CLIC: Beam Dynamics and Limitations on Main Parameters

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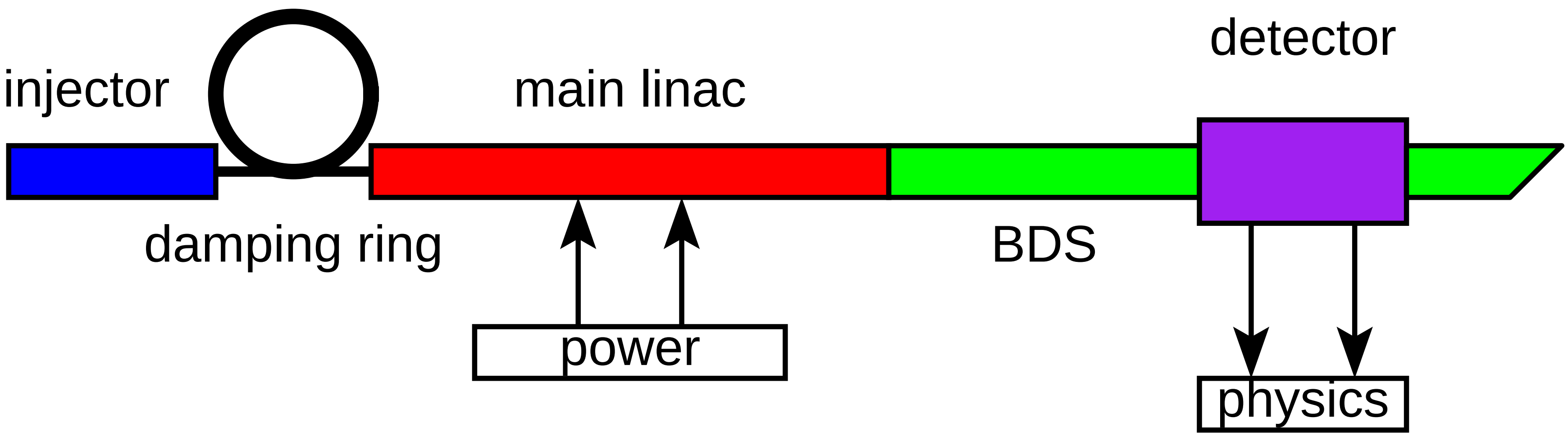
Layout



injector
main linac
detector
damping ring
BDS
power
physics

Luminosity

Simplified treatment and approximations used throughout

$$\mathcal{L} = H_D \frac{N^2 f_{rep} n_b}{4\pi\sigma_x\sigma_y}$$

$\sigma_{x,y} \propto \sqrt{\beta_{x,y}\epsilon_{x,y}/\gamma}$

$N f_{rep} n_b \propto \eta P$

$$\mathcal{L} \propto H_D \frac{N}{\sqrt{\beta_x\epsilon_x}\sqrt{\beta_y\epsilon_y}} \eta P$$

typically $\epsilon_x \gg \epsilon_y$, $\beta_x \gg \beta_y$

$$\epsilon_x = \epsilon_{x,DR} + \epsilon_{x,BC} + \epsilon_{x,BDS} + \ldots$$

$$\begin{aligned}\epsilon_y &= \epsilon_{y,DR} + \epsilon_{y,BC} + \epsilon_{y,linac} + \epsilon_{y,BDS} \\ &\quad + \epsilon_{y,growth} + \epsilon_{y,offset} \cdots\end{aligned}$$

Example: CLIC

basic idea: high frequency $\Rightarrow$ high gradient
$\Rightarrow$ short machine $\Rightarrow$ cheap

$\Rightarrow f_{RF} = 30\,\mathrm{GHz}$, $G = 150\,\mathrm{MV/m}$

Parameter	symbol	value
luminosity in the peak [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$\mathcal{L}_1$	3×10^{34}
pulses per second	f_{rep}	$100\,\mathrm{Hz}$
bunches per pulse	n_b	154
bunch separation	Δt	$0.67\,\mathrm{ns}$
particles per bunch	N	4×10^9
hor. beam size at IP	σ_x	$\approx 60\,\mathrm{nm}$
target	σ_x	$43\,\mathrm{nm}$
vert. beam size at IP	σ_y	$\approx 0.7\,\mathrm{nm}$
target	σ_y	$1\,\mathrm{nm}$
bunch length at IP	σ_z	$35\,\mu\mathrm{m}$

normalised emittances

- damping ring exit $\epsilon_x = 450\,\mathrm{nm}$, $\epsilon_y = 3\,\mathrm{nm}$
- linac entrance $\epsilon_x = 600\,\mathrm{nm}$, $\epsilon_y = 5\,\mathrm{nm}$
- linac exit $\epsilon_x = 680\,\mathrm{nm}$, $\epsilon_y = 10\,\mathrm{nm}$
- IP $\epsilon_{x,eff} \approx 1700\,\mathrm{nm}$, $\epsilon_{y,eff} \approx 20\,\mathrm{nm}$

Beam Dynamics Parameter Drivers

main linac

- couples bunch length $\sigma_z(N)$ to N via longitudinal wakefield

  (lowest allowed σ_z)

  structure design and gradient dependent

- limits N (via stability requirement or emittance growth)

damping ring

- yields lower limits of $\epsilon_x(N)$, $\epsilon_y(N)$, $\epsilon_z(N)$
- can limit repetition frequency

