The Beam-Beam Effect and Its Consequences for High Energy e-p Colliders such as the LHeC and FCC-he

Edward Nissen

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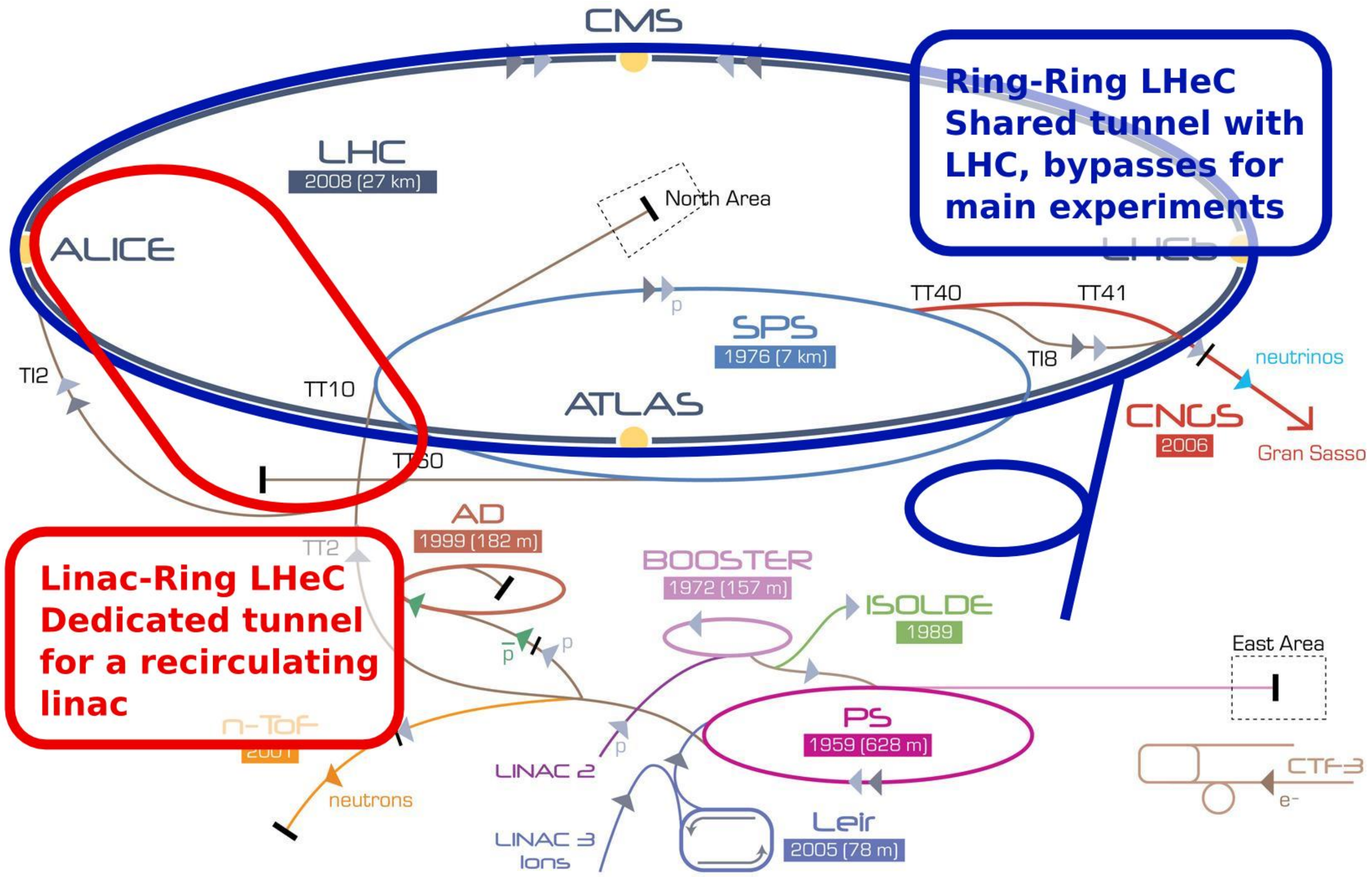
- LHeC and FCC-he projects
- The software in question
- Initial single pass studies of the beam-beam effect
- The effects of waist shift on the beam, and the luminosity
- Emittance growth measurements
- Spent electron beam concerns
- Beam steering solutions
- Conclusions

The LHeC Accelerator:
An energy recovery linac in a racetrack configuration



A. Valloni

The LHeC Accelerator:
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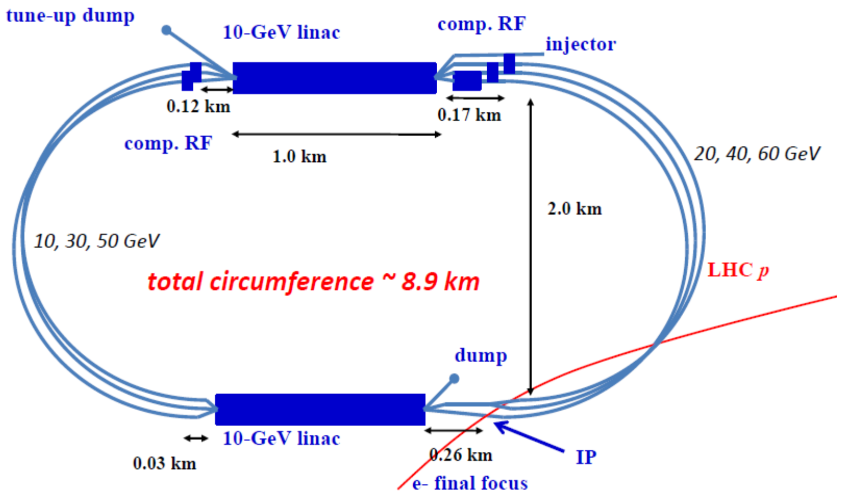
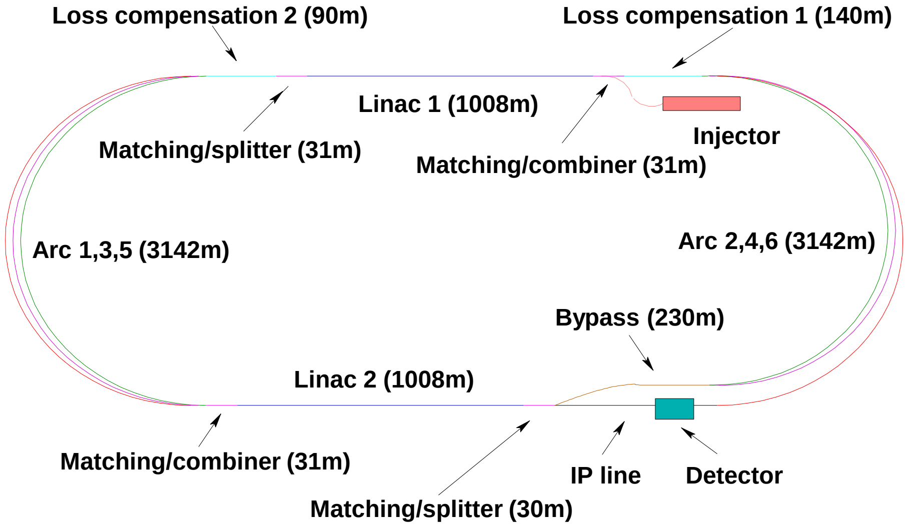




RECIRCULATOR COMPLEX

1. 0.5 Gev injector
2. A pair of SCRF linacs with energy gain 10 GeV per pass
3. Six 180° arcs, each arc 1 km radius
4. Re-accelerating stations to compensate energy lost by SR
5. Switching stations at the beginning and end of each linac
6. Matching optics
7. Extraction dump at 0.5 GeV

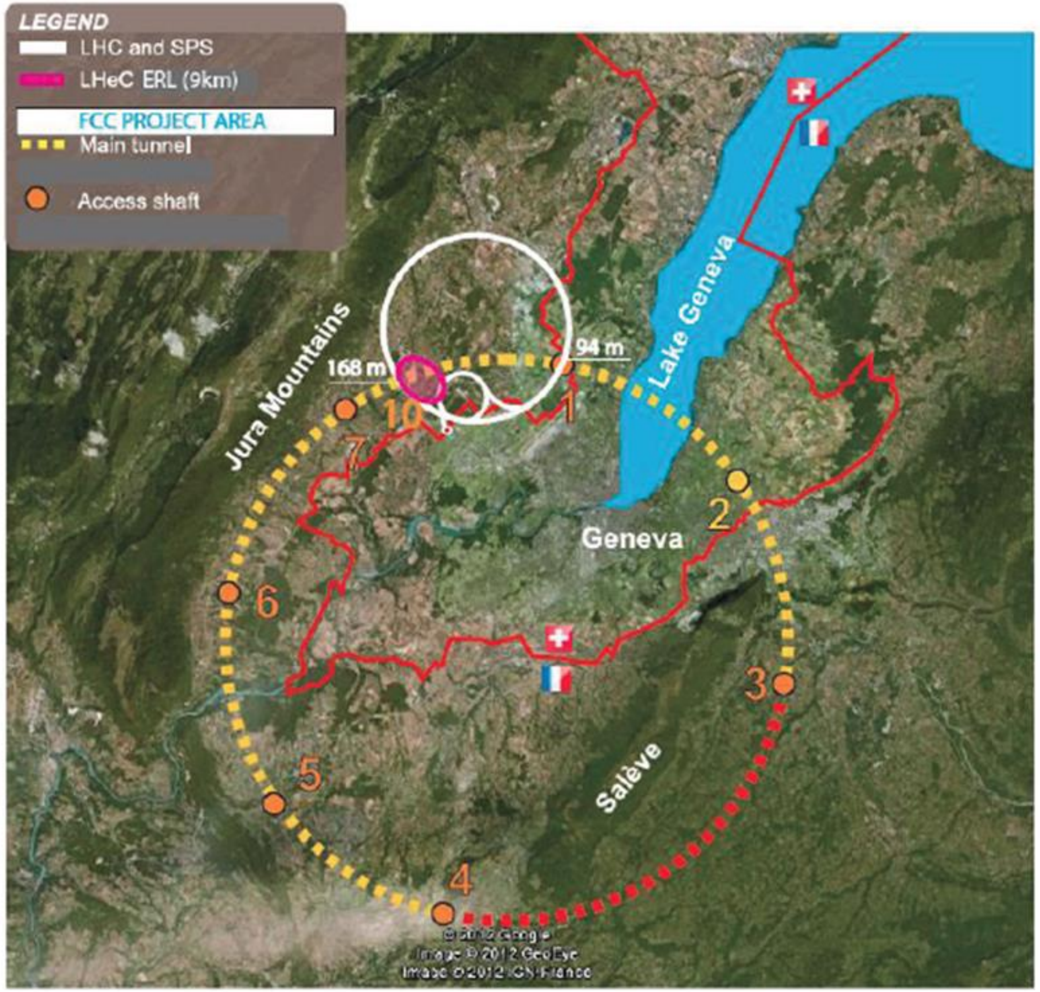
A. Valloni

LHeC (parameter list)

	Value	Nominal Parameters	High Luminosity
Particle Energy (ion/electron)	GeV	7000/60	7000/60
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 D-Parameter (i/e)		3.62×10^{-6}/5.99	9.05×10^{-6}/29.1

FCC project (Future Circular Collider)

- Proposed 100km circumference ring that would either collide protons at a c.m. energy of 100 TeV (FCC-hh), or electrons at a variety of c.m. energies between 91 GeV for Z production and 350 GeV for tt production (FCC-ee).
- The work here refers to the FC-he which would use the LHeC linac with the FCC-hh ring for ep collisions.



Parameter sets

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

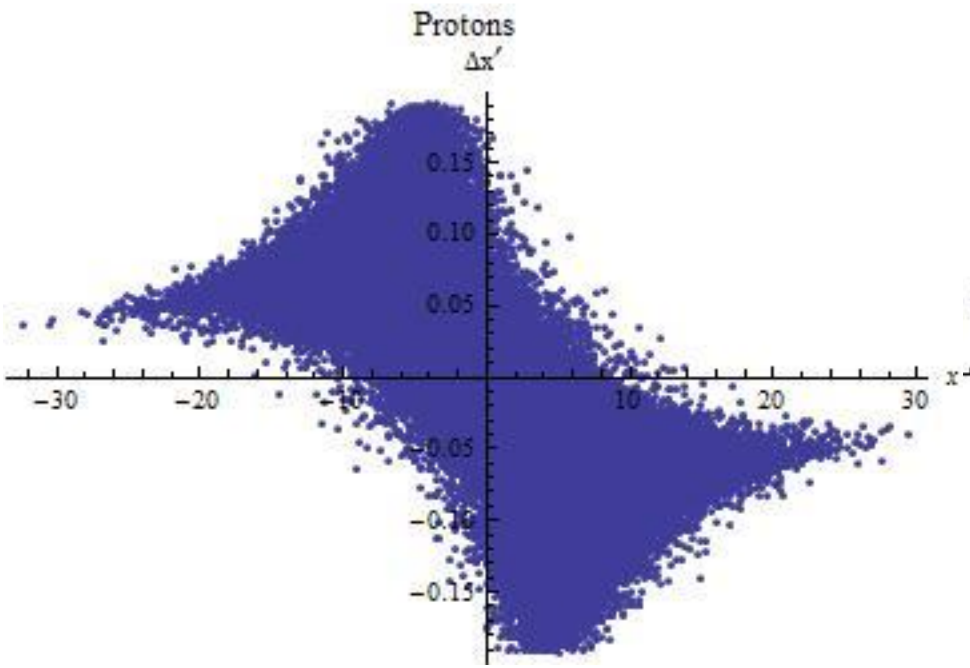
		Nominal		Ultimate	
		Proton	Electron	Proton	Electron
Energy	GeV	50000	60	50000	60
β^*	mm	1100	109	300	9.692
$\epsilon_{x,yn}$	µm	2.2	50	0.7333	50
σ_z	mm	75	0.3	75	0.3
Particle number	10^{11}	1	0.03	1	0.03
B-B Tune Shift		.000164	0.45	.000426	0.382
D-Parameter		5.6×10^{-7}	3.89	5.35×10^{-6}	37.2

Software in use

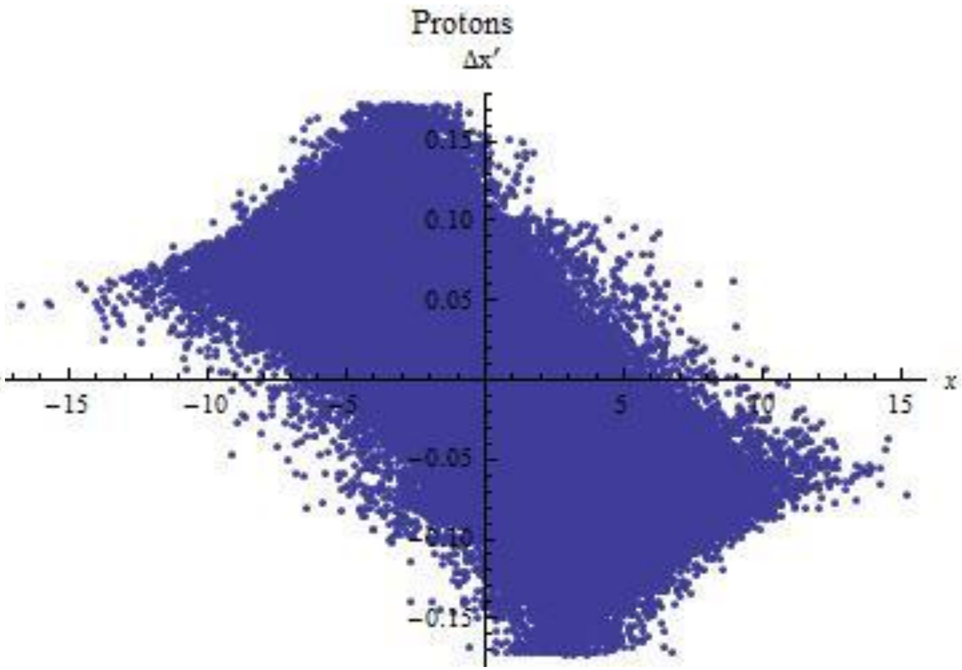
- Guinea-Pig (C version) beam-beam code.
- Uses a strong-strong algorithm to calculate beam-beam interactions

Transverse Effects

Nominal



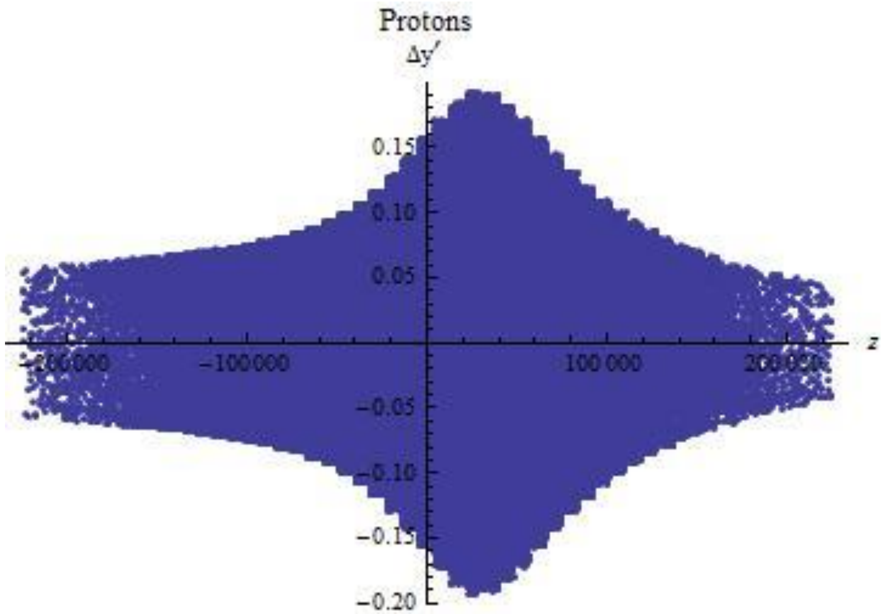
High Luminosity



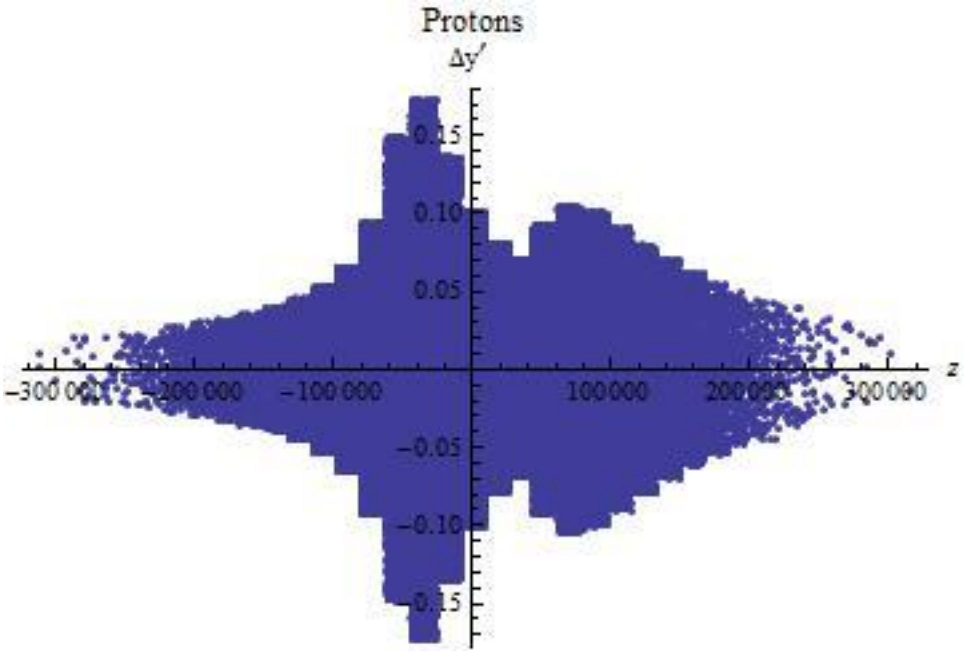
Difference between outgoing x’ with and without beam-beam effects

