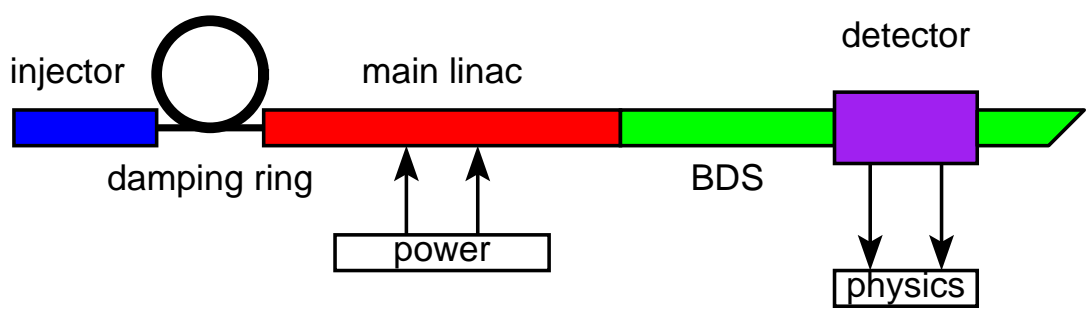


# CLIC: Beam Dynamics and Limitations on Main Parameters

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## Layout



## Example: CLIC

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

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

Parameter	symbol	value
<b>luminosity in the peak</b> [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$\mathcal{L}_1$	$3 \times 10^{34}$
pulses per second	$f_{rep}$	100 Hz
bunches per pulse	$n_b$	154
bunch separation	$\Delta t$	0.67 ns
particles per bunch	$N$	$4 \times 10^9$
hor. beam size at IP target	$\sigma_x$	$\approx 60 \text{ nm}$
vert. beam size at IP target	$\sigma_y$	43 nm
bunch length at IP target	$\sigma_y$	$\approx 0.7 \text{ nm}$
bunch length at IP target	$\sigma_z$	1 nm
bunch length at IP target		35 $\mu\text{m}$

normalised emittances

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

## Luminosity

Simplified treatment and approximations used throughout

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

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

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

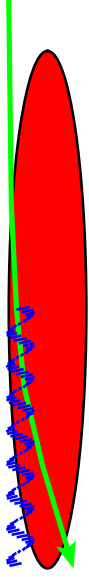
$$\mathcal{L} \propto H_D \frac{N}{\sqrt{\beta_x\epsilon_x\sqrt{\beta_y\epsilon_y}}}\eta P$$

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

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

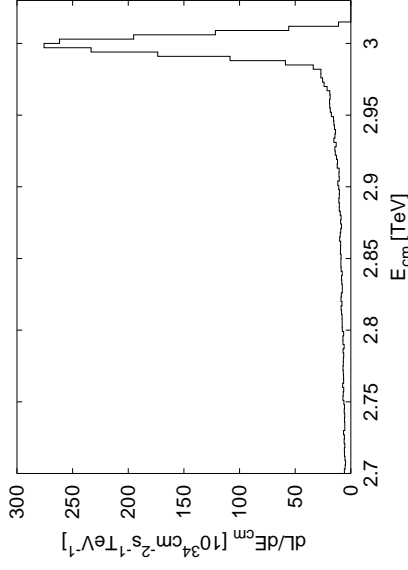
$$\epsilon_y = \epsilon_{y,DR} + \epsilon_{y,BC} + \epsilon_{y,linac} + \epsilon_{y,BDS} + \epsilon_{y,growth} + \epsilon_{y,offset} \dots$$

## Beam-Beam Interaction



Small beam  $\Rightarrow$  strong electro-magnetic field

- focuses the oncoming beam
- increases luminosity
- beamstrahlung  $\Rightarrow$  luminosity spectrum



$\mathcal{L}_1 = \mathcal{L}(E_{cm} \geq 0.99 \times E_{cm,0})$   
 current parameters  $n_\gamma = 1.7$ ,  $\Delta E/E \approx 20\%$ ,  
 $\mathcal{L}_1 \approx 0.4\mathcal{L}$

