Linear Collider Beam Dynamics
I, II and III

D. Schulte

Introduction

Stepping Stones

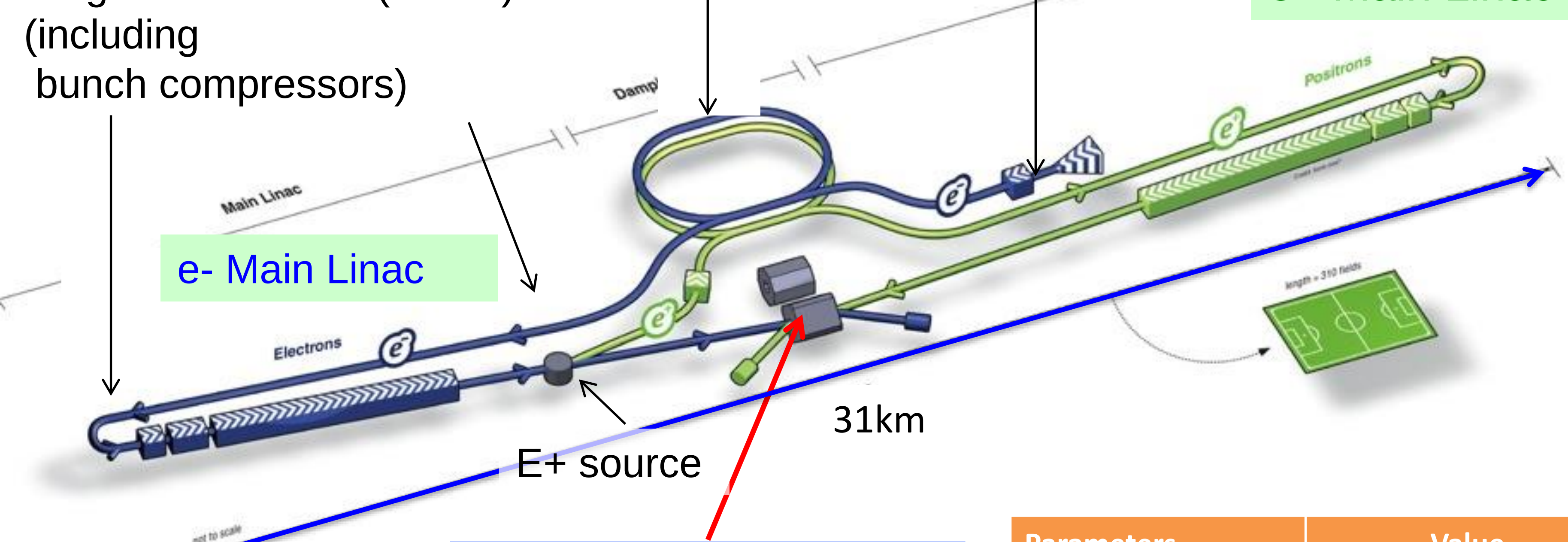
- Beam parameters and main systems
  - Luminosity
  - Main linac and efficiency

- Main linac and beam parameter choice
  - Single bunch energy spread
  - Single bunch beam break-up
  - Multi-bunch beam break-up

- Emittance Preservation
  - Static imperfections
  - Dynamic imperfections

Overall Design and Parameters

ILC



Ring to Main Linac (RTML) (including
bunch compressors)

Damping Rings

Polarised electron source

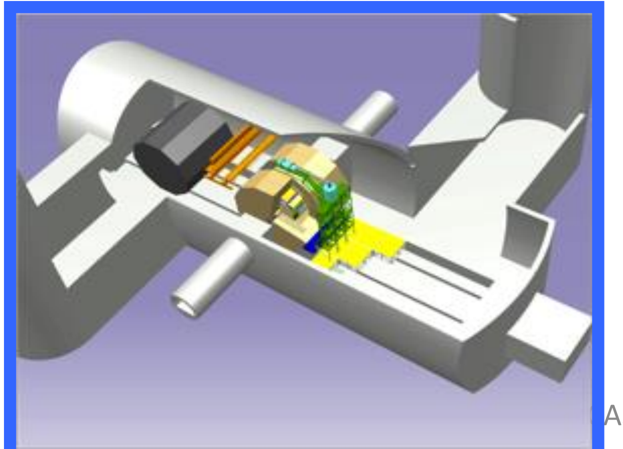
e+ Main Linac

e- Main Linac

E+ source

31km

ILC Scheme | © www.form-one.de



Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam power	10.5 MW
Beam Rep. rate	5 Hz
E gradient	31.5 MV/m +/-20%

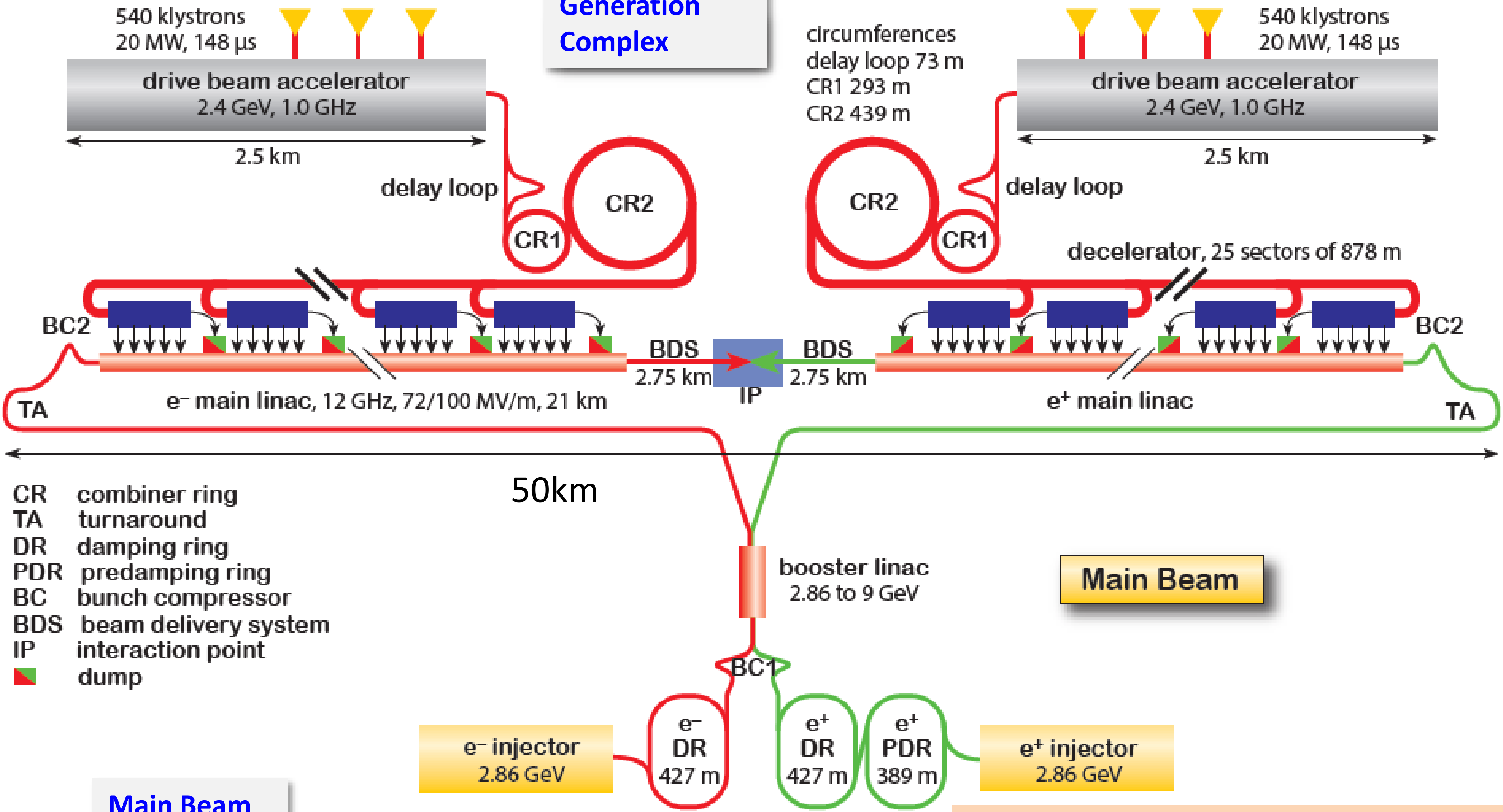
CLIC (3 TeV)

⇒ Steinar Stapnes Thursday 22.2.

Goal: Lepton energy frontier

CLIC at 3TeV shown

Drive Beam Generation Complex



Main Beam

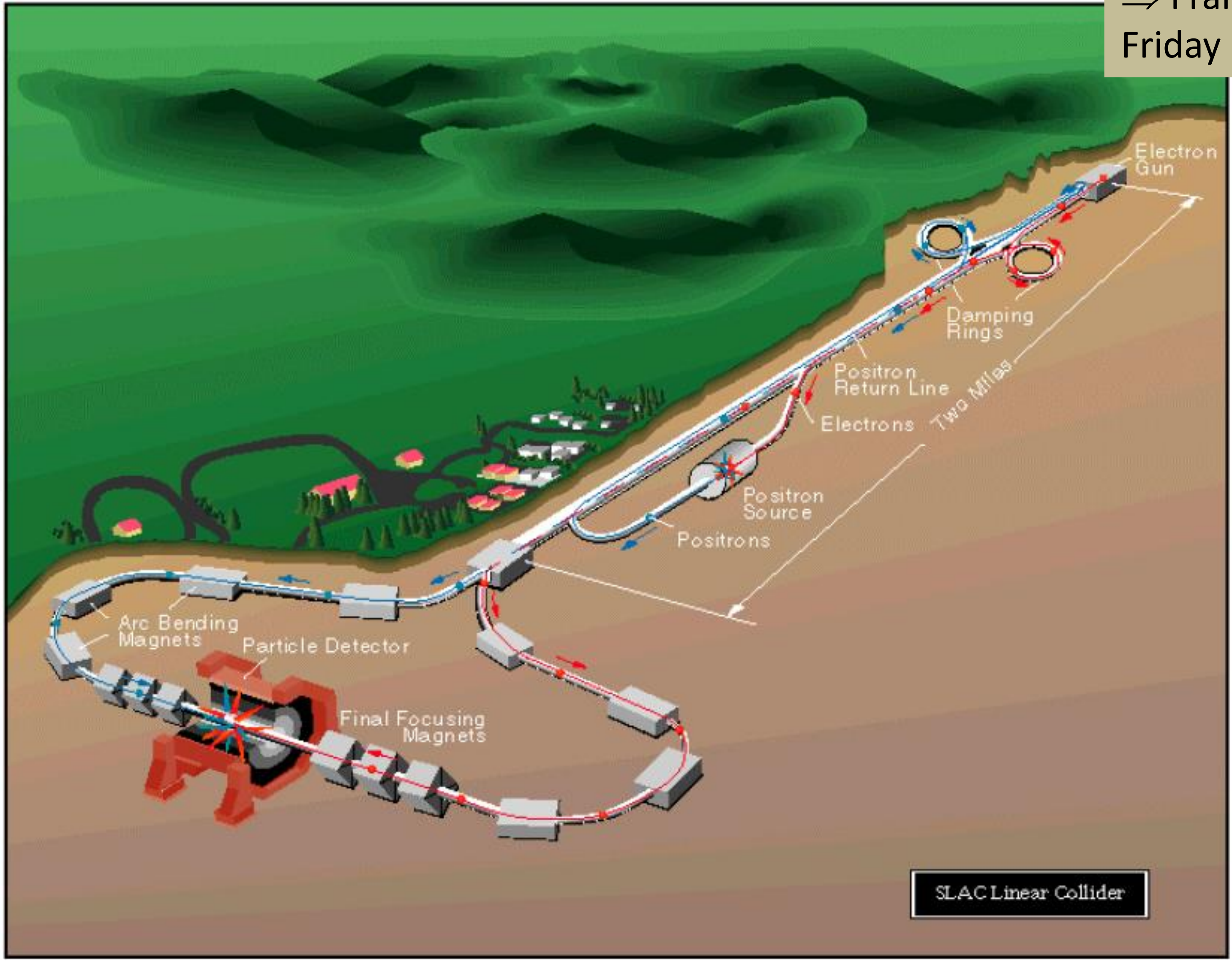
Main Beam Generation Complex

Stages at E_{cms}=0.38, 1.5 and 3TeV

L=6x10^{34}cm^{-2}s^{-1} at 3TeV

Beam power 30MW at 3TeV

SLC: The only Linear Collider that existed



⇒ Frank Zimmermann
Friday 2.3.

he Z^0 and demonstrate linear collider feasibility

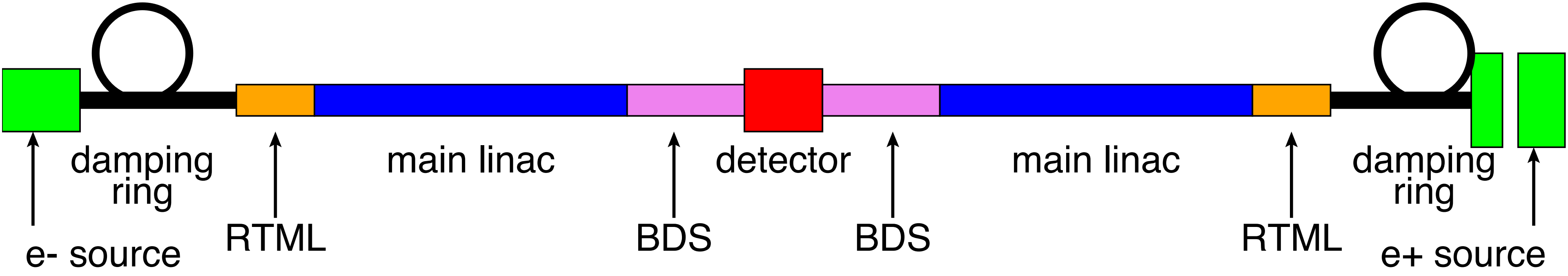
Energy = 92 GeV

Luminosity = 2e30

Has all the features of a 2nd gen. LC except both e+ and e- used the same linac

A 10% prototype!

Sources



Produce the electron beam

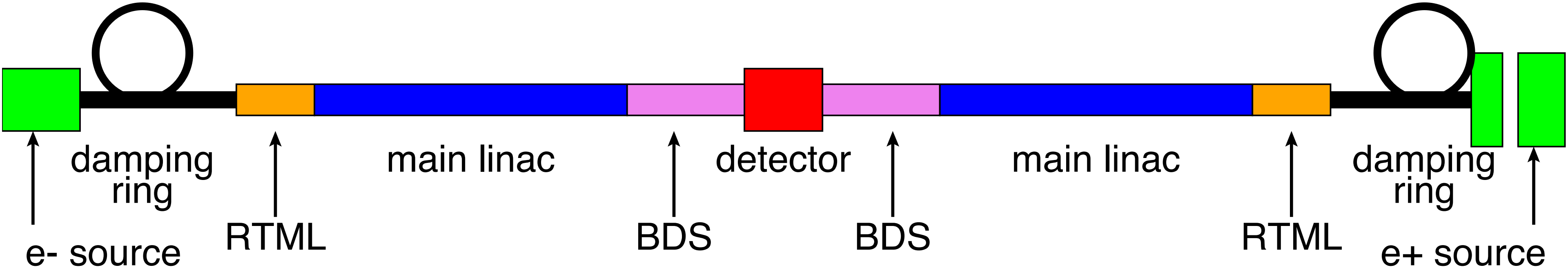
- use a laser to kick electrons out of a cathode

⇒ Masao Kuriki Thursday 1.3.

Produce the positron beam

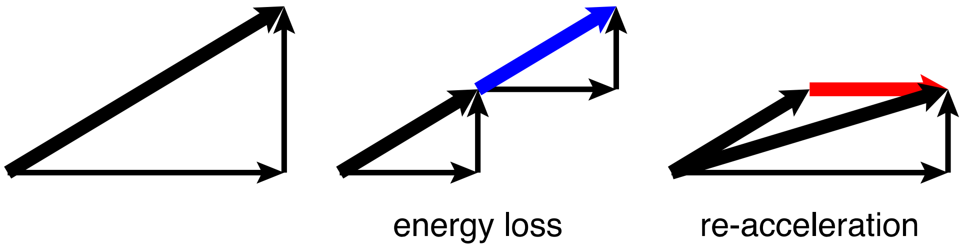
- use an electron beam to produce photons
  - In CLIC in a crystal
  - In ILC in a wiggler
- the photons produce showers in matter
  - harvest the positrons

Damping Rings



Cool the beams

- in particular positron beam



Produce flat beams due to physics

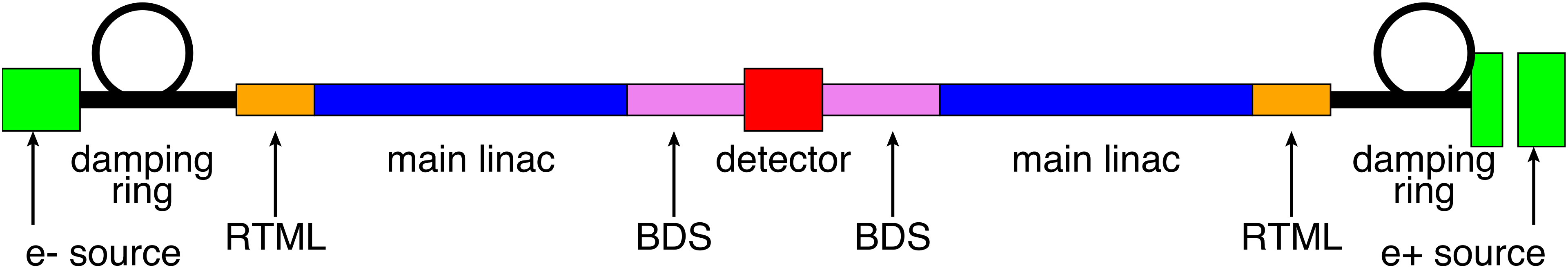
Minimum emittances exist (zero current emittances)

For larger charges they can increase due to collective beam dynamics

⇒ Hermann Schmickler
Friday 23.2. ☺

⇒ Katsunobu Oide
Monday 26.2., Tuesday 27.2.

Ring To Main Linac Transport



damping ring

main linac

detector

main linac

damping ring

e- source

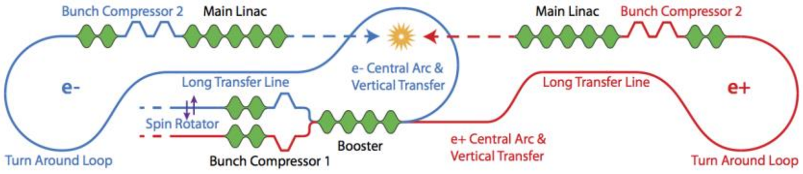
RTML

BDS

BDS

RTML

e+ source

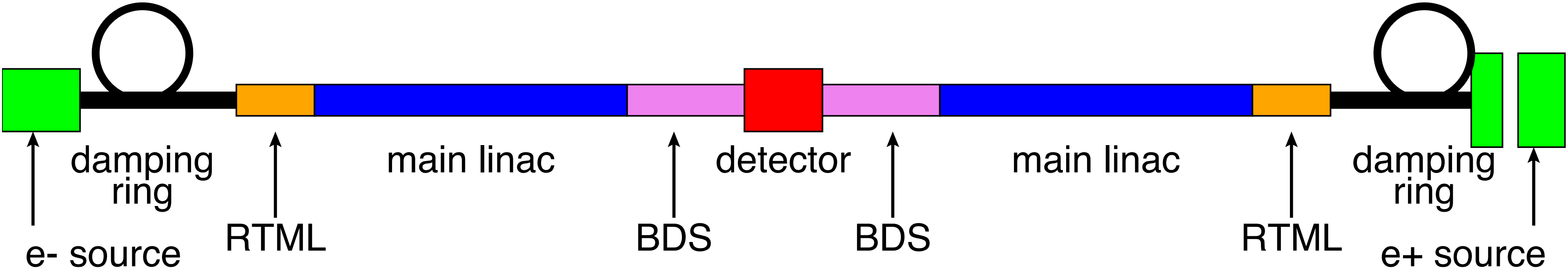


Transports beam from damping ring to main linac

- Compresses bunches from damping ring to main linac (e.g. from 1.6 mm to 70 µm in CLIC)
- Increase the beam energy to be high enough for transport and main linac

⇒ Frank Tecker
Saturday 24.2.

Main Linac



Beam power (both beams)
ILC @ 500 GeV : 11 MW
CLIC @ 3 TeV: 28 MW

The key for higher energies

The main cost driver

Main power consumer

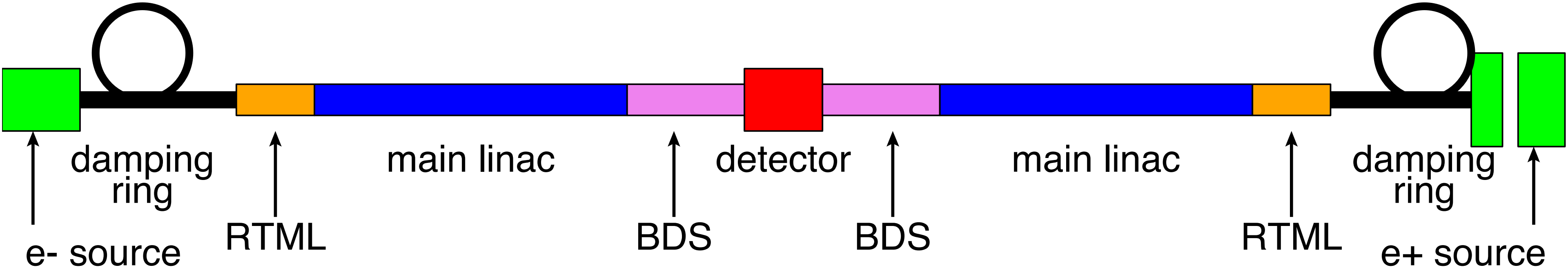
A main ingredient for site choice

The key design driver for other systems

Core of this lecture

Note: 12 hours of main linac lecture in linear collider school only scratches the surface

Beam Delivery System


damping ring

main linac

detector

main linac

damping ring

e- source

RTML

BDS

BDS

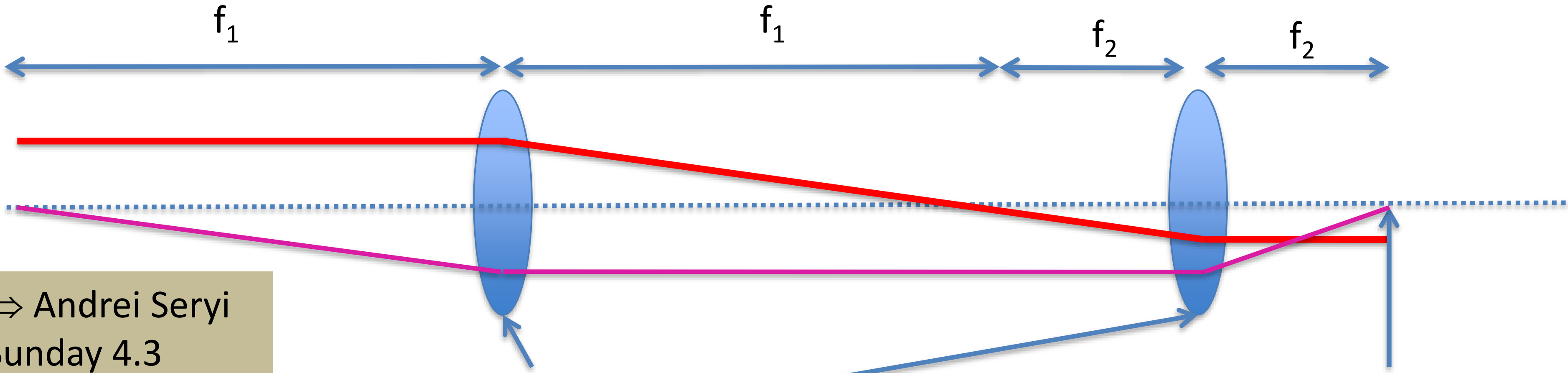
RTML

e+ source

Cleaning of the beams from tails and halo

- machine protection issue
- Important to avoid background in the detector

Final focus system: Telescope to squeeze the beam to small size, i.e. small beta-function challenging because of the beam energy spread



Focusing lens
Actually a doublet of quadrupoles

IP, i.e. focal point

⇒ Andrei Seryi
Sunday 4.3

⇒ Werner Herr
Monday 26.2.

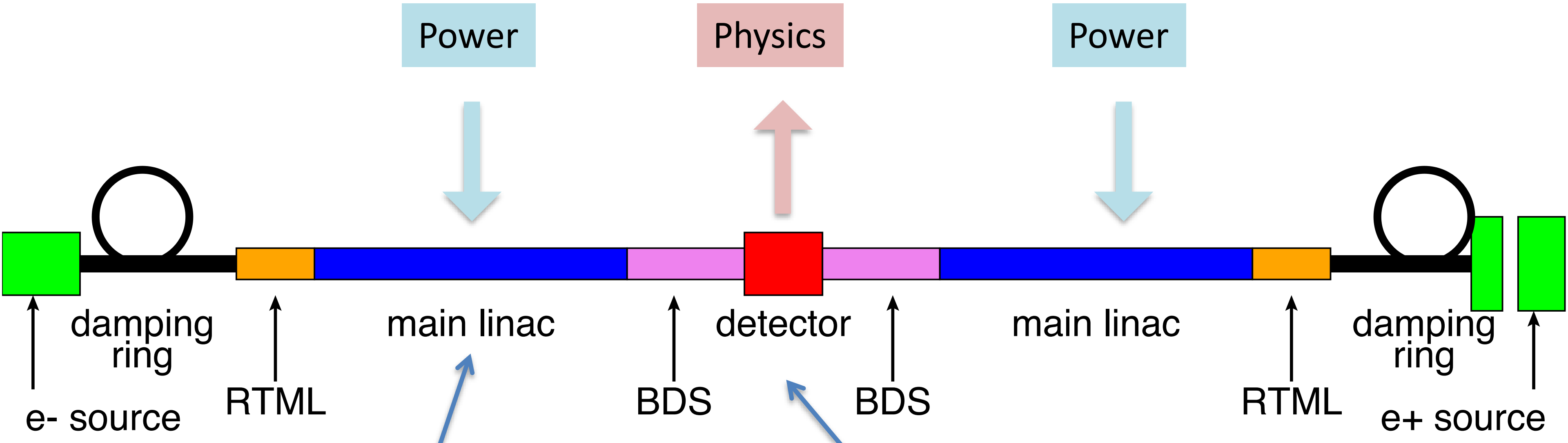
Challenges: Energy and Luminosity

Key Parameters

Parameter	Symbol [unit]	SLC	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	92	500	380	3000
Luminosity	L [10^{34}cm^{-2}s^{-1}]	0.0003	1.8	1.5	6
Luminosity in peak	$L_{0.01}$ [10^{34}cm^{-2}s^{-1}]	0.0003	1	0.9	2
Gradient	G [MV/m]	20	31.5	72	100
Particles per bunch	N [10^9]	37	20	5.2	3.72
Bunch length	σ_z [μm]	1000	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	474/5.9	143/2.9	40/1
Emittance	$\epsilon_{x,y}$ [μm/nm]	~3/3000	10/35	0.95/30	0.66/20
IP beta functions	$\beta_{x,y}$ [mm/mm]	87/10	11/0.48	8/0.1	6/0.07
Bunches per pulse	n_b	1	1312	352	312
Bunch distance	Δz [mm]	-	554	0.5	0.5
Repetition rate	f_r [Hz]	120	5	50	50

Energy and luminosity goals are defined by physics

Main Linear Collider Challenges



Single pass in linac to reach energy

⇒ Technology challenge

Single pass to reach luminosity

⇒ Technology and beam dynamics

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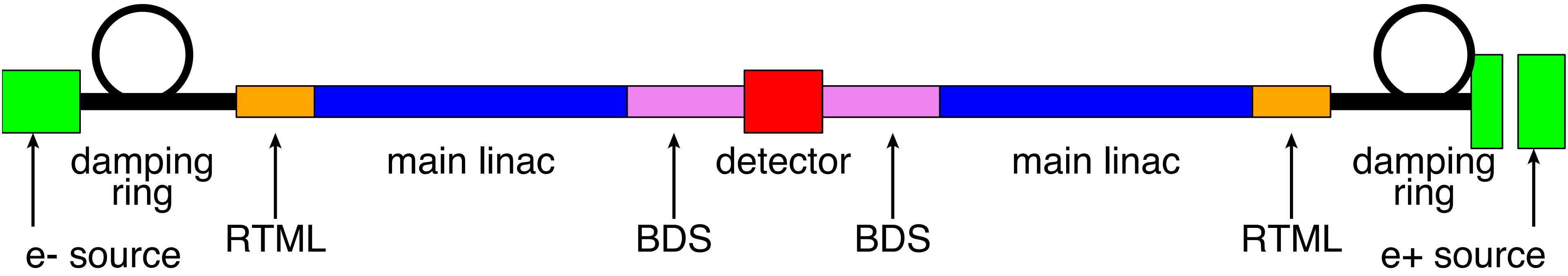
Note: Emittances are always normalised

Beam Parameters Along the Collider (CLIC 380)



	ε_x [nm]	ε_y [nm]	σ_z [μm]	N [10^9]	E [GeV]
Damping ring exit	700	5	1600	5.2	2.86
End of RTML	850	10	70	5.2	9.0
End of main linac	920	20	70	5.2	190.0
Interaction point	950	30	70	5.2	190.0

Mainly damping ring defines horizontal emittance

Bunch energy defined by main linac

Final bunch length defined by main linac

All systems contribute to vertical emittance

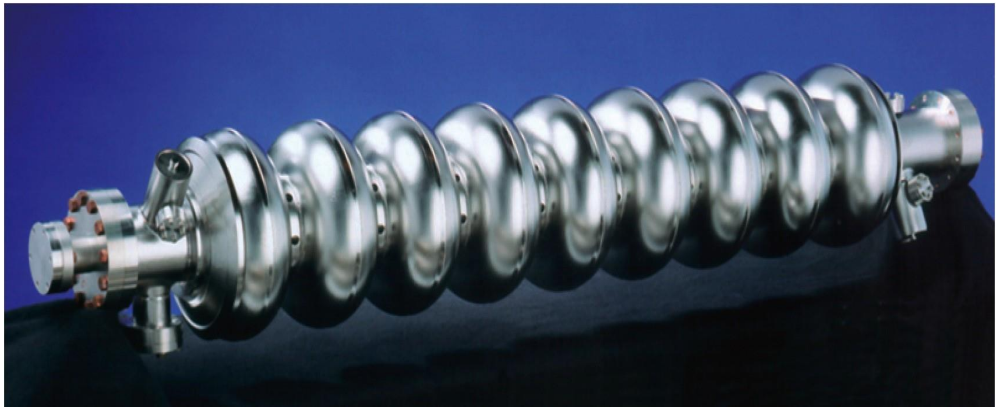
Bunch charge defined by main linac

Energy Drivers

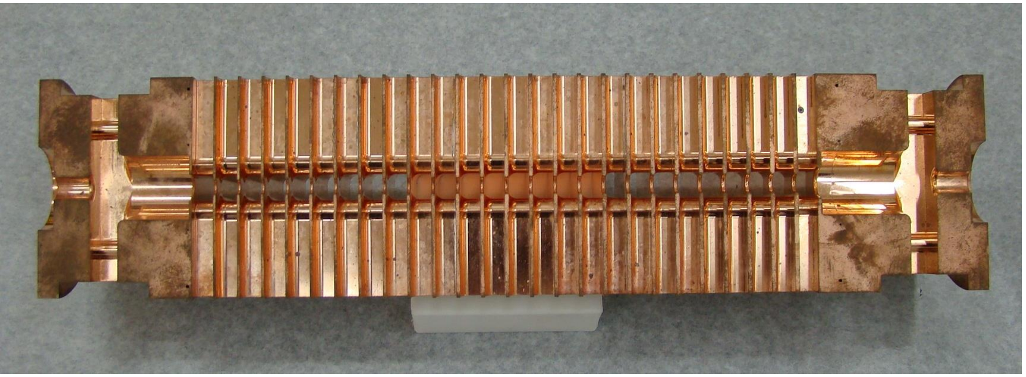
Energy is given by linac length and gradient
⇒ Key technology challenge
⇒ Bulk of the cost
⇒ Bulk of the power consumption

Affordability of the project depends on main linac

Also drives beam parameters



⇒ Erk Jensen,
Thursday 1.3.



⇒ Walter Wuensch,
Sunday/Monday 4/5.3.

ILC:
Superconducting cavity at 31.5 MV/m
The highest field that is deemed possible in mass production

CLIC:
Normal conducting accelerating structures at 100 MV/m for 3 TeV and 72 MV/m for 380 GeV
Gradient optimised for cost

Luminosity Drivers

Can re-write normal luminosity formula

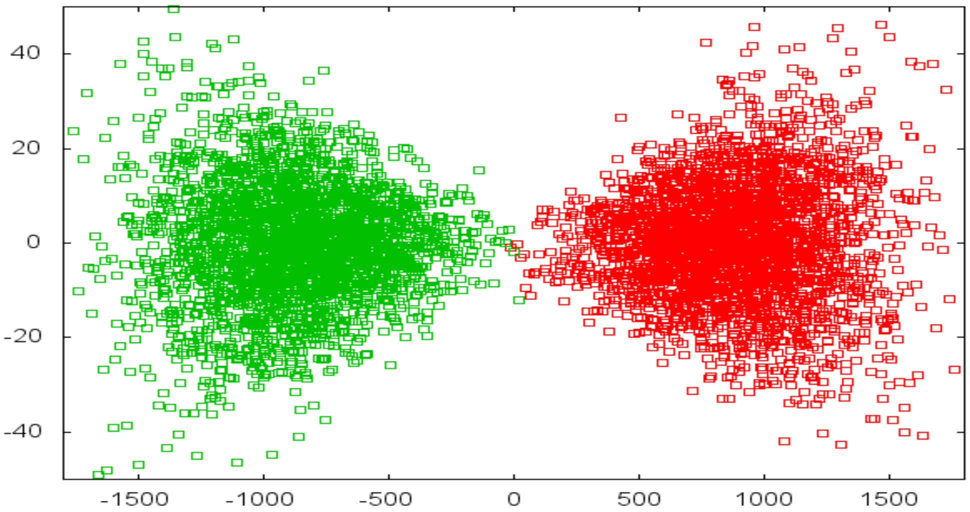
$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

$$\mathcal{L} \propto H_D \underbrace{\frac{N}{\sigma_x}}_{\text{Luminosity spectrum}} \underbrace{N n_b f_r}_{\text{Beam current}} \underbrace{\frac{1}{\sigma_y}}_{\text{Beam Quality (+bunch length)}}$$

H_D : pinch enhancement, typically 1-2
N : number of particles per bunch
n_b : number of bunches per train
f_r : number of trains per second
$\sigma_{x,y}$: transverse beamsizes

How to Produce Luminosity

Note: We use crab crossing
Can ignore crossing angle



Squeeze as much out of first part

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

Single bunch parameters at IP
Determined by upstream accelerator:

$N, \epsilon_x, \epsilon_y, \sigma_z$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Define the target for the beam delivery system:

Make beta small and create a small waist

How to Produce Luminosity

Note: We use crab crossing
Can ignore crossing angle

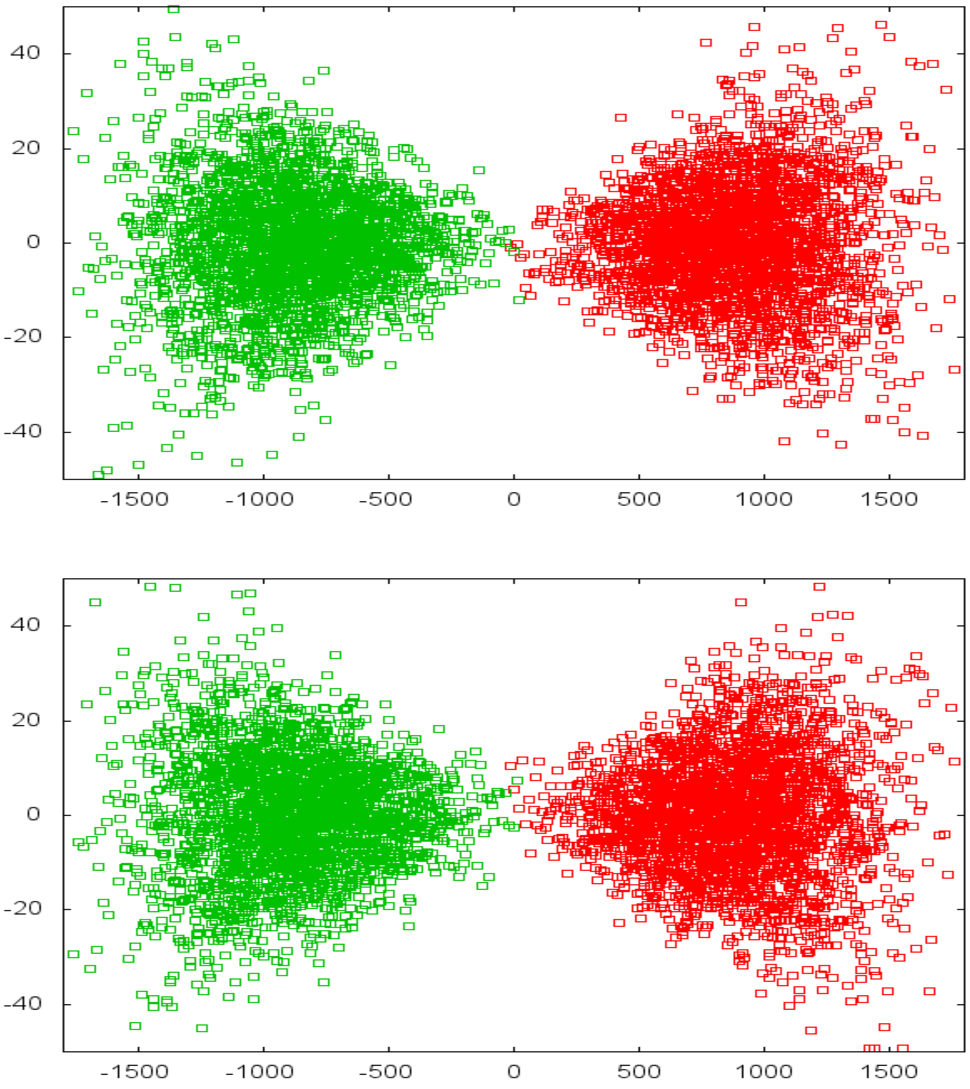
Squeeze as much out of first part

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

Single bunch parameters at IP
Determined by upstream accelerator:

$N, \varepsilon_x, \varepsilon_y, \sigma_z$

Beams focus each other
We get more luminosity



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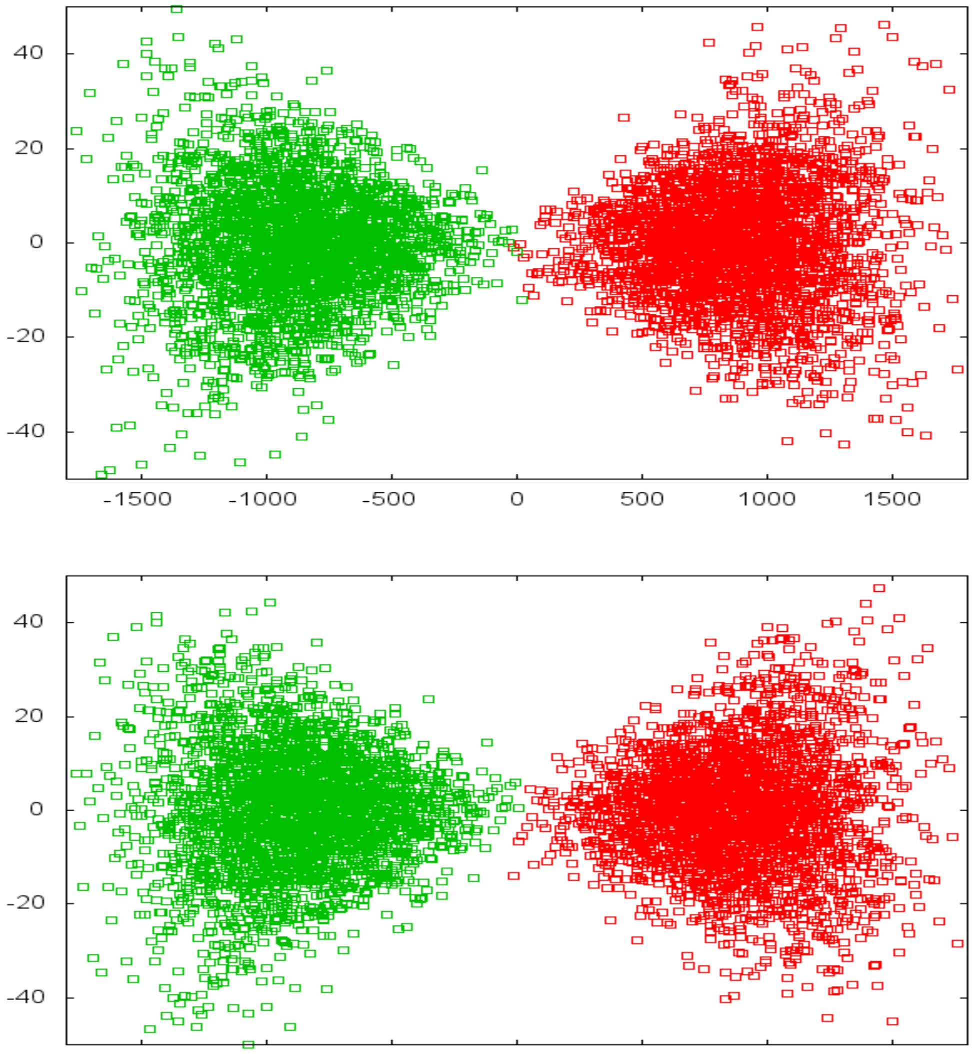
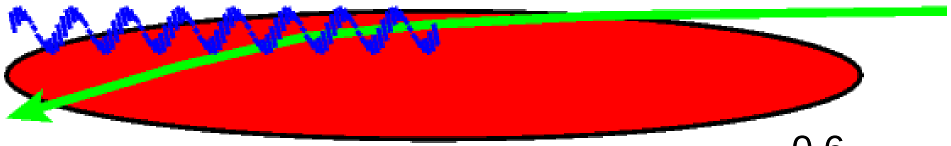
Single bunch parameters at IP
Determined by upstream accelerator:

$N, \epsilon_x, \epsilon_y, \sigma_z$

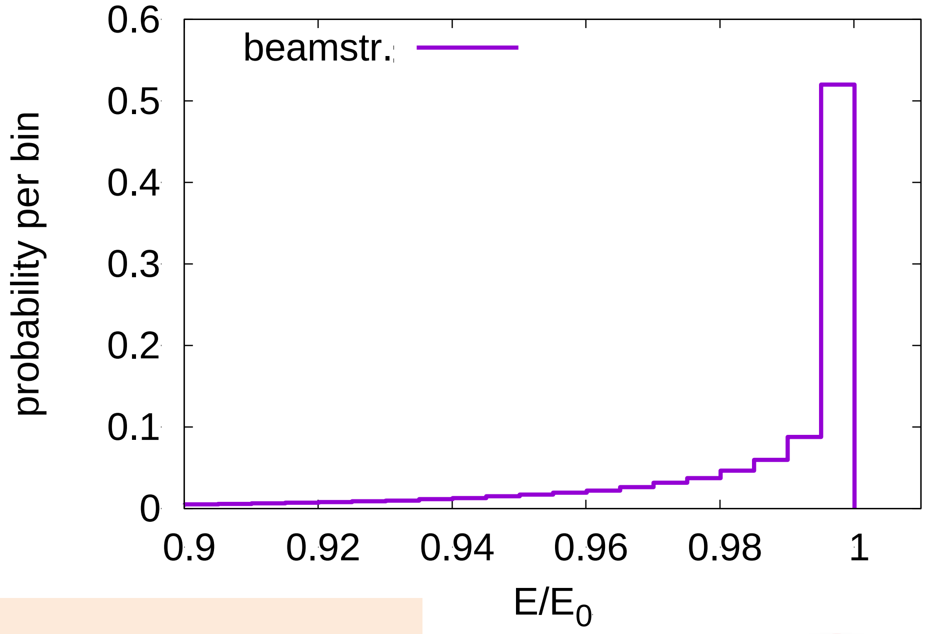
Photons are emitted and particles lose energy
The experiments will not like this



Beamstrahlung



⇒ Werner Herr
Monday 26.2.