Longitudinal Effects

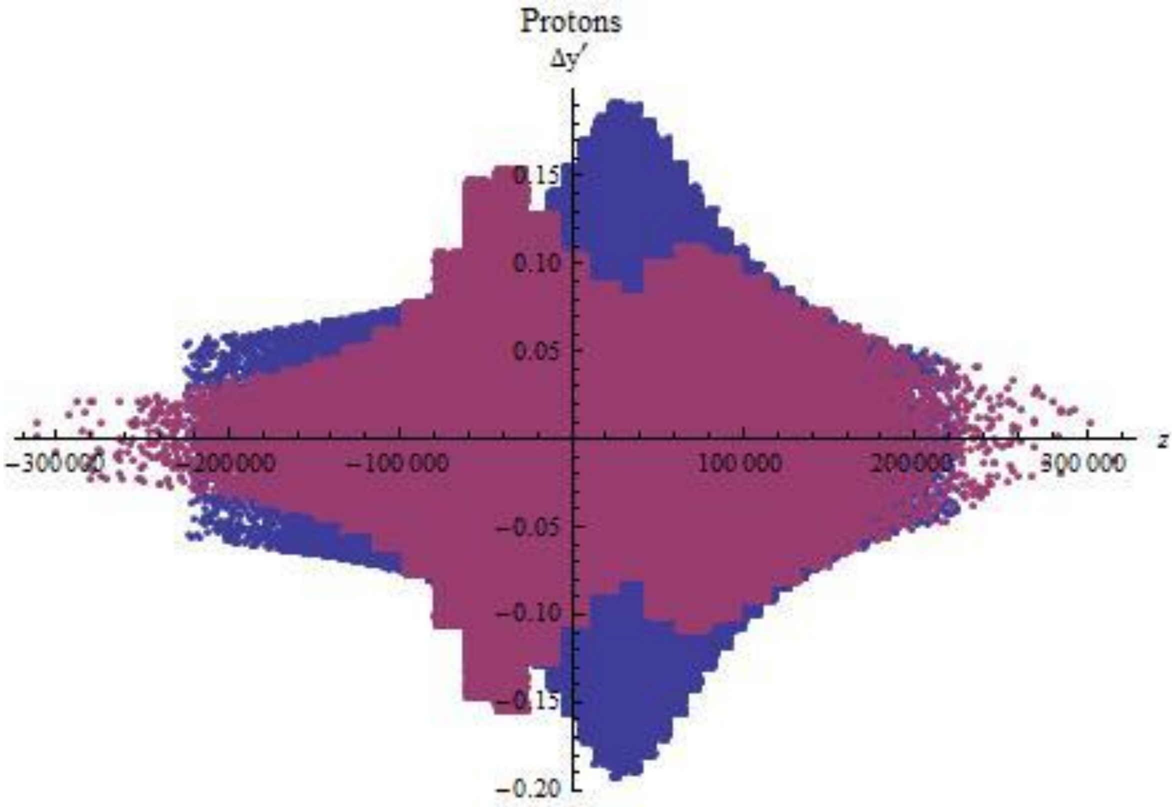
Nominal



High Luminosity

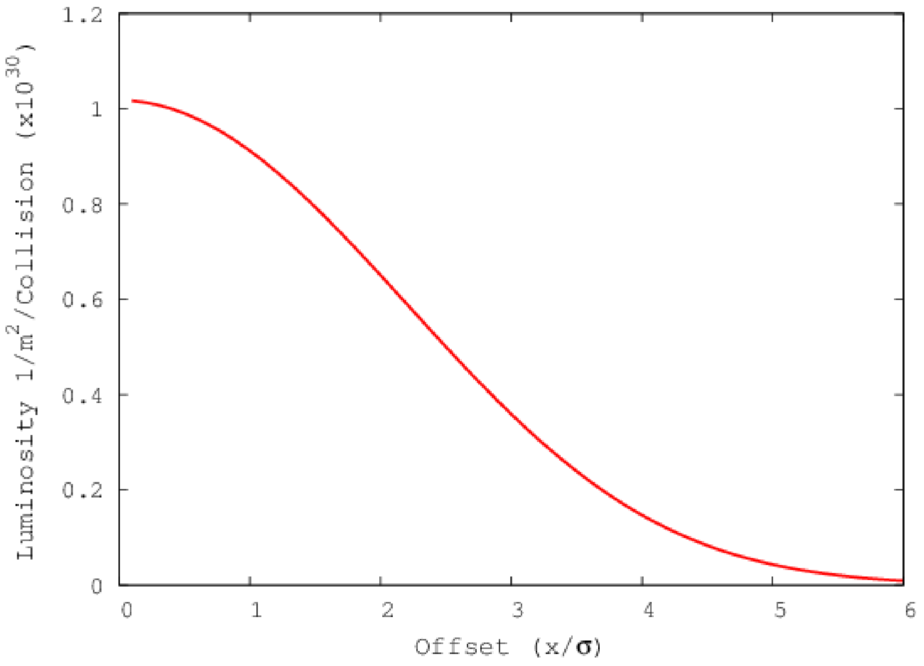


Longitudinal Effects

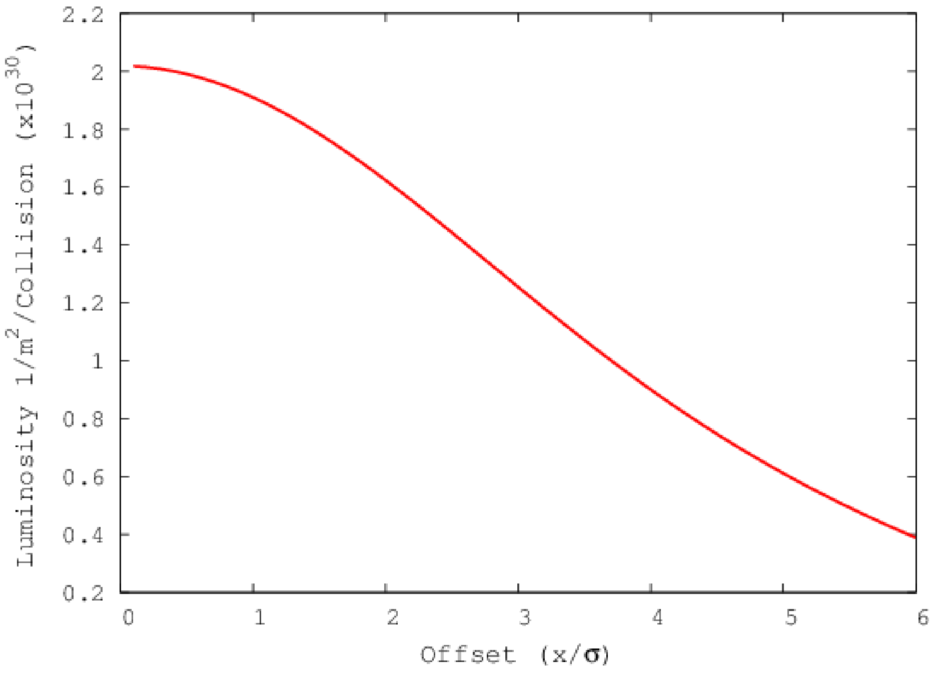


Single Pass Luminosities (LHeC)

Nominal

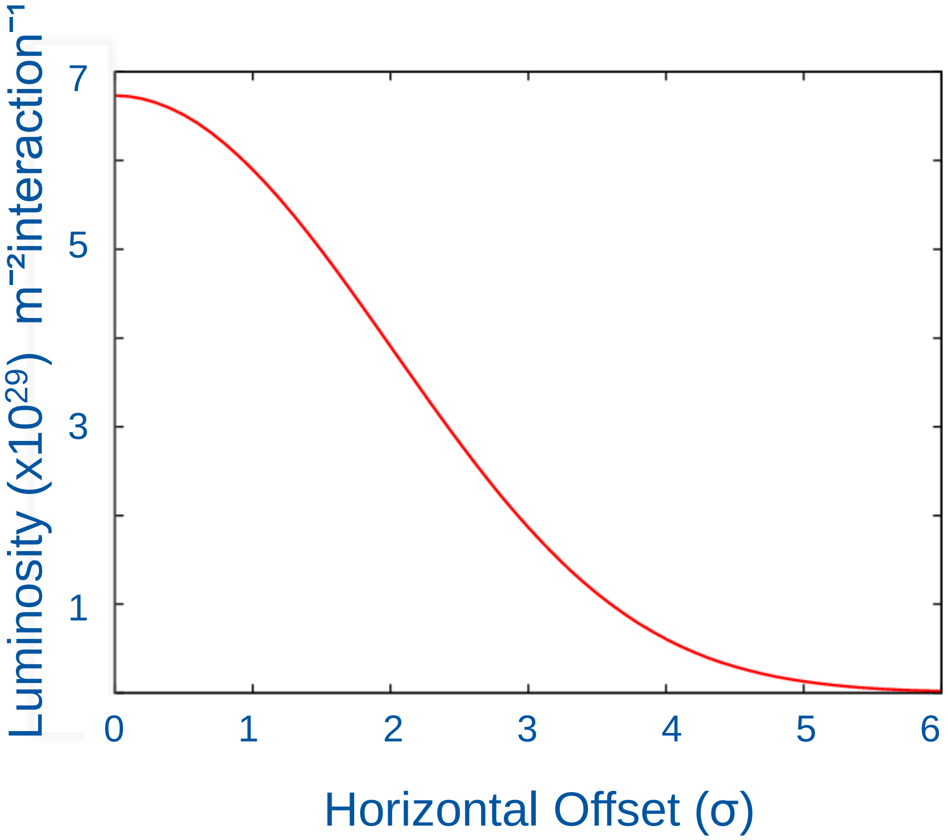


High Luminosity

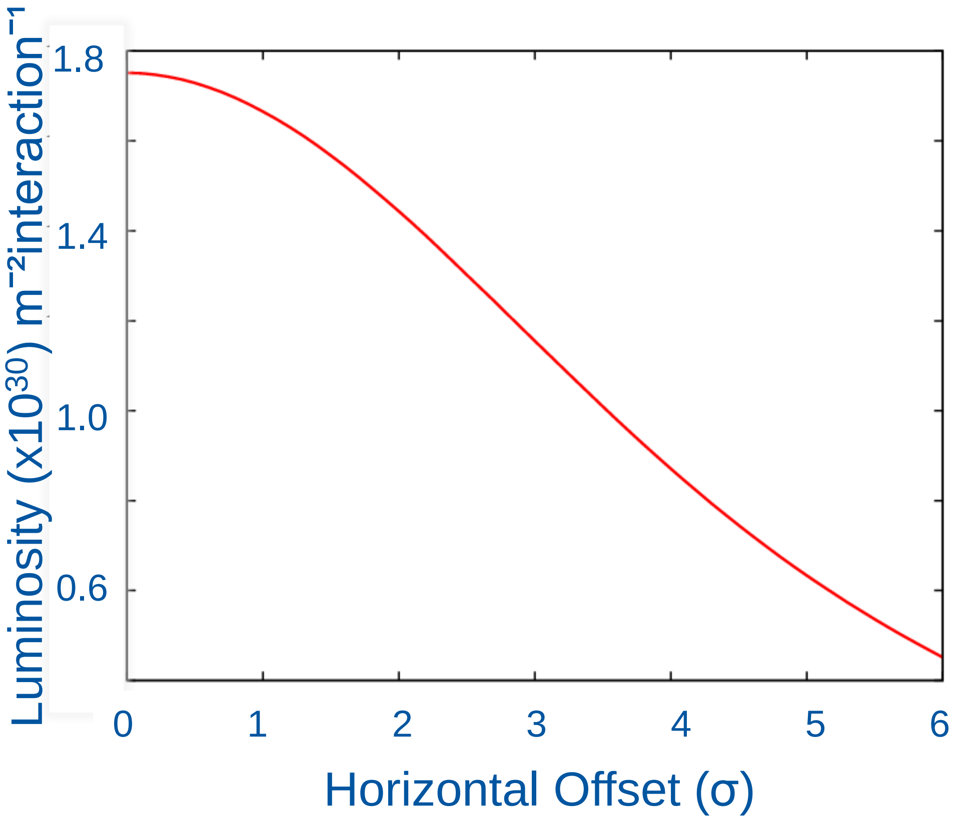


Single Pass Luminosity (FCC-he)

Nominal Parameters



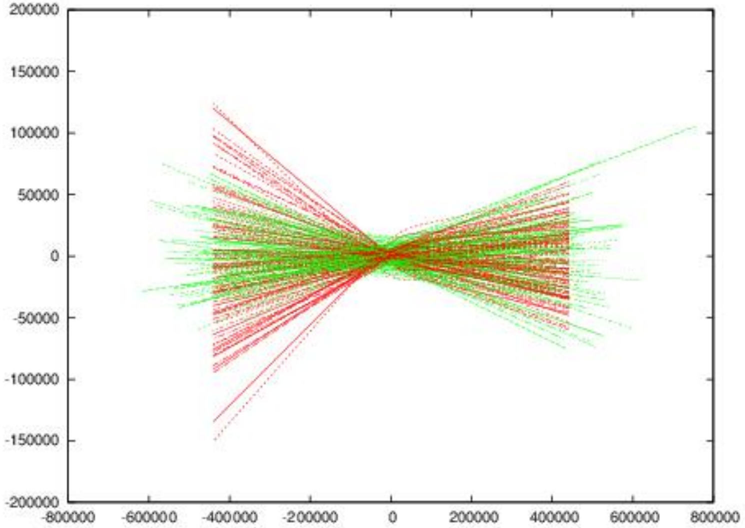
Ultimate Parameters

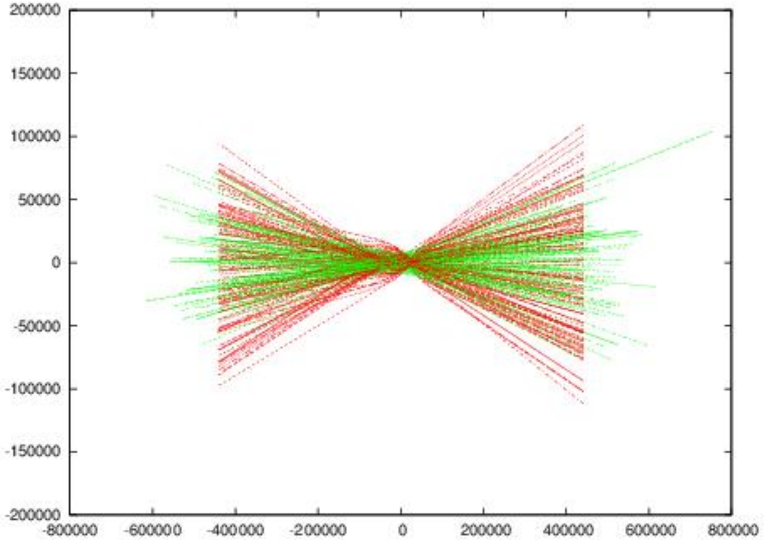


Trajectories with offsets (LHeC)

