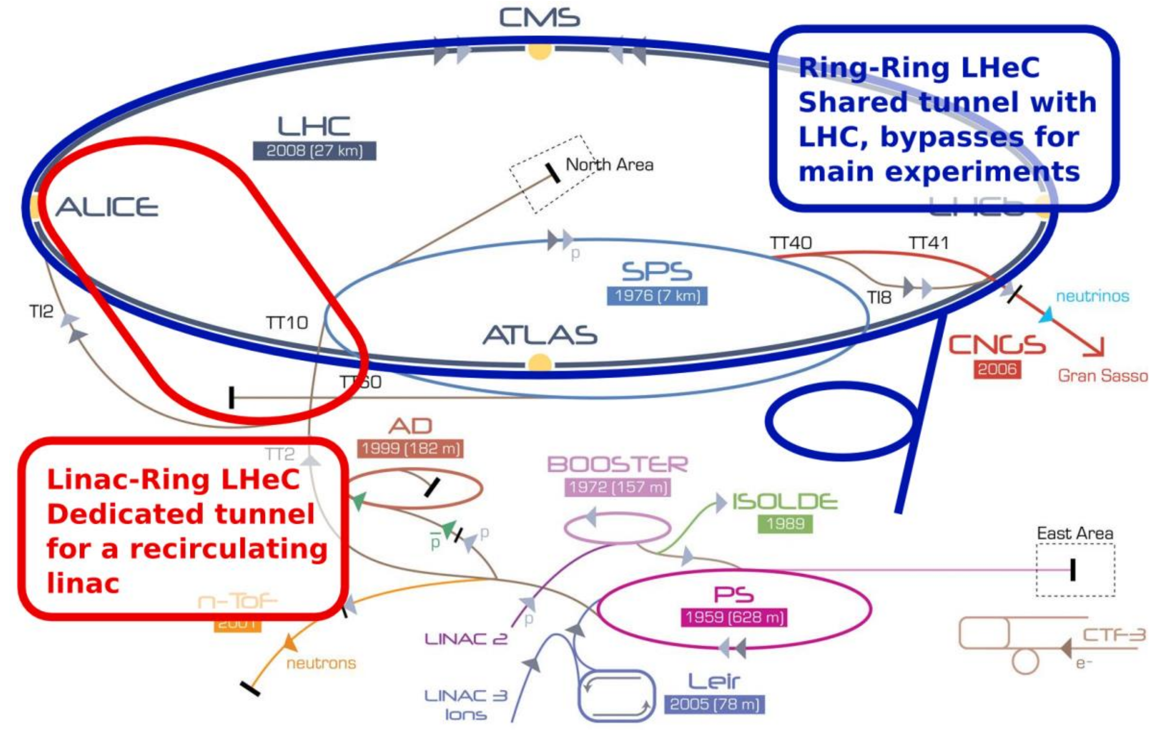
Beam-Beam Effects in Circular Colliders Workshop

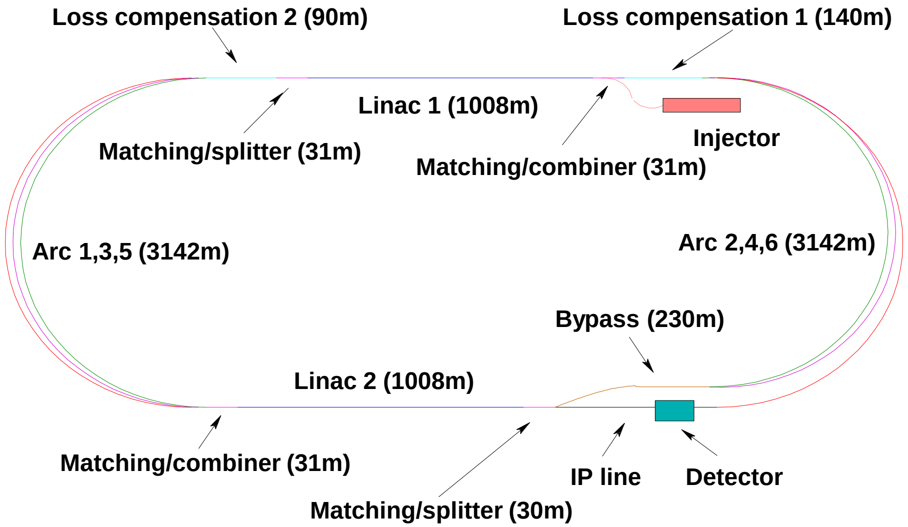
2/6/2018

Outline

- Machine and code background
- Effects on the spent electron beam
- Effects on the recirculated proton beam
- Potential analytical treatments for the proton beam
- Conclusions

LHeC Design





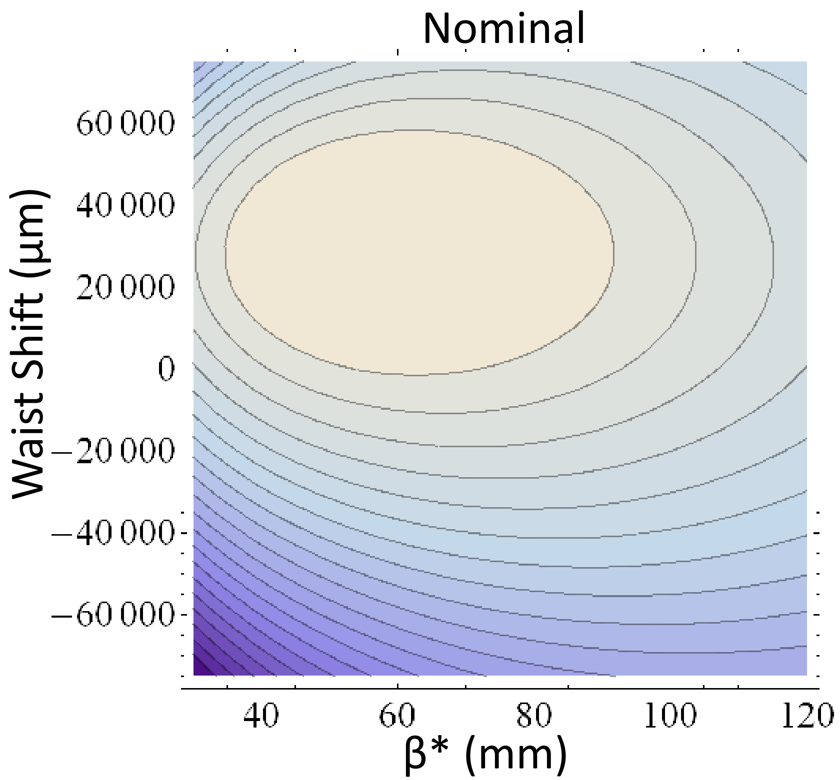
A 3 pass up, 3 pass down recirculating electron linac at 60 GeV top energy. This would interact with the LHC beam at the current ALICE detector.

Beam code and Parameters

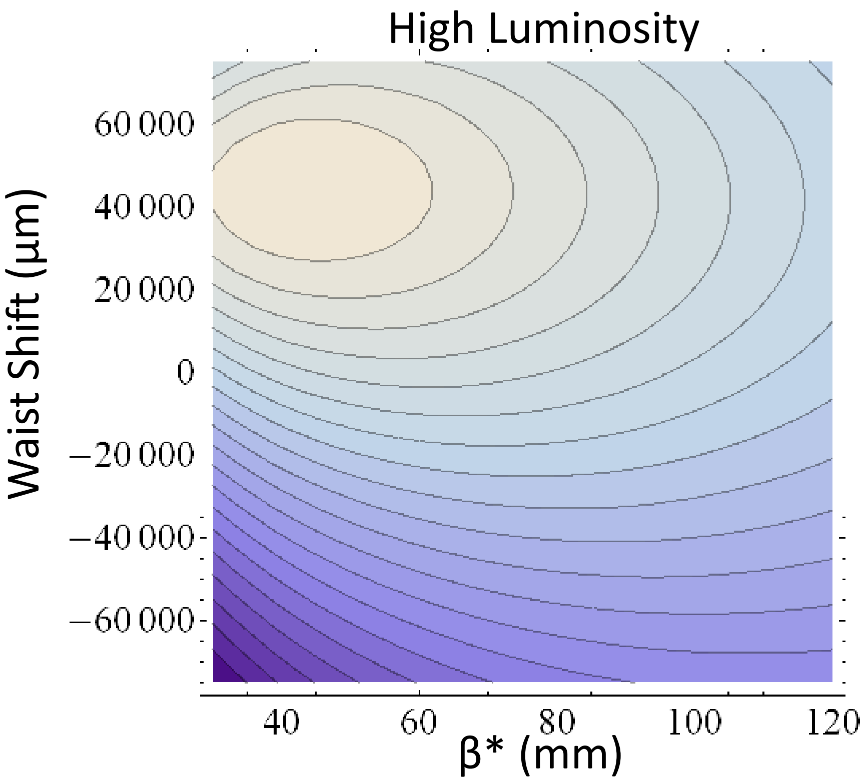
- The code in use is Guinea-Pig, a strong-strong code.