Number of photons dominates $L_{0.01}/L$

$$n_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

+

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

$$\sigma_x \gg \sigma_y$$

$$\sigma_x + \sigma_y \approx \sigma_x$$

Note:
Somewhat different for 3 TeV
But does not change principle

$$\propto n_\gamma$$

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

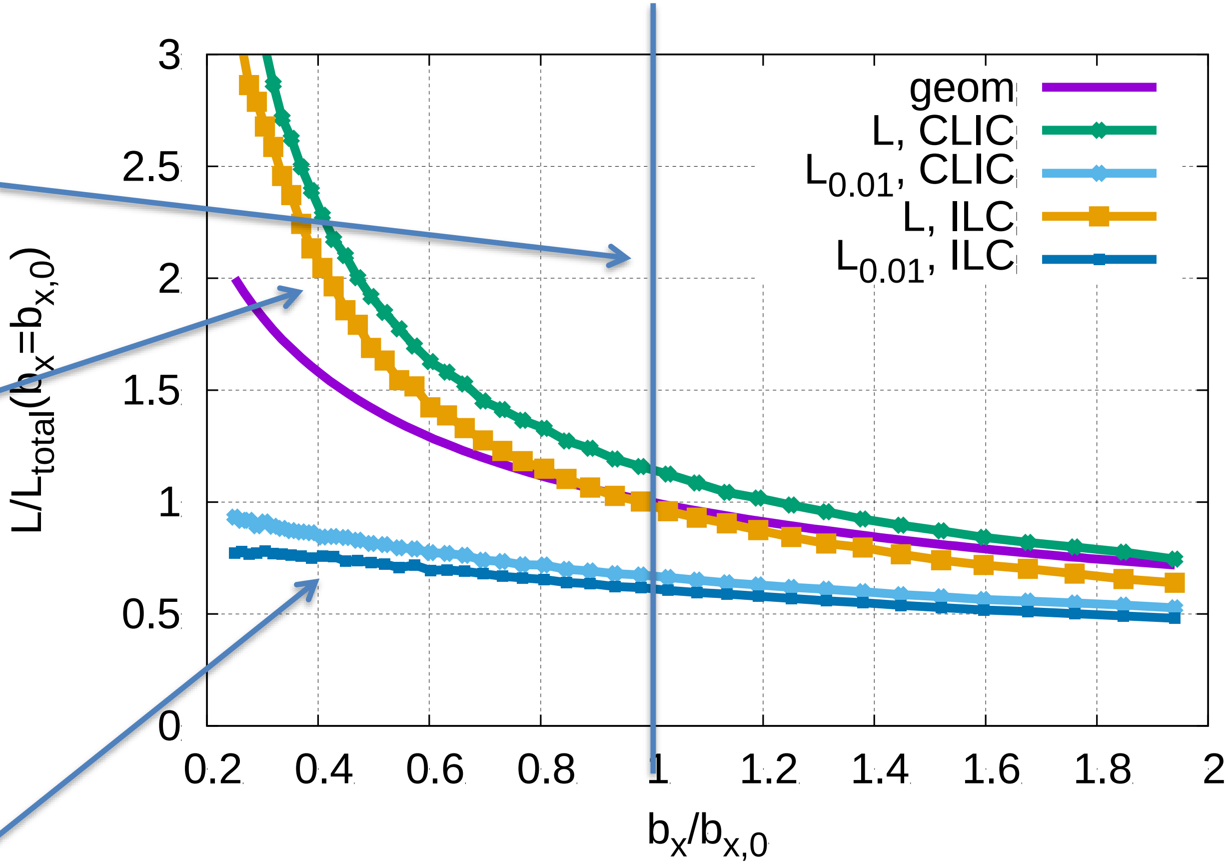
Choice of Horizontal Beta-function

Design value $L_{0.01}/L=60\%$ is good compromise for most physics studies
$n_{\gamma}\approx(1)$

The total luminosity L varies strongly with beta-function

But $L_{0.01}$ does not change so much

Hard to push beta-functions That low



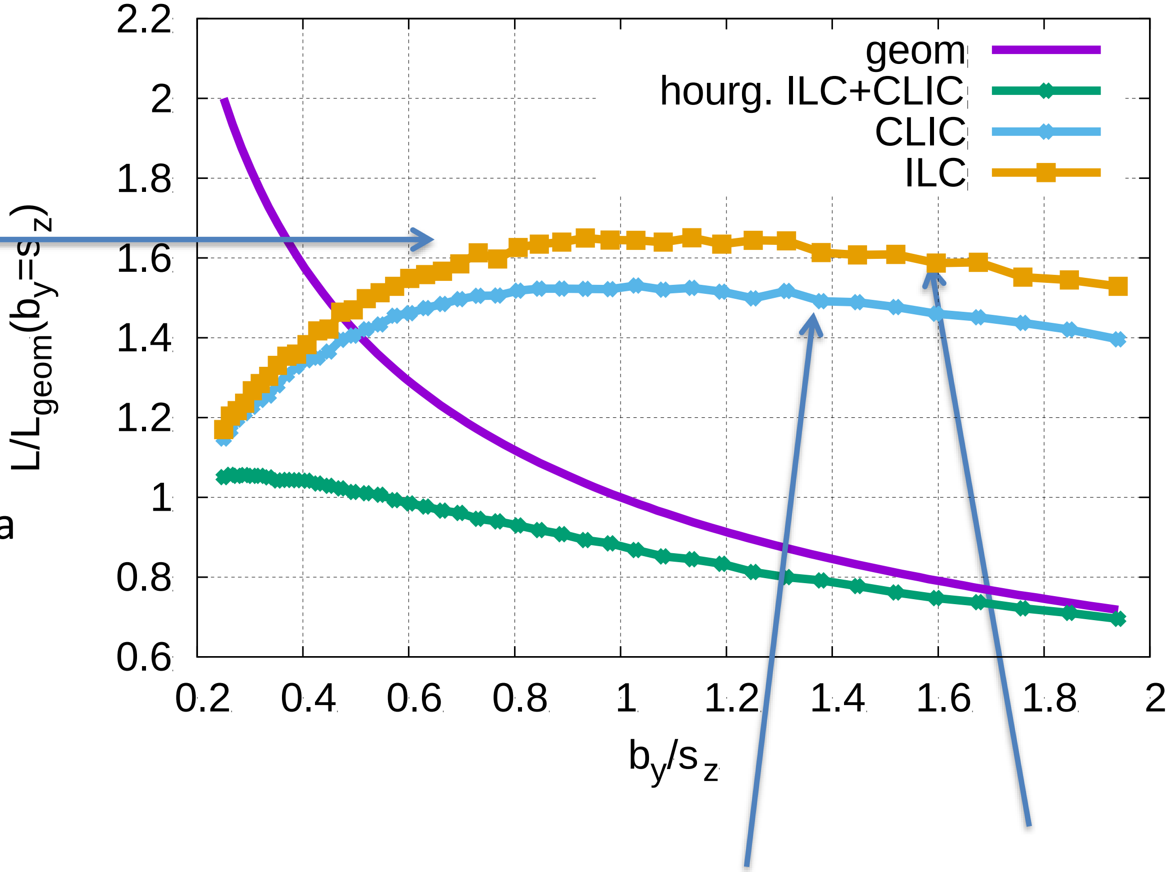
Hence large β_x (ILC: 11 mm, CLIC 380: 8 mm)
And large ε_x is acceptable

Note both help to make the vertical counterpart small

Choice Vertical Beta-function

Including pinch effect

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



CLIC choice

ILC choice

There is an optimum value for beta

For smaller beta-function the geometric luminosity would increase but the enhancement is reduced

Choose $\beta_y \approx \sigma_z$

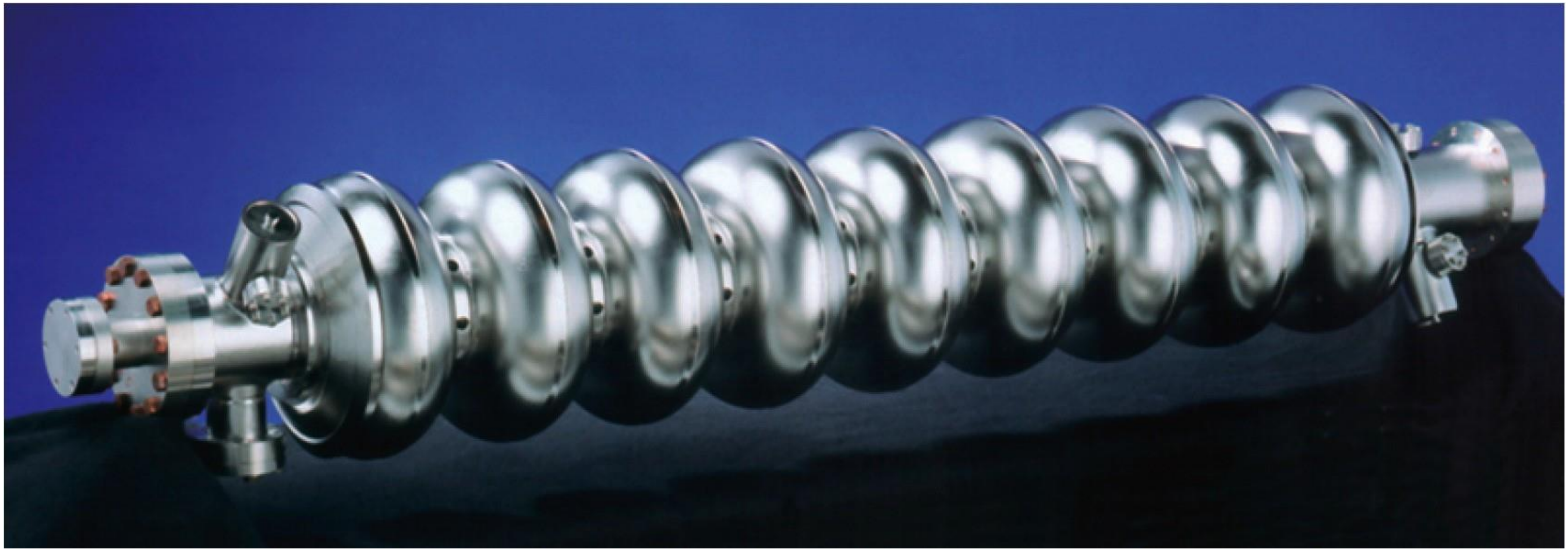
Note: at higher energies this becomes increasingly difficult to achieve

More luminosity for smaller vertical emittance ε_y

Additional limits cannot be discussed here

Main Linac and Efficiency

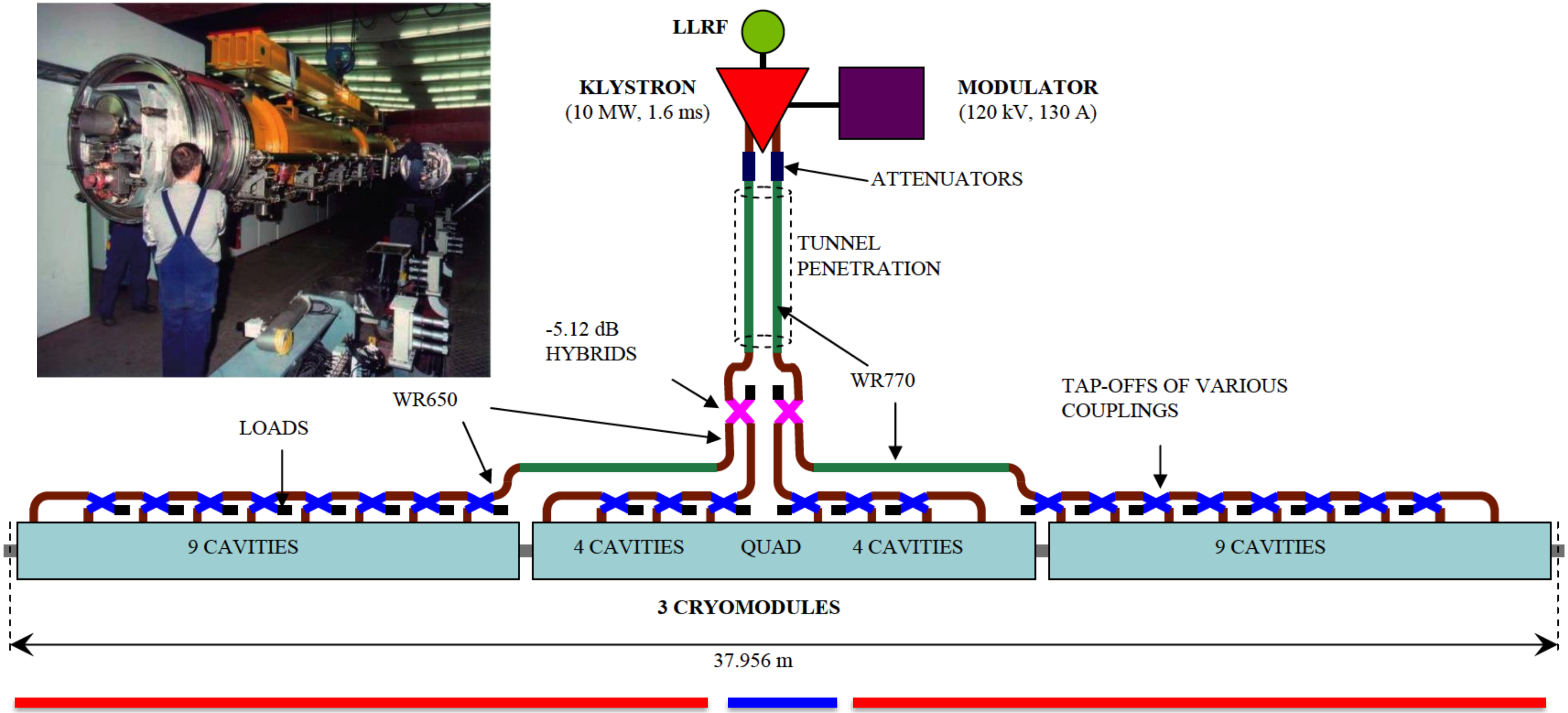
ILC Accelerating Cavity



- About 1 m long cavity with 31.5 MV/m,
  - super-conducting
  - 1.3 GHz
  - standing wave
  - constant impedance

⇒ Erk Jensen,
⇒Thursday 1.3.

Main Linac Unit



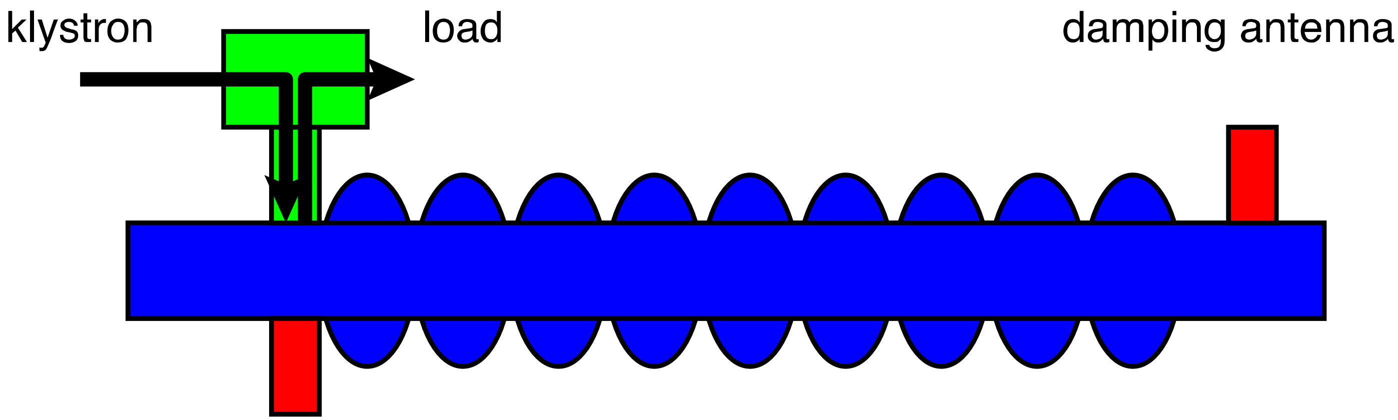
Accelerating cavities
O(65%) of linac length

Beam guiding quadrupole
Beam position monitor
Corrector kicker

Accelerating cavities

Total length for 500 GeV cms 31 km, some length for beam cleaning and focusing

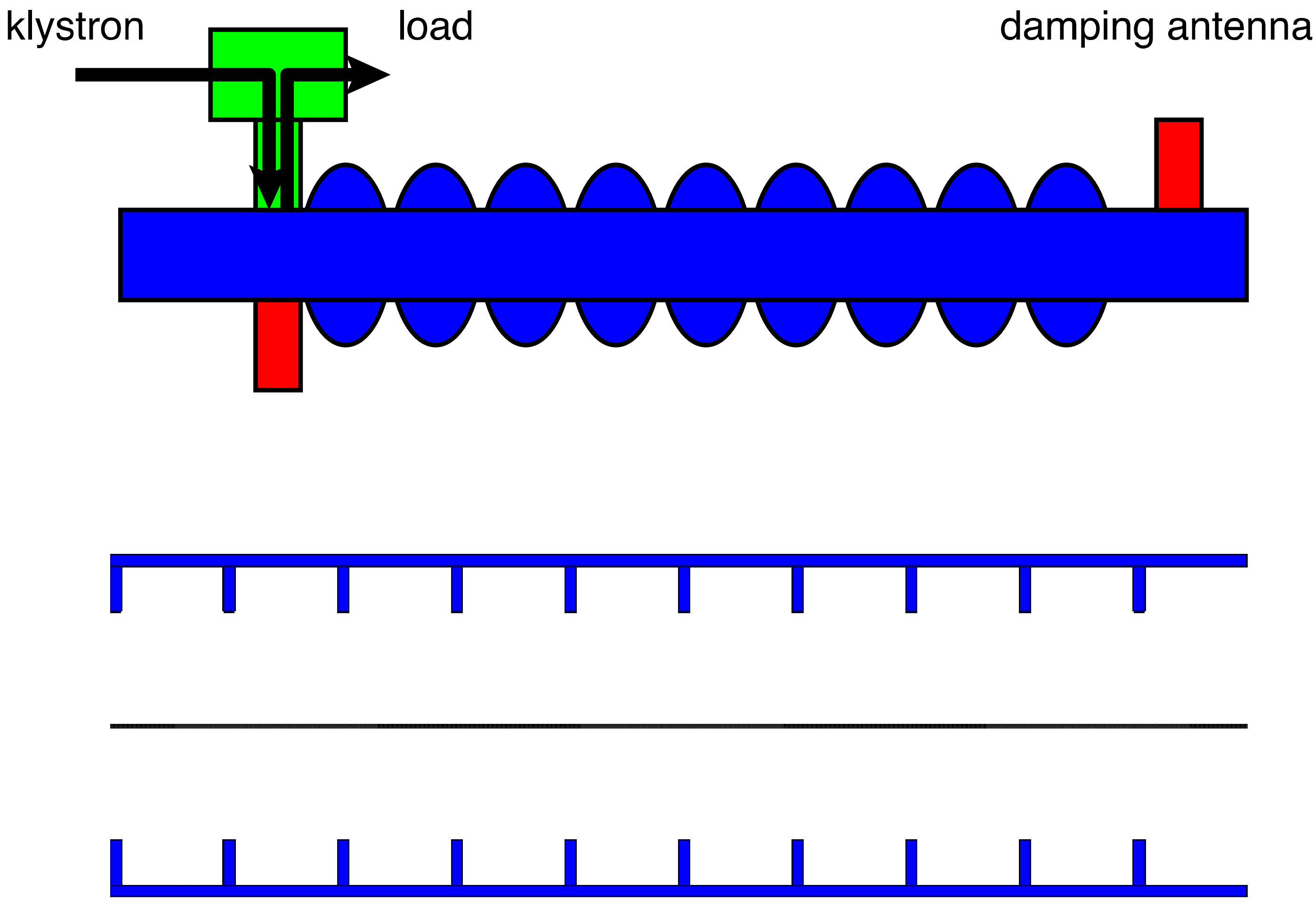
Standing Wave Cavity



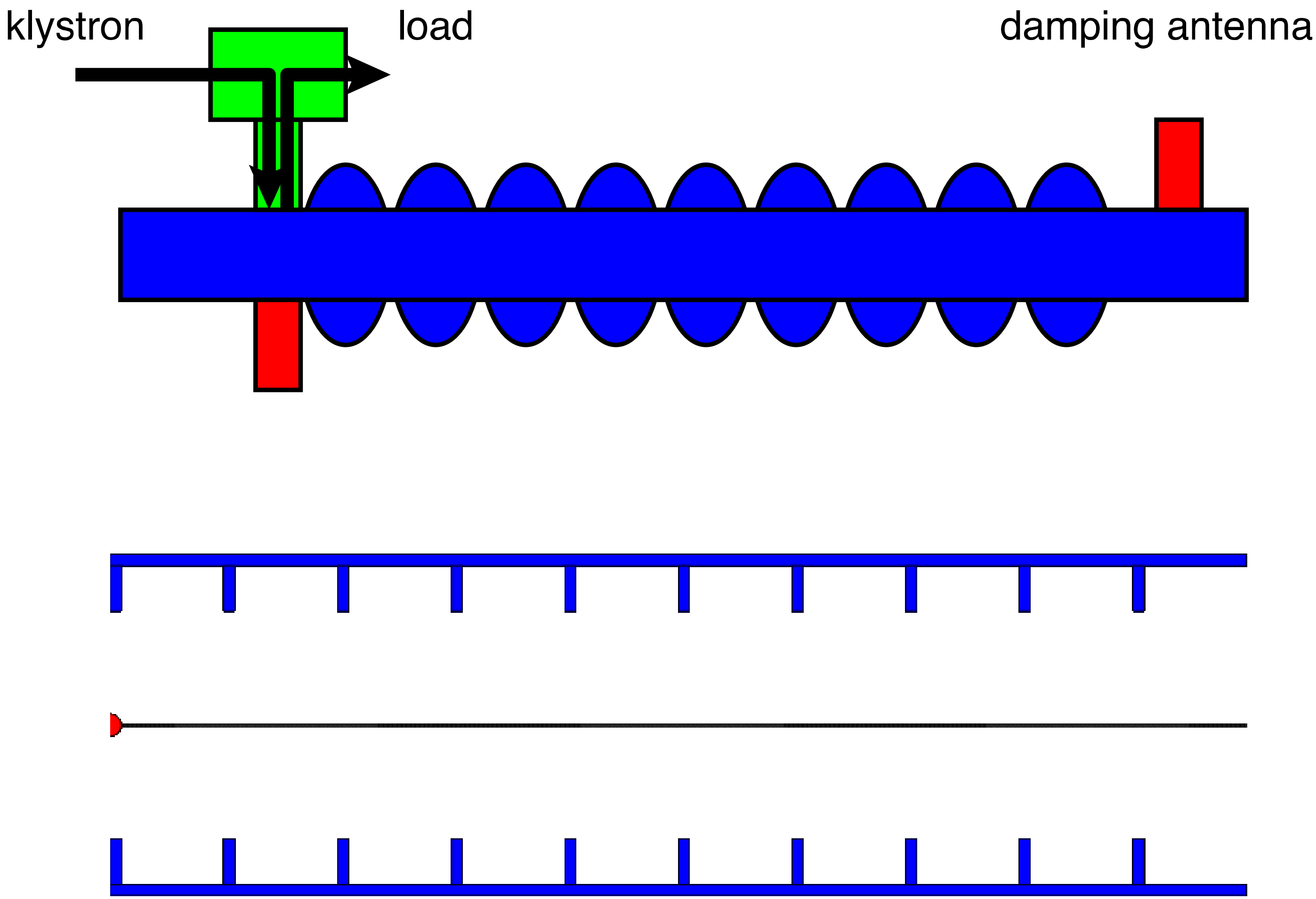
- The power is feed into one end
  - the power is reflected at the coupler
  - as the power in the cavity is increasing, the reflection is reduced
- there is a level when there is no reflection

⇒ now switch on the beam

Standing Wave Cavity



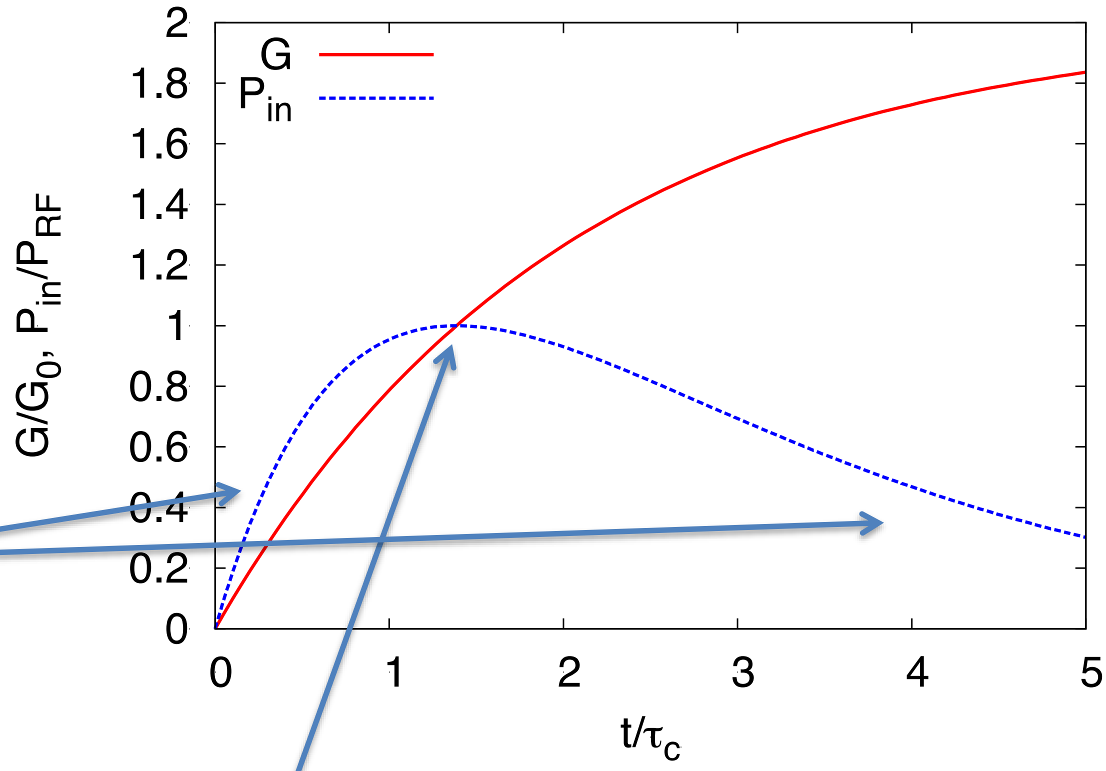
Standing Wave Cavity



Filling a Standing-wave Cavity

Select the target gradient G_0

Adjust the coupling of the cavity to the RF "external Q"



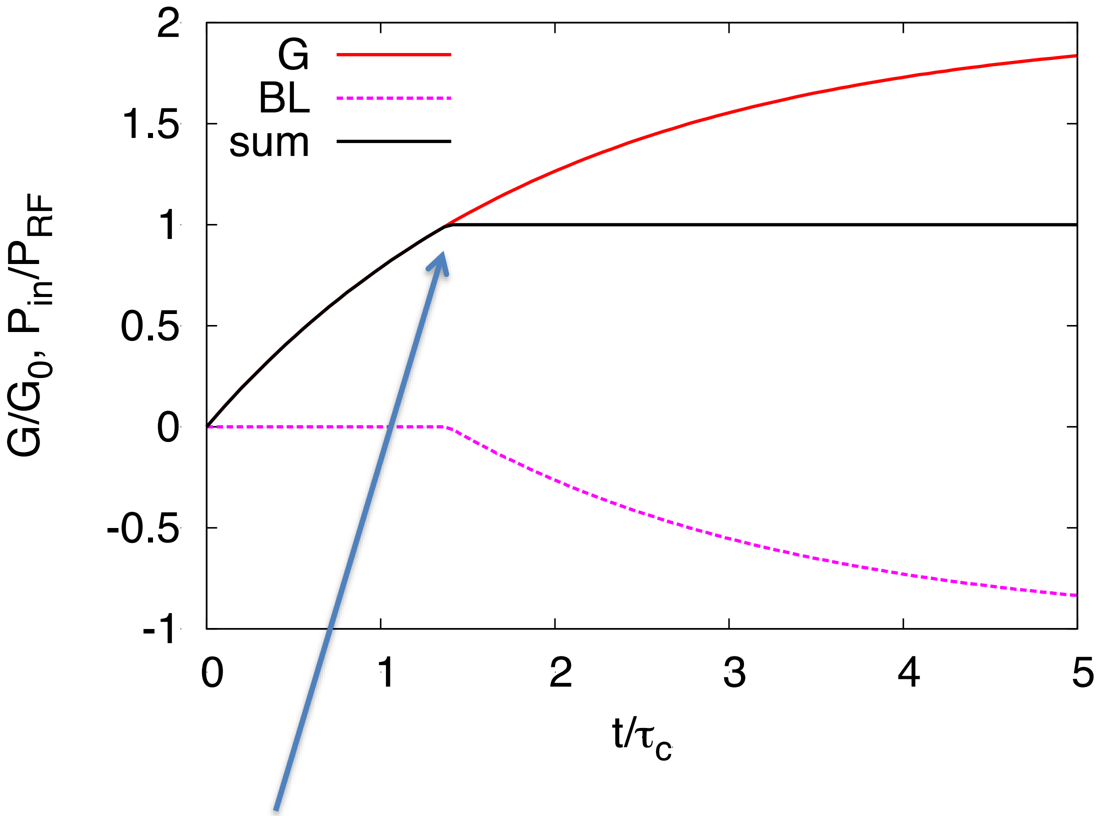
Only part of RF power flows into cavity

All the RF power flows into cavity

In ILC
Filling time is 900 μs
Beam time is 720 μs

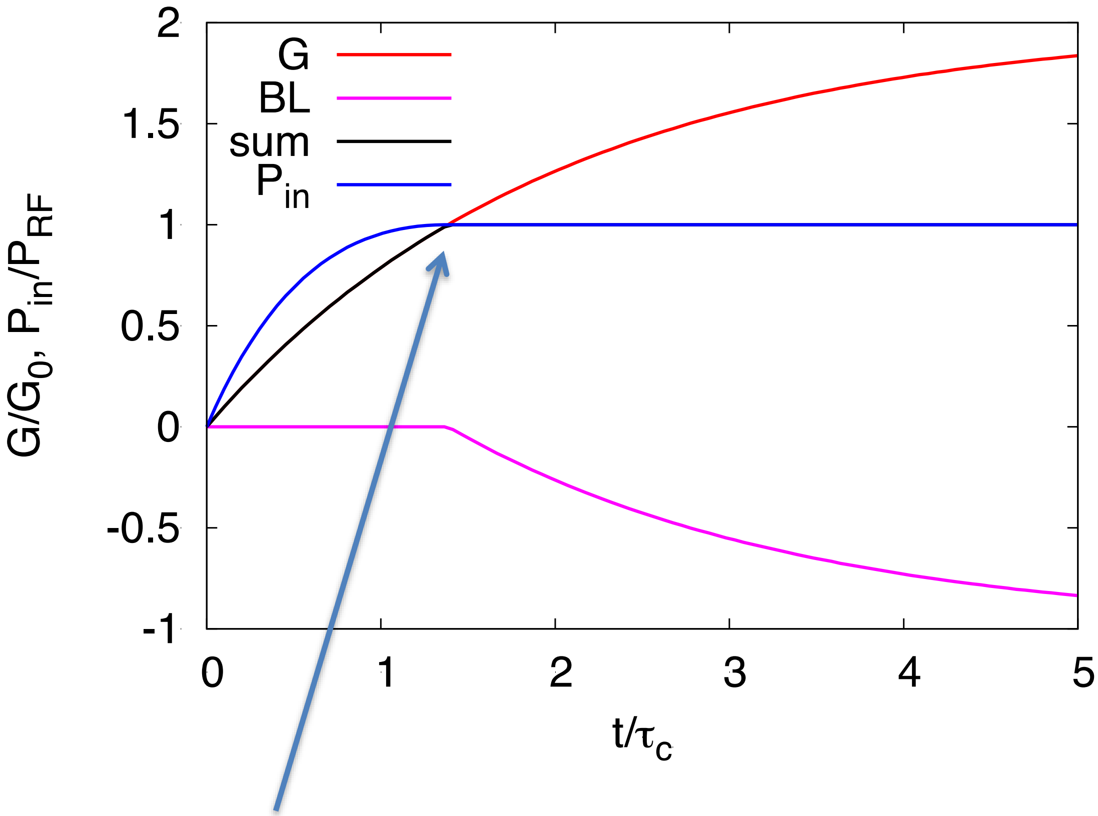
⇒ Erk Jensen, Thursday 1.3.

Filling a Standing-wave Cavity



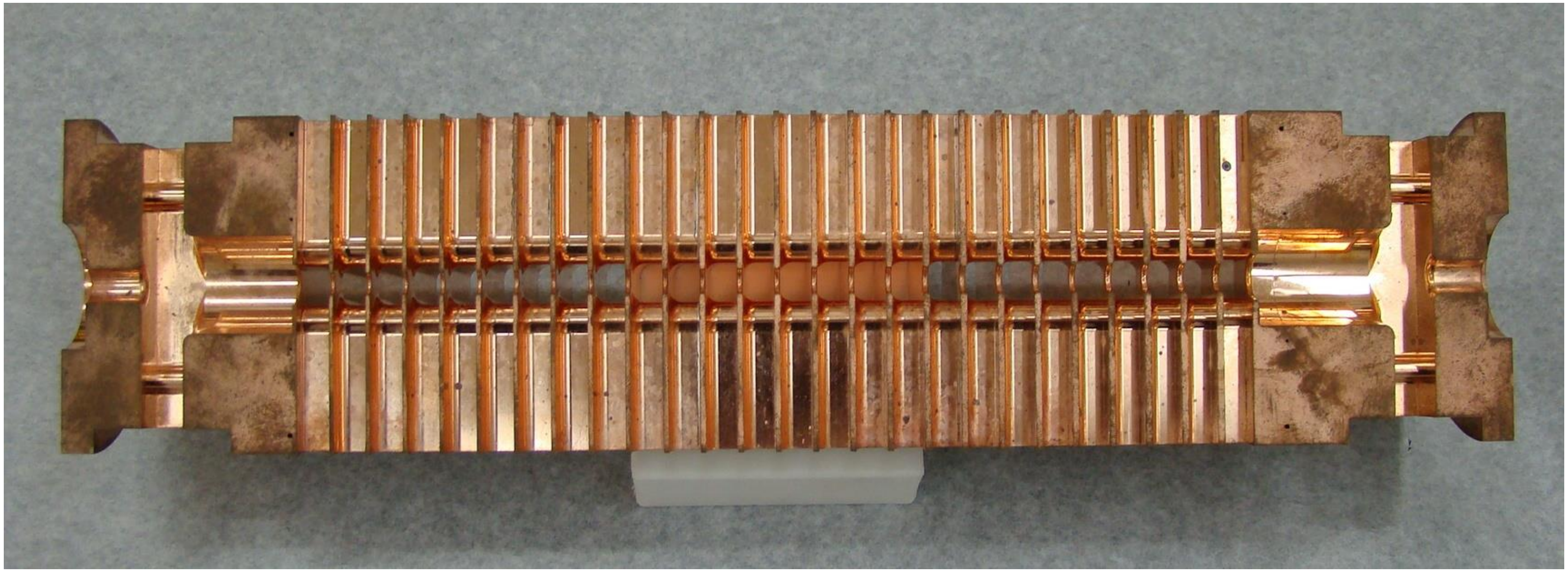
Switch the beam on
Takes as much power from cavity as flows in
Gradient remains constant
All RF power continues to flow in

Filling a Standing-wave Cavity



All RF power continues to flow in

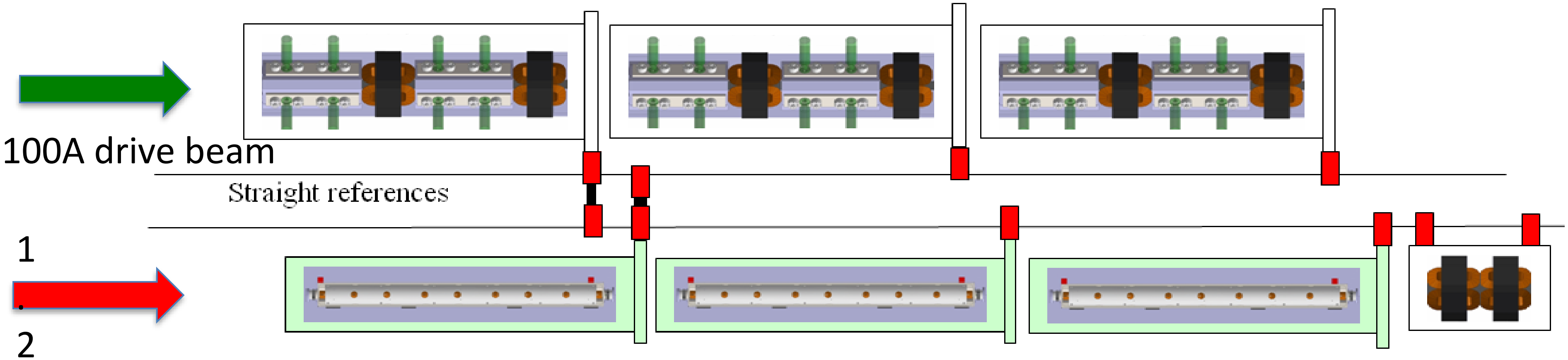
CLIC Accelerating Structure

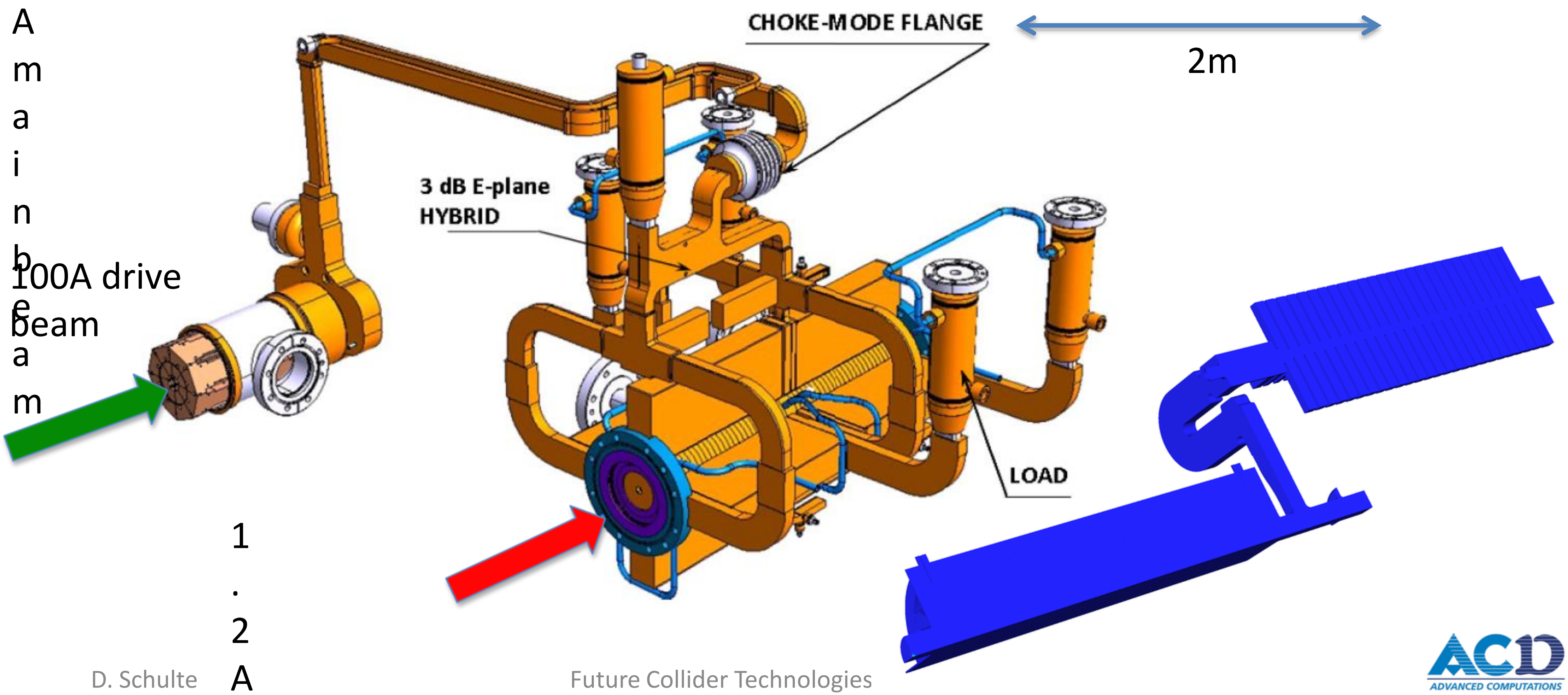


- About 23 cm long structure with G = 100 MV/m
  - normal-conducting
  - 12 GHz
  - travelling wave
  - constant gradient (almost)

$\Rightarrow$ Walter Wuensch, Sunday/Monday 4/5.3.

CLIC Two-beam Concept





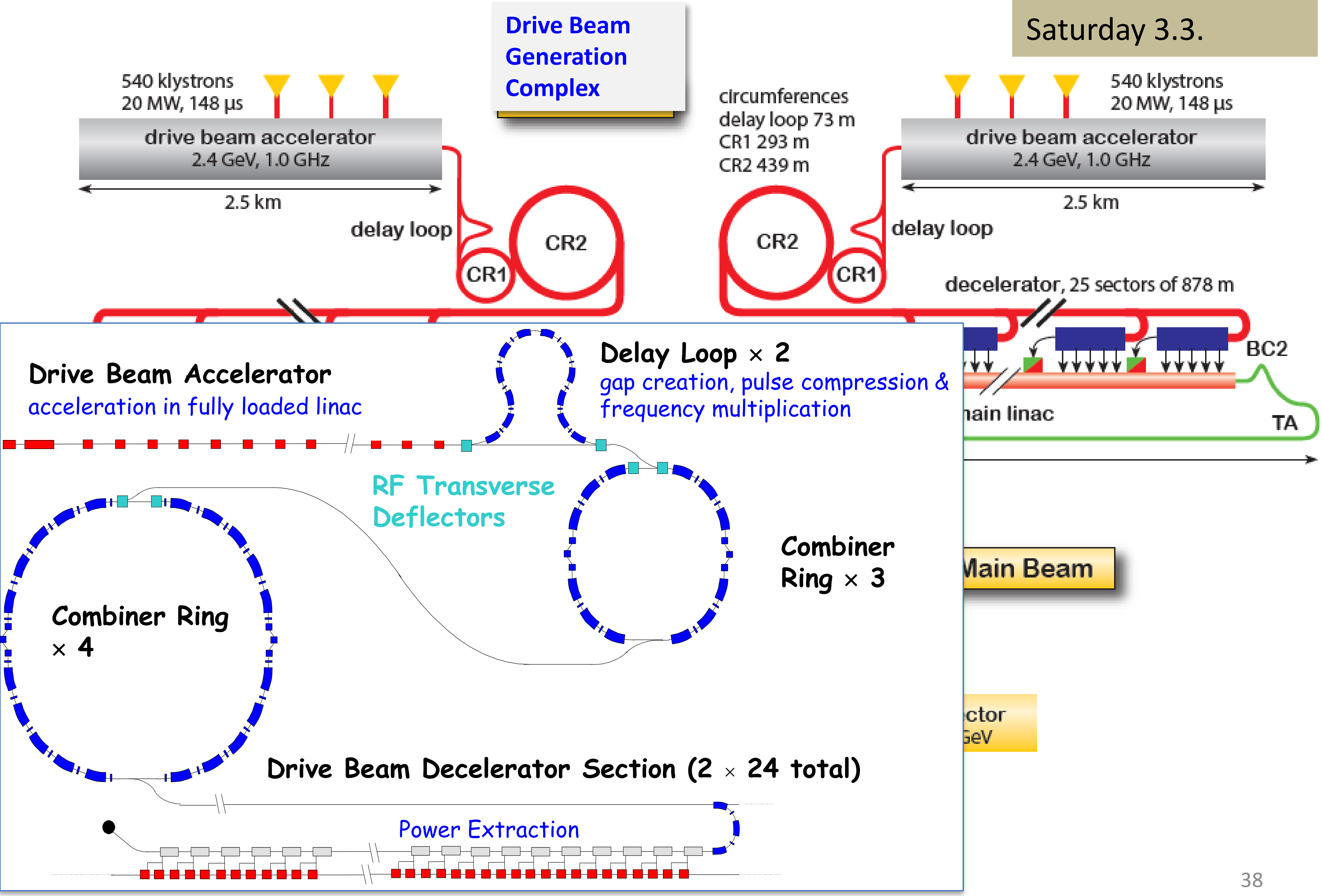
CLIC Two-beam Module

1st module

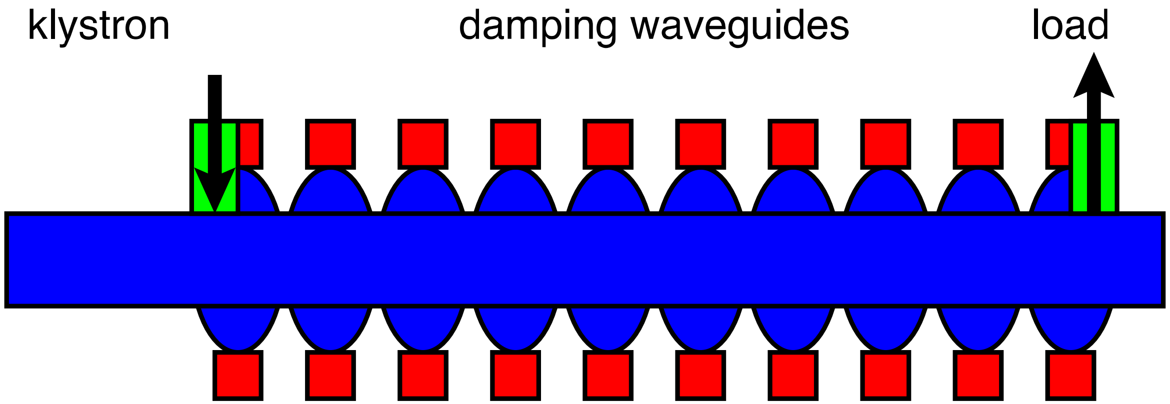
80 % filling with accelerating structures
11 km for 380 GeV cms
50 km for 3 TeV

CLIC: Drive Beam

⇒ Steffen Doebert
Saturday 3.3.