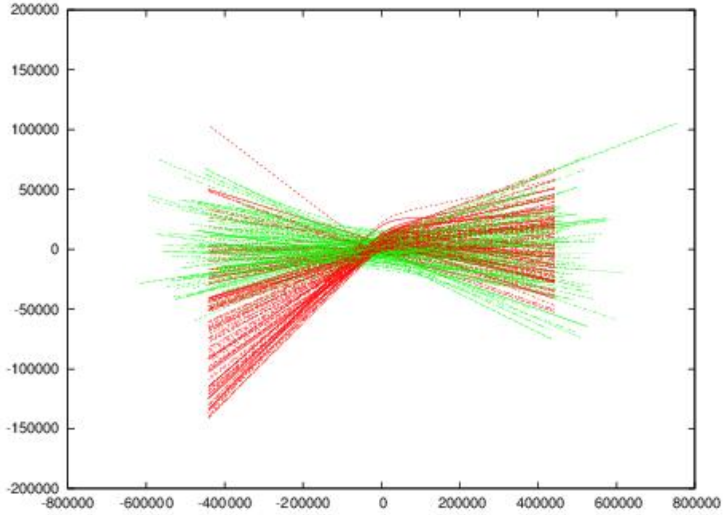
Nominal Parameters

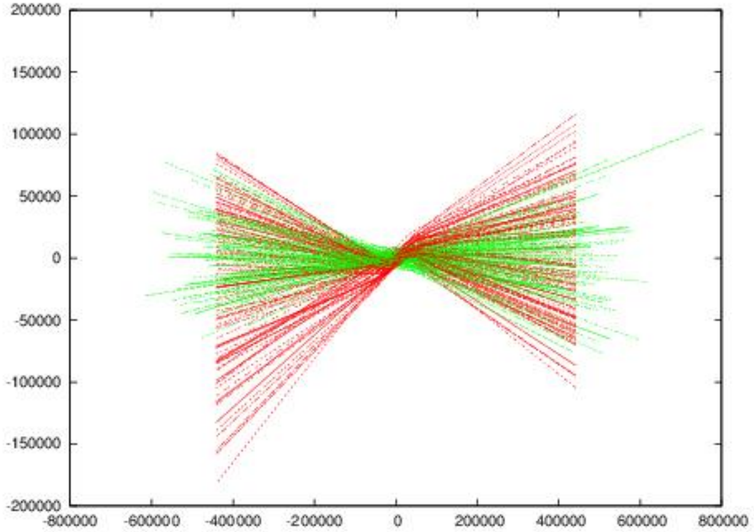
High Luminosity





Head-on

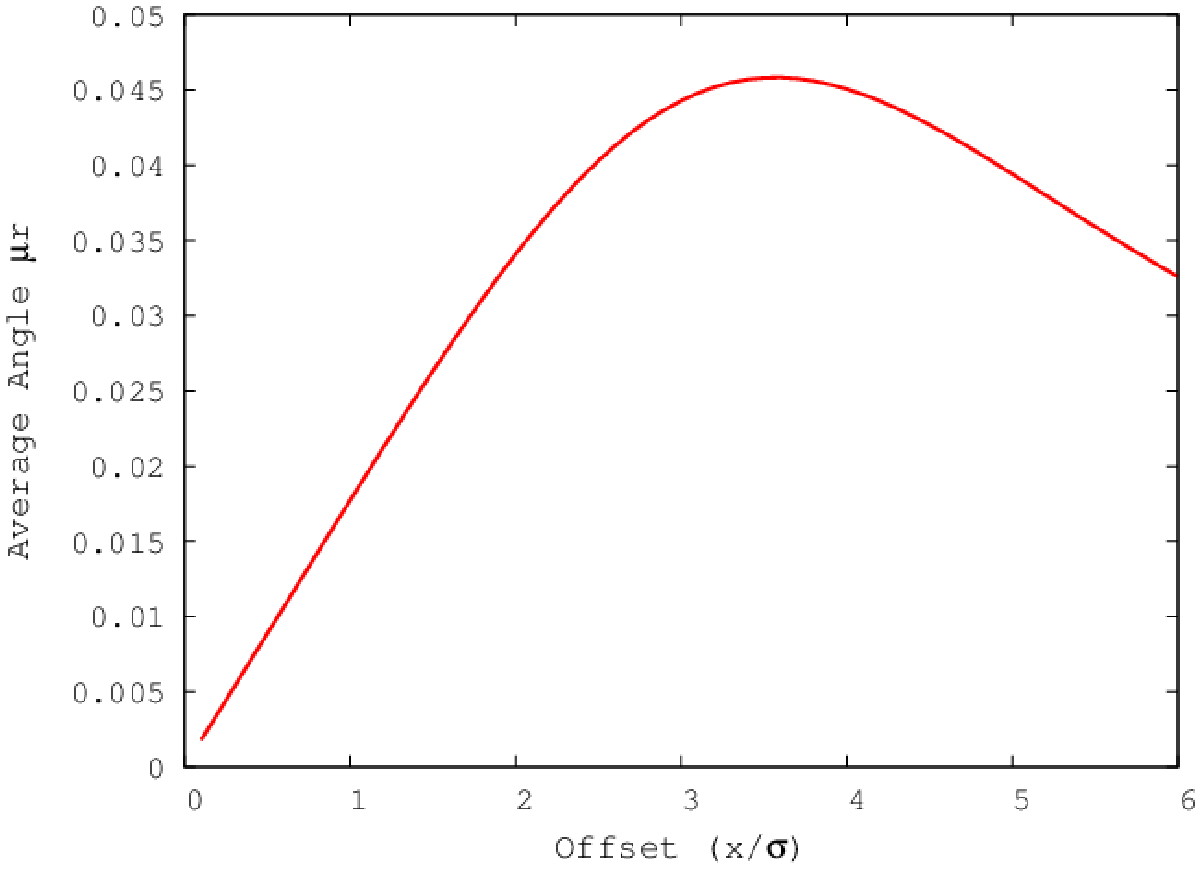




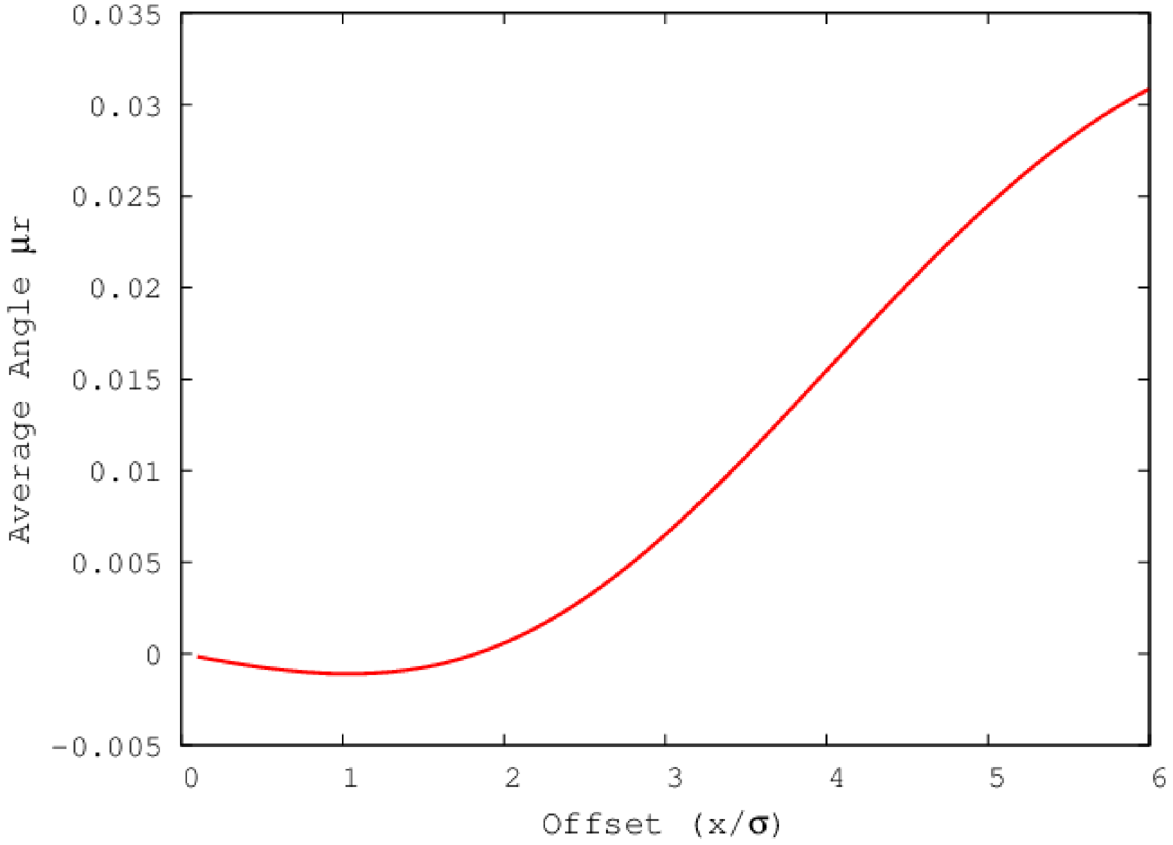
1σ offset

Single Pass Offsets (LHeC)

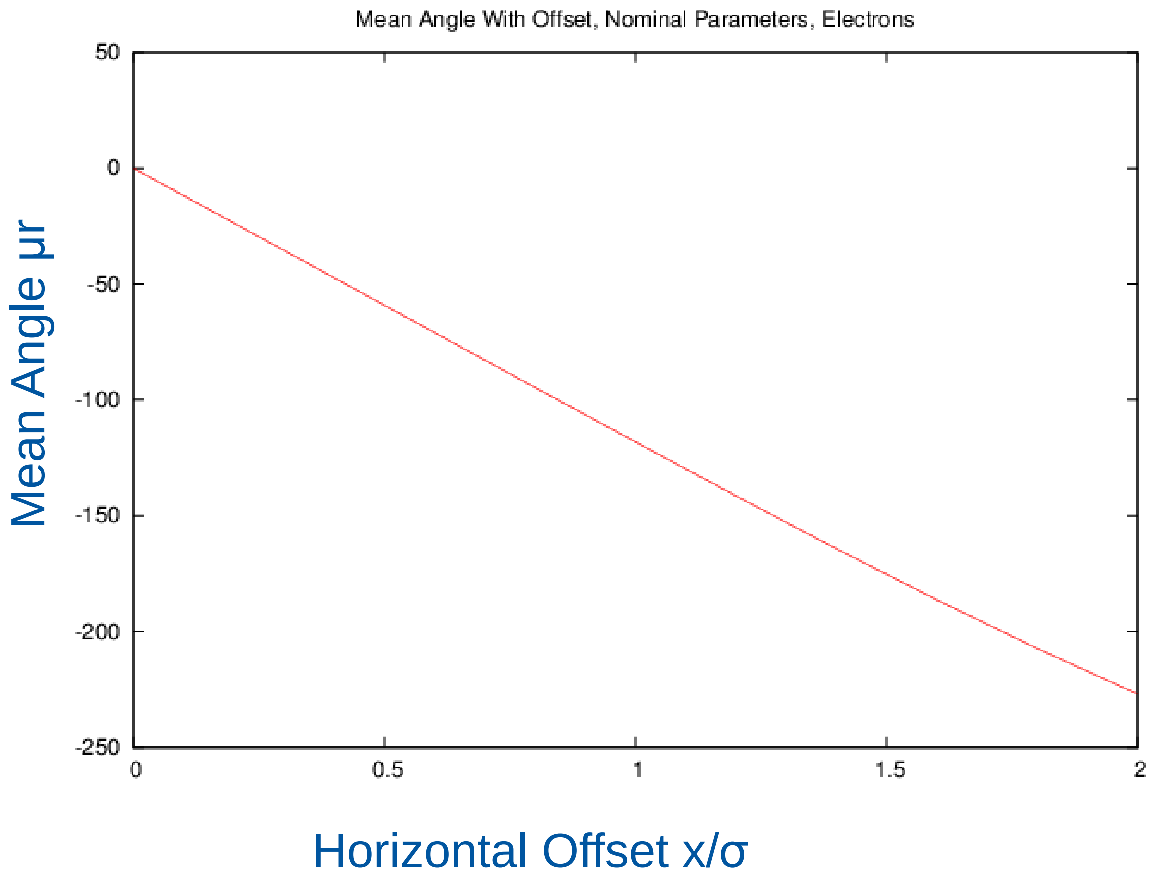
Nominal

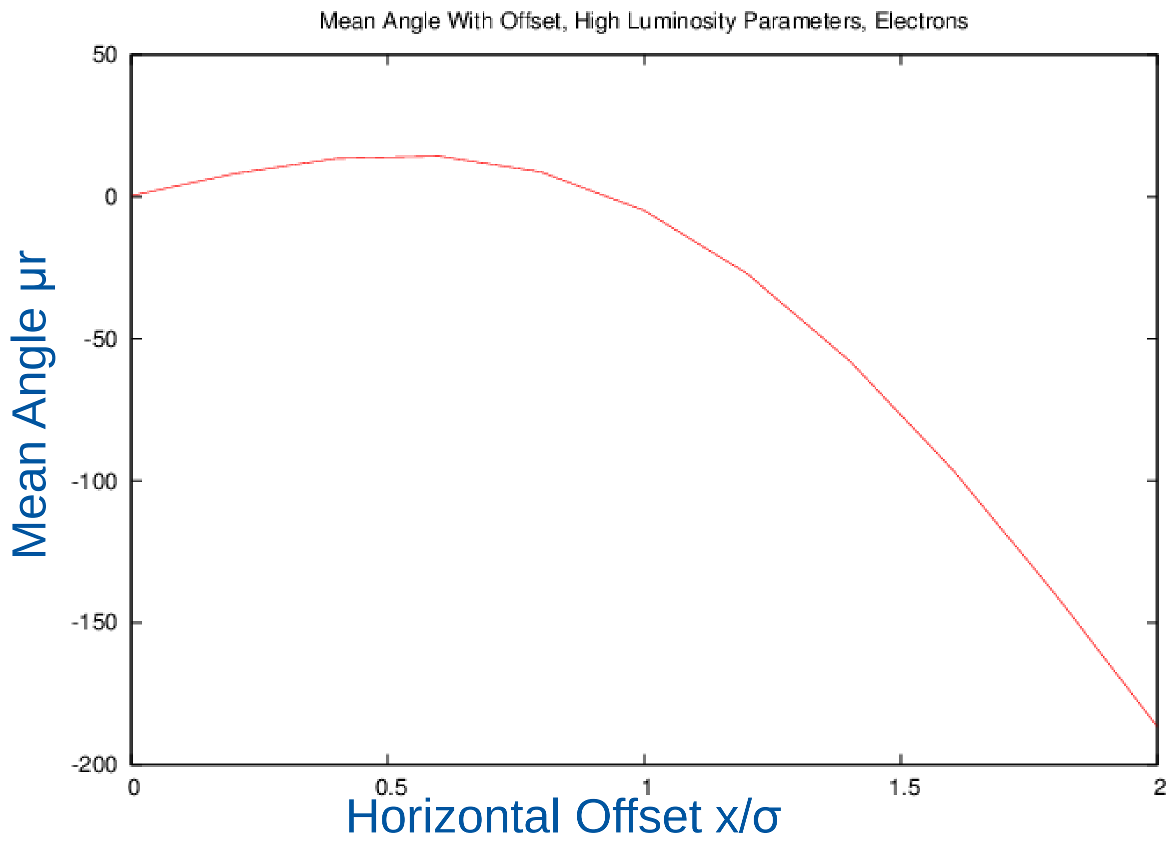


High Luminosity



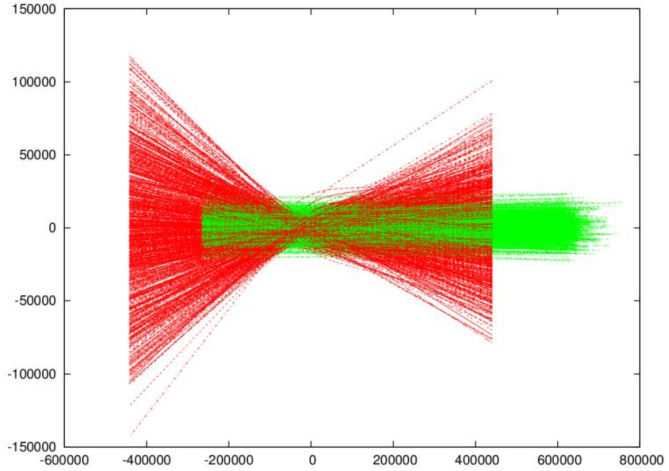
Single Pass Offsets (LHeC)



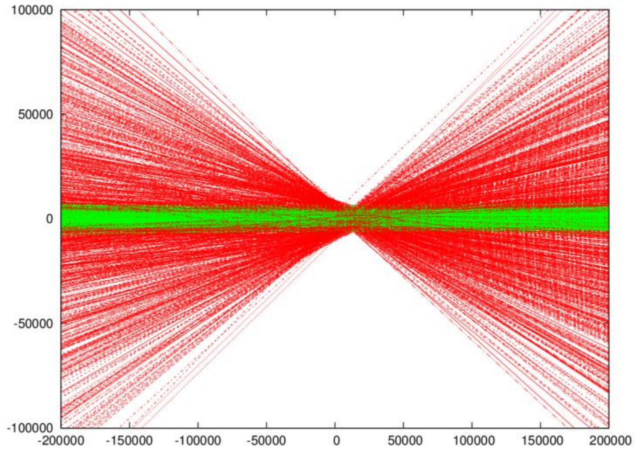


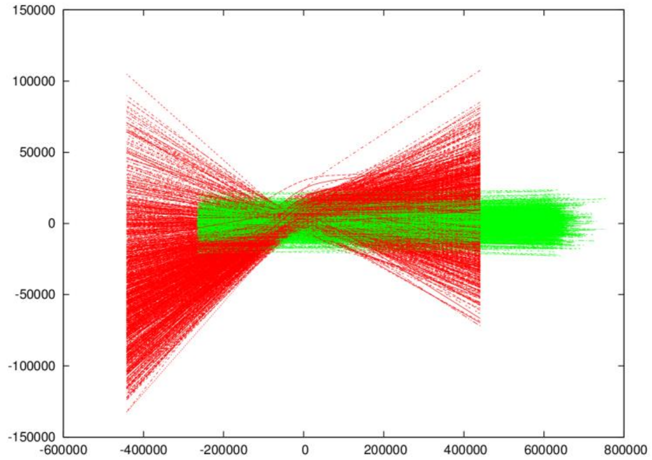
Single Pass (offsets cont'd)