	Value	Nominal Parameters	High Luminosity
Particle number (ion/electron)	10^{10}	17/0.3	22/0.2
β* ion	mm	100	50
β* electron	mm	120	32
$\epsilon_{x,y}$ ion	mm mr	3.75	2
$\epsilon_{x,y}$ electron	mm mr	50	50
Beam-Beam Tune Shift (i/e)		9.61×10^{-5}/0.76	1.20×10^{-5}/0.987
Beam Beam Disruption parameter (i/e)		3.62×10^{-6}/5.99	9.05×10^{-6}/29.1

Waist Shift and Beta Function Optimization



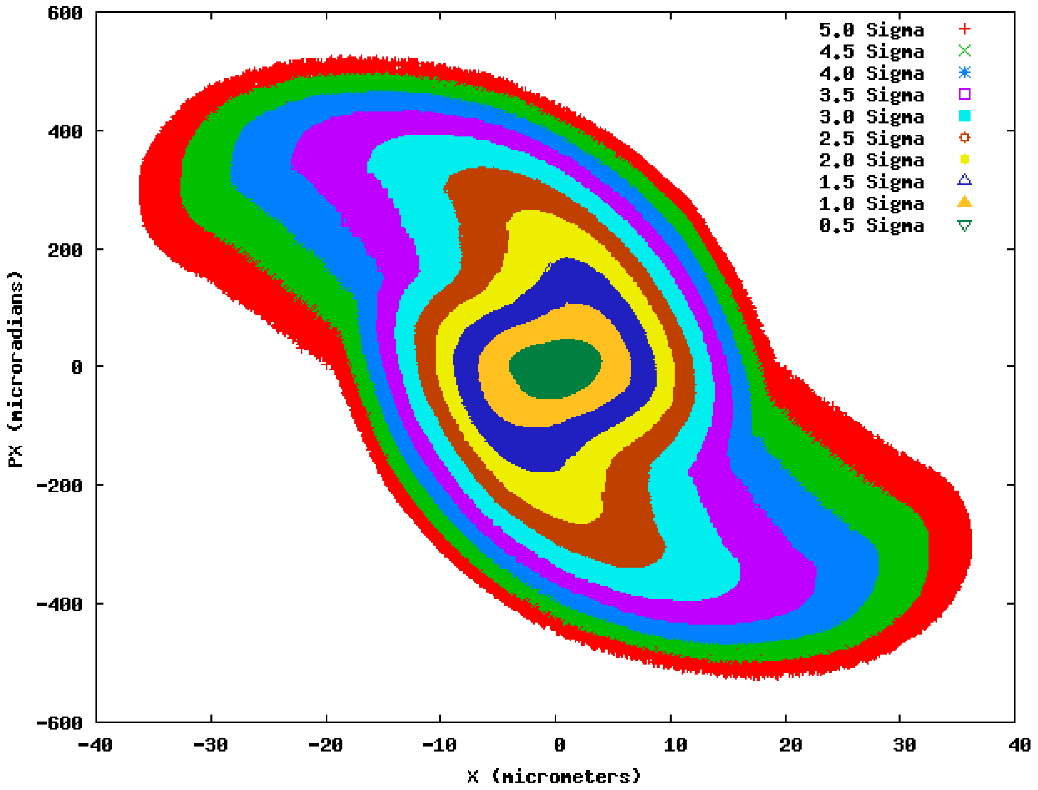
β*~57mm,
WS~30mm,
Luminosity Increase~7.4%



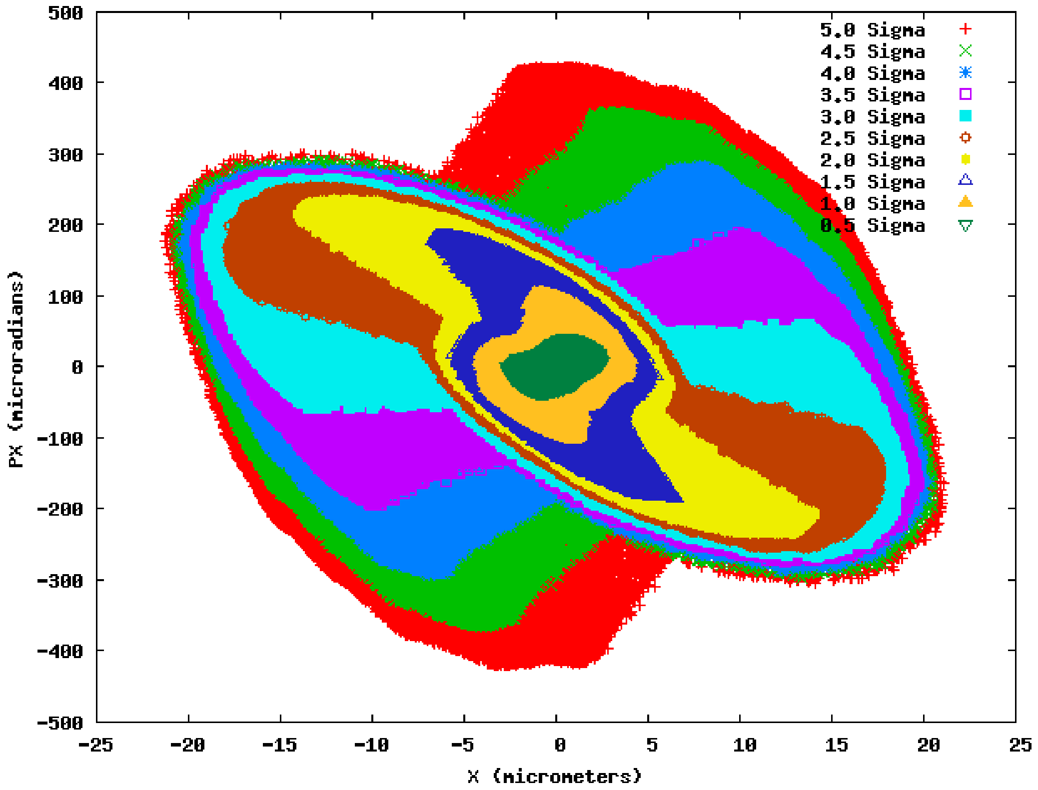
β*~42mm,
WS~45mm,
Luminosity Increase~17.8%

