Beam-beam Effects in LHeC

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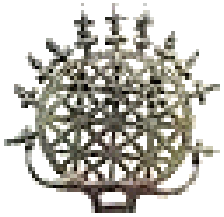
BB2013, CERN, March 2013

LHeC Goal

- Collide LHC beam with electrons or positrons
  - Required lepton energy is ≥60GeV
  - Luminosity of $\approx 10^{33} cm^{-2} s^{-1}$
  - Polarisation
  - No interference with pp physics
  - Detector acceptance down to 1°
  - Power consumption for lepton complex ≤100MW

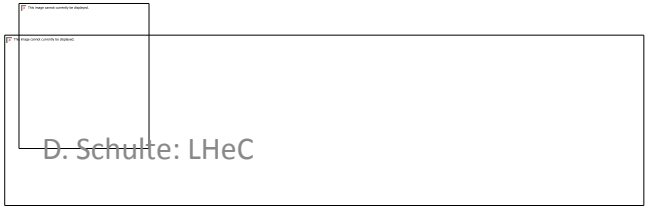
- Study team provided final version of CDR in 2012
  - Ring-ring option
  - Linac-ring option
  - Shows that a solution exists, will now have to find the best solution
    - Already have a baseline and alternatives for some components
  - See http://www.cern.ch/hec
  - The preferred option is the linac-ring design
    - Less interference with LHC

Participating Institutes

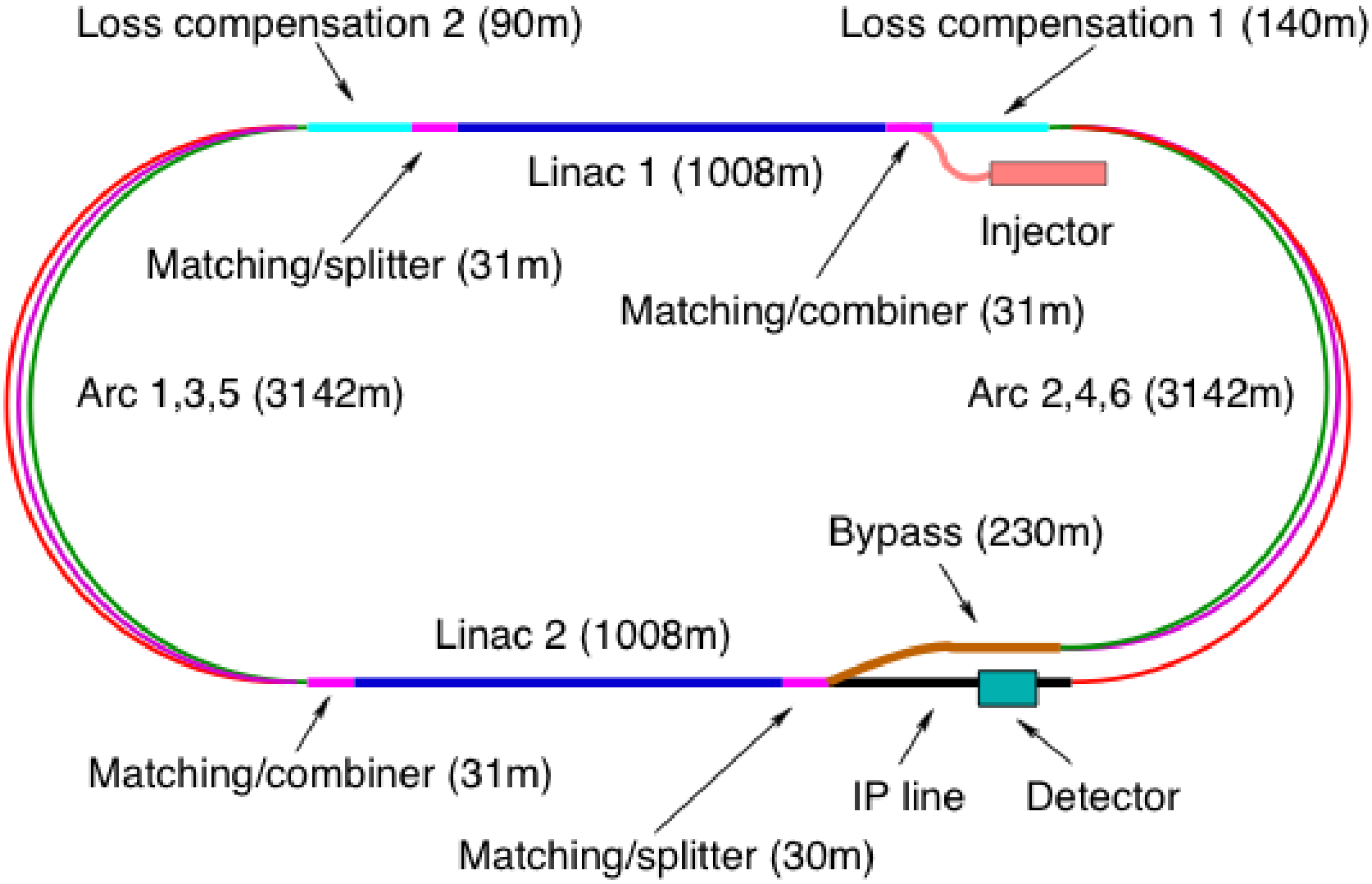


TOBB ETU

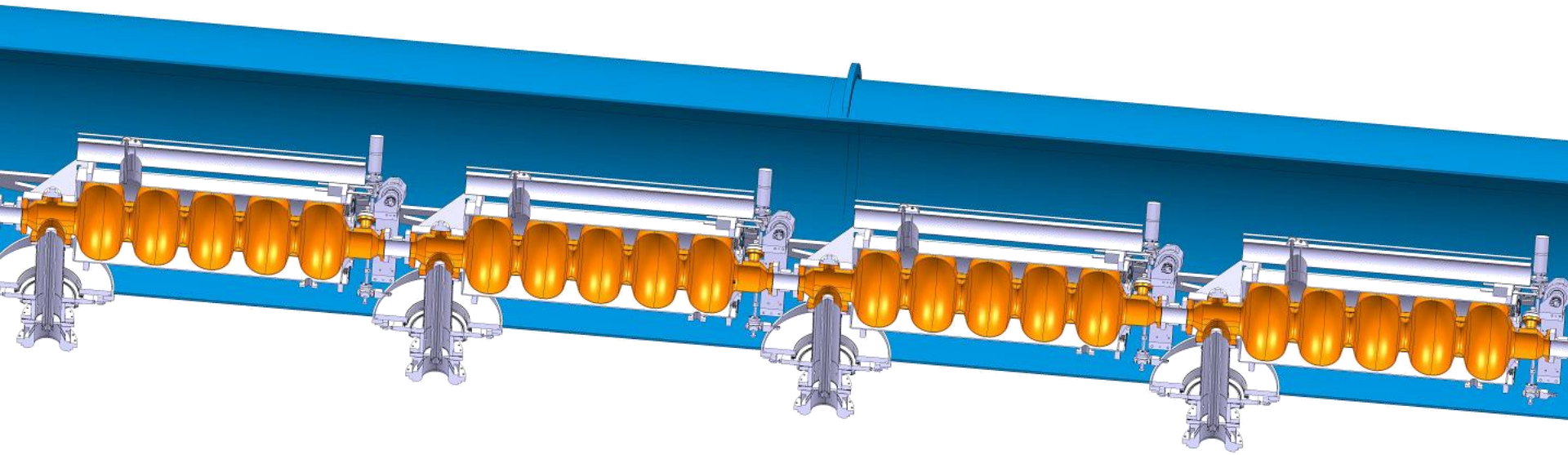
KEK



Baseline Linac-ring Layout

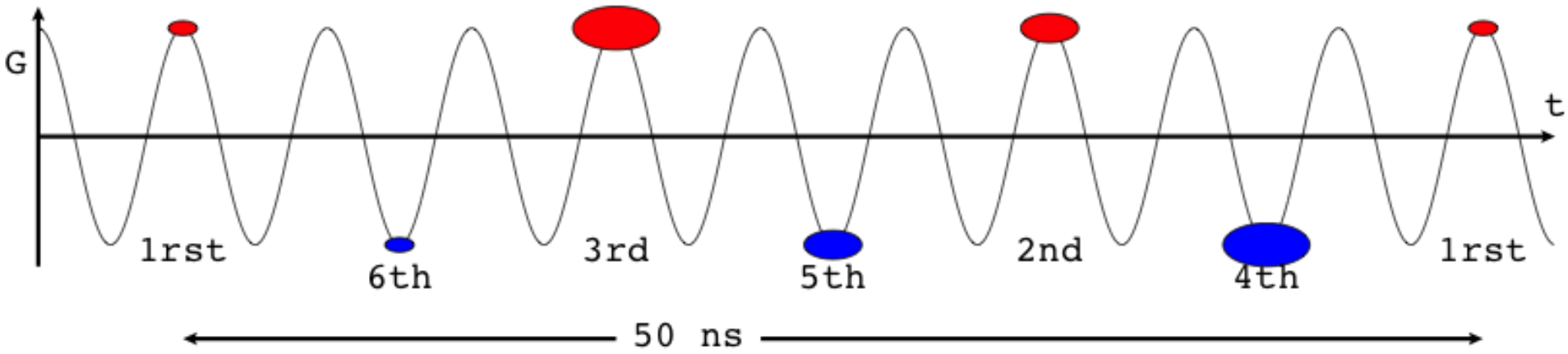


Linac Design



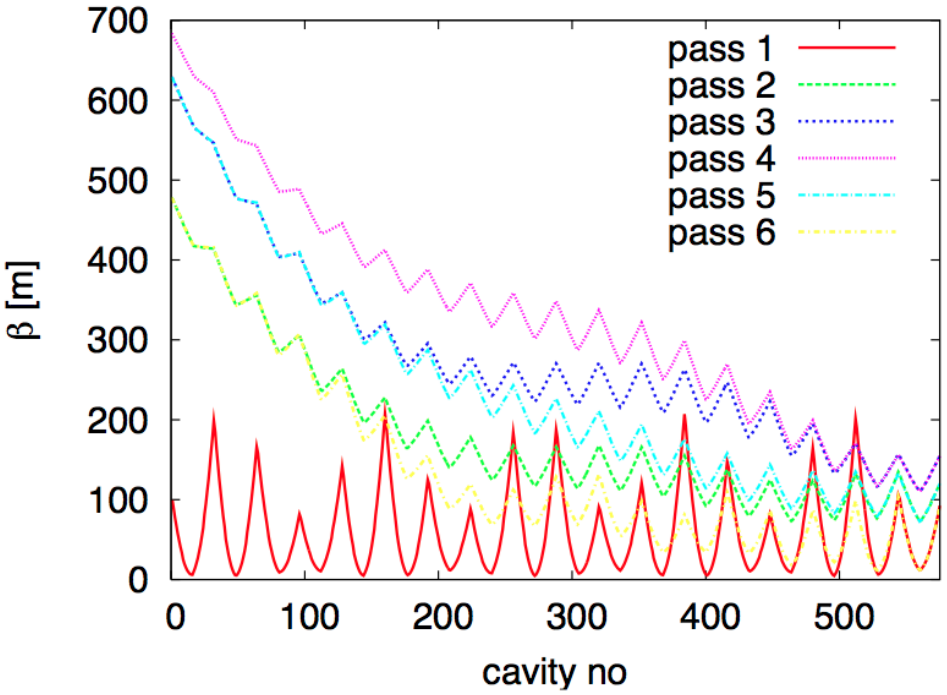
- In CDR: 8 cavities per 14m long module
  - 721.42MHz, 1.06m, 570Ω (linac convention), 20GV/m, (now 800MHz)
  - Will go to 802MHz
  - Q_0=2.5 10^{10} assumed, R=1.43 10^{13}Ω (ILC: R=1.04 10^{13}Ω)
- 2 modules per quadrupole pack (2m)
- ~60 modules per 900m long linac
- Beam physicists assumed slightly different parameters (and only 18MV/m)

Beam Structure in Linac



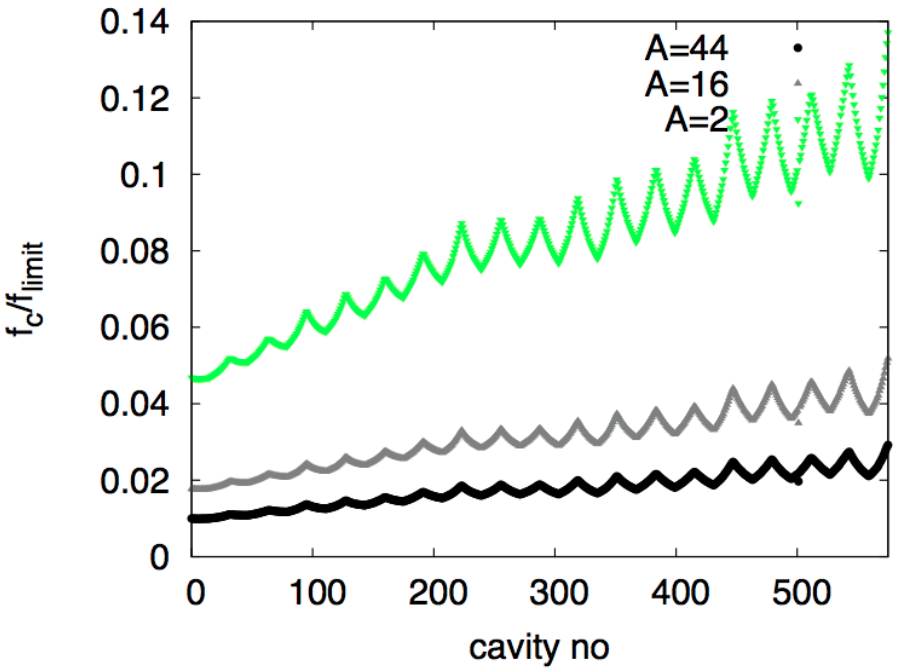
Bunches of different turns are interleaved