Nominal Parameters | Ultimate Parameters

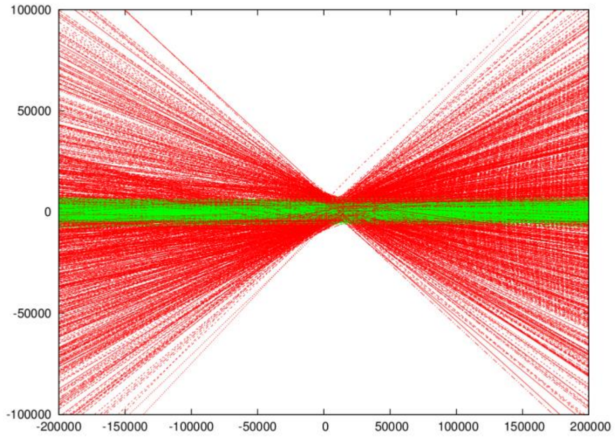


Head-on

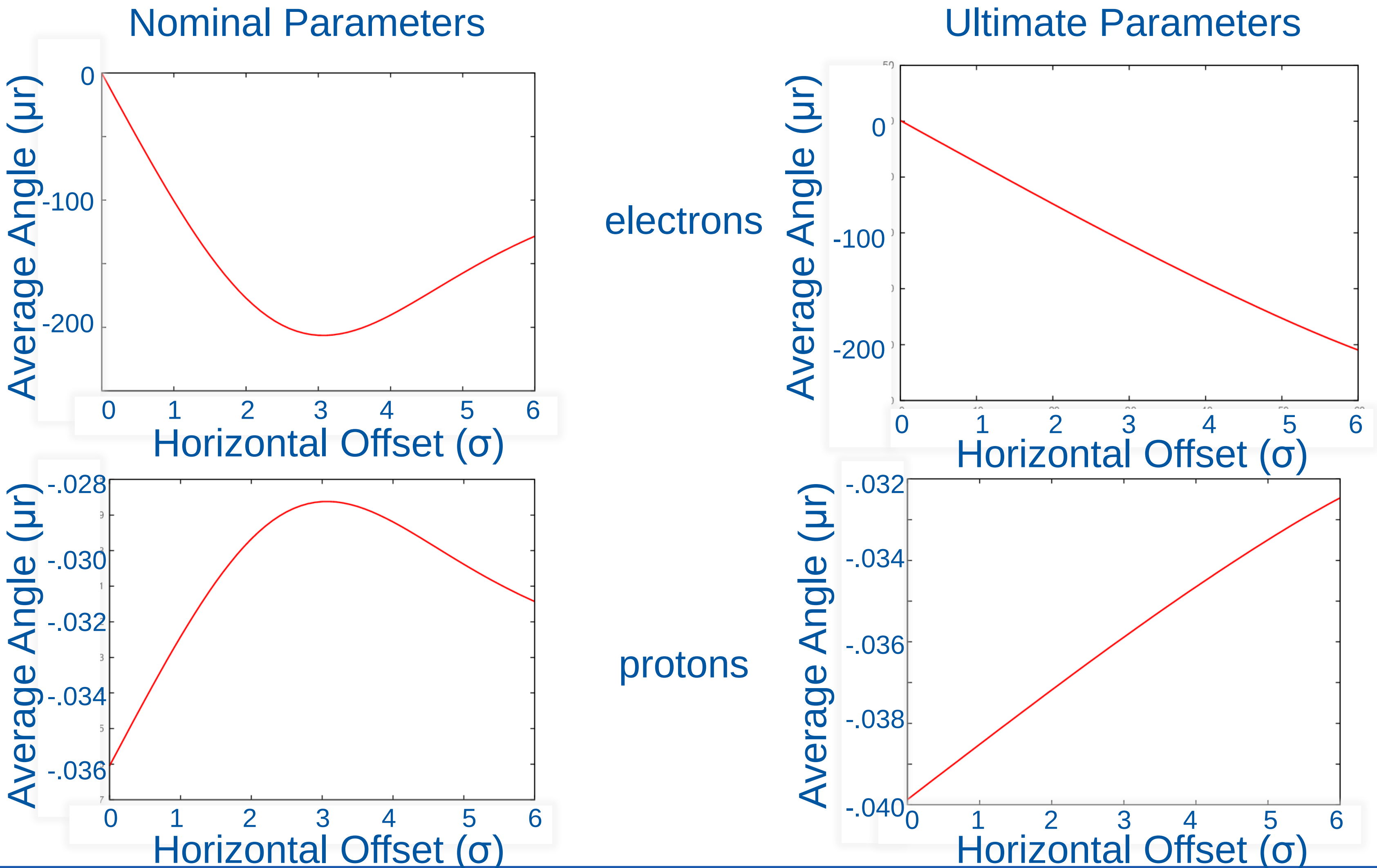




1σ offset

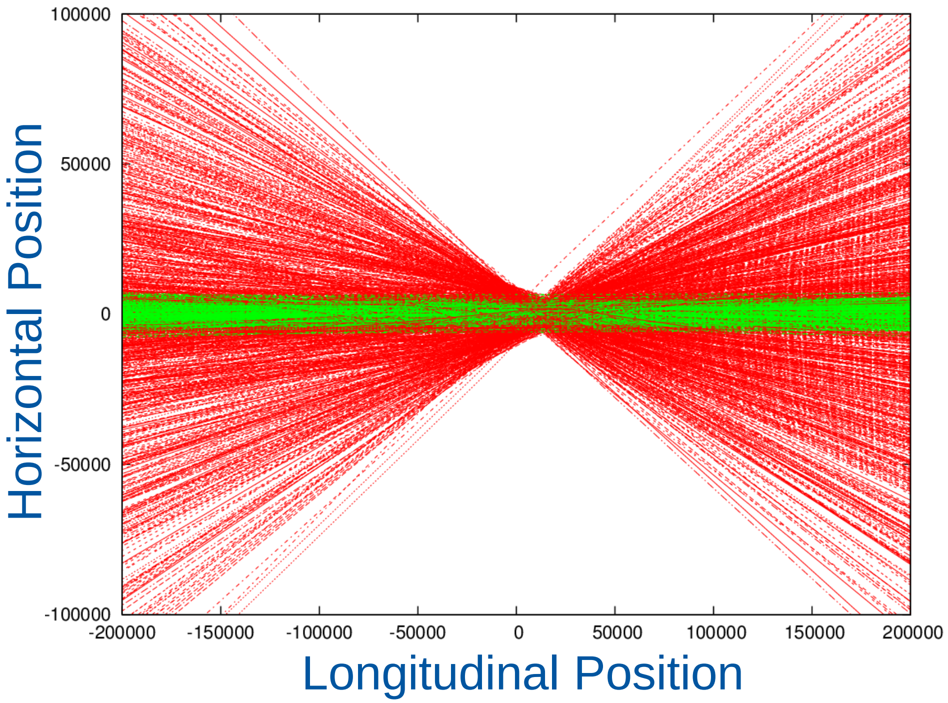


Single Pass (offsets)

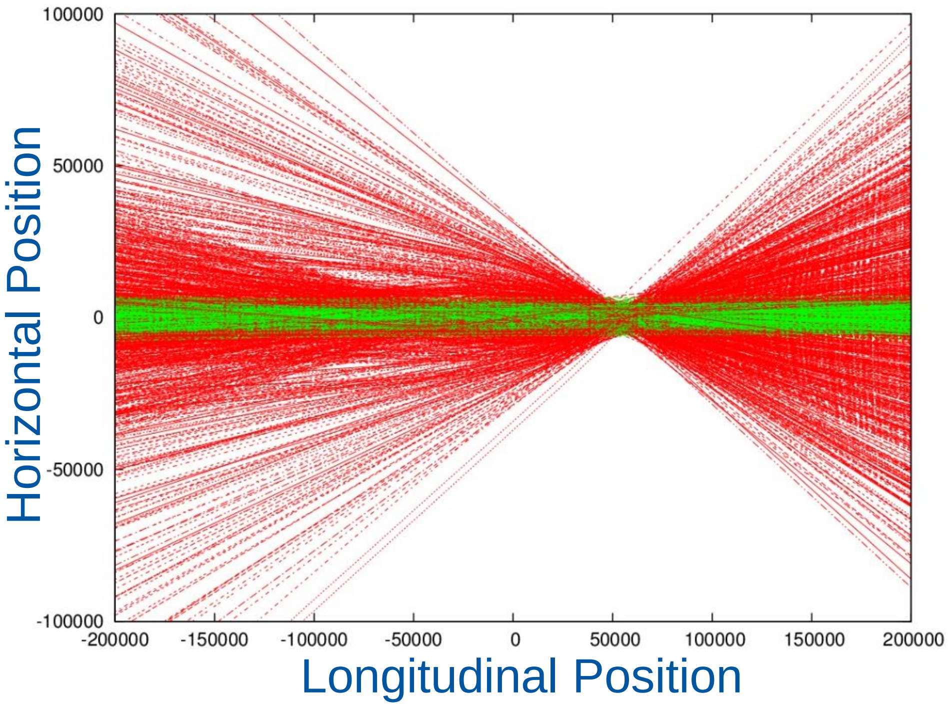


Waist Shift Background

No Waist Shift

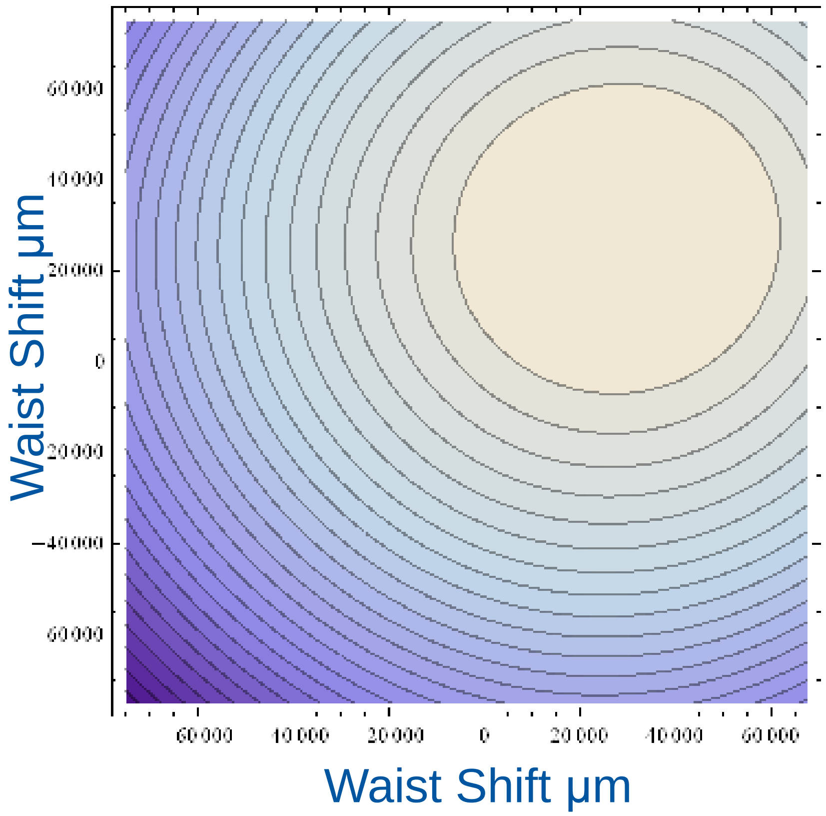


Waist Shifted $0.65\sigma_{zproton}$



Waist Shift optimization (LHeC)

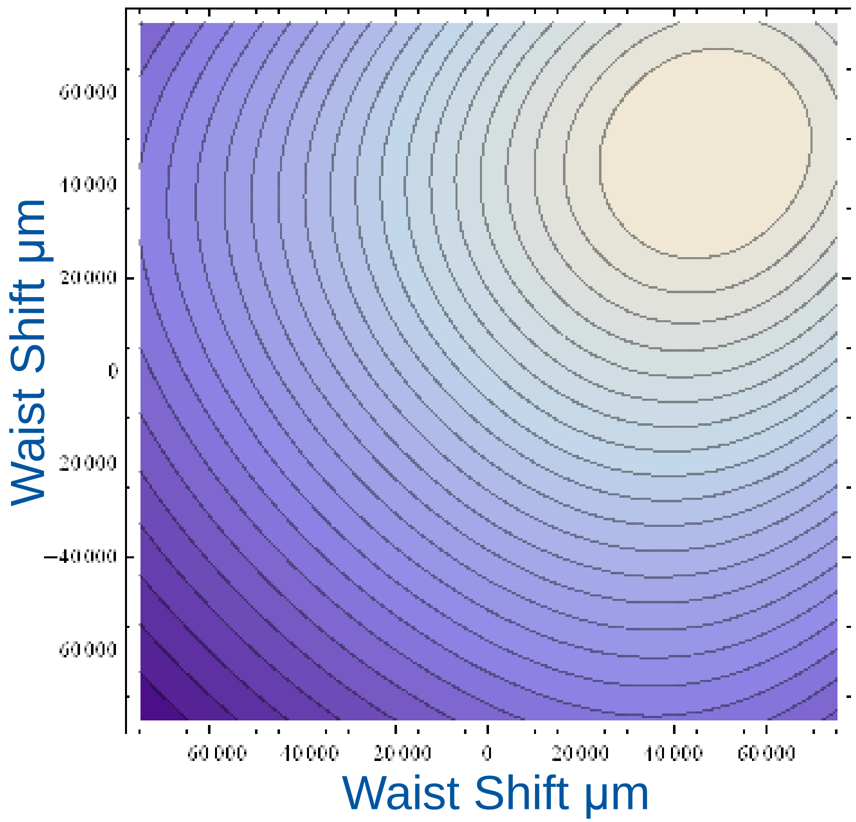
Nominal Parameters



Contour range:
$9.04^{29} – 1.028x10^{30}$

1.1% increase

High Luminosity

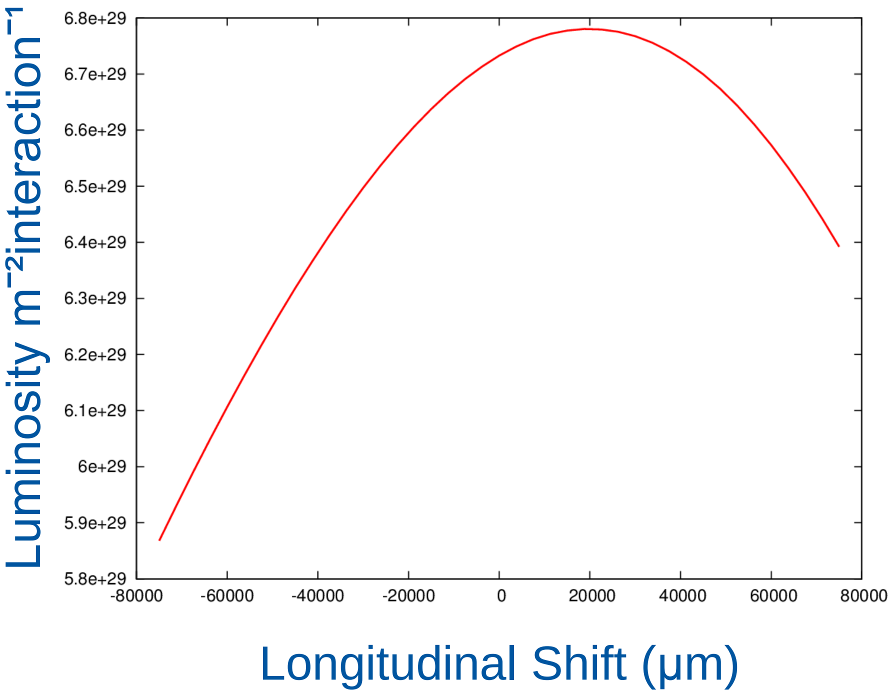


Contour range:
$1.23x10^{30} – 2.396x10^{30}$

18.7% increase

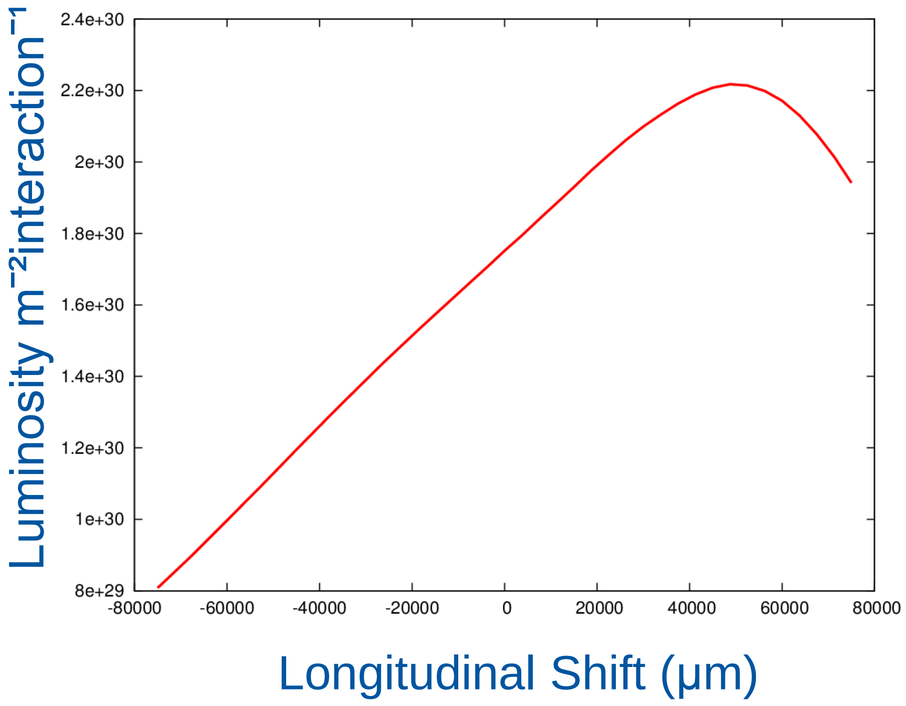
Waist Shift optimization (FCC-he)

