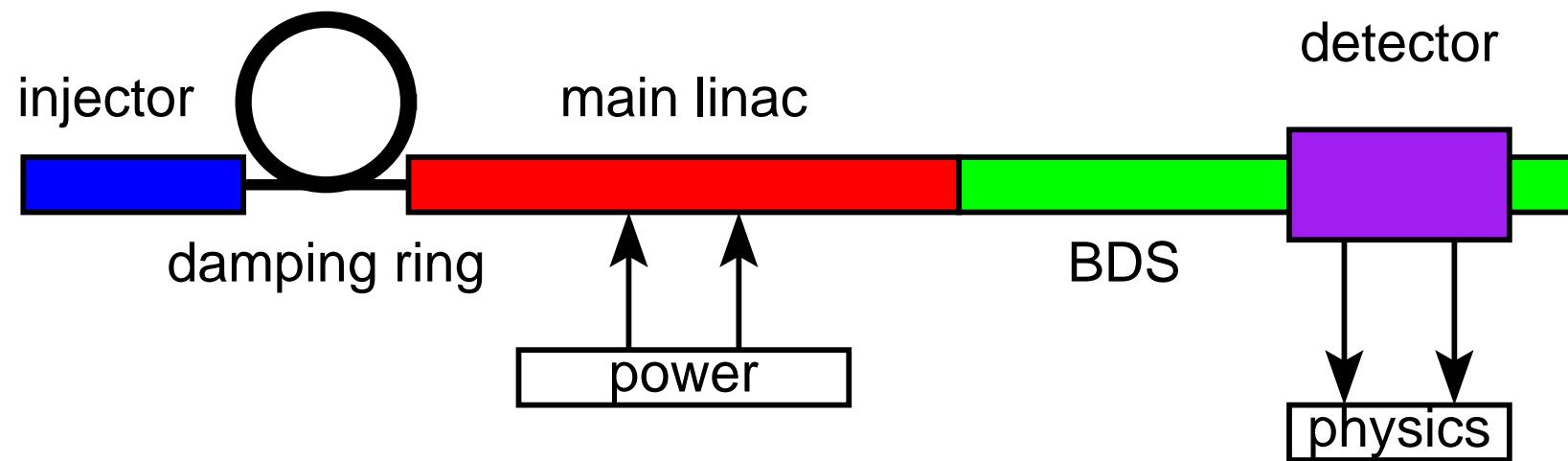


Beam Dynamics Driving the Parameter Choice

Daniel Schulte

Layout



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

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

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

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

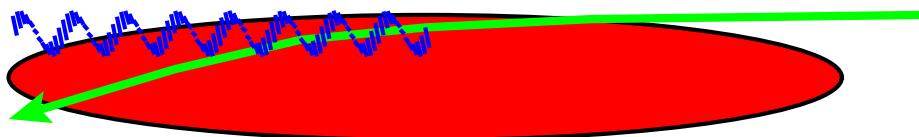
final focus system

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

beam-beam interaction

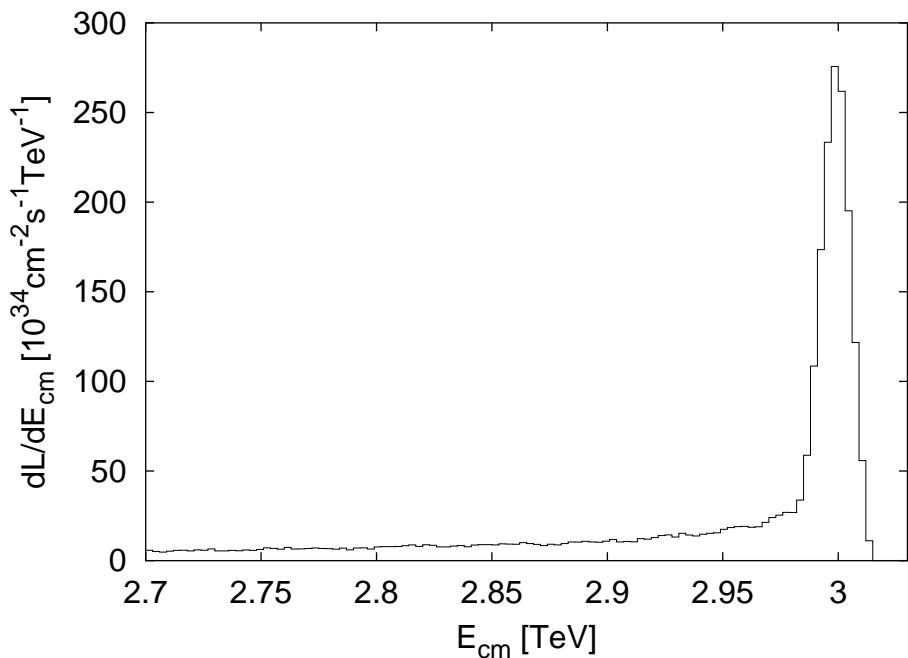
- leads to requirement for optimum $(N/\sigma_x)(\sigma_z)$