Interesting challenge for optics design and collective effects
- different energies
- wakefields
- fast beam-ion instability



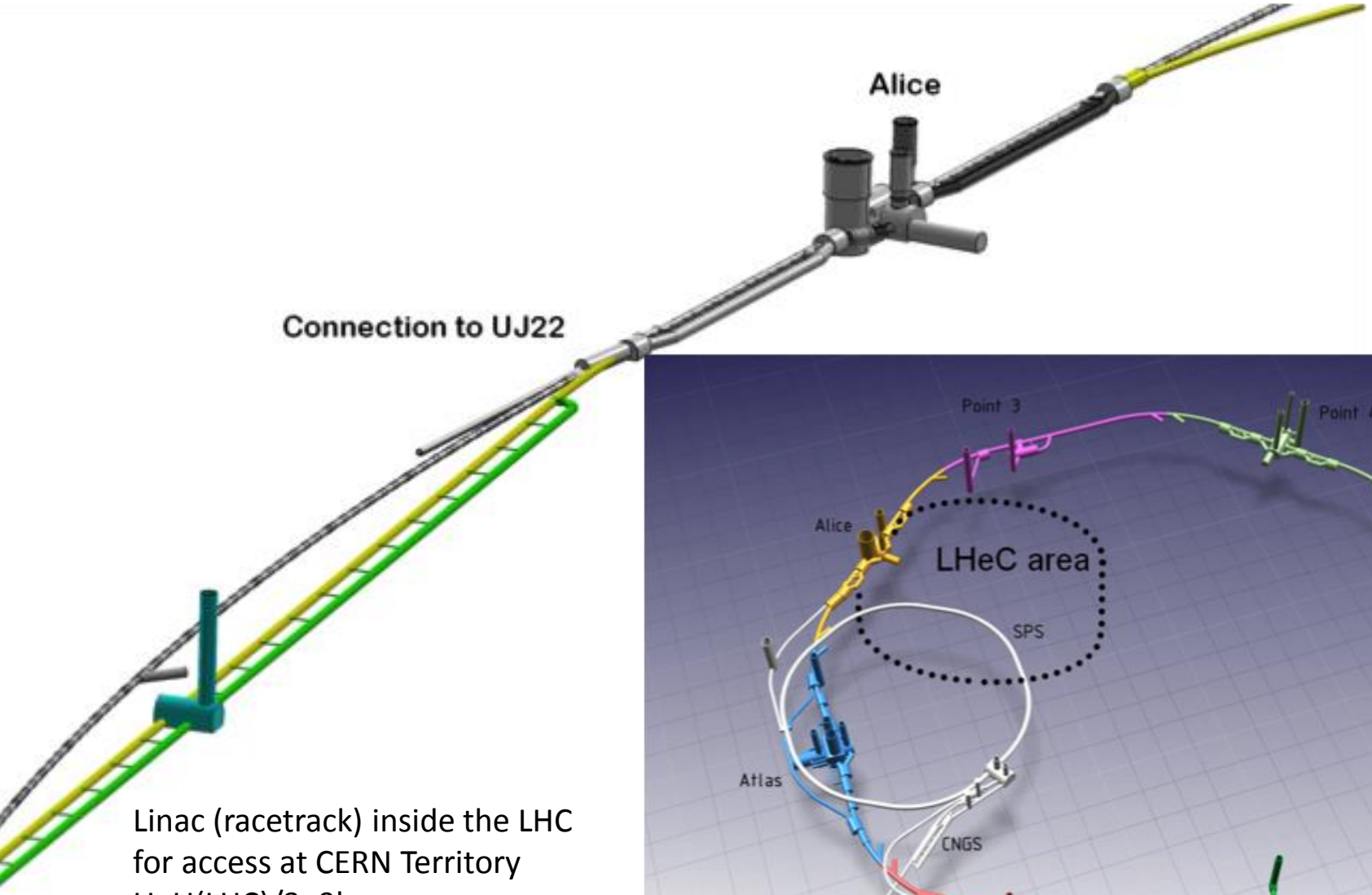
Potential Beam Pulse

- Parameter list does not consider gaps in LHC beam
  - Fewer bunches with more charge
- Fast beam-ion instability may require long gap
  - All ions are trapped in continuous beam ($f_c<f_{limit}$)
  - Beam will become unstable before neutralisation is reached
- Fix LHeC circumference to be 1/n of LHC
  - Each LHC bunch always or never collides with electron bunches



- Increase bunch charge by 50% to 3 10^9
  - Needs to be reviewed

Integration with LHC



Linac (racetrack) inside the LHC for access at CERN Territory
U=U(LHC)/3=9km

Interaction Region

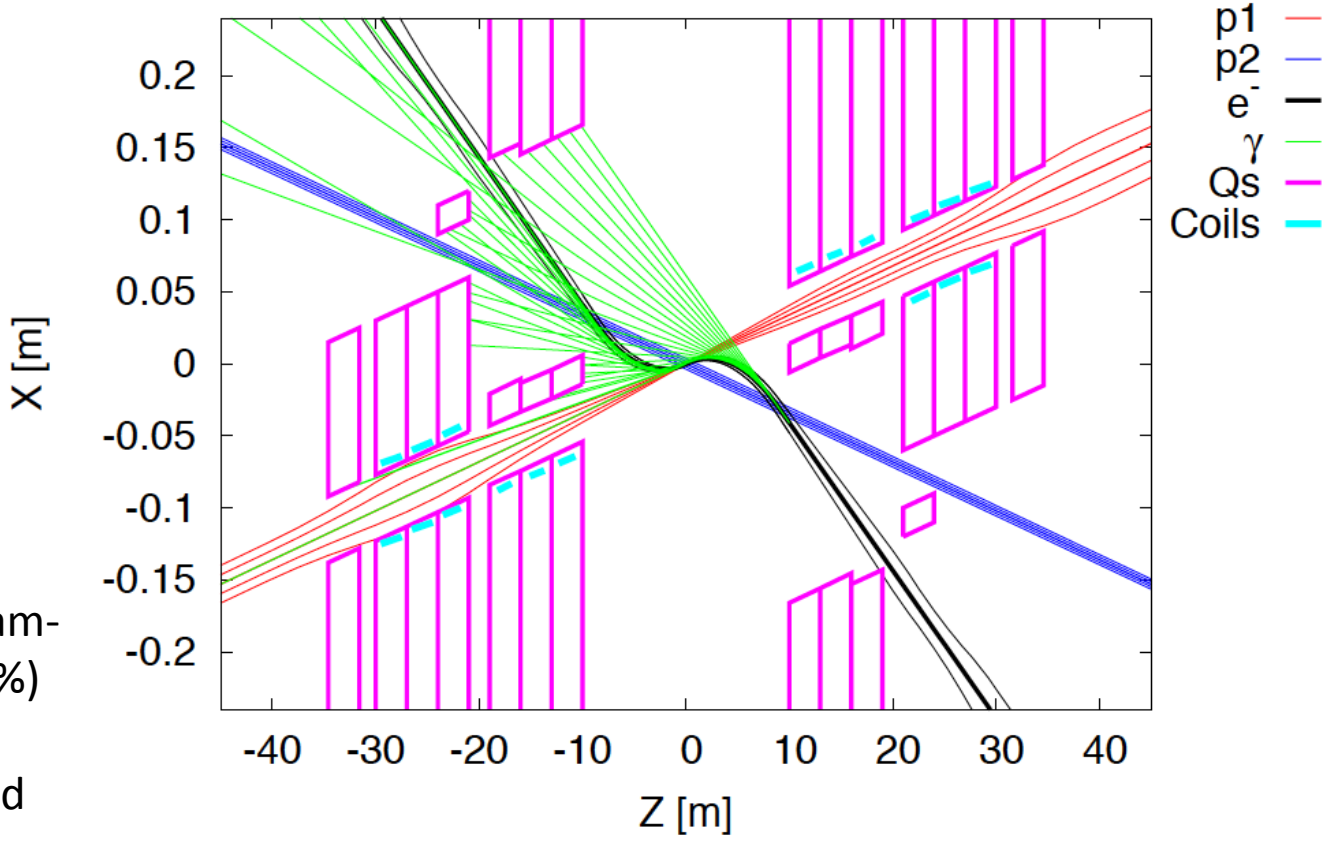
0.3T dipole field to allow head-on collision

Looked into spent electron beam, synchrotron radiation and beamstrahlung inside of the detector

Only started to look into beam-beam effects (still done at 0%)

Focus on colliding proton and electron beam for now

Assume simple head-on collision



Worst (best?) of two worlds: linac and rings

IP Parameters (ERL option)

	protons	electrons
beam energy [GeV]	7000	60
Lorentz factor γ	7460	117400
normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
geometric emittance $\varepsilon_{x,y}$ [nm]	0.50	0.43
IP beta function $\beta^*_{x,y}$ [m]	0.10	0.12
rms IP beam size $\sigma^*_{x,y}$ [μm]	7	7
rms IP divergence $\sigma'_{x,y}$ [μrad]	70	58
beam current [mA]	≥430	6.6
bunch spacing [ns]	25 or 50	50
bunch population	1.7×10^{11}	2×10^{9}
crossing angle	0.0	

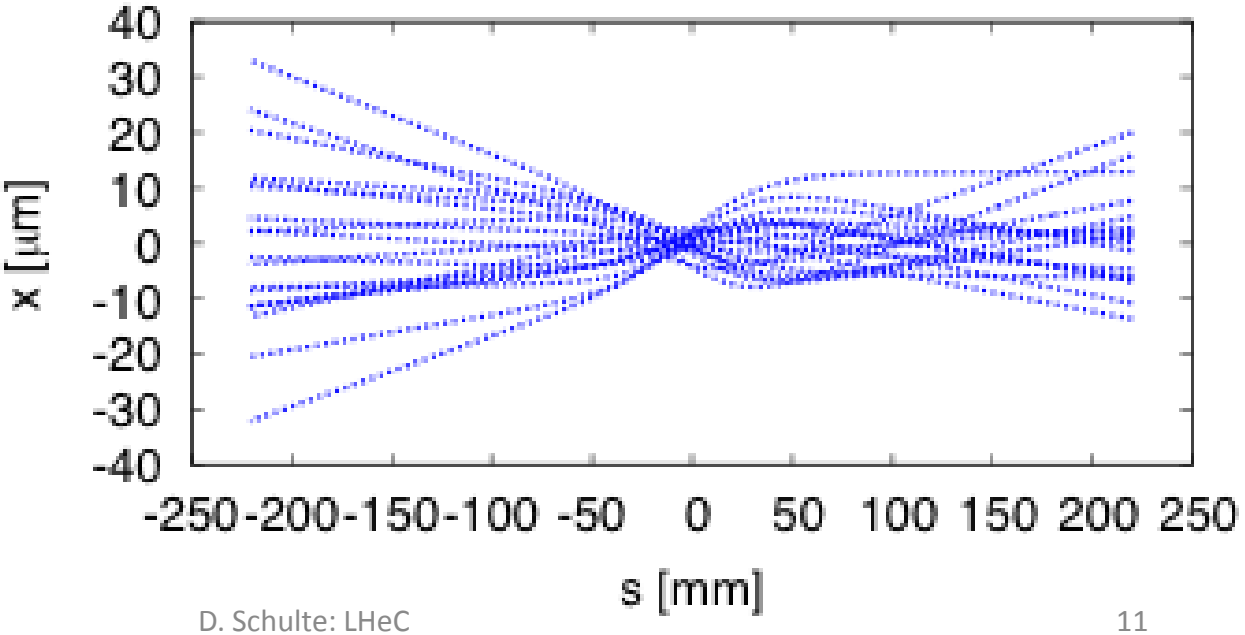
Beam-beam Effect

Beam-beam tune shift
10^{-4} for protons
0.8 for electrons

Disruption parameter
Ratio of focal length to bunch length
10^{-5} for protons (different values for $\sigma_{z,e}$)
6.2 for electrons

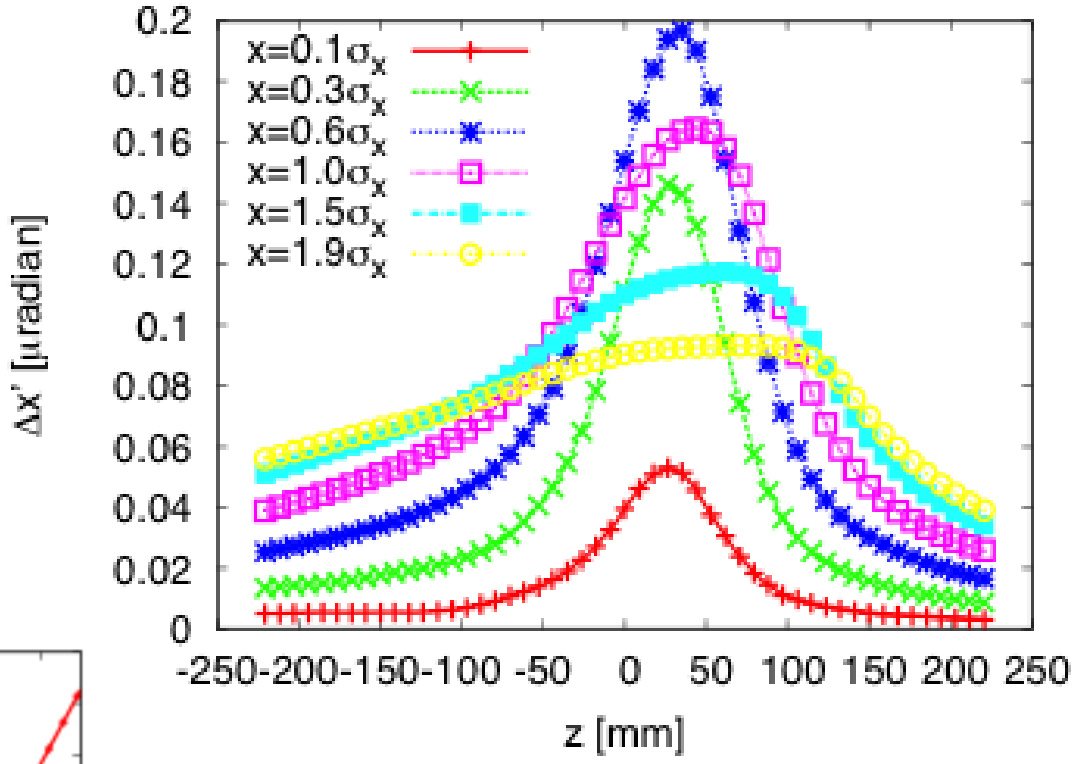
Electron trajectories at the collision point (coming from the right)