## Beam Dynamics Parameter Drivers

main linac

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

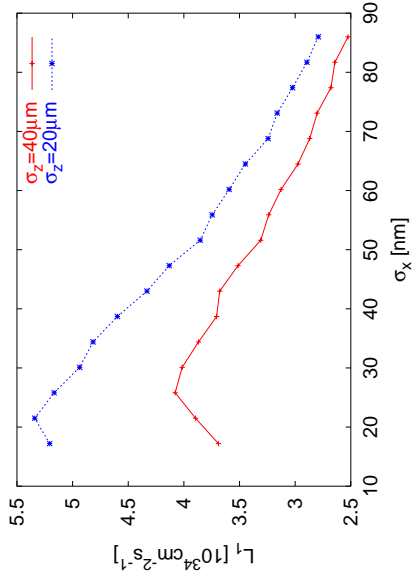
final focus system

- lower limit on  $\beta_x$ ,  $\beta_y$
- can contribute to emittances

beam-beam interaction

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

## Luminosity Optimisation



total luminosity

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

large  $n_\gamma$

• higher  $\mathcal{L}$

• degraded spectrum

optimum  $n_\gamma$  exists

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

## Beamstrahlung

Two regimes exist

beamstrahlung parameter

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

$\Upsilon \ll 1$ : classical regime

$\Upsilon \gg 1$ : quantum regime

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

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

⇒ partial suppression of beamstrahlung

⇒ coherent pair production

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

## 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  $\sigma_x \approx 65$  nm,  $\sigma_y \approx 0.7$  nm

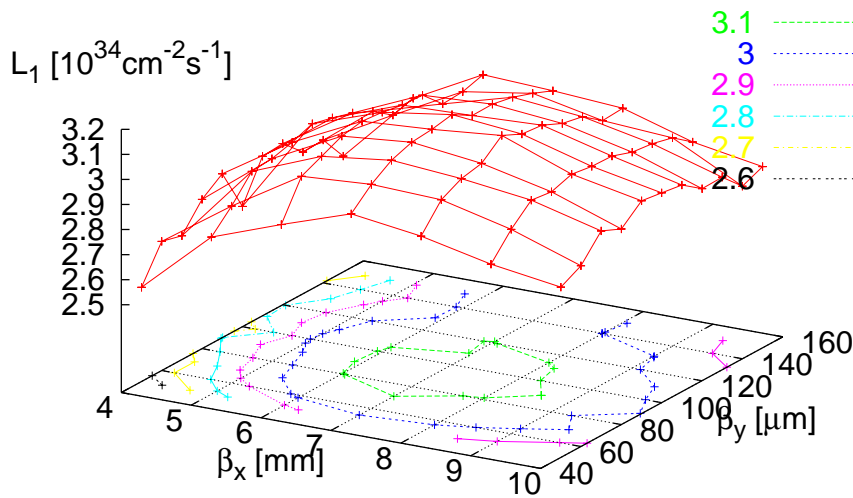
$\mathcal{L}_1 \propto 1/\sqrt{\epsilon_y}$ ,  $\sigma_x \approx 40$  nm for  $\epsilon_x = 0$

lower limit of  $\sigma_x$

for small  $N$  optimum  $n_{e\gamma}$  cannot be reached

luminosity factor 2 smaller than nominal

## Optimisation



thanks to F. Zimmermann for the MAD deck

## 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, feedback, re-tuning, re-alignment
- combination of dynamic and static imperfections can be severe
- use codes to evaluate linac performance

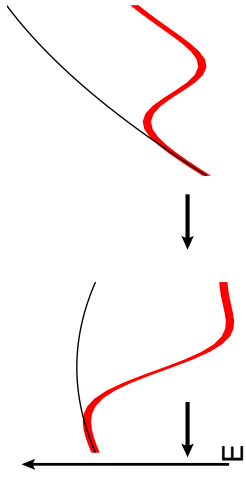
## Damping Ring

- Three main challenges
- horizontal emittance at low intensity
  - small coupling for vertical emittance
  - collective effects must be small enough
- no complete solution so far for CLIC
- current problems
- intra-beam scattering
  - electron cloud
- close to a solution
- dynamic aperture
- larger  $N$  may be simpler since one can allow

$$\epsilon_x \propto N^2$$

## Beam Loading and Bunch Length

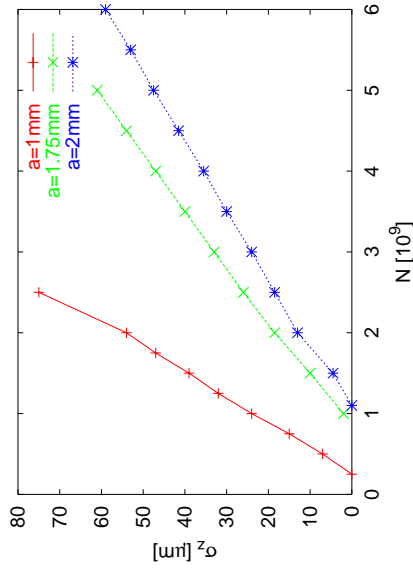
Multi-bunch beam loading compensated by RF