Nominal Parameters



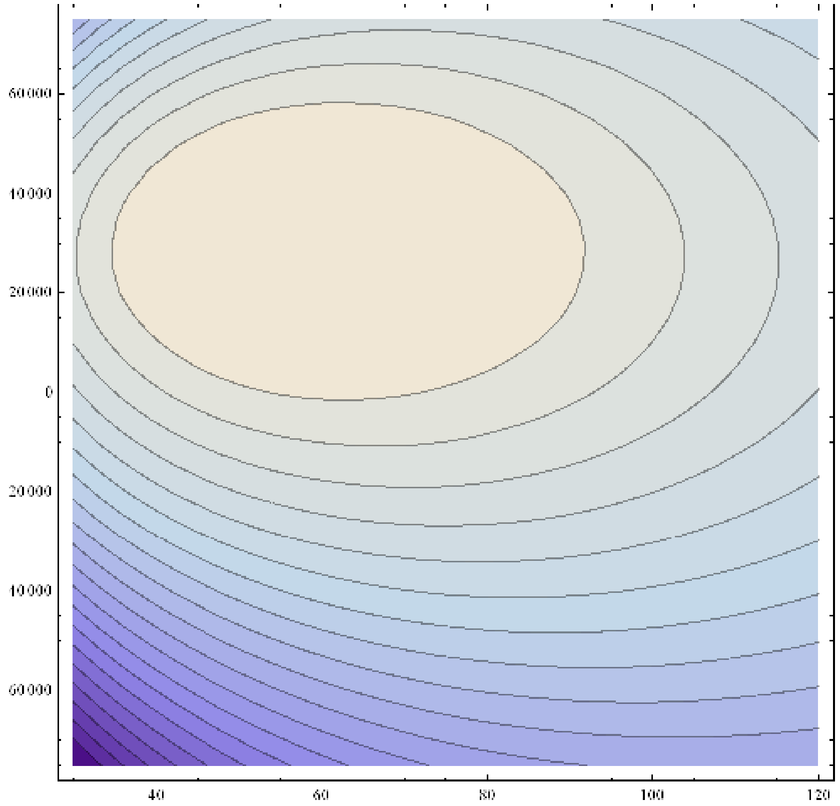
0.7% increase

Ultimate Parameters

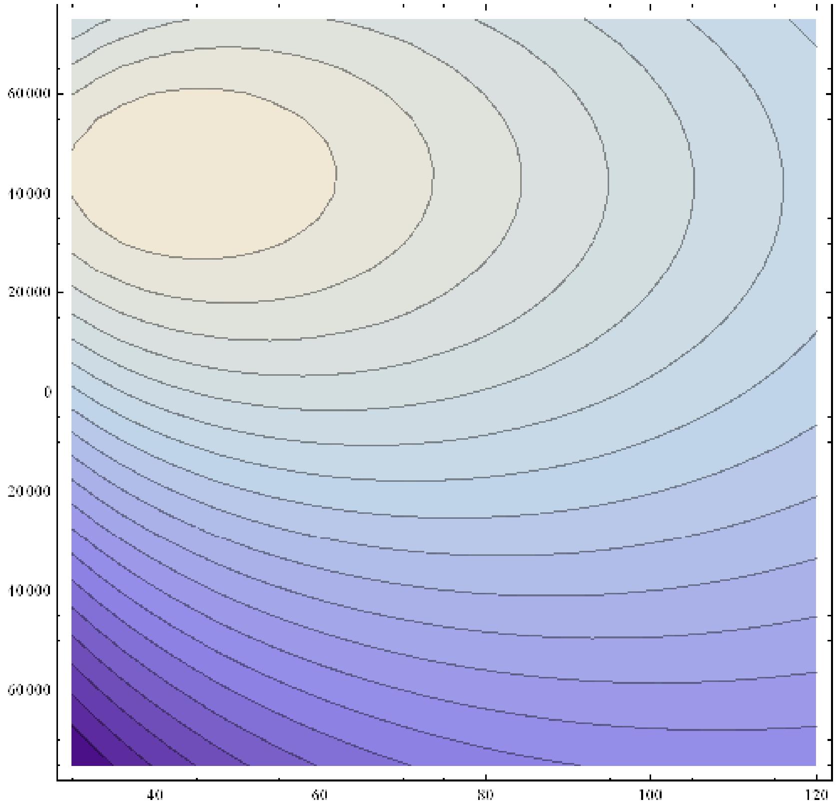


27% increase

Combination of Waist Shift and beta Function



Max 1.0997e30, min 7.44915e29

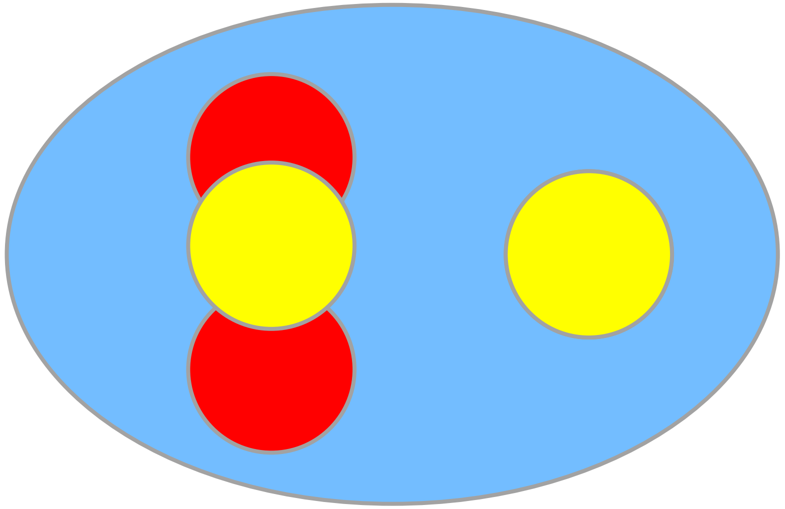


Max2.44e30, min 1.24e30

Multi-turn simulations

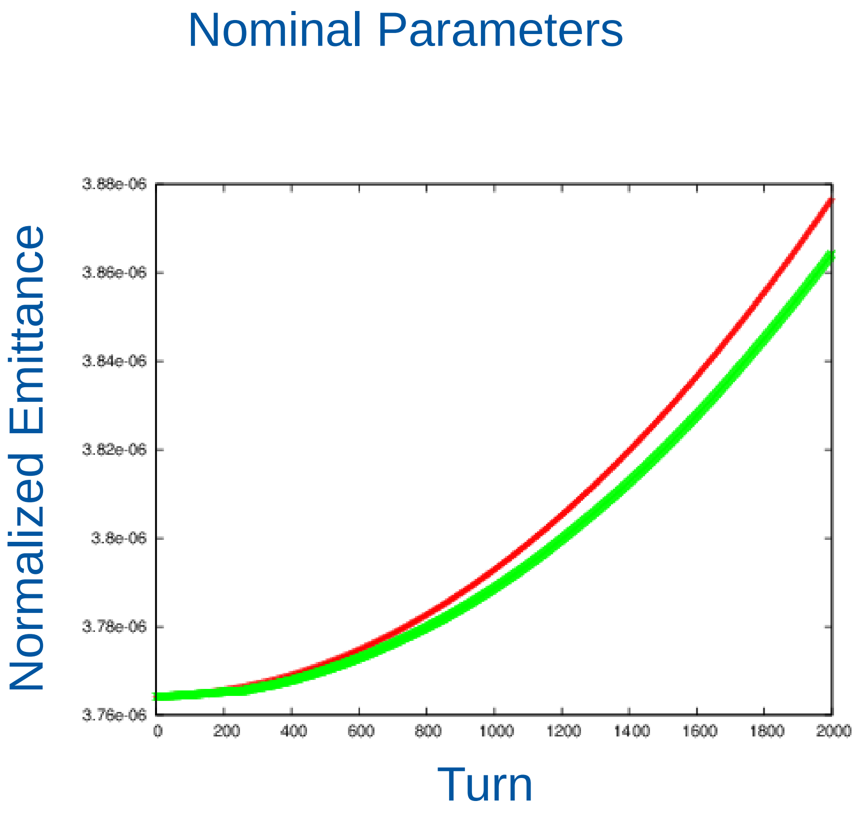
- Beam-Beam effect is simulated using Guinea-Pig
- The resulting particles are then acted on by a linear map of the LHeC/FCC with longitudinal motion
- The electrons are stored and used repeatedly with an offset governed by a random number generator seeded by the turn number
- The initial conditions for the protons are created using different random number seeds

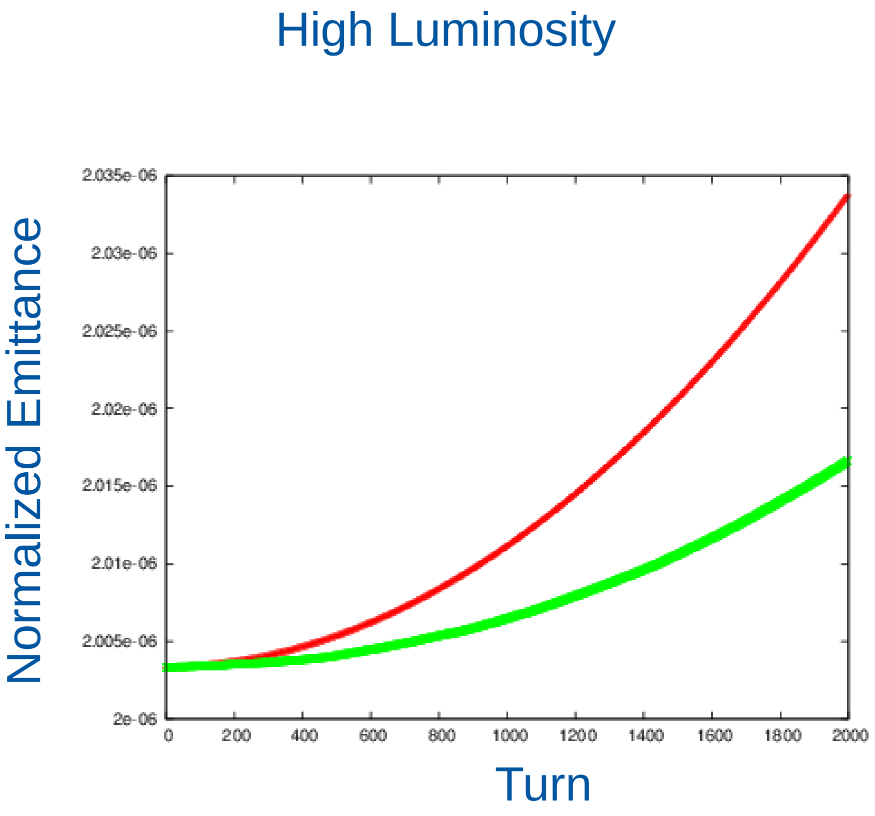
Induce an instability



Attempt to induce instability in recirculating proton beam by matching the electron beam to always hit with a set offset at the same section of the beam, based on the horizontal tune.

Growth Rate (resonant LHeC)

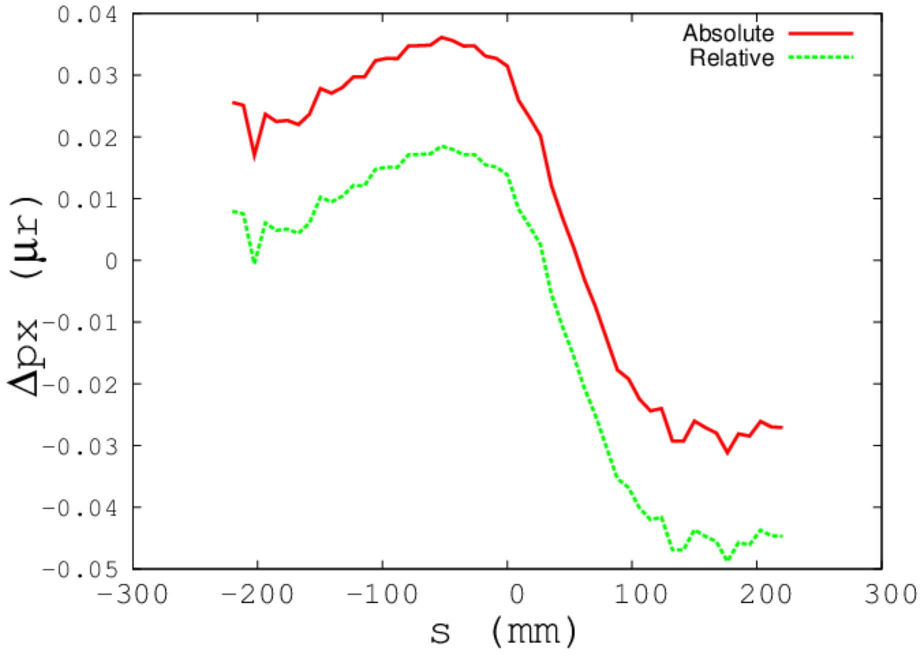




Red lines indicate no longitudinal motion, green lines indicate longitudinal motion

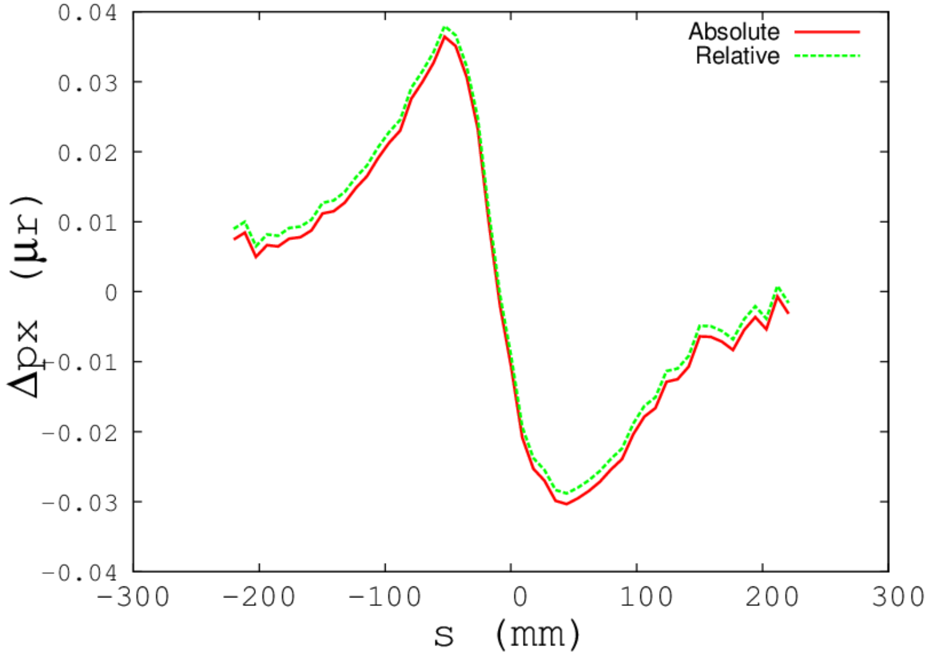
HeadTail effect (LHeC)

Nominal Parameters



Predicted $=5.2838\times10^{-14}$/turn

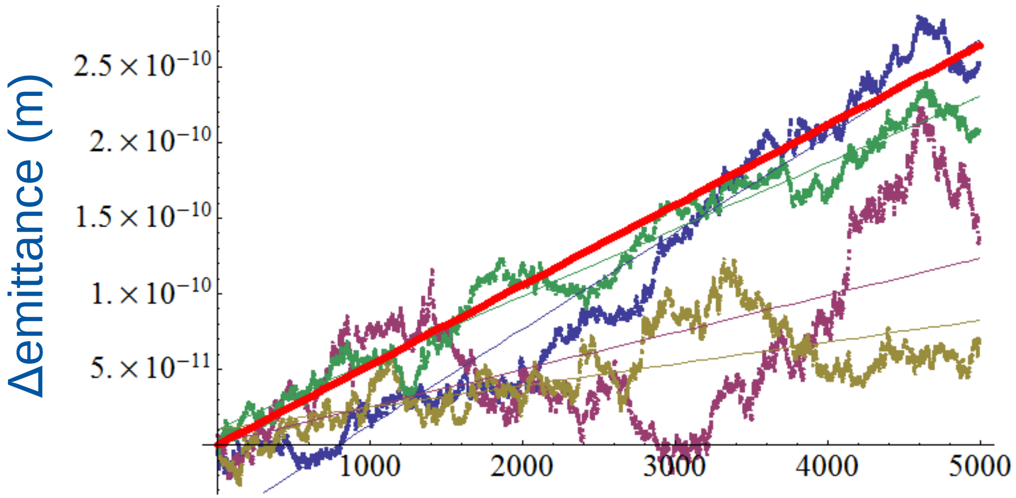
High Luminosity Parameters



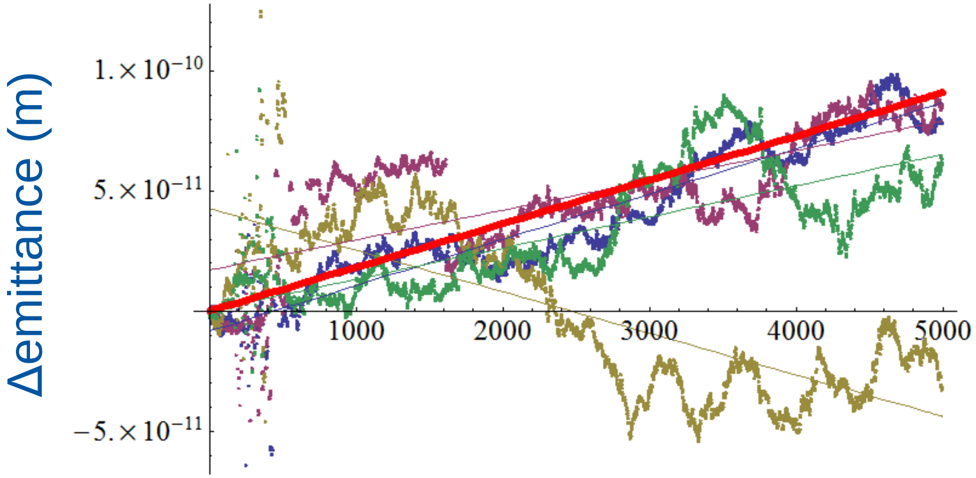
Predicted $=1.821\times10^{-14}$/turn

Growth Rate comparison (LHeC)

Nominal



High Luminosity



Calculated growth rates are shown with the trendlines, while the predicted growth rate is shown with the thick red line.

Nominal

Predicted $=5.2838\text{x}10^{-14}$

Average $=3.665\text{x}10^{-14}$

Growth Rate$=1.47\text{x}10^{-8}(\sigma_{jitter}/\sigma_x)^2$m/s

1 day doubling time jitter of 5.4%

High Luminosity

Predicted $=1.821\text{x}10^{-14}$

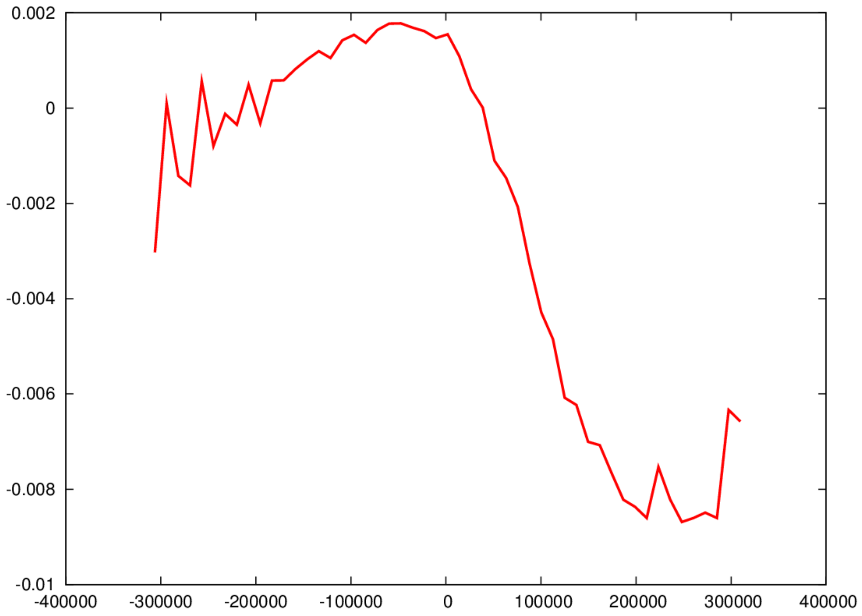
Average $=0.679\text{x}10^{-14}$

Growth Rate$=5.06\text{x}10^{-9}(\sigma_{jitter}/\sigma_x)^2$m/s

1 day doubling time jitter of 6.7%

Head Tail Effect (FCC-he)

Nominal Parameters

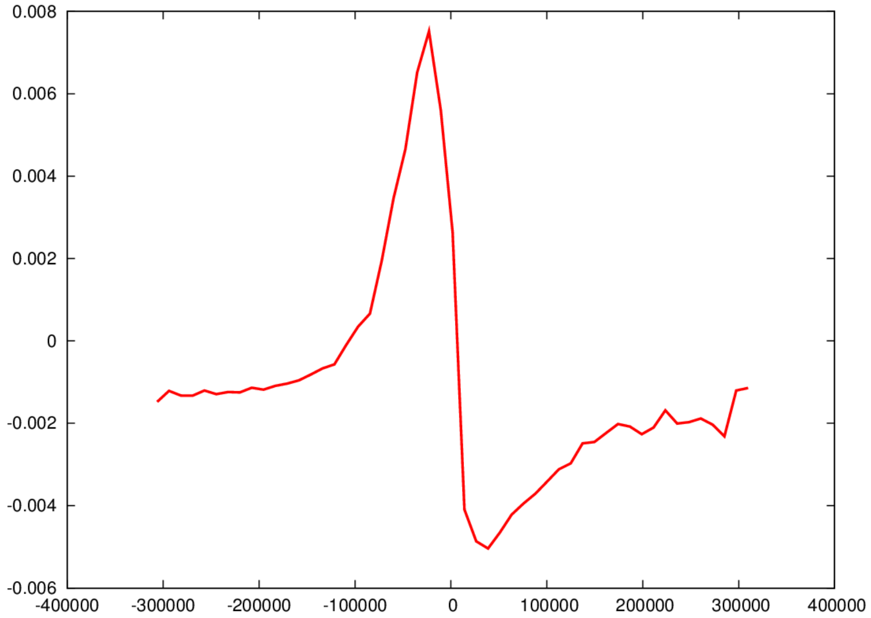


Δp_x at 1σ offset (μr)