Beam-Beam Interaction



Small beam \Rightarrow strong electro-magnetic field

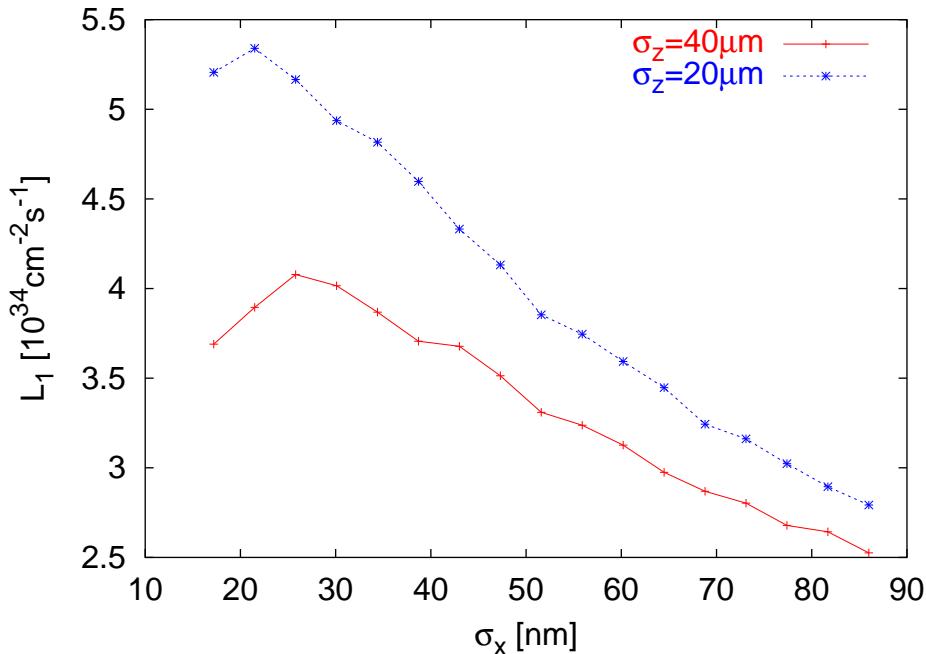
- focuses the oncoming beam
- increases luminosity
- beamstrahlung \Rightarrow luminosity spectrum



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

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

Luminosity Optimisation



total luminosity

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

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 $\sigma_x \approx 65 \text{ nm}$, $\sigma_y \approx 0.7 \text{ nm}$

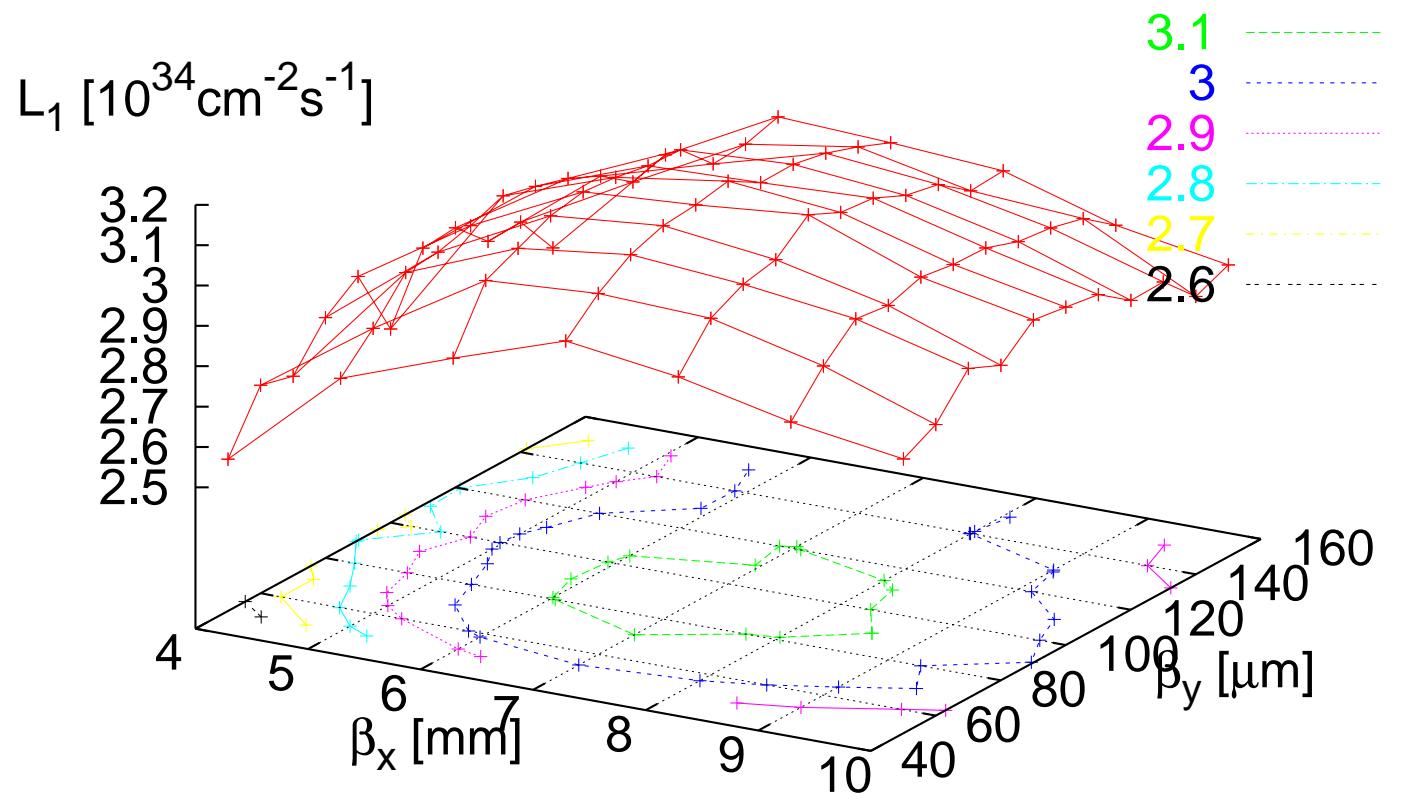
$\mathcal{L}_1 \propto 1/\sqrt{\epsilon_y}$, $\sigma_x \approx 40 \text{ nm}$ for $\epsilon_x = 0$