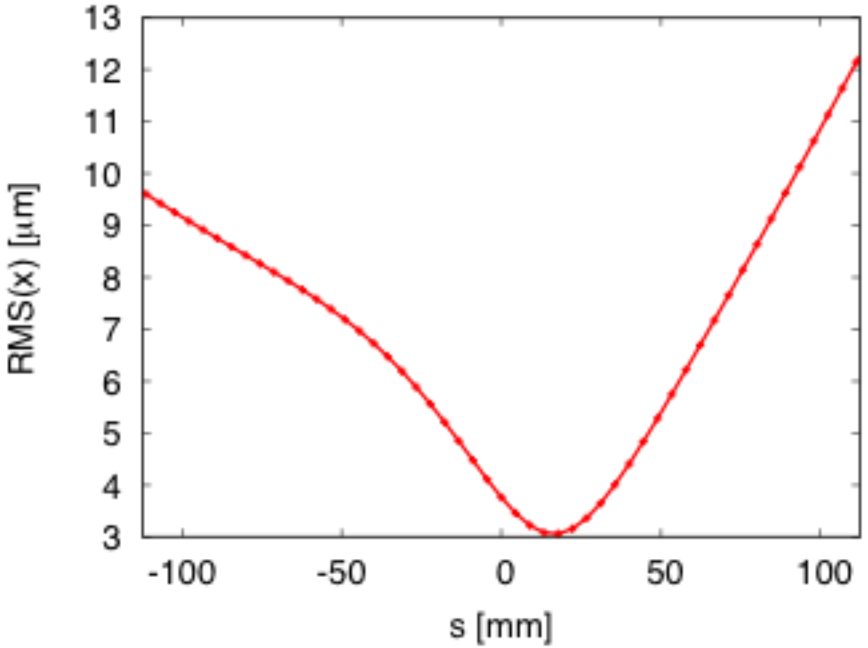
Electron behave like in a linear collider
Protons like in a storage ring



Force of Electron Bunch

Due to strongly changing electron beam size the force on protons changes as well





Minimum electron beam size less than half the nominal

Largest proton deflection at $x=0.6\sigma_x$

Beam-beam Code: GUINEA-PIG

- Strong-strong code developed for linear colliders
  - Splits beams into slices
  - Can read/write particle files or generate distributions on the fly

- Includes
  - Beam-beam force/pinching
  - Emission of beamstrahlung
  - Production of electro-magnetic and hadronic background
  - Tracking of background

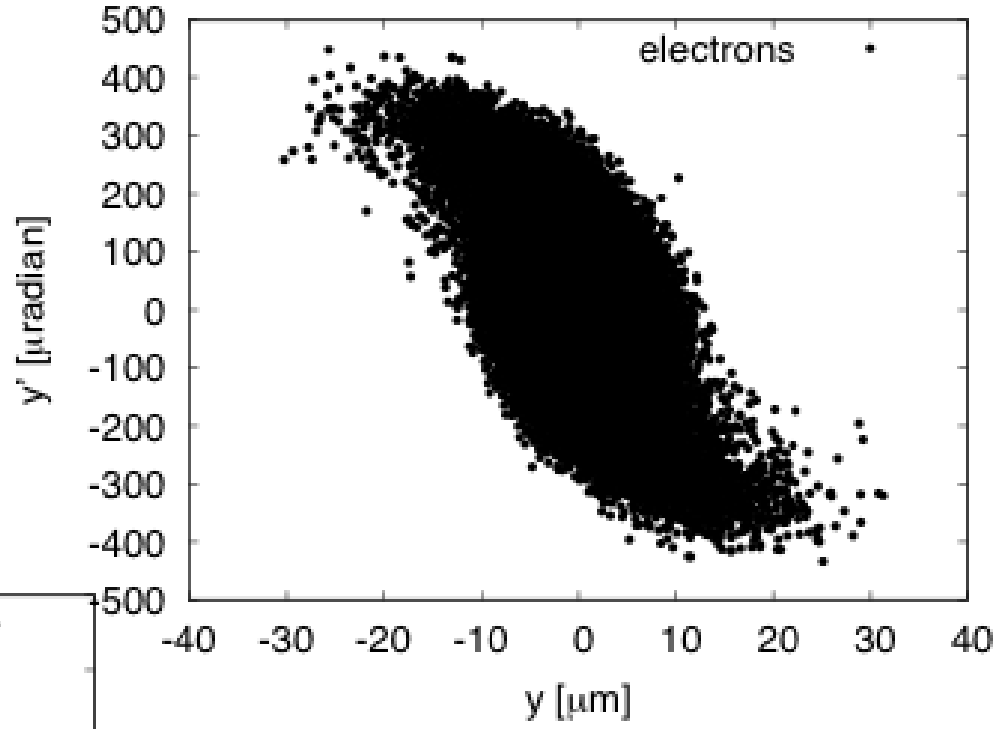
- Simulates electron-proton collision in 4s on my laptop
  - 10^5 particles, 51 slides, 128x128 cells
  - Could be made faster by removing unnecessary parts

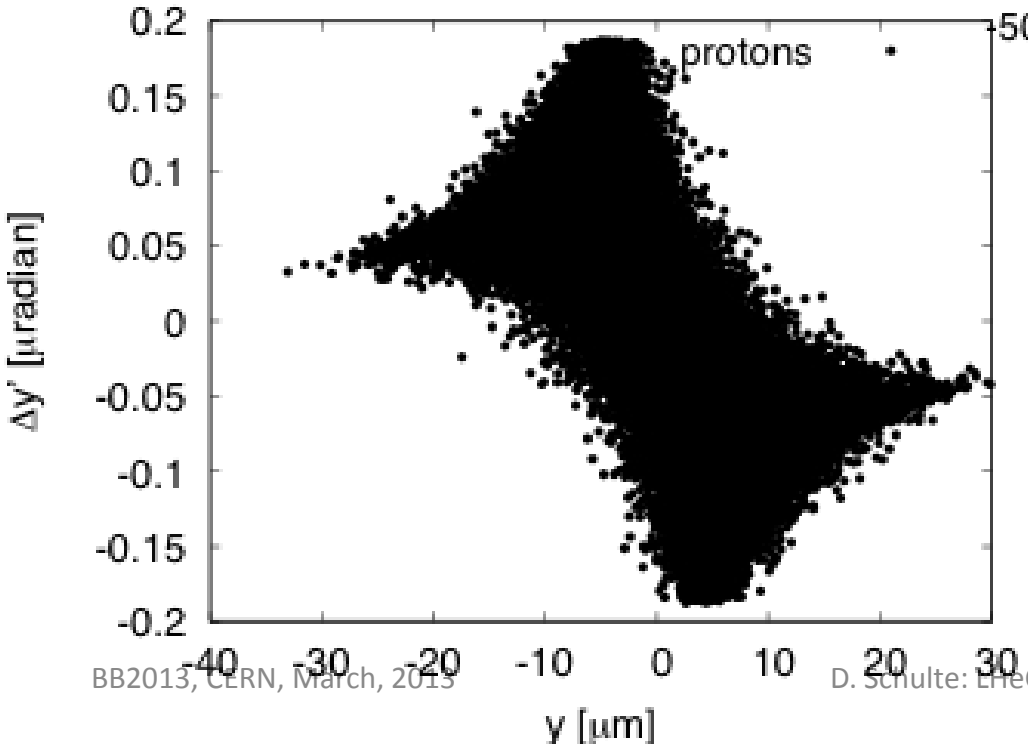
Electron Phase Space

The electron beam is strongly disrupted by the proton beam

Leads to strong mismatch of outgoing beam with current optics

Pinch effect enhances luminosity by 38% (positrons would be 1/3)





Deflection of protons is small compared to divergence (70μradian)

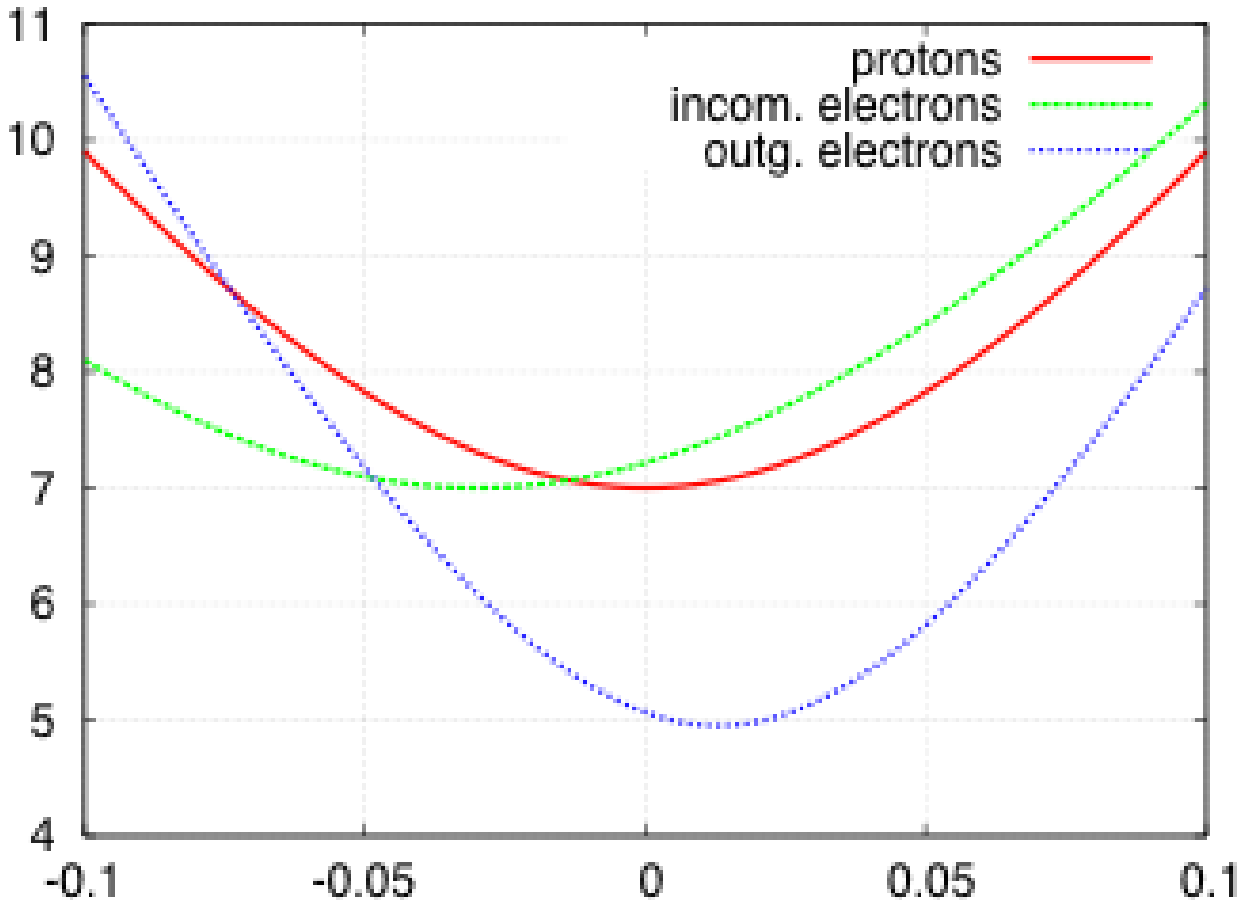
Hence only calculate deflection

For impact on electrons could use weak-strong model

Optics Adjustments

Proton beam acts as a strong lens
-> consider mismatch of incoming and outgoing electron optics to account for this
-> described by different waist positions and by different beta-functions in the waists

Leads to mismatch for non-colliding beams and particles at large amplitudes



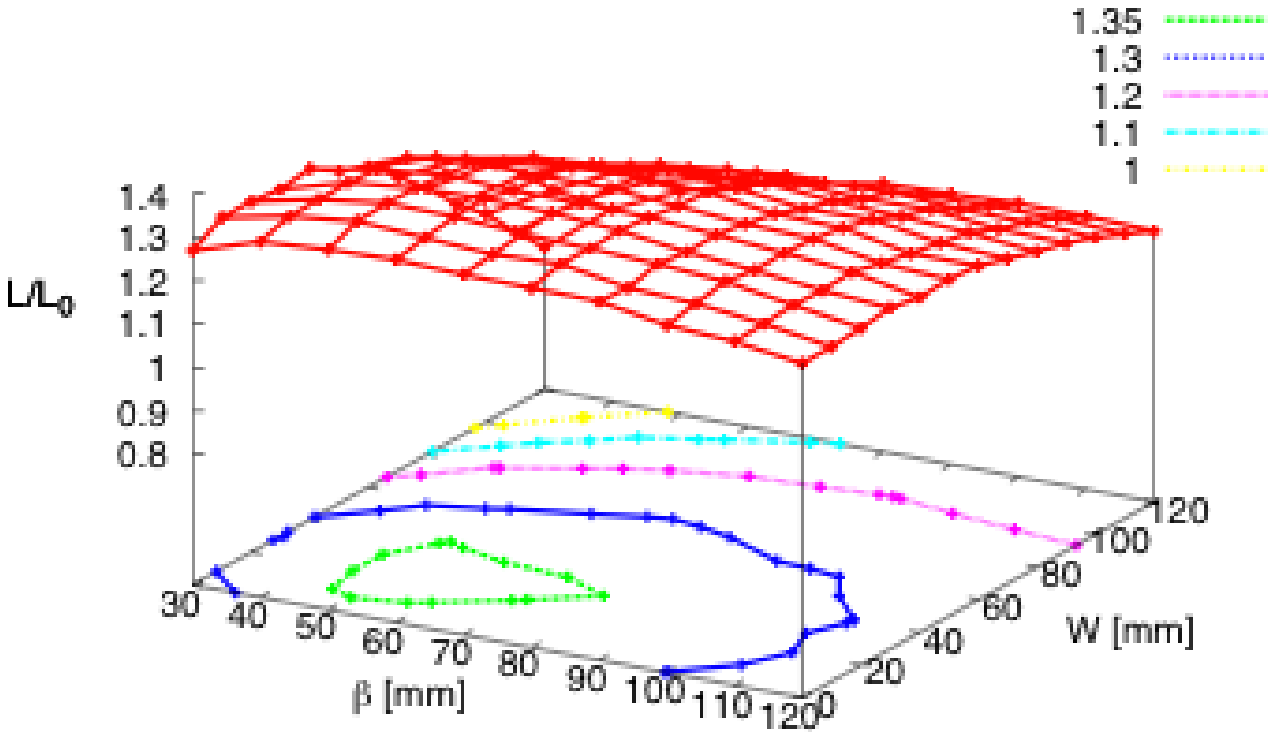
Optimum Beta-function and Waist Position