Spent Electron Beam

Nominal Parameters

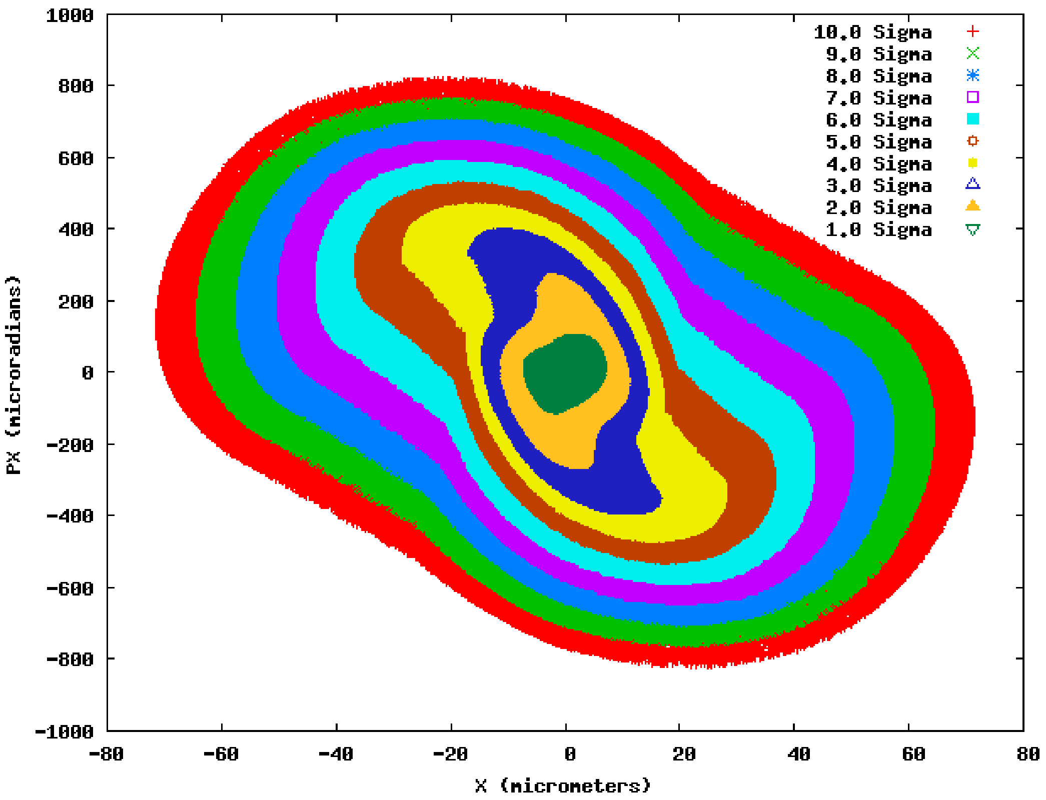


High Luminosity Parameters

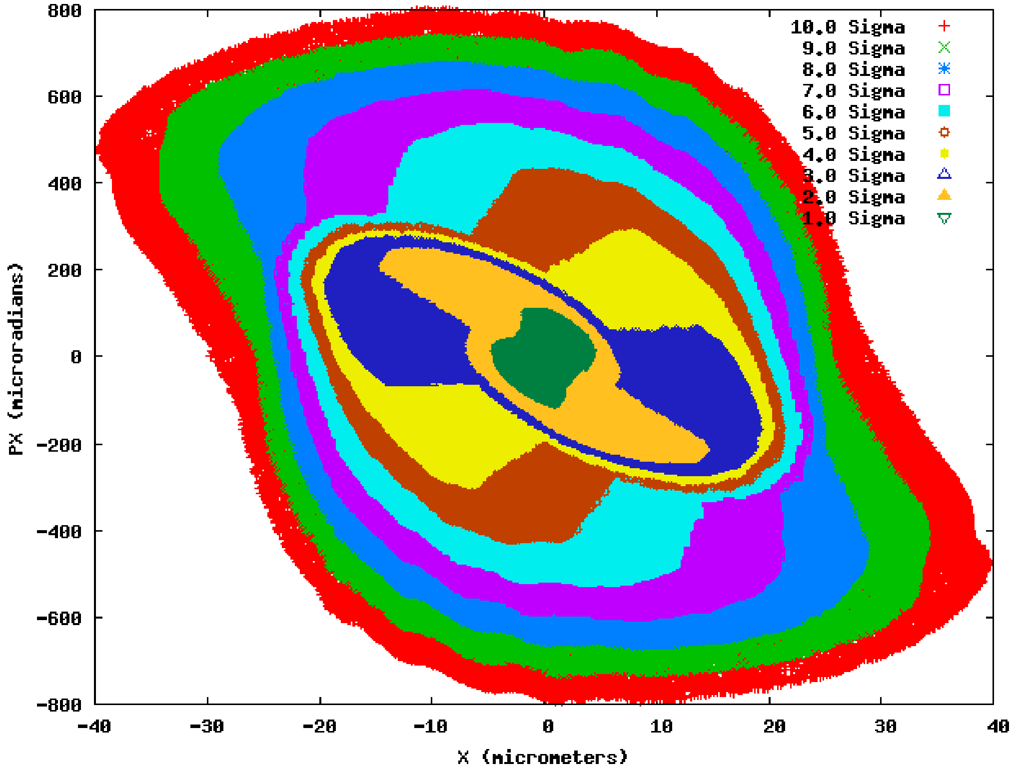


Spent Electron Beam

Nominal Parameters

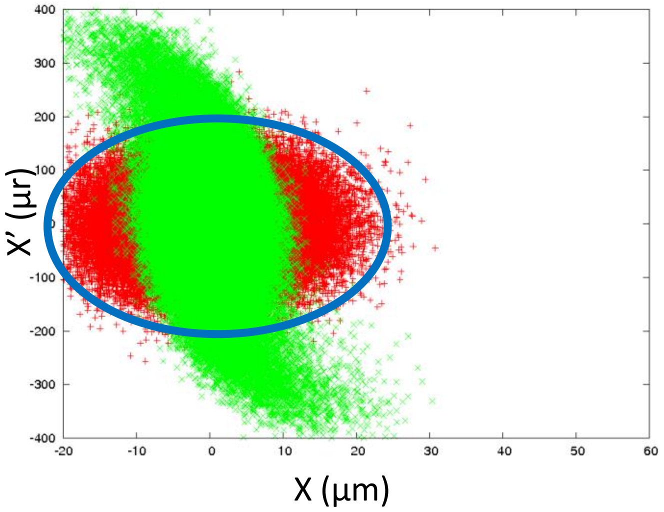


High Luminosity Parameters

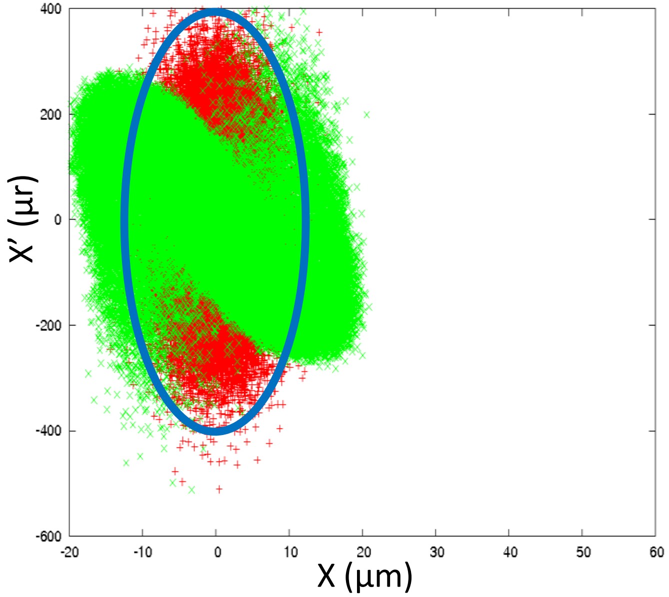


Spent Electron Beam

Nominal Parameters

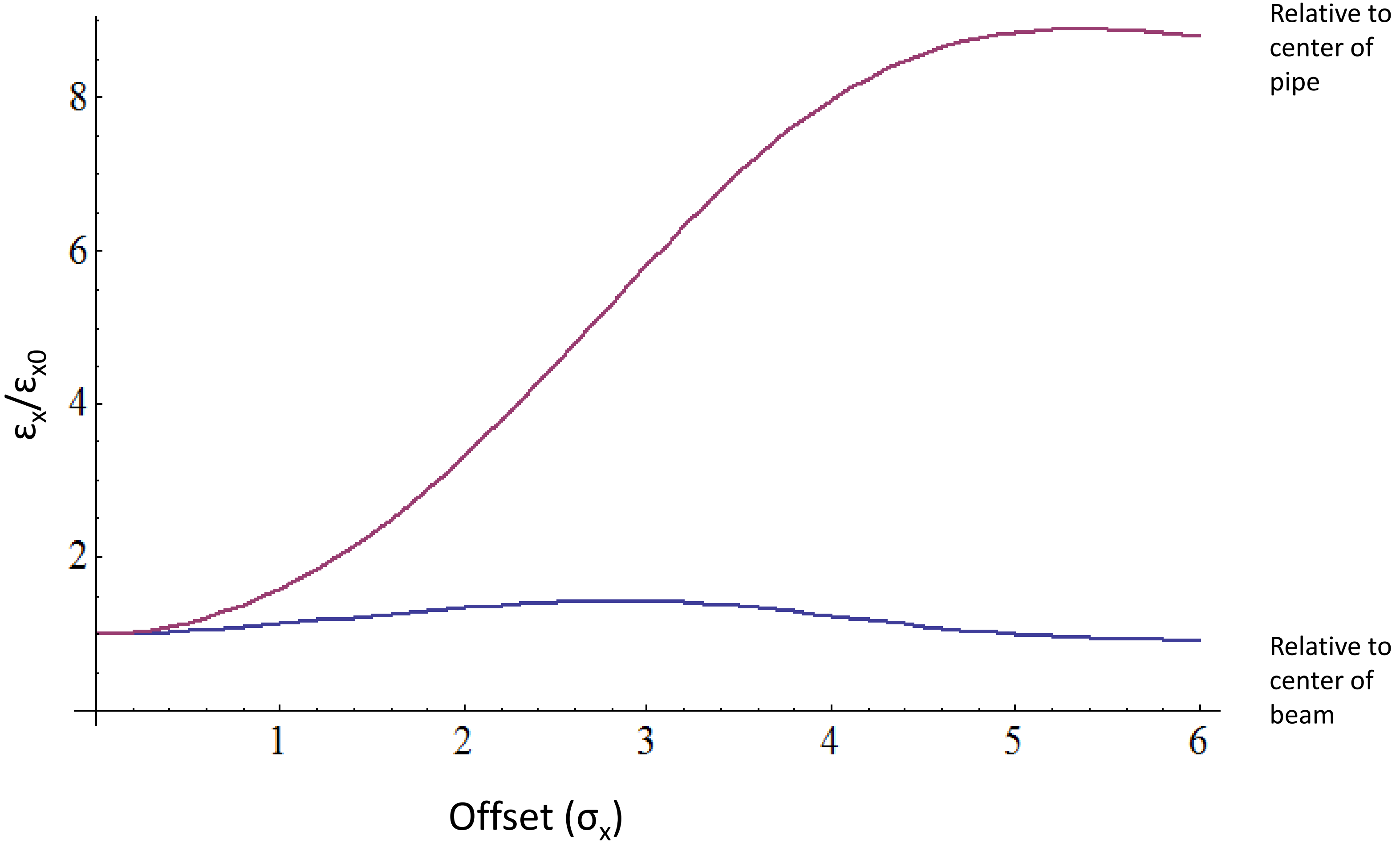


High Luminosity

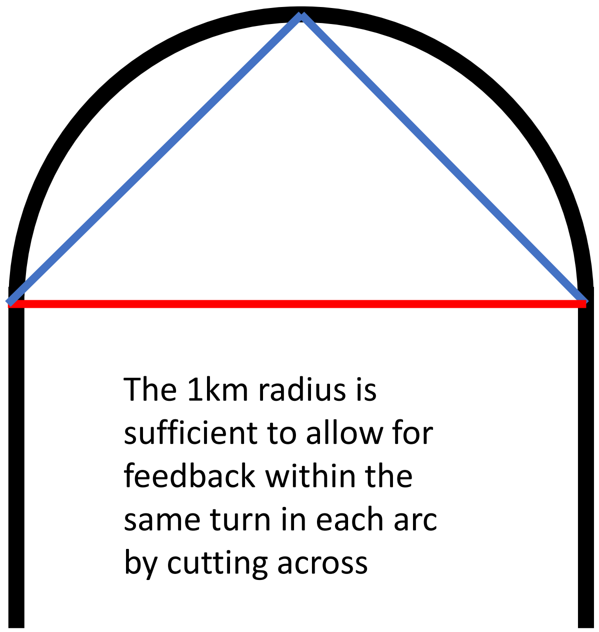


Red particles show the beam without beam-beam effects, green particles show the electron beam with beam-beam effects. Each frame is a single interaction at an increasing offset.

Spent Electron Beam Emittance



Electron Linac (kicker correction system)



n_{kicks}	Δt (nanoseconds)	Δs (meters)
1	3434.351419	1029.592654
2	148.7120948	44.58276442

- Assuming a circular arc, with a depth of 56 m

Using numbers from FONT1 latency is 65ns and voltage is 350 volts

Electron Linac (kicker parameters)