lower limit of σ_x

for small N optimum n_γ cannot be reached

luminosity factor 2 smaller than nominal

Optimisation

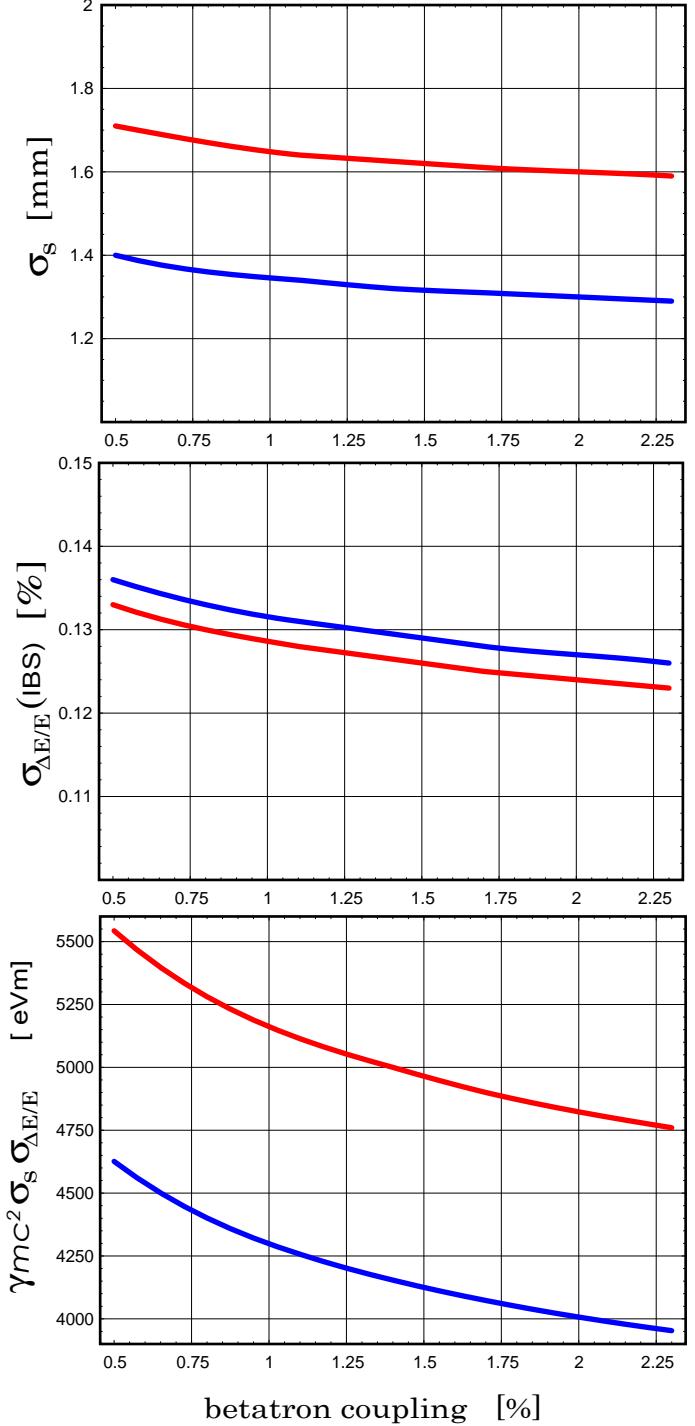
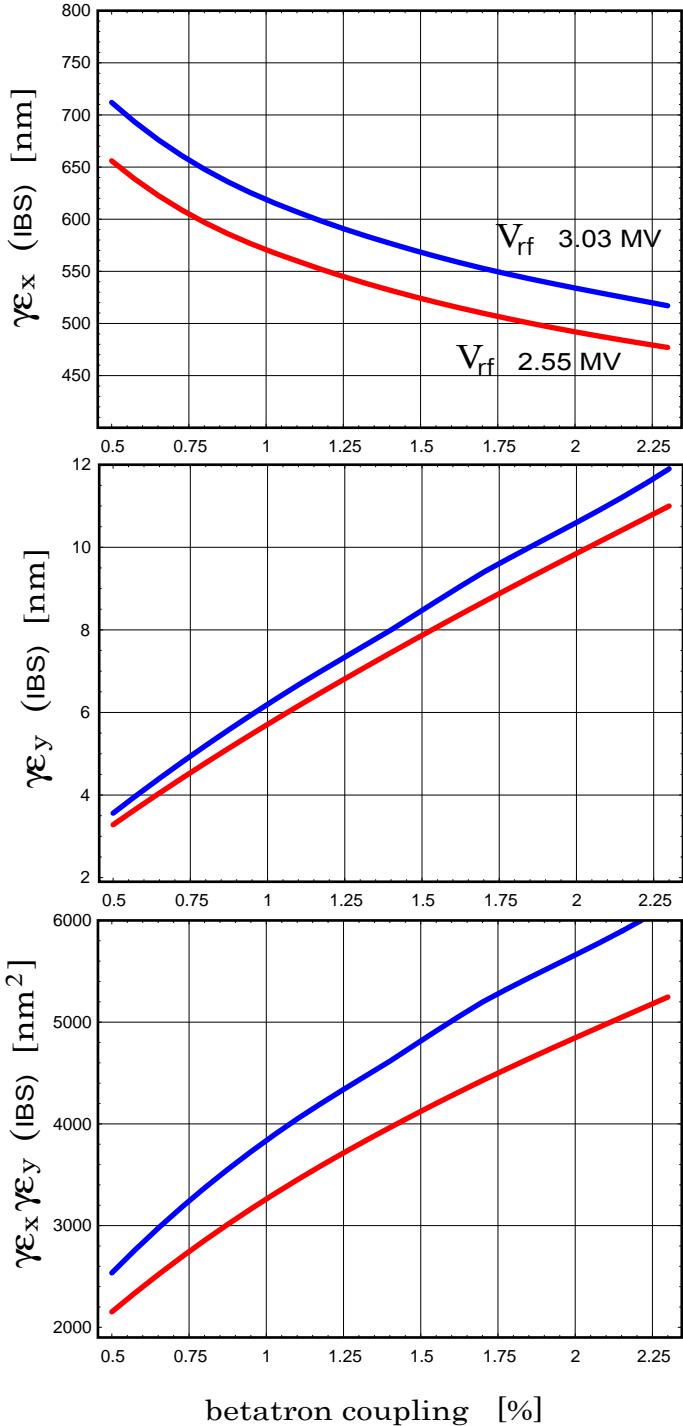