In linear colliders shifting the waist before the collision point increases the luminosity due to strong disruption

Nominal parameters L=1.26 $10^{33}cm^{-2}s^{-1}$

Best waist (30mm before IP) L=1.28 $10^{33}cm^{-2}s^{-1}$

Best beta (60mm) and waist (30mm) L=1.36 $10^{33}cm^{-2}s^{-1}$

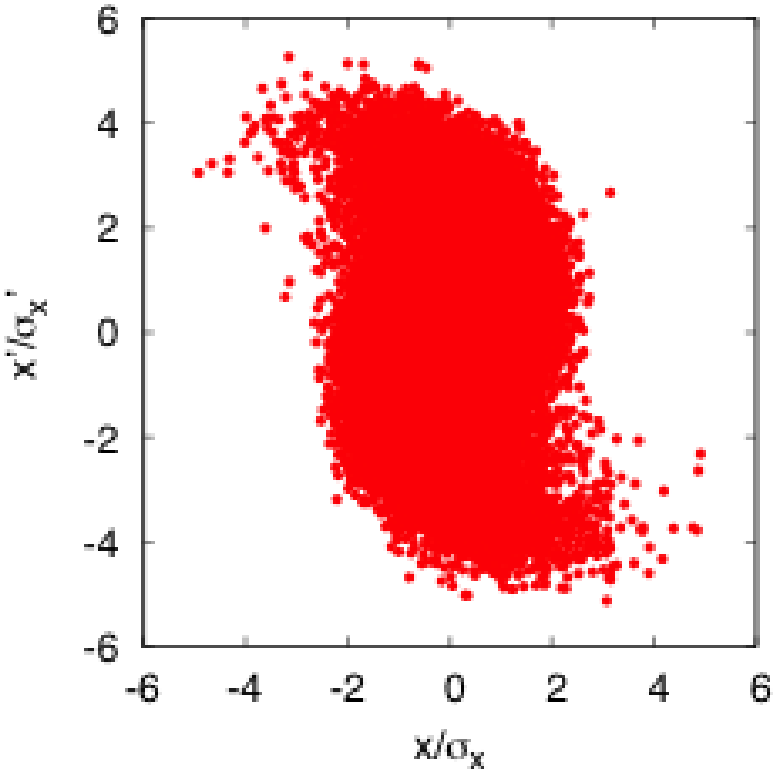


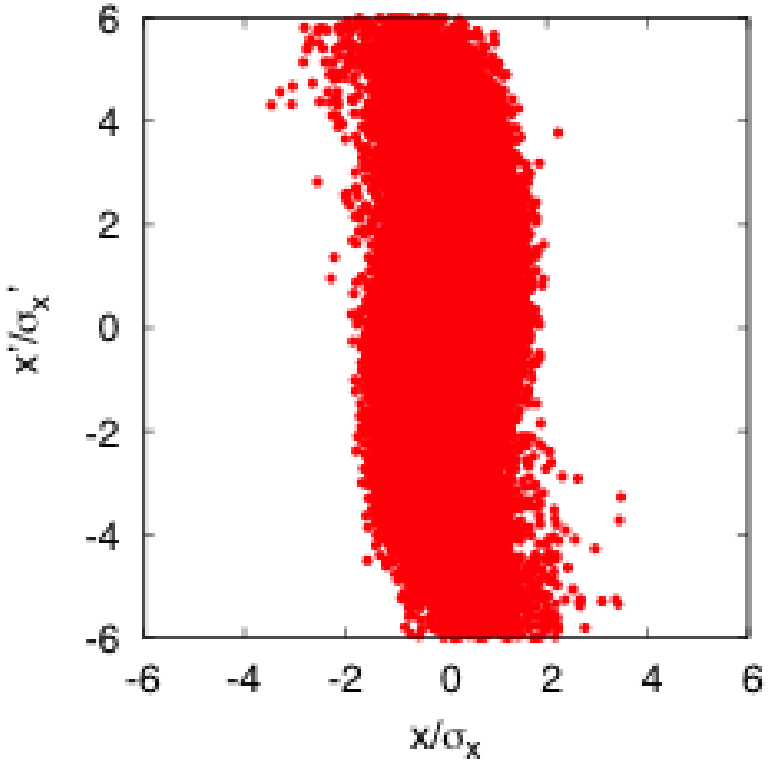
Small gain in LHeC, since only electron beam is disrupted

Spent Electron Phase Space

Nominal case, waist shift has little impact

Outgoing phase is distorted
-> remove correlation with waist shift
Straightforward
-> match beta of spent beam line
Requires new design





Good choice is W_{extr}=23mm and β_{extr}=6cm

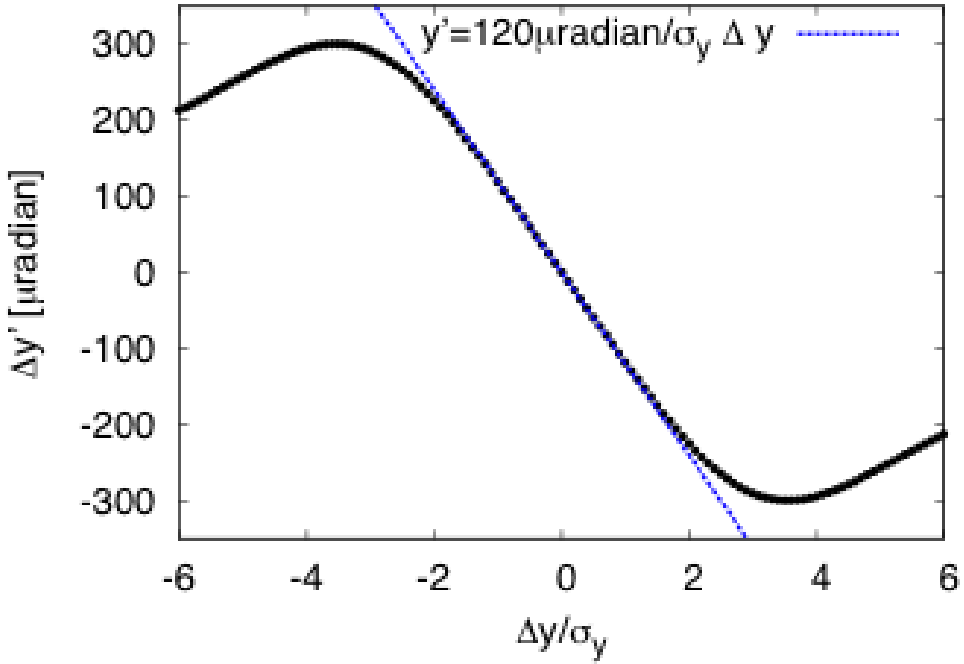
Both changes causes some trouble for non-colliding beam
-> operational constraints need to be studied

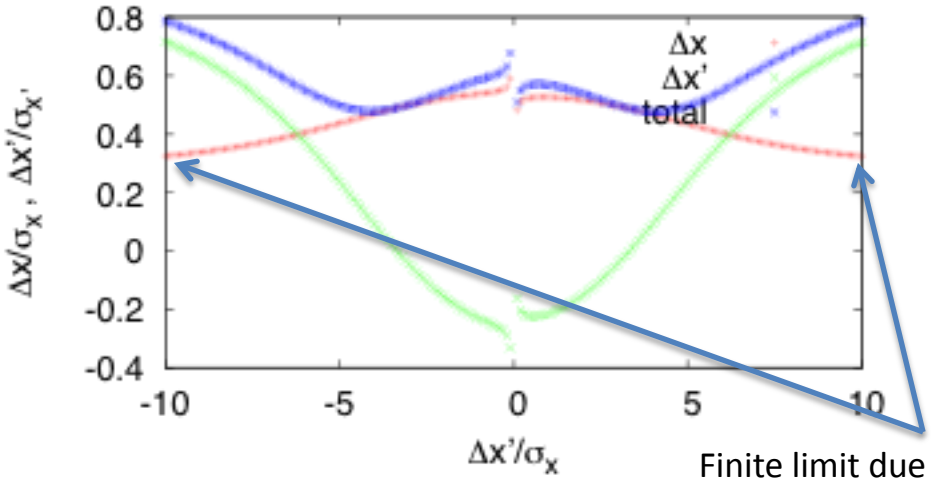
Beam-beam Deflection

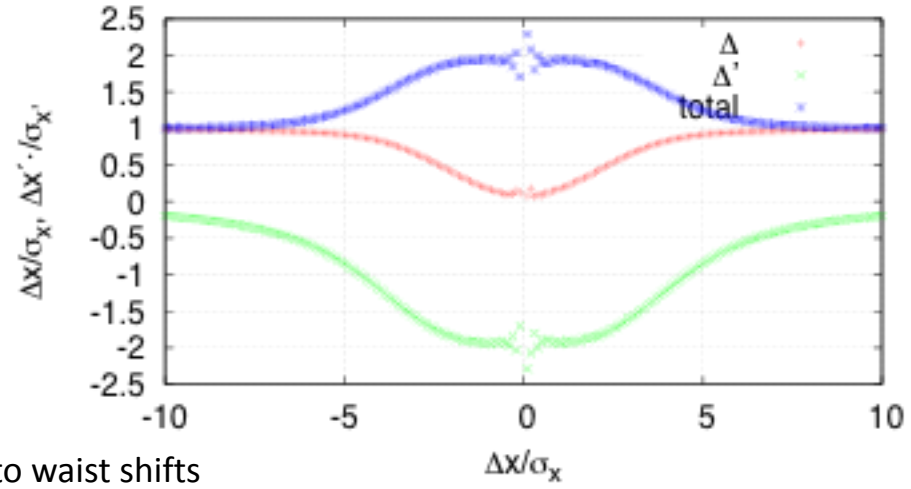
Strong deflection of electron beam
For nominal case:

Action of bunch centre can be amplified

Proton bunch deflection is 1.5 10^{-4} times smaller, maximum is 6.5 10^{-4} $\sigma_{x'}$