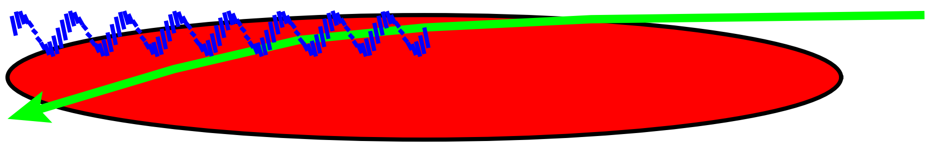
final focus system

- lower limit on β_x, β_y
- can contribute to emittances

beam-beam interaction

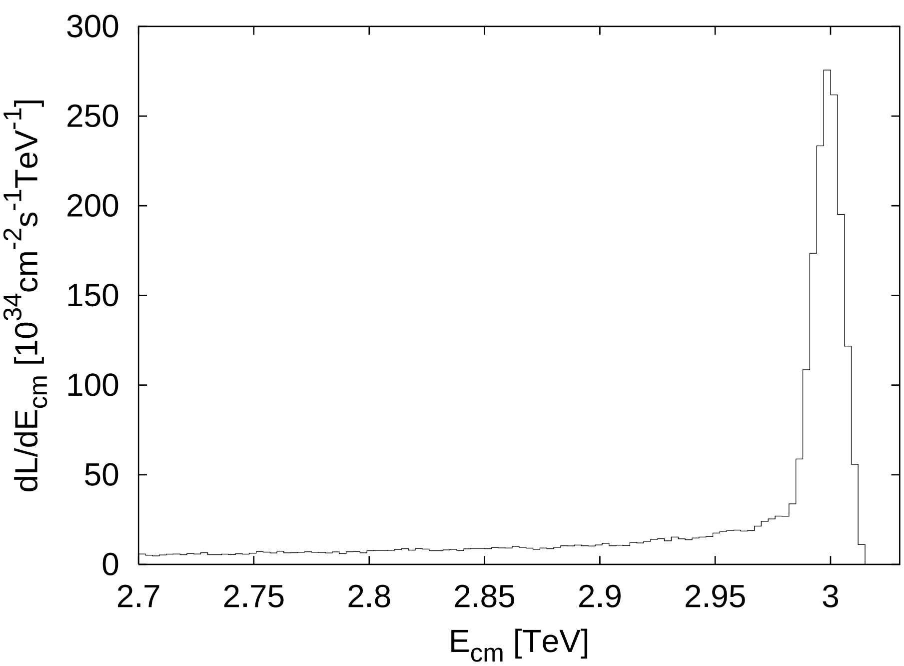
- leads to requirement for optimum $(N/\sigma_x)(\sigma_z)$

Beam-Beam Interaction



Small beam ⇒ strong electro-magnetic field

- focuses the oncoming beam
- increases luminosity
- beamstrahlung ⇒ luminosity spectrum



$$\mathcal{L}_1 = \mathcal{L}(E_{cm} \geq 0.99 \times E_{cm,0})$$

current parameters $n_\gamma = 1.7$, $\Delta E/E \approx 20\%$, $\mathcal{L}_1 \approx 0.4\mathcal{L}$

Beamstrahlung

Two regimes exist

beamstrahlung parameter

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E_0}$$

$\Upsilon \ll 1$: classical regime

$\Upsilon \gg 1$: quantum regime

$$\Upsilon \propto \frac{N\gamma}{(\sigma_x + \sigma_y)\sigma_z}$$

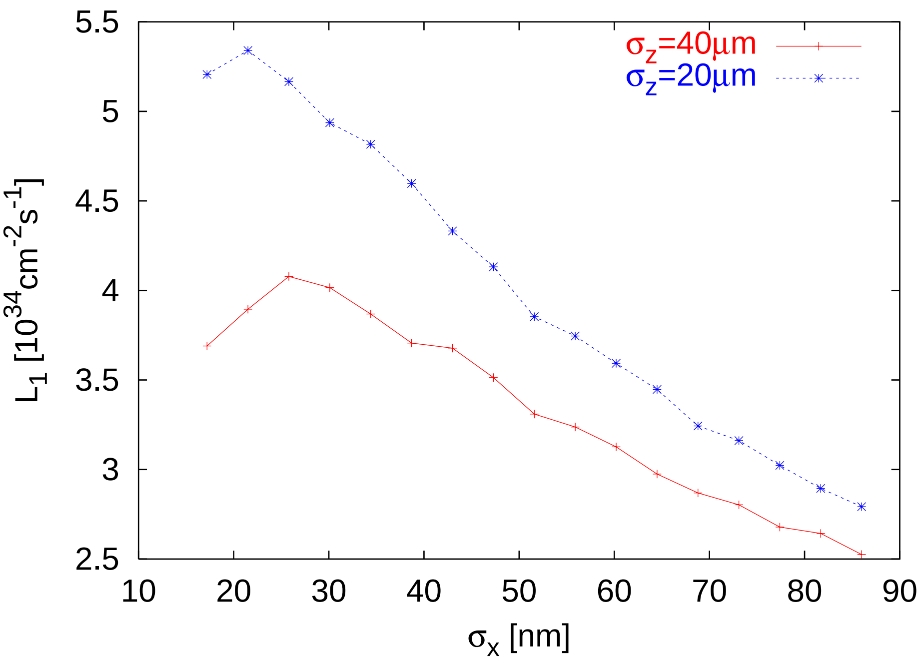
at high energy and high luminosity $\Upsilon \gg 1$

$\Rightarrow$ partial suppression of beamstrahlung

$\Rightarrow$ coherent pair production

in CLIC $\langle\Upsilon\rangle \approx 4$, $N_{coh} \approx \mathcal{O}(0.1N)$

Luminosity Optimisation



total luminosity

$$\mathcal{L} \propto \frac{N}{\sigma_x}\frac{\eta}{\sigma_y} \propto \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}}\frac{\eta}{\sigma_y}$$

large n_γ

- higher $\mathcal{L}$
- degraded spectrum

optimum n_γ exists

$$\mathcal{L}_1 \propto \frac{\eta}{\sqrt{\sigma_z}\sigma_y}$$

Beam Delivery System

Final focus system squeezes beams to small sizes

main problems

beam has energy spread (RMS of $\approx 0.3\%$)

$\Rightarrow$ avoid chromaticity

synchrotron radiation in bends

$\Rightarrow$ use weak bends $\Rightarrow$ long system

radiation in final doublet (Oide Effect)

large $\beta_{x,y}$ $\Rightarrow$ large nominal beam size

small $\beta_{x,y}$ $\Rightarrow$ large distortions

beam-beam simulation of nominal case:

effective $\sigma_x \approx 65\,\mathrm{nm}$, $\sigma_y \approx 0.7\,\mathrm{nm}$