thanks to F. Zimmermann for the MAD deck

Normalized emittances and rms bunch length & energy spread in CLIC_DR with wiggler period of 10 cm (instead of 20 cm). Energy is 2.424 GeV

V_{rf}  2.55 MV

V_{rf}  3.03 MV



$$\gamma\varepsilon_x = 580 \text{ [nm]} \quad \text{at } 1.4 \text{ [%] of betatron coupling,}$$

$$\gamma\varepsilon_y = 8 \text{ [nm]} \quad \text{at } 1.78 \text{ [T] of wiggler field &}$$

$$3.03 \text{ [MV] of RF voltage}$$

Maxim Korostelev

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)

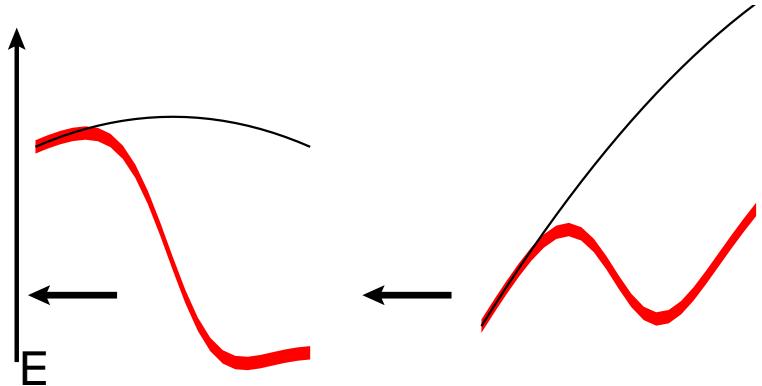
Δy very good prealignment
sophisticated beam-based alignment

N trivial, but $\eta \propto N$

σ_z large a , small N

Beam Loading and Bunch Length

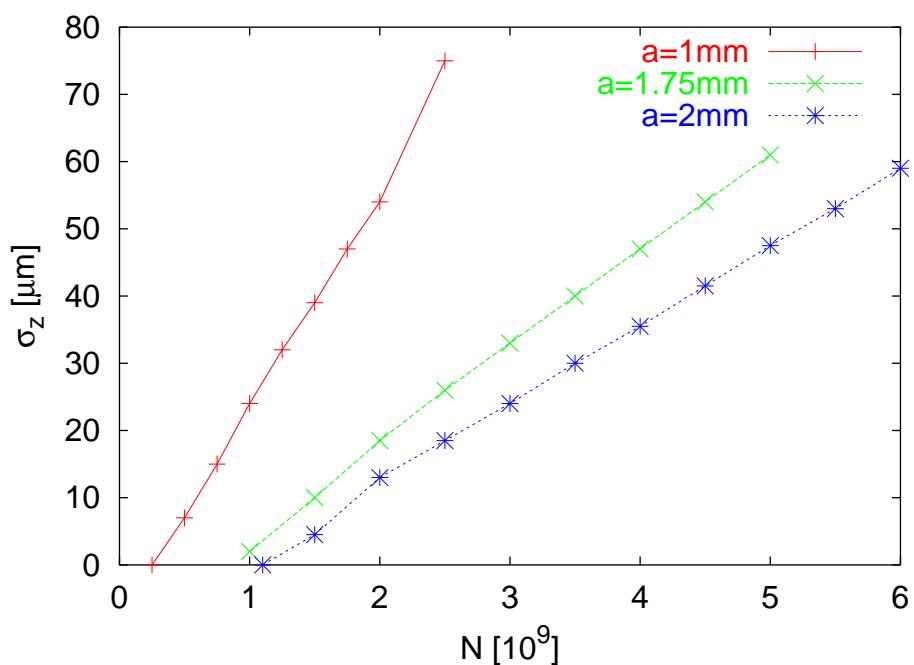
Multi-bunch beam loading compensated by RF