Longitudinal Position (μm)

Predicted rate 9.470x10^{-14} m/turn

Ultimate Parameters



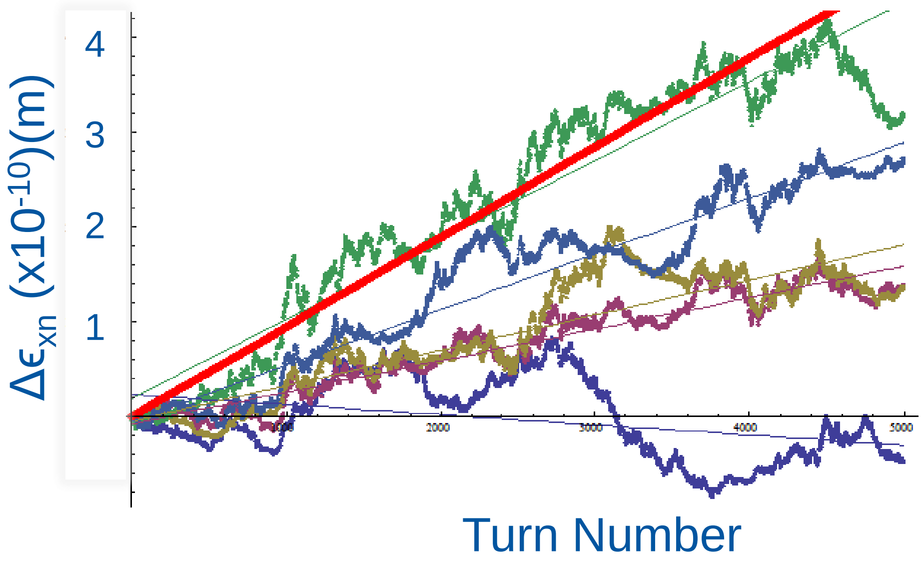
Δp_x at 1σ offset (μr)

Longitudinal Position (μm)

Predicted rate 1.249x10^{-14} m/turn

Growth rate comparison (FCC-he)

Nominal Parameters

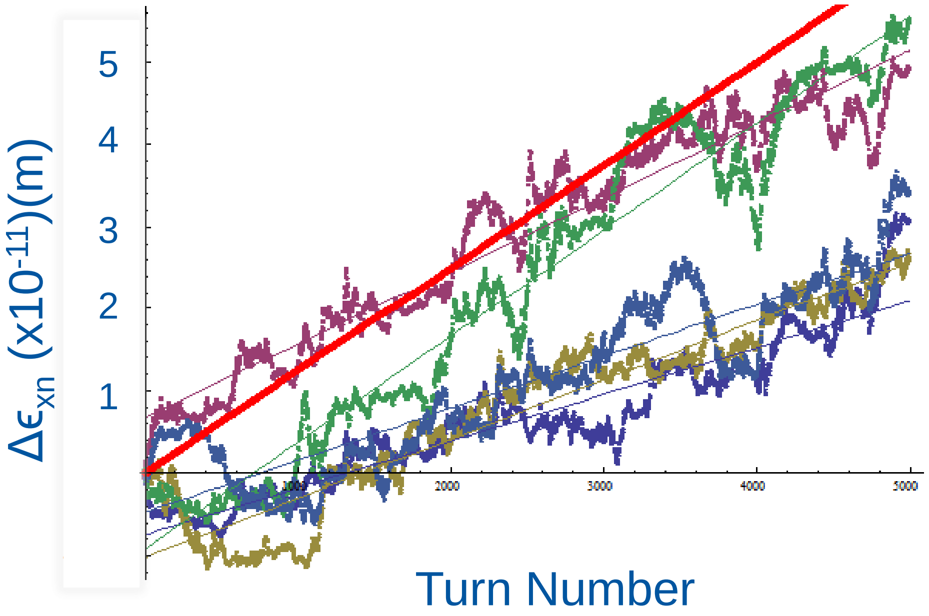


Predicted rate 9.470×10^{-14}
Mean calculated rate 4.046×10^{-14}

$\Delta\epsilon_{xn}/\Delta t=7.095\times10^{-9}(\sigma_{jitter}/\sigma_x)^2$m/s

Doubling time 1 day $\sigma_{jitter}/\sigma_x=5.99\%$

Ultimate Parameters

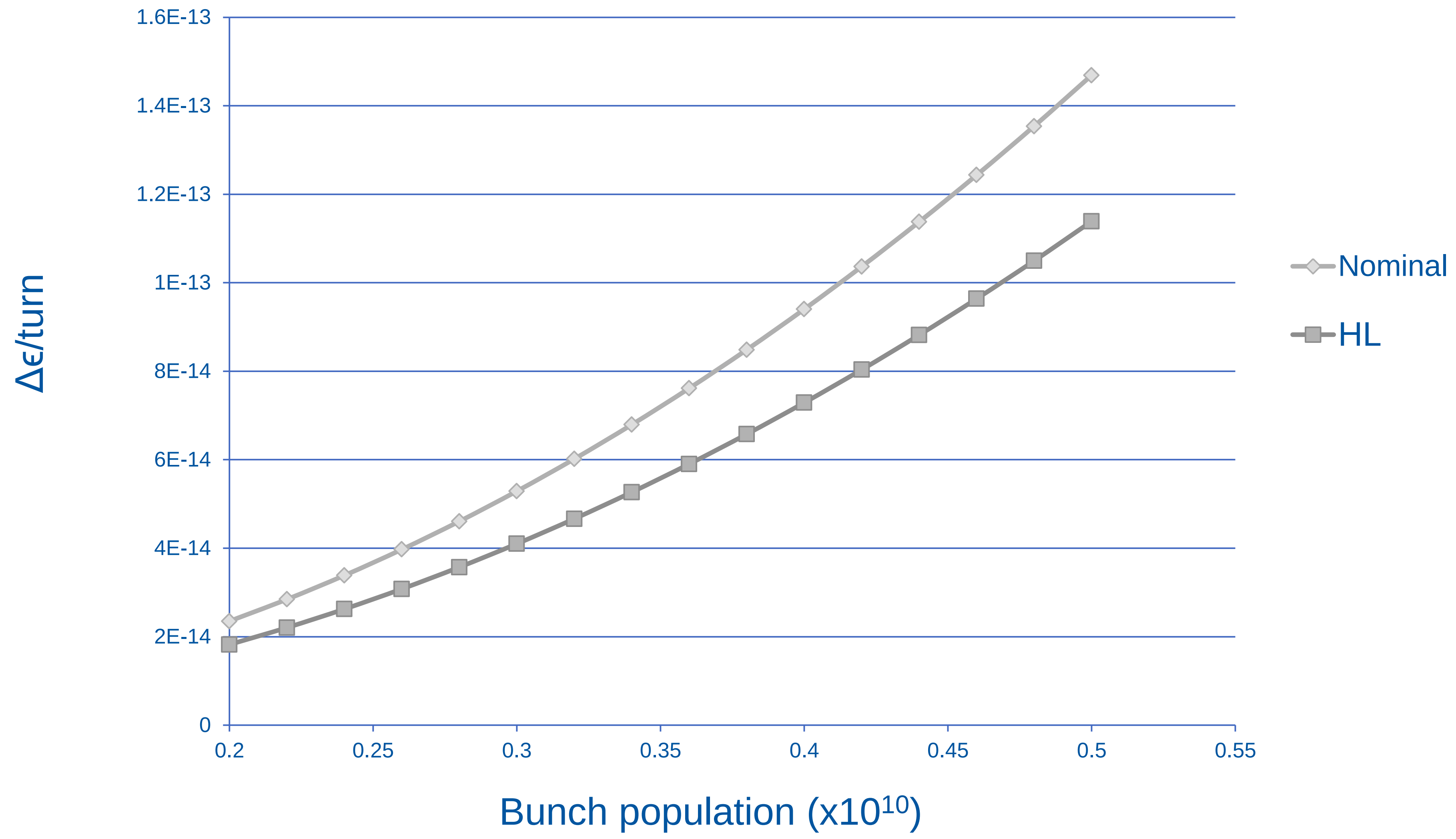


Predicted rate 1.249×10^{-14}
Mean calculated rate 8.212×10^{-15}

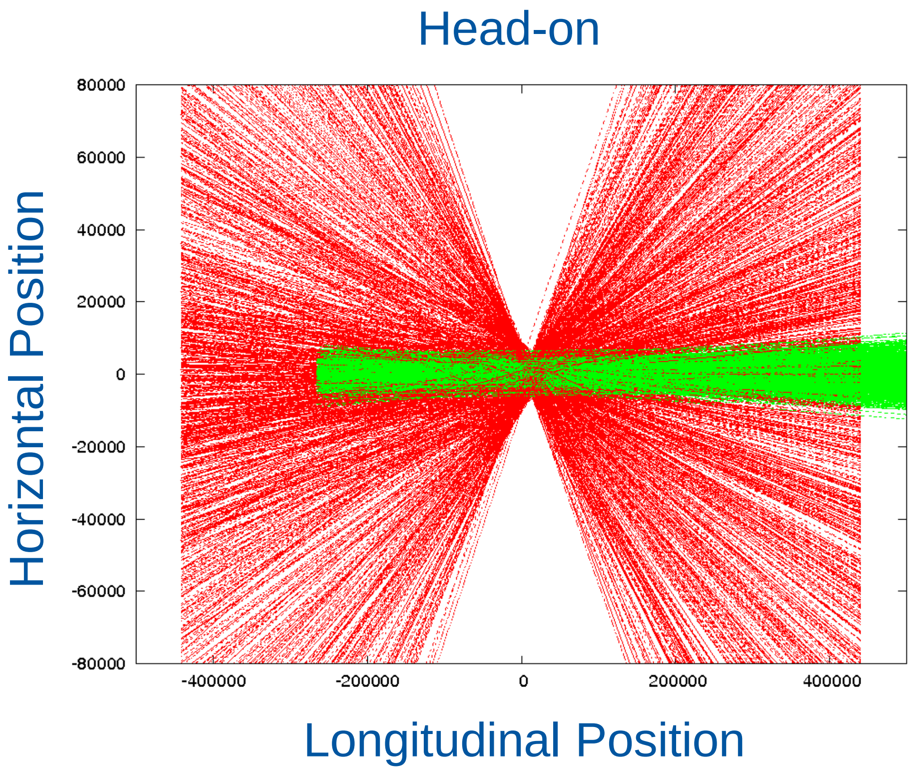
$\Delta\epsilon_{xn}/\Delta t=9.36102\times10^{-10}(\sigma_{jitter}/\sigma_x)^2$m/s

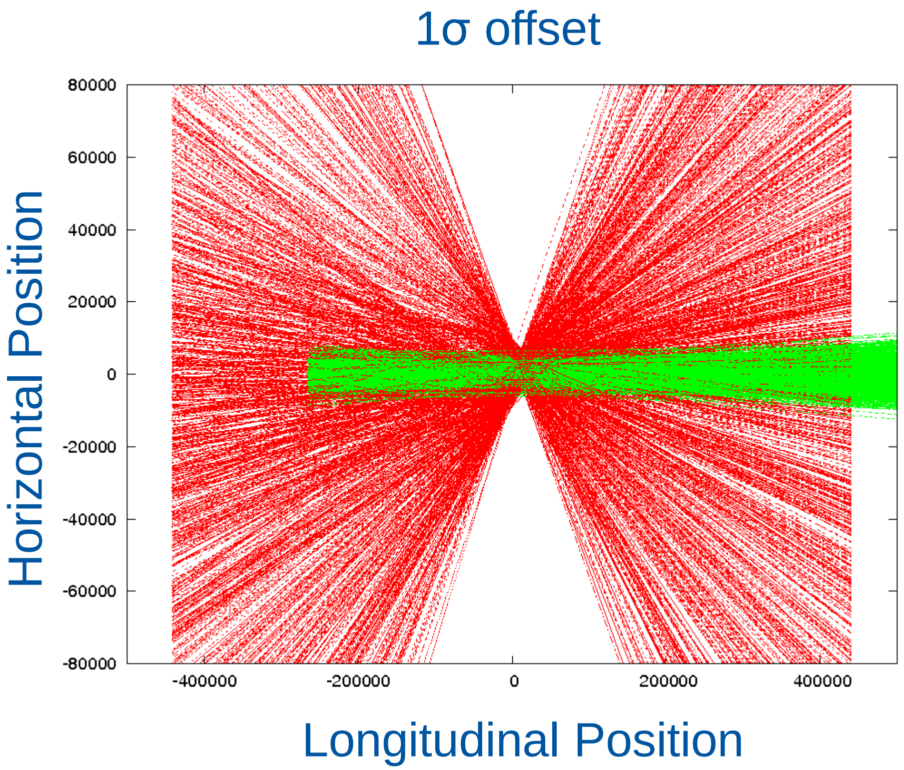
Doubling time 1 day $\sigma_{jitter}/\sigma_x=9.5\%$

Growth rate with Charge (LHeC)