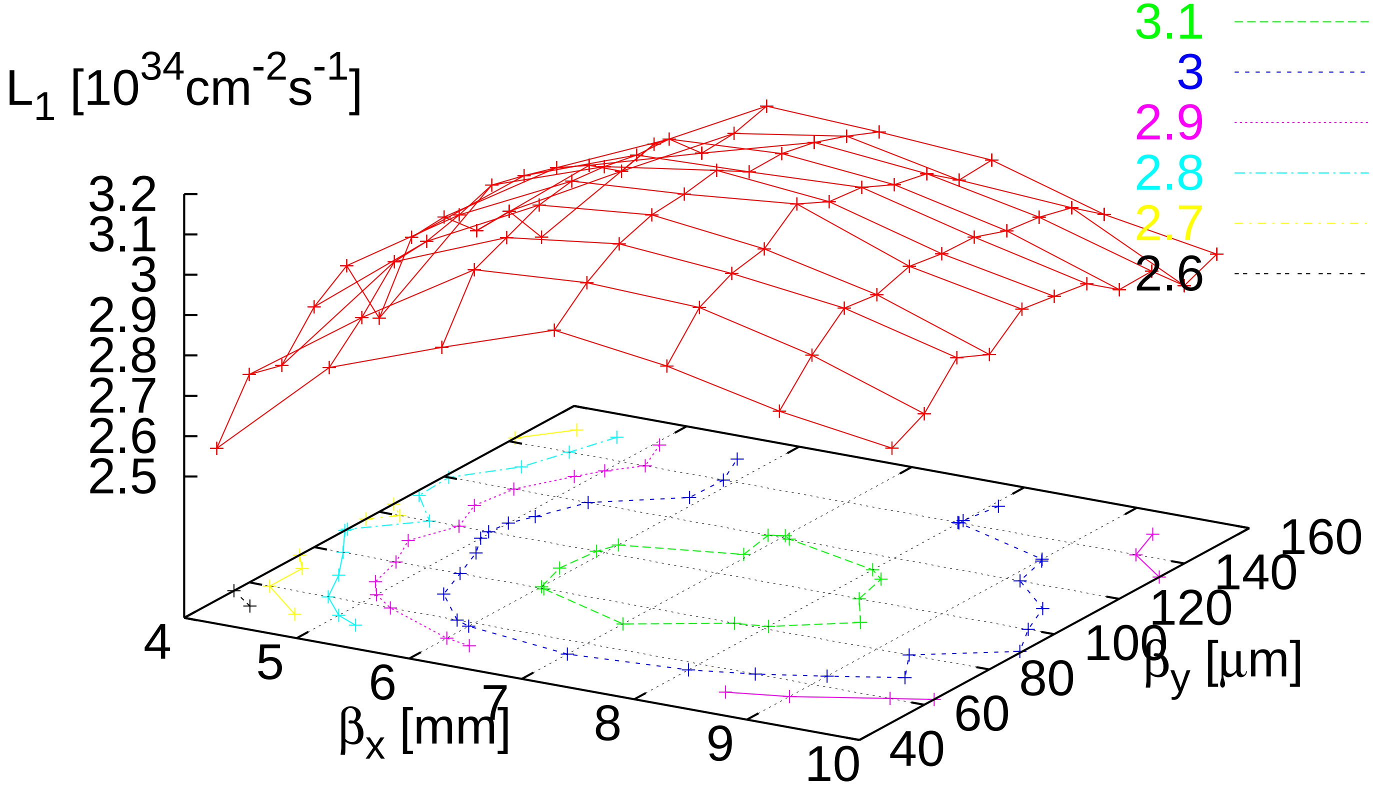
$\mathcal{L}_1 \propto 1/\sqrt{\epsilon_y}$, $\sigma_x \approx 40\,\mathrm{nm}$ for $\epsilon_x = 0$

lower limit of σ_x

for small N optimum n_γ cannot be reached

luminosity factor 2 smaller than nominal

Optimisation



thanks to F. Zimmermann for the MAD deck

Damping Ring

Three main challenges

- horizontal emittance at low intensity
- small coupling for vertical emittance
- collective effects must be small enough

no complete solution sofar for CLIC

current problems

- intra-beam scattering
- electron cloud

  close to a solution

- dynamic aperture

larger N may be simpler since one can allow

$$\epsilon_x \propto N^2$$

Low Emittance Transport Challenges

- static imperfections

  errors of reference line, elements to reference line, elements...

  excellent pre-alignment, lattice design, beam-based alignment, beam-based tuning

- dynamic imperfections

  element jitter, RF jitter, ground motion, beam jitter, electronic noise,...

  component stabilisation, lattice design, feed-back, re-tuning, re-alignment

- combination of dynamic and static imperfections can be severe

- use codes to evaluate linac performance

Emittance Preservation

$\epsilon_x \gg \epsilon_y \Rightarrow$ consider only ϵ_y

two problems

- wakefields
- dispersion

$$\Delta\epsilon_y \propto (W_\perp N \sigma_z \Delta y)^2$$

$W_\perp$ large a (iris radius)

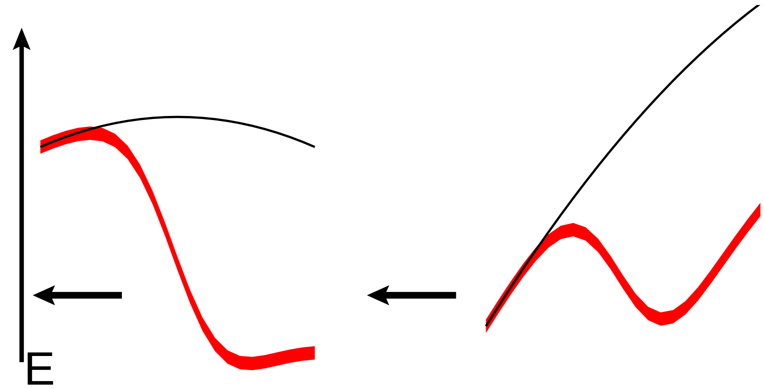
Δy very good prealignment
sophisticated beam-based alignment