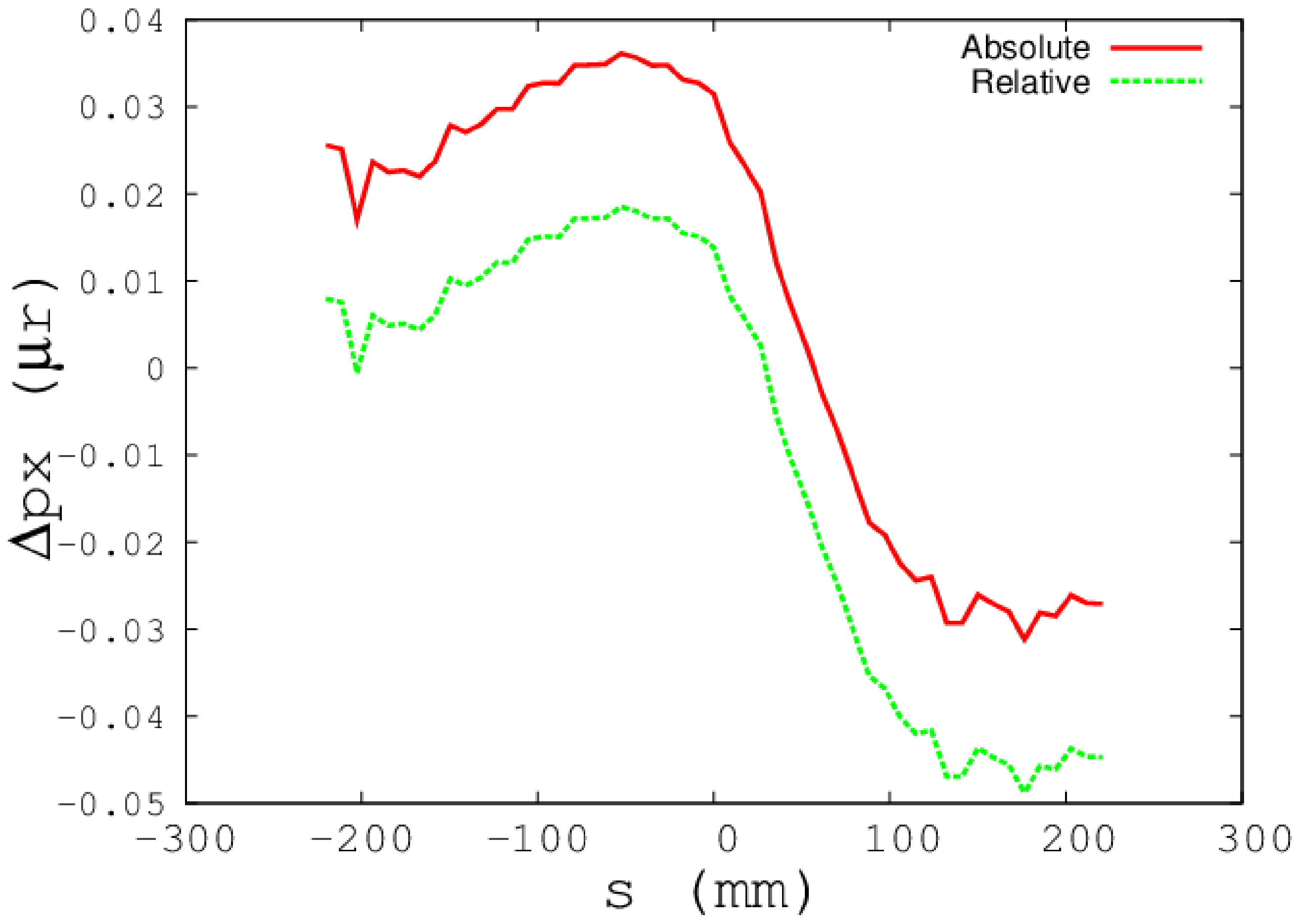
Voltage	350 kicks	2			
energy	max kick μrad	beta	geometric emittance (nm)	σ_{px} (μr)	max offset σ
10.5	1.3333	100	2.43321	4.9328	0.540603
20.5	0.6829	100	1.24631	3.5303	0.386893
30.5	0.4590	25	83.7691	5.7886	0.158594
40.5	0.3457	50	63.0856	3.5521	0.194636
50.5	0.2772	50	50.5935	3.1810	0.174303
60	0.2333	50	42.5830	2.9183	0.159909

Using one set of kicks at the opposite side, a 1σ offset can be corrected with a voltage of ~4400V

Long Term Beam Evolution

- The beam beam interaction is modeled using Guinea-Pig
- This is combined with a linear 1-turn map of the LHC for the protons, and a new beam for the electrons.

Emittance Growth from Transverse Offsets



Predicting the Emittance Growth Rate

- If we assume that the kicks given to the beam constitute a change to the momentum only, i.e. Δp_x then we can determine an approximate growth rate.

$$\Delta\varepsilon_n = \frac{1}{2}(\beta\gamma)\beta^* < \Delta p_x{}^2 > \frac{\sigma_{jitter}^2}{\sigma_x^2}.$$

- The next step is to determine $<\Delta p_x{}^2>$.

Predicting Emittance Growth Rates

We can use the round beam approximation of the Basetti-Erskine formula,

$$\Delta p_x = -\frac{2Nr_{e/p}}{\gamma}\frac{(e^{\frac{-x^2}{2\sigma_x^2}} - 1)}{x}$$

With

$$\sigma_x(z) = \sqrt{\varepsilon(\beta^* + \frac{z^2}{\beta^*})}$$

To solve,

$$< \Delta {p_x}^2 >= (\frac{2Nr_p}{\gamma})^2 \frac{\int \frac{(e^{\frac{-x^2}{2\sigma_x^2}} - 1)^2 e^{\frac{-z^2}{2\sigma_z^2}}}{x^2} dz}{\int e^{\frac{-z^2}{2\sigma_z^2}} dz}$$

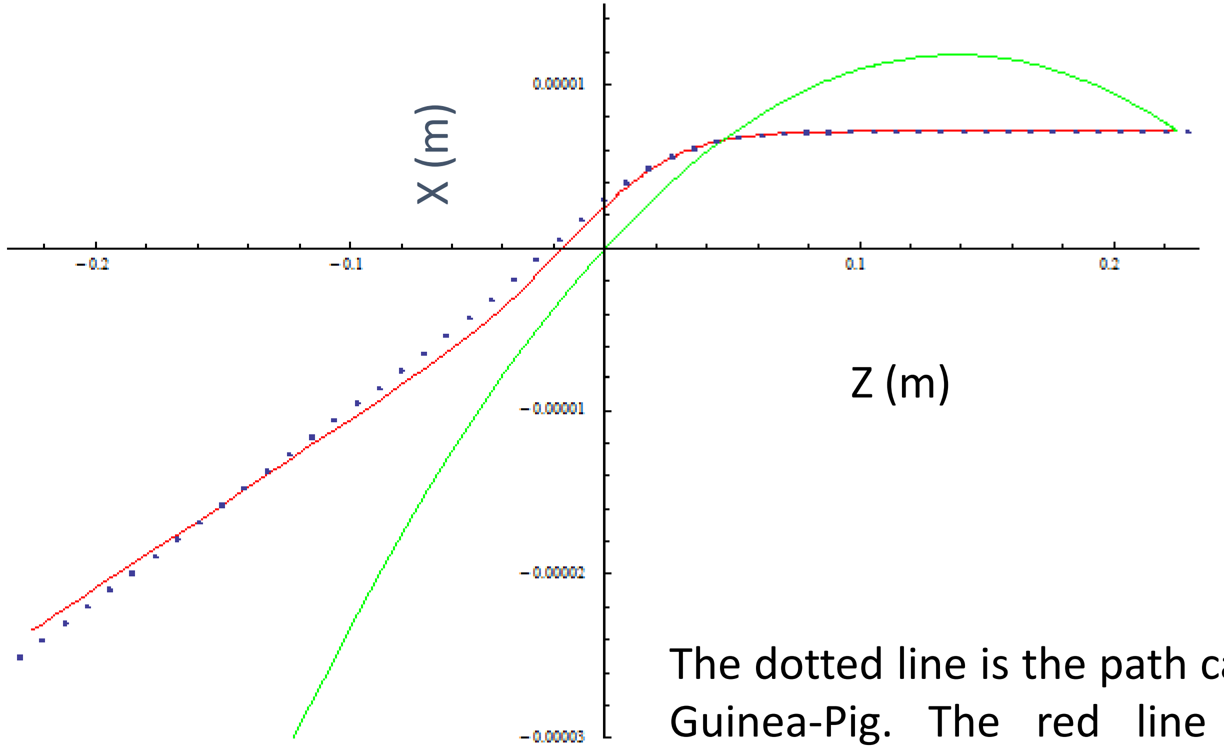
- Now we need to determine X(z)

Predicting Emittance Growth Rates

- The path through the proton beam can be tracked using Guinea-Pig, and can also be calculated directly using a numerical solver and the Basetti-Erskine formula.
- Other approximations can be used to try to create an analytic formula for the growth rate.
- One ansatz tested is,

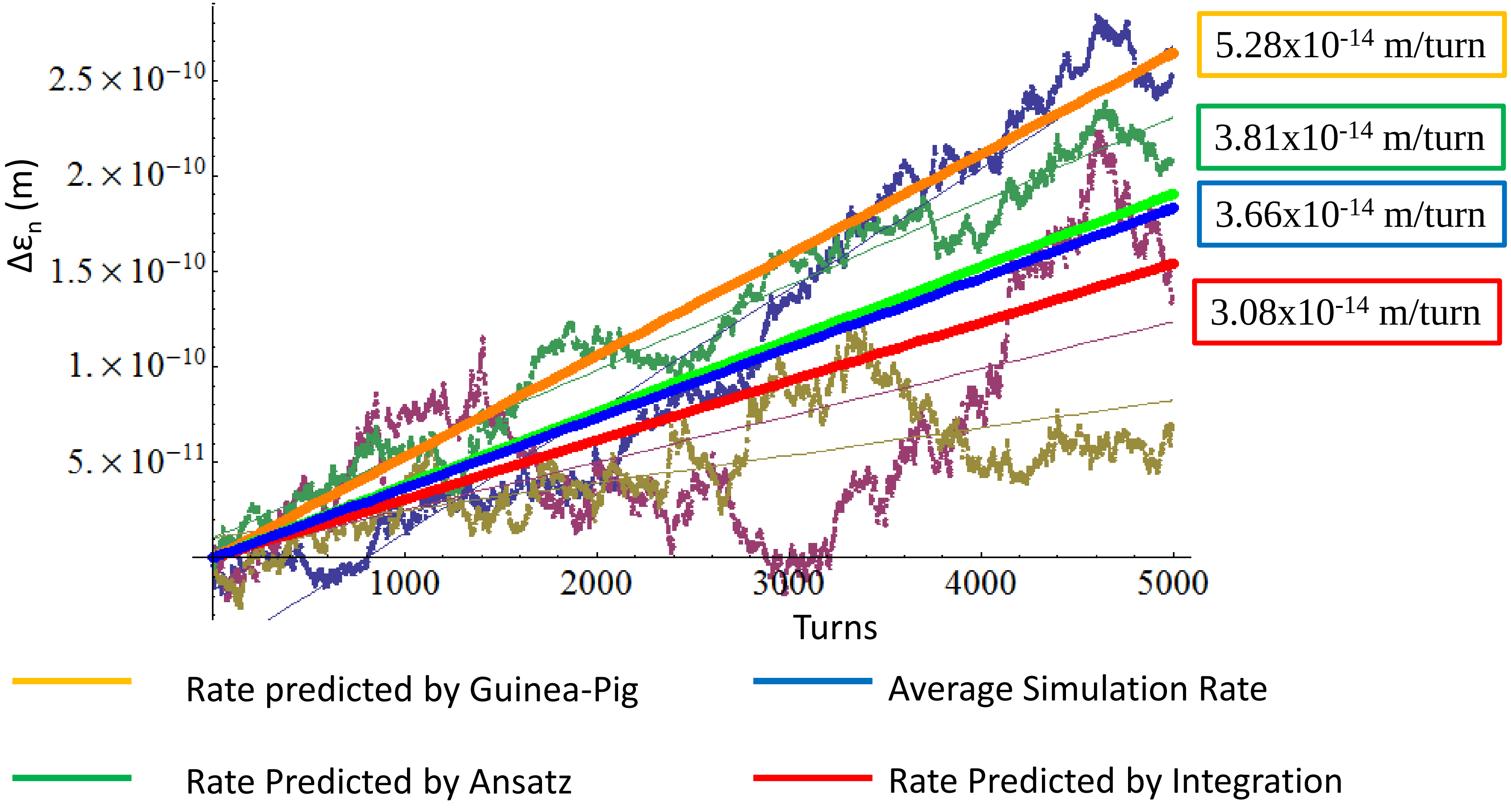
$$x(z) = Az^2 + Bz \qquad A = \frac{\varphi - \frac{r_0}{z_0}}{2z_1 - z_0} \qquad B = \frac{2r_0\frac{z_1}{z_0} - z_0\varphi}{2z_1 - z_0}$$