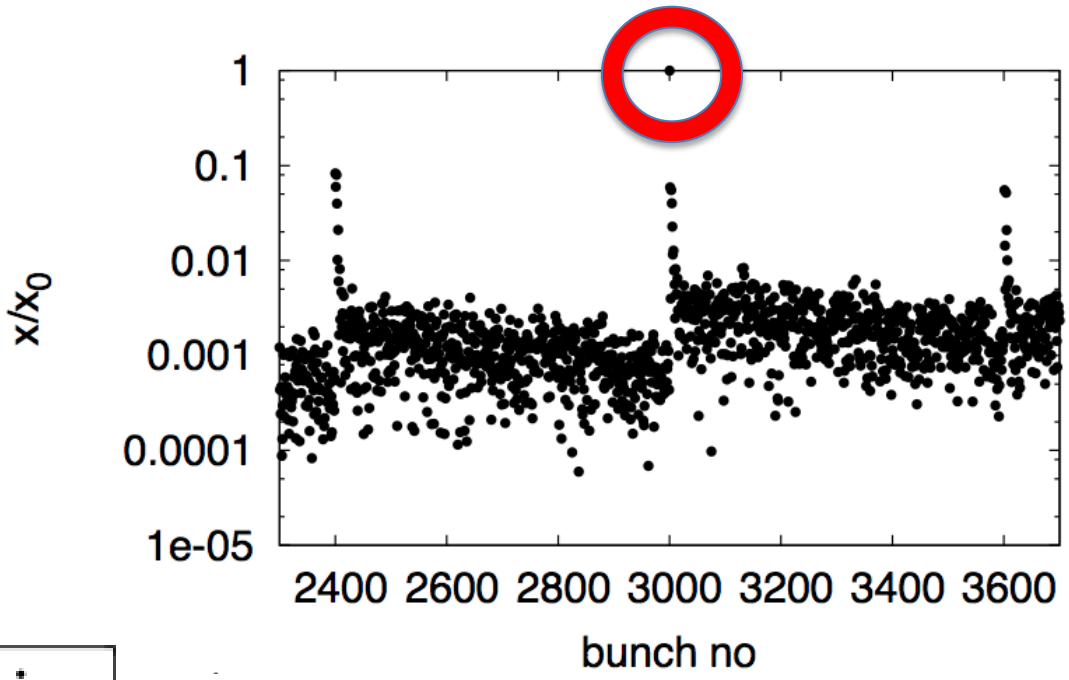
Finite limit due to waist shifts

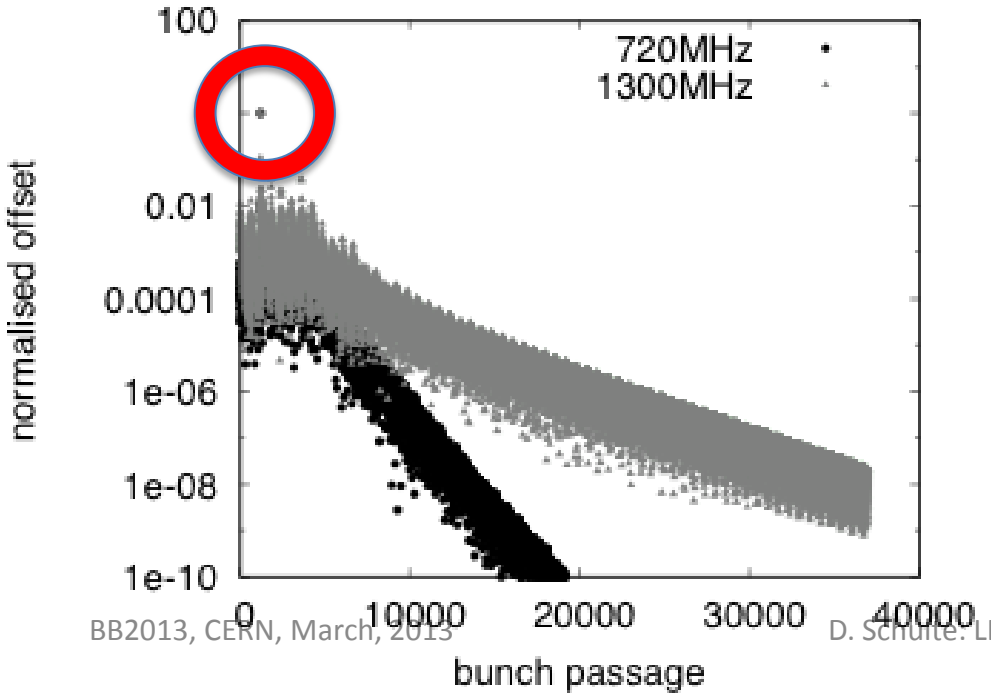
Multi-bunch Beam Break-up

- ILC cavities from TESLA TDR
- SPL cavity dipole modes from M. Schuh, assume $Q=10^5$
- 0.1% mode detuning in both cases

Dedicated code:

- Point-like bunches
- Response to one offset bunch
- O(1minute) for 4 10^4 bunches





Use increased charge N=3 10^9 but ignore gaps

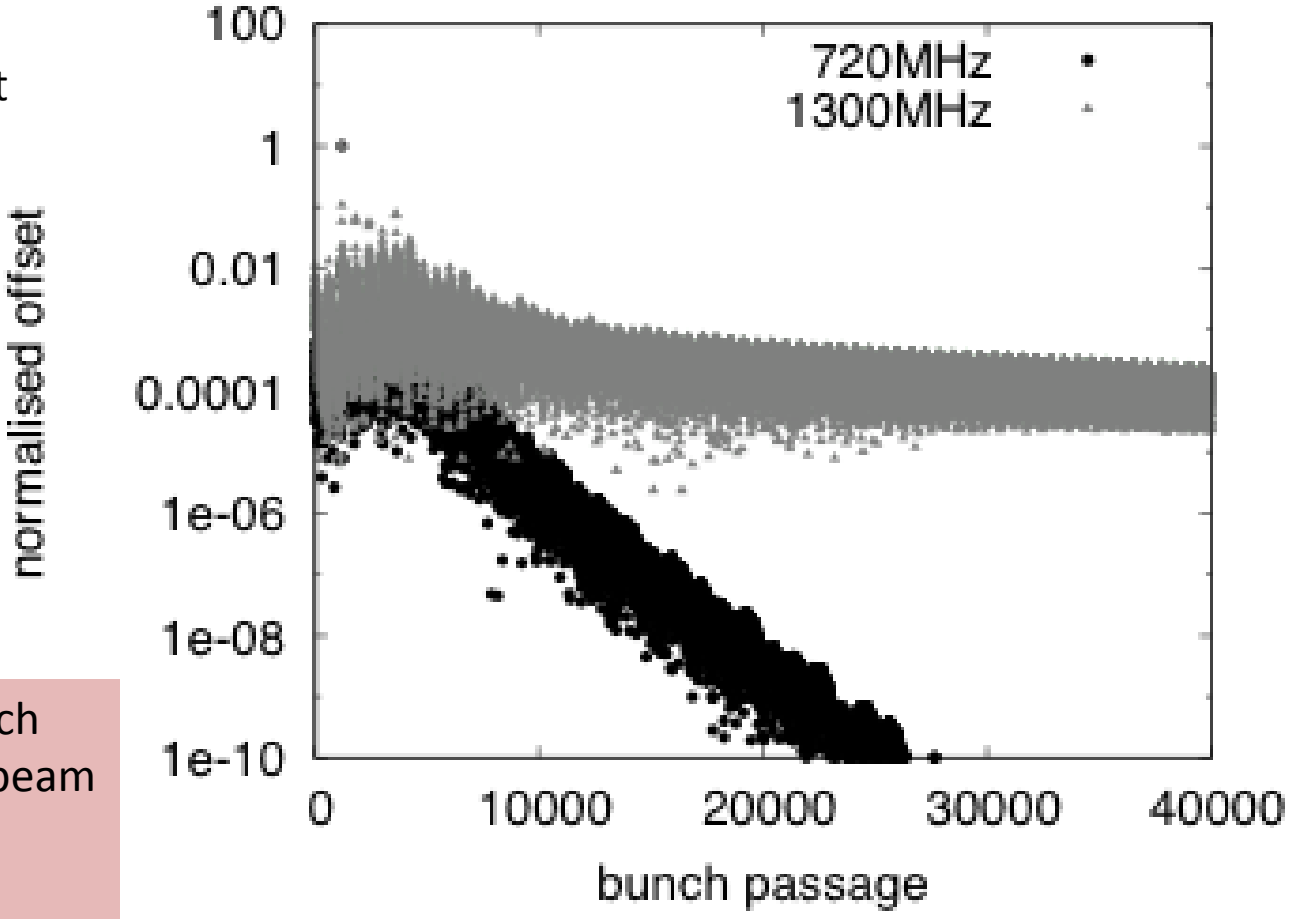
F_{rms}=1.05 for ILC cavity
F_{rms}=1.001 for SPL cavity

Multi-bunch Instability and Beam-beam

N=3 10^9
Beam-beam effect included as linear kick (using small offset values)

Result depends on seed for frequency spread
"worst" of ten seed shown

F_{rms}=1.135 for ILC cavity
F_{rms}=1.002 for SPL cavity



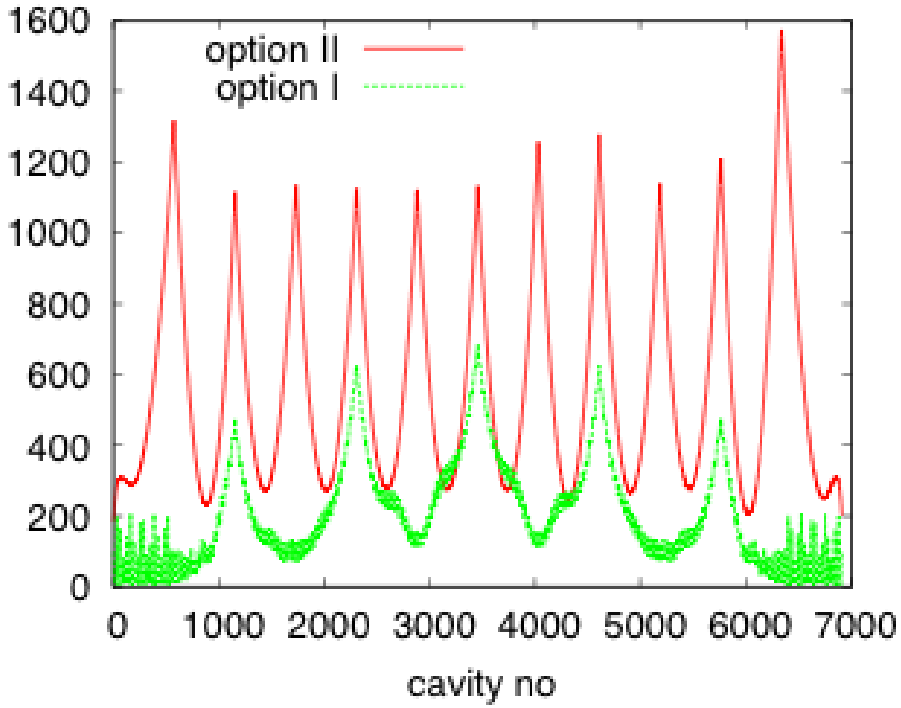
Coupling between multi-bunch wakefield effects and beam-beam is very important

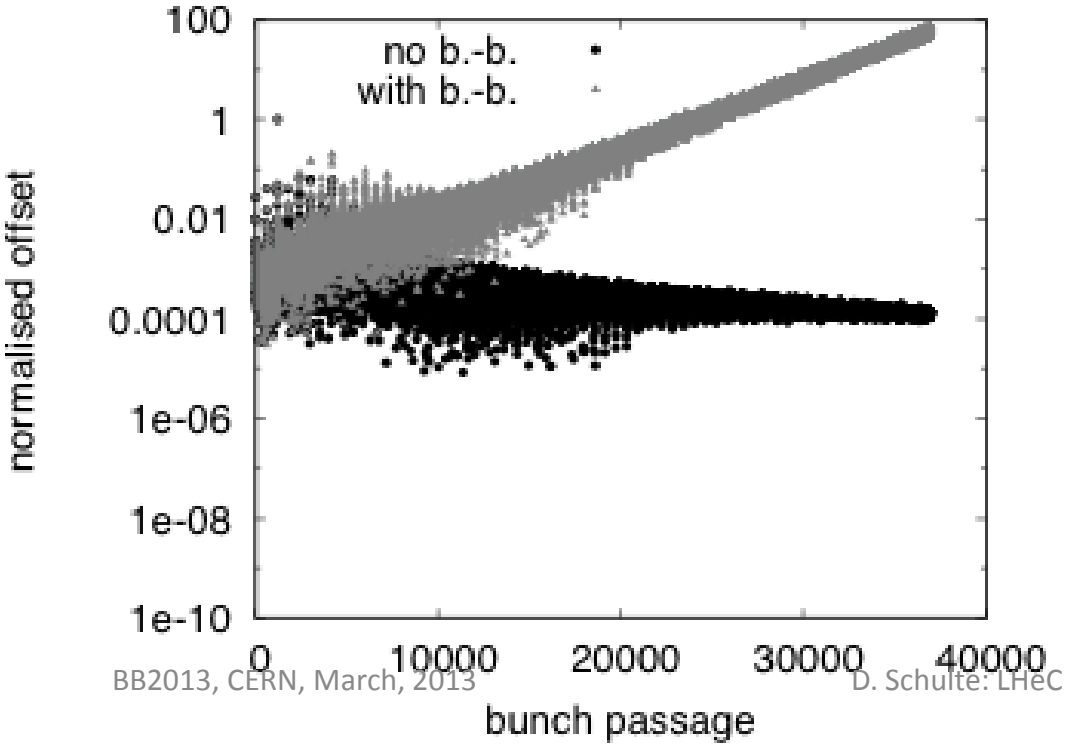
Beam is stable but very small margin with 1.3GHz cavity

Multi-bunch Instability and Beam-beam II

Alternative lattice with no focusing appeared possible with 720MHz, if beam-beam effects are ignored

F_{rms}=1.06





But inclusion reveals that beam is unstable even with 720GHz

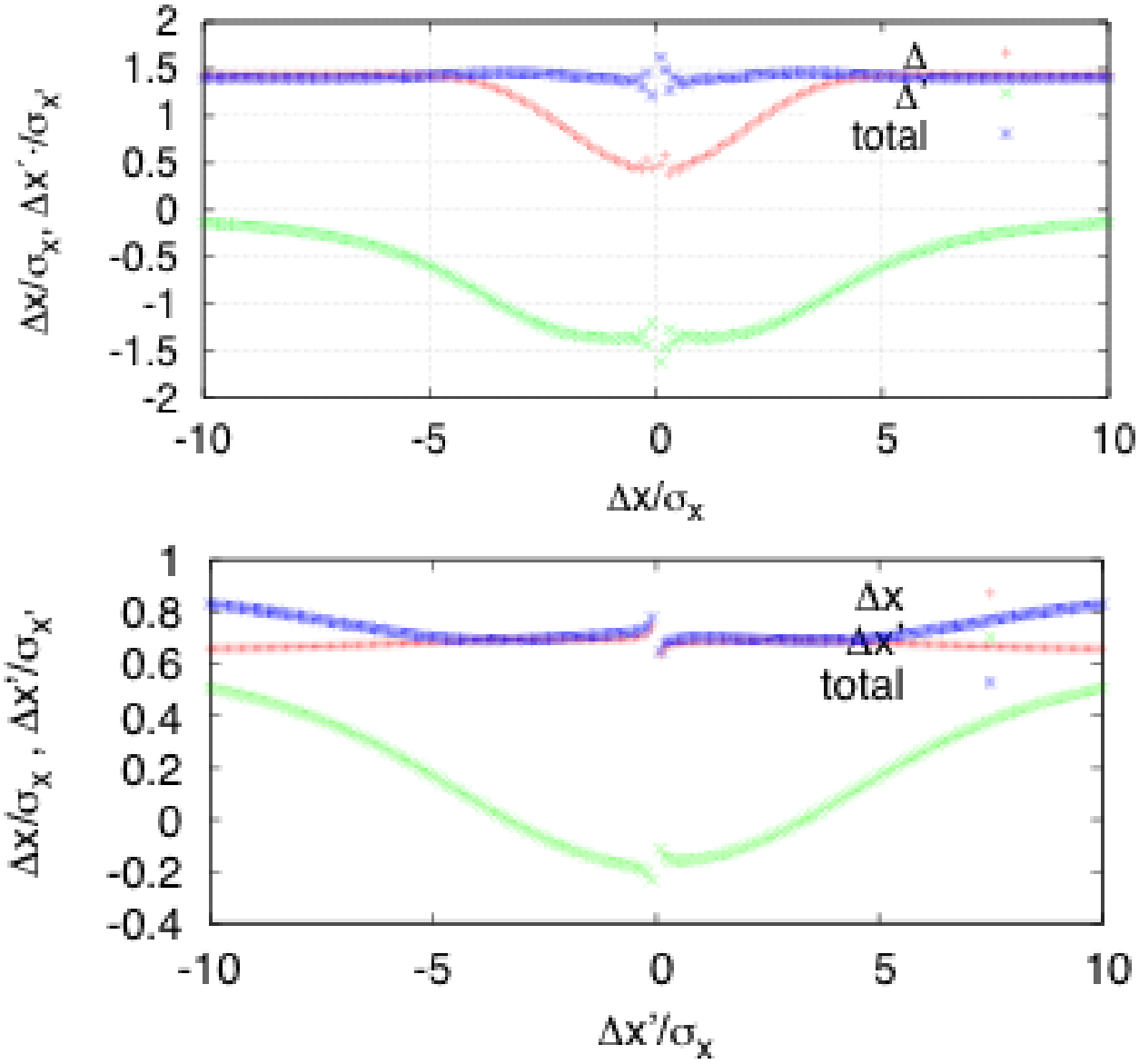
Modified Post Collision Line

Can adjust beta-function and waist of extraction line to minimise beam-beam effects