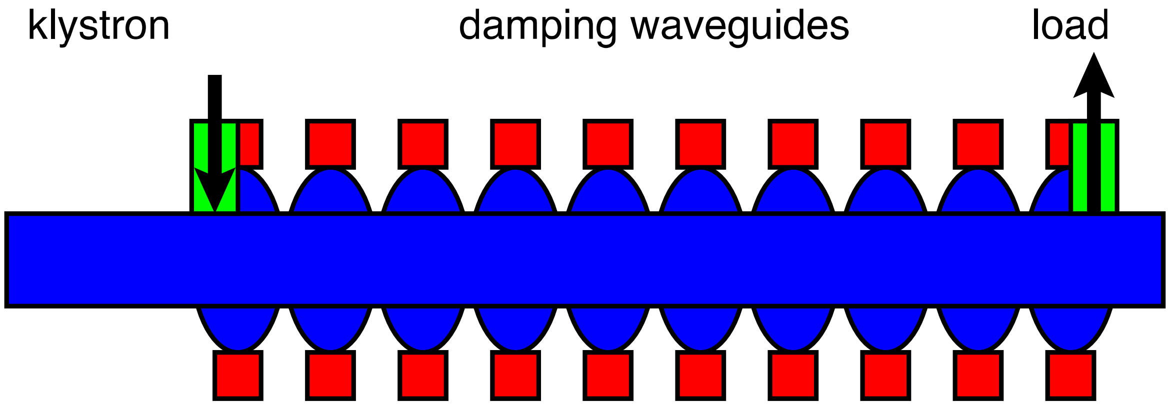


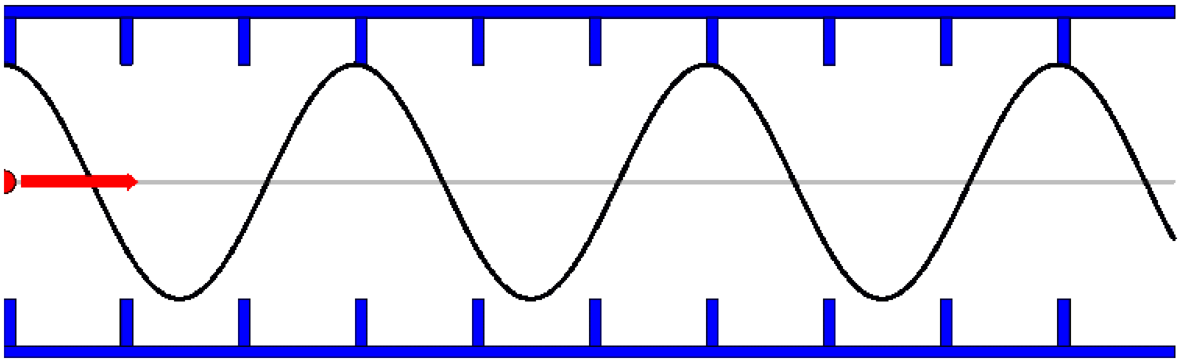
Travelling Wave Structure



- The power is feed into one end
  - no reflection if designed properly
- It slowly moves through the structure
  - group velocity is typically a few percent of the speed of light

Travelling Wave Structure





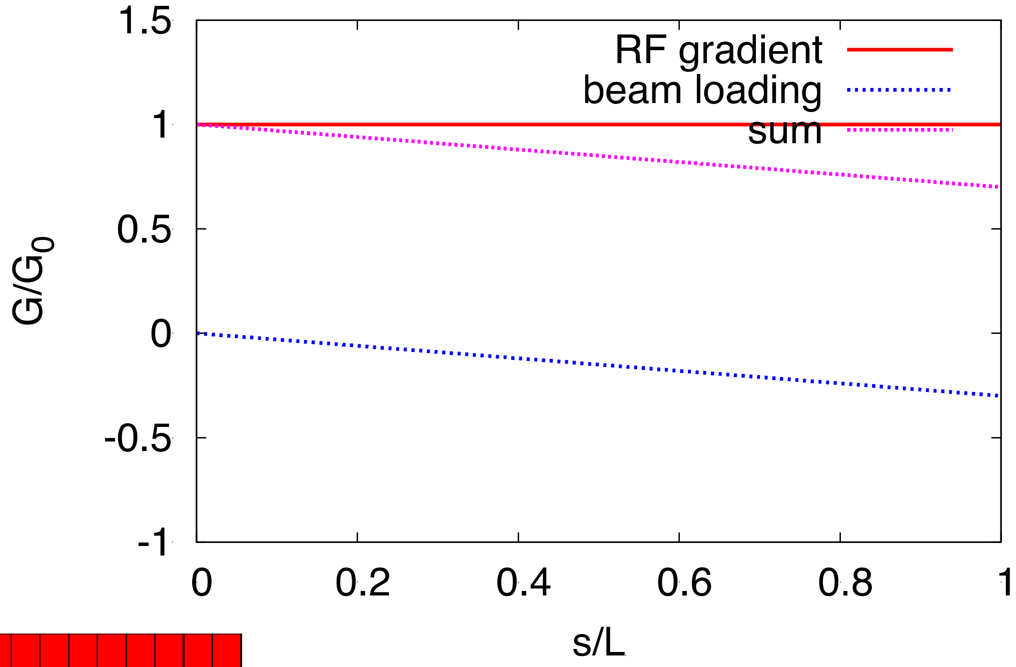
Note: Field should also vary with position, but that exceeds my graphic competences

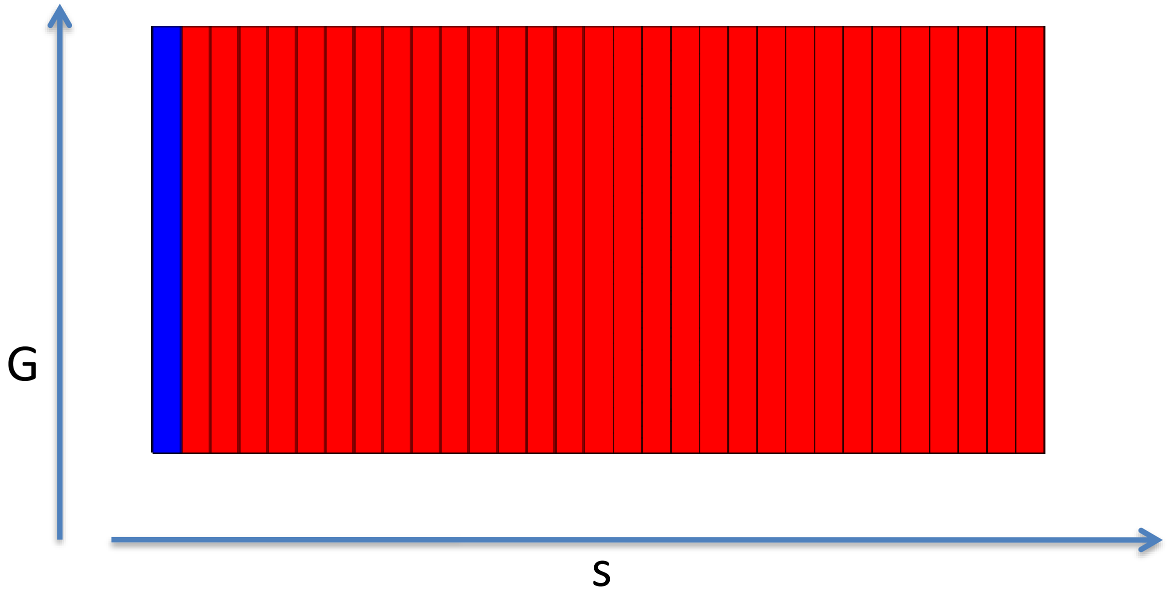
Filling a Travelling Wave Structure

The RF energy is flowing along the structure

Some is given to the beam, some is lost in the wall

Gradient profile developes





Some power is leaking out at the end

Beam-loading Compensation

In CLIC filling time is O(80 ns) and beam time (O 160 ns)
Slightly different for different structures

RF Power to Beam Efficiency

$$\mathcal{L} \propto H_D \, n_\gamma \, \eta_{RF->beam} \frac{P_{RF}}{E_{cm}} \frac{1}{\sigma_y}$$

$$\eta_{RF\rightarrow beam} = \frac{\text{Energy taken by one beam pulse}}{\text{Energy in each RF pulse}}$$

For constant RF pulse power

$$\eta_{RF\rightarrow beam} = \frac{\tau_{beam}}{\tau_{RF}} \cdot \frac{P_{beam}}{P_{RF}}$$

Power into beam
During beam passage

RF power during pulse

Simplified

$$\eta_{RF\rightarrow beam} = \frac{\tau_{beam}}{\tau_{beam} + \tau_{fill}} \cdot \frac{P_{beam}}{P_{beam} + P_{loss} + P_{out}}$$

Note: what I call τ_{fill} contains several components of which the fill time is the most important; RF experts will learn more

RF to Beam Power Efficiency

$$\eta_{RF\rightarrow beam} = \frac{\tau_{beam}}{\tau_{beam}+\tau_{fill}} \cdot \frac{P_{beam}}{P_{beam}+P_{loss}+P_{out}}$$

Super-conducting cavity

- Almost no RF power lost in walls
- But cavity cooling requires power

$$\eta_{RF\rightarrow beam} = \frac{\tau_{beam}}{\tau_{beam}+\tau_{fill}}$$

Normal conducting structure

- Important fraction of RF power lost in walls
- Some power draining out of travelling wave structure (usually)

$$\eta_{RF\rightarrow beam} = \frac{\tau_{beam}}{\tau_{beam}+\tau_{fill}} \cdot \frac{P_{beam}}{P_{beam}+P_{loss}+P_{out}}$$

Impedance

Energy in the cavity or accelerating cell

Voltage along cavity or cell

$$U = \frac{(GL)^2}{(R/Q)\omega}$$

Impedance, depends on shape of cavity/cell, does not depend on frequency

RF frequency

High R/Q means high wakefields
A bunch extracts the same amount of energy for higher R/Q
But field in cavity must change more since less energy is stored

Important example: smaller apertures yield higher R/Q

Impedance

Energy in the cavity or accelerating cell

Voltage along cavity or cell

$$U = \frac{(GL)^2}{(R/Q)\omega}$$

Impedance, depends on shape of cavity/cell, does not depend on frequency

RF frequency

High R/Q mea

A bunch extra /Q

But field in ca tored

Important exa

Warning

This definition is in “Linac Ohms”

People also use “Circuit Ohms”

2 “Linac Ohms” = 1 “Circuit Ohm”

Power Lost in the Structure

Voltage

Power loss

$$P_{loss} = \frac{U}{Q}\omega = \frac{(GL)^2}{R/Q}\frac{1}{Q}$$

Cavity design

Cavity material

$$Q = \frac{\text{Stored energy}}{\text{Ohmic energy loss per radian of RF cycle}} = \frac{U}{P_{loss}}\omega$$

Examples: Q=O(10^{10}) for superconducting and O(10^4) for normal conducting

But frequency dependent

Examples

parameter	CLIC	ILC (RDR)
R'/Q	$\approx 11\,\mathrm{k\Omega/m}$	$1.036\,\mathrm{k\Omega/m}$
Q	≈ 6000	$\approx 10^{10}$
R'	$\approx 66\,\mathrm{M\Omega/m}$	$\approx 10^{7}\,\mathrm{M\Omega/m}$

- ILC: $I \approx 5.8\,\mathrm{mA}$

$\Rightarrow$

$$\frac{P'_{beam}}{P'_{wall}} \approx 1650$$

- CLIC: $I \approx 1.2\,\mathrm{A}$

$\Rightarrow$

$$\frac{P'_{beam}}{P'_{wall}} \approx 0.8$$

- Efficiency is

$$\eta = \frac{\tau_{beam}}{\tau_{beam} + \tau_{fill}} \frac{P_{beam}}{P_{beam} + P_{loss} + P_{out}}$$

- Plugging in numbers for ILC

$$\eta \approx \frac{730\,\mu\mathrm{s}}{730\,\mu\mathrm{s} + 900\,\mu\mathrm{s}} \approx 0.45$$

- Plugging in (slightly older) numbers for CLIC

$$\eta = \frac{156\,\mathrm{ns}}{156\,\mathrm{ns} + 83\,\mathrm{ns}} \cdot \frac{27\,\mathrm{MW}}{27\,\mathrm{MW} + 25\,\mathrm{MW} + 12\,\mathrm{MW}} \approx 0.65 \cdot 0.42 \approx 0.277$$

Cryogenics Power (ILC)

Cavities have small losses

$$P_{loss} = const \frac{1}{Q_0} \times G^2$$

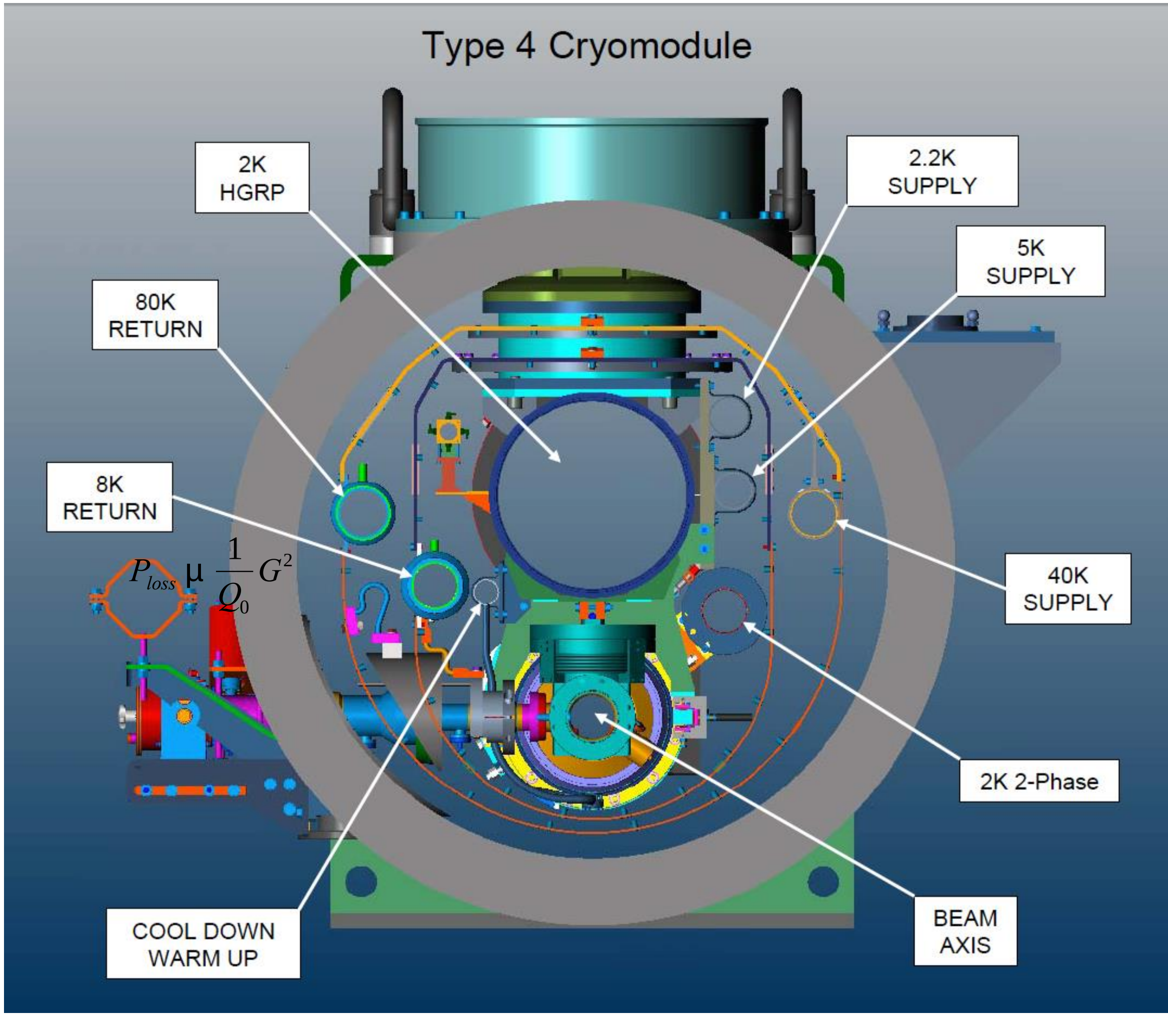
About 1W/m

But cooling costly at low temperatures

Remember Carnot:

$$P_{cryo} = \frac{1}{\eta} \frac{T_{room} - T_{source}}{T_{source}} \times P_{loss}$$

$$P_{cryo} \approx 700 \times P_{loss}$$



The typical heat load of 1 W/m
⇒ about 1 kW/m for cryogenics

Average RF power: 1.6kW/m (3kW/m)
Power into beam about 0.7kW/m

ILC Main Linac Pulse Optimisation

Bema current is given by installed RF power

Disclaimer: there have been heated discussions on how that should be optimised…

More RF peak power

Higher beam current
Shorter cavity fill time

Higher cost (klystrons and modulators)
Either higher bunch charge or more bunches

Longer RF pulses
Higher pulse rate

Higher average beam current
Cavity fill time is smaller fraction of pulse (longer pulses)
Higher cost (modulators and klystrons)
More cooling required
Either higher bunch charge or more bunches

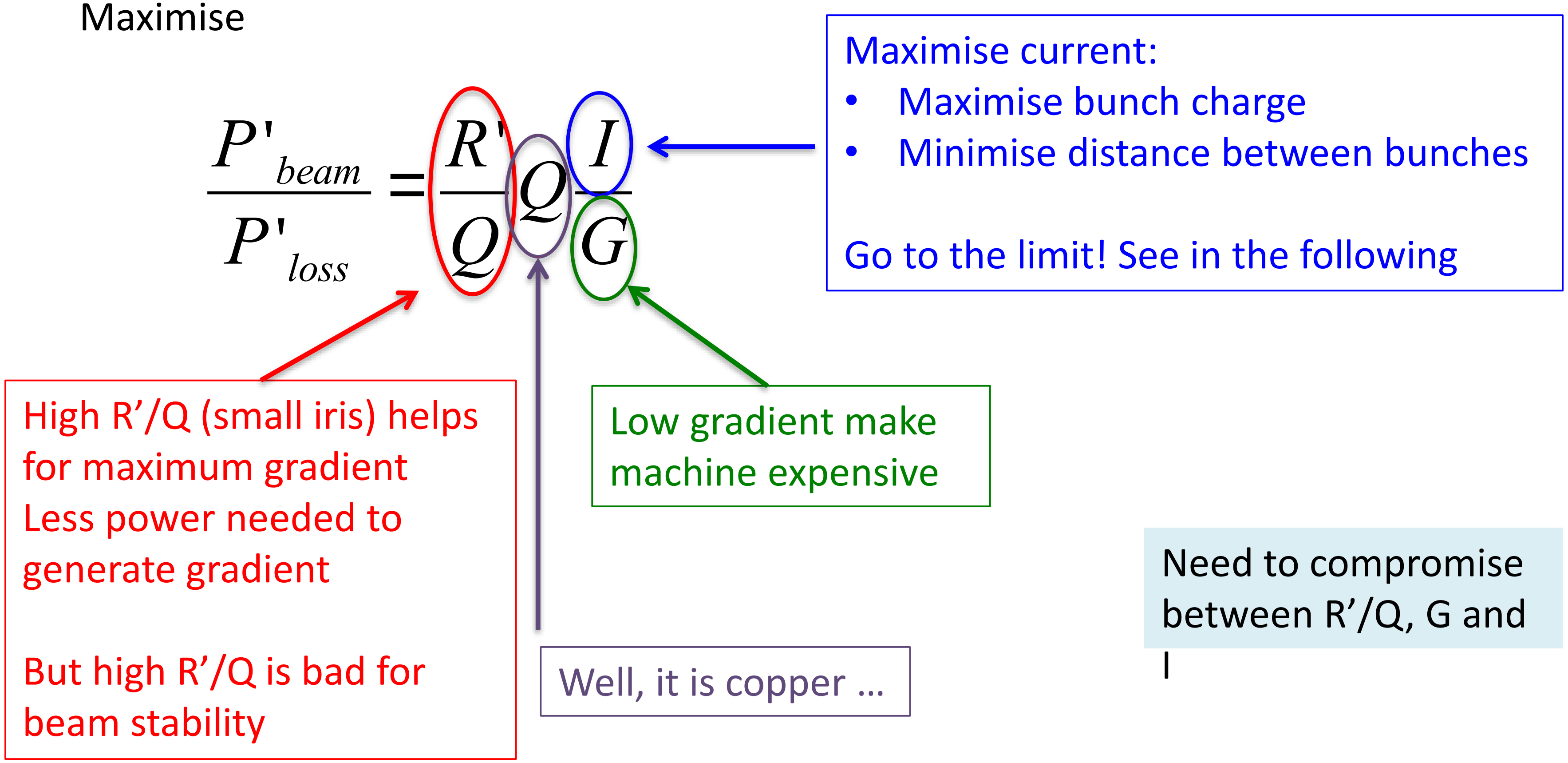
Higher average beam power leads to more cost but also more luminosity

CLIC Main Linac Pulse Optimisation

Power to beam $$P'_{beam} = IG$$

Power lost in structure $$P'_{loss} = \frac{G^2}{R'}$$

Maximise



$$\frac{P'_{beam}}{P'_{loss}} = \frac{R'}{Q} Q \frac{I}{G}$$

Maximise current:
- Maximise bunch charge
- Minimise distance between bunches

Go to the limit! See in the following

High R'/Q (small iris) helps for maximum gradient
Less power needed to generate gradient

But high R'/Q is bad for beam stability

Low gradient make machine expensive

Well, it is copper …

Need to compromise between R'/Q, G and I

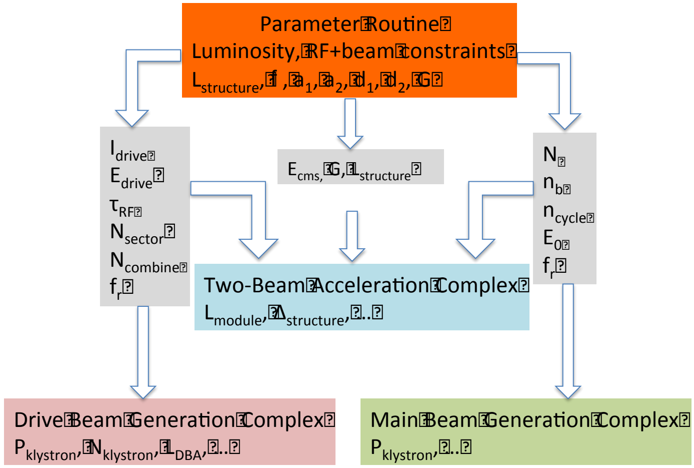
Note: CLIC Optimisation

Scan 1.7 billion cases:

Fix structure design parameters:
$a_1,a_2,d_1,d_2,N_c,\phi,G$

⇒ key beam parameters

⇒ Luminosity, cost and power
(including other systems)



Parameter Routine
Luminosity, RF+beam constraints
$L_{structure}$, f, a_1, a_2, d_1, d_2, G

I_{drive}
E_{drive}
τ_{RF}
N_{sector}
$N_{combine}$
f_r

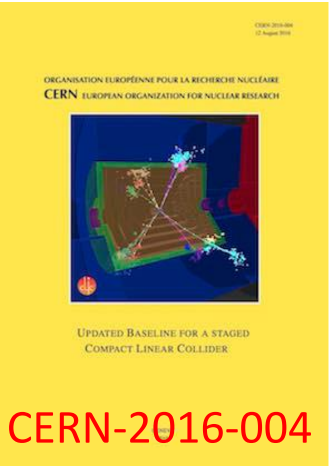
E_{cms}, G, $L_{structure}$

N
n_b
n_{cycle}
E_0
f_r

Two-Beam Acceleration Complex
L_{module}, $\Delta_{structure}$, ...

Drive Beam Generation Complex
$P_{klystron}$, $N_{klystron}$, L_{DBA}, ...

Main Beam Generation Complex
$P_{klystron}$, ...

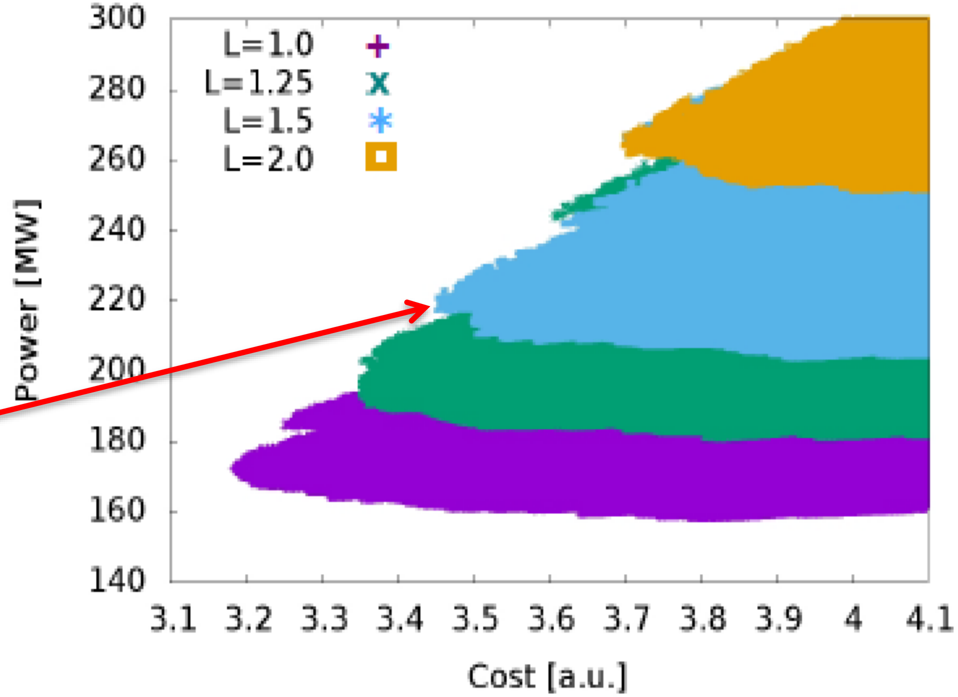


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER

CERN-2016-004

Resulting designs:
Colors indicate luminosities



This is the one we picked

Bunch Charge, Length and Spacing Choice

Note: Coordinate System

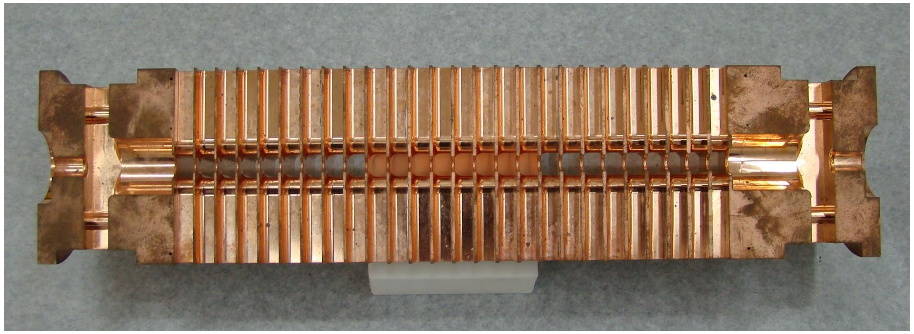
- We use two frames, the laboratory frame and the beam frame
- The nominal direction of motion of the beam is called *s* in the laboratory frame, the beam moves toward increasing *s*
- The longitudinal direction is called *z* in the beam frame, with particles at smaller *z* moving ahead of particles with larger *z*
- A particle preserves its longitudinal position within the beam
- The transverse dimensions are *x* in the horizontal and *y* in the vertical plane, in both coordinate systems
- People use different systems so find out what they talk about

Main Linac Beam Parameter Choice for CLIC

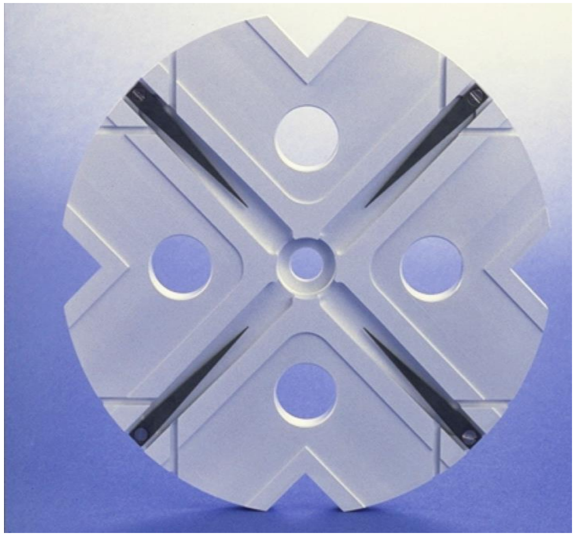
Want highest beam current for luminosity
$\Rightarrow$ Maximise bunch charge
$\Rightarrow$ Minimise bunch distance

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

Short-range longitudinal wakefields induce energy spread, compensated with RF
$\Rightarrow$ bunch charge defines bunch length $\sigma_z(N,W_L)$



Short-range transverse wakefields can make beam instable
$\Rightarrow$ limits the bunch charge N $(W_T\ \sigma_z(N))$



Transverse long-range wakefield can make the beam instable
$\Rightarrow$ limits the distance between bunches

Beam stability for strongest practical lattice defines beam parameters

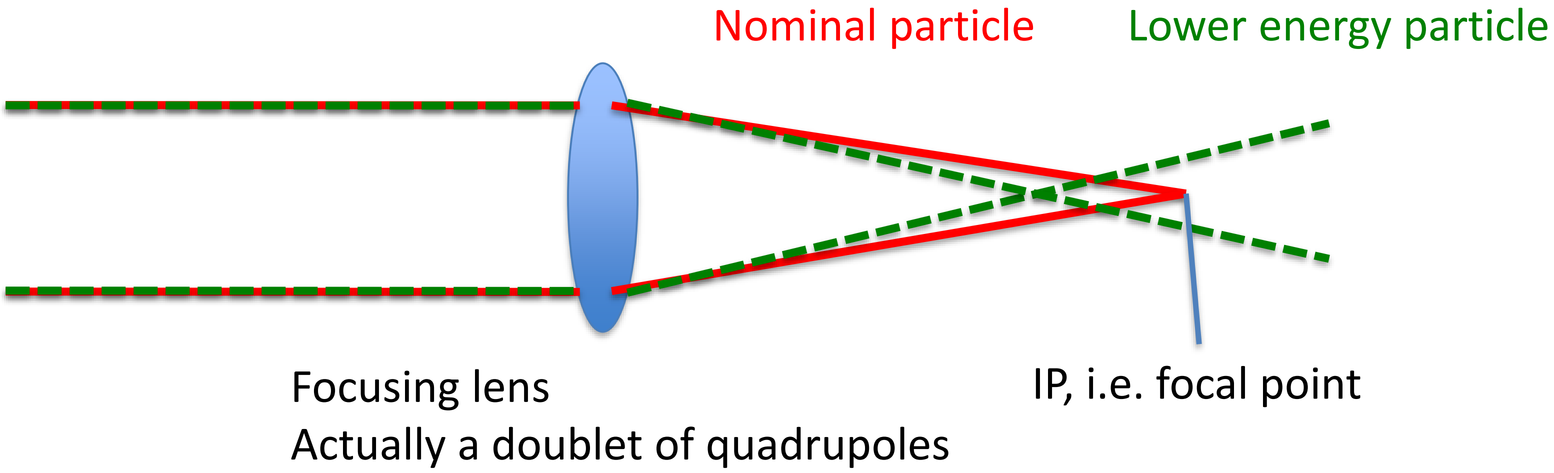
Energy Spread Goal

Energy spread at the end of the linac is critical

The final focus system is limited in energy acceptance
Similar problem to camera lens

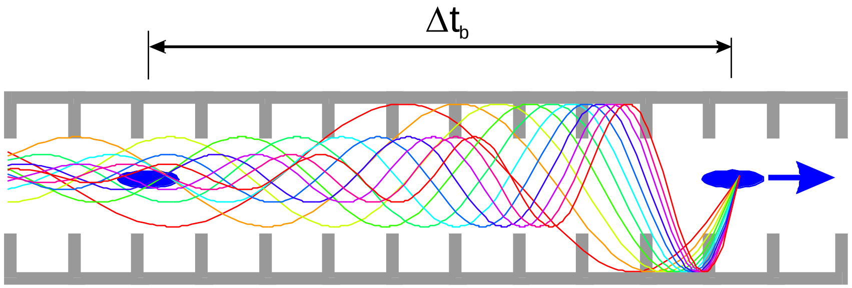
Compensation scheme is used but is also limted in performance

⇒ Have to limit the beam energy spread
⇒ CLIC goal is 0.35% RMS spread



Wakefields

Particle leaves fields behind that affect subsequent particles: “Wakefields”



Use wakefields to describe the effect of first particle on second one, here relevant are

$$P_z c = NeW_L(z)Le$$

$$P_x c = NeW_\perp(z)Le\Delta x$$

$$P_y c = NeW_\perp(z)Le\Delta y$$

Charge of driving particle

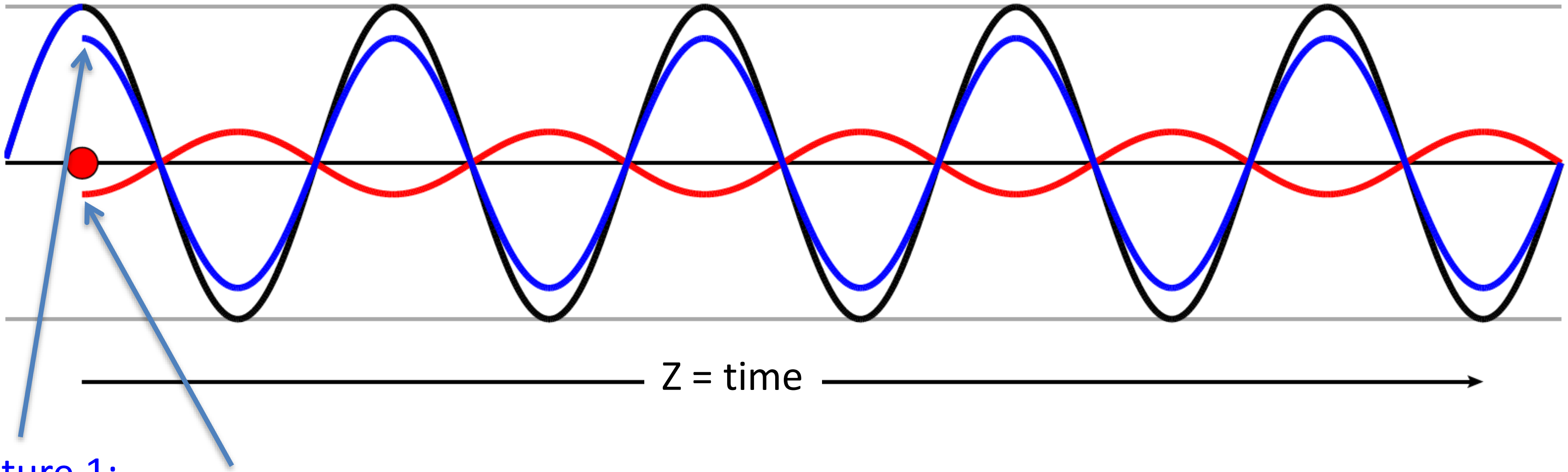
Longitudinal/transverse wakefield

Structure length

Witness particle charge

Transverse offset

Longitudinal Wakefield and Energy



Picture 1:
Bunch
extracts
energy

Picture 2:
Bunch
induces
field

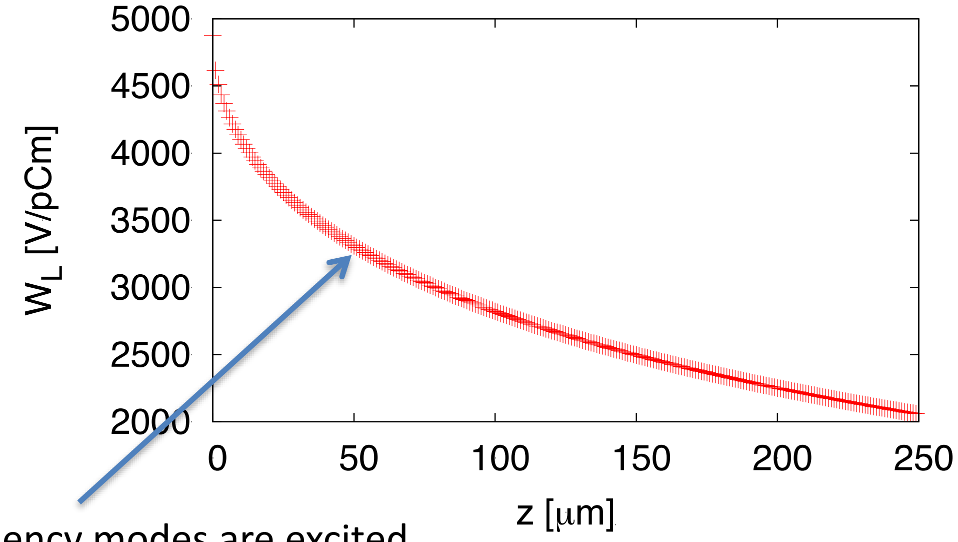
Consider only the fundamental mode in the structure

The field is always the same
The extracted energy is automatically correct

If a bunch extracts a large fraction of the energy in the structure the tail will gain much less energy

Longitudinal Wakefield (CLIC)

Particle z-position is constant
$\Rightarrow$ Same wakefield in each accelerating structure
$\Rightarrow$



Many high-frequency modes are excited
They add because they are cosine-like
But they decohere rapidly

- We will use wakefields based on fits derived by Karl Bane

  l length of the cell

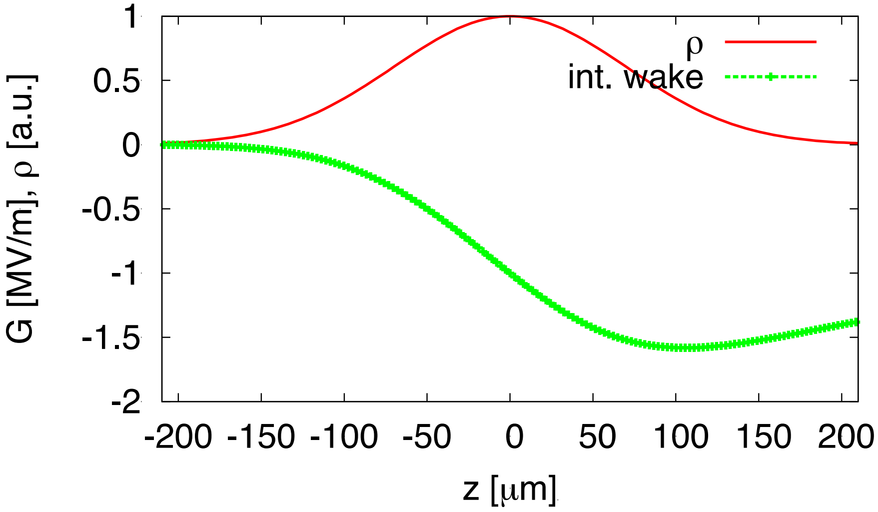
  a radius of the iris aperture

  g length between irises

$$z_0 = 0.41 a^{1.8} g^{1.6} \left(\frac{1}{l}\right)^{2.4}$$

$$W_L(z) = \frac{Z_0 c}{\pi a^2} \exp\left(-\sqrt{\frac{z}{z_0}}\right)$$

- Use CLIC structure parameters

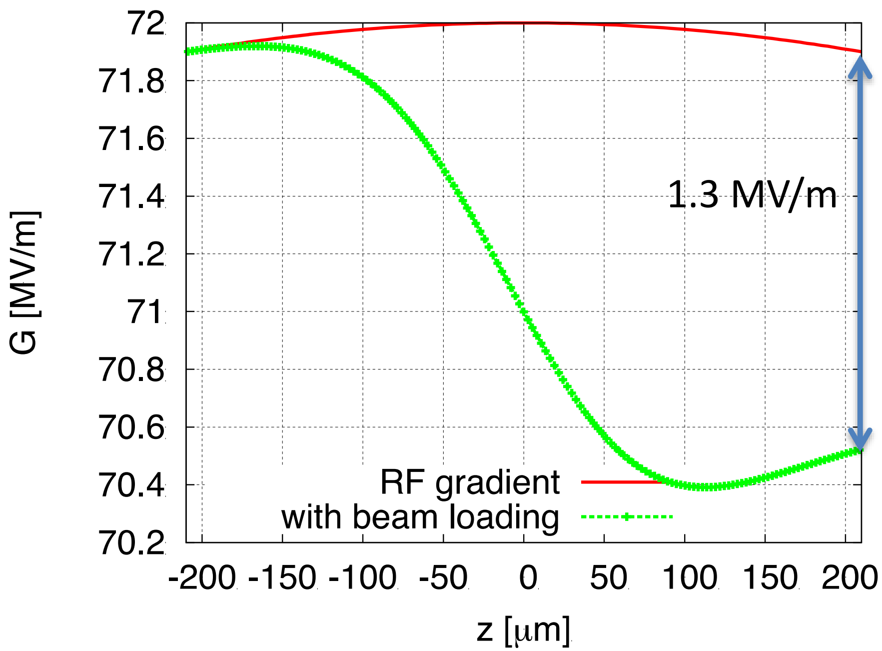


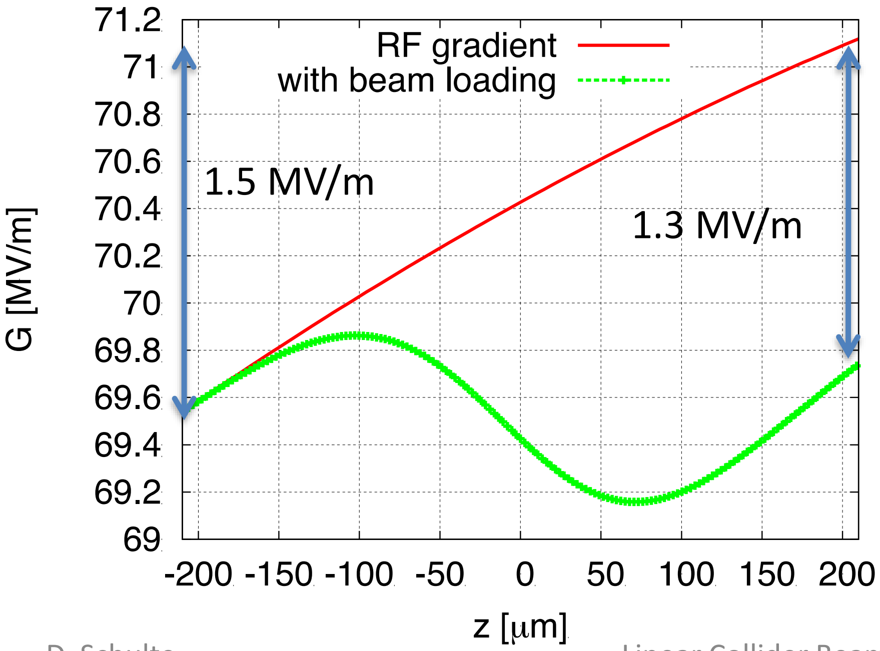
Longitudinal Wakefields and Energy Spread

Loaded gradient along bunch

On-crest acceleration:

- ➢ more than 2% full gradient spread
- ➢ 0.7% RMS energy spread





Off-crest acceleration (12°):

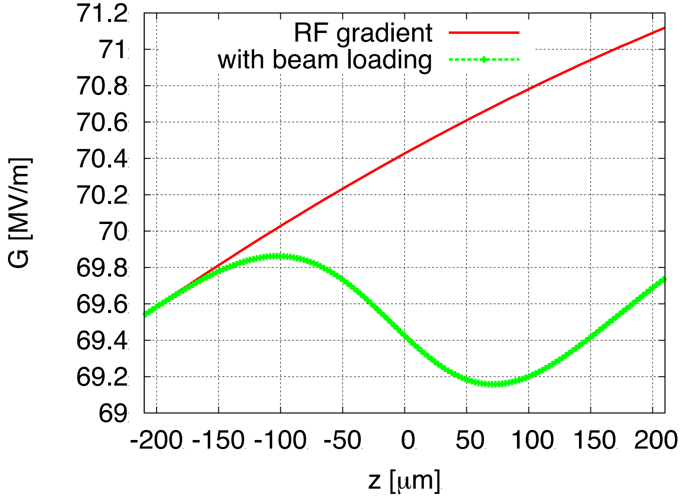
- ➢ 1% full gradient spread
- ➢ 0.35% RMS gradient spread
- ➢ Loose about 2% in gradient