Path Through Proton Beam



The dotted line is the path calculated with Guinea-Pig. The red line is the path integrated directly, and the green is the ansatz

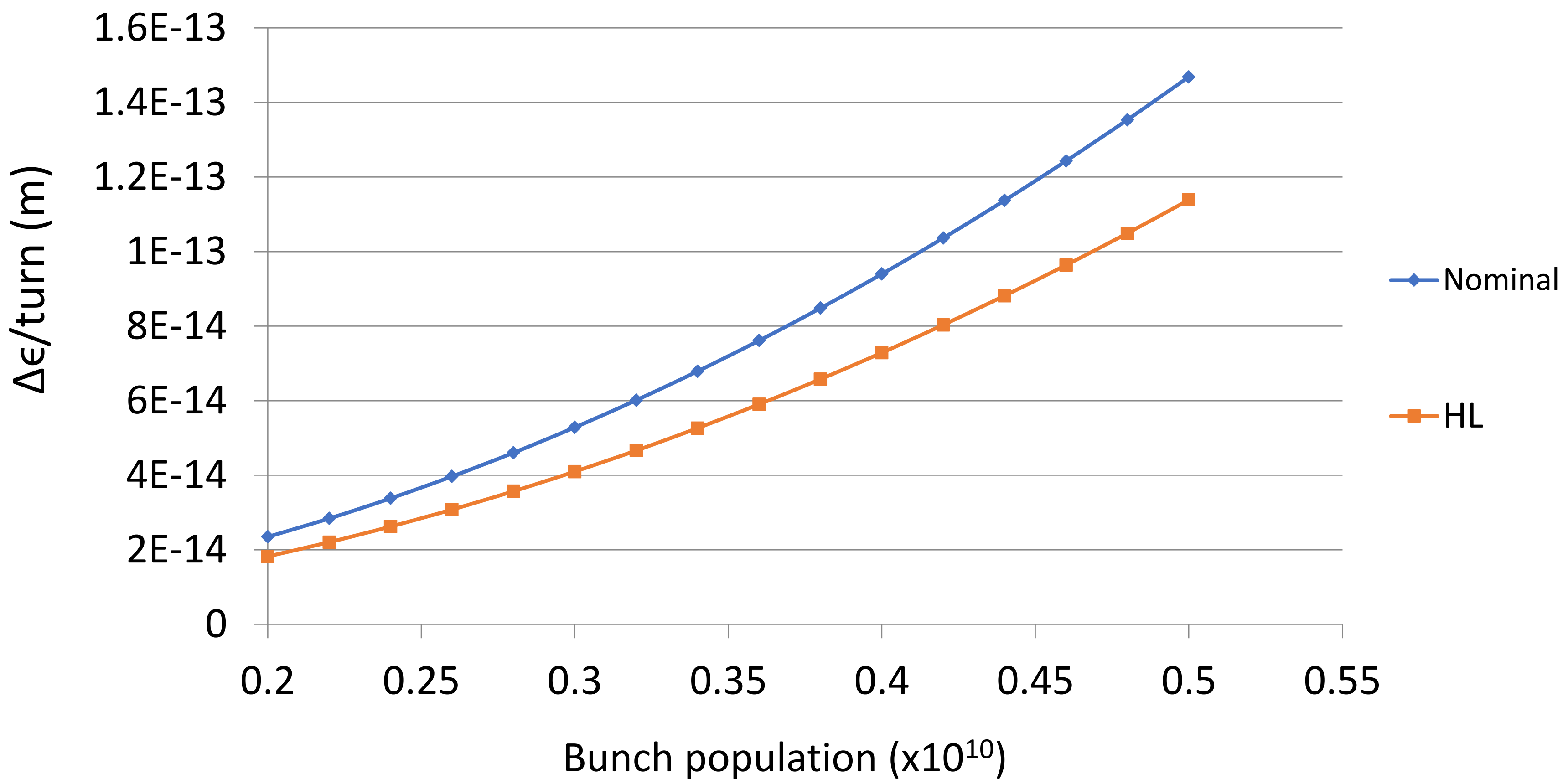
Predicted Growth Rates



Emittance Growth Rates and Correction Tolerances

	Time Growth Rate (m/s)	Doubling time (s)	Ɛ0 (m)	Jitter tolerance
Simulations Average	1.01667E-08 $x(\sigma_{jitter}/\sigma_x)^2$	86400	0.00000375	6.53%
Guinea-Pig	1.46667E-08 $x(\sigma_{jitter}/\sigma_x)^2$	86400	0.00000375	5.44%
Numerically Integrated	8.55556E-09 $x(\sigma_{jitter}/\sigma_x)^2$	86400	0.00000375	7.12%
Ansatz	1.05833E-08 $x(\sigma_{jitter}/\sigma_x)^2$	86400	0.00000375	6.40%

Growth Rate with Charge (LHeC)



Calculated for a 20%σ offset jitter

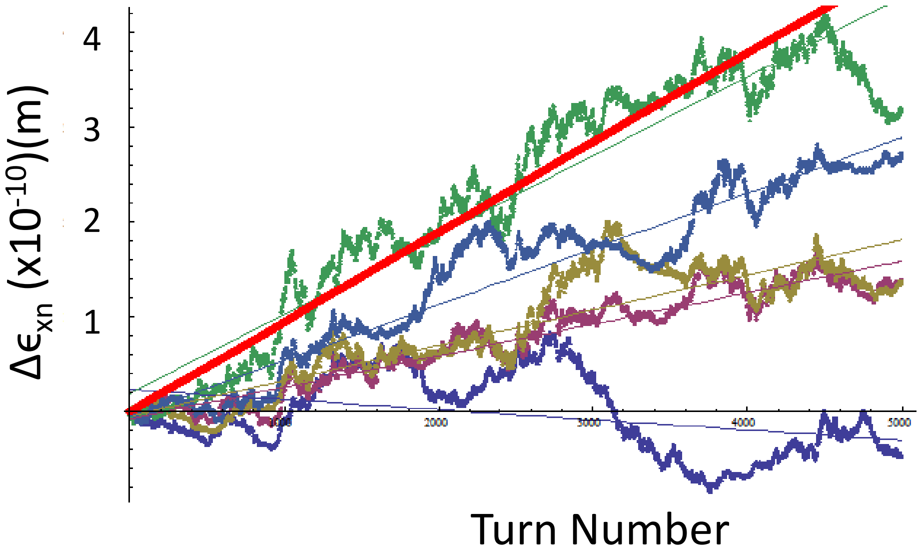
Other Possibilities

- FCC is modeled using the 100km FCC-hh design with 25 ns bunch spacing
- Electron beam is the LHeC linac

		Nominal		Ultimate	
		Proton	Electron	Proton	Electron
Energy	GeV	50000	60	50000	60
β^*	mm	1100	109	300	9.692
$\epsilon_{x,yn}$	µm	2.2	50	0.7333	50
σ_z	mm	75	0.3	75	0.3
Particle number	10^{11}	1	0.03	1	0.03
Beam-Beam Tune Shift		.000164	0.45	.000426	0.382

Multipass Emittance Growth FCC-he

Nominal Parameters

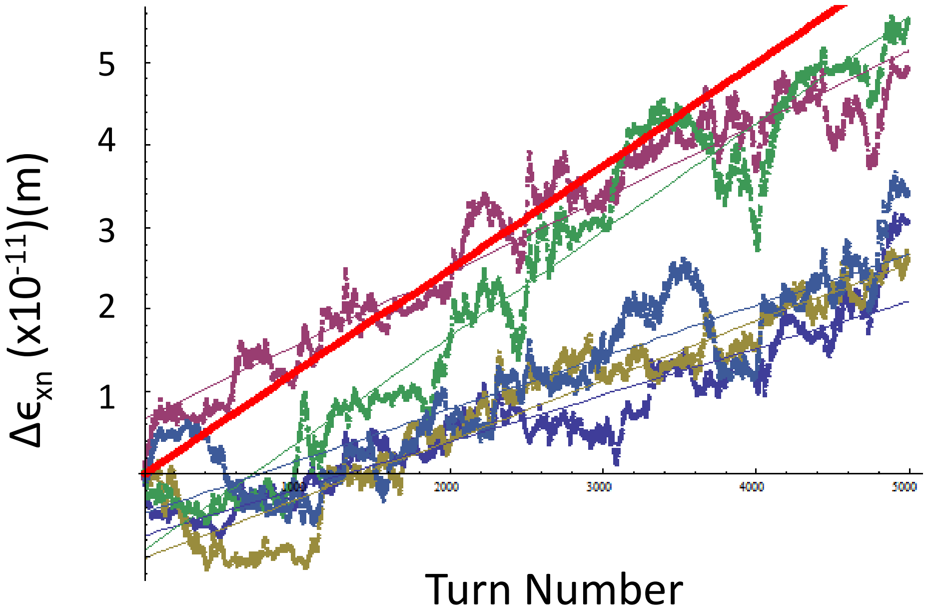


Predicted rate 9.470x10^{-14}
Mean calculated rate 4.046x10^{-14}

$\Delta\epsilon_{xn}/\Delta t$=7.095x10^{-9}($\sigma_{jitter}/\sigma_x$)^{2}m/s

Doubling time 1 day σ_{jitter}/σ_x=5.99%

Ultimate Parameters



Predicted rate 1.249x10^{-14}
Mean calculated rate 8.212x10^{-15}

$\Delta\epsilon_{xn}/\Delta t$=9.36102x10^{-10}($\sigma_{jitter}/\sigma_x$)^{2}m/s

Doubling time 1 day σ_{jitter}/σ_x=9.5%

Assumptions for an Analytical Approach

- One beam's position an be considered constant (Reference beam) while the other is colliding with it (colliding beam). (i.e. weak-strong)
- Both beams are round transversely (σ_x=σ_y)
- They have Gaussian profiles (Basetti-Erskine an be used)
- When calculating the kick on the stationary (or ”Rest”) beam, the colliding beam an be modeled as a Gaussian disk of charge acting on a line of charge at the centroid.