- Incoming electron waist at 30mm
- Outgoing β_{extr} =6cm, W_{extr}=13mm
- similar optimum as for phase space

- Can reduce effective beam-beam deflection for small offsets

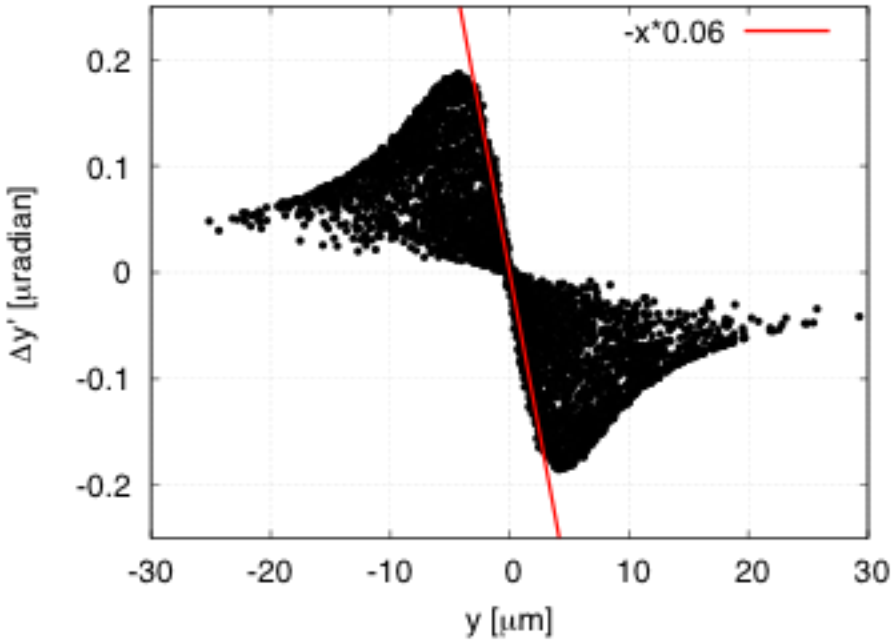
- Increases impact of large offsets

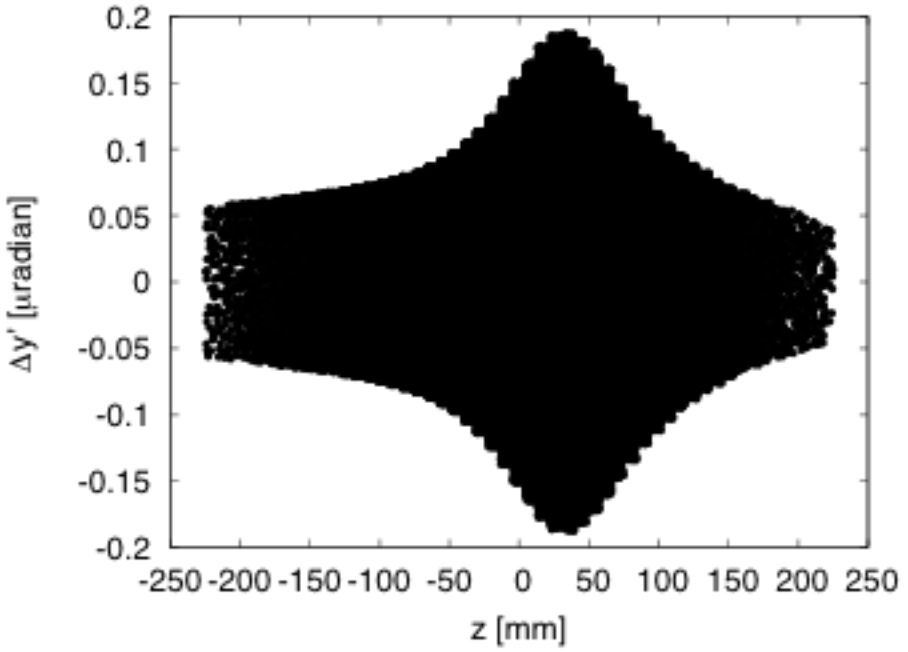


Impact on Proton Beam

Strong variation of tune shift along the bunch
->time dependent quadrupole
-Also position changes with time

Calculate tune shift for each slice of proton beam at the location of the collision with the electron beam





- Effective tune shift in worst slice is about 5 10^{-4}
- strong variation along the bunch

-> Smaller than in LHC collision points
-> opposite sign
-> small linear region

Beam-beam Offset

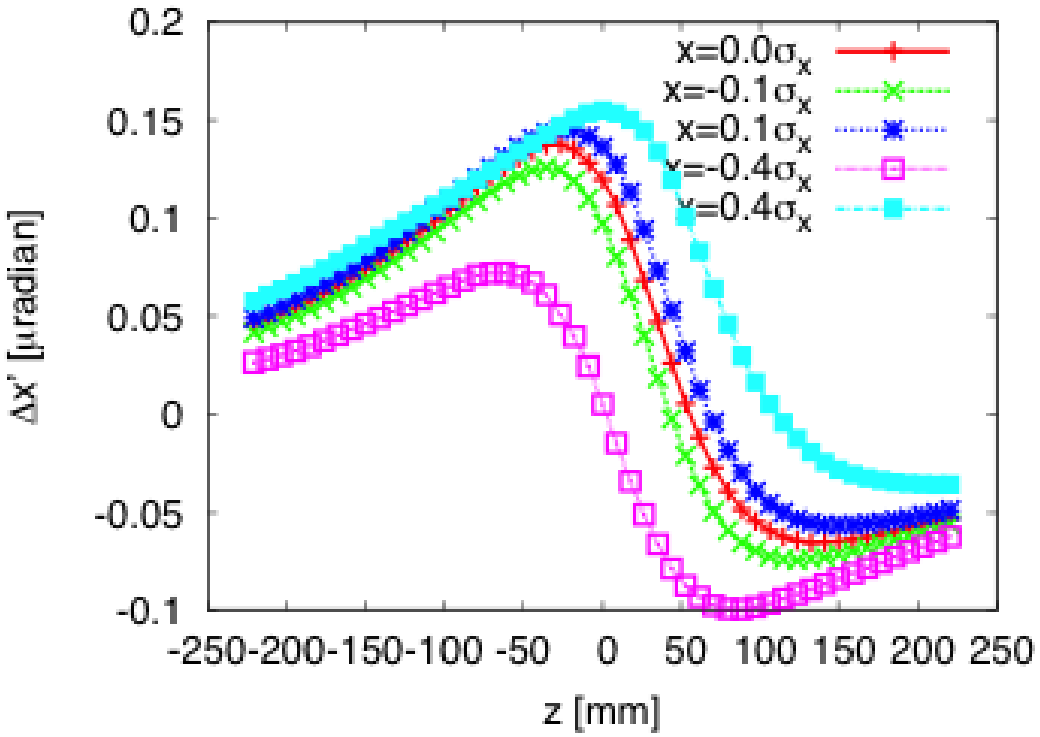
Proton deflection due to coherent offset between electron and proton shown

Centroid motion is cured by damper

Head-tail motion could lead to instability, stabilised by synchrotron motion

Simplified, conservative criterion (Y. Hao)

Slightly violated ($3.5\ 10^{-3}$ vs. $2.5\ 10^{-3}$



Deflection as function of offset in proton bunch for a beam-beam offset of $1\sigma_x$