Single bunch longitudinal wakefield needs to be compensated

⇒ accelerate off-crest

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



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

Lattice Design

Linac lattice is a trade-off
strong focusing

- small sensitivity to wakefields
- dispersive effects important

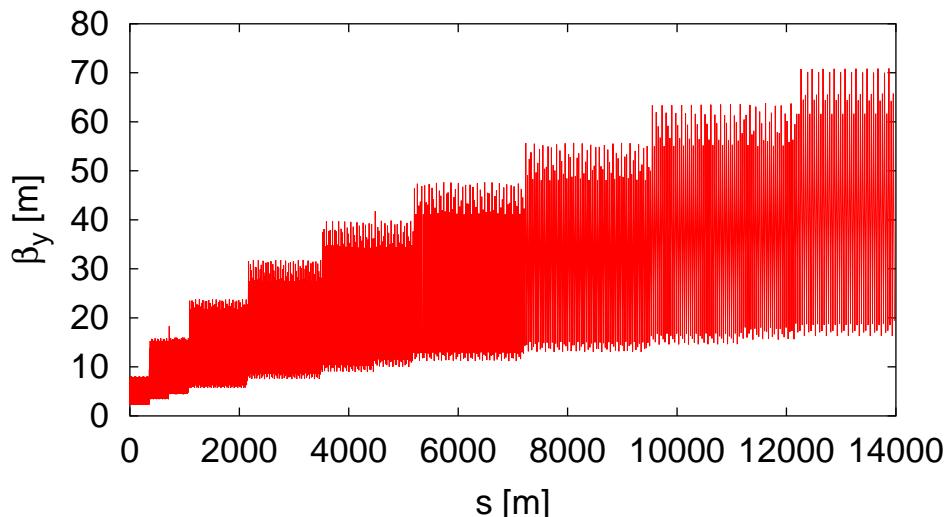
weaker focusing

- high sensitivity to wakefields
- dispersive effects smaller

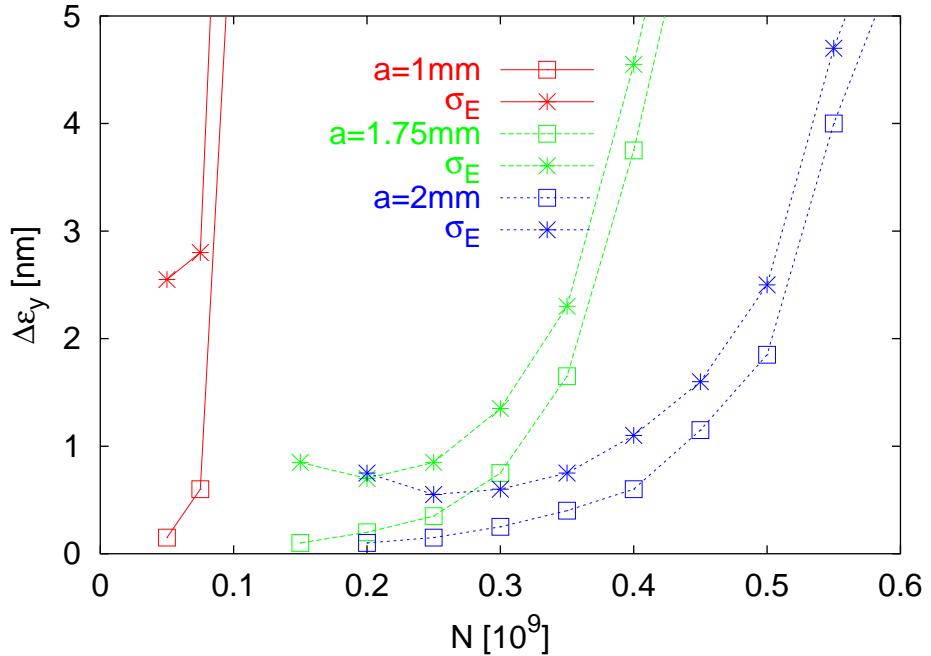
⇒ increase beta-function along machine