Single bunch longitudinal wakefield needs to be compensated

⇒ accelerate off-crest

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



## Emittance Preservation

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

two problems

- wakefields
- dispersion

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

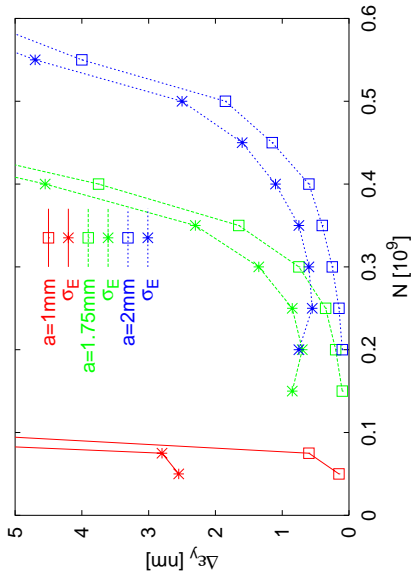
$W_{\perp}$  large  $a$  (iris radius)

$\Delta y$  very good prealignment  
sophisticated beam-based alignment

$N$  trivial, but  $\eta \propto N$

$\sigma_z$  large  $a$ , small  $N$

## Emittance Growth



Prealignment: RMS error  $10 \mu\text{m}$

beam-based alignment

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

reference structure has  $a = 2 \text{ mm}$

⇒ yields  $\Delta\epsilon_y \approx 1.4 \text{ nm}$  for CLIC

multi-bunch effects are small

## Lattice Design

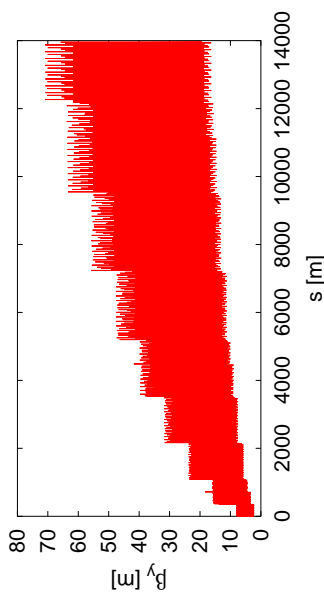
Linac lattice is a trade-off  
strong focusing

- small sensitivity to wakefields
  - dispersive effects important
- weaker focusing
- high sensitivity to wakefields
  - dispersive effects smaller

⇒ increase beta-function along machine

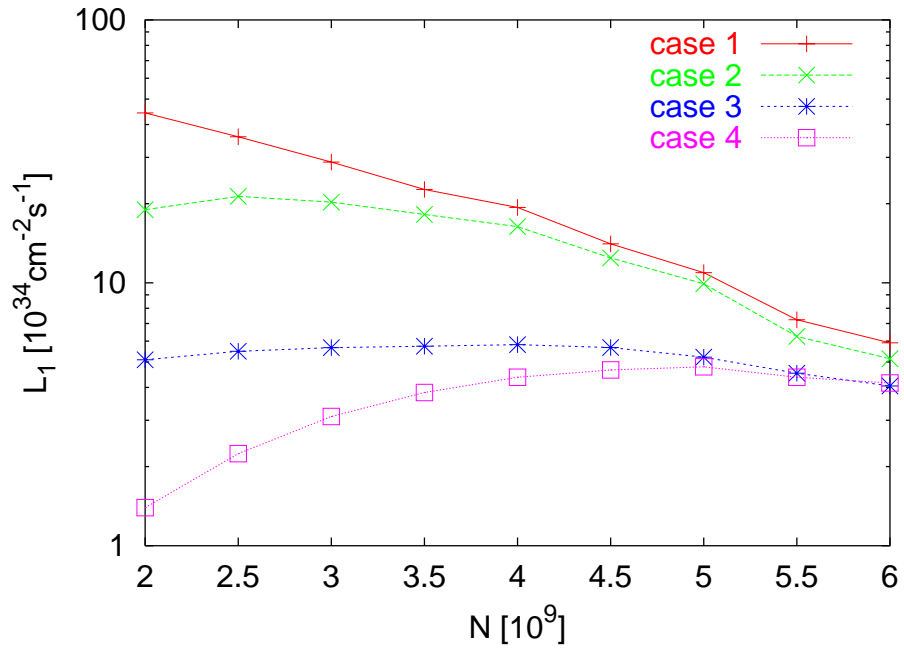
$$\beta \propto \sqrt{E}, \Delta\phi = \text{const}$$