Bunch Length Choice

Fix mean RF phase at 12°

Make the bunch just long enough to reach final RMS energy spread of 0.35%

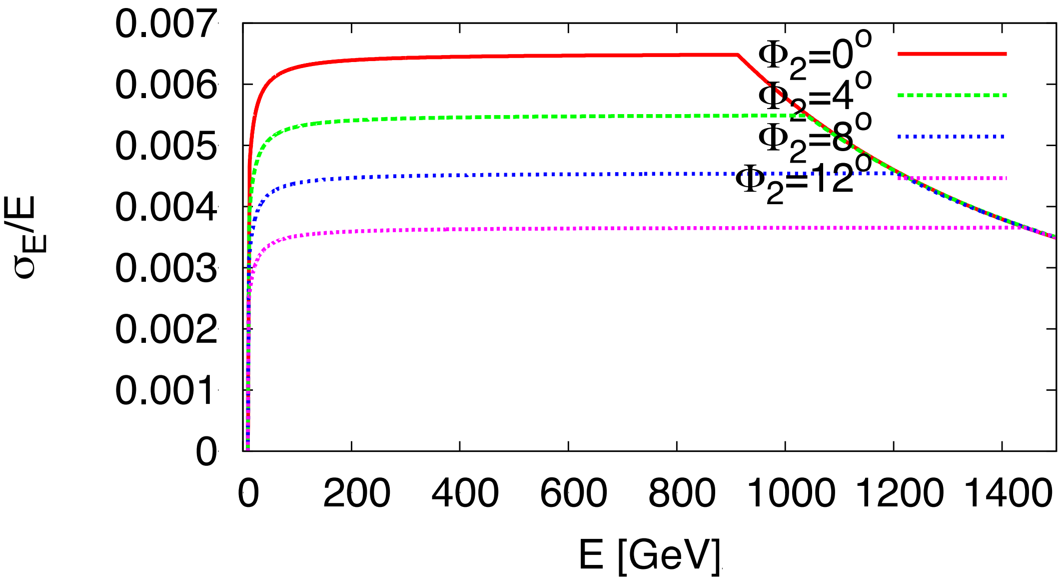
Hence $\sigma_z = \sigma_z(N)$



Can chose different RF phases along the linac

- Small phase in the main part
- and 30° at the end
- To have **average** phase of 12°

Allows to have larger energy spread in the main part of the linac than at the end

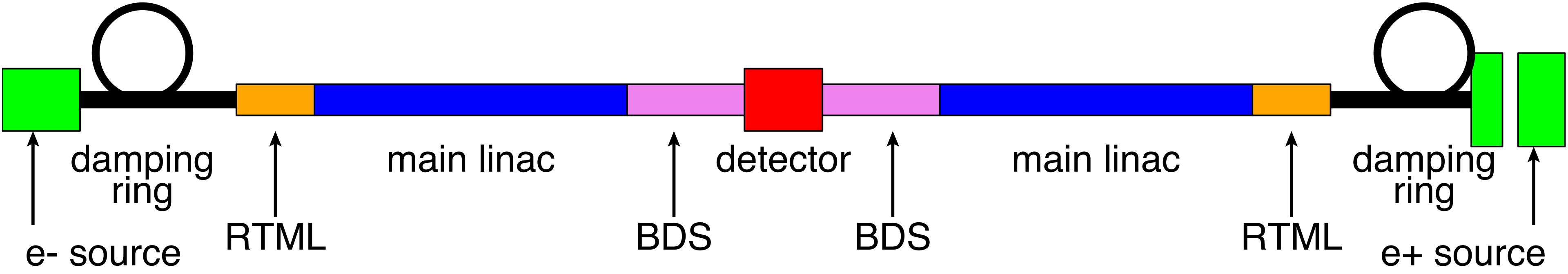


This can help beam stability

⇒ See next section

Single-bunch Stability

Beam Parameters Along the Collider (CLIC 380)



	Design limits $\Delta\varepsilon_y$ [nm]	Static imperfections $\Delta\varepsilon_y$ [nm]	Dynamic imperfections $\Delta\varepsilon_y$ [nm]
Damping ring exit	5	0	0
End of RTML	1	2	2
End of main linac	0	5	5
Interaction point	0	5	5
sum	6	12	12

Require 90% probability to meet goal

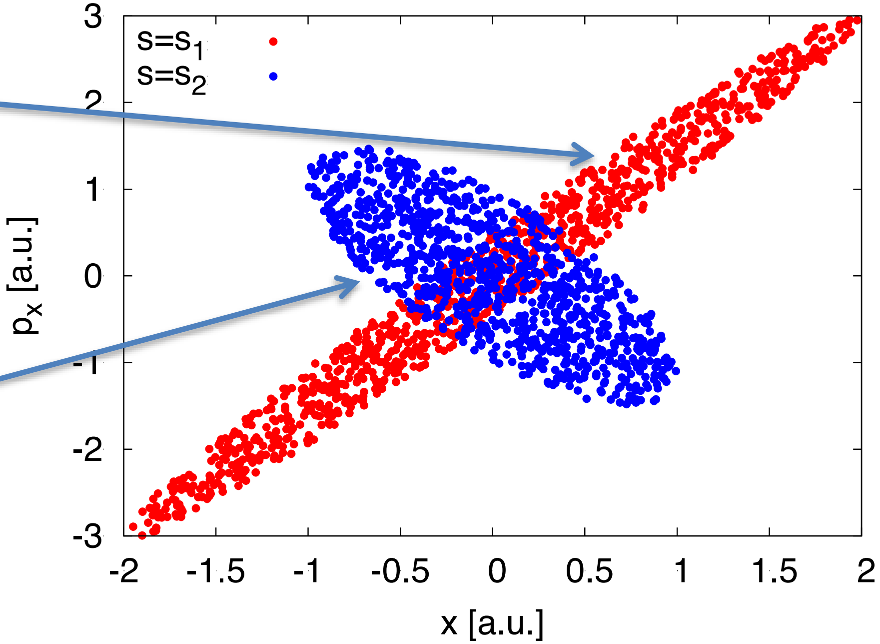
Average over time

Emittance

The beam particles have different coordinates; they occupy some phase space

Liouville theorem (from the Liouville equation): the density in phase space around a trajectory remains constant in an unperturbed system, i.e. “the phase space is preserved”

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial t} + \sum_{i=1}^{N}\left[\frac{\partial\rho}{\partial q_i}\dot{q}_i + \frac{\partial\rho}{\partial p_i}\dot{p}_i\right] = 0$$



Particle coordinates at one location

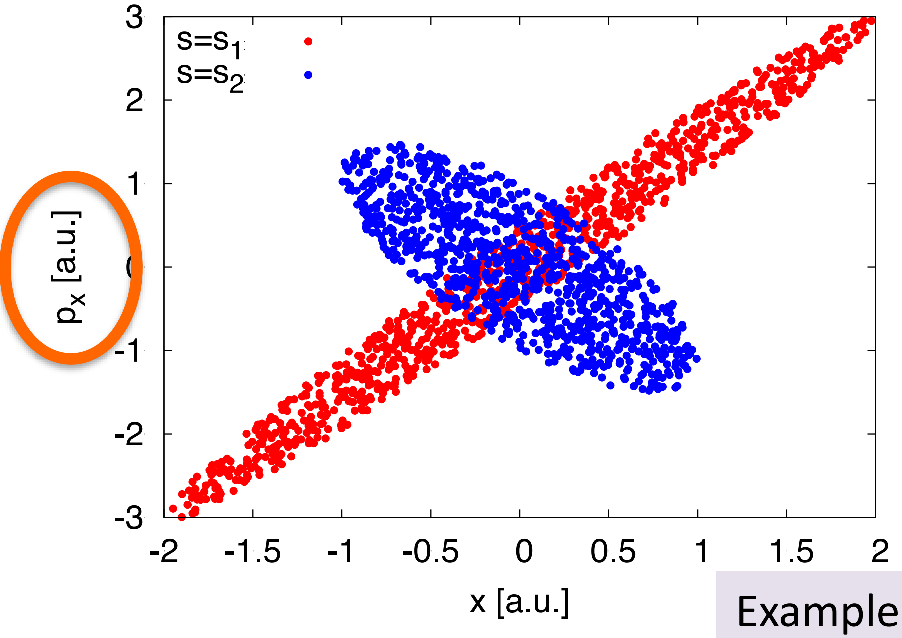
Particle coordinates at other location

Area does not change

Emittance and Acceleration

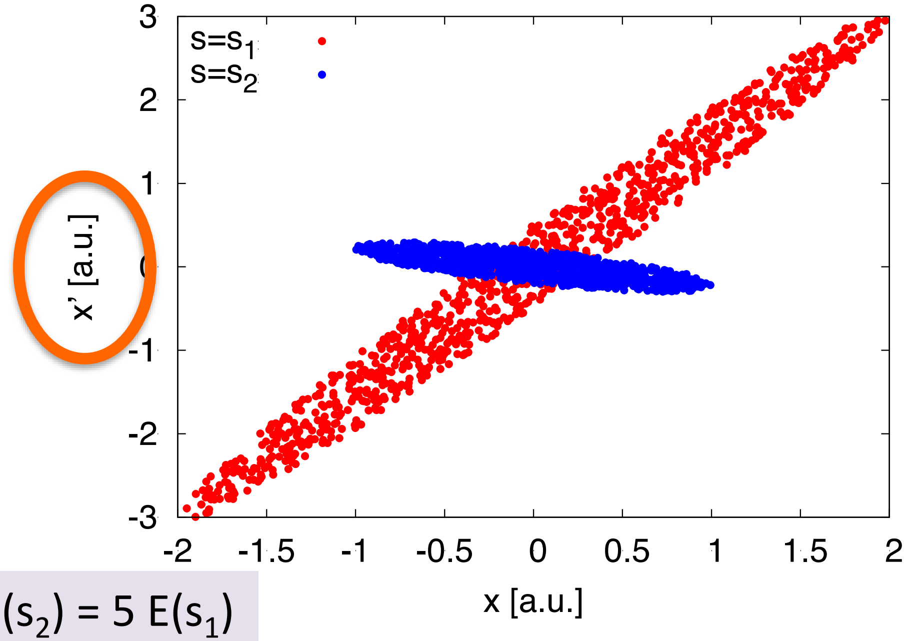
When accelerating the phase space remains constant in canonical coordinates

$$(x, y, z, p_x, p_y, p_z)$$



But with the definition used in accelerators emittance shrinks

$$(x, y, z, x', y', E)$$



Example: $E(s_2) = 5\,E(s_1)$

To avoid this linac experts use **normalised emittance** $\varepsilon_N=\gamma\varepsilon$ that does not change
I will always do that here but not use the index N

Emittance Definition

Use projected emittance

$$e=\sqrt{\left\langle\left(x-\overline{x}\right)^{2}\right\rangle\left\langle\left(x'-\overline{x'}\right)^{2}\right\rangle-\left\langle\left(x-\overline{x}\right)\left(x'-\overline{x'}\right)\right\rangle^{2}}$$

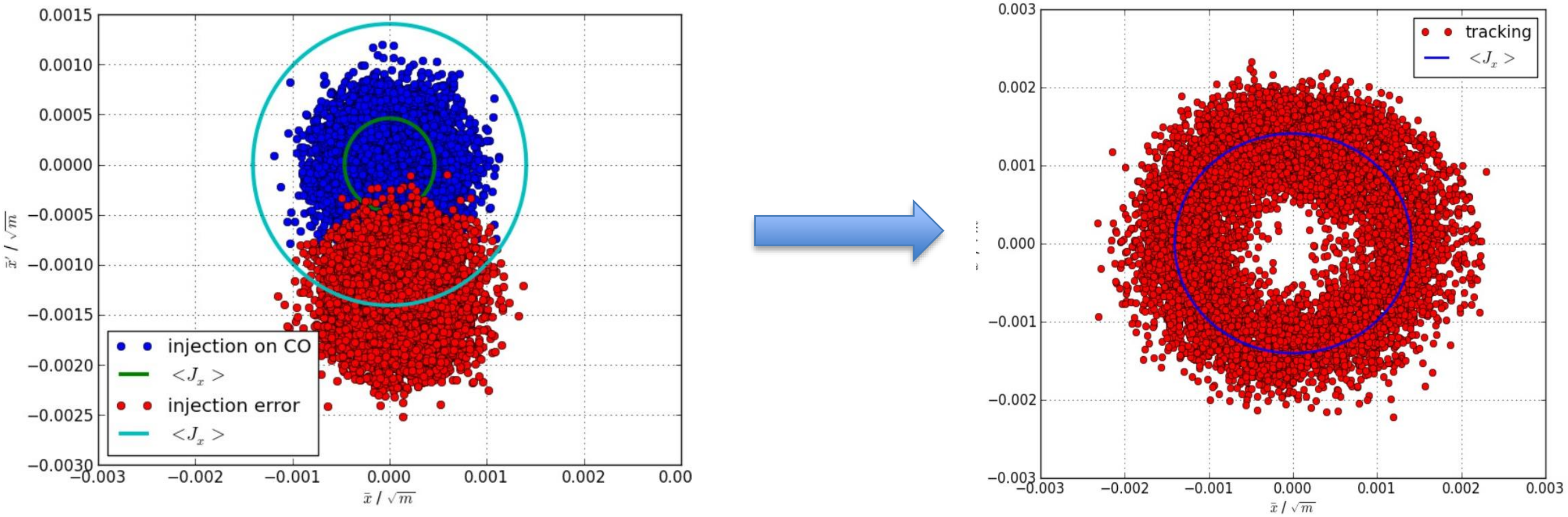
Note: we have to be careful with this, come back at the end

Also ignore coupling between x and y

Offset

Beam jitter leads to luminosity loss

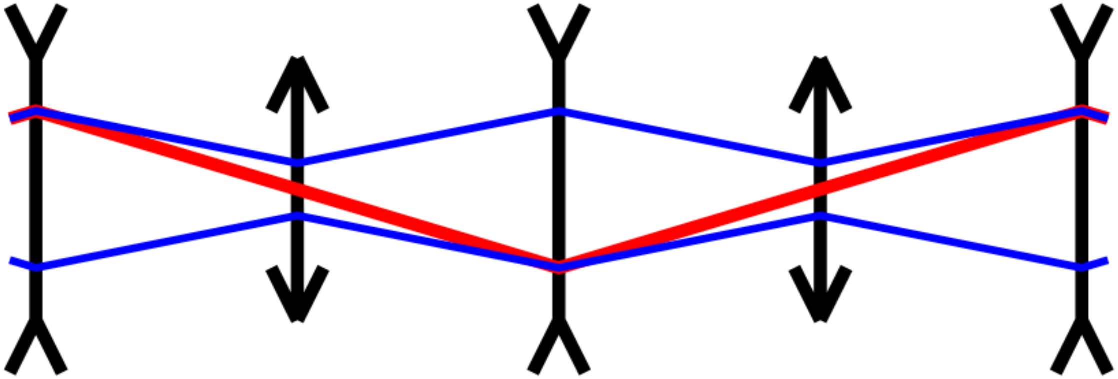
Beam jitter can increase emittance (decoherence), luminosity loss on average remains constant
But cannot correct downstream



Can use the “multi-pulse emittance” (combine phase space of subsequent bunches/pulses)

But transverse wakefields can make a jittering beam explode
Main linac is huge source of wakefield effects
This is why the main linac defines the bunch charge and length
Let us have a look

Main Linac Lattice Concept



FODO lattice is used in main linacs

Guiding quadrupoles act like a spring

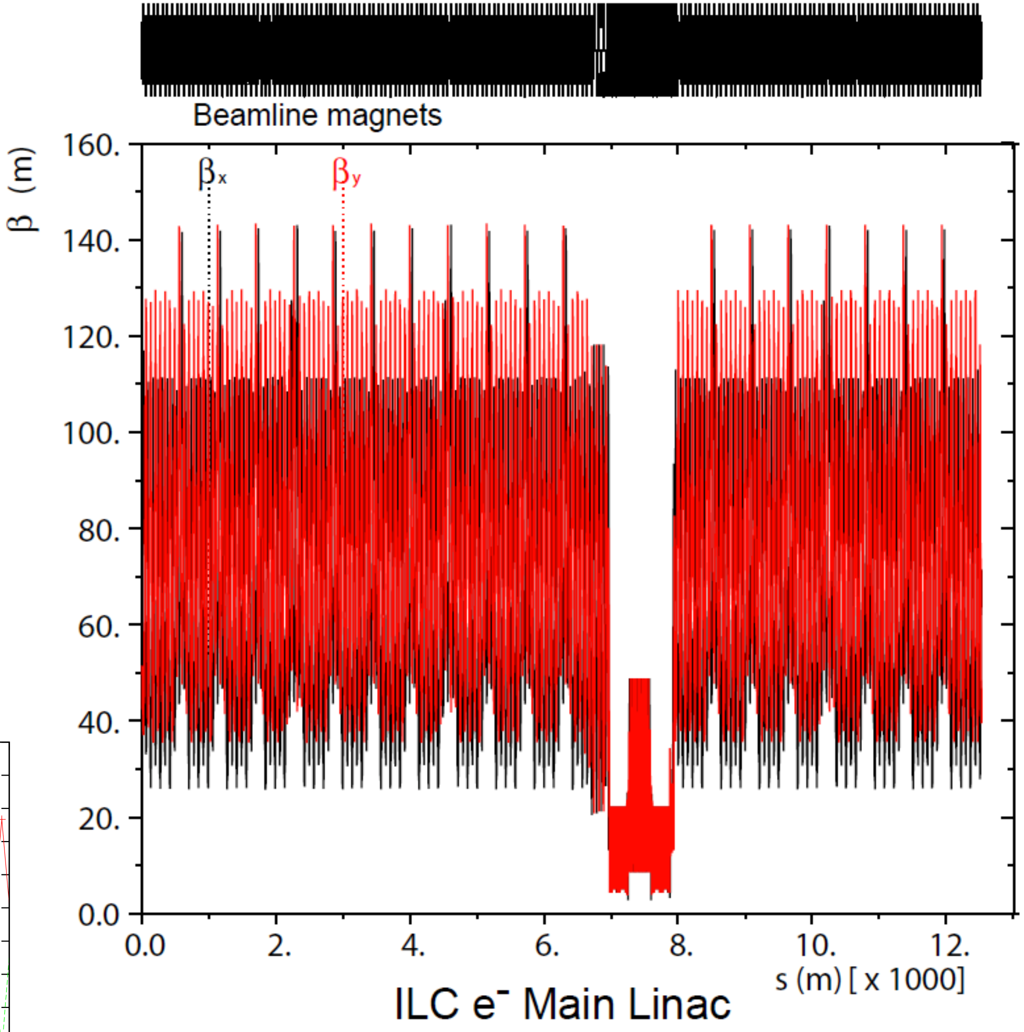
Particle is comparable to harmonic oscillator (driven with wakes)

$$x_1''(s) + \frac{1}{\beta^2} x_1(s) = 0$$

Local wavelength is β
Strong focusing means smaller β

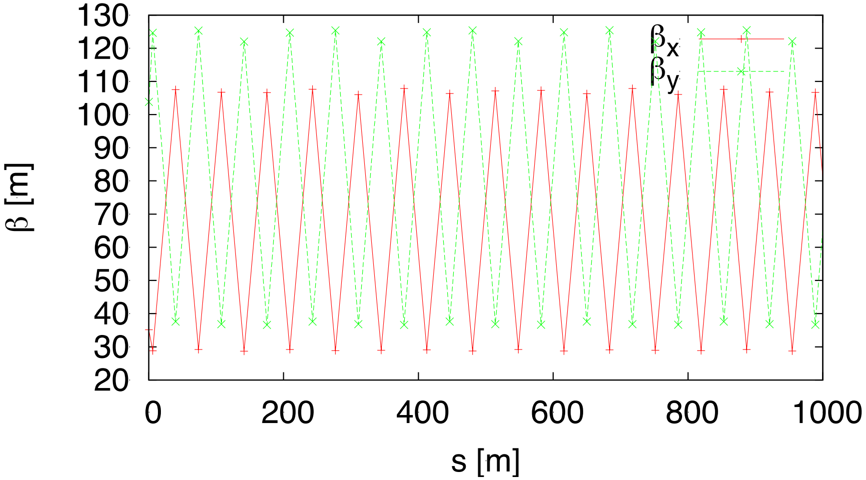
A function of longitudinal position s
But equivalent to time dependence t

ILC Lattice Design



Constant quadrupole spacing
Constant phase advance

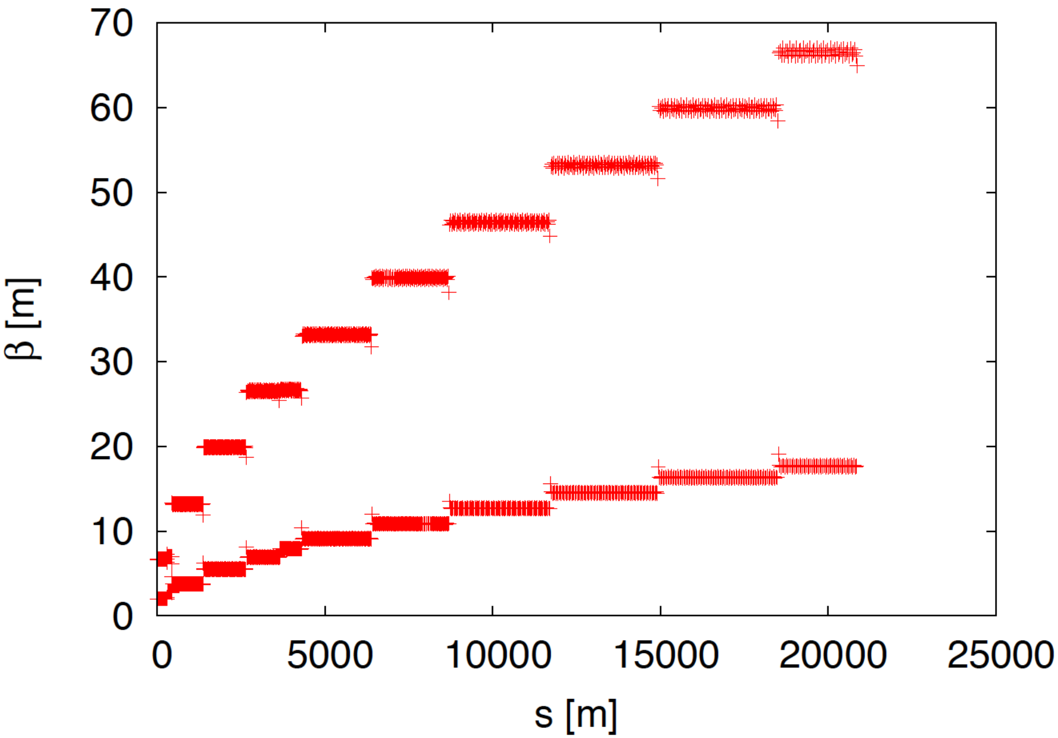
Different phase advance in horizontal and vertical to decouple planes against wakefield effects



CLIC Lattice Design (3 TeV)

- Use strong focusing (small ®) to stabilise beam
  - 10% of linac are quadrupoles
- Used ® $\propto E^{1/2}$, □√ = const
  - Quadrupole spacing and length scale as $E^{1/2}$

  ⇒ roughly constant fill factor
  - phase advance is chosen to balance between wakefield and ground motion effects
- Total length 20867.6m
  - fill factor 78.6%



- 12 different sectors used
- Matching between sectors using 7 quadrupoles to allow for some energy bandwidth

  Note: fill factor = active length/total length

Passage Through the Linac

For simplicity consider constant beta-function
Replacing FODO lattice with permanent focusing
Great approximation to understand physics

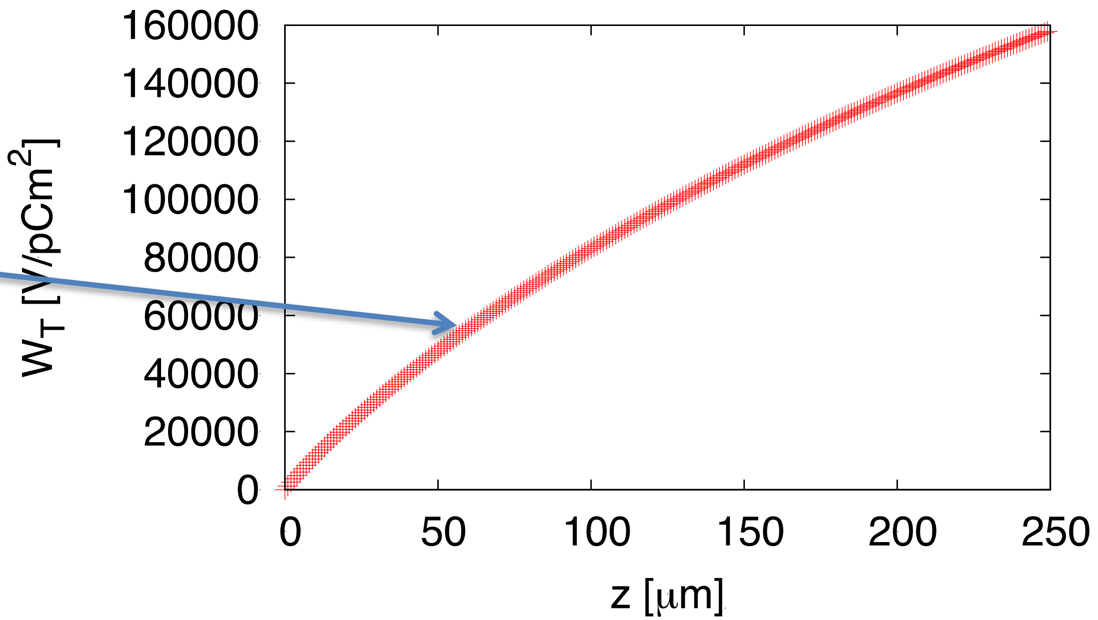
$$x_1''(s) + \frac{1}{\beta^2} x_1(s) = 0$$

$$x_1(0) = x_0 \quad x_1'(0) = 0$$

Solution is well-known

$$x_1(s) = x_0 \cos\left(\frac{s}{\beta}\right)$$

Transverse Wakefields



For short distances the wake-field rises linear

Summation of an infinite number of sine-like modes with different frequencies

Parametrisation (K. Bane)

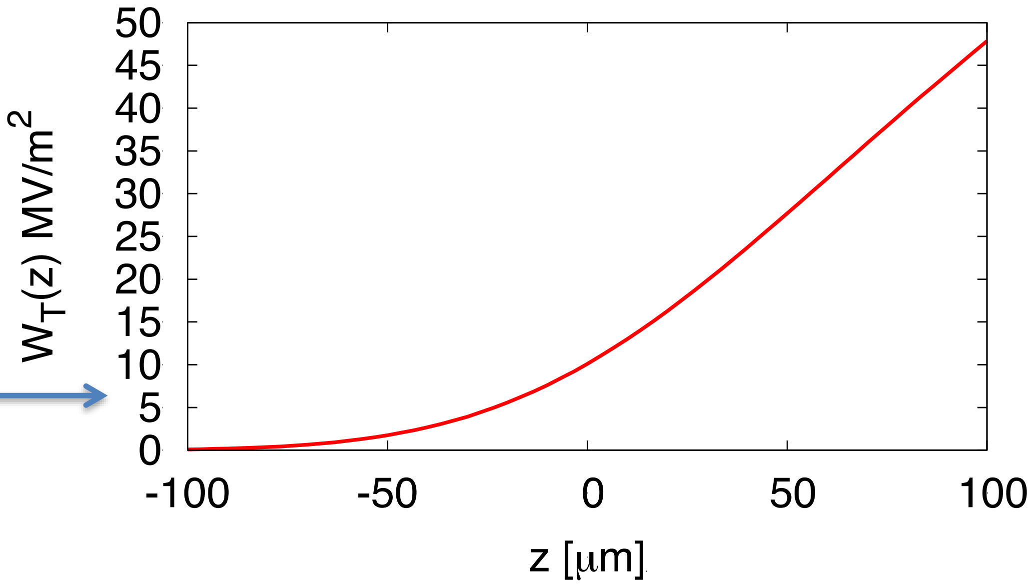
$$W_\perp(z) = 4\frac{Z_0 c z_0}{\pi a^4}\left[1-\left(1+\sqrt{\frac{z}{z_0}}\right)\exp\left(-\sqrt{\frac{z}{z_0}}\right)\right]$$

$$z_0 = 0.169 a^{1.79} g^{0.38}\left(\frac{1}{l}\right)^{1.17}$$

$$W_\perp(z \ll z_0) \approx 2\frac{Z_0 c}{\pi a^4} z$$

Coherent bunch offset (worst case)

The tail is deflected to the outside



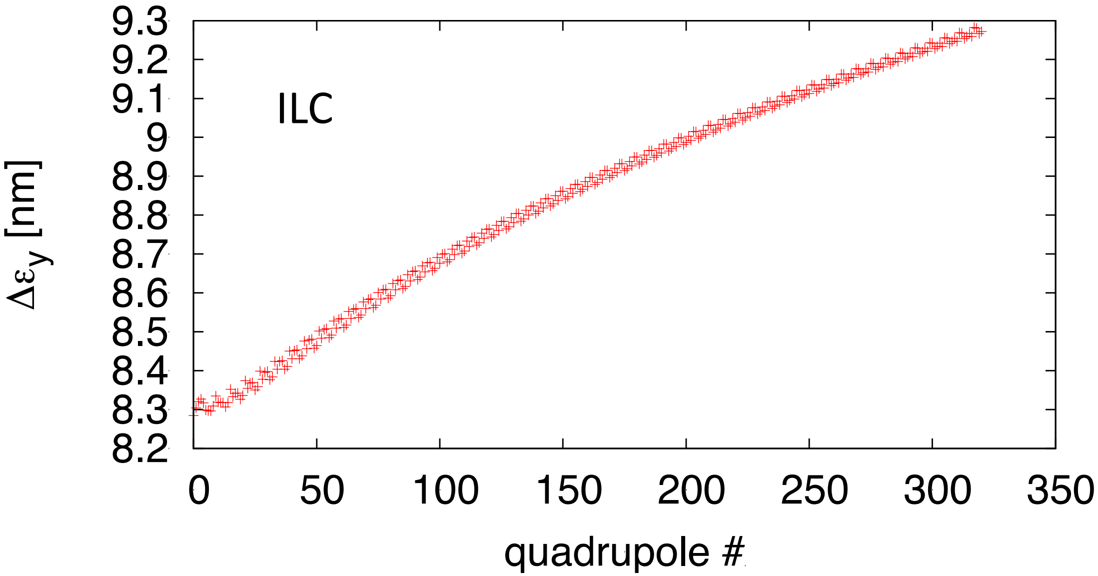
Emittance in Linac

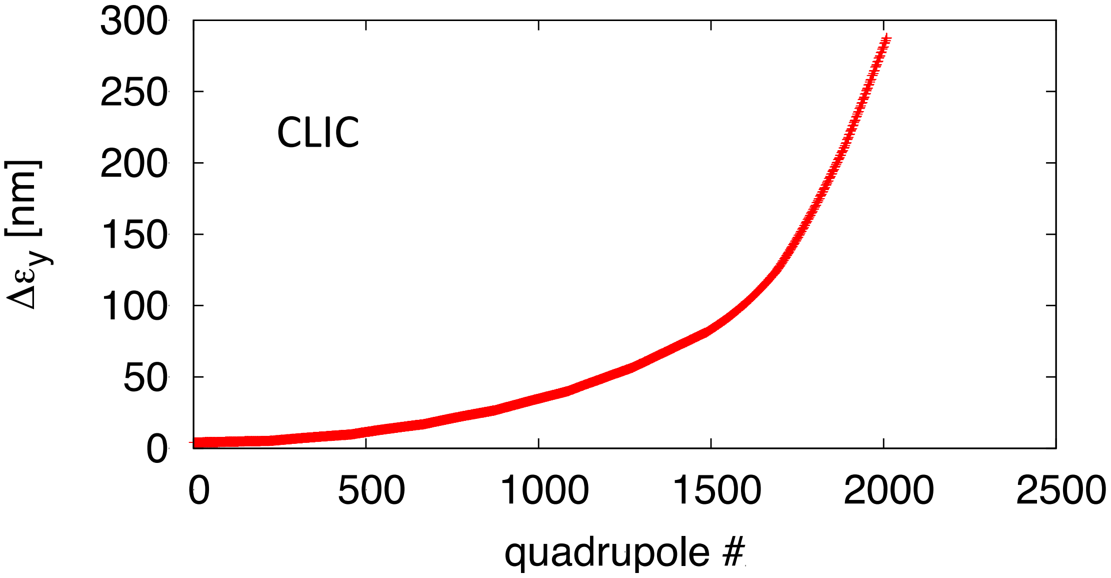
Transverse stability of beam with initial offset σ_y

- No energy spread
- Emittance with respect to beam axis shown

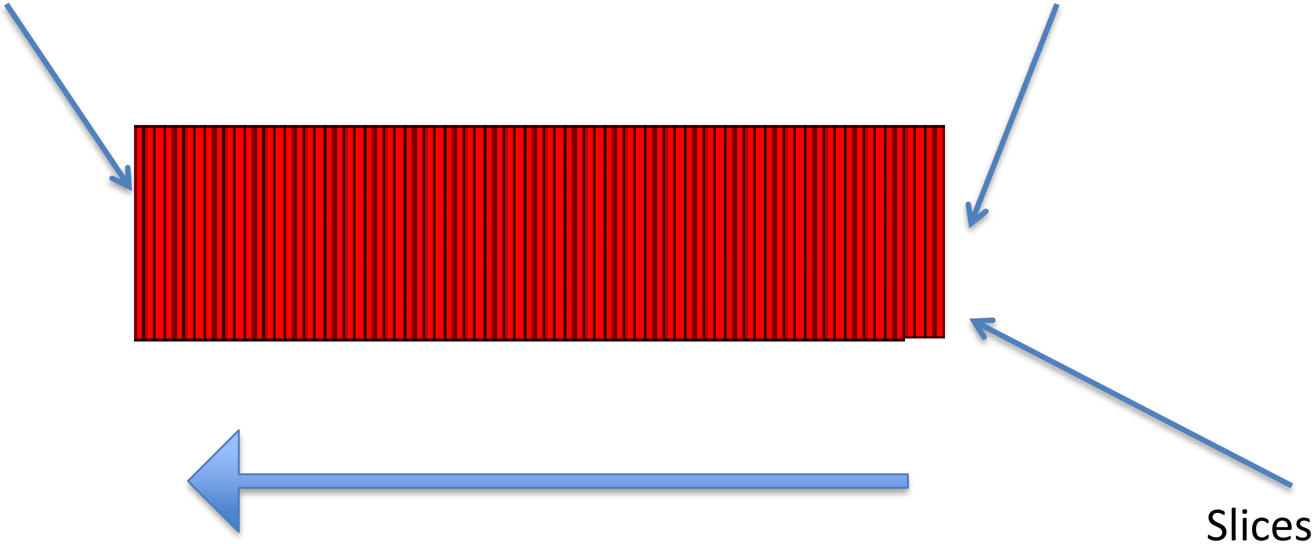
$\Rightarrow$ Acceptable for ILC

$\Rightarrow$ Not acceptable for CLIC





Bunch Transverse Motion (CLIC)



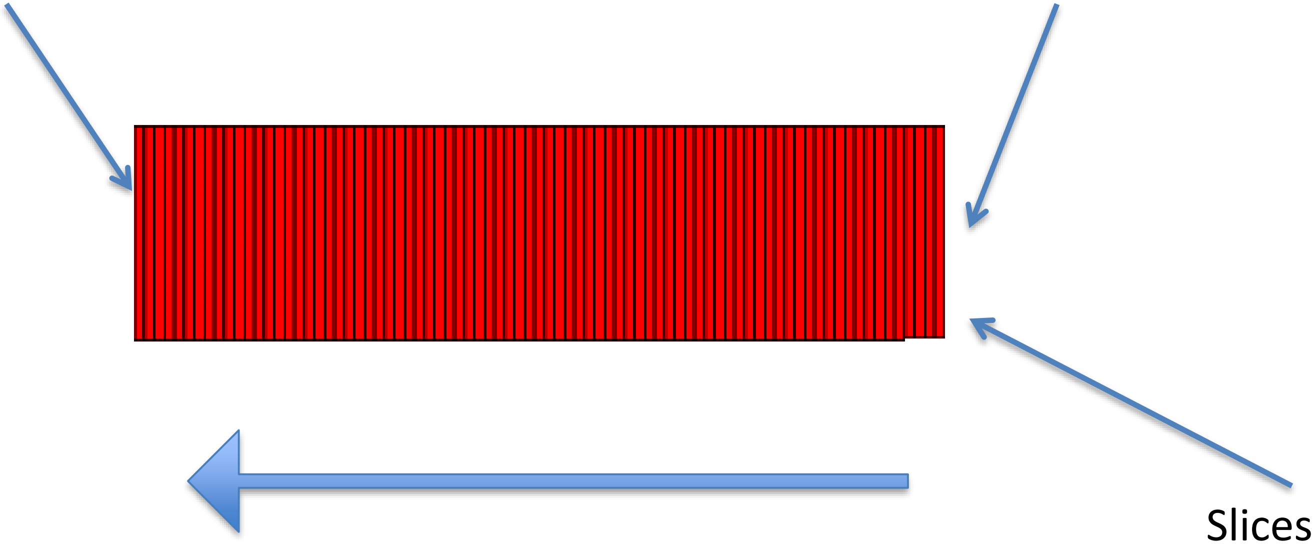
Head performs simple betatron oscillation

Tail starts to flap around

Direction of motion

Slices will shrink due to energy increase

Bunch Transverse Motion (CLIC)



Head performs simple betatron oscillation

Tail starts to flap around

Direction of motion

Slices will shrink due to energy increase

Wakefield Model

Assume bunch can be represented by two particles and constant $K(s) = 1/\beta^2$

- Second particle is kicked by transverse wakefield

$$x_2''(s) + \frac{1}{\beta^2} x_2(s) = \frac{Ne^2 W_\perp(\Delta z)}{\boxed{P_L c}} x_1(s)$$

$$= E$$

$$x_2(0) = x_0 \quad x_2'(0) = 0$$

$$x_1(s) = x_0 \cos\left(\frac{s}{\beta}\right)$$

Solution is simple with an ansatz

$$x_2(s) = x_0 \cos\left(\frac{s}{\beta}\right) + x_0 \left(Ne^2 W_\perp(\Delta z)\right) \left(\frac{\beta s}{2E}\right) \sin\left(\frac{s}{\beta}\right)$$

⇒ Amplitude of second particle oscillation is growing linearly with *s*

Discussion

$$x_2(s) = x_0 \cos\left(\frac{s}{\beta}\right) + x_0 \left(Ne^2 W_\perp(\Delta z)\right) \left(\frac{\beta s}{2E}\right) \sin\left(\frac{s}{\beta}\right)$$

With proper calculation one finds $\frac{\beta s}{E} \Rightarrow \int \frac{\beta(s)}{E(s)} ds$

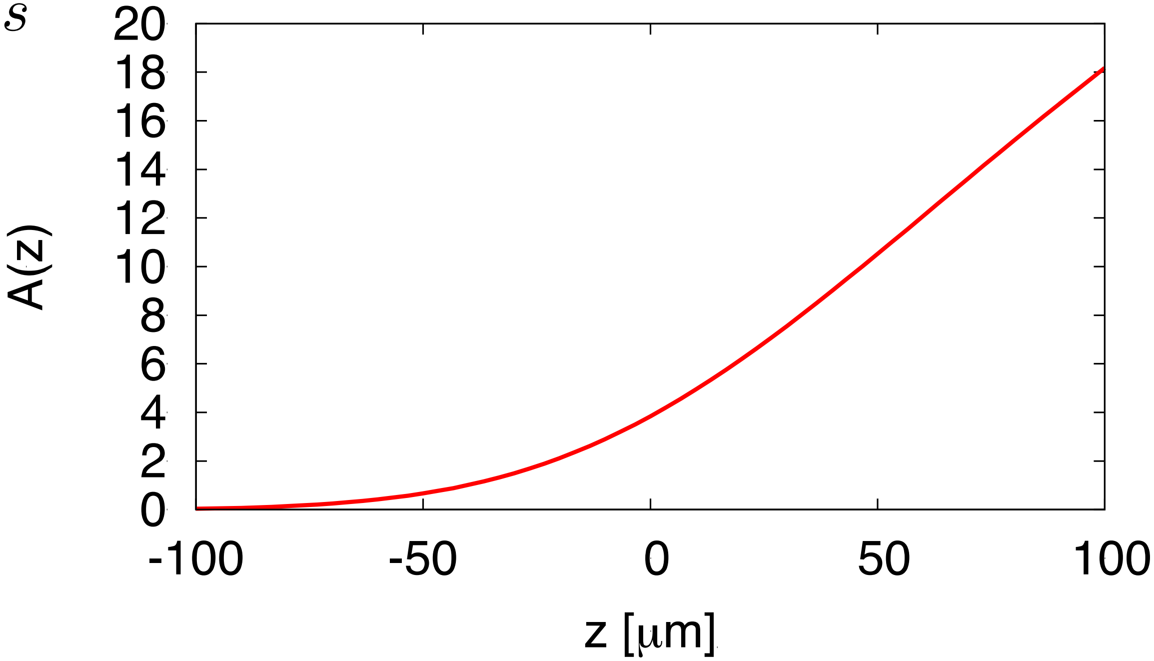
- Factors for the amplitude growth of the second particle
  - β: small beta-function (strong focusing) helps
  - 1/*E*: high energy helps
  - $W_\perp$: small wakefield helps
  - Shorter bunches
  - *N* : small bunch charge helps
  - *s*: shorter linac helps (i.e. higher gradient G)

Discussion

$$x_2(s) = x_0 \cos\left(\frac{s}{\beta}\right) + x_0 \left(Ne^2 W_\perp(\Delta z)\right)\left(\frac{\beta s}{2E}\right) \sin\left(\frac{s}{\beta}\right)$$

$$\tilde{W}_\perp(z_0) = \int_{-\infty}^{z_0} \rho(z) W_\perp(z_0 - z) Ne dz$$

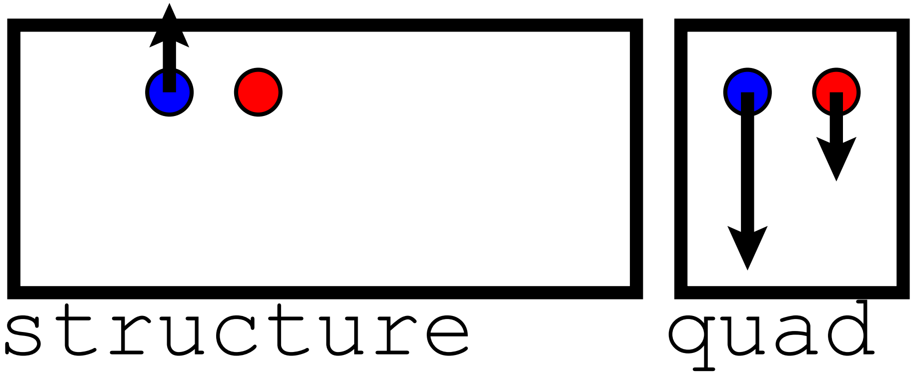
$$A(z_0) = \tilde{W}_\perp(z_0) e \int \frac{\beta(s)}{2E} ds$$



BNS Damping Concept

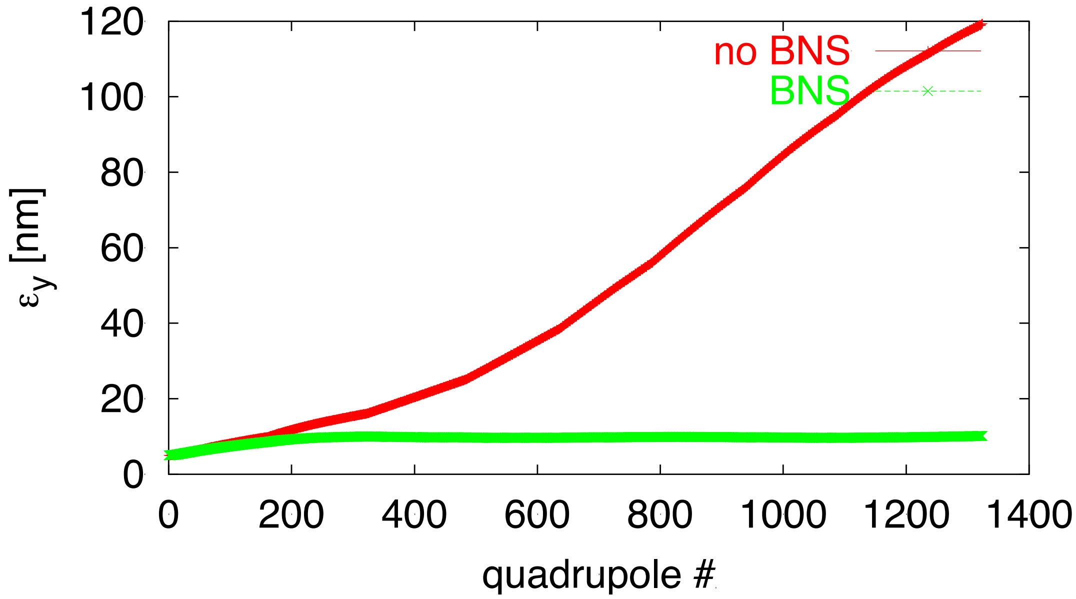
Transverse wakes act as defocusing force on tail