N trivial, but $\eta \propto N$

σ_z large a, small N

Beam Loading and Bunch Length

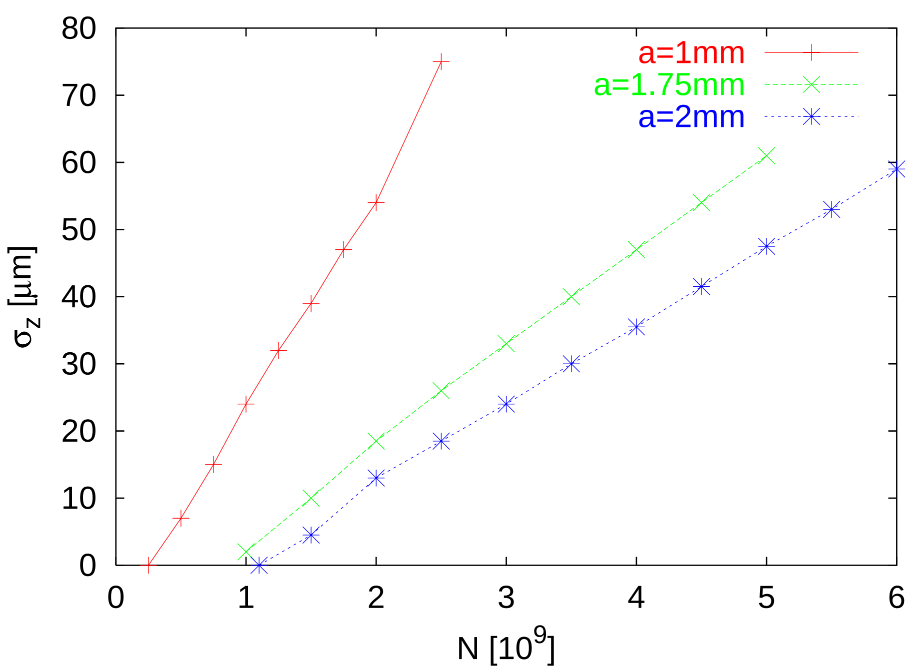
Multi-bunch beam loading compensated by RF



Single bunch longitudinal wakefield needs to be compensated

$\Rightarrow$ accelerate off-crest

limit $\Delta\Phi \leq 12^\circ$



Lattice Design

Linac lattice is a trade-off

strong focusing

- small sensitivity to wakefields
- dispersive effects important

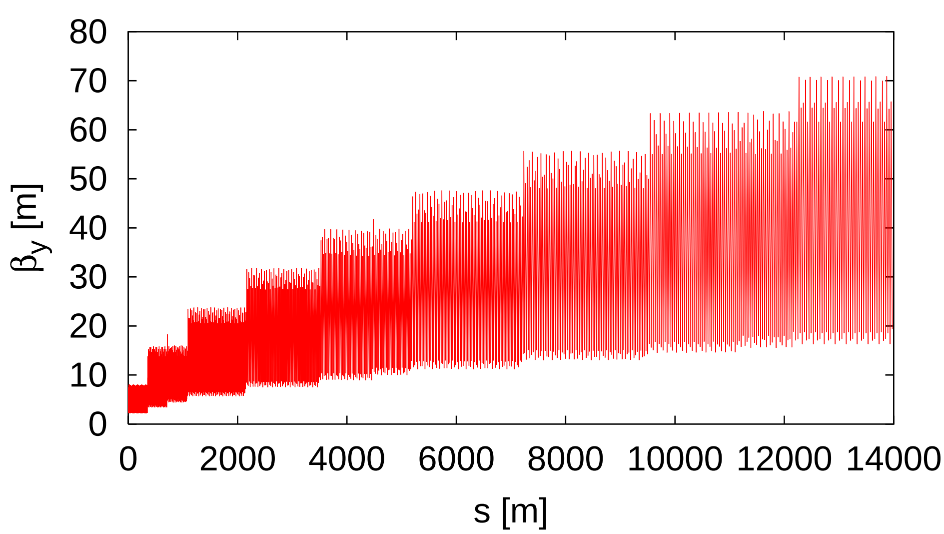
weaker focusing

- high sensitivity to wakefields
- dispersive effects smaller

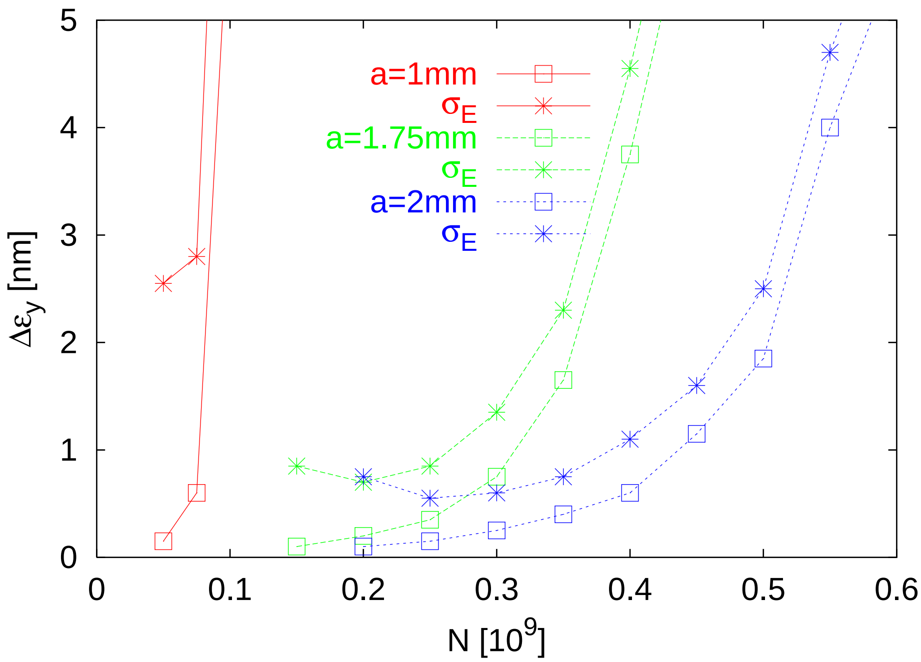
$\Rightarrow$ increase beta-function along machine