Determining Angular Spread

- We take the differential equation for the beams,

$$r''(z) + \frac{2Nr_{particle}}{\gamma\sqrt{2}\sigma_z} f(r(z), \sigma_r) e^{-(z/\sigma_z)^2} = 0.$$

- And using the Beam-beam disruption parameter,

$$D_{x,y} = \frac{2Nr_{particle}\sigma_z}{\gamma\sigma_{x,y}(\sigma_x + \sigma_y)},$$

- We can reduce it to,

$$r''(z) + \frac{2D_C}{\sqrt{2}} f(r(z), \sigma_r) e^{-z^2} = 0$$

Note: the subscripts refer to which beam "sees" the given factor. D_C is the disruption parameter experienced by the colliding beam.

Determining Angular Spread (cont'd)

- By casting the equations of motion in D-coordinates the angular spread can be calculated with,

$$< \Delta p_r^2 >= 4D_R^2 \left(\frac{\sigma_{r_C}}{\sigma_{z_C}}\right)^2 N(D_C)$$

- Where $N(D_C)$ is a dimensionless factor determined by D_C. For non-hourglass beams it becomes,

$$N(D_C) = \frac{\int \frac{(e^{-\frac{r(z_0;D_C)^2}{2}}-1)^2}{r(z_0;D_C)^2} e^{-2z_0^2} dz_0}{\int e^{-2z_0^2} dz_0}$$

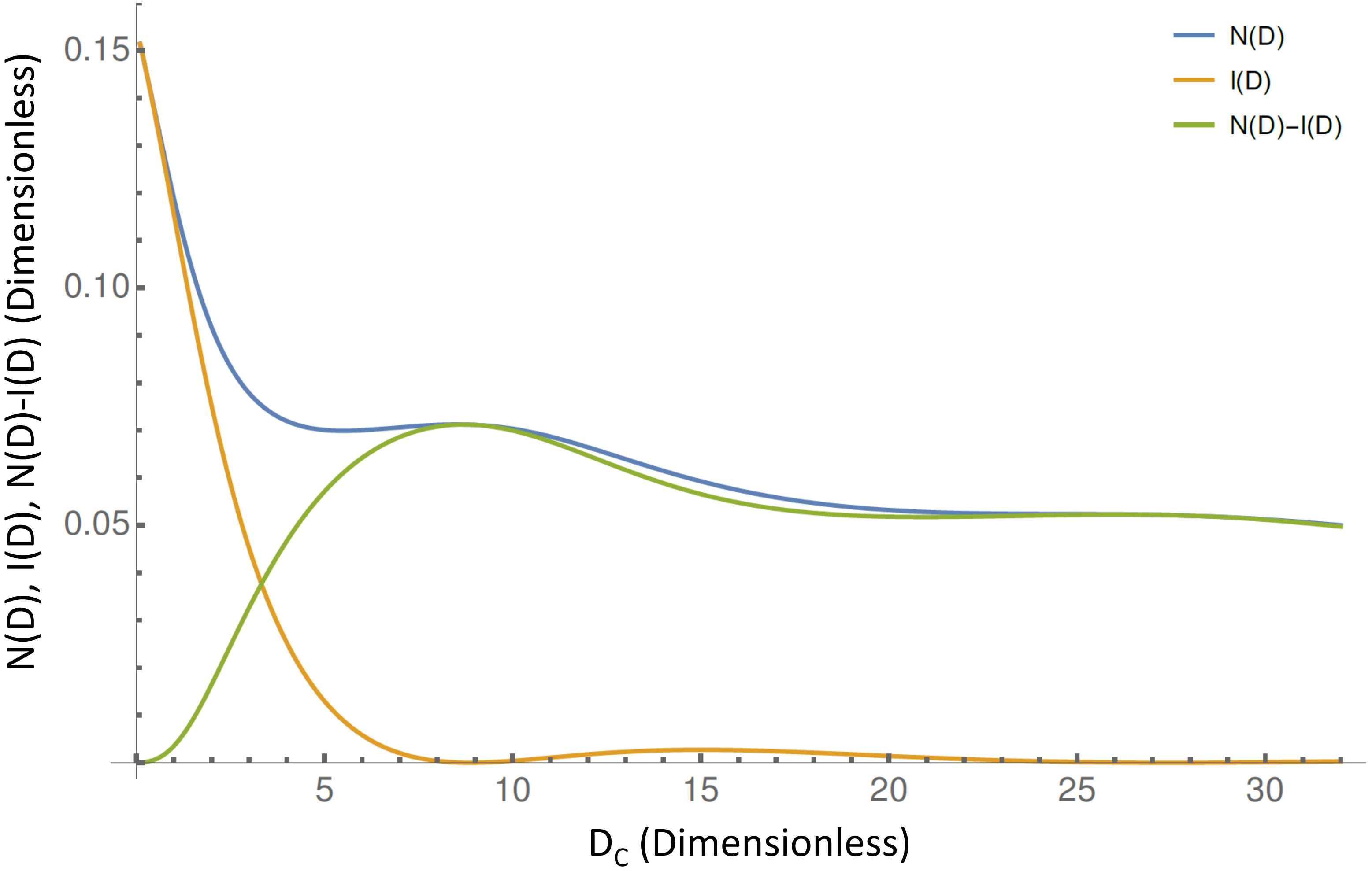
Determining Angular Spread (cont'd)

- If we want to compensate for the overall angular kick given to the reference beam we subtract it out,

$$N(D_C) = \frac{\int \frac{\left(e^{-\frac{r(z_0;D_C)^2}{2}} - 1\right)^2}{r(z_0;D_C)^2} e^{-2z_0^2} dz_0}{\int e^{-2z_0^2} dz_0}$$

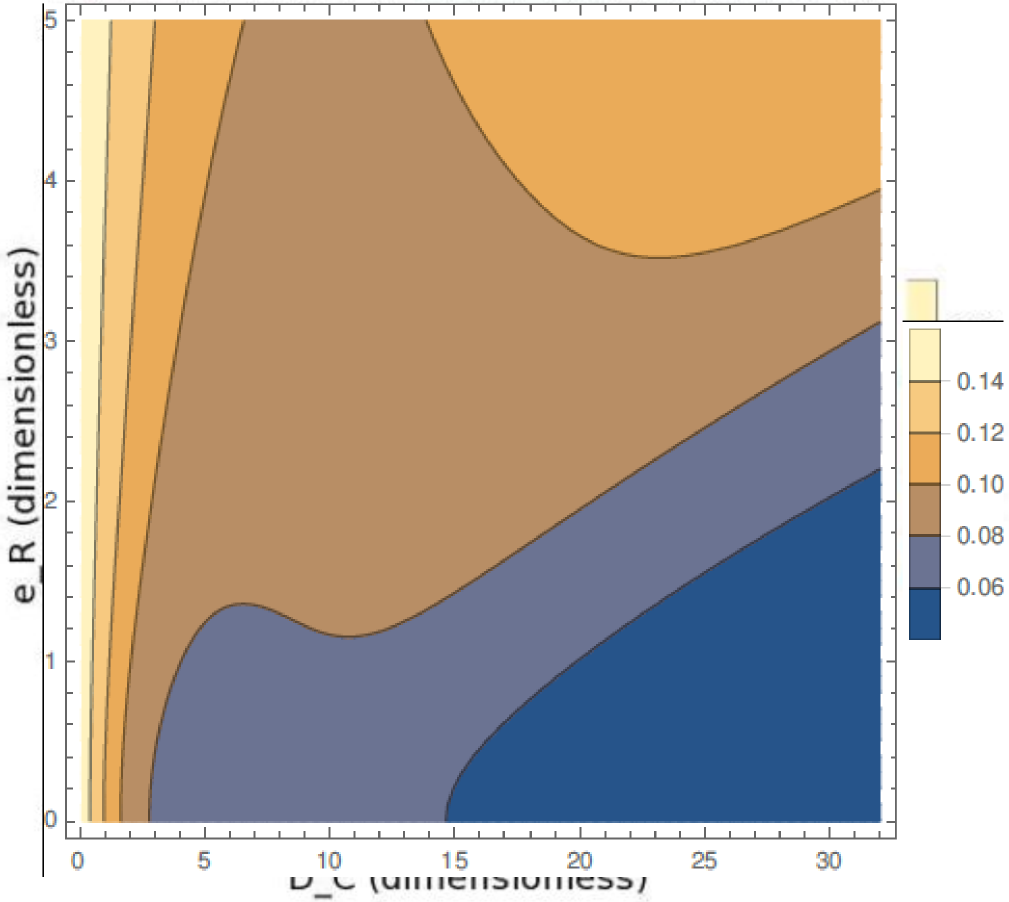
$$I(D_C) = \frac{\left(\int \frac{\left(e^{-\frac{r(z_0;D_C)^2}{2}} - 1\right)}{r(z_0;D_C)} e^{-2z_0^2} dz_0\right)^2}{\int e^{-2z_0^2} dz_0}$$