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

in practice sectors with constant FODO cells are used



Emittance Growth



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

beam-based alignment

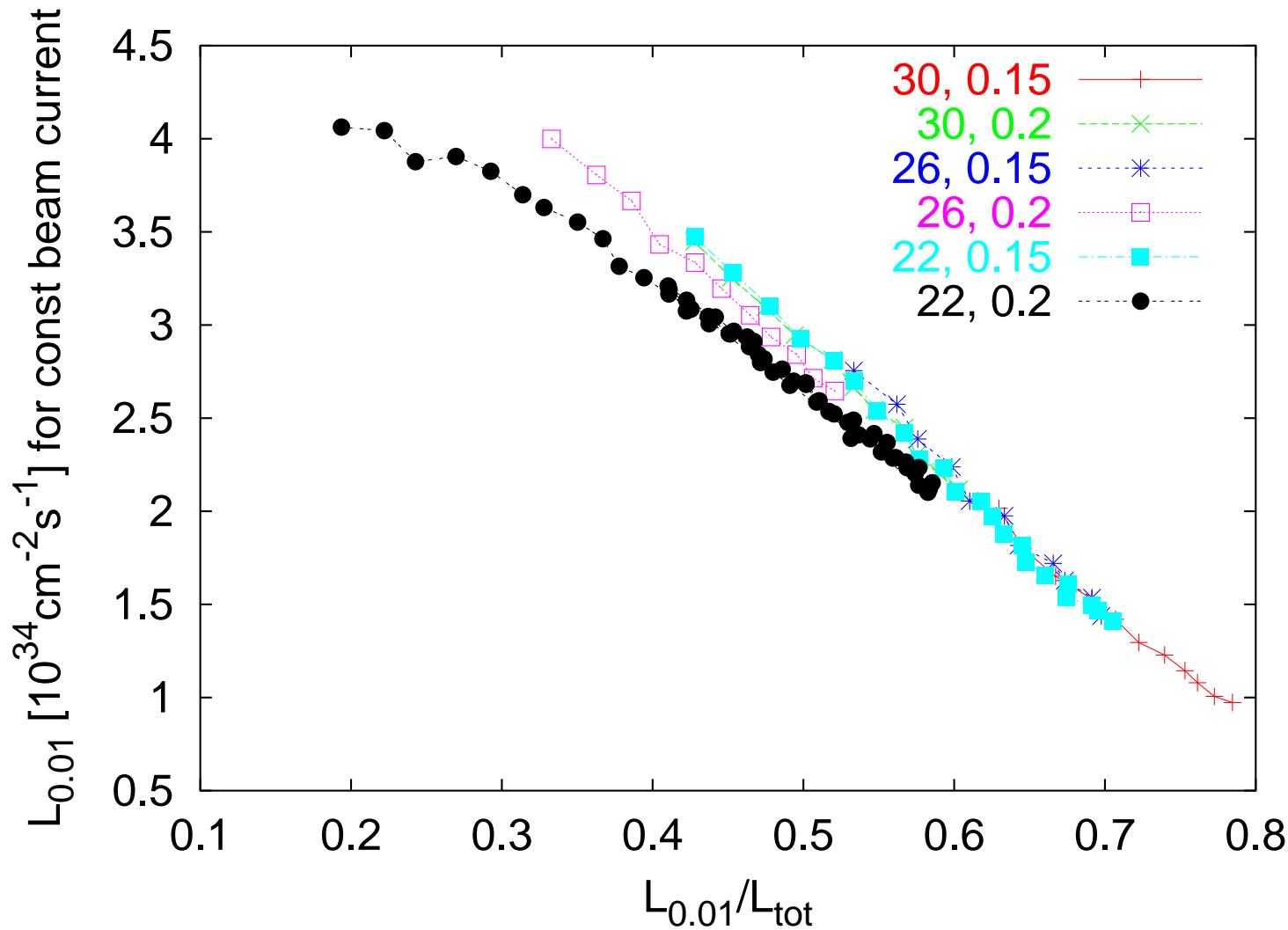
three structures $a = 1 \text{ mm}, a = 1.75 \text{ mm}, a = 2 \text{ mm}$

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

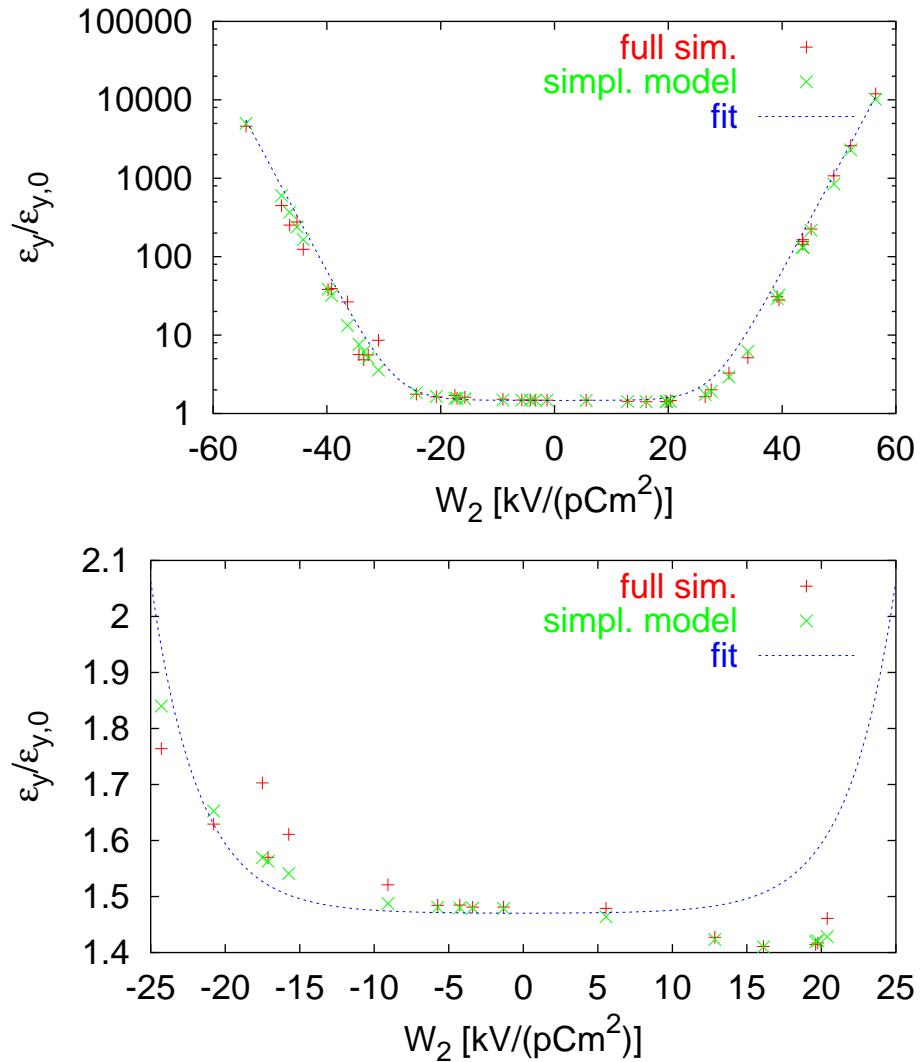
\Rightarrow yields $\Delta\epsilon_y \approx 1.4 \text{ nm}$ for CLIC