$$\beta \propto \sqrt{E},\ \Delta\phi = \mathrm{const}$$

in practice sectors with constant FODO cells are used



Emittance Growth



Prealignment: RMS error $10\,\mu\mathrm{m}$

beam-based alignment

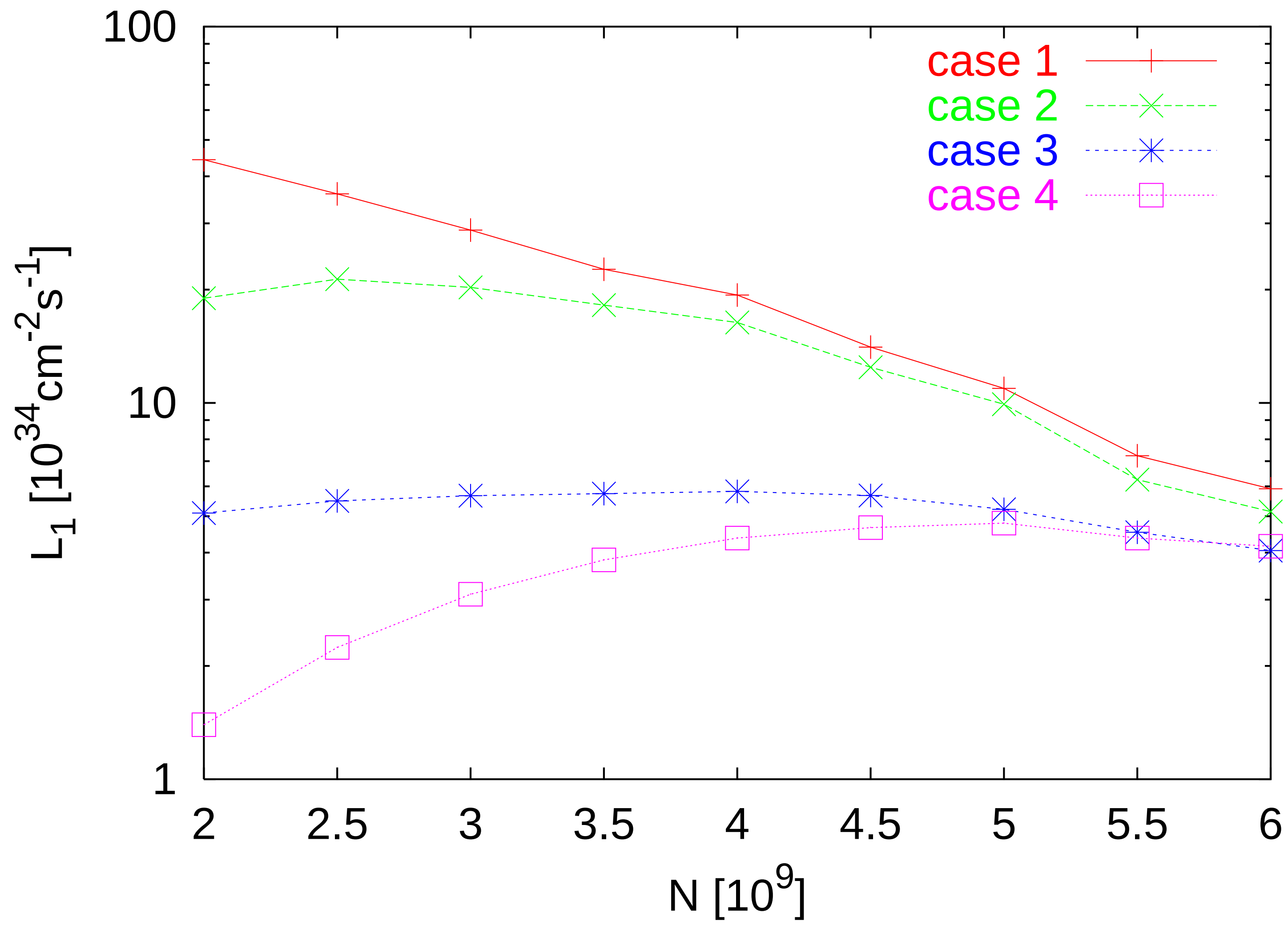
three structures $a = 1\,\mathrm{mm}$, $a = 1.75\,\mathrm{mm}$, $a = 2\,\mathrm{mm}$