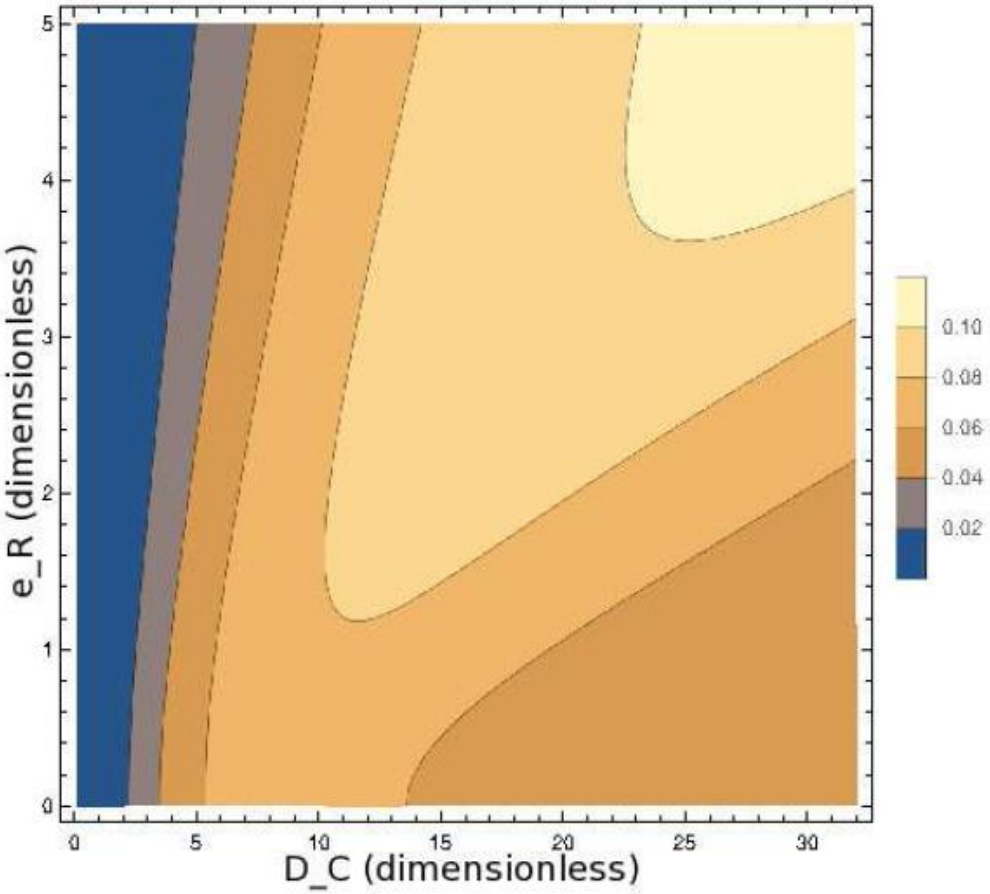
Determining Angular Spread (cont'd)



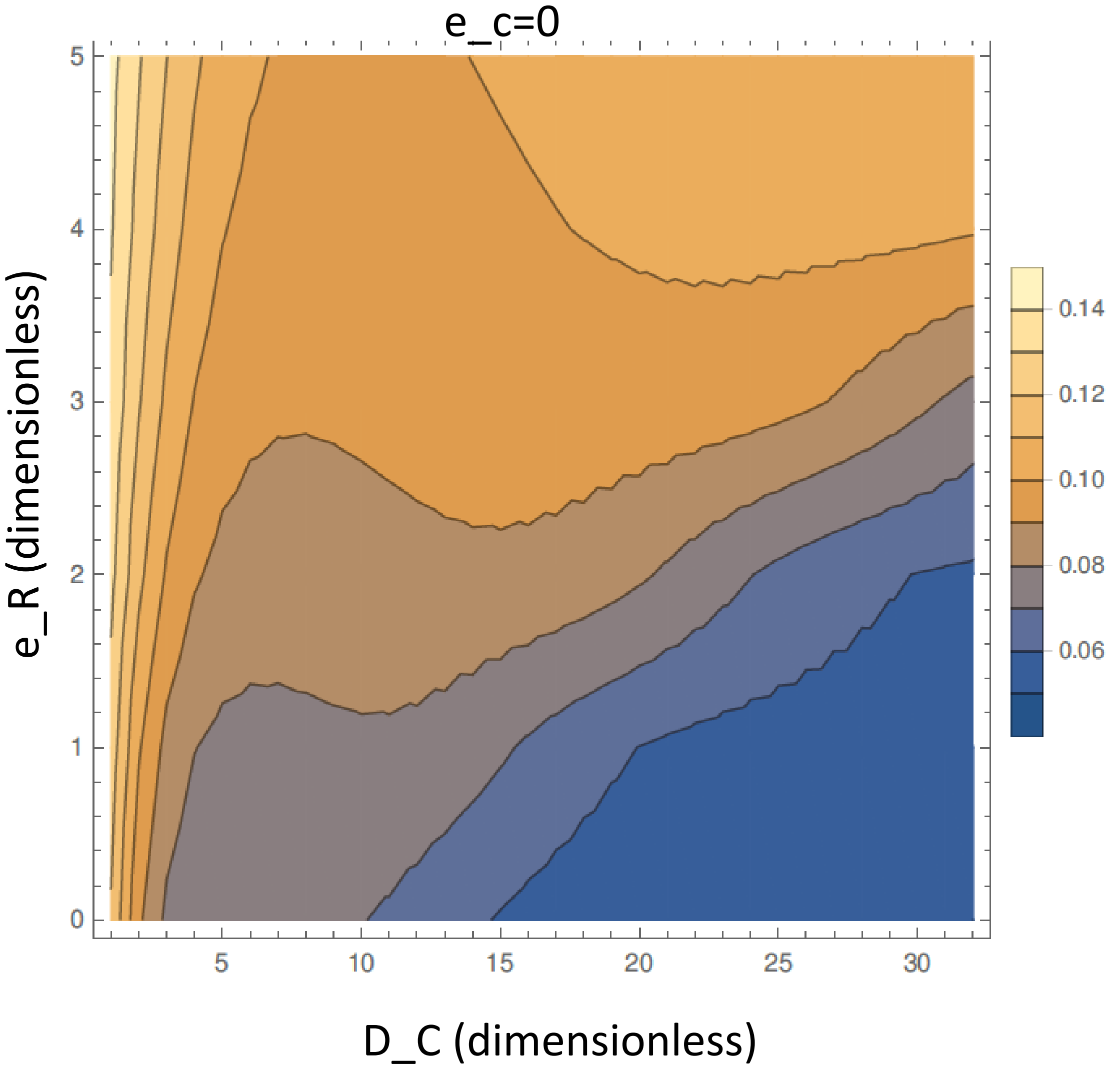
What about the Hourglass?

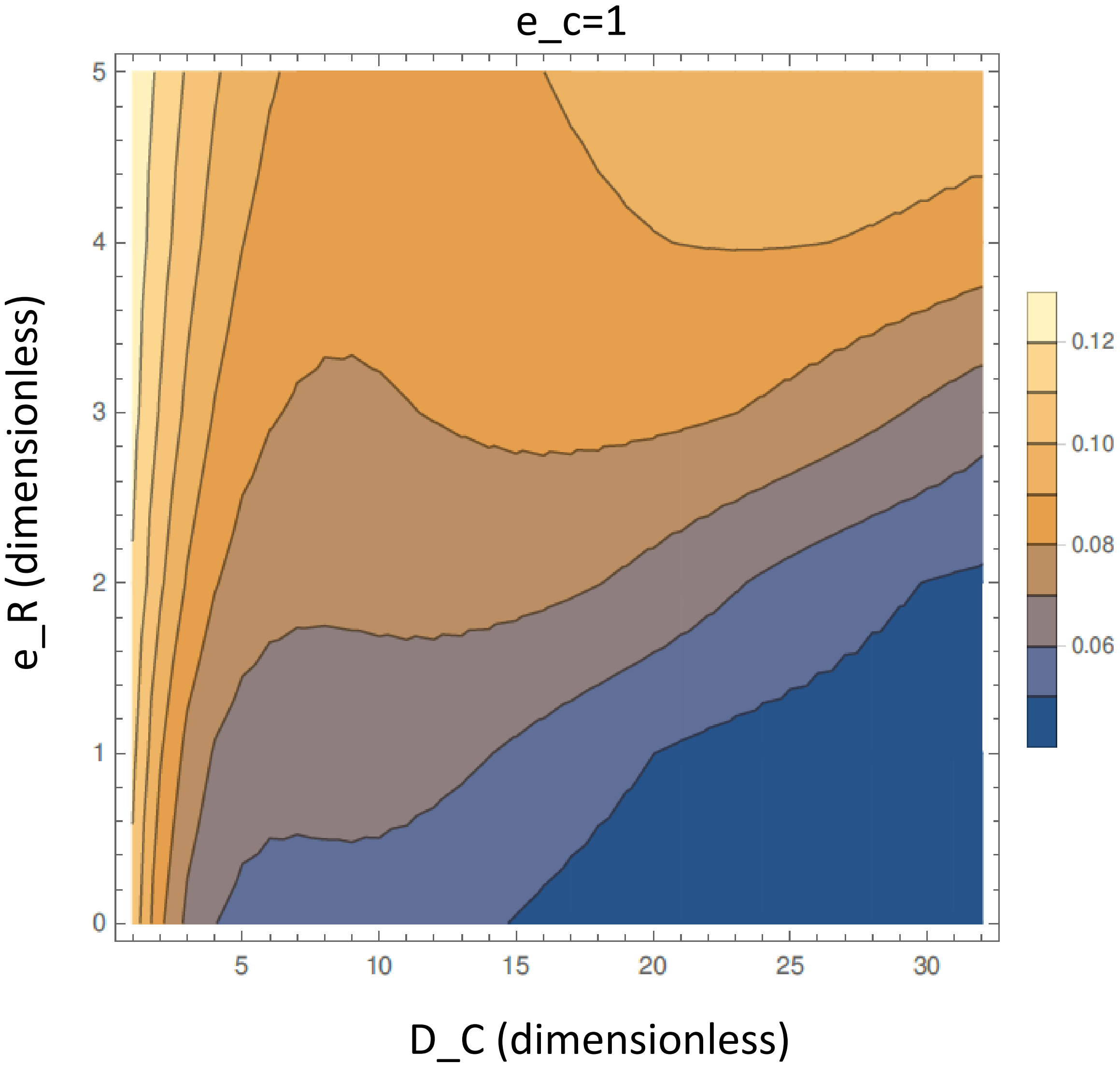
- If we assume a factor $e=\sigma_z/\beta^*$ for the stationary beam it will alter the path of the colliding beam,