⇒ beam jitter is exponentially amplified



BNS damping (Balakin, Novokhatsky and Smirnov) prevents this growth

- manipulate RF phases to have energy spread
- take spread out at end



BNS Damping

For simplicity assume initial offset but no angle

First particle performs a harmonic oscillation

$$x_1(s) = x_0 \cos\left(\frac{s}{\beta}\right)$$

We **want** the second particle to perform the **same oscillation**, i.e.

$$x_2(s) = x_0 \cos\left(\frac{s}{\beta}\right)$$

Change particle energy for this purpose

$$x_2''(s) + \frac{1}{\underbrace{(1+\delta)\beta^2}} x_2(s) = \frac{Ne^2 W_\perp(\Delta z)}{E} \overbrace{x_0 \cos\left(\frac{s}{\beta}\right)}^{x_1(s)}$$

Same as changing mass in
harmonic oscillator

BNS Damping

$$x_2''(s) + \frac{1}{(1+\delta)\beta^2} x_2(s) = \frac{Ne^2 W_\perp(\Delta z)}{E} x_0 \cos\left(\frac{s}{\beta}\right)$$

Plugging in our **wanted** solution for $x_2(s)$

$$x_2(s) = x_0 \cos\left(\frac{s}{\beta}\right) = x_1(s)$$

we find

$$-\frac{1}{\beta^2} x_0 \cos\left(\frac{s}{\beta}\right) + \frac{1}{(1+\delta)\beta^2} x_0 \cos\left(\frac{s}{\beta}\right) = x_0 \frac{Ne^2 W_\perp(\Delta z)}{E} \cos\left(\frac{s}{\beta}\right)$$

BNS Damping

$$-\frac{1}{\beta^2}\cancel{x_0}\,\cancel{\cos\left(\frac{s}{\beta}\right)}+\frac{1}{(1+\delta)\beta^2}\cancel{x_0}\,\cancel{\cos\left(\frac{s}{\beta}\right)}=\cancel{x_0}\,\frac{Ne^2W_\perp(\Delta z)}{E}\,\cancel{\cos\left(\frac{s}{\beta}\right)}$$

which is fulfilled for

$$\frac{1}{(1+\delta)\beta^2}-\frac{1}{\beta^2}=\frac{Ne^2W_\perp(\Delta z)}{P_Lc}$$

$$\delta\approx-\frac{\beta^2}{E}Ne^2W_\perp(\Delta z)$$

Small beta-function

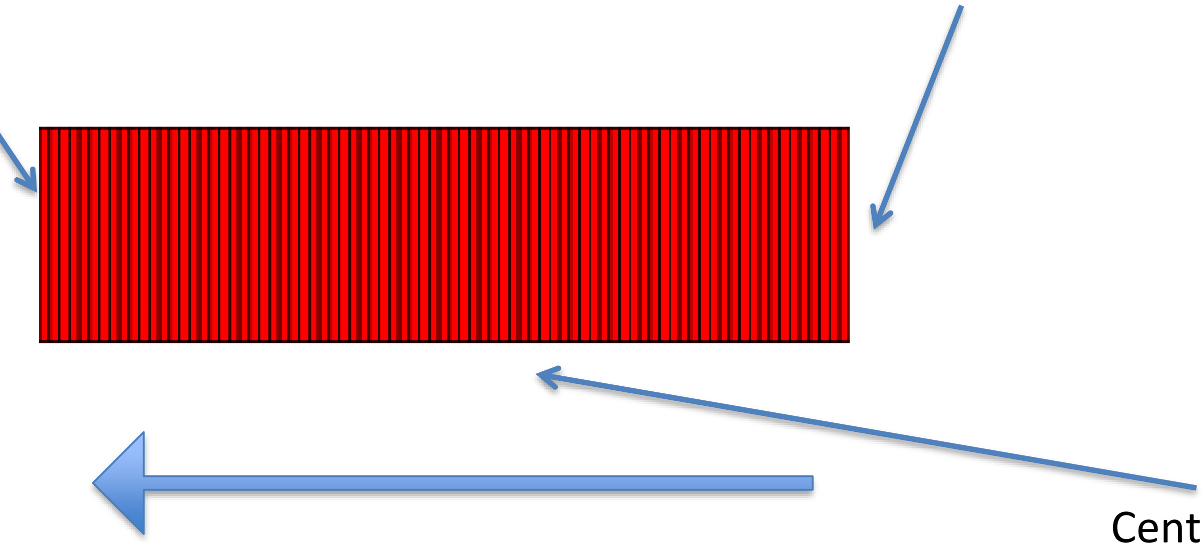
Small bunch charge

Small wakefields

CLIC choice $\beta(s)\propto\sqrt{E(s)}$

Allows $\delta=\mathrm{const}$

Bunch in Main Linac



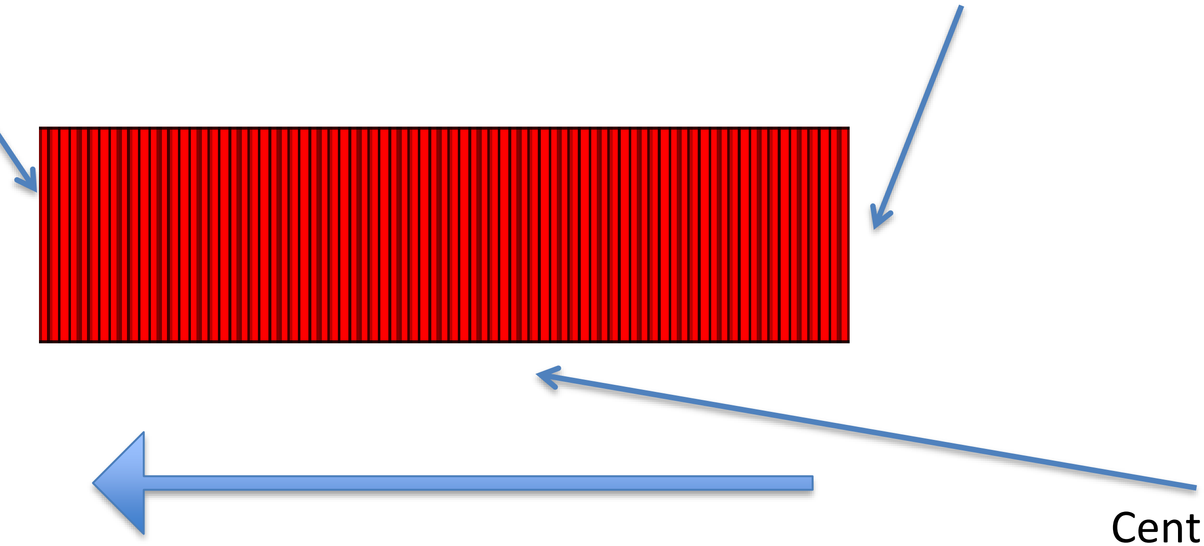
Head still performs simple betatron oscillation

Tail still flaps a little bit

Direction of motion

Centre of bunch is much more stable

Bunch in Main Linac



Head still performs simple betatron oscillation

Tail still flaps a little bit

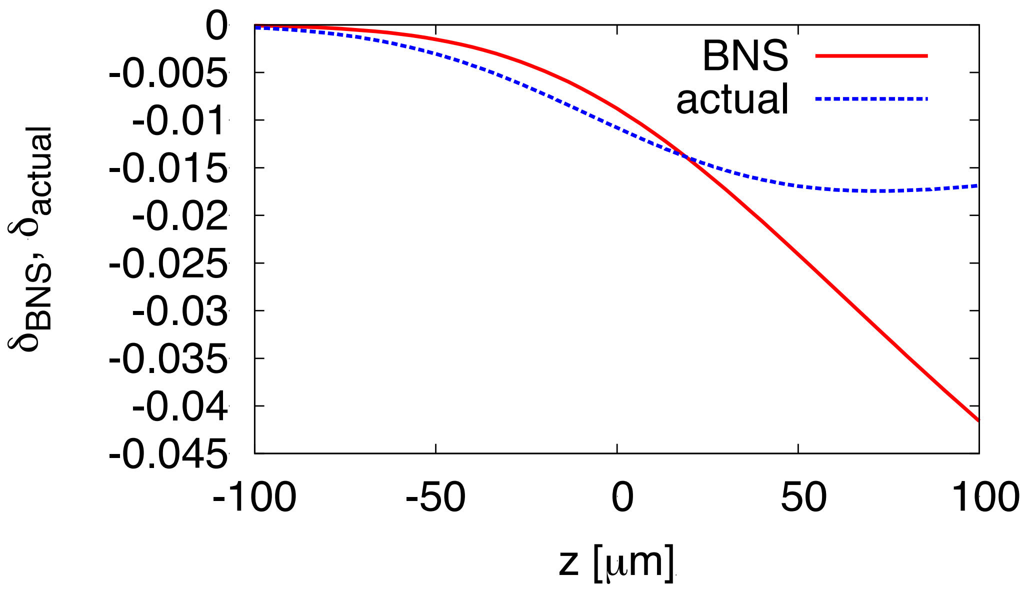
Direction of motion

Centre of bunch is much more stable

Energy Spread in the Linac

Cannot exactly match energy profile and wakefield

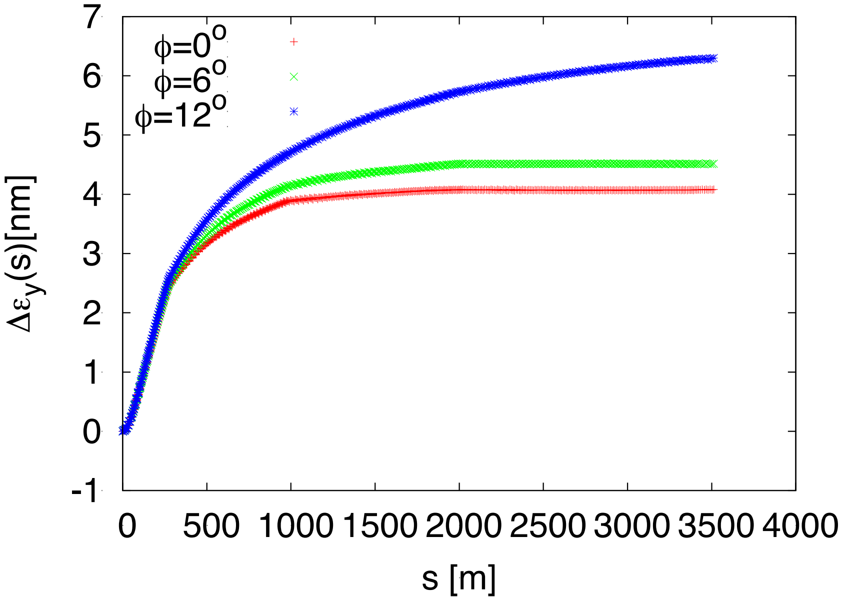
$\Rightarrow$ Shapes of energy spread and integrated wake differ



Only cure coherent offset

$\Rightarrow$ Slope along bunch still has an effect

Energy spread also helps detuning



In summary

$\Rightarrow$ Can only obtain some correction

$\Rightarrow$ Broad acceptable range

$\Rightarrow$ Different RF phases in linac are OK

Multi-bunch Stability

Multi-bunch Wakefields

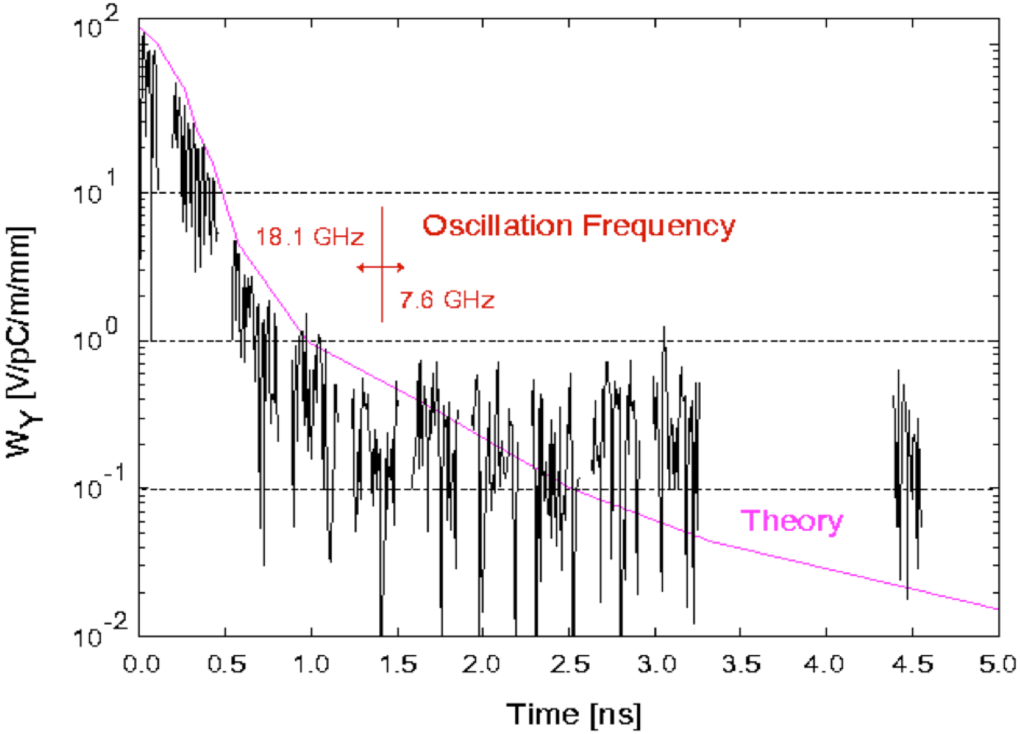
- Long-range transverse wakefield determines how close one can put the bunches in the linac

- Longrange transverse wakefields are sine-like

- They can be reduced by

  - Damping

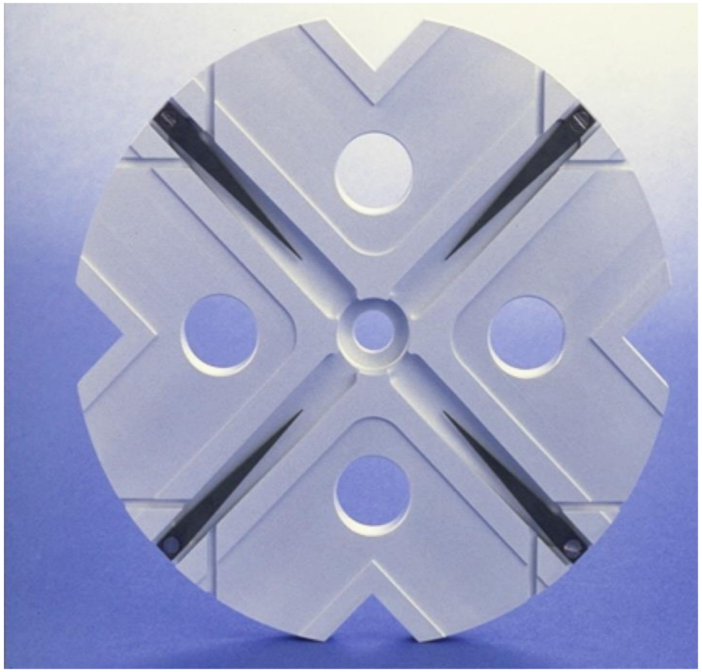
  - Detuning

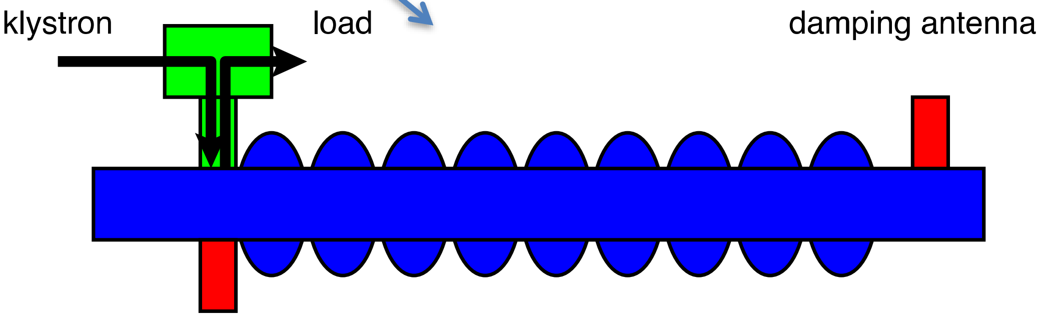


$$W_{\perp}(z) = \sum_{i}^{\infty} 2k_i \sin\left(2\pi\frac{z}{\lambda_i}\right) \exp\left(-\frac{\pi z}{\lambda_i Q_i}\right)$$

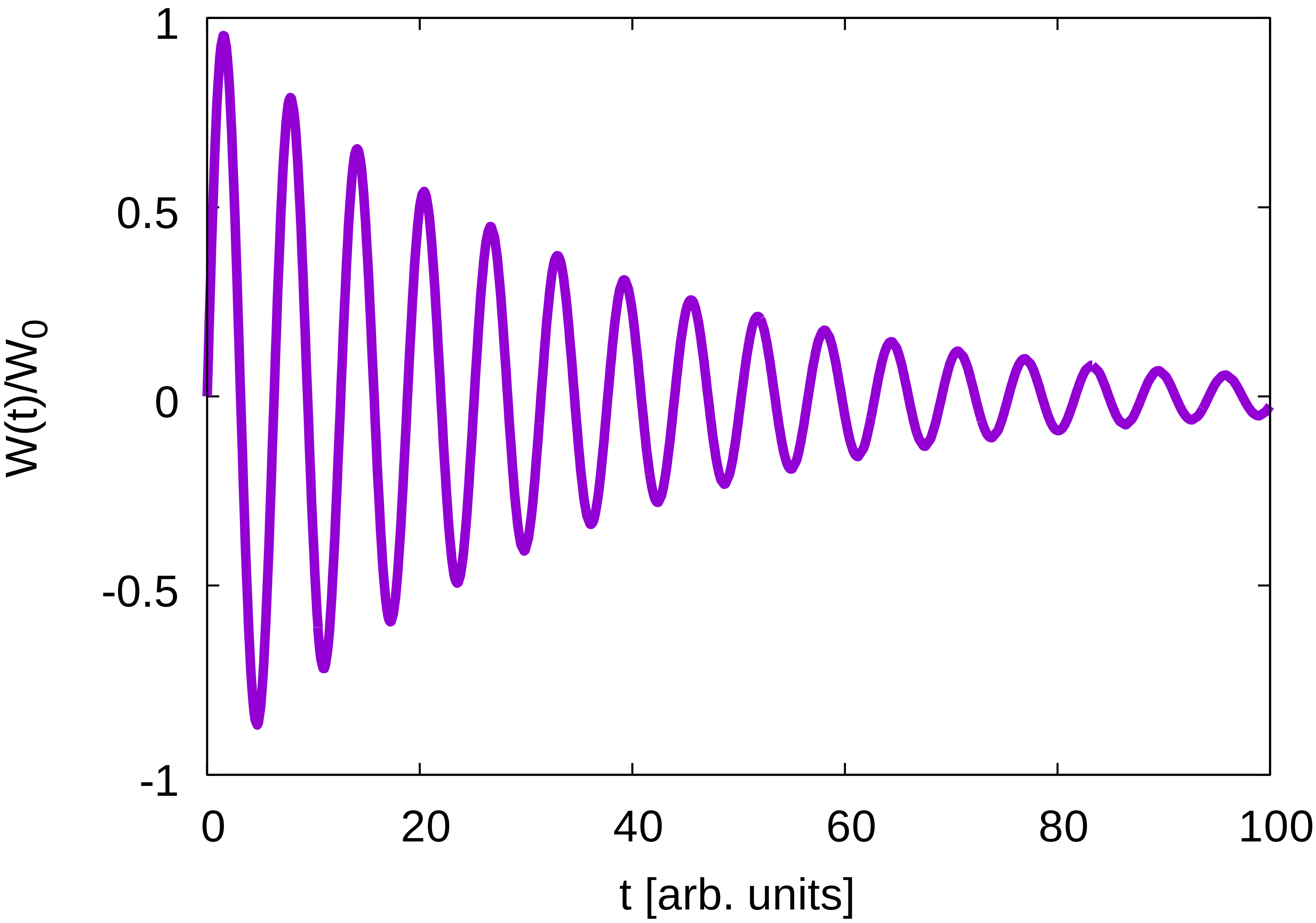
Damping

- Damping = extract power of transverse modes
- In CLIC, each cell has waveguides
  - Fundamental mode cannot escape
  - Strong damping, Q=O(10)
- ILC has antennas at the end
  - Weaker damping, Q=O(10^4)





Effect of Damping



Detuning

Introducing a spread in wakefield frequencies helps:

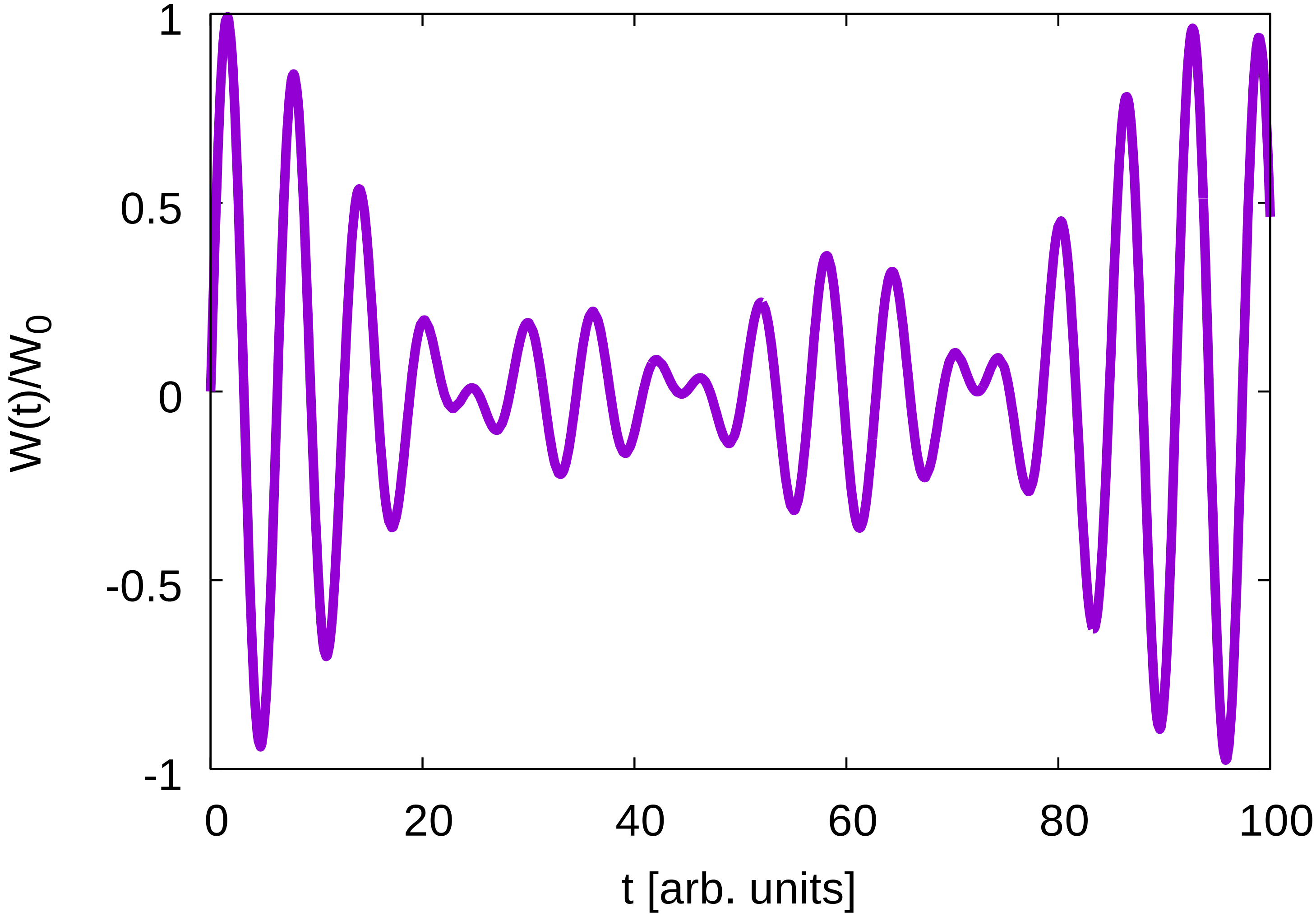
Example for two modes

$$W(z) = W_0 \frac{\sin((k+\Delta)z) + \sin((k-\Delta)z)}{2}$$

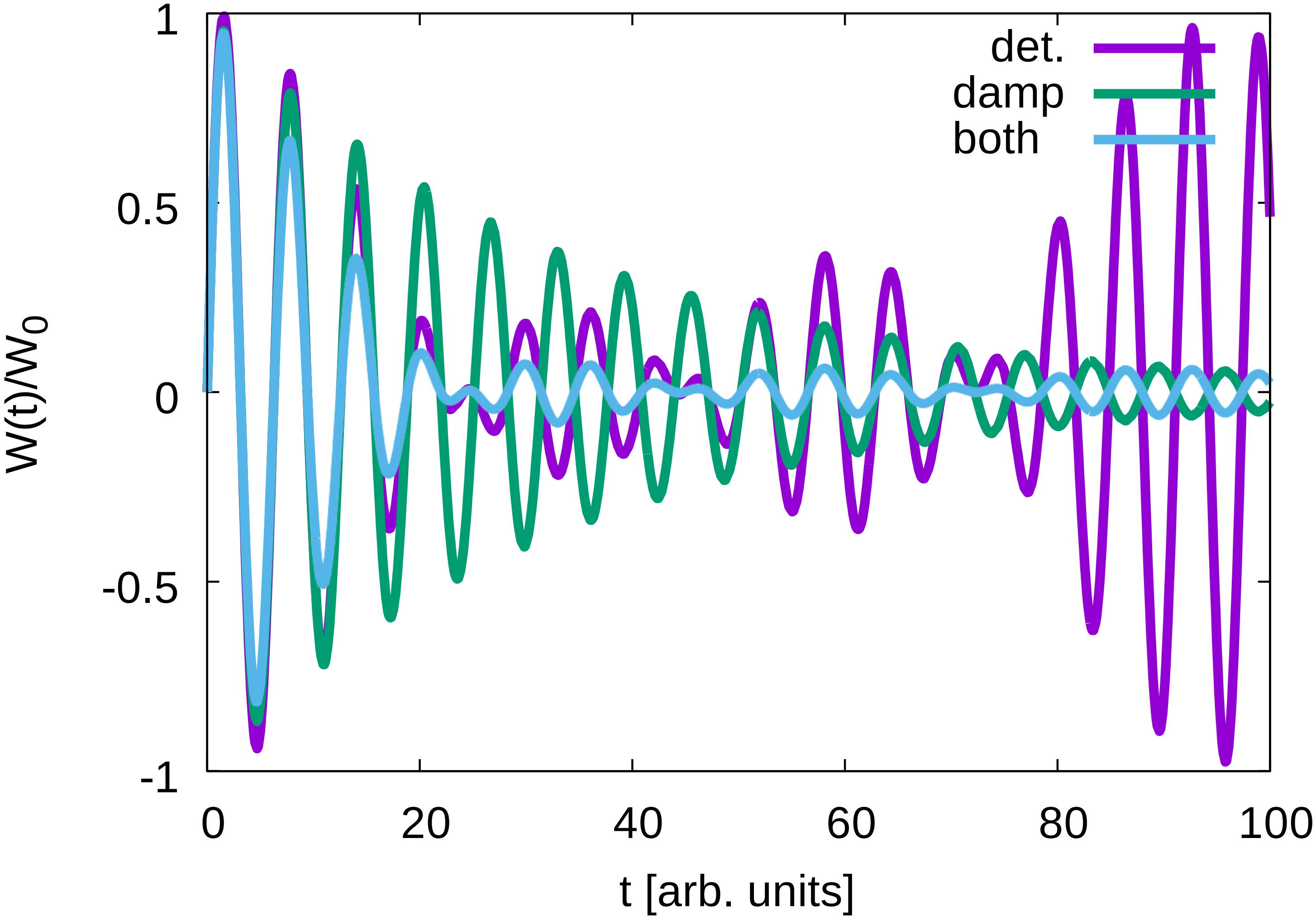
$$W(z) = W_0 \sin(kz) \cos(\Delta z)$$

In CLIC structure each cell is different, has a different transverse mode

Illustration of Detuning



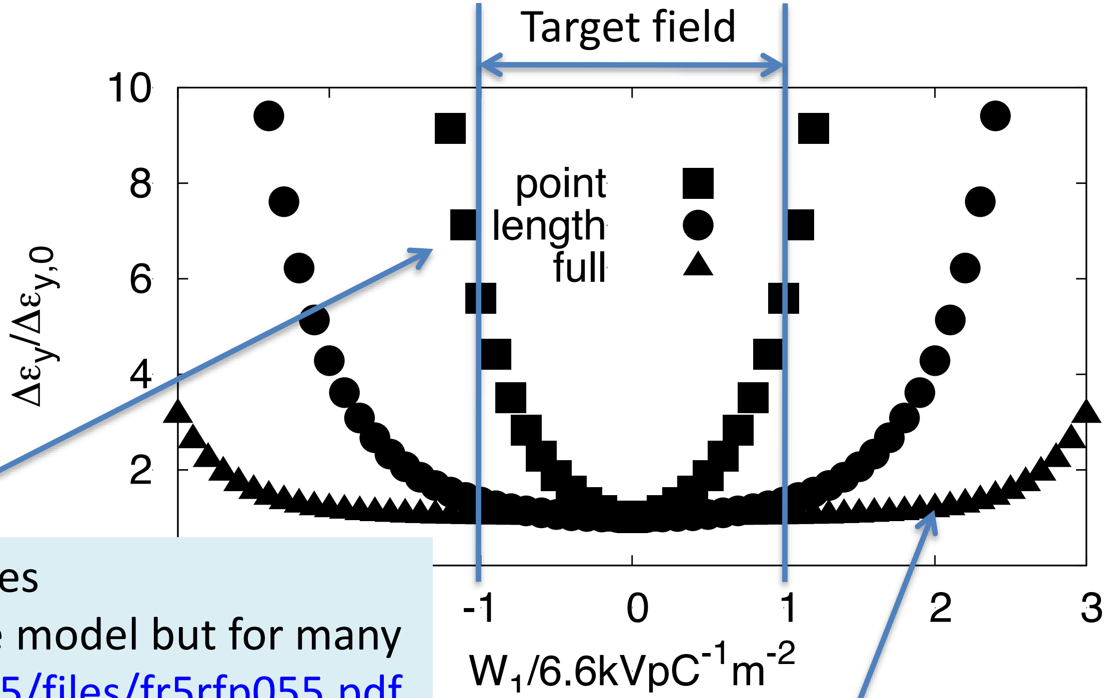
Combined Effect



Multi-bunch Effect in CLIC

Wakefield amplitudes are large
Strong damping (Q=O(10))
Detuning (each cell is different)

Each bunch mainly kicks the immediately following one



Analytic estimate: point-like bunches
Using model similar to two-particle model but for many
https://cds.cern.ch/record/1227215/files/fr5rfp055.pdf

Luminosity loss is amplified by factor 4.9, acceptable

Chose smallest spacing consistent with maximum wakefield

6 buckets, i.e. 0.5ns

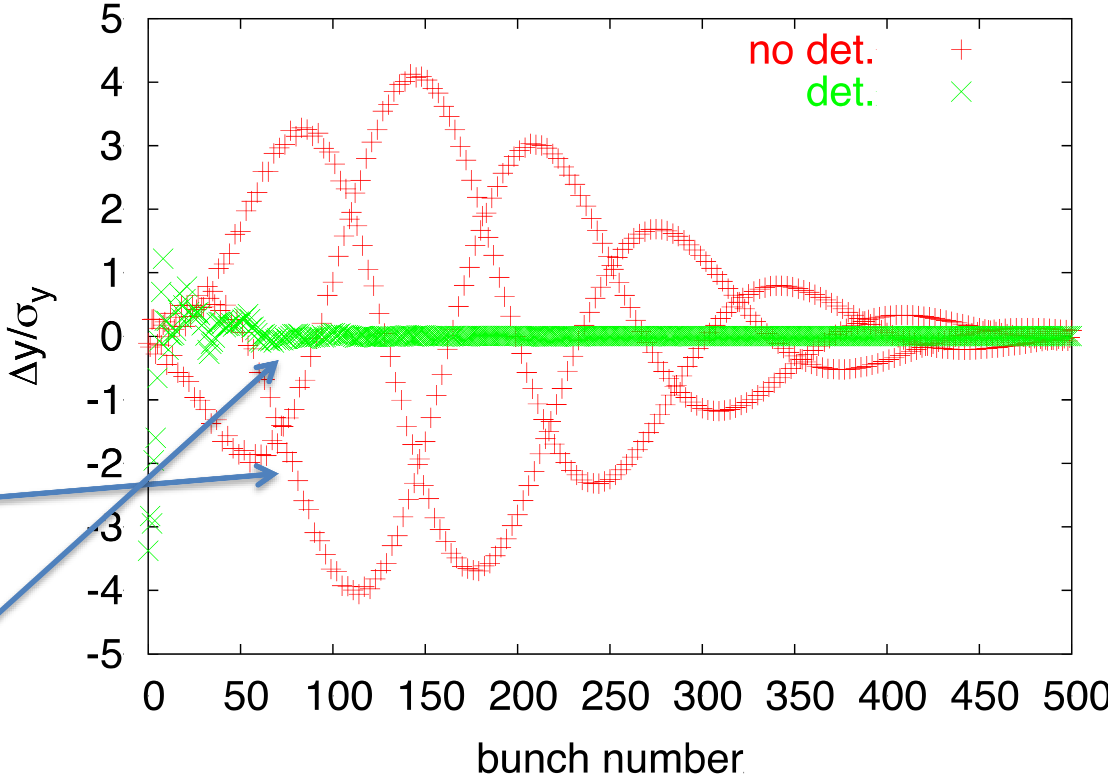
Fully real simulation:
Energy spread stabilises, very acceptable

Multi-bunch effect in ILC

Small wakefield amplitudes

- little damping (Q=O(10^4))
- random detuning cavity to cavity (O(10^{-3}))

Cavity misalignment simulated



No detuning is not acceptable

Residual bunch-to-bunch offsets with detuning
But should be acceptable

Imperfections

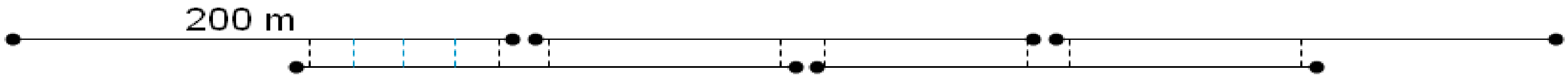
Reminder

Imperfections are the main source of final vertical emittance

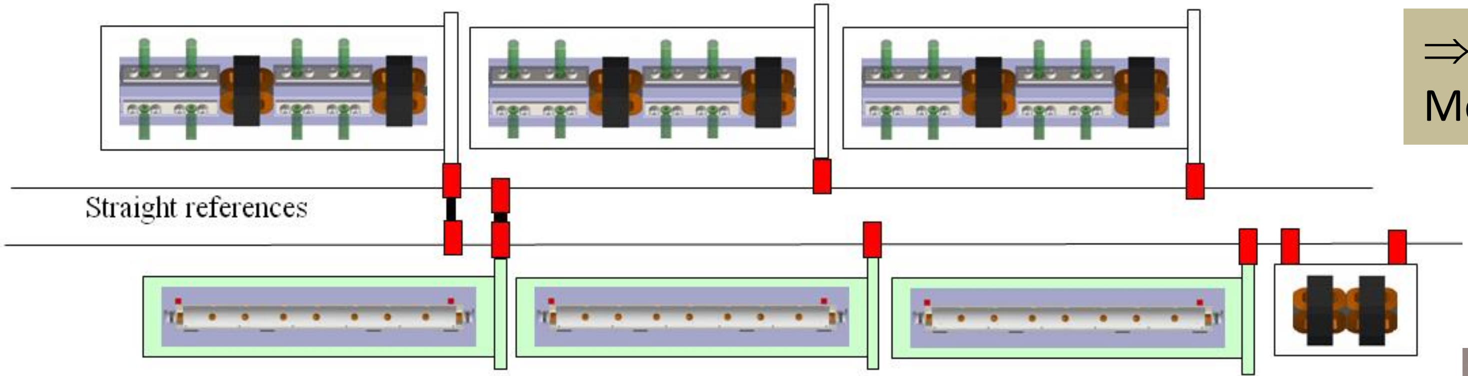
	Design limits $\Delta\varepsilon_y$ [nm]	Static imperfections $\Delta\varepsilon_y$ [nm]	Dynamic imperfections $\Delta\varepsilon_y$ [nm]
Damping ring exit	5	0	0
End of RTML	1	2	2
End of main linac	0	5	5
Interaction point	0	5	5
sum	6	12	12

Discuss them for the main linac as an example

CLIC Pre-alignment Procedures



Establish reference system with overlapping wires, has some error but is not critical



⇒ Dominique Missiaen Monday 5.3

Modules have sensors for wire position and can be moved remotely

The error for this is most critical, required accuracy of reference points is O(10µm)

Pre-alignment Performance

Element	error	with respect to	alignment	
			ILC	CLIC
Structure	offset	Girder	300 μm	5 μm
Structure	tilts	Girder	300 $\mu radian$	200($*$) μm
Girder Girder	offset	survey line	200 μm	9.4 μm
Quadrupole	tilt	survey line	20 $\mu radian$	9.4 $\mu radian$
	offset	girder/survey line	300 μm	17 μm
Quadrupole	roll	survey line	300 $\mu radian$	$\leq$ 100 $\mu radian$
BPM	offset	girder/survey line	300 μm	14 μm
BPM	resolution	BPM	$\approx 1\,\mu m$	0.1 μm
Wakefield mon.	offset	center wake center	—	3.5 μm

Difficult to pre-align components in superconducting module

Important R&D development has been carried out for CLIC

* This is mainly bookshelfing

Emittance Growth (ILC)

Error	with respect to	value	$\Delta\varepsilon_y$ [nm]
Cavity offset	module	300 μm	3.5
Cavity tilt	module	300 μradian	2600
BPM offset	module	300 μm	0
Quadrupole offset	module	300 μm	700000
Quadrupole roll	module	300 μradian	2.2
Module offset	perfect line	200 μm	250000
Module tilt	perfect line	20 μradian	880