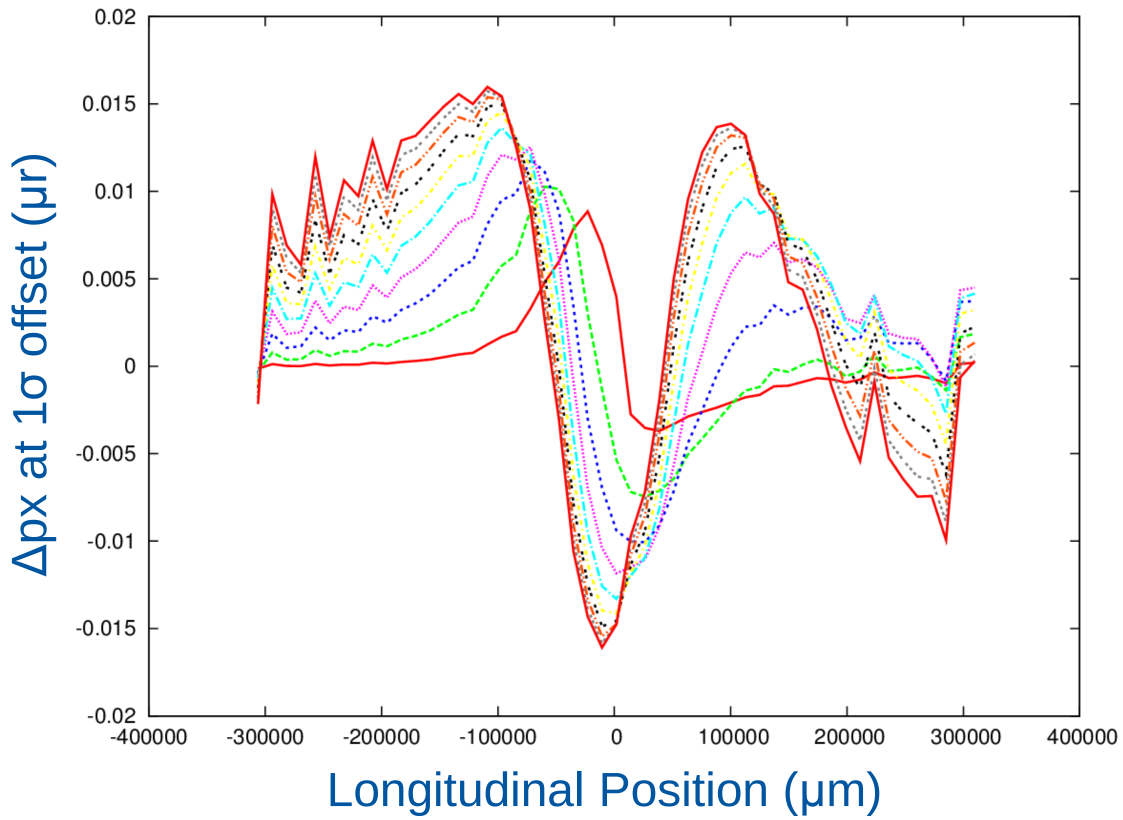


Adjusted Beta Shift



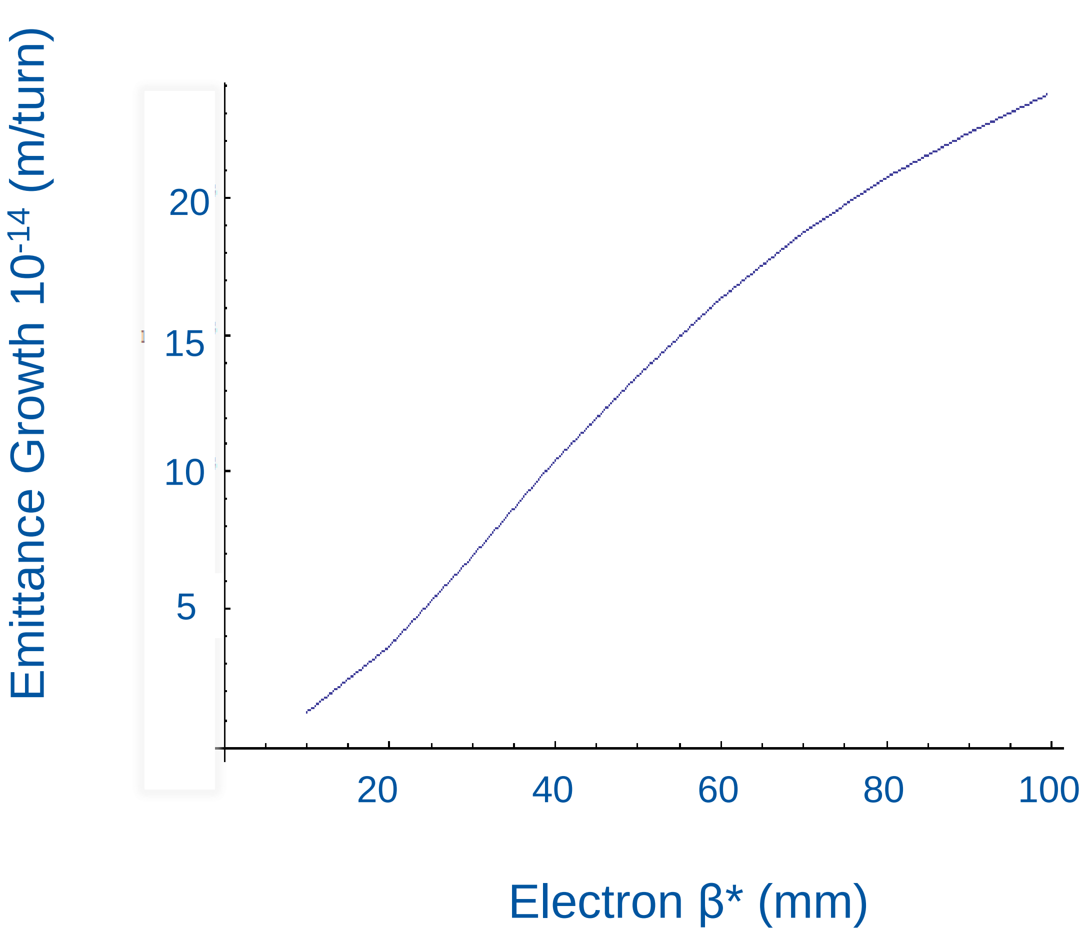


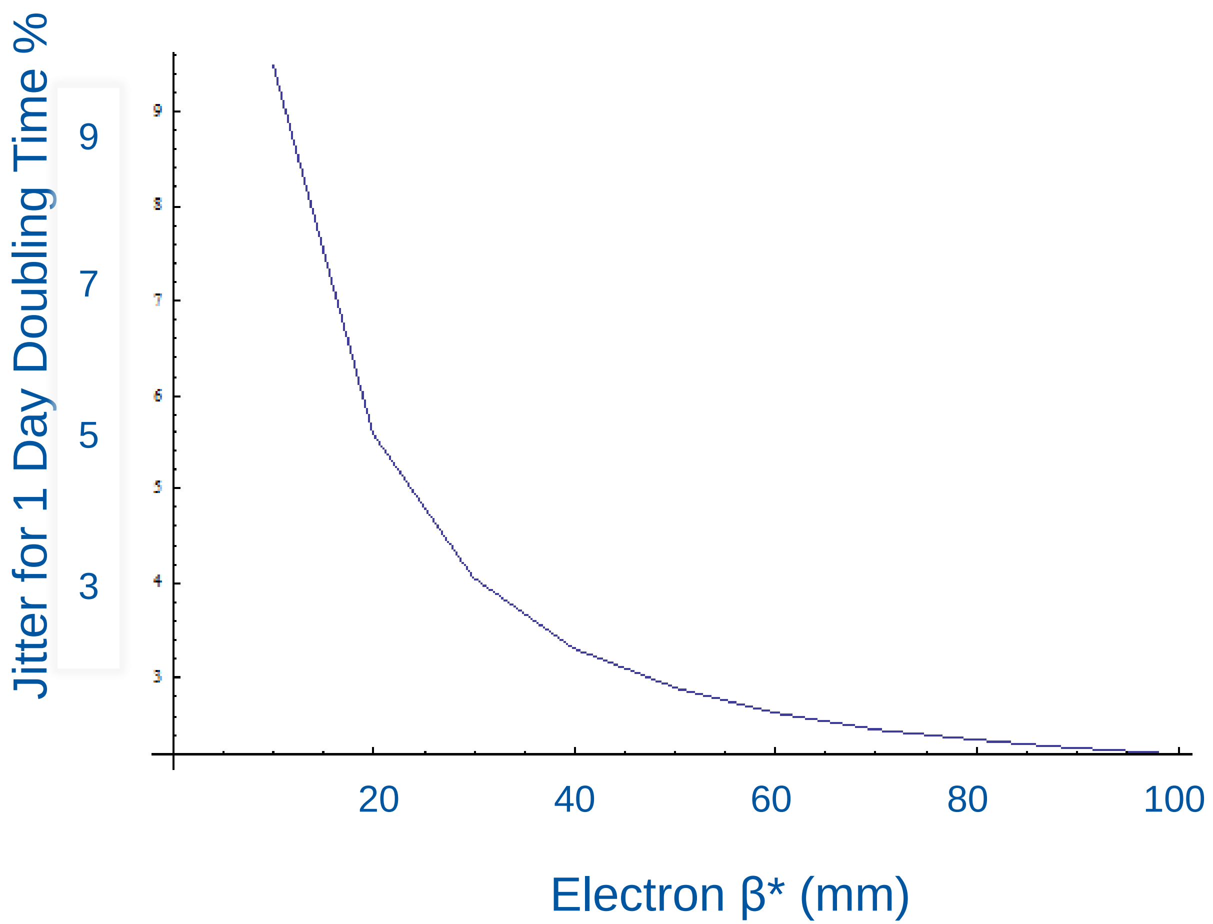
Beta Shift (headtail)



β* is increased with a corresponding reduction in emittance to keep a constant spot size

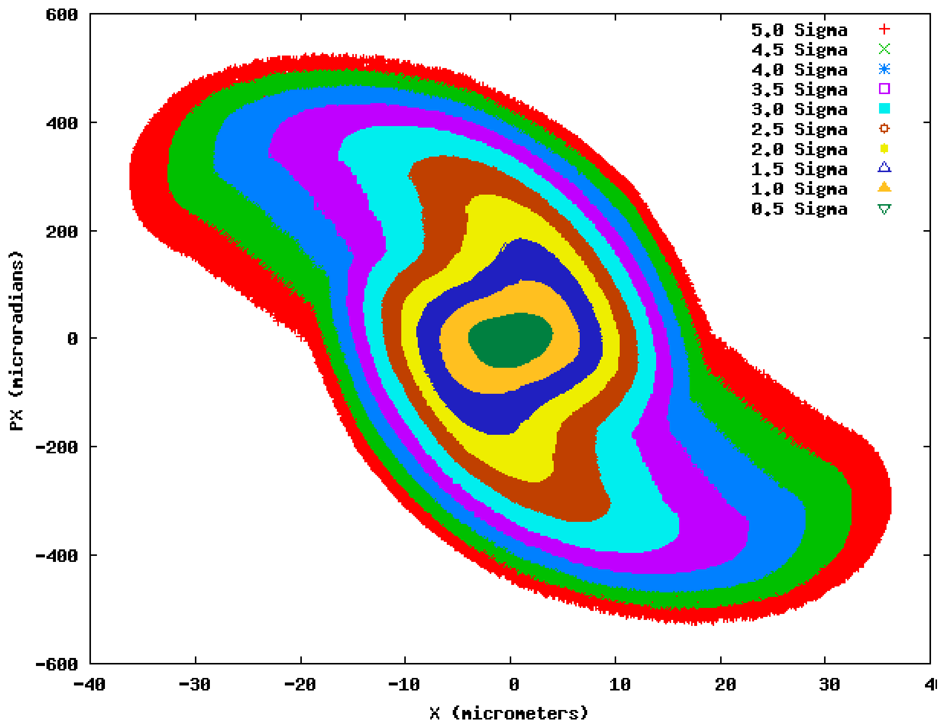
Beta Shift (growth rates)



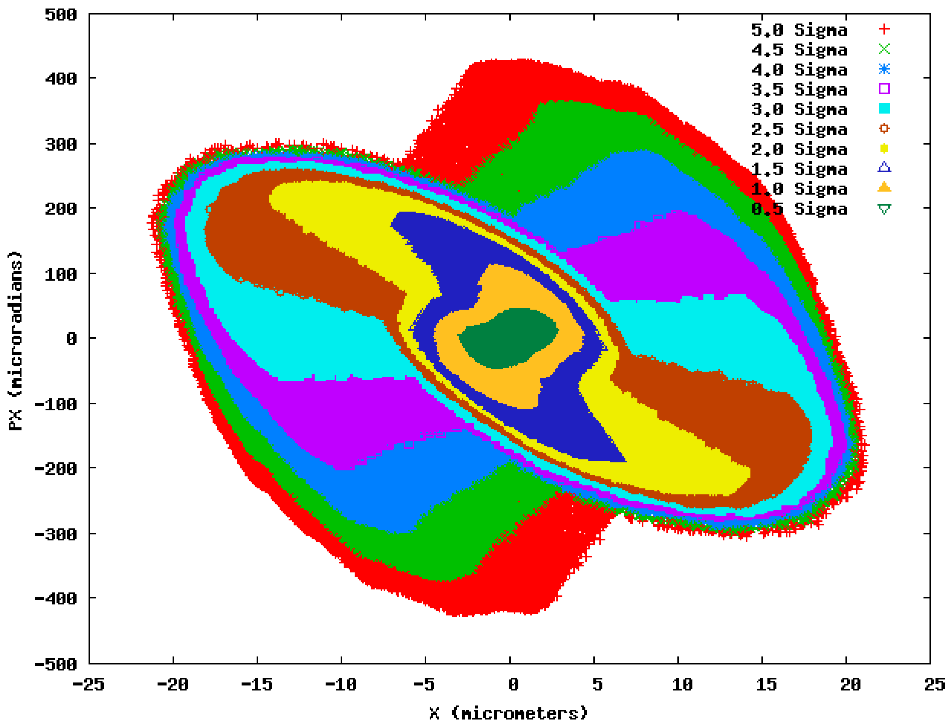


Spent Electron Beam (matching LHeC)

Nominal Parameters

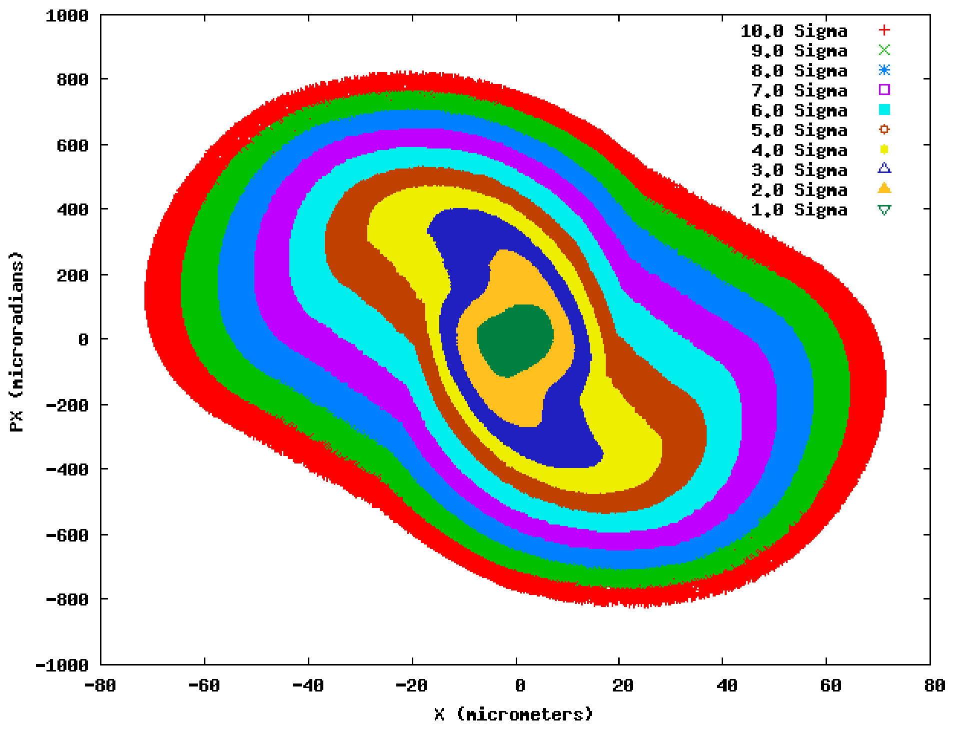


High Luminosity Parameters

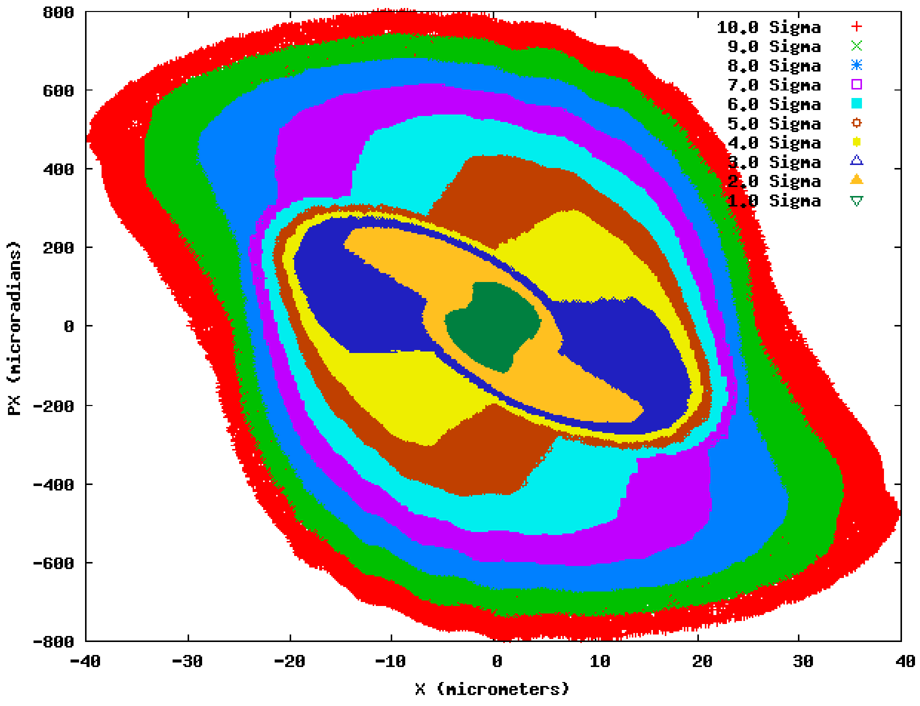


Spent Electron Beam (matching LHeC cont'd)

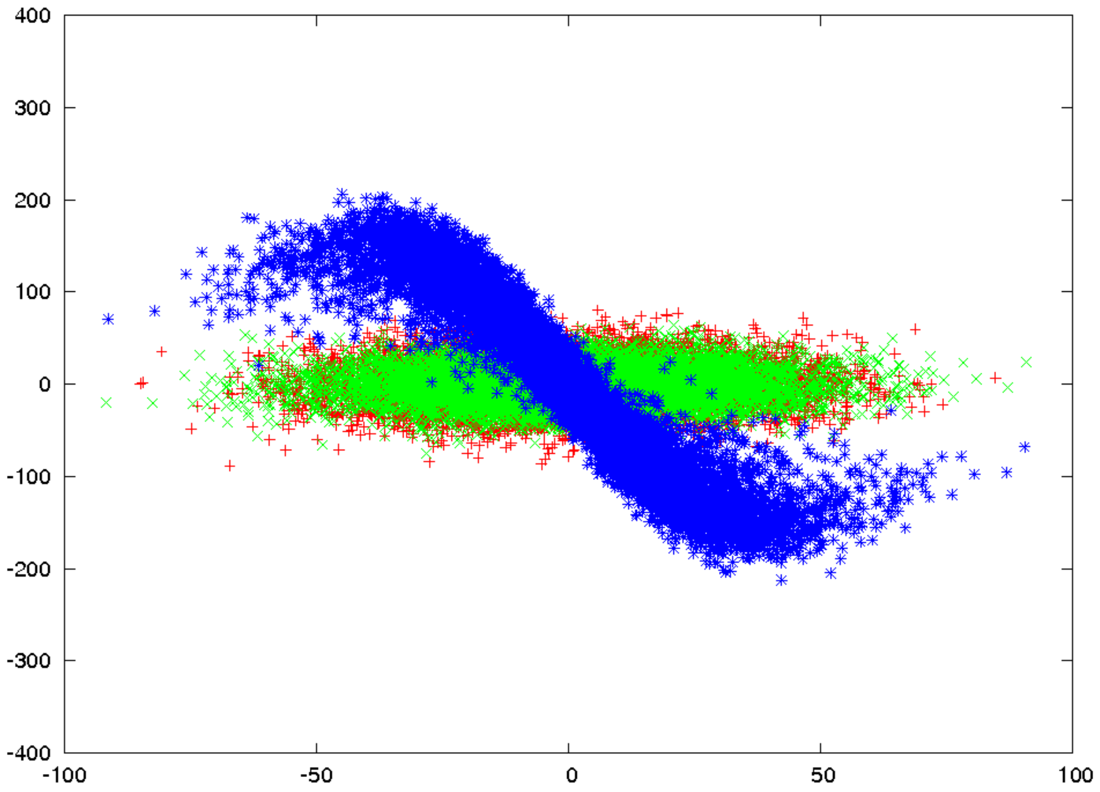
Nominal Parameters



High Luminosity Parameters

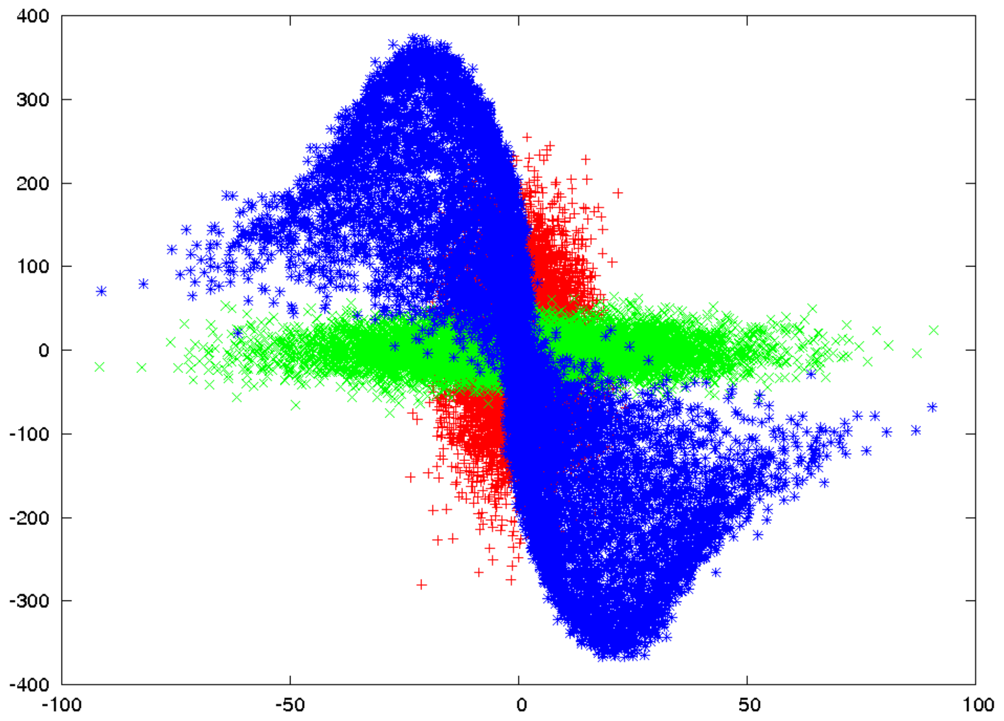


Betatron Squeeze



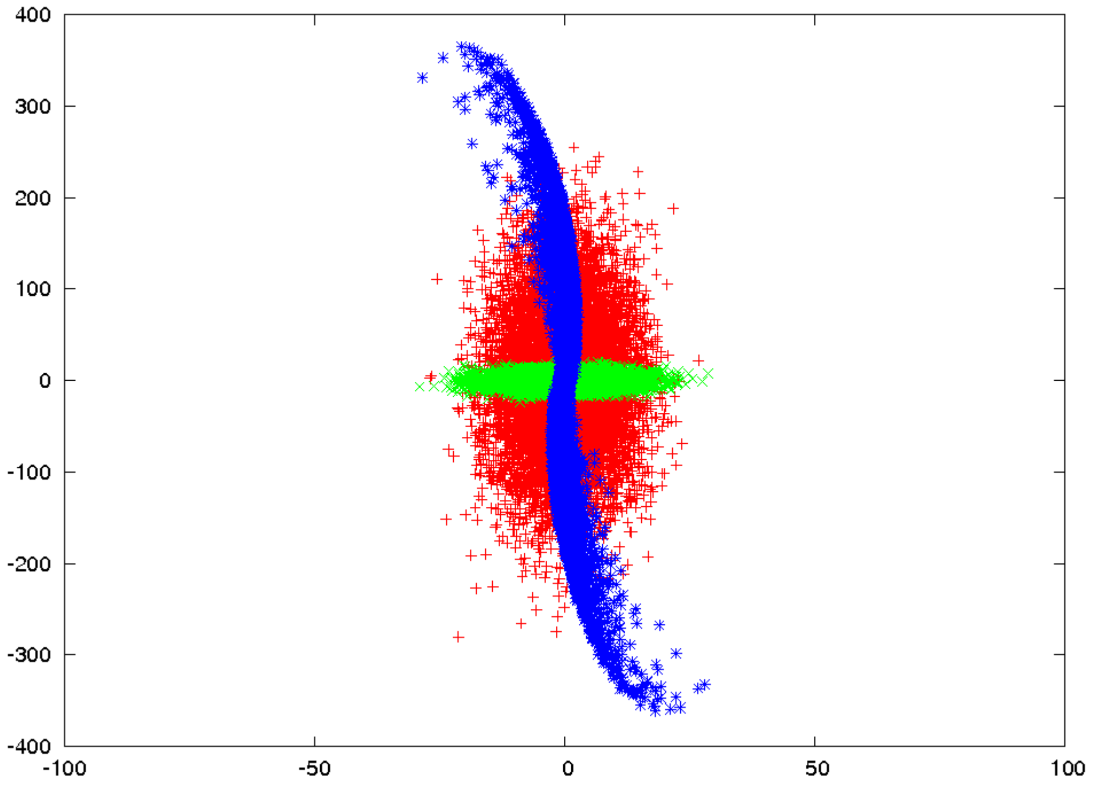
- Option 1, Squeeze both the protons and the electrons together while in collision.
- Reduces nonlinearities in the spent electron beam
- Difficult to achieve with simultaneous operations