Preliminary Simulations

Simple linear lattice

No further beam-beam kicks, Impedances, …

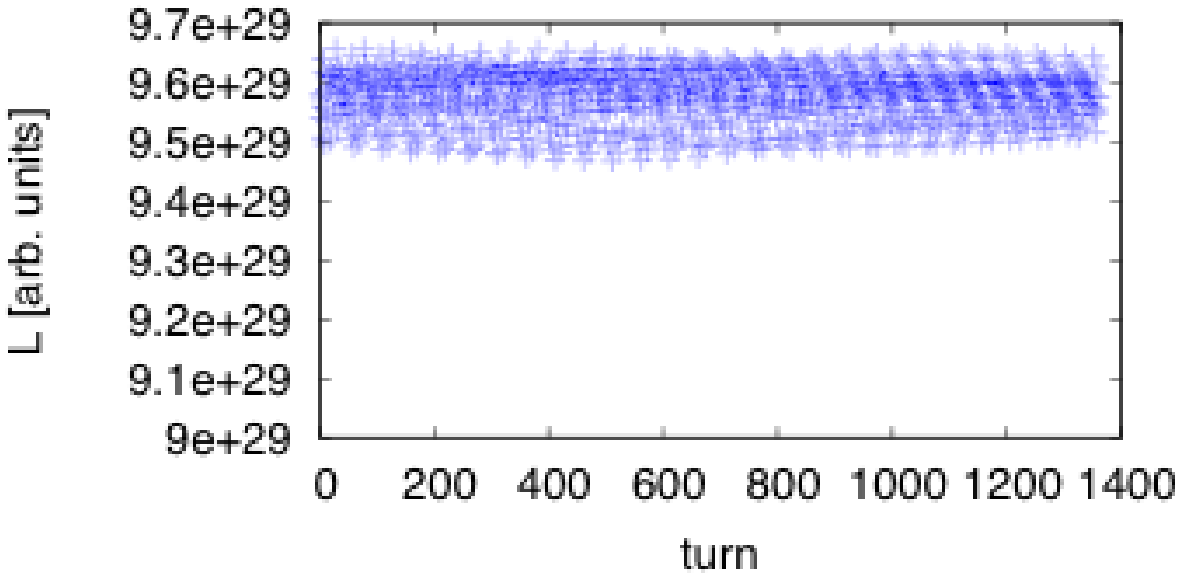
No synchrotron motion, dampers, …

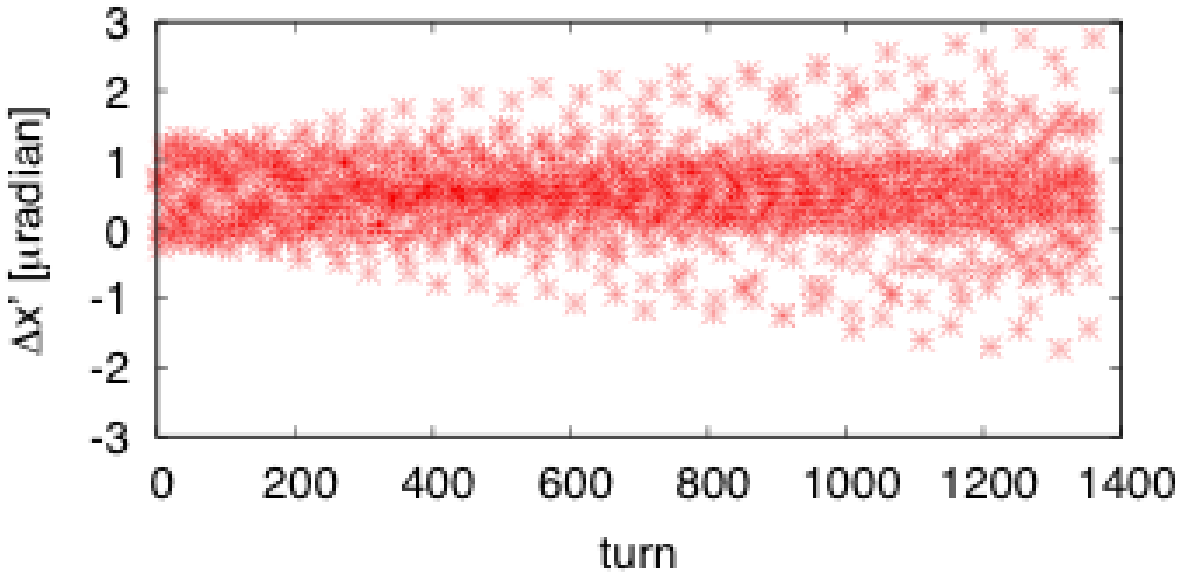
No dramatic instability

Periodic behaviour of the luminosity, as expected

But slight growth in collision offset

Not yet fully conclusive





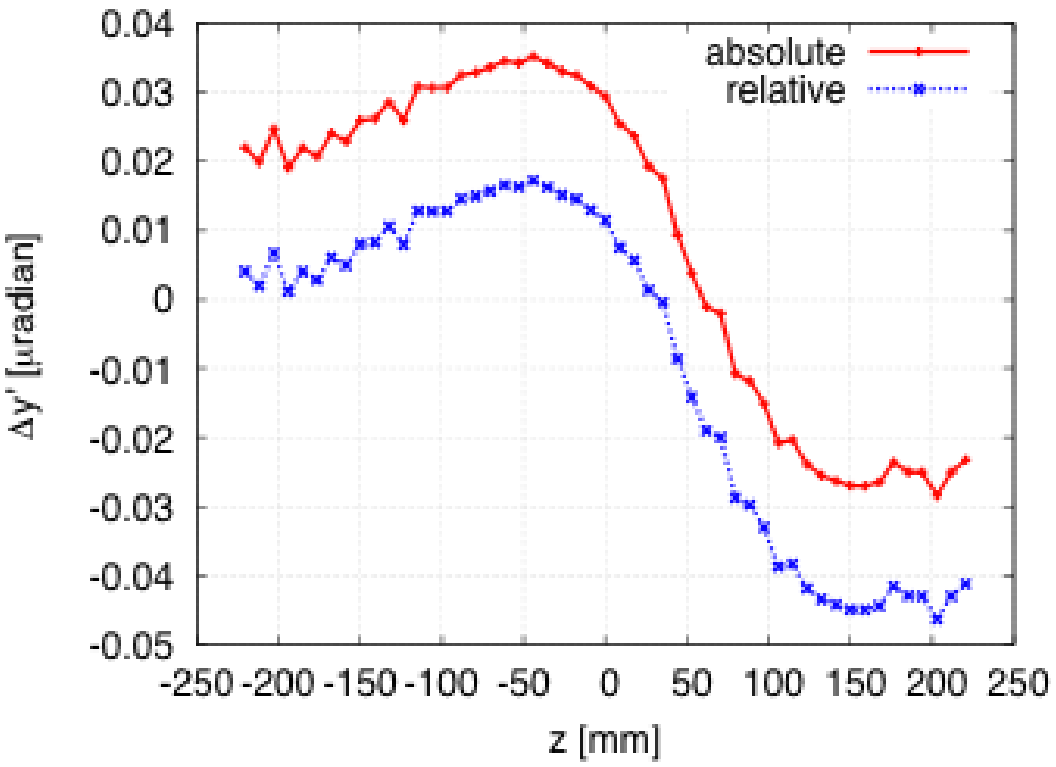
Emittance Growth

Electron bunches will have offsets and angles

Assume that electron bunch offset is random for each collision
-> amplitudes grow with $N_C^{1/2}$

Difference in head and tail deflection is washed out by synchrotron motion in ~500 turns

(Too?) simplified model for reasidual emittance growth is to take RMS of slice mean angles



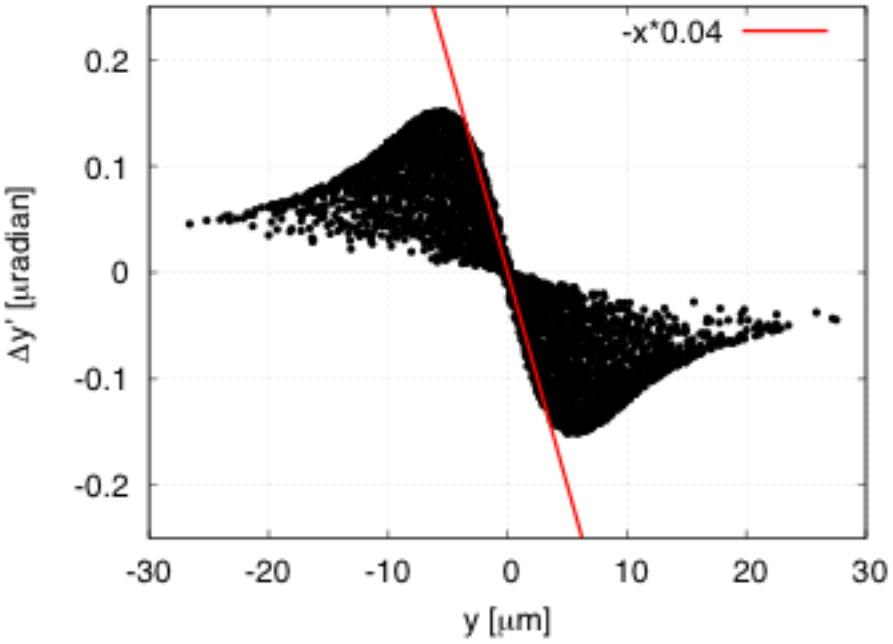
Growth rate per collision is

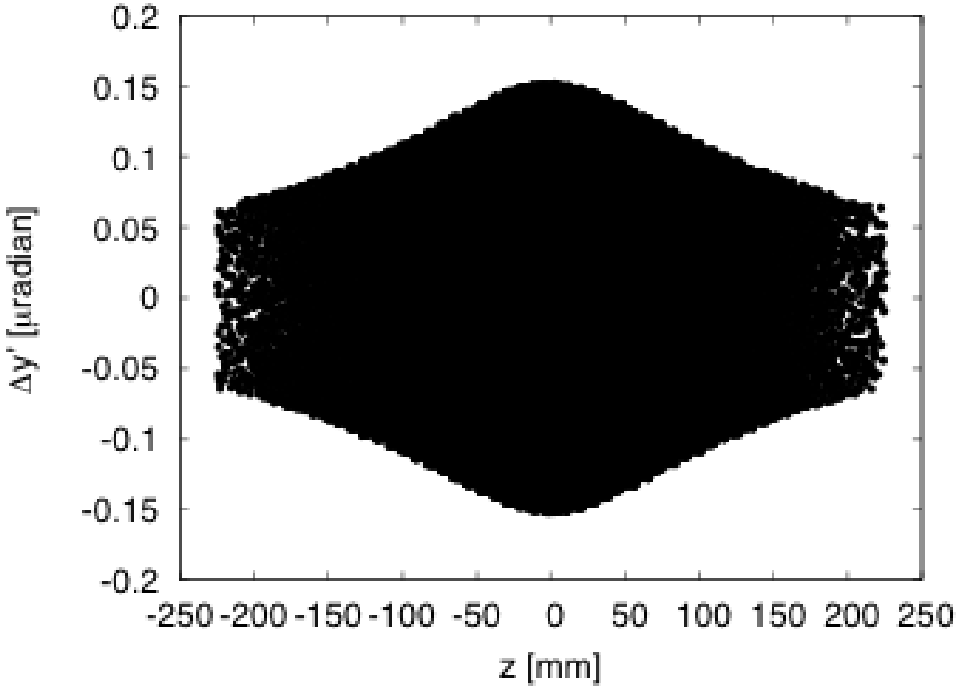
-> 10% jitter might be a problem, 1% would be OK

Needs to be looked at in more detail

Impact on Proton Beam, Optimised Collision

Waist shift of incoming beam has little effect
Change of incoming beta-function and waist shift for the electron beam has significant effect

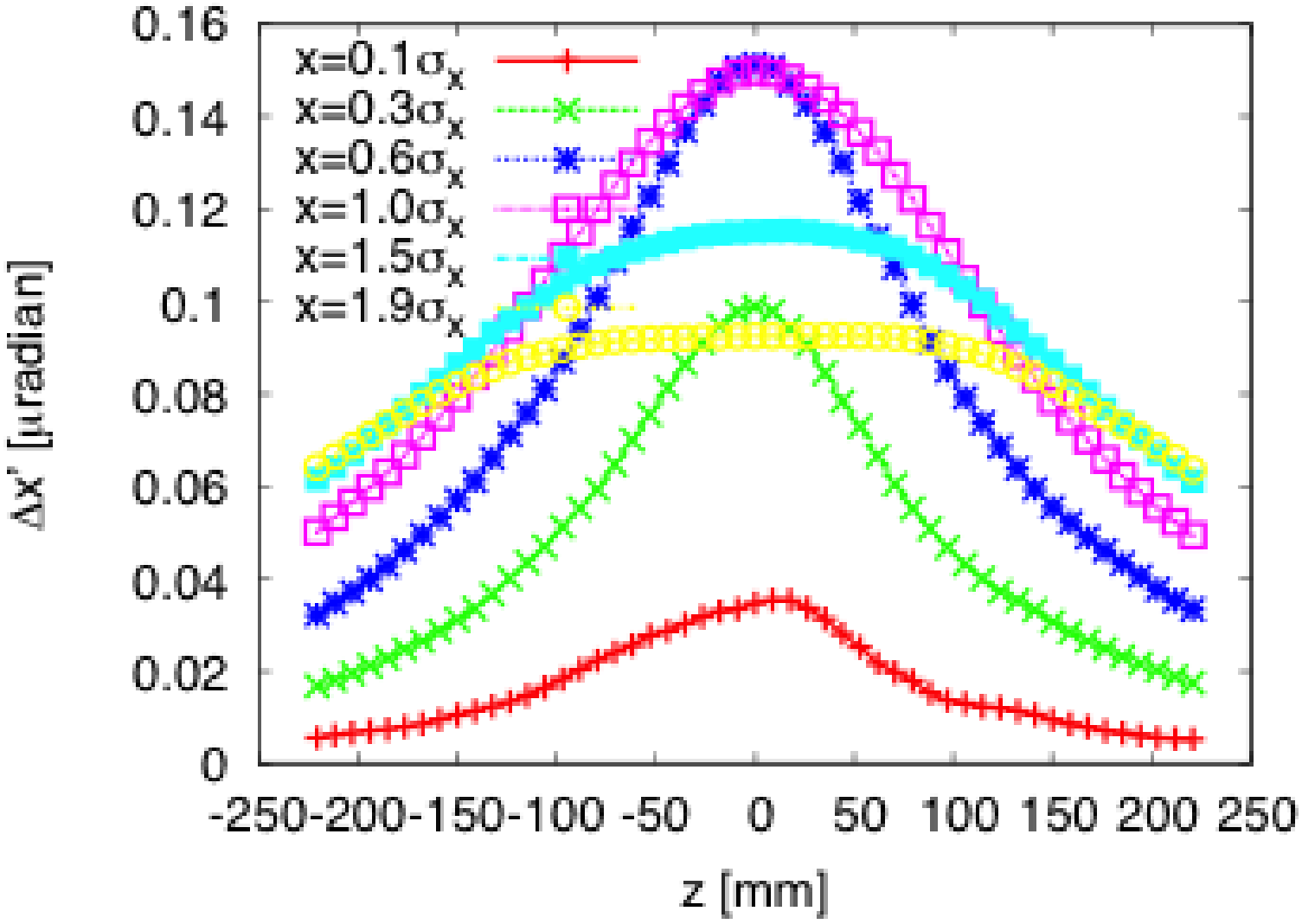




- Effective tune shift in worst slice is reduced to about 3 10^{-4}
- Varies by factor 4 along bunch

-> may still be a concern

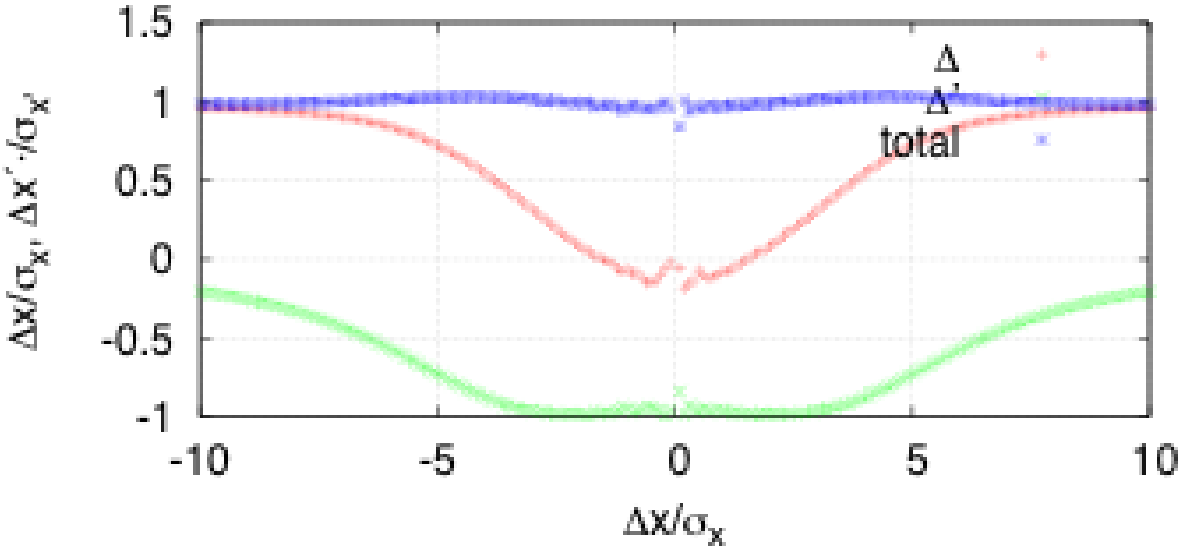
Force of Electron Bunch



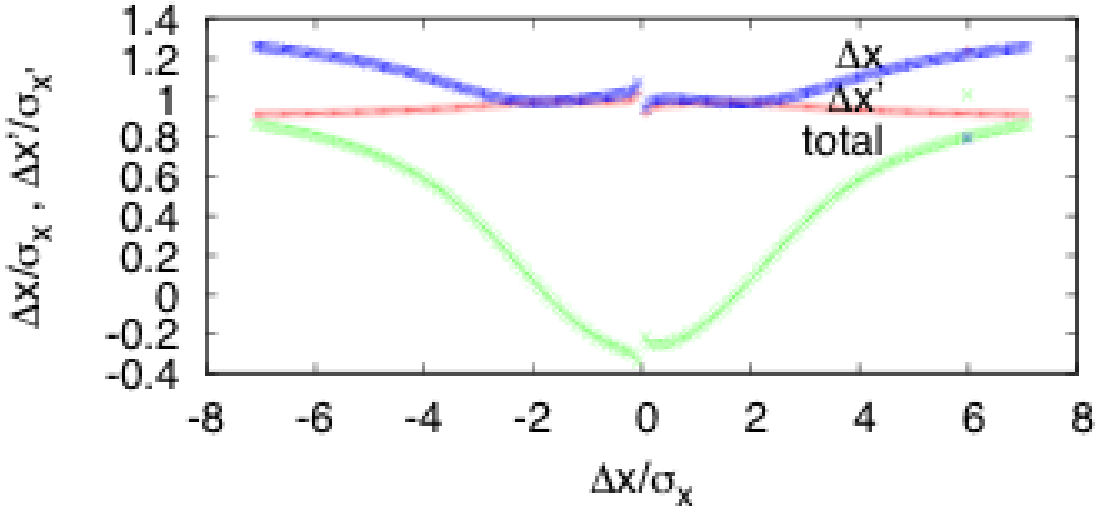
Electron Jitter Amplification

Can adjust beta-function and waist of extraction line to minimise beam-beam effects