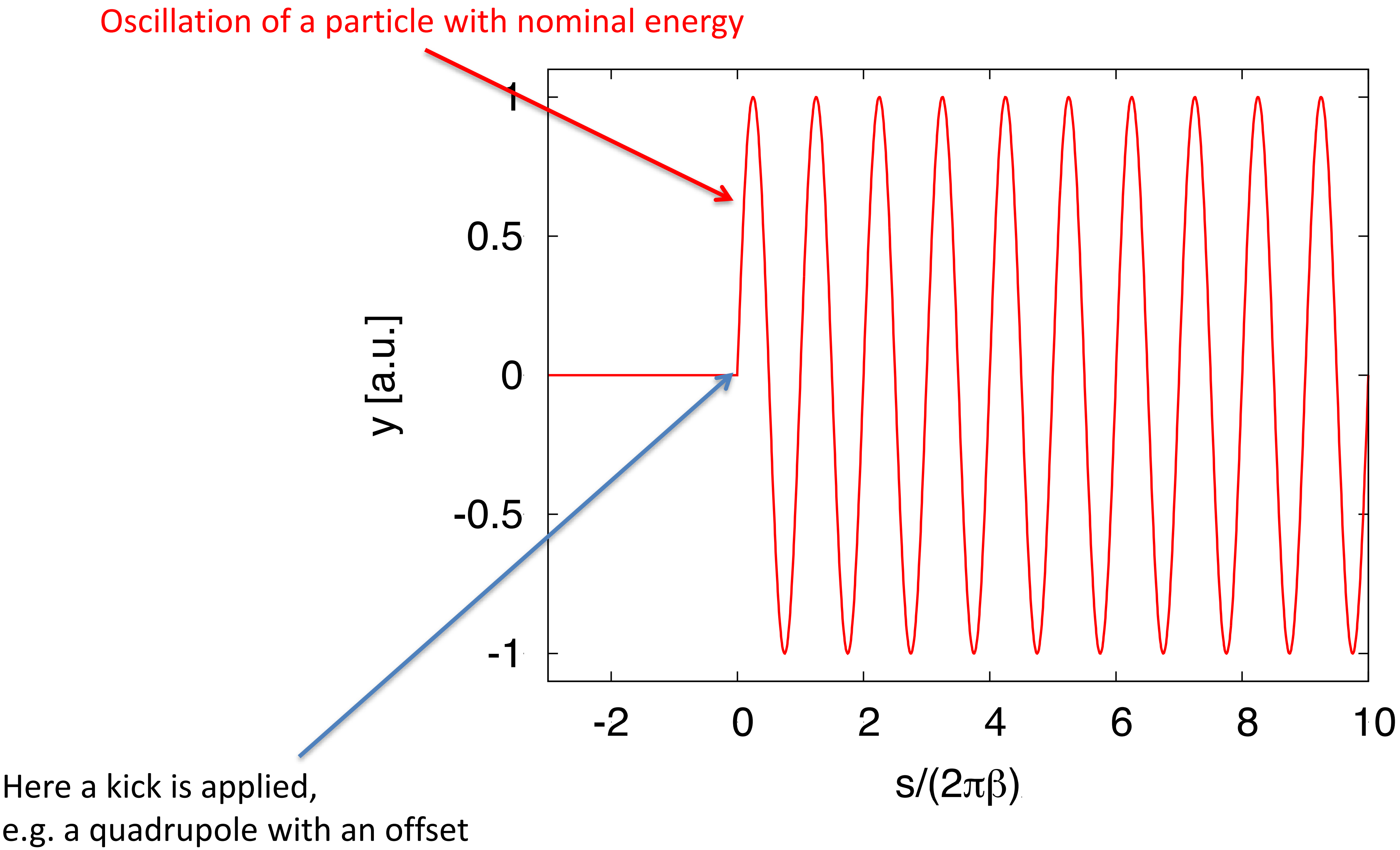
Largest problem
quadrupole
offsets

Cavity tilts are important
Beam is kicked by accelerating field

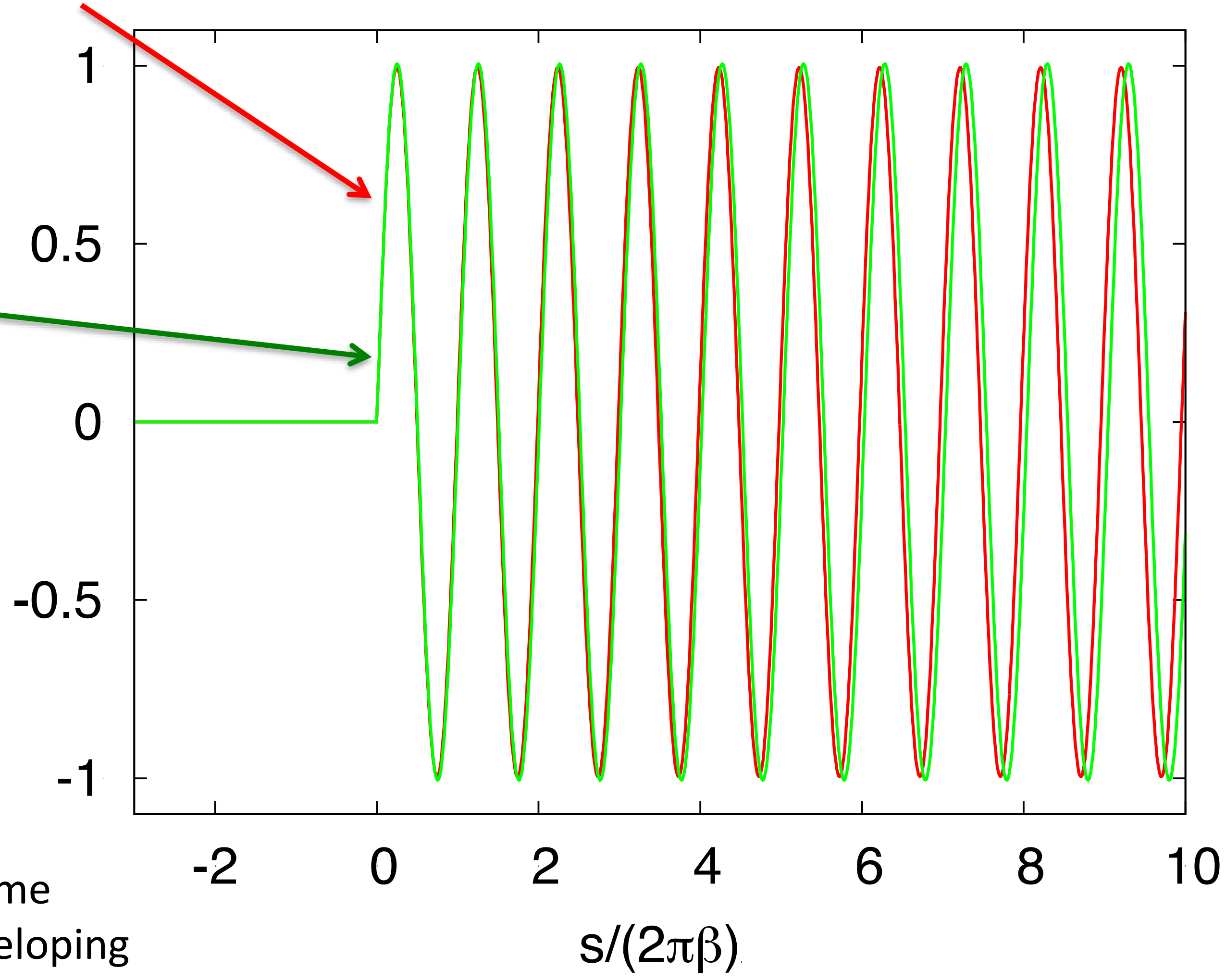
Module angles lead to cavity tilts

Module offset
offsets
quadrupole

Dispersion and Emittance Growth



Dispersion and Emittance Growth

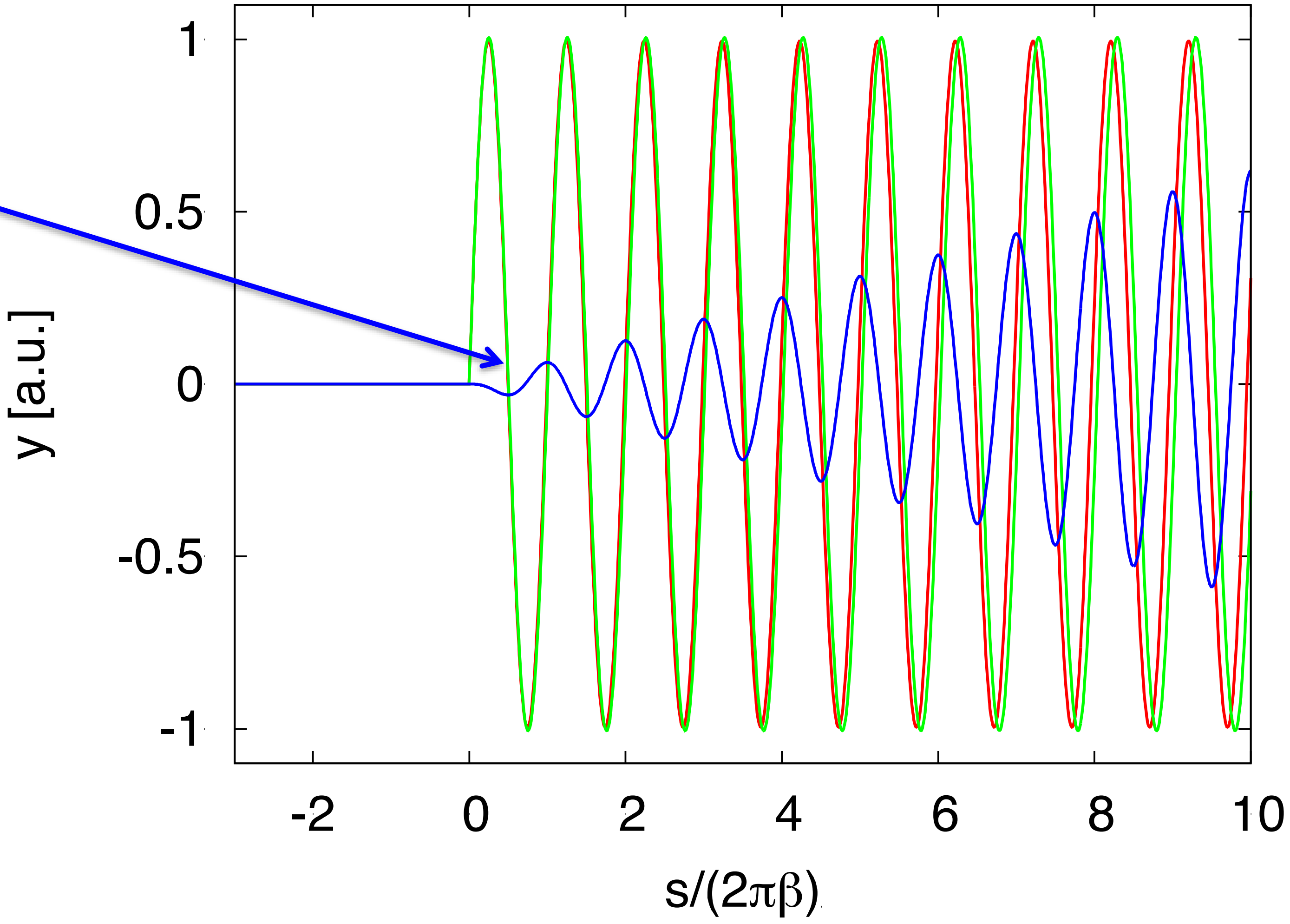


Oscillation of a particle with 100.5 % of nominal energy

Oscillation of a particle with
99.5% of nominal energy

Amplitude is almost the same
But slight dephasing is developing

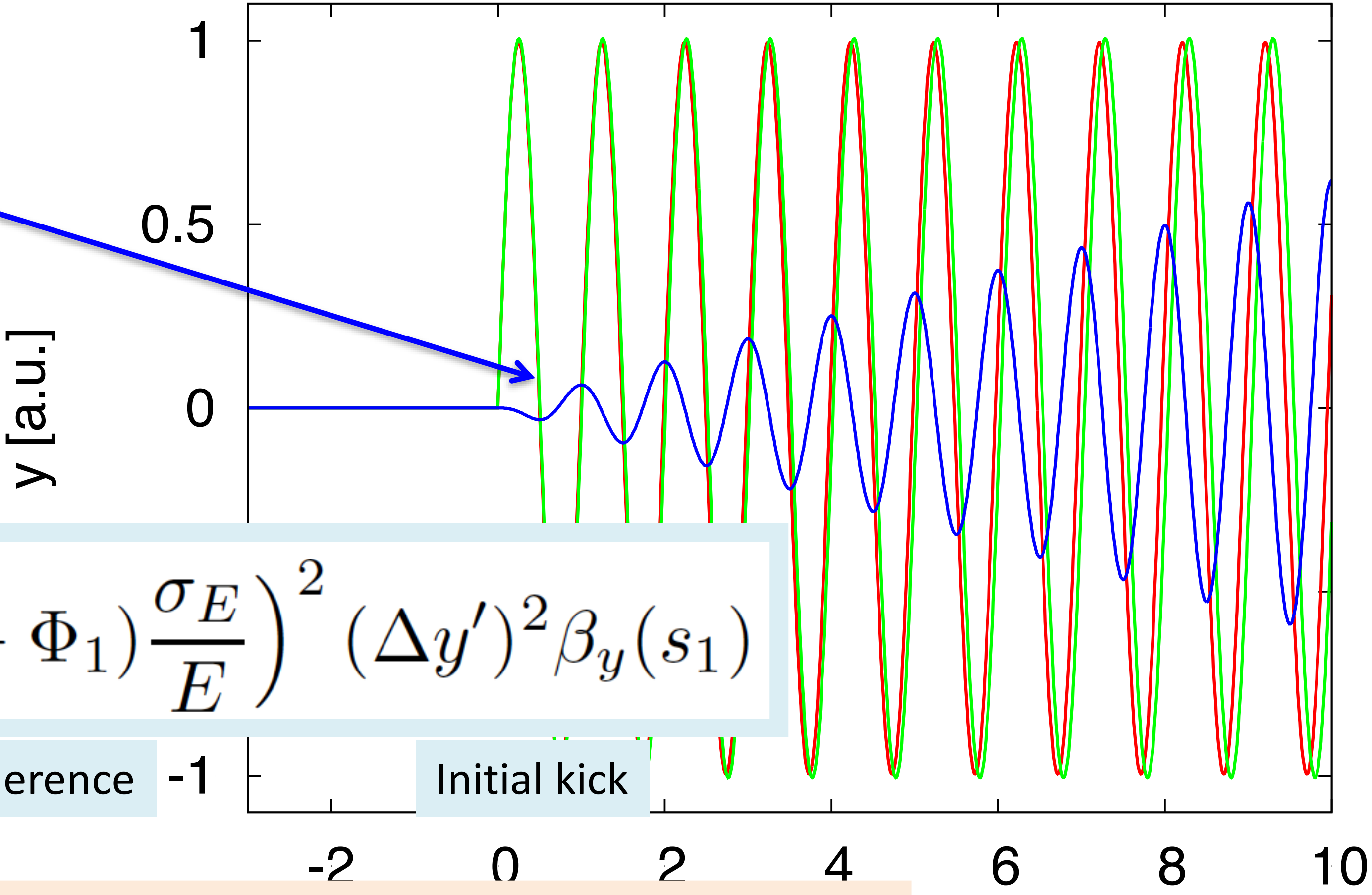
Dispersion and Emittance Growth



Difference between trajectories grows along accelerator

Dispersion and Emittance Growth

Difference between trajectories grows along accelerator



Emittance grows as

$$\Delta\epsilon_1 \propto \left((\Phi_e - \Phi_1)\frac{\sigma_E}{E}\right)^2 (\Delta y')^2 \beta_y(s_1)$$

Decoherence

Initial kick

For long linacs

$$\Delta\epsilon_1 \propto (\Delta y')^2 \beta_y(s_1)$$

Beam-based Alignment and Tuning

- Make beam pass linac by aligning quadrupoles
  - one-to-one correction

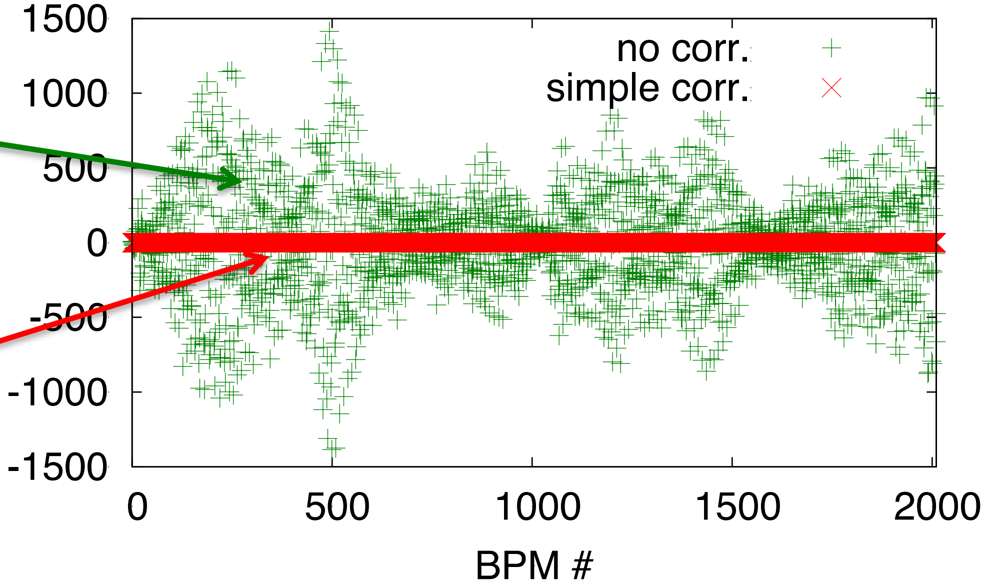
- Remove dispersion by aligning BPMs and quadrupoles
  - dispersion free steering
  - Ballistic alignment
  - kick minimisation

- Remove wakefields locally (CLIC only)
  - RF alignment

- Remove dispersive and wakefield effects globally
  - Emittance tuning bumps
  - Luminosity tuning bumps

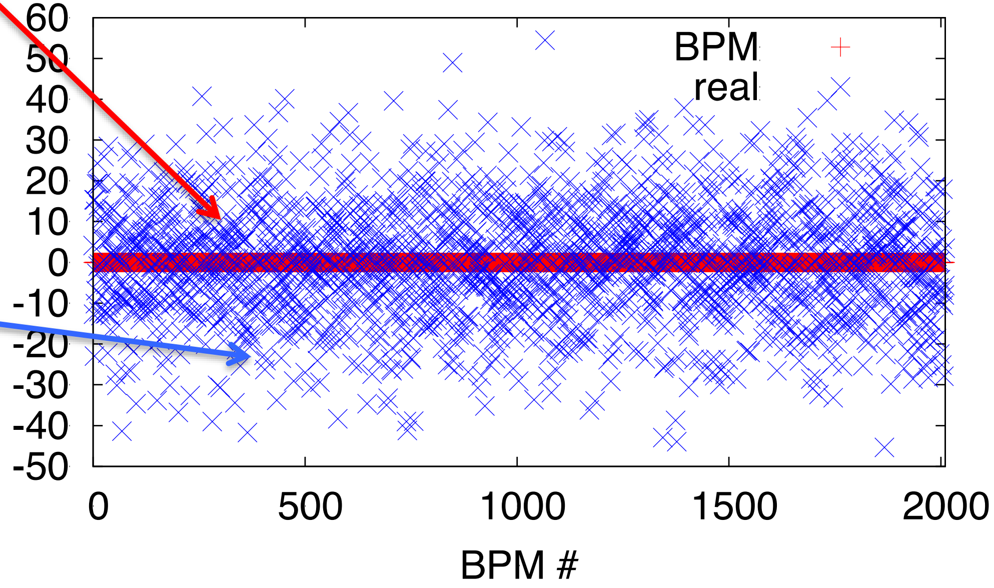
Trajectory with Simple Correction

BPM readings if no beam-based correction is applied



After one-to-one correction all BPMs read zero

But beam still is offset, because BPMs have offsets

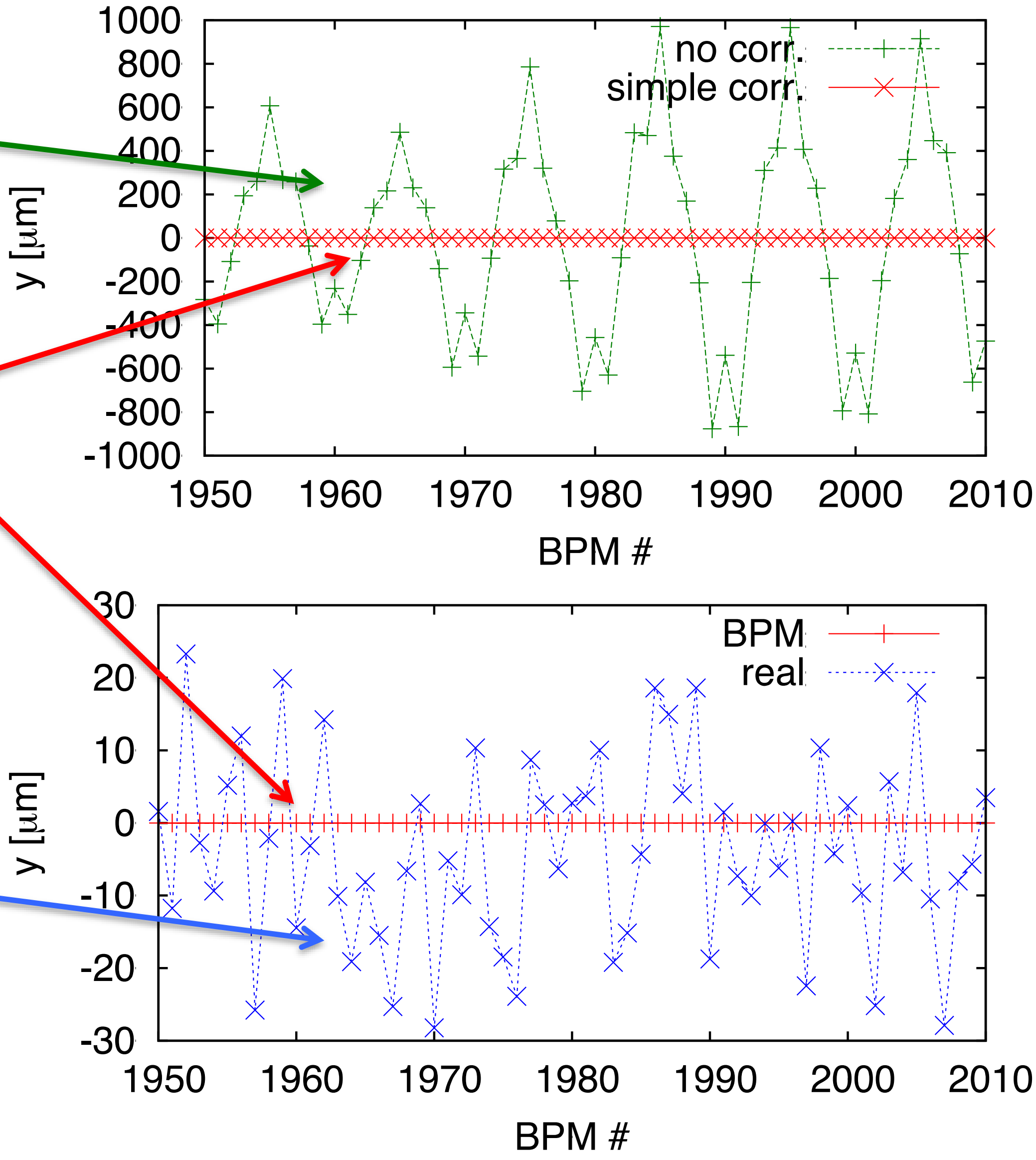


Trajectory at the End of the Linac

With no correction, at the end of the linac beam performs betatron oscillation

After one-to-one correction all BPMs read zero

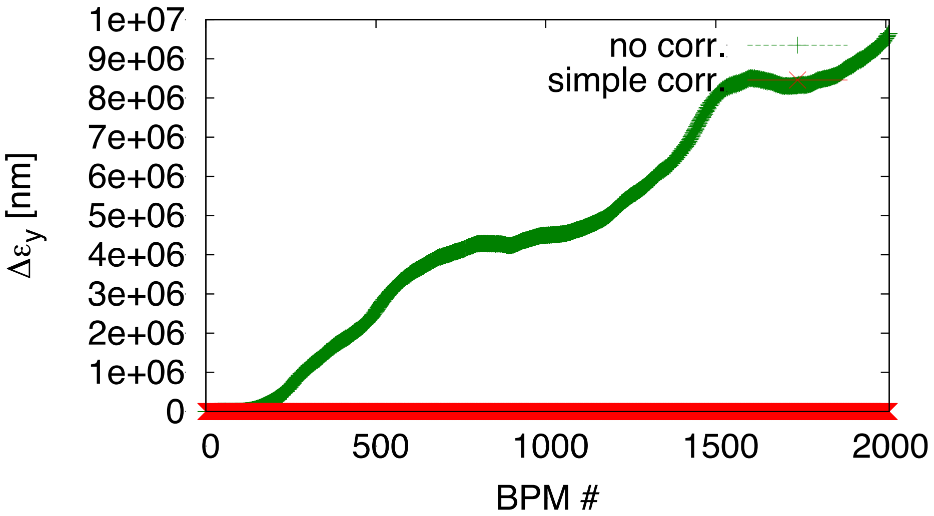
No betatron oscillation has been build-up if we use one-to-one correction



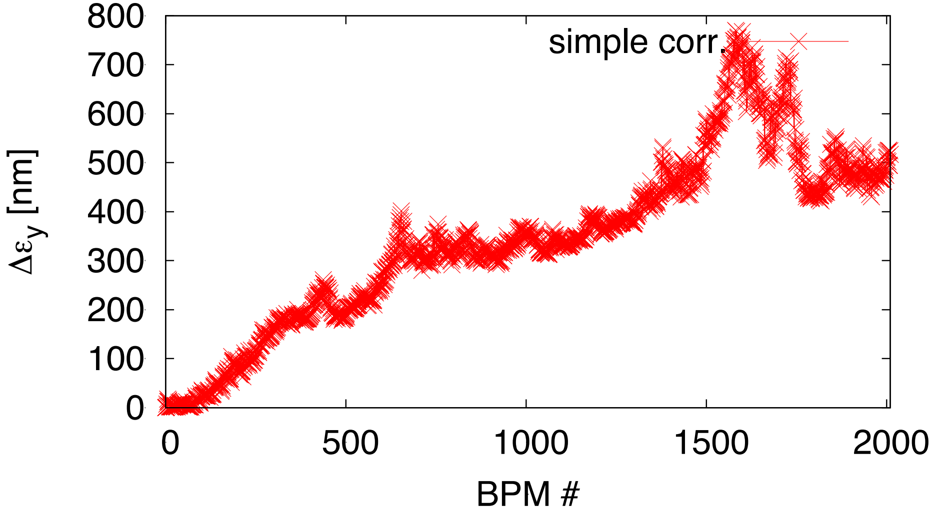
Emittance Growth

The emittance growth with no correction is very large

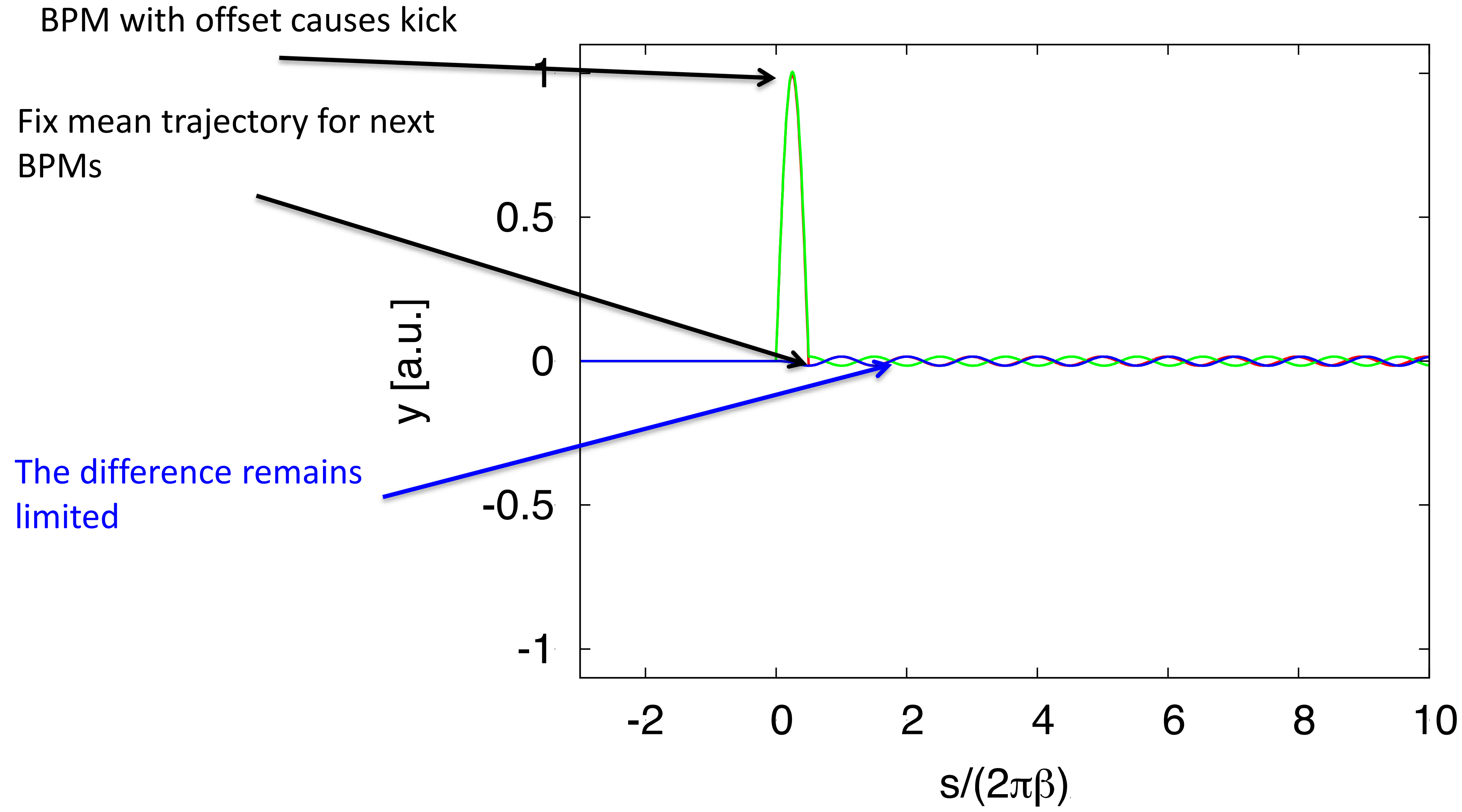
The simple steering yields many orders of magnitude improvement



But still the emittance growth is far above the target



Dispersion and Emittance Growth

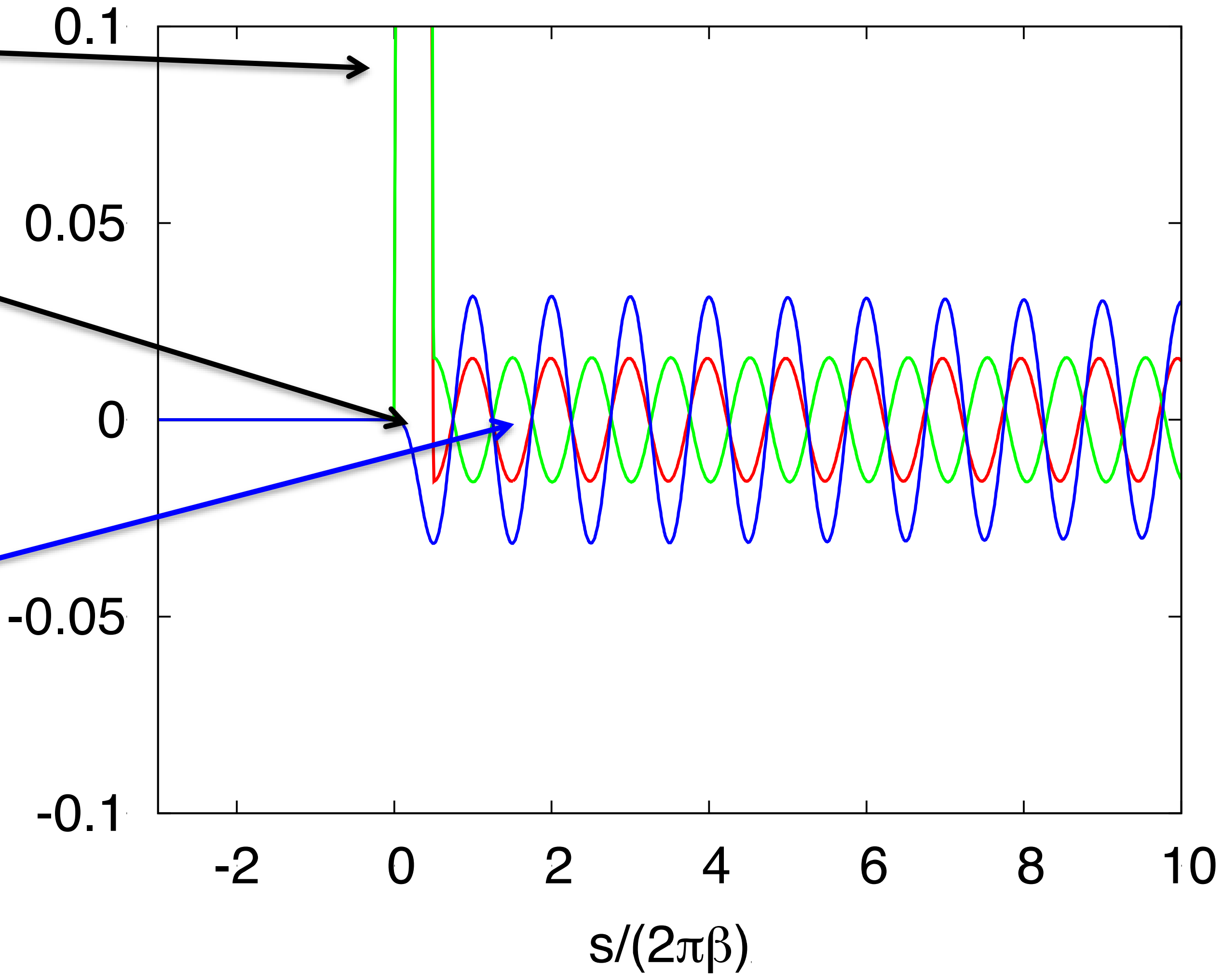


BPM with offset causes kick

Fix mean trajectory for next BPMs

The difference remains limited

Dispersion and Emittance Growth



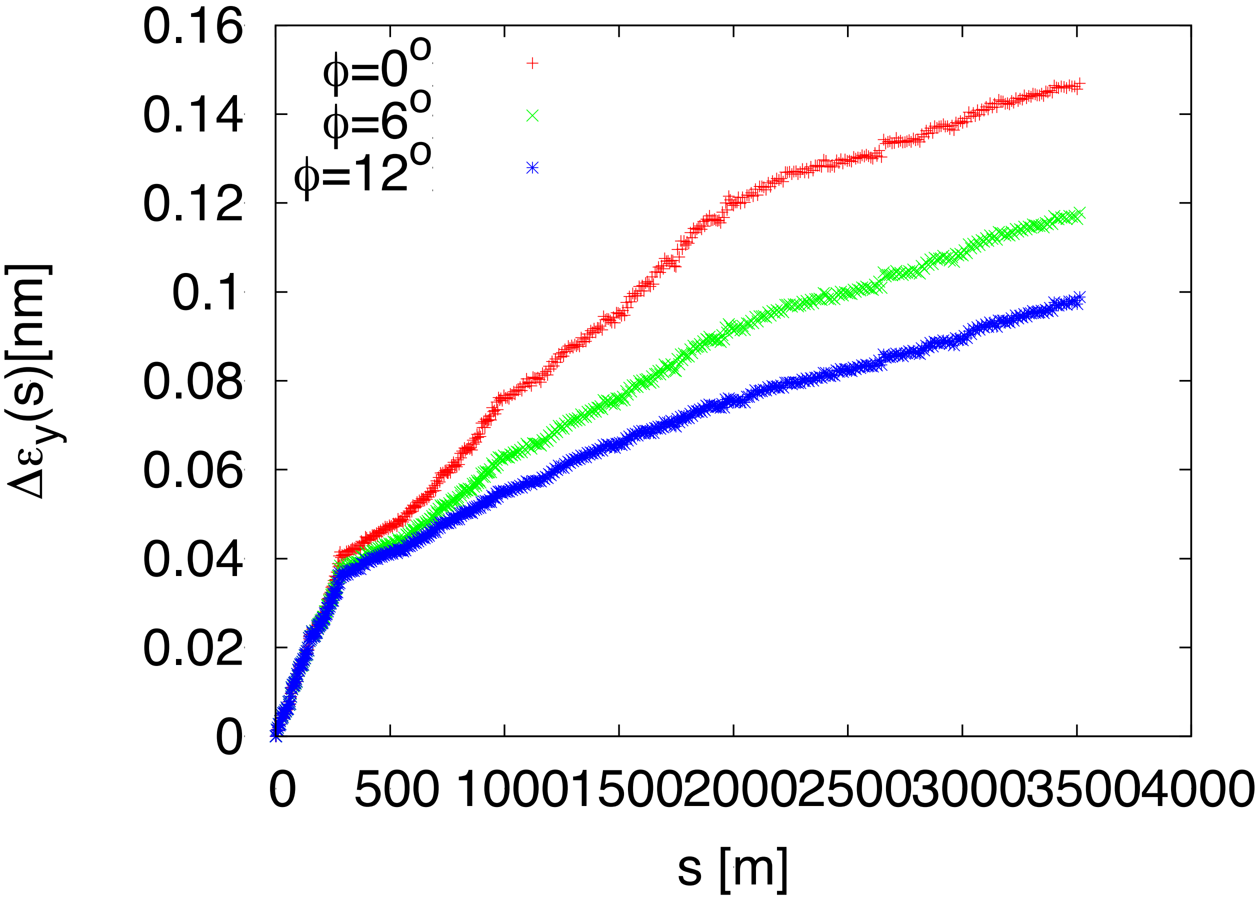
BPM with offset causes kick

Fix mean trajectory for next BPMs

The difference remains limited

Illustration: BPM Misalignment (CLIC 380 GeV)

Larger energy spread makes us more sensitive to BPM misalignments



Emittance Growth after One-to-one Steering (ILC)

Error	with respect to	value	$\Delta\varepsilon_y$ [nm]	$\Delta\varepsilon_{y,121}$ [nm]
Cavity offset	module	300 μm	3.5	0.2
Cavity tilt	module	300 μradian	2600	< 0.1
BPM offset	module	300 μm	0	360
Quadrupole offset	module	300 μm	700000	0
Quadrupole roll	module	300 μradian	2.2	2.2
Module offset	perfect line	200 μm	250000	155
Module tilt	perfect line	20 μradian	880	1.7

Quadrupole issue solved

BPM issue created
Module offset leads to BPM offset

Still much better than before

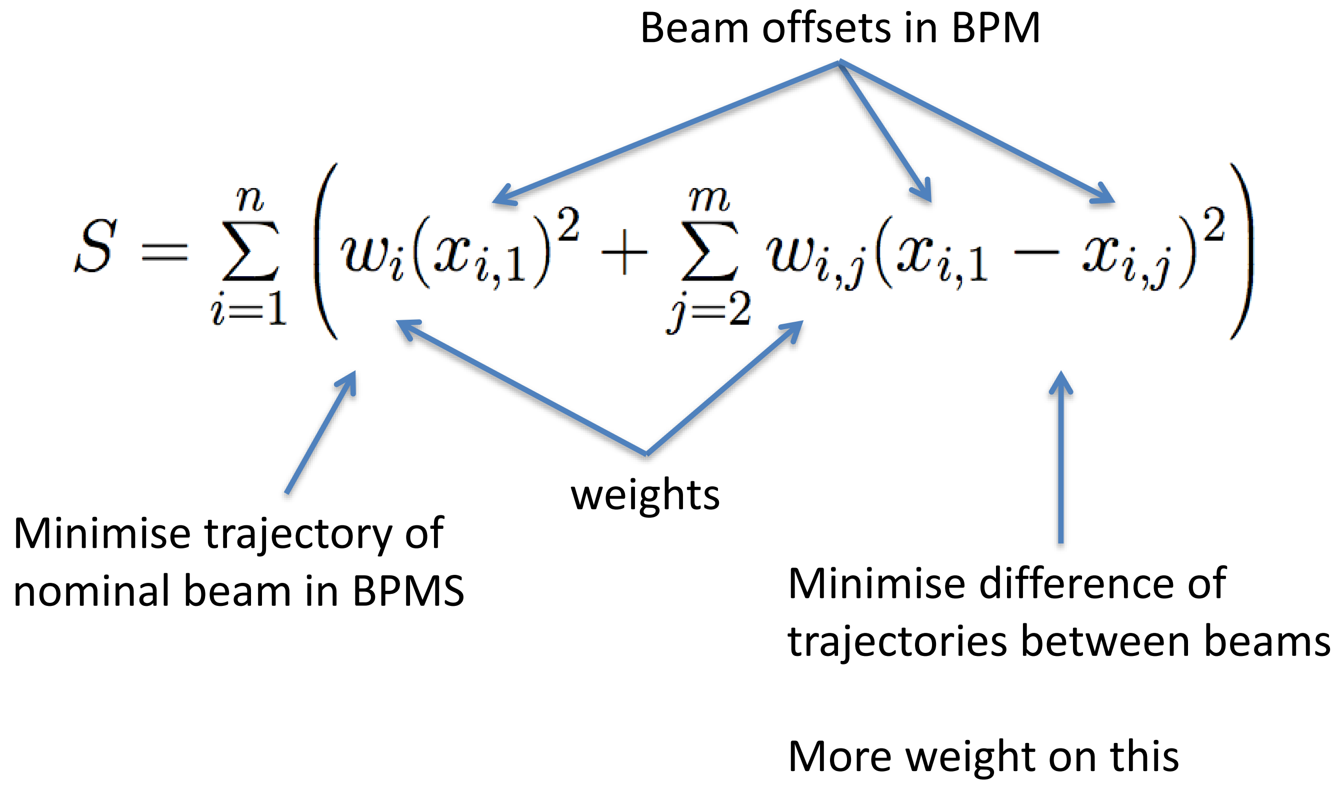
Note:
Emittance should scale as

$$\Delta\epsilon \propto (\Delta y)^2$$

✓

Dispersion Free Steering

- Basic idea: use different beam energies
- Accelerate beams with different gradient and initial energy
- Optimise trajectories for different energies together



Beam offsets in BPM

$$S = \sum_{i=1}^{n} \left(w_i (x_{i,1})^2 + \sum_{j=2}^{m} w_{i,j} (x_{i,1} - x_{i,j})^2 \right)$$

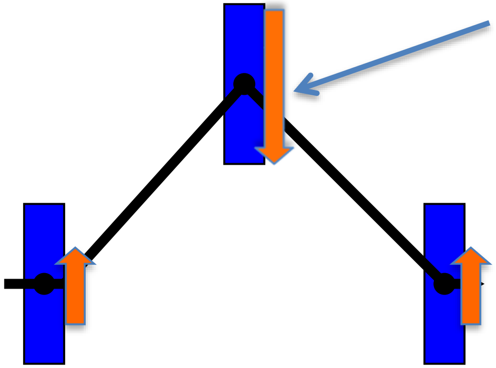
weights

Minimise trajectory of nominal beam in BPMS

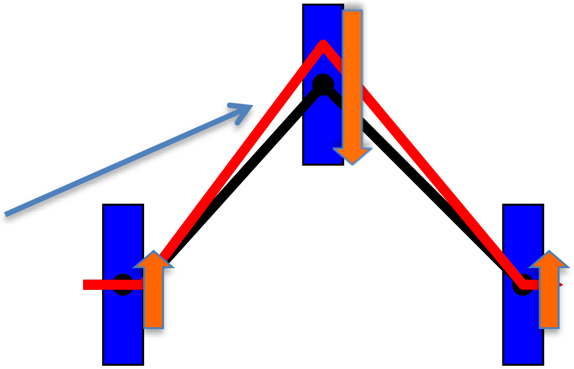
Minimise difference of trajectories between beams

More weight on this

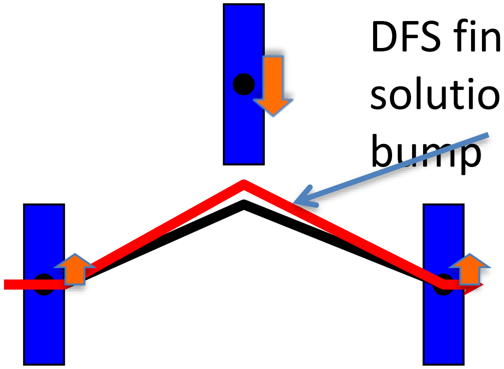
Dispersion Free Illustration



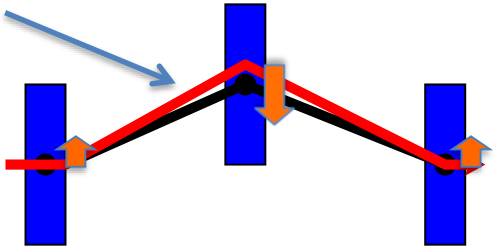
Offset BPM produces bump



Off-energy beam has different bump



DFS finds new solution with smaller bump

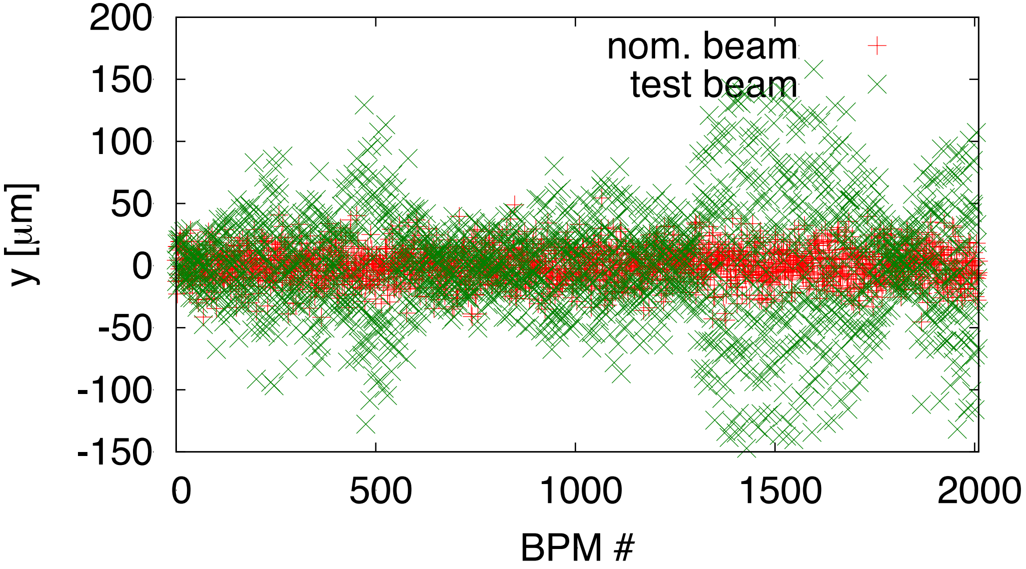


Adjust BPM reference to be on new trajectory

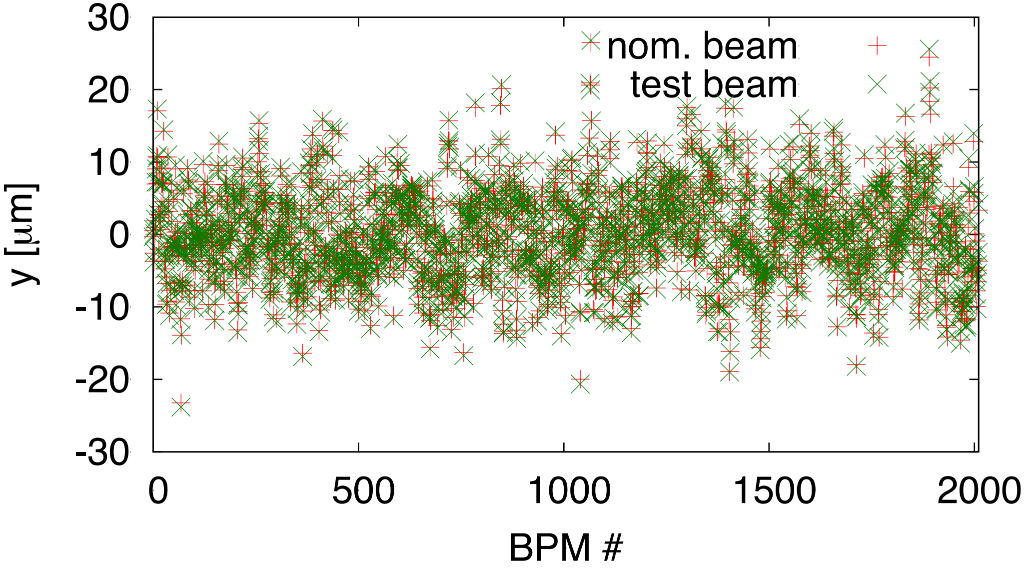
Dispersion Free Steering BPM Readings

A beam that has a different energy has a bad trajectory

The cancellation of different corrector kicks does not work very well because the phase advance is different for different energies