Betatron Squeeze



- Option 2 Squeeze electrons into an existing proton beam
- Simple with simultaneous operations
- Nonlinear phase space downstream

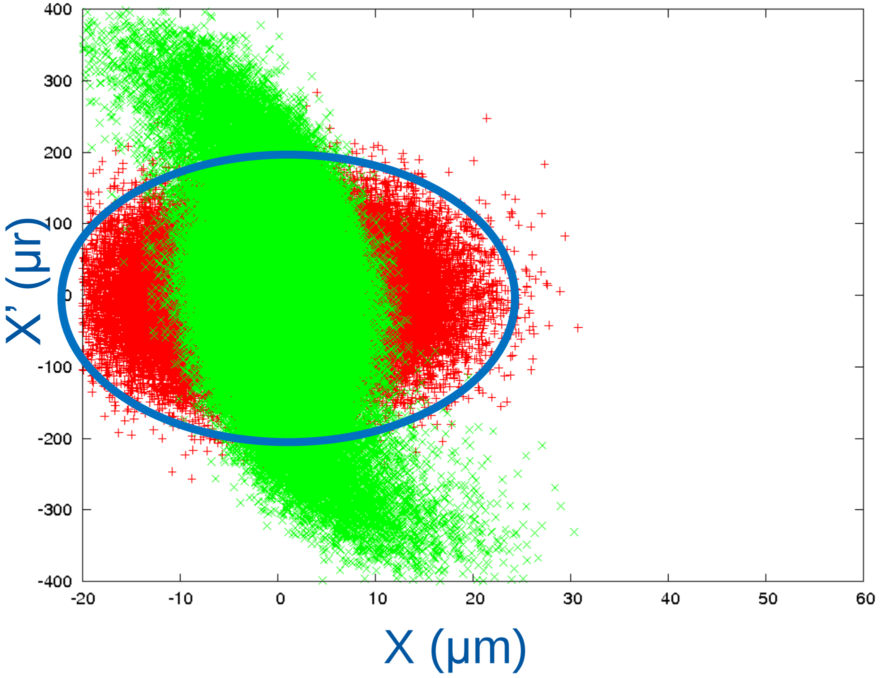
Betatron Squeeze



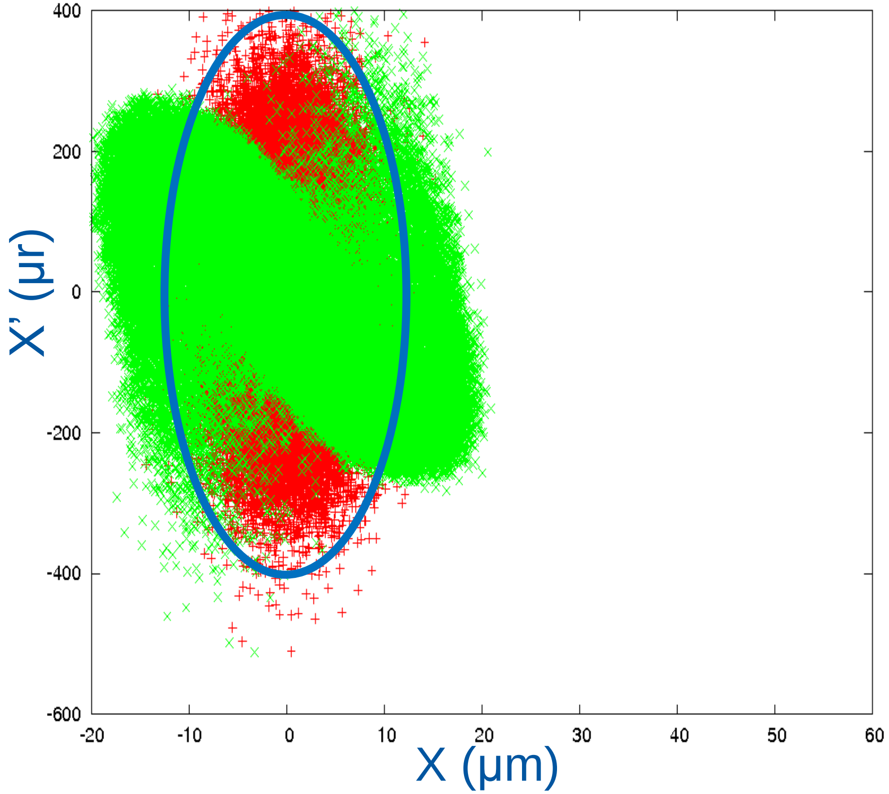
- Option 3, reduce electron emittance and increase along with squeeze
- Operates well with simultaneous operations
- Avoids nonlinear downstream issues
- Difficult to realize in practice

Spent Electron Beam (LHeC)

Nominal Parameters



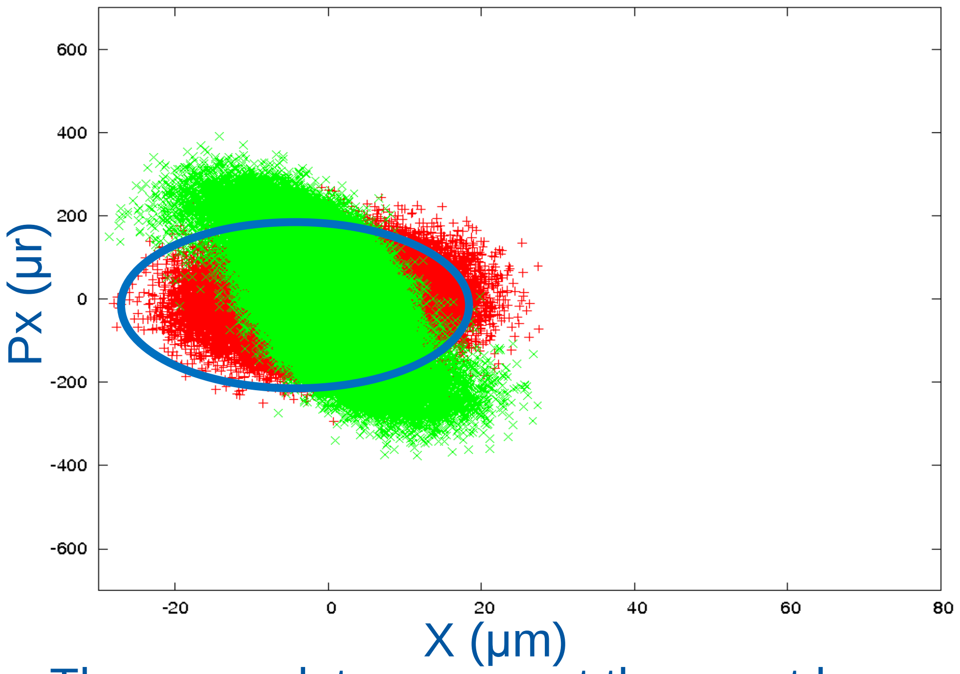
High Luminosity



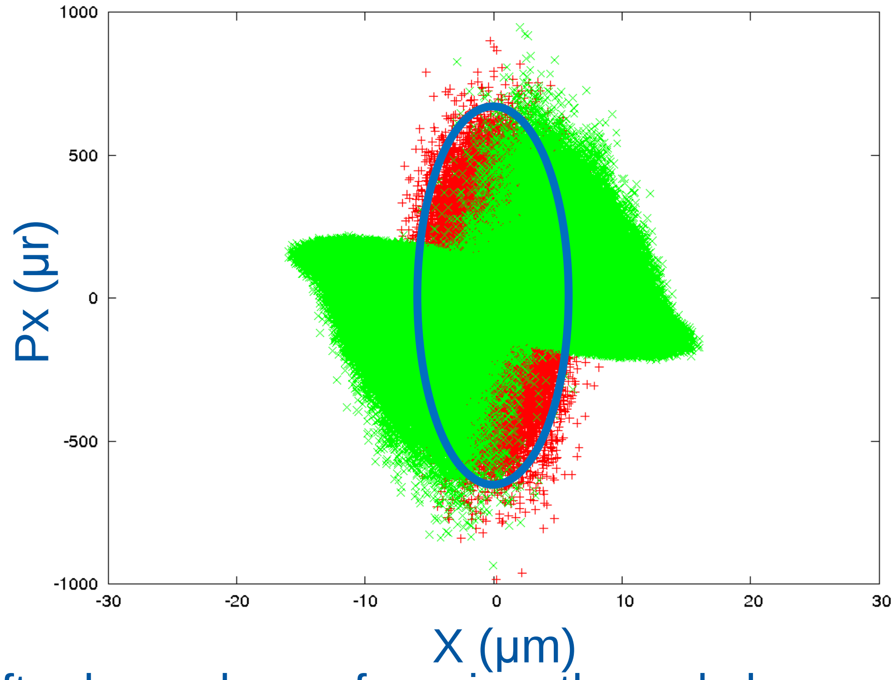
Red particles show the beam without beam-beam effects, green particles show the electron beam with beam-beam effects. Each frame is a single interaction at an increasing offset.

Spent Electron Beam (FCC-he)

Nominal Parameters

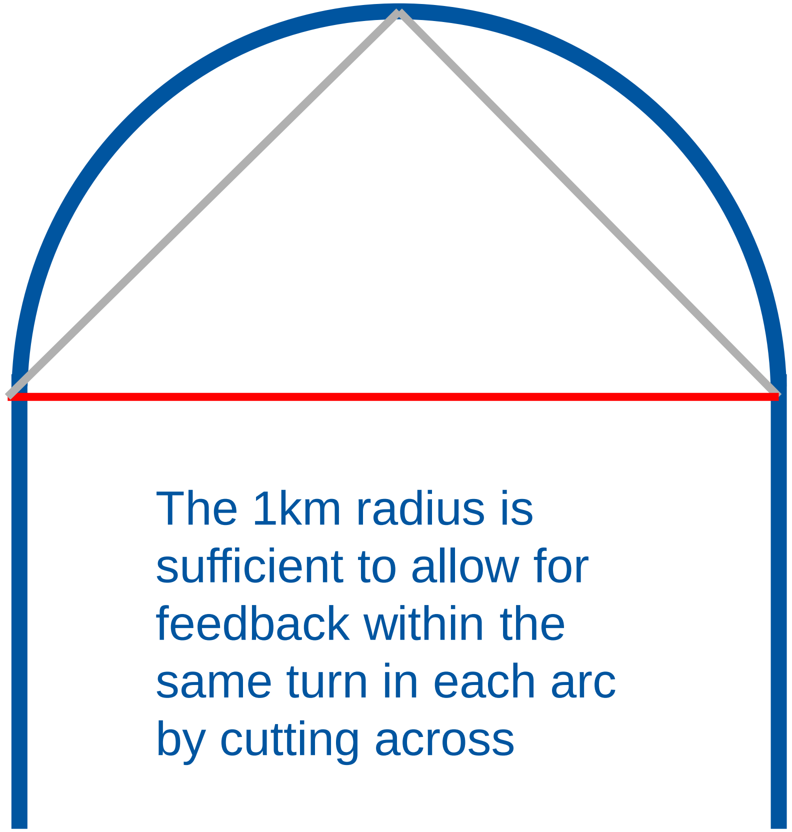


Ultimate Parameters



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.

Electron Linac (kicker correction system)



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

The 1km radius is sufficient to allow for feedback within the same turn in each arc by cutting across

Assuming a circular arc, with a depth of 56 m

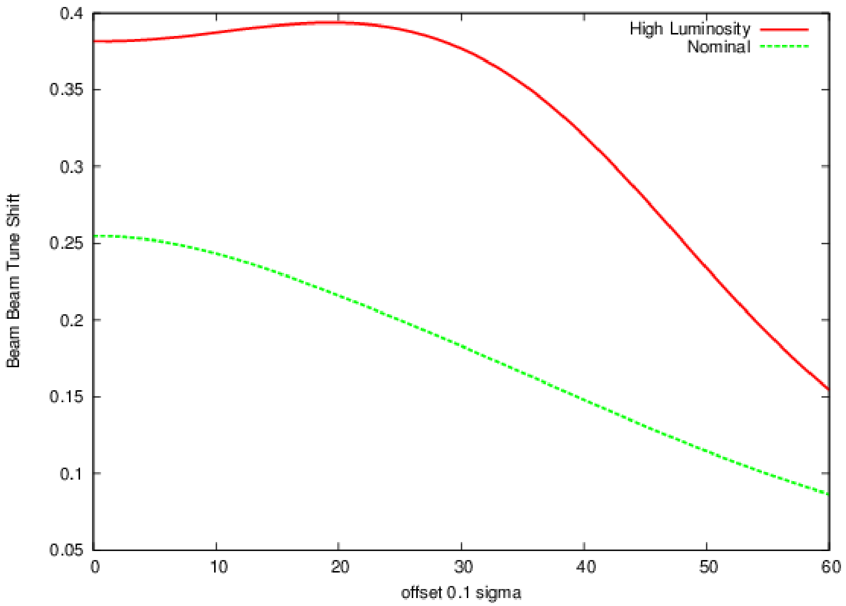
Using numbers from FONT1 latency is 65ns and voltage is 350 volts

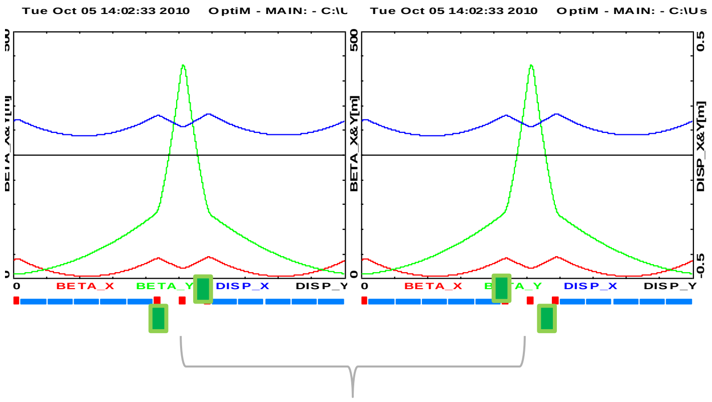
Electron Linac (kicker parameters)

Voltage	350 kicks	2			
energy	max kick μrad	beta	geometric emittance (nm)	σpx (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

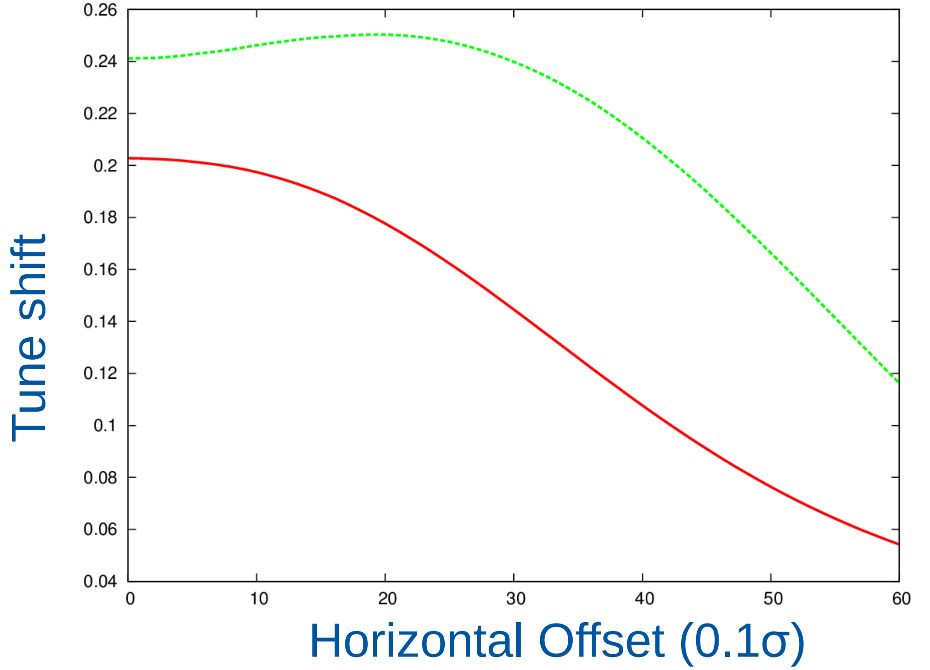
Electron Linac (tune shift correction)





Add Symmetric triplet cell

Correcting for the beam-beam induced tune shift could be accomplished with a pole tip voltage of less that 1.5 kV for a 1σ offset.



Difference at 1sigma is .011 for nominal and -.005826 for HL

Conclusions

- Beam Beam effects in asymmetric collisions provide some interesting physics
- Can be a limitation on beam lifetime and luminosity
- Can be managed if we don’t push the parameters too hard
- Correction Schemes can keep the beam jitter within acceptable limits
- Methods can be employed to correct for tune shifts from offsets