- Electron waist at 30mm, β_{in}=6cm
- case 1:
  - W_{extr}=15mm

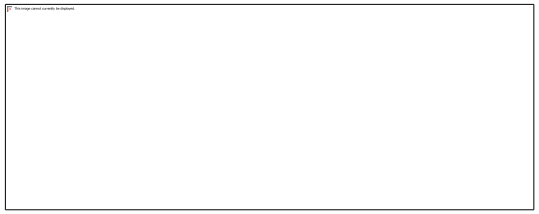


- Collision is much better matched
- Almost no amplification but only phase shift (90° for small offsets)

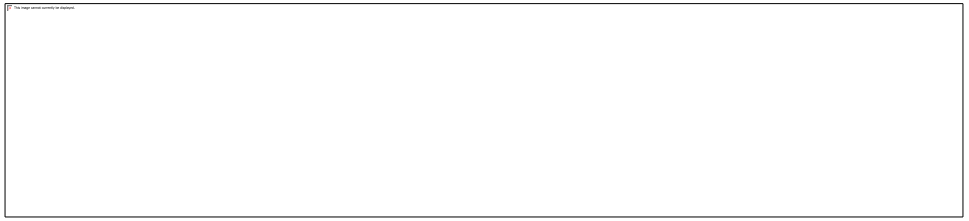


Scaling with Bunch Charge

Fix luminosity and vary number of particle per proton bunch
Need to adjust emittance to keep luminosity

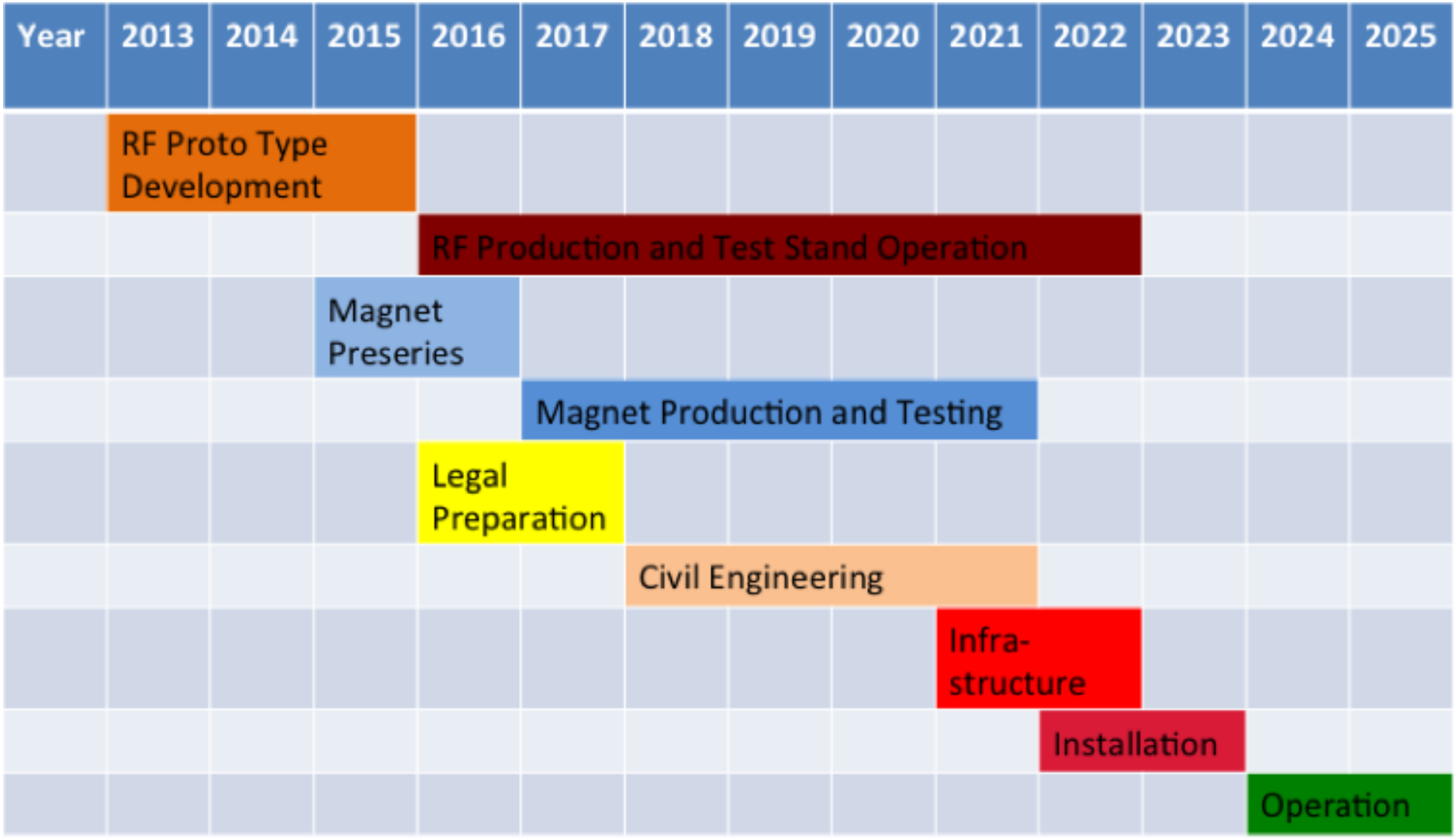


Impact of protons on electrons scales with disruption
If proton bunch length remains fixed, disruption of electrons remains unchanged



Impact of electrons on protons scales with tune shift
Need to reduce electron beam size with proton beam size and scale charges the same way
Tune shift remains unchanged for fixed proton beta-function and proton current

LHeC Tentative Time Schedule



O. Brüning

Summary and Outlook

- A Conceptual Design Report exists for both options of LHeC
  - They appear feasible
  - The linac ring option is preferred since the ring-ring option likely interferes with LHC operation
  - Significant room for optimisation in design

- The phase space of the electron beam is strongly distorted by the proton beam
  - In the electron linac multi-bunch transverse wakefields and beam-beam effects interact strongly
  - Better matching of the electron post collision line appears possible
  - Other multi-bunch effects need to be looked at (e.g. FBII)

- Impact of electron beam on protons may be important
  - But not clear if impact is critical
  - Further study needed

- Significant work ahead

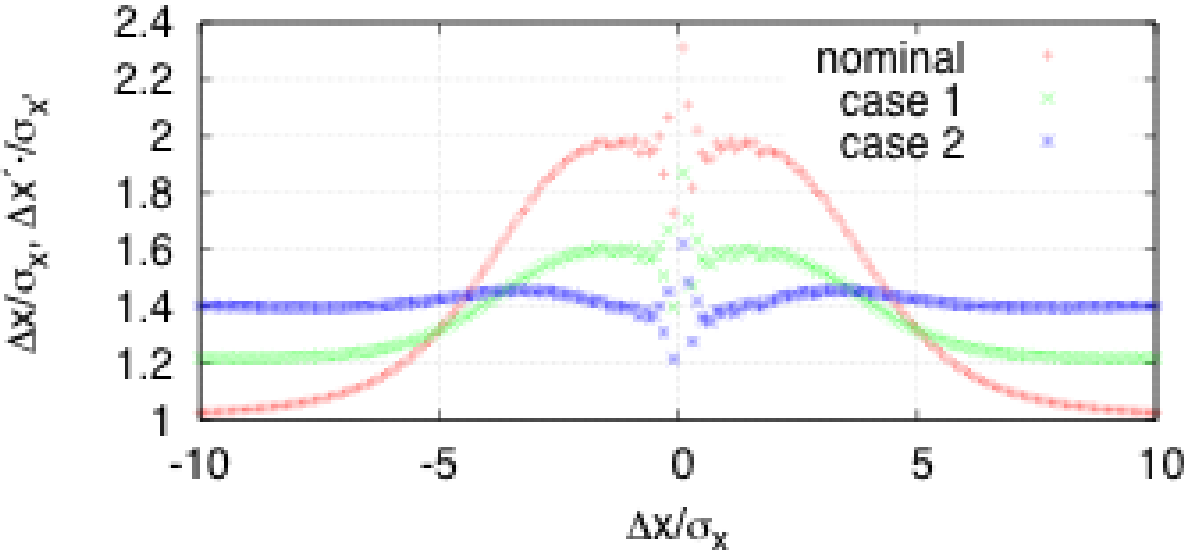
Thanks to R. Tomas, T. Pieloni, O. Brüning, F. Zimmermann

Reserve

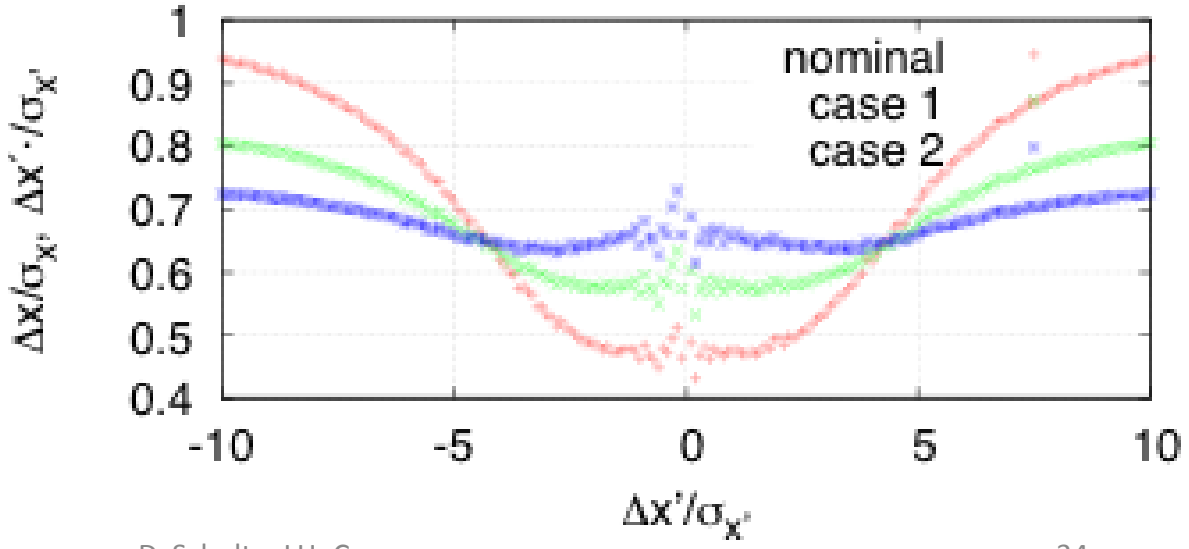
Improved Post Collision Line

Can adjust beta-function and waist of extraction line to minimise beam-beam effects

- Electron waist at 30mm
- case 1:
  - β_{extr} =8cm, W_{extr}=13mm
- case 2:
  - β_{extr} =6cm, W_{extr}=13mm



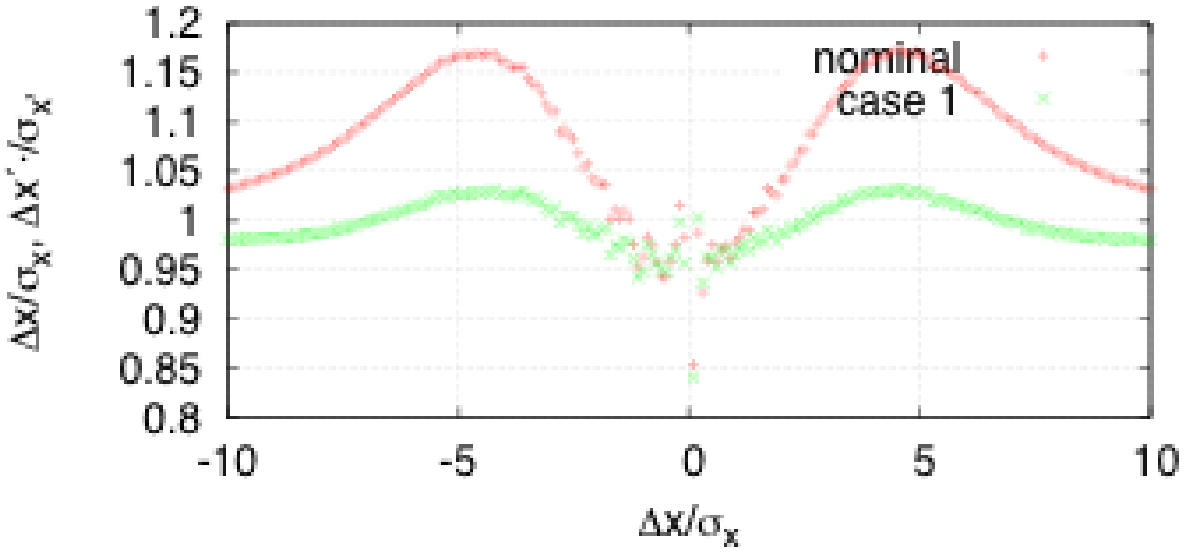
- Can reduce beam-beam deflection for small offsets
- Increases impact of angle
- Increases impact of large offsets



Improved Post Collision Line II

Can adjust beta-function and waist of extraction line to minimise beam-beam effects

- Electron waist at 30mm, β_{in}=6cm
- case 1:
  - W_{extr}=15mm



- Collision is much better matched