reference structure has $a = 2\,\mathrm{mm}$

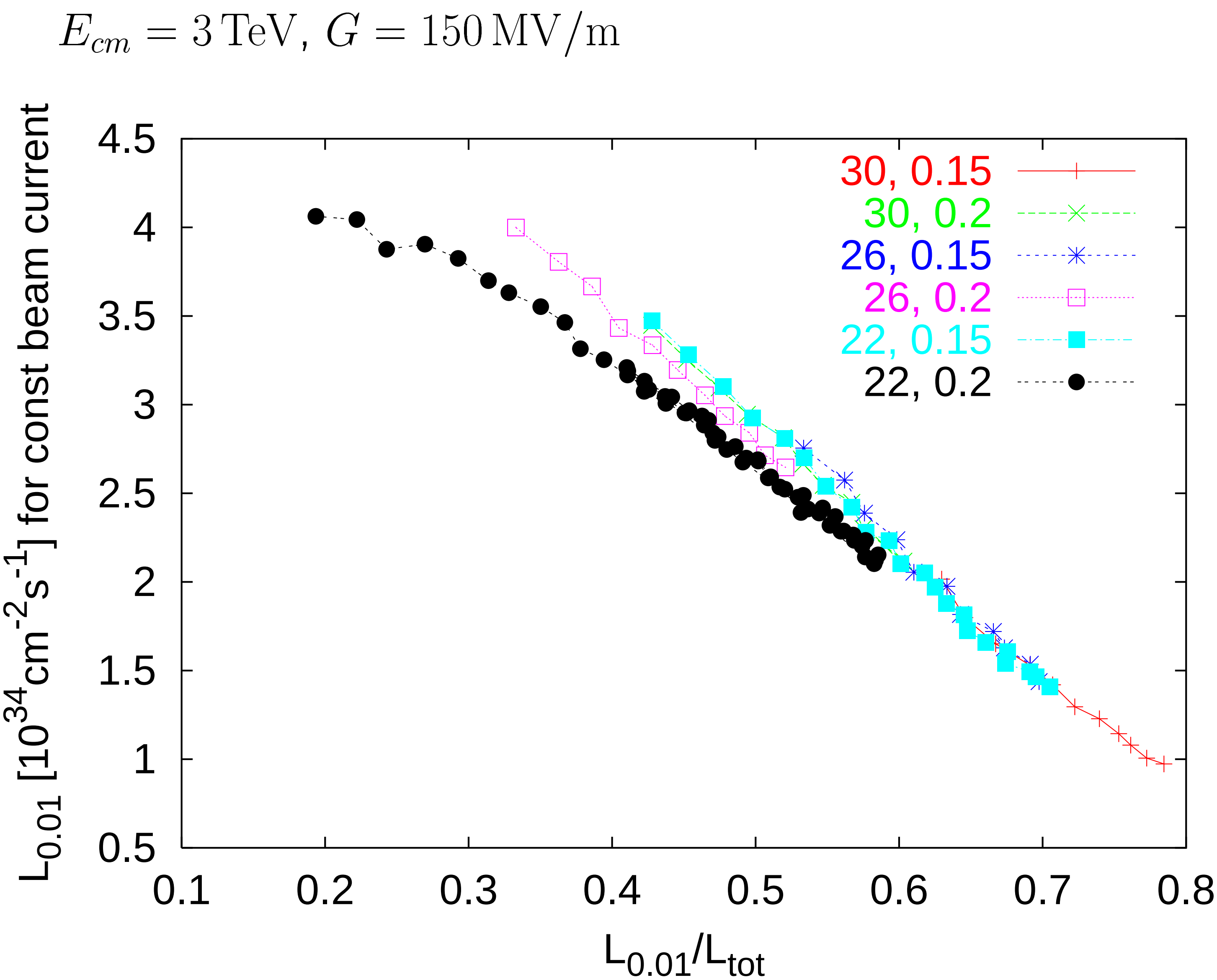
$\Rightarrow$ yields $\Delta\epsilon_y \approx 1.4\,\mathrm{nm}$ for CLIC

multi-bunch effects are small

Luminosity

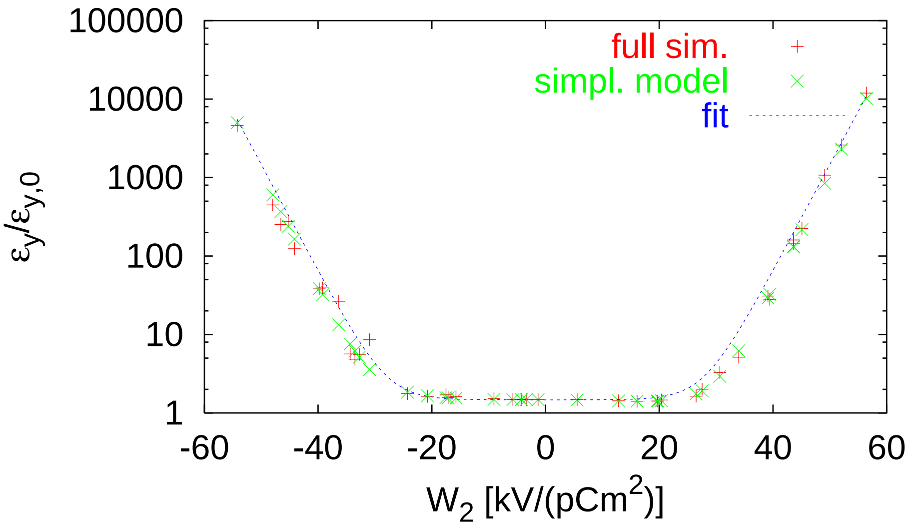


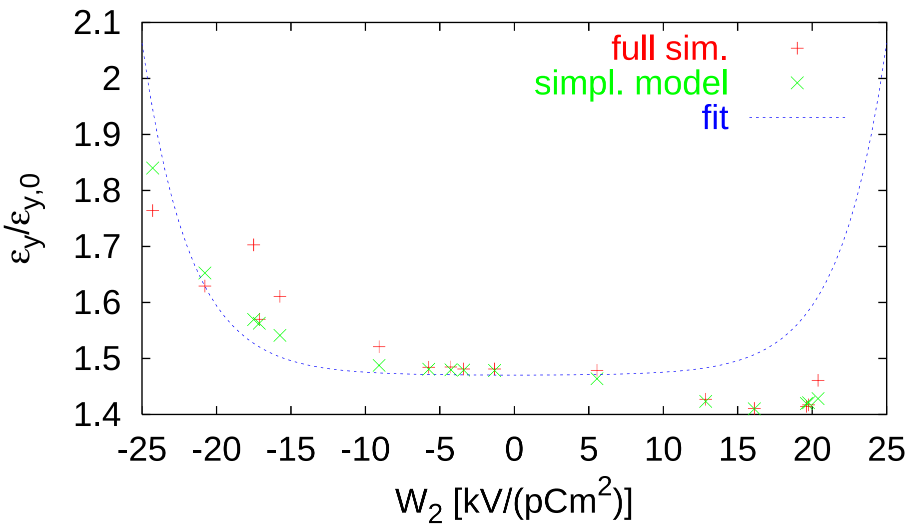
$\Rightarrow$ optimum $N \approx 4.5 \times 10^9$ exists



$E_{cm} = 3\,\mathrm{TeV},\, G = 150\,\mathrm{MV/m}$
$L_{0.01}$ [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] for const beam current
$L_{0.01}/L_{tot}$
30, 0.15
30, 0.2
26, 0.15
26, 0.2
22, 0.15
22, 0.2
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