multi-bunch effects are small

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



CLIC Multi-Bunch Stability

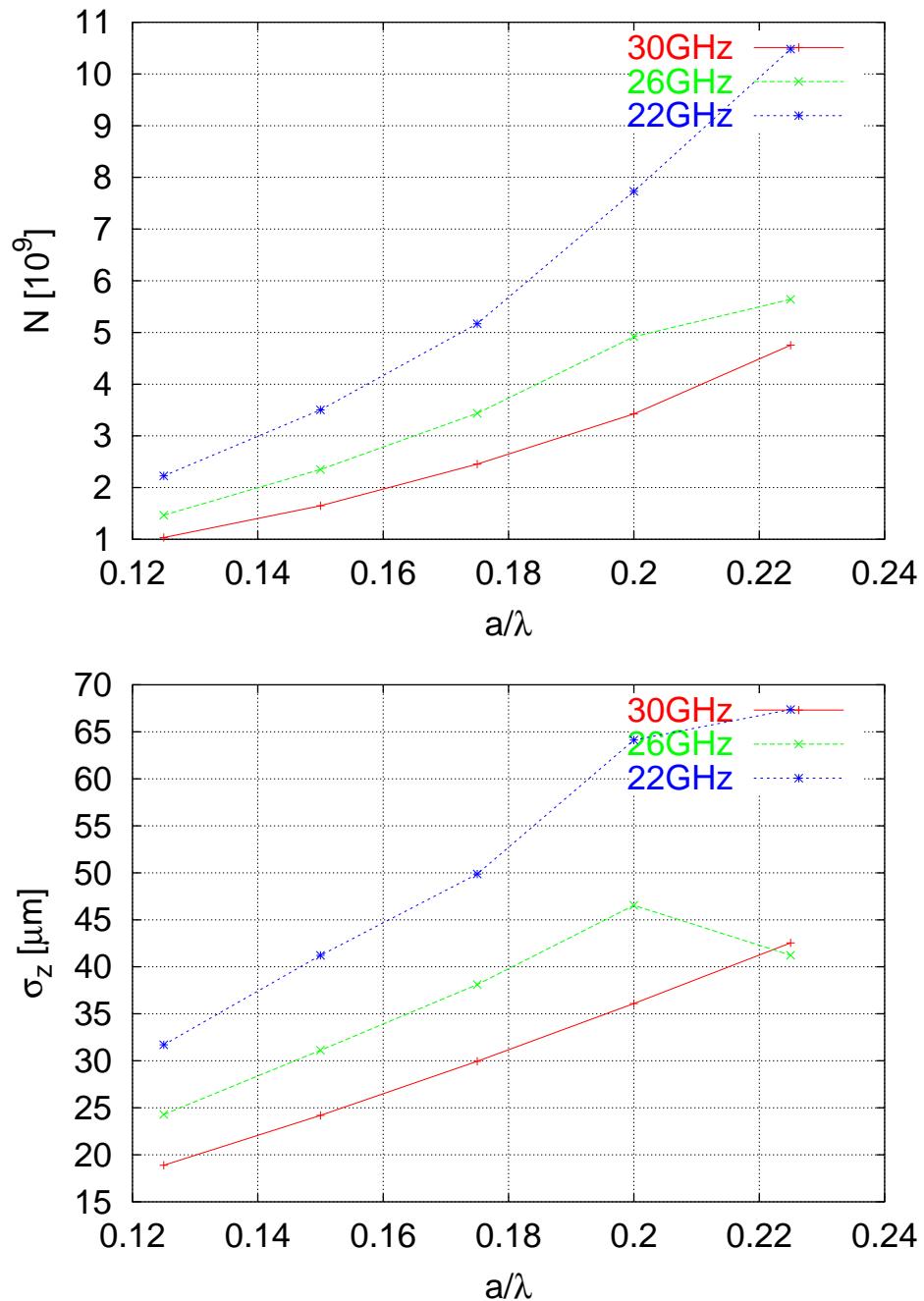


Exponential growth

small below ≈ 20 kV/(pCm²) (for $N = 4 \times 10^9$)