in practice sectors with constant FODO cells are used



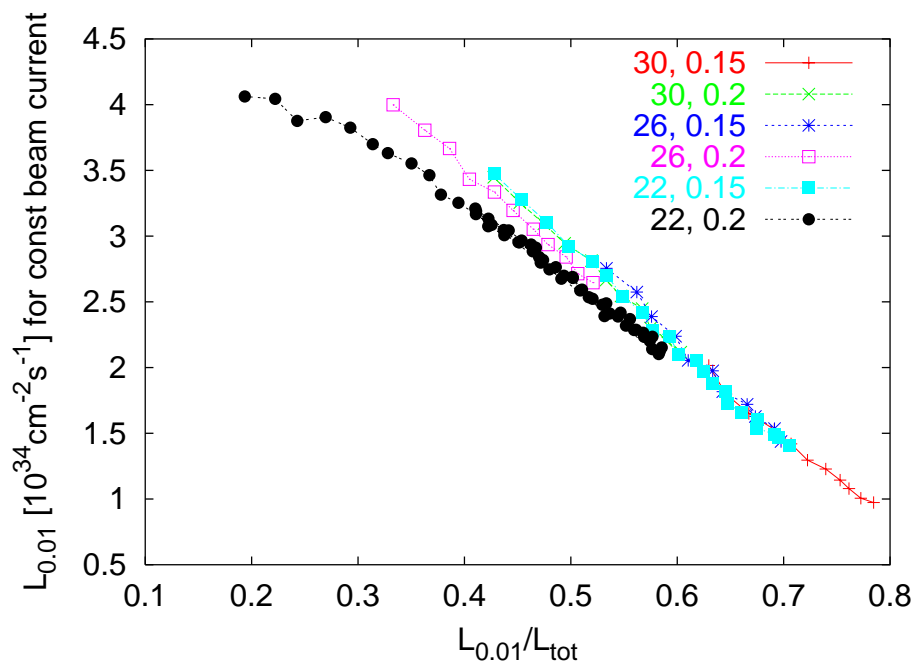


# Luminosity



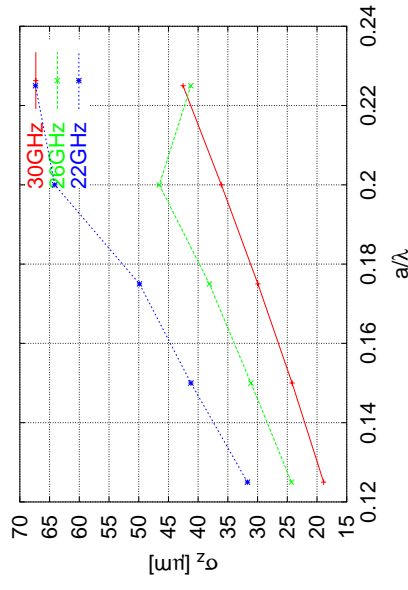
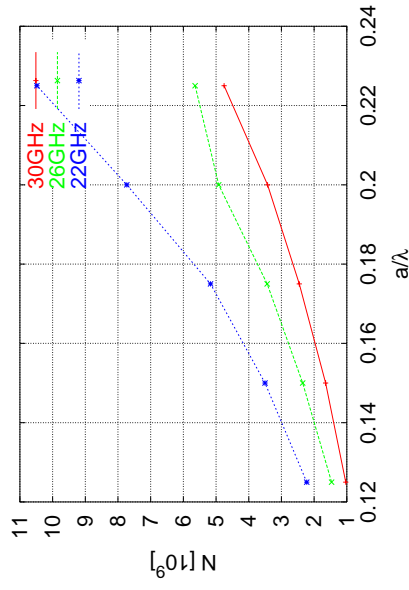
$\Rightarrow$  optimum  $N \approx 4.5 \times 10^9$  exists