CLIC Multi-Bunch Stability



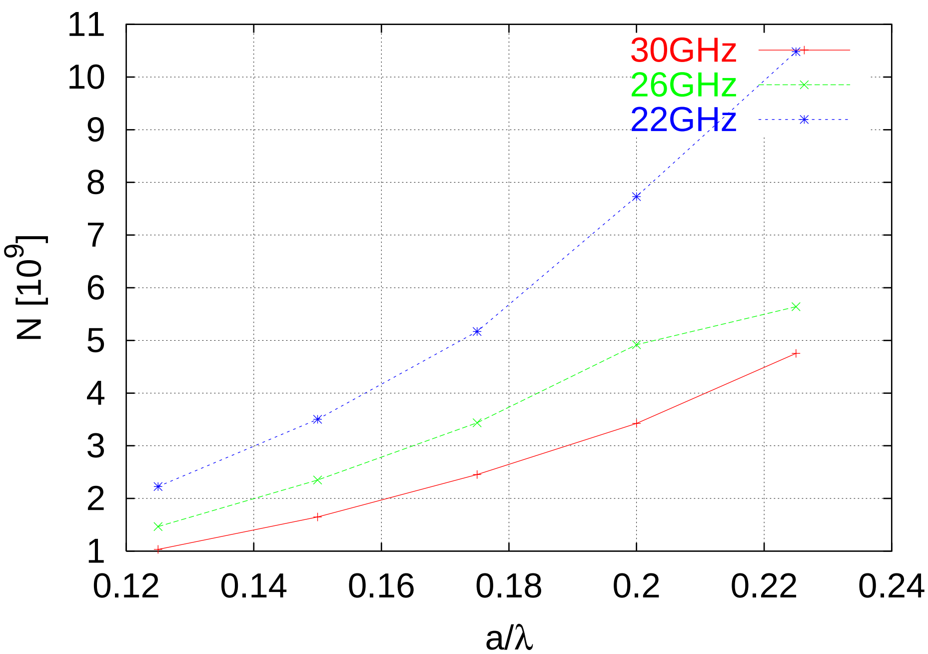


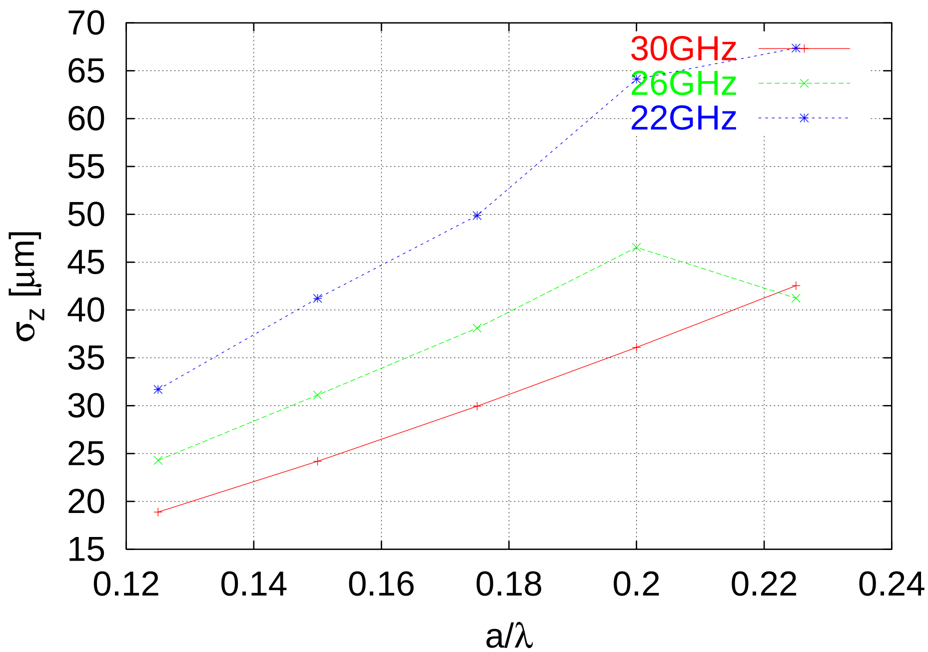
Exponential growth

small below $\approx 20\,\mathrm{kV/(pCm^2)}$ (for $N = 4\times10^9$)

Single Bunch Parameters

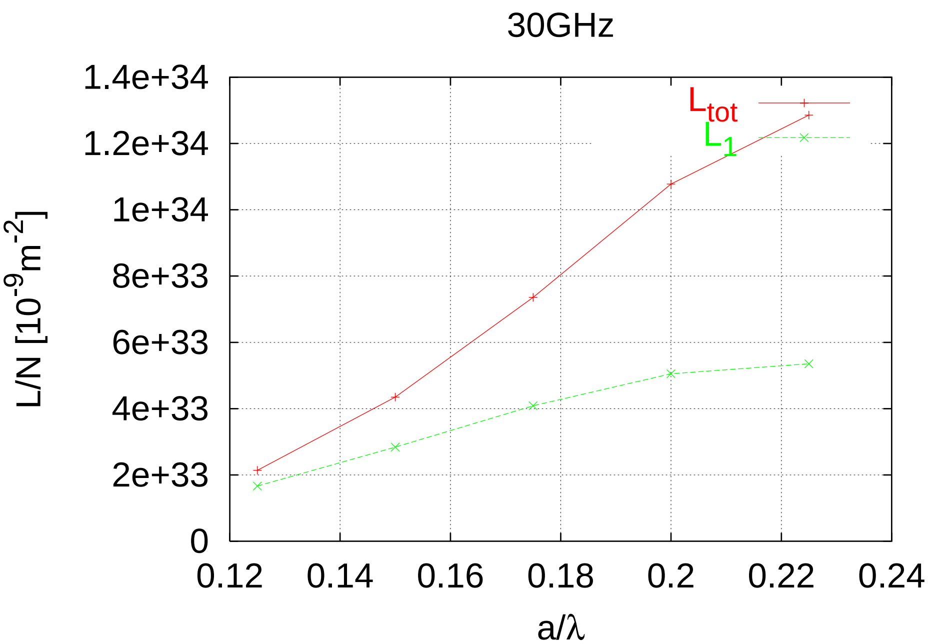
- use anyalytic formulae to calculate wakes (K. Bane)