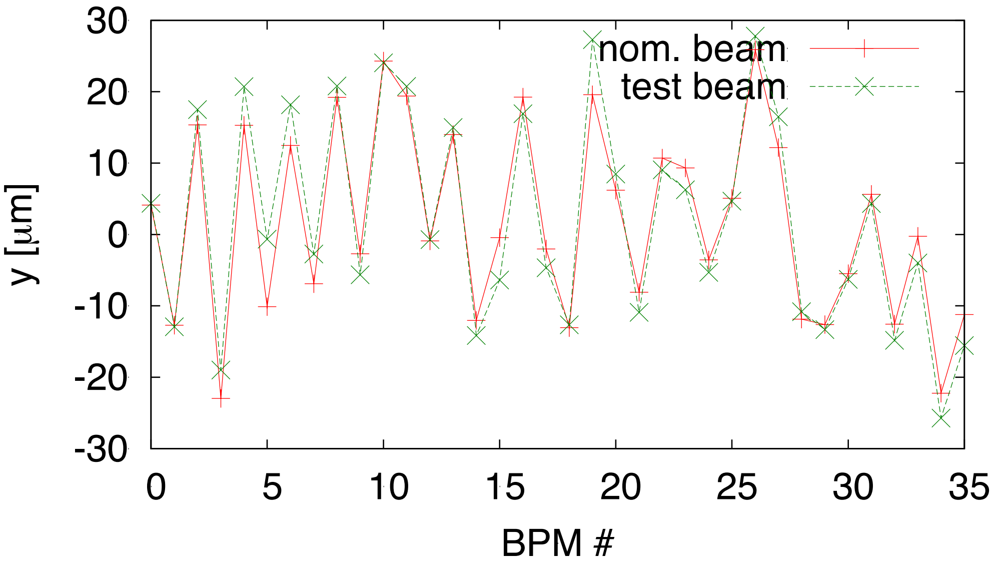


After dispersion free steering both beams take almost the same path

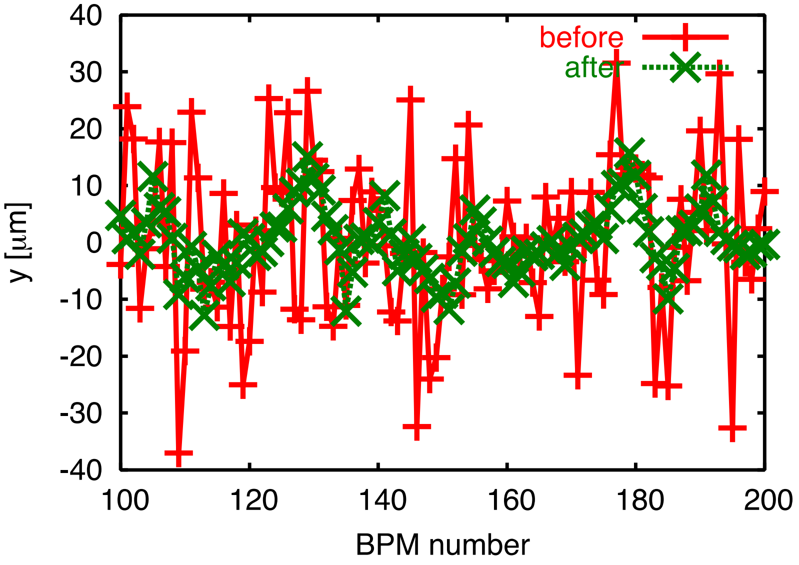


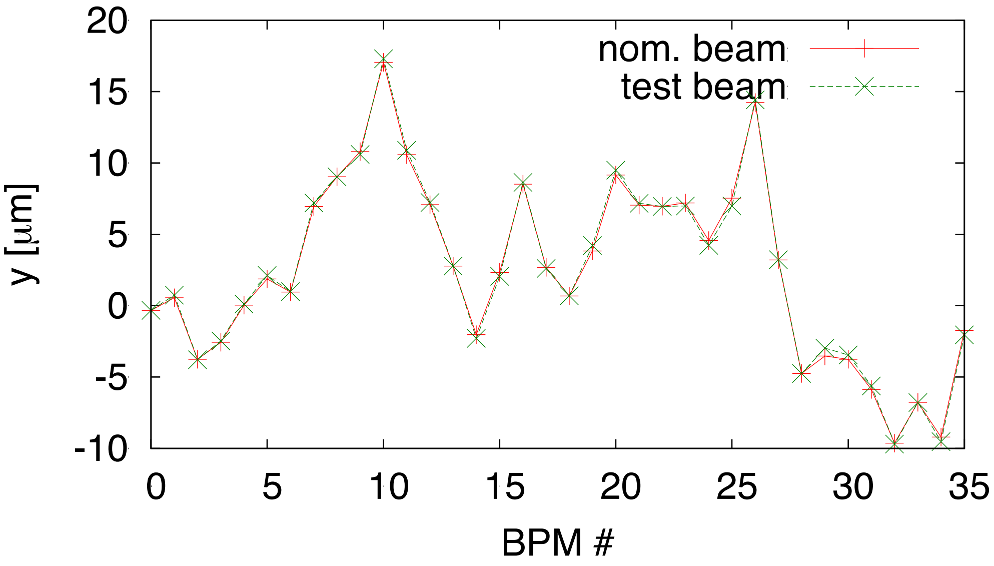
At the Beginning of the Linac

A small difference in trajectories starts between the two beams



The dispersion free steering almost completely removes this difference





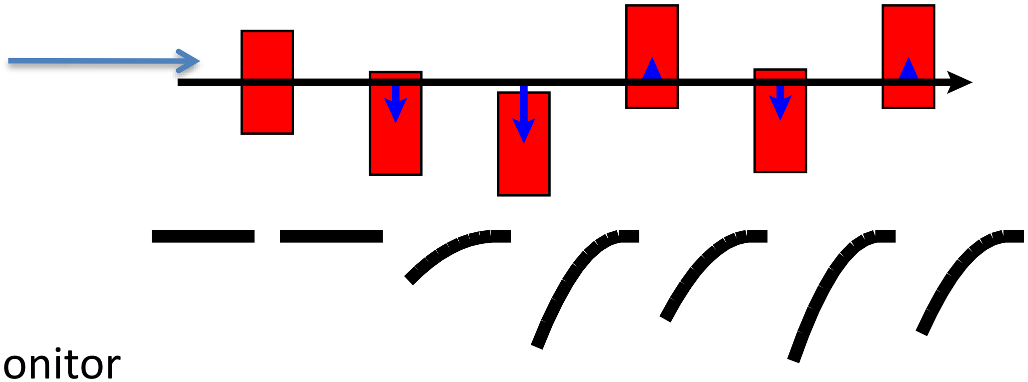
Resulting Emittance Growth (ILC)

Error	with respect to	value	$\Delta\varepsilon_y$ [nm]	$\Delta\varepsilon_{y,121}$ [nm]	$\Delta\varepsilon_{y,dfs}$ [nm]
Cavity offset	module	300 μm	3.5	0.2	0.2(0.2)
Cavity tilt	module	300 μradian	2600	< 0.1	1.8(8)
BPM offset	module	300 μm	0	360	4(2)
Quadrupole offset	module	300 μm	700000	0	0(0)
Quadrupole roll	module	300 μradian	2.2	2.2	2.2(2.2)
Module offset	perfect line	200 μm	250000	155	2(1.2)
Module tilt	perfect line	20 μradian	880	1.7	—

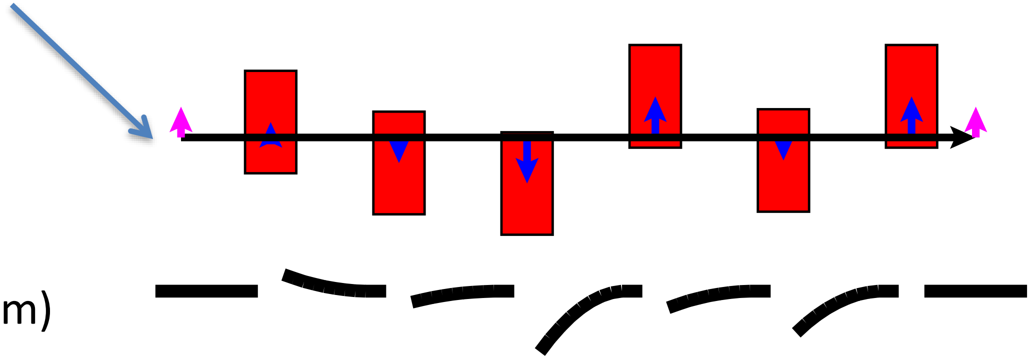
Dispersion free steering largely cures the BPM offset issue

RF Structure Alignment

Structures are scattered on the girder
⇒ Wakefield kick



Measure beam offset with wakefield monitor
Move girder to remove mean offset
⇒ No net wakefield kick

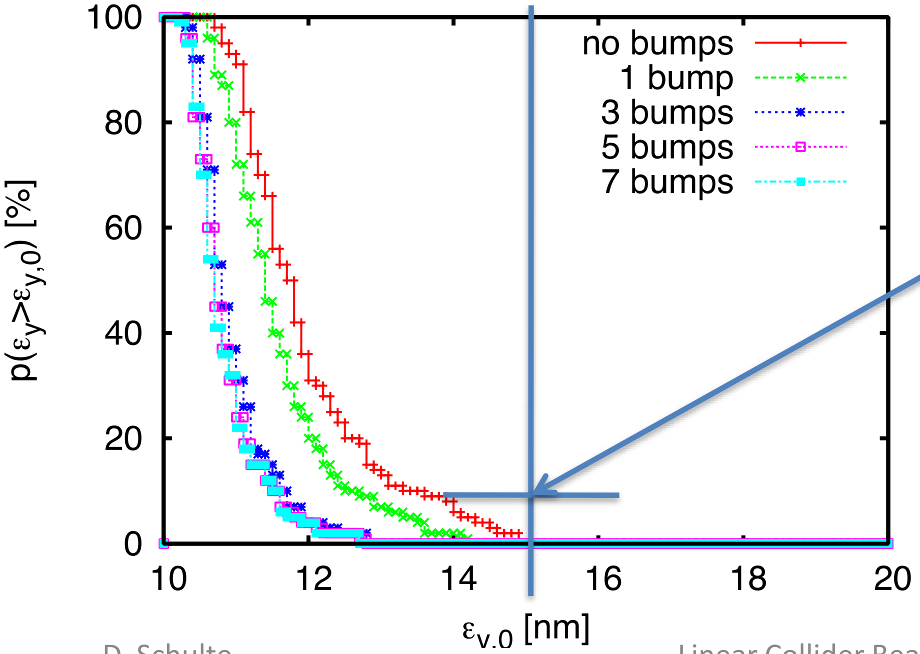


Limit mainly from

- accuracy of wakefield monitors (3.5 μm)
- reproducibility of wakefield
- tiny variation of betatron phase along girder

Final Emittance Growth (CLIC 3 TeV)

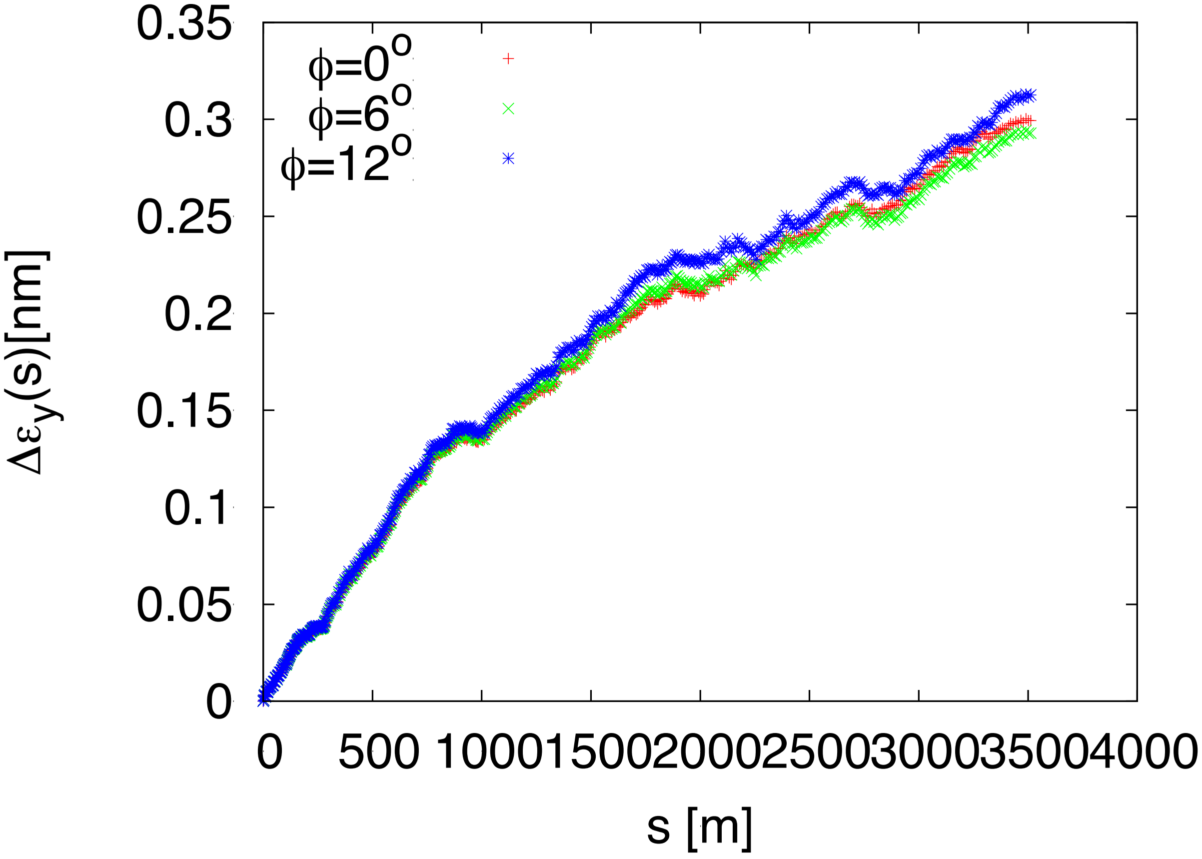
imperfection	with respect to	symbol	value	emitt. growth
BPM offset	wire reference	σ_{BPM}	14 μm	0.367 nm
BPM resolution		σ_{res}	0.1 μm	0.04 nm
accelerating structure offset	girder axis	σ_4	10 μm	0.03 nm
accelerating structure tilt	girder axis	σ_t	200 μradian	0.38 nm
articulation point offset	wire reference	σ_5	12 μm	0.1 nm
girder end point	articulation point	σ_6	5 μm	0.02 nm
wake monitor	structure centre	σ_7	3.5 μm	0.54 nm
quadrupole roll	longitudinal axis	σ_r	100 μradian	$\approx$ 0.12 nm



Goal: less than 10% above 15 nm ✓

Further improvement using tuning bumps

Illustration: Structure Misalignment (CLIC 380 GeV)



Almost not sensitive to energy spread

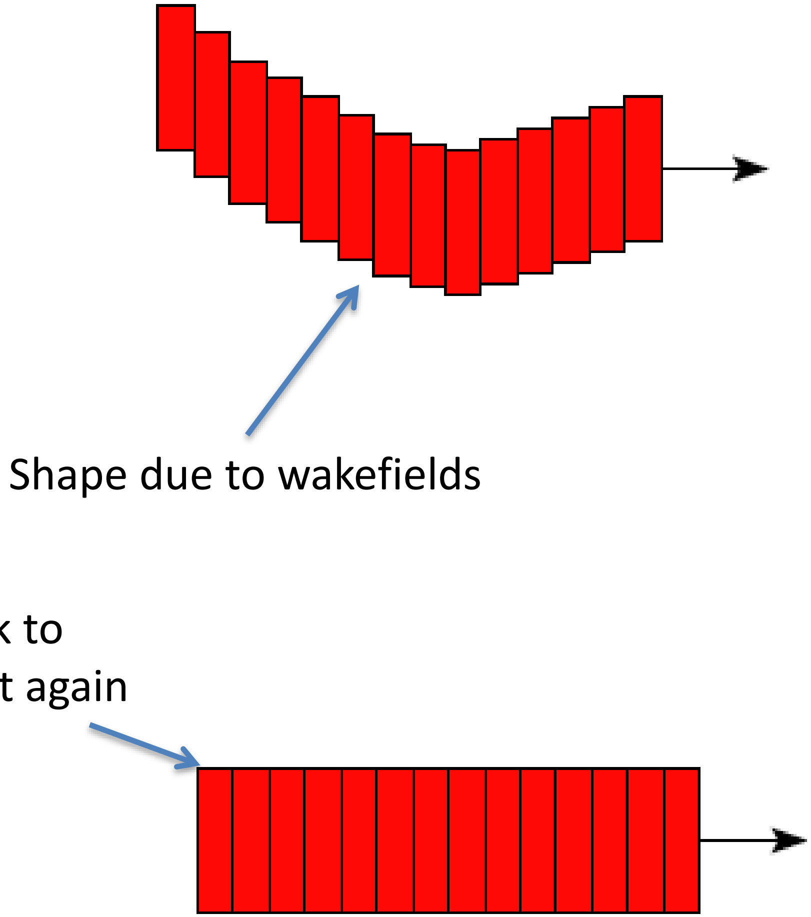
Tuning Bumps

Compensate an effect globally

Minimise beam size/emittance
or maximise luminosity

Remove a correlation between particles
e.g. average wakefield kick can be
compensated in one location

Energy spread and phase advance give limits

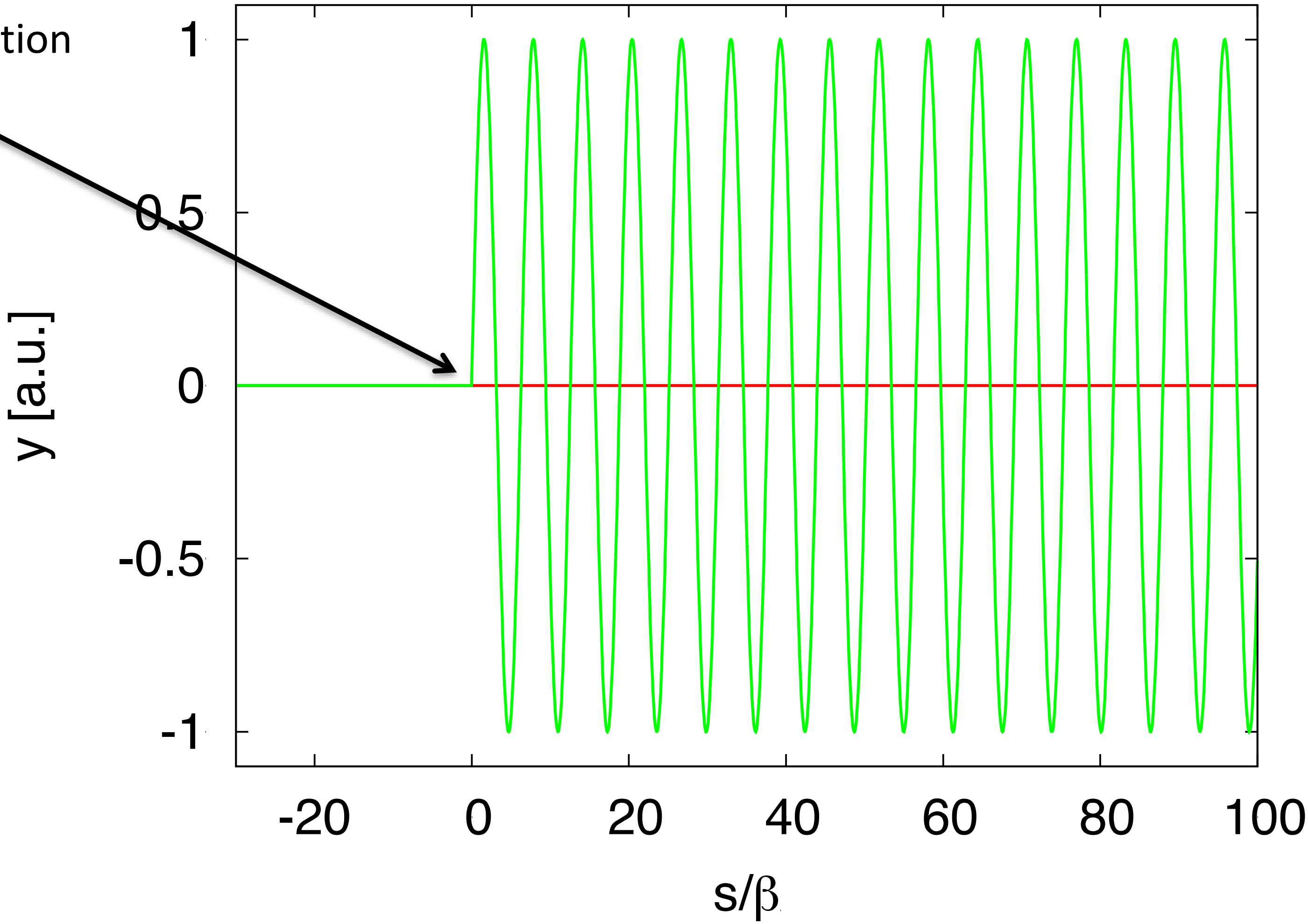


Shape due to wakefields

Apply wakefield kick to
make bunch straight again

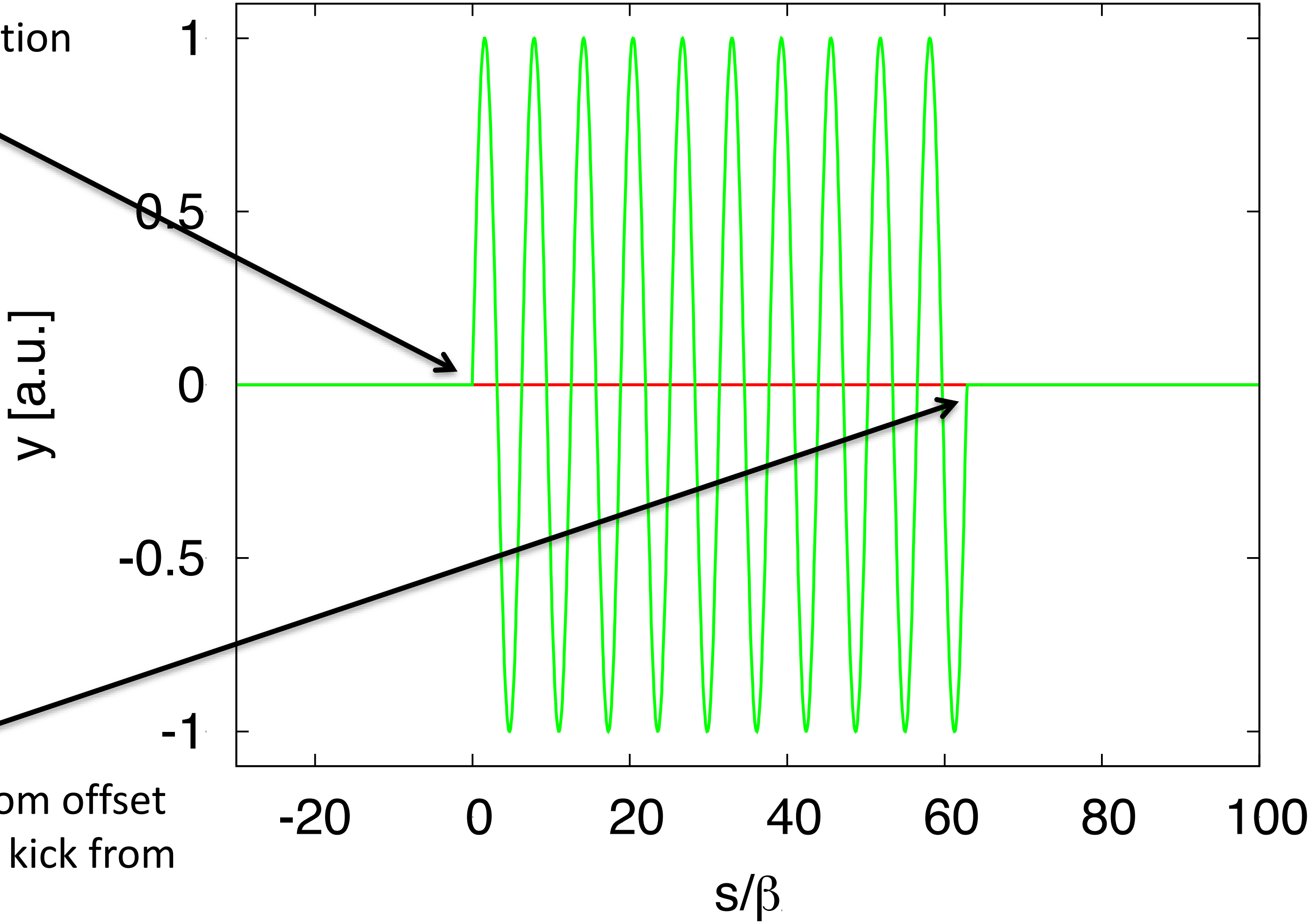
Simple Wakefield Model

Wakefield kick from offset structure
First particle is not kicked
Second starts and oscillation



Simple Wakefield Bump Model

Wakefield kick from offset structure
First particle is not kicked
Second starts and oscillation

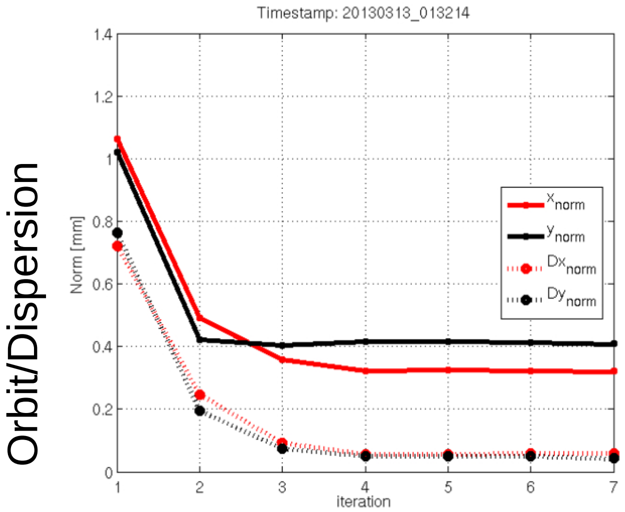


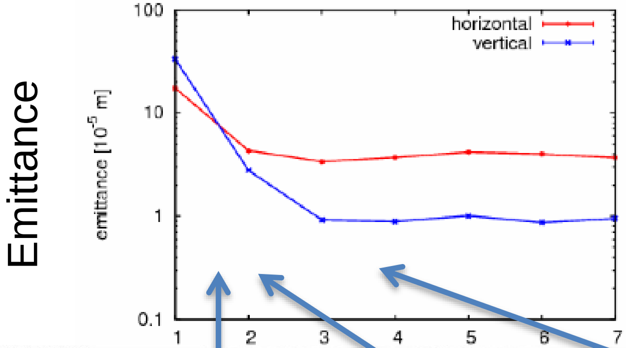
Second wakefield kick from offset
Happens to compensate kick from first one

CLIC Beam-Based Alignment Tests at FACET

Dispersion-free Steering (DFS) proof of principle – March 2013

A. Latina,
J. Pfingstner,
E. Adli,
D. Schulte

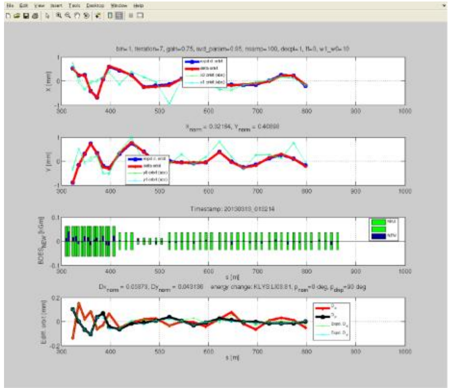


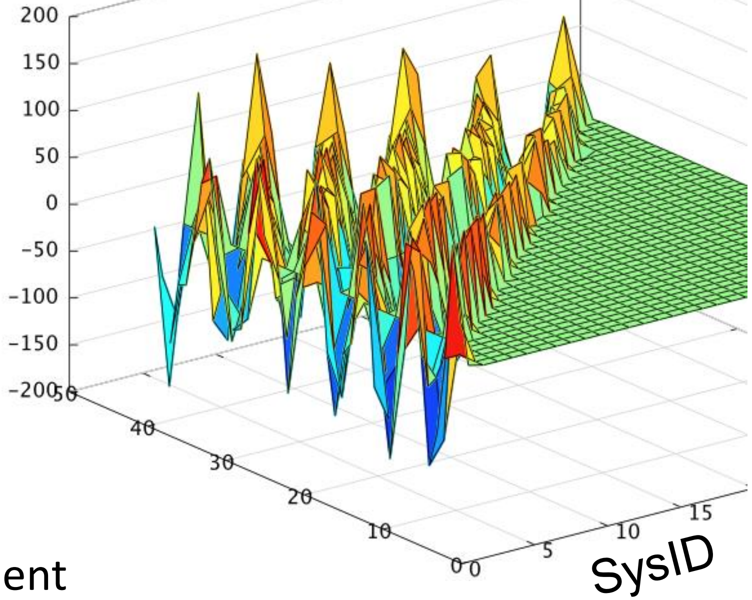


DFS correction applied to 500 meters of the SLC linac

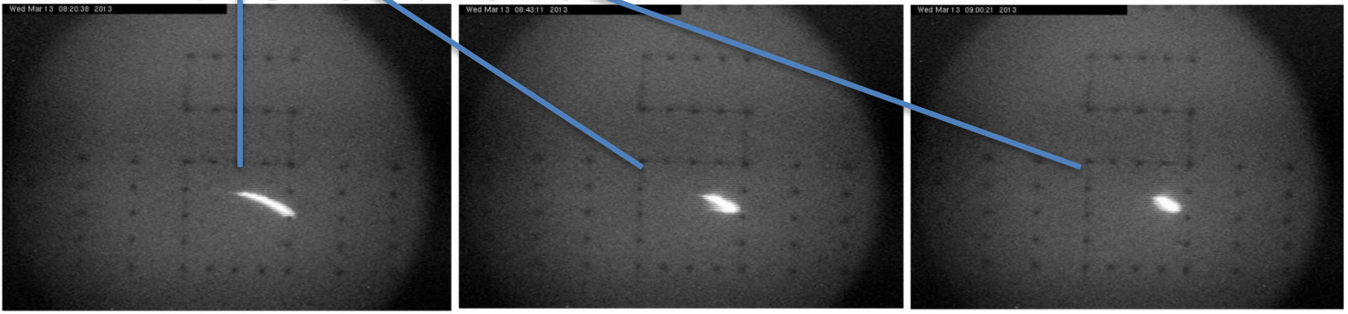
- SysID algorithms for model reconstruction
- DFS correction with GUI
- Emittance growth is measured

Graphic User Interface:





Beam profile measurement



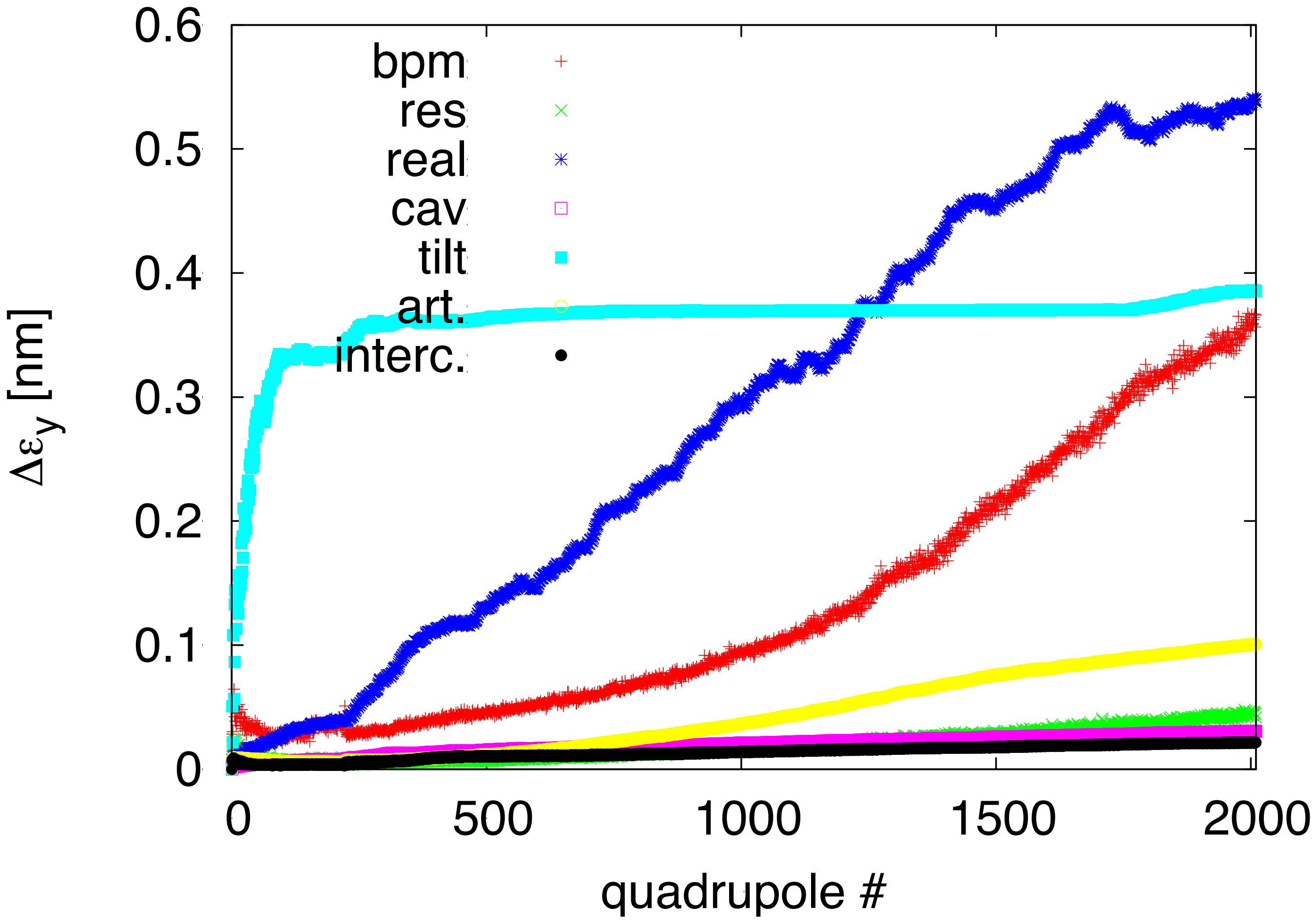
Before correction

After 1 iteration

After 3 iterations

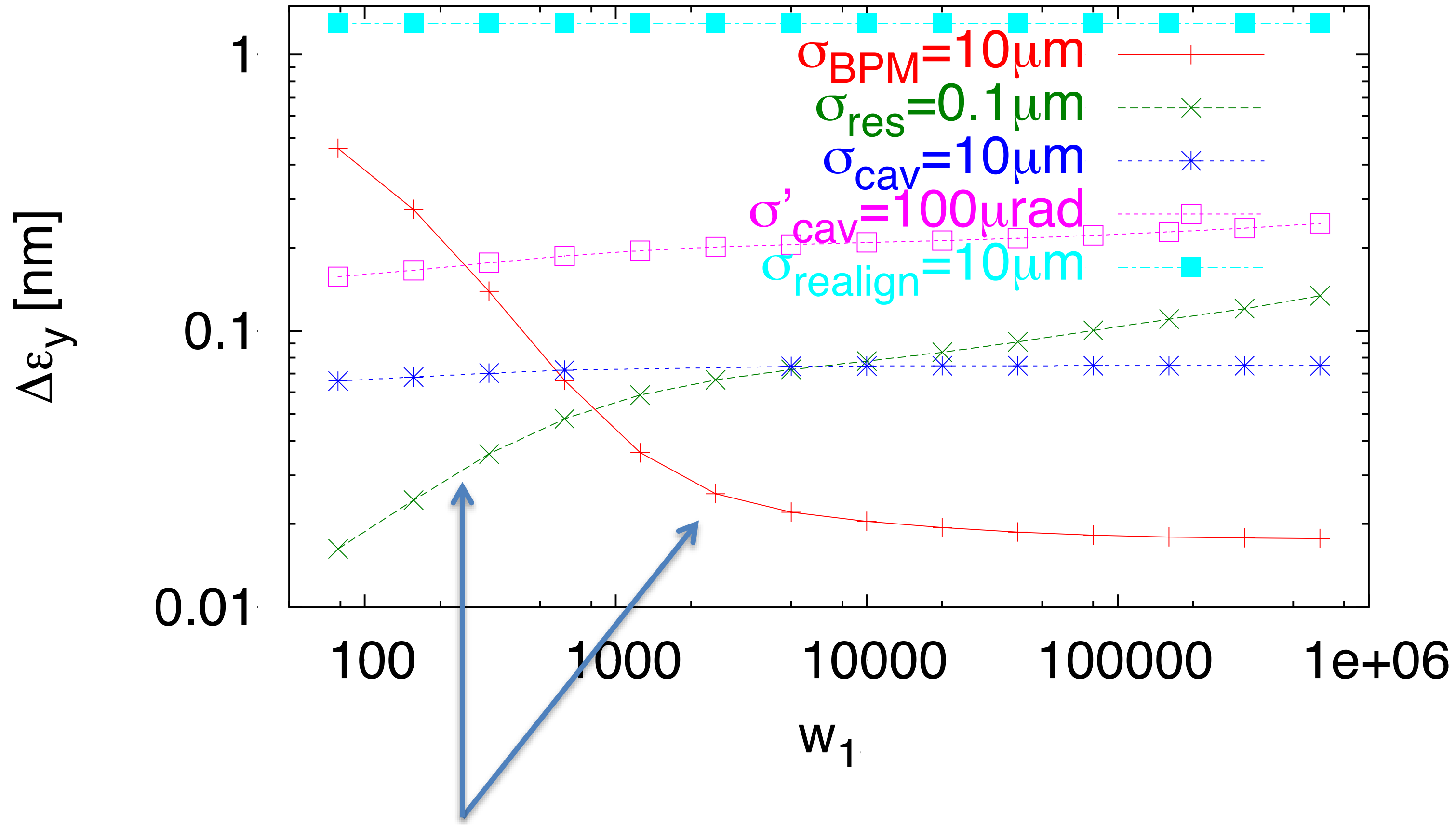
Incoming oscillation/dispersion is taken out and flattened; emittance in LI11 and emittance growth significantly reduced.

Note: Emittance Along Linac (CLIC 3 TeV)



Note: Choice of Weights

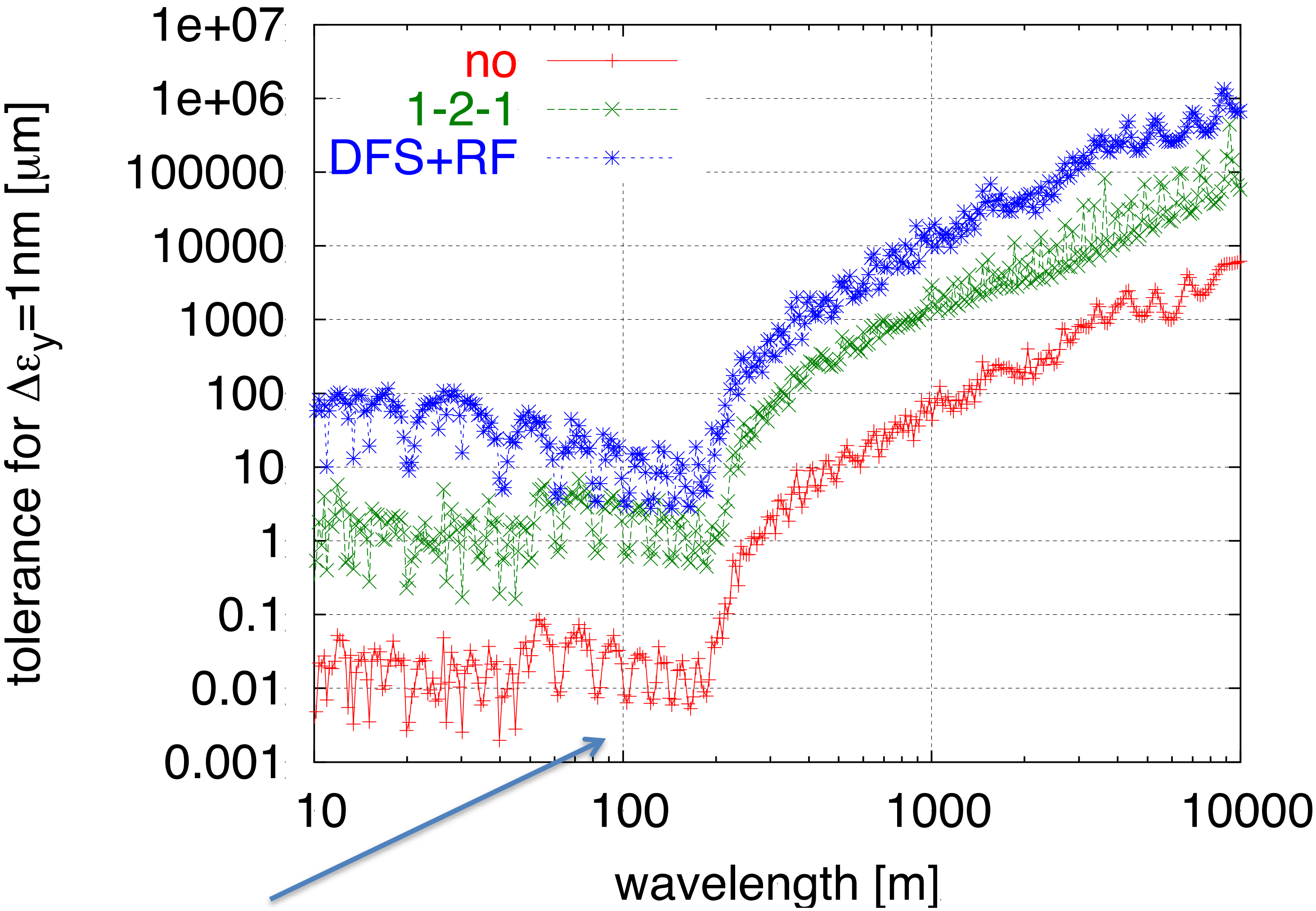
For some old CLIC design



Main trade-off is for BPM offset and resolution

Note: Emittance and Wavelength

Reference line error with given wavelength



Betatron wavelengths of the different sectors

Dynamic Imperfections

Dynamic Imperfections

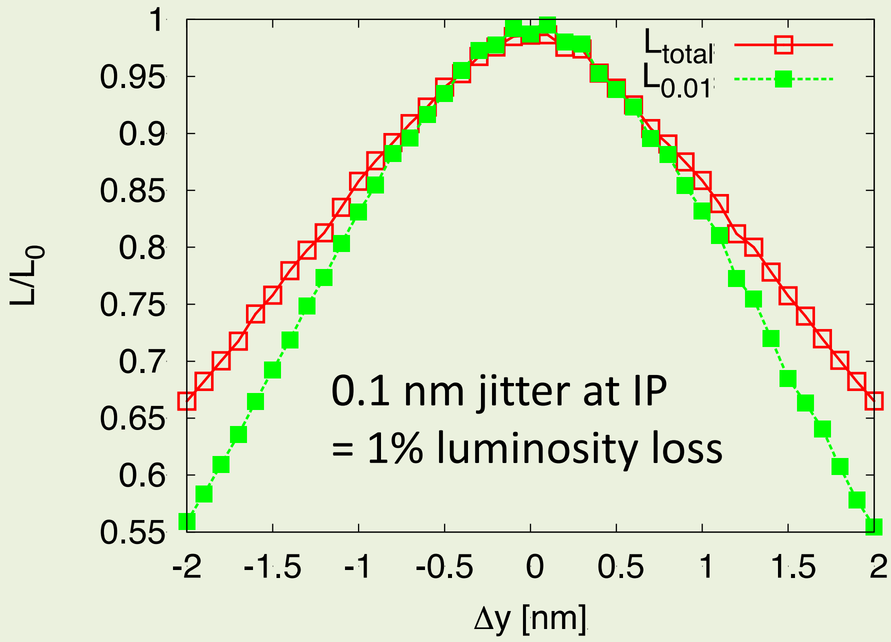
Many imperfections, e.g.