$$E_{cm} = 3 \text{ TeV}, G = 150 \text{ MV/m}$$

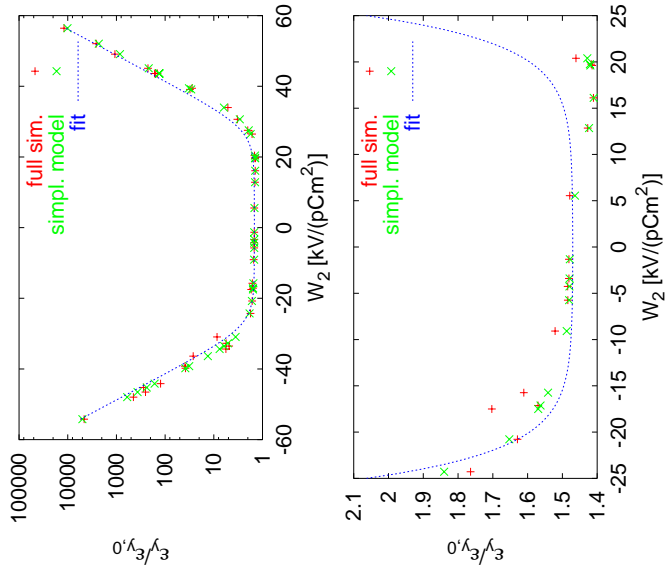


## Single Bunch Parameters

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



## CLIC Multi-Bunch Stability

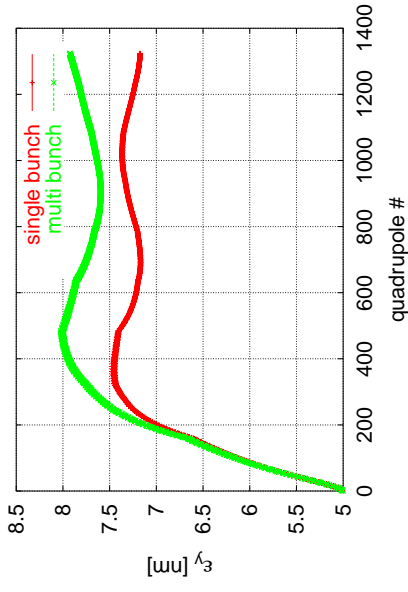


Exponential growth

small below  $\approx 20 \text{ kV} / (\text{pCm}^2)$  (for  $N = 4 \times 10^9$ )

## Full Simulation

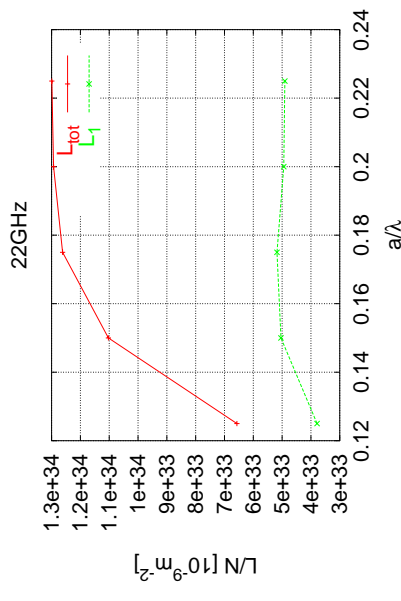
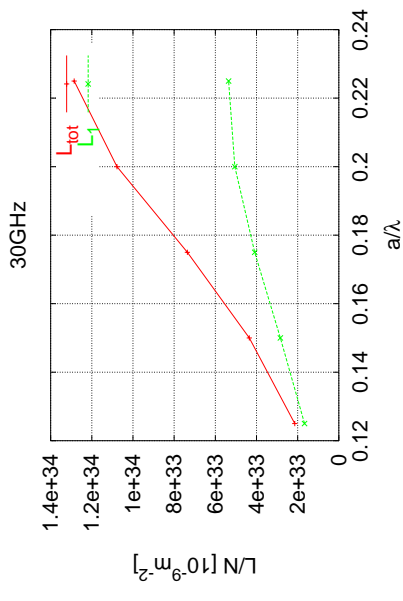
- Verification of beam stability using single and multi-bunch wakefields
- single-bunch wakefields from Karl Bane
- deriving long-range wakes from spline interpolation in between three cells



- tracking through linac+BDS
  - beam-beam interaction
- ⇒ luminosity

## Calculate Luminosity

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



## QCD Explorer

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

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

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

## Conclusion

- Beam-beam interaction
  - $\Rightarrow$  optimum  $\sigma_x \propto N \sqrt{\sigma_z}$
- damping ring and BDS
  - $\Rightarrow \sigma_x \geq 60 \text{ nm} > \text{optimum}$
- linac alone  $\Rightarrow$  small  $N$
- other effects  $\Rightarrow$  large optimum  $N$ 
  - $N = 4 \times 10^9$
  - $\Rightarrow \sigma_z = 35 \mu\text{m}$
  - $\Rightarrow \mathcal{L}_1 \approx 3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- parameter seem reasonable
- no obvious large gain
- optimisation possible  $\Delta_{RF} > 12^\circ$