Second Hourglass





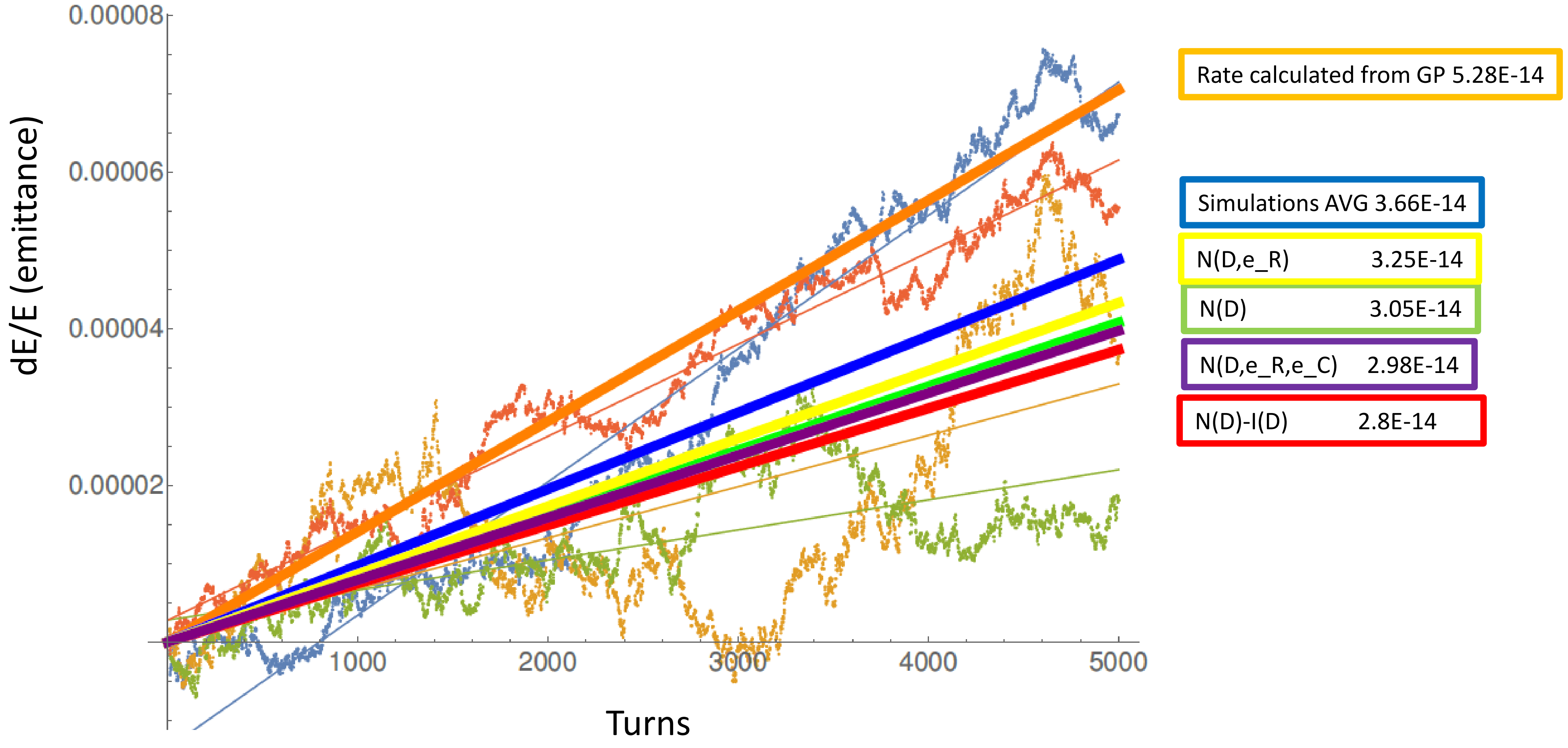
Roundup

$$\Delta\epsilon_n = 2\beta^*(\beta\gamma)D_R^2\left(\frac{\sigma_{rC}}{\sigma_{zC}}\right)^2\left(\frac{\sigma_{jitter}}{\sigma_{rR}}\right)^2 E(D_c, e_R, e_C)$$

$$E(D_c, e_R, e_C) = \mathrm{N}(D_c, e_R, e_C) - k\mathrm{I}(D_c, e_R, e_C)$$

With choices of e_R e_C as appropriate. If no hourglass is needed in a given system, then the appropriate e_R and/or e_C would be set to zero. K is either 1 or 0 depending on whether the overall motion of the beam is damped or not. If a machine has perfect correction systems, then k=1. If no corrections are given then k=0.

Examples



Example is the LHeC nominal parameters with 4 separate random seeds using Guinea Pig with a linear particle advancing code.

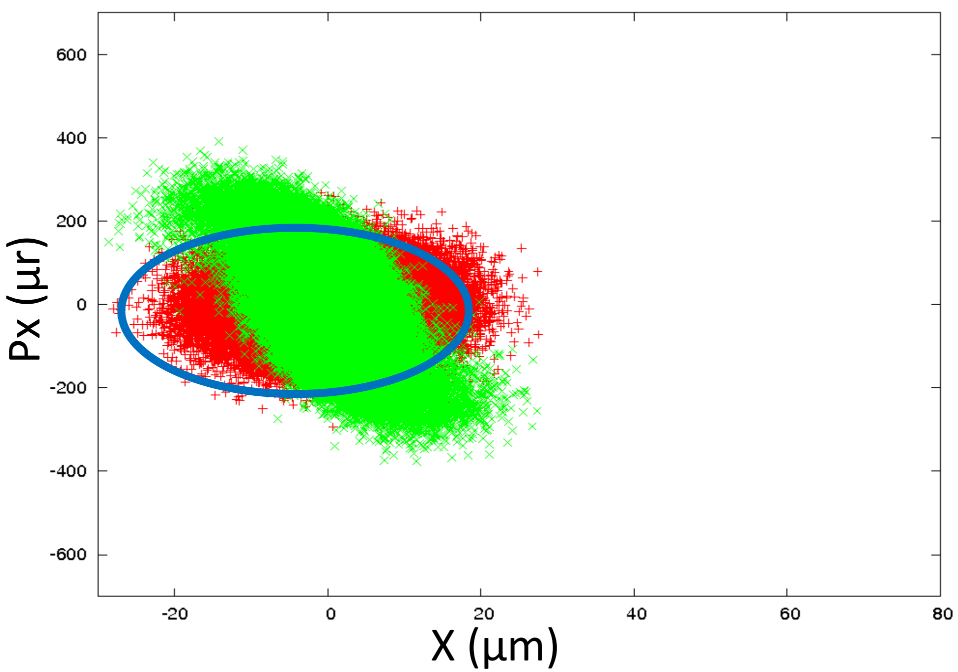
Conclusions

- The LHeC exists in a regime where the beam-beam effect can affect the luminosity of the beam.
- As long as the return arcs of the recirculating linac remain linear, and proper damping is applied, then the electron beam should be energy recoverable.
- The beam-beam effect can cause an emittance growth in the proton beam, but it is manageable with appropriate beam damping.
- The nature of the parameter sets for the LHeC can allow an analytic understanding of the growth of the beam based on its parameters.

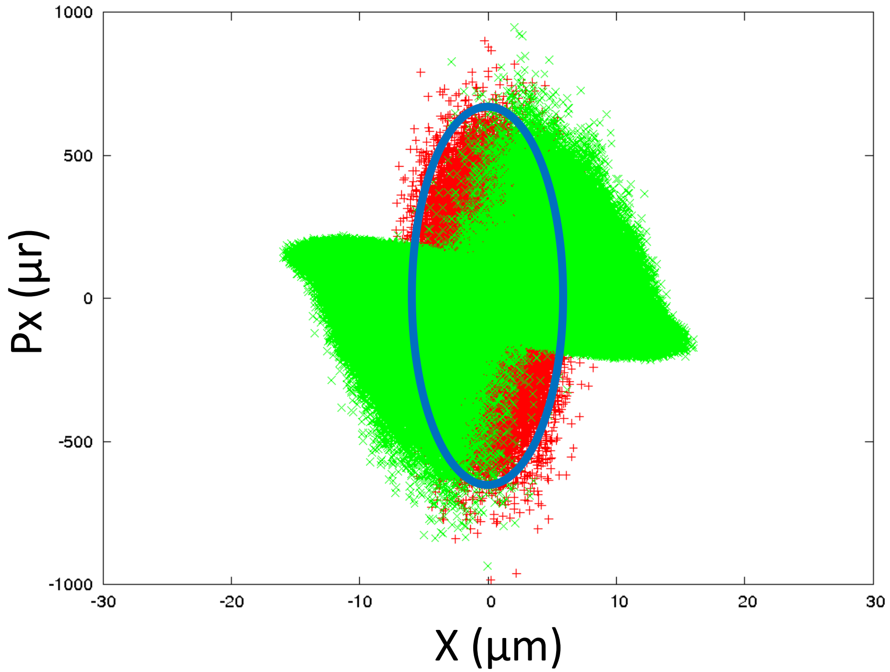
Thank You for Your Attention

Spent Electron Beam (FCC-he)

Nominal Parameters



Ultimate Parameters



The green data represent the spent beam after beam-beam focusing, the red shows the electron beam without the beam-beam effect for comparison. The blue circle shows the position of the proton beams, the beam is offset from 0 to 6σ in 0.1σ intervals.