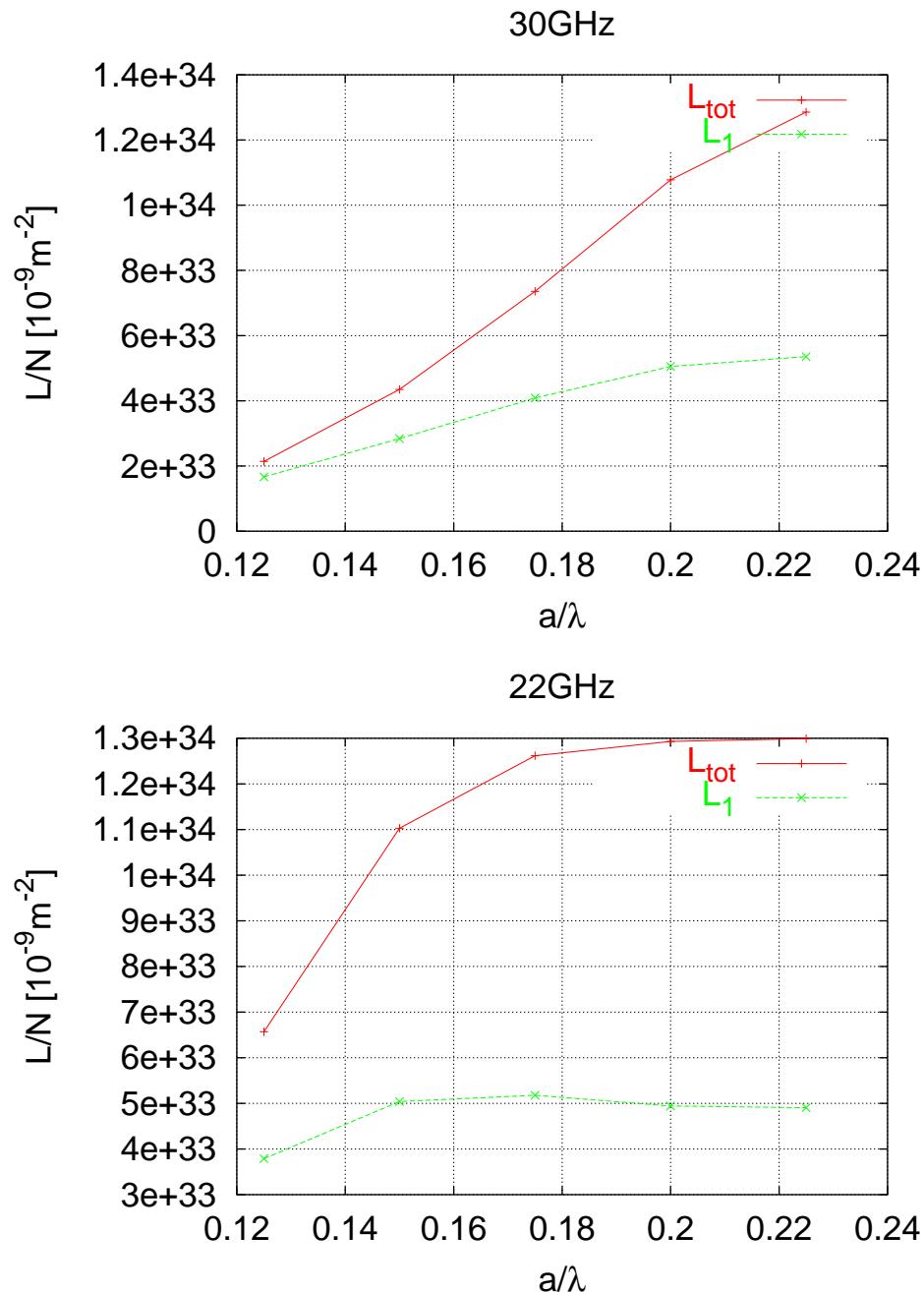
Single Bunch Parameters

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



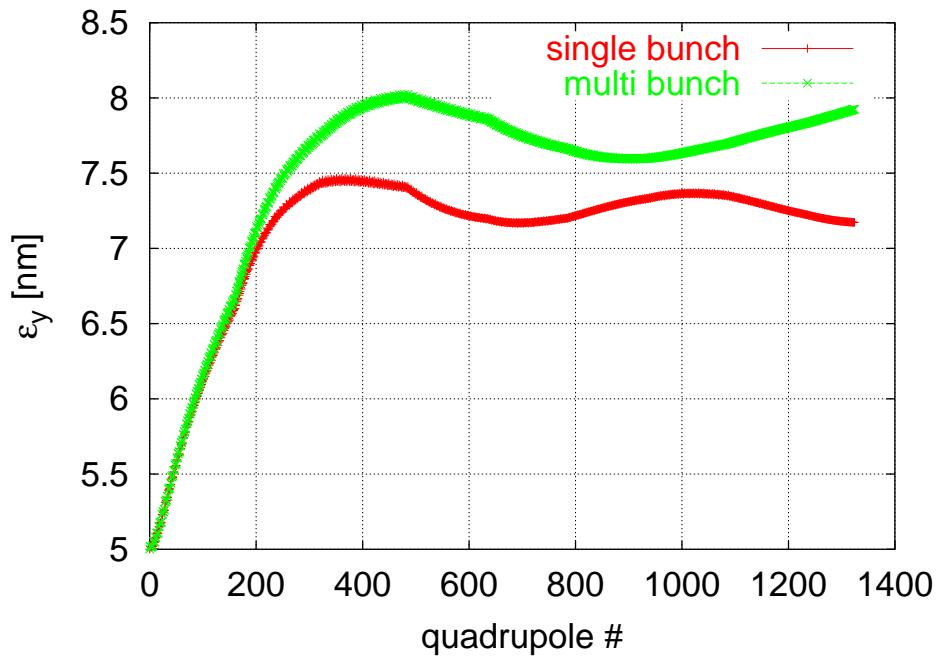
Calculate Luminosity

- 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
- ⇒ luminosity

New Parameters for HDS 80?

- $\epsilon_x \approx 580 \text{ nm}$ from DR
- assuming $\epsilon_x = 680 \text{ nm}$ at BDS
⇒ check bunch compressor
- $\epsilon_y \approx 8 \text{ nm}$ from DR (could be better?)
- $\Delta\epsilon_y \approx 7 \text{ nm}$
⇒ more study of static and dynamic effects
- bunch charge $N = 2.36 \times 10^9$
- bunch length $\sigma_z = 28 \mu\text{m}$
- $L_{tot} = 1.73 \times 10^{34} \text{ m}^{-2}\text{bx}^{-1}$, $L_1 = 0.92 \times 10^{34} \text{ m}^{-2}\text{bx}^{-1}$ ($\epsilon_y = 10 \text{ nm}$)
- $L_{tot} = 1.32 \times 10^{34} \text{ m}^{-2}\text{bx}^{-1}$, $L_1 = 0.7 \times 10^{34} \text{ m}^{-2}\text{bx}^{-1}$ ($\epsilon_y = 15 \text{ nm}$)
- $n_\gamma = 1.1$, $\Delta E/E = 15\%$, $n_{coh} = 0.023$, $P_{coh}/P_{beam} = 0.003$, $\Upsilon_{max} \approx 11$