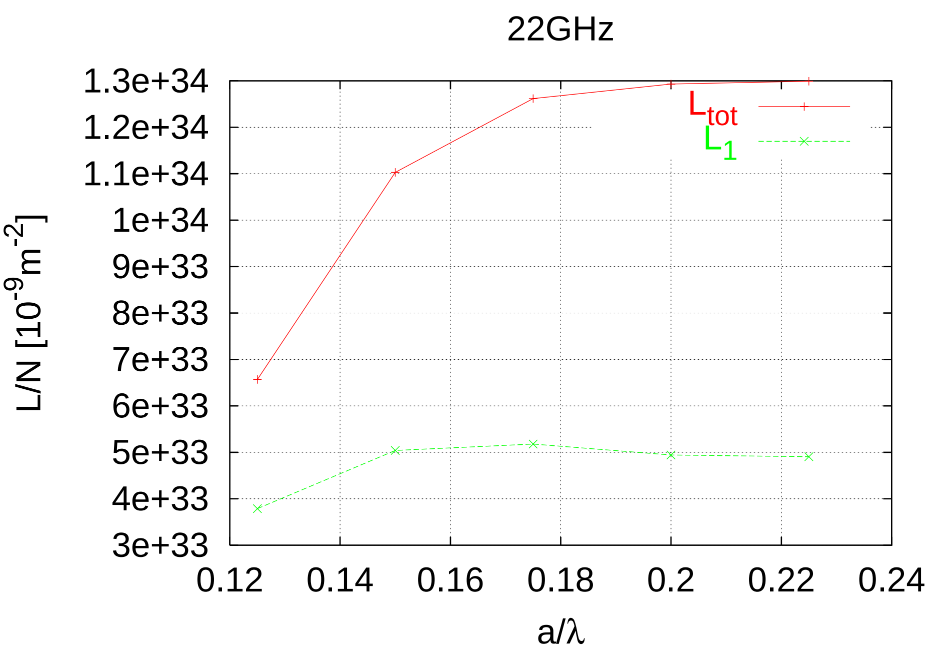




Calculate Luminosity

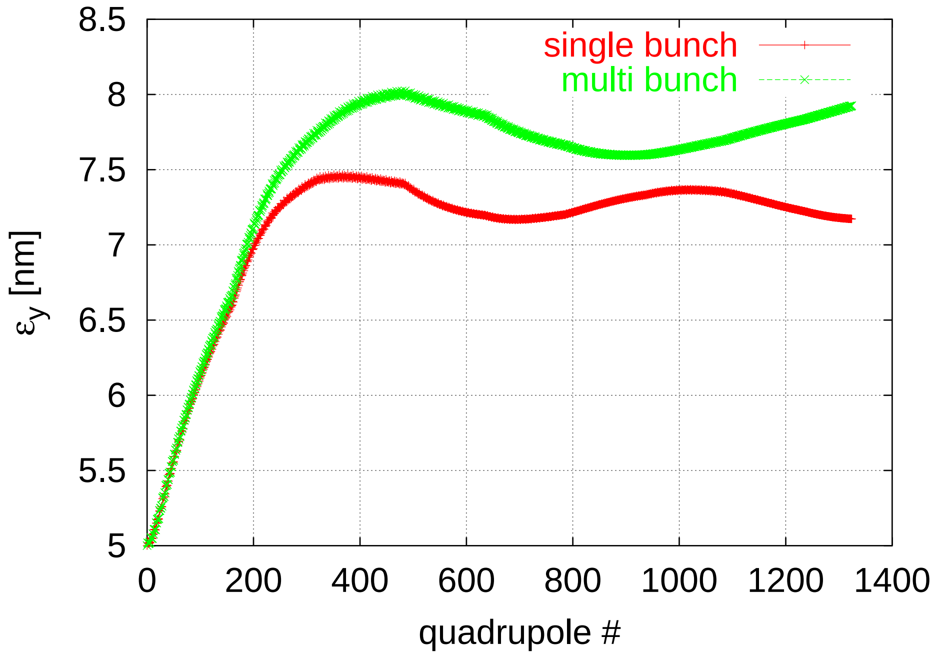
- select $L_1/L_{tot} = 0.4$, approximate BDS





Full Simulation

- Verification of beam stability using single and multi-bunch wakefields
- single-bunch wakefields from Karl Bane
- deriving long-range wakes from spline interpolation in between three cells



- tracking through linac+BDS
- beam-beam interaction

$\Rightarrow$ luminosity

Conclusion

Beam-beam interaction

$\Rightarrow$ optimum $\sigma_x \propto N\sqrt{\sigma_z}$

damping ring and BDS

$\Rightarrow \sigma_x \geq 60\,\mathrm{nm} > \mathrm{optimum}$

linac alone $\Rightarrow$ small N

other effects $\Rightarrow$ large optimum N

$N = 4 \times 10^9$

$\Rightarrow \sigma_z = 35\,\mu\mathrm{m}$

$\Rightarrow \mathcal{L}_1 \approx 3 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

parameter seem reasonable

no obvious large gain

optmisation possible $\Delta_{RF} > 12^\circ$

QCD Explorer

- Use one sector of CLIC on LHC superbunch to match time structure

Param.	elec.	prot.
E_0	75 GeV	7 TeV
N	4×10^9	6.5×10^{13}
σ_z	$35\,\mu\mathrm{m}$	$9\,\mathrm{m}$
L_{sep}	0.2 m	—
$\sigma_{x,y}$	$11\,\mu\mathrm{m}$	$11\,\mu\mathrm{m}$
$\beta_{x,y}$	$0.25\,\mathrm{m}$	$0.25\,\mathrm{m}$
$\epsilon_{x,y}$	$73\,\mu\mathrm{m}$	$3.75\,\mu\mathrm{m}$

- length of interaction region $l = 2\,\mathrm{m}$
- seperation by vertical and horizontal bend
- $L \approx 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Concerns
  - proton beam stability
  - interaction region layout
  - electron beam energy spread (beam loading compensation)