- Ground motion
- RF amplitude and phase jitter
- Magnet power supply ripple
- …

Impact on luminosity

- Direct loss
  - (trajectory jitter, emittance growth)
- Luminosity fluctuations
  - can impact tuning
- Trajectory jitter
  - can impact beam-based alignment

Example: Beam-beam offset at IP



0.1 nm jitter at IP
= 1% luminosity loss

Mitigation methods

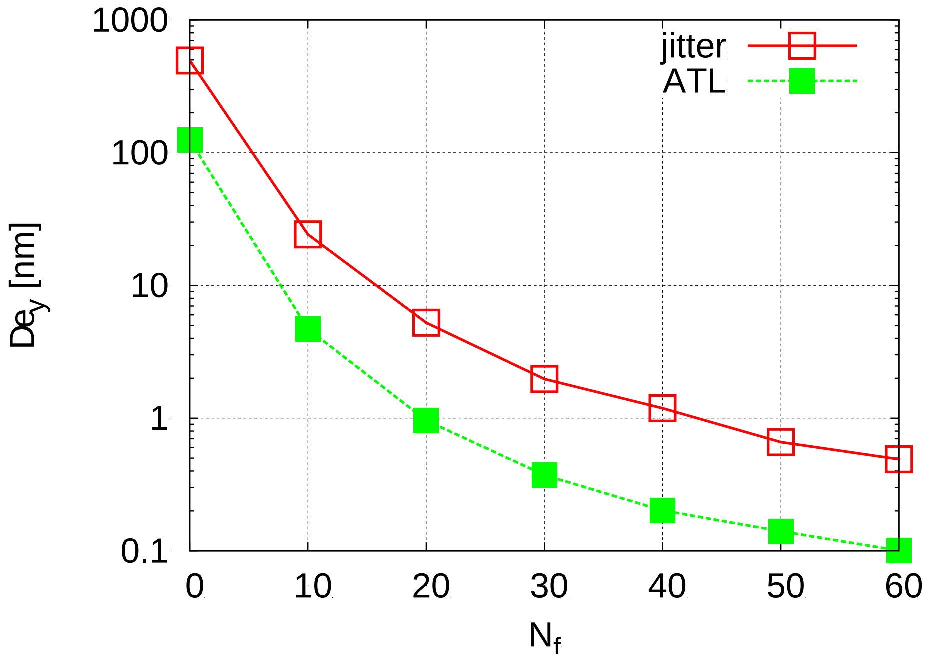
- Beam-based feedback
- Stable hardware
- Specific systems

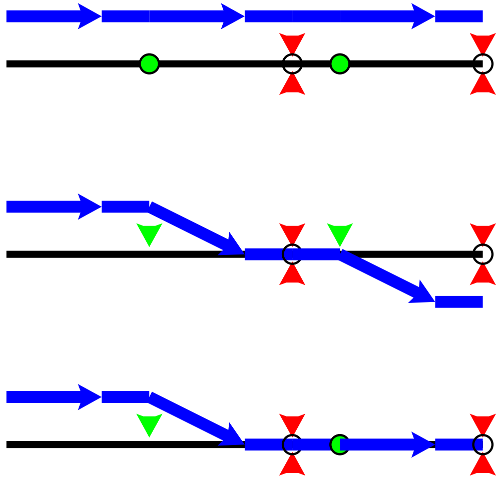
Feedback Design

Local feedback

- E.g. fix trajectory at collision point
- But does not cure emittance growth

Several trajectory feedback points help
But lead to overcorrection if independent





Use MIMO (Multiple Input Multiple Output)

- Take all information and correct globally
- One feedback loop

Feedback Design and Speed

Local feedback

- Can be used within beam pulse
  - Marginal for CLIC (170 ns pulse, but beam-beam feedback)
  - Possible for ILC (554 ns between bunches), bunch-to-bunch noise amplified along the machine

MIMO feedback

- Used from pulse to pulse
  - Hard within ILC beam pulse (720 μs vs. 100 μs roundtrip for linac)
  - Impossible for CLIC
- Important basis of the feedback systems, e.g. trajectory feedback

⇒ But cannot correct faster than 20 μs (CLIC) and 200 μs (ILC)

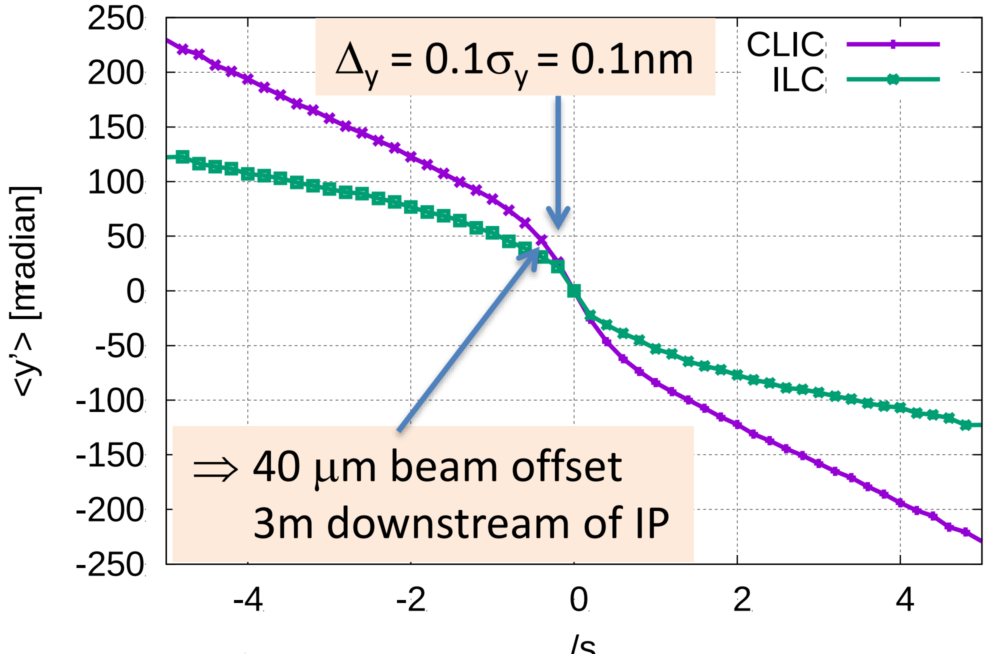
⇒ Use additional feedback systems for fast effects, independent of the beam

CLIC Beam-beam Feedback System

Strong deflection allows to easily measure and correct offset

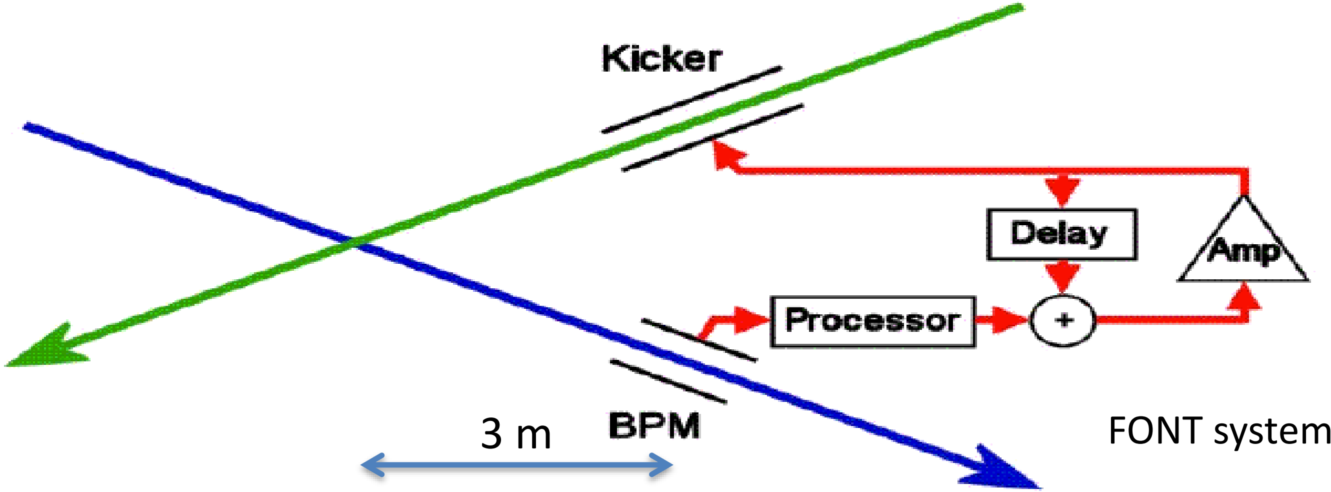
10 ns from IP to BPM
13 ns to apply correction kick
10 ns from kicker to IP

33 ns latency vs 170 ns beam pulse



$\Delta_y = 0.1\sigma_y = 0.1\text{nm}$

$\Rightarrow$ 40 μm beam offset
3m downstream of IP



FONT system (Oxford): 13 ns

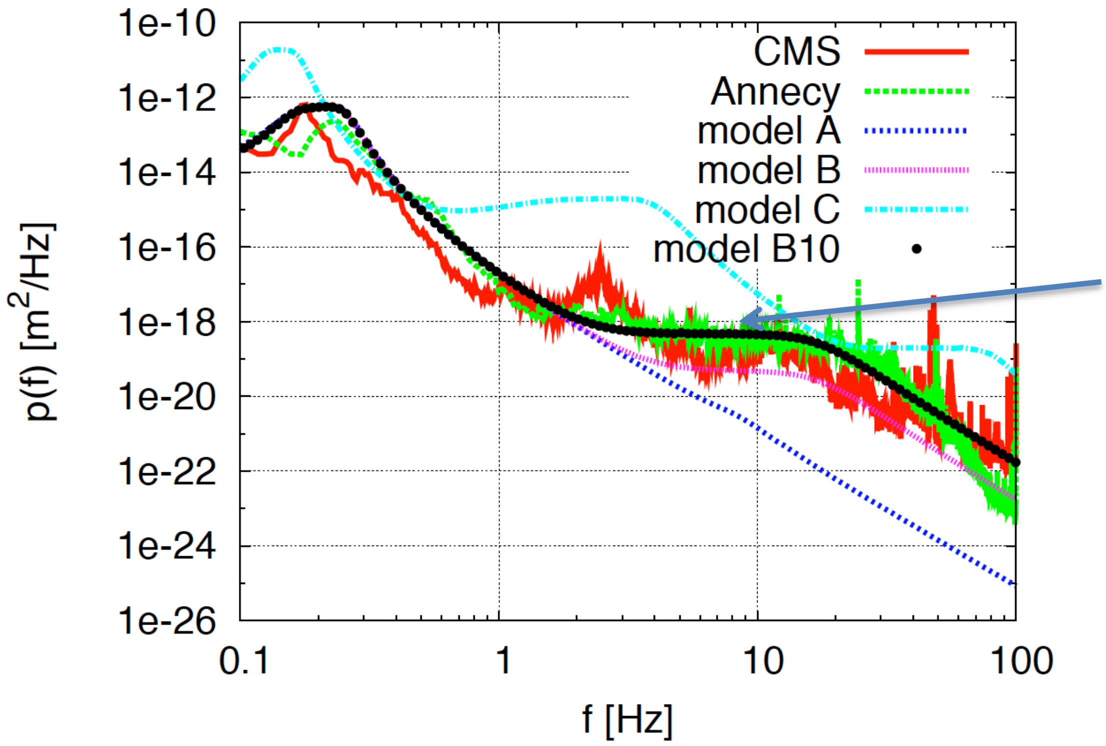
Example: Ground Motion

In CLIC can reduce dynamic effects at frequencies lower than a few Hz

⇒ Andrei Seryi
Friday 2.3.

In ILC can use a bunch-bunch feedback system

- But be careful, bunch-to-bunch noise will be amplified
- e.g. the damping ring extraction kicker kicks each bunch separately, so it will induce noise

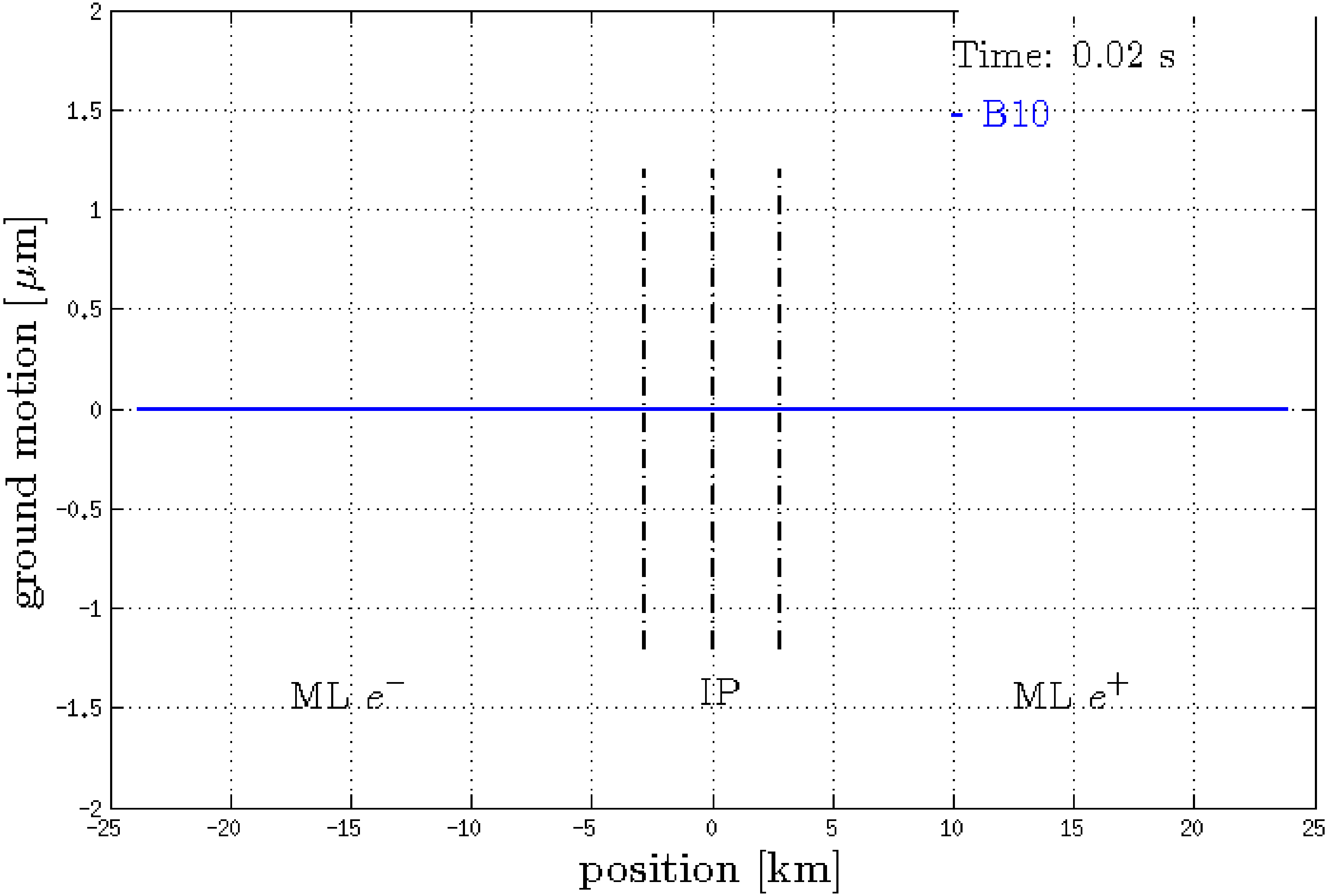


We spot a problem:

Frequencies cannot be mitigated by beam feedback

Example Issue: Ground Motion

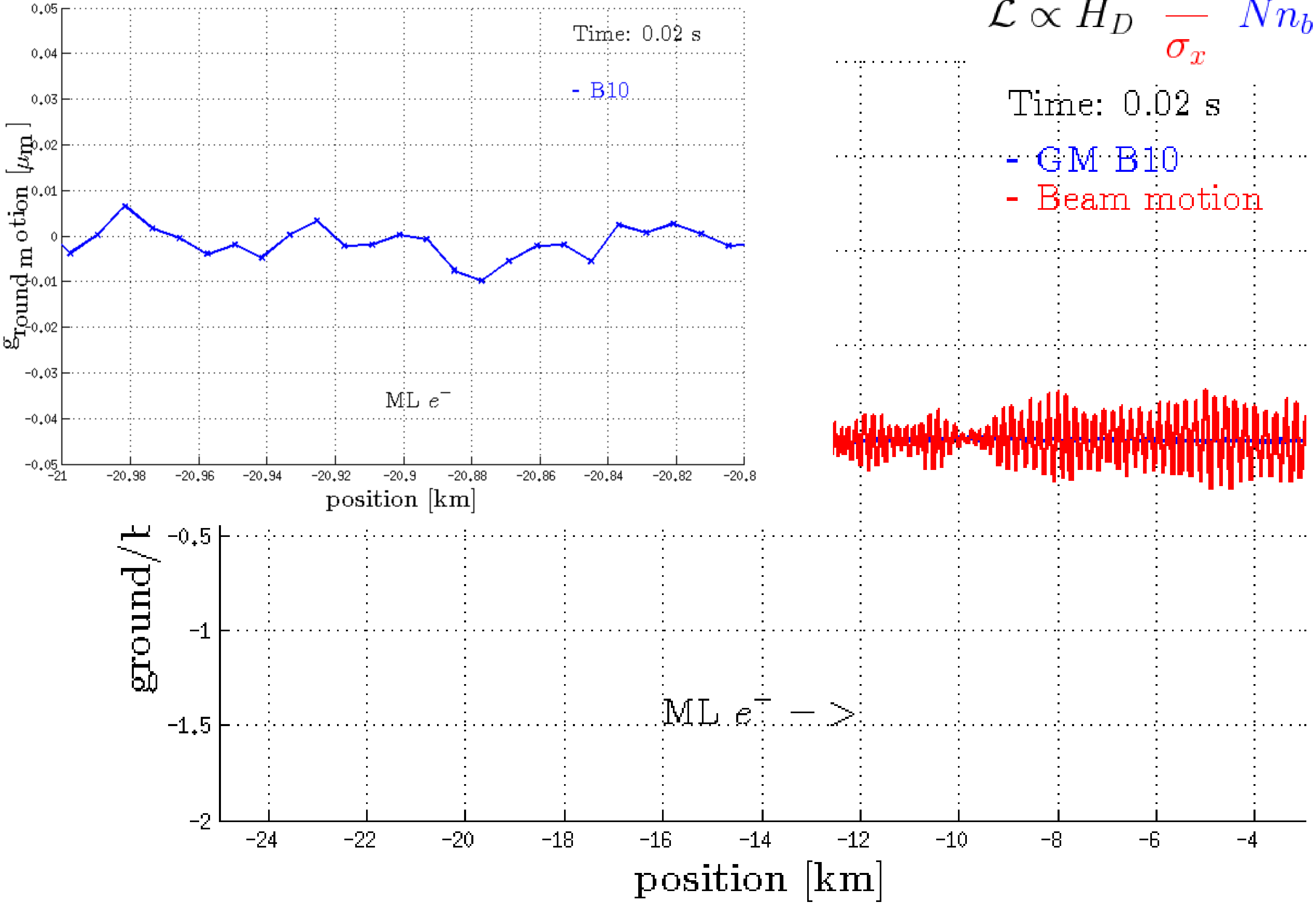
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

Resulting Beam Jitter

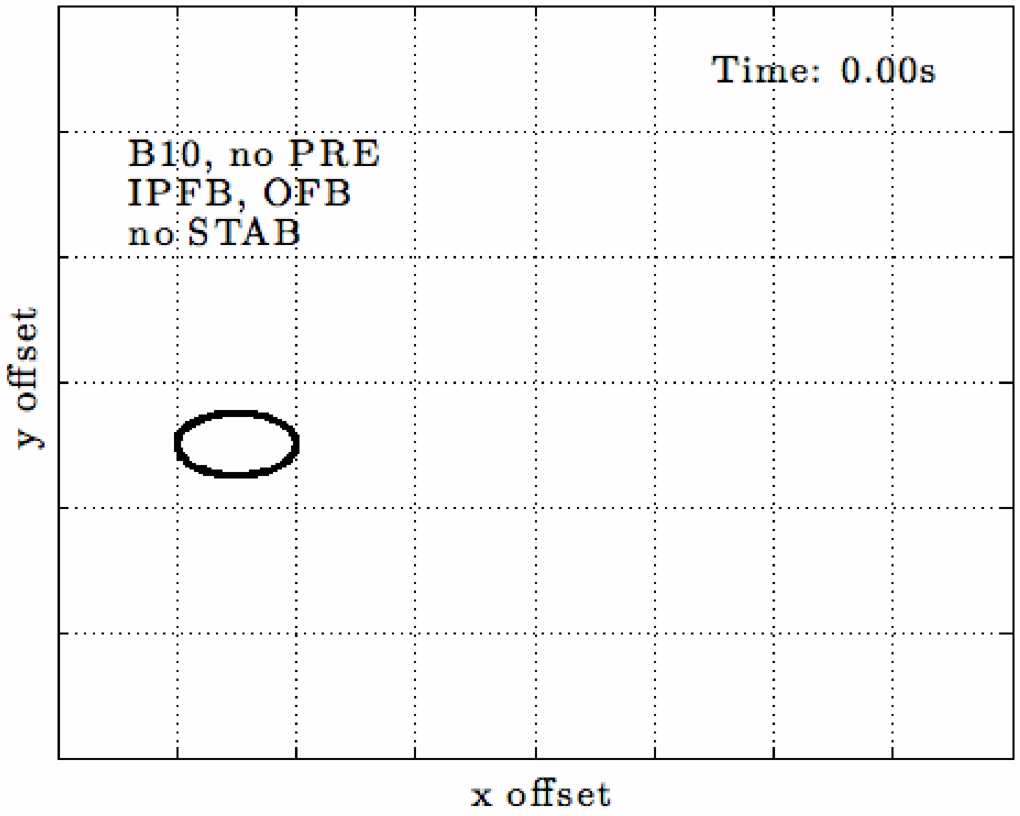
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



J. Pfingstner

Beams at Collision

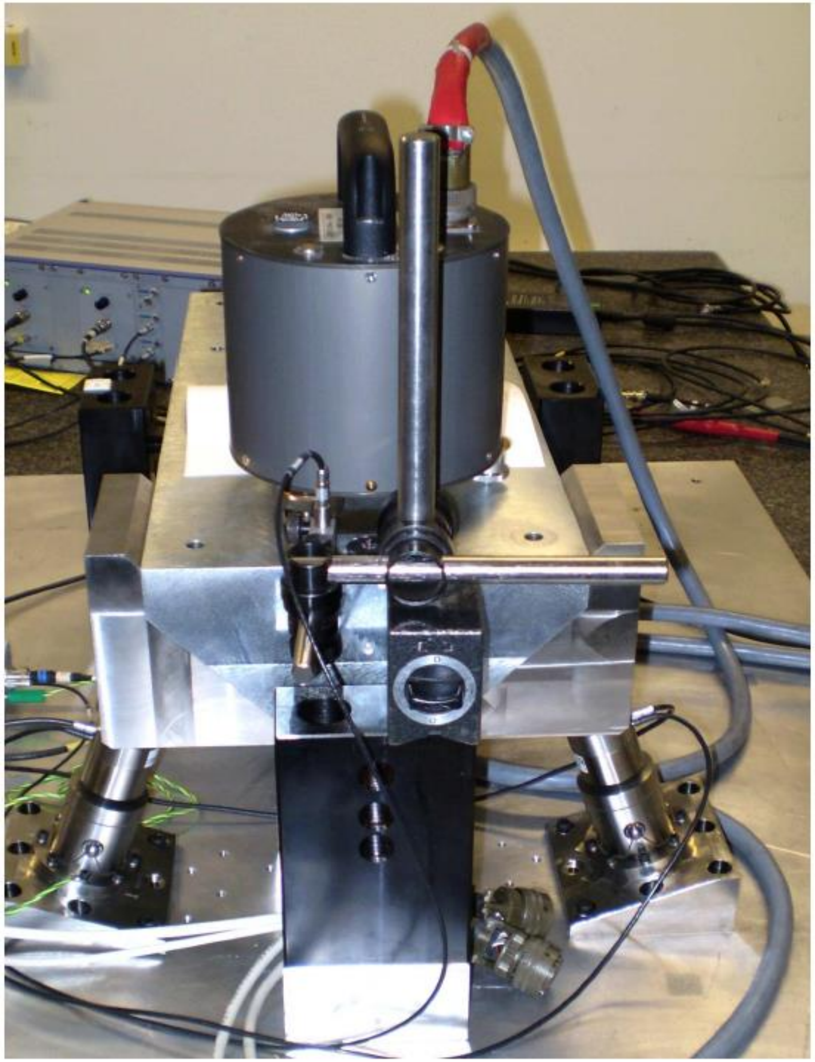
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



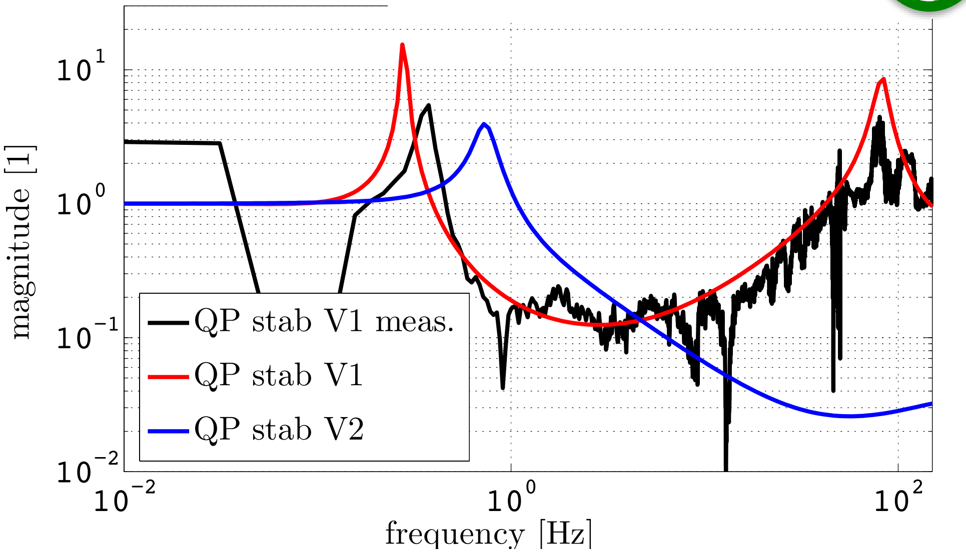
J. Pfingstner

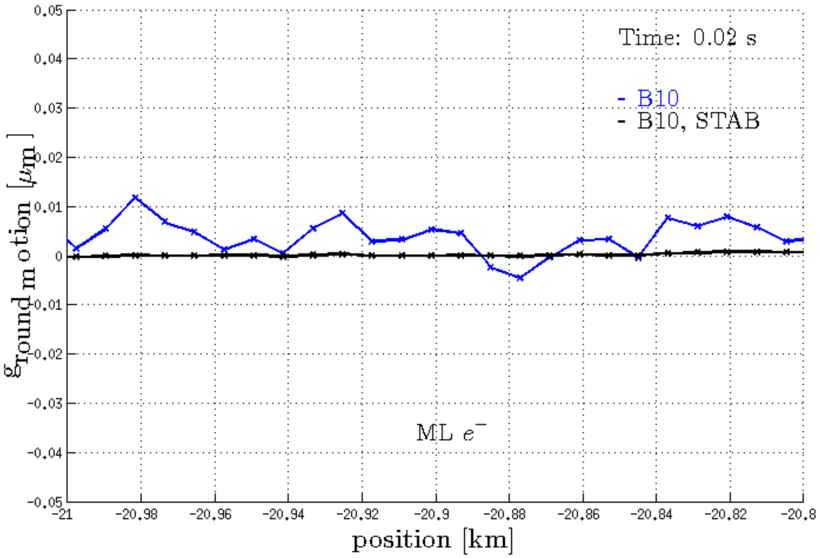
Stabilisation System

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



K. Artoos et al.

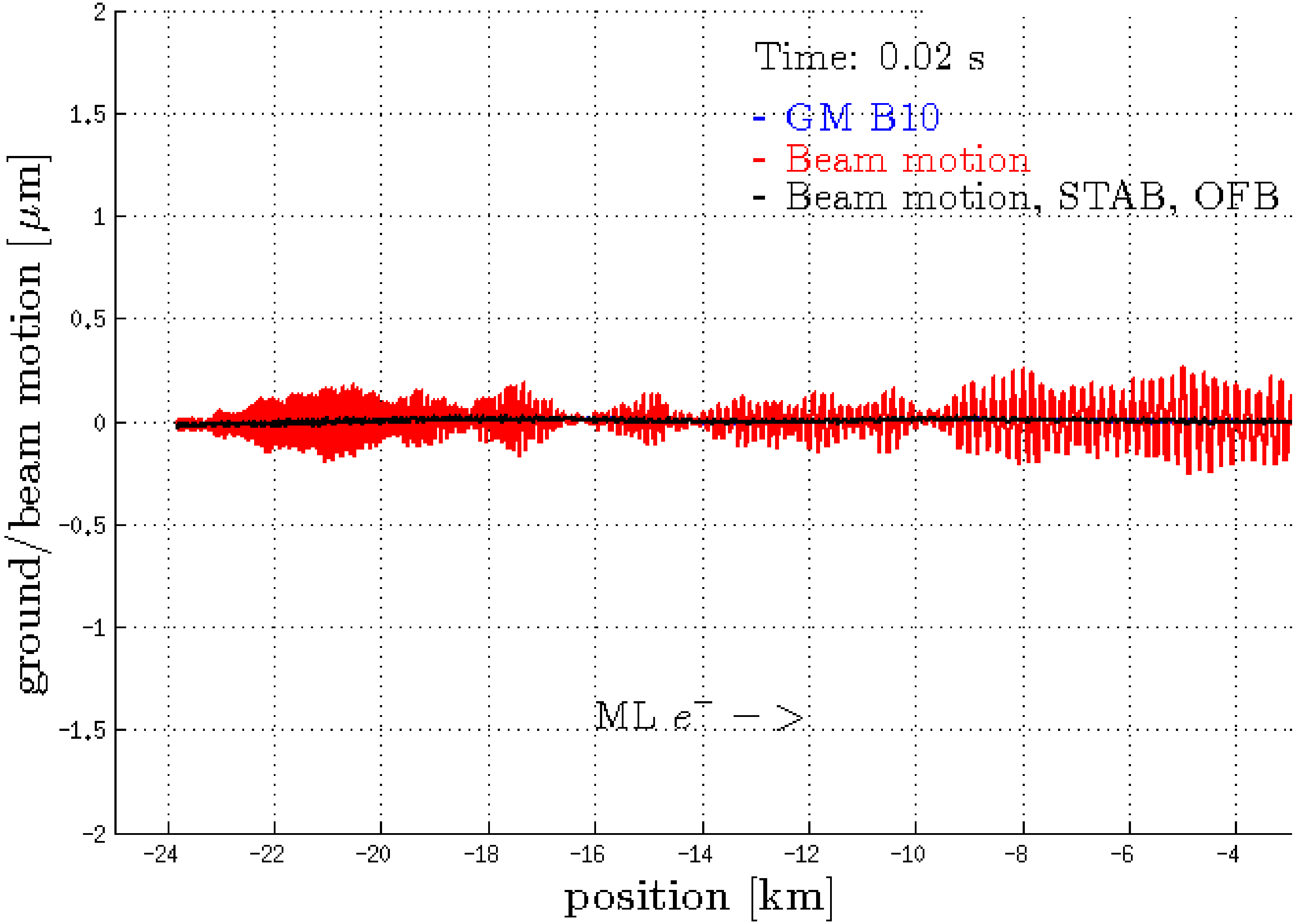




J. Snuverink, et al.

Impact of Stabilisation on Beam

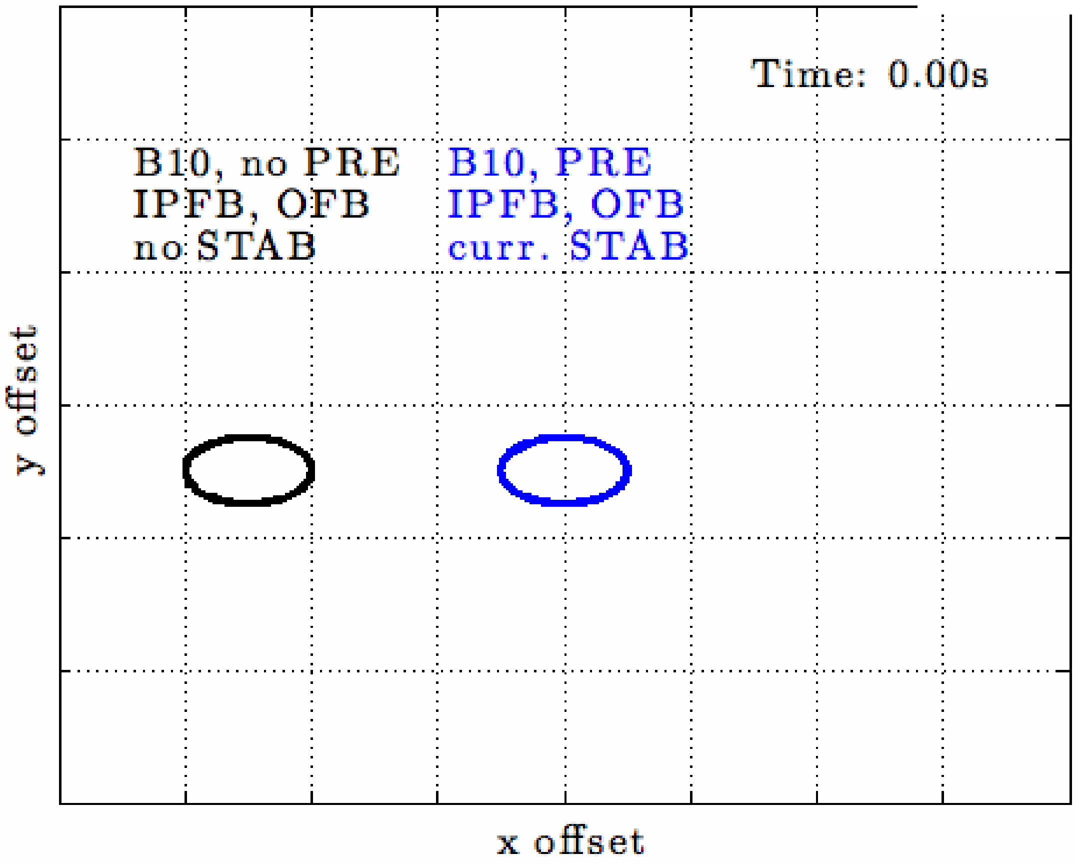
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



J. Pfingstner

Beam at Collision

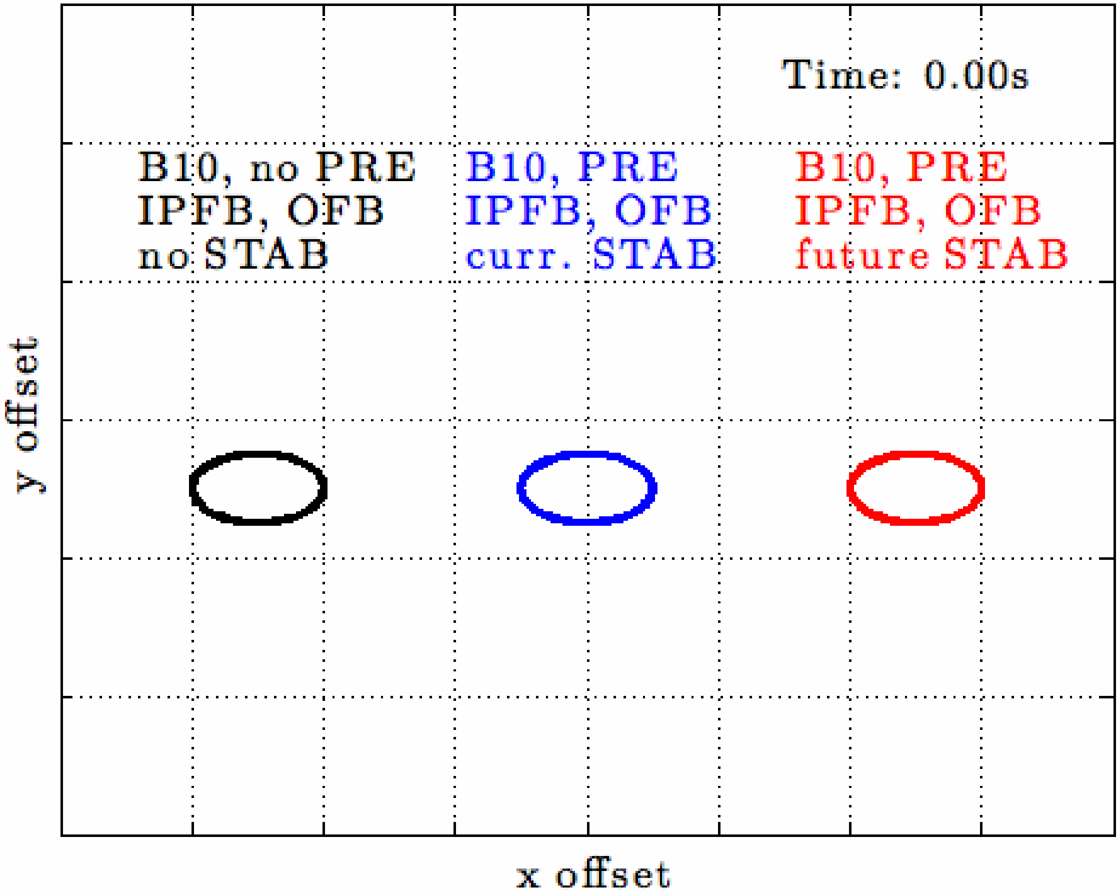
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



J. Pfingstner

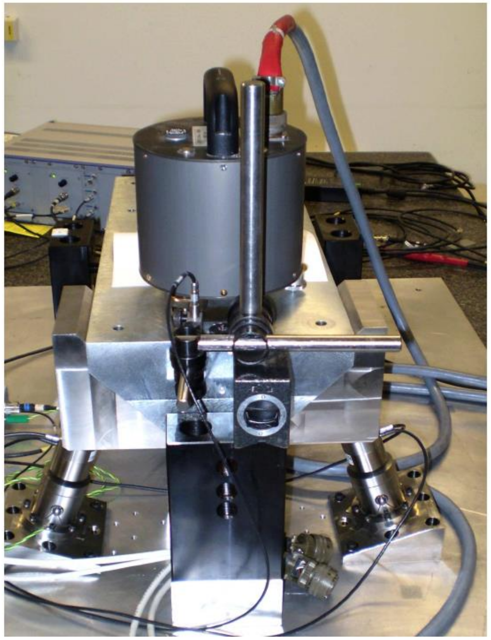
Beam at Collision

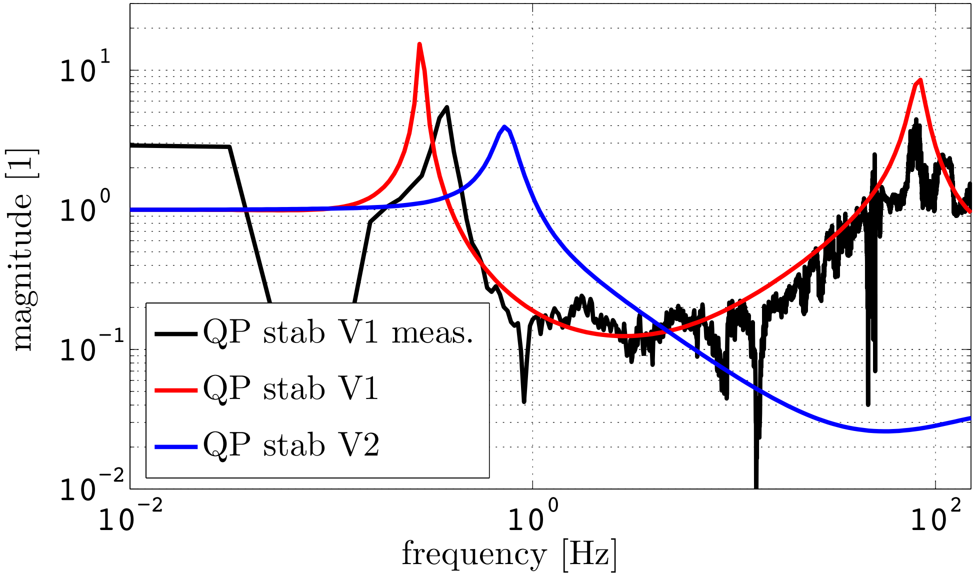
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

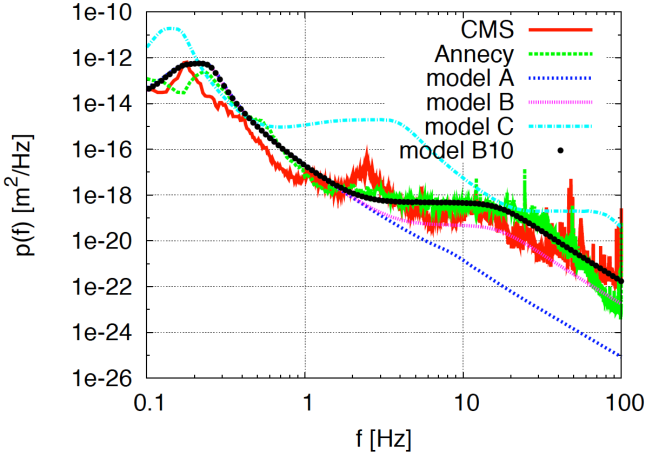


J. Pfingstner

Active Stabilisation Results







Code

Machine model
Beam-based feedback

Luminosity achieved/lost [%]	B10
No stab.	53%/68%
Current stab.	108%/13%
Future stab.	118%/3%

Close to/better than target

Tools and Warnings

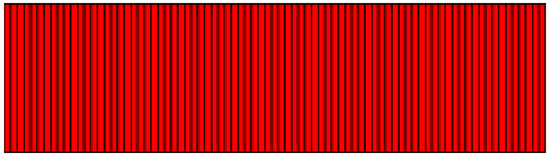
Tools

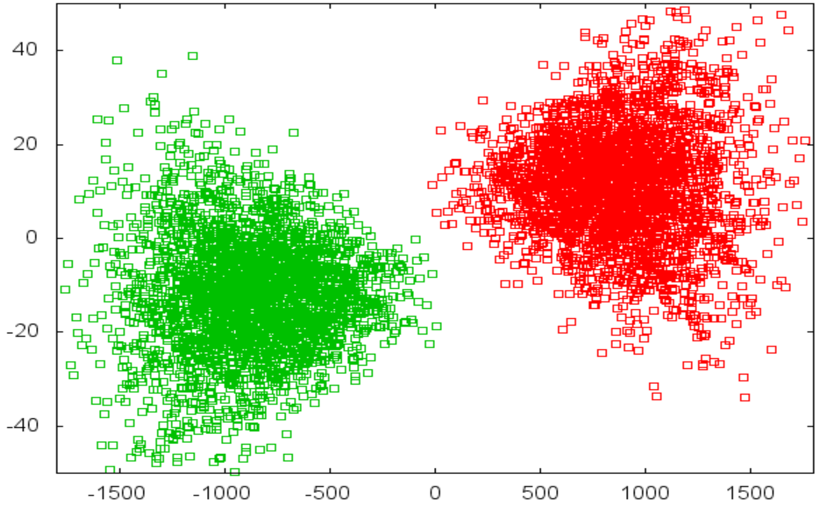
Analytic calculations to understand general physics

But need simulation tools for quantitative predictions

Beam-beam interaction (e.g. GUINEA-PIG, other code CAIN)

Beam tracking (e.g. PLACET, several other codes)



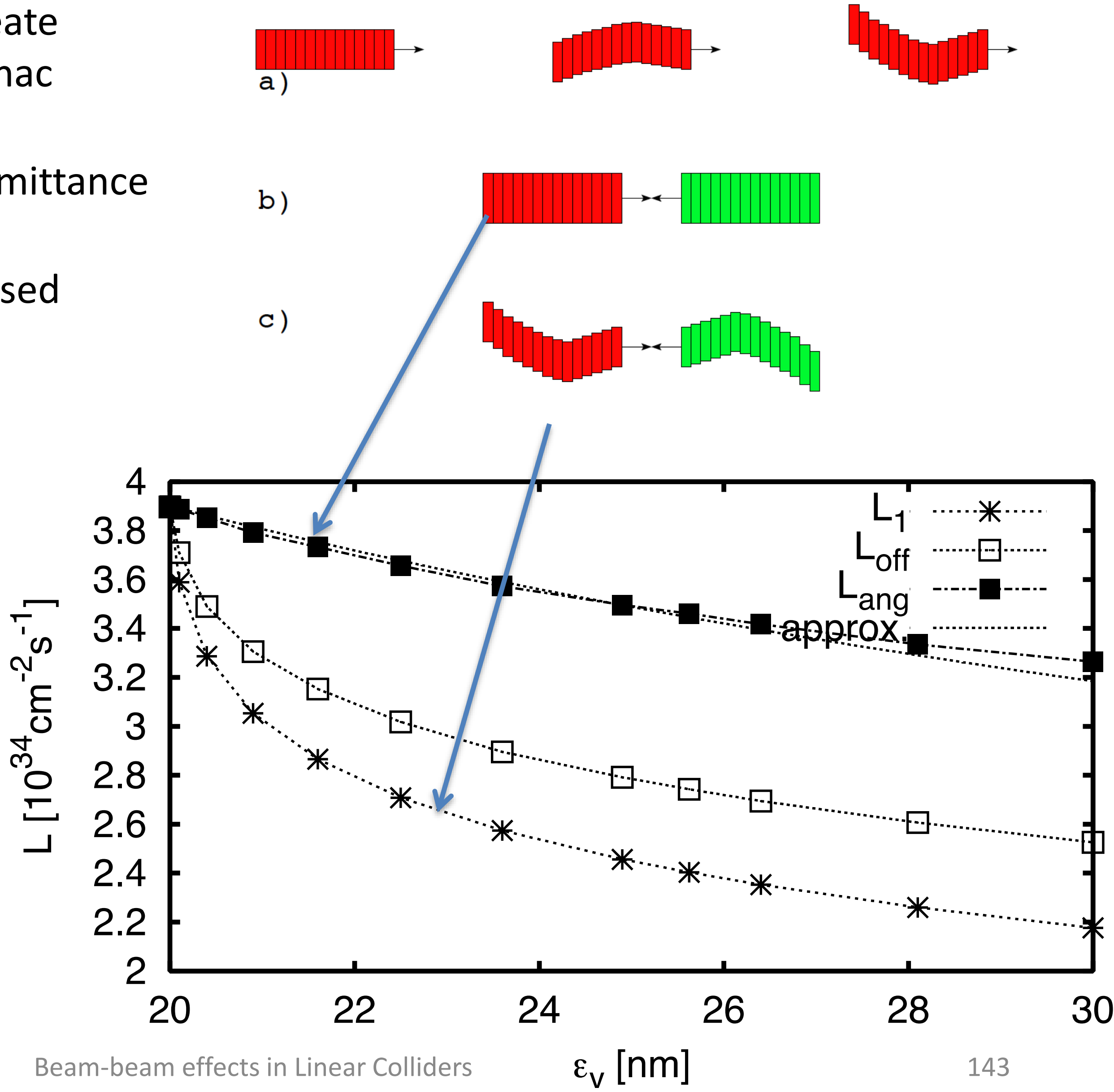


Note: The Banana Effect

a) Wakefields+dispersion can create banana-shaped bunch in main linac

b) Often model with projected emittance

c) The correct shape should be used



For large disruption (ILC) banana can reduce luminosity

Study done for TESLA
Similar disruption as ILC

Note: More Information

CAS on Intensity Limitations 2015 (https://indico.cern.ch/event/362960/):
Main Linac:
https://indico.cern.ch/event/362960/contributions/1776181/attachments/1181326/1710423/Ferrario_Lectrure_PWA_final.pdf
Beam-beam (linear collider):
https://indico.cern.ch/event/362960/contributions/1776145/attachments/1183340/1714476/Beam-beamx.pptx

Linear Collider School 2016 (https://agenda.linearcollider.org/event/7333/)
Linac:
AB_basic https://agenda.linearcollider.org/event/7333/contributions/38078/
A1_1 https://agenda.linearcollider.org/event/7333/contributions/38078/
A1_2 https://agenda.linearcollider.org/event/7333/contributions/38084/
A1_3 https://agenda.linearcollider.org/event/7333/contributions/38090/
And much more …

DFS steering:
SLAC-PUB-5222

Some linac formulae:
https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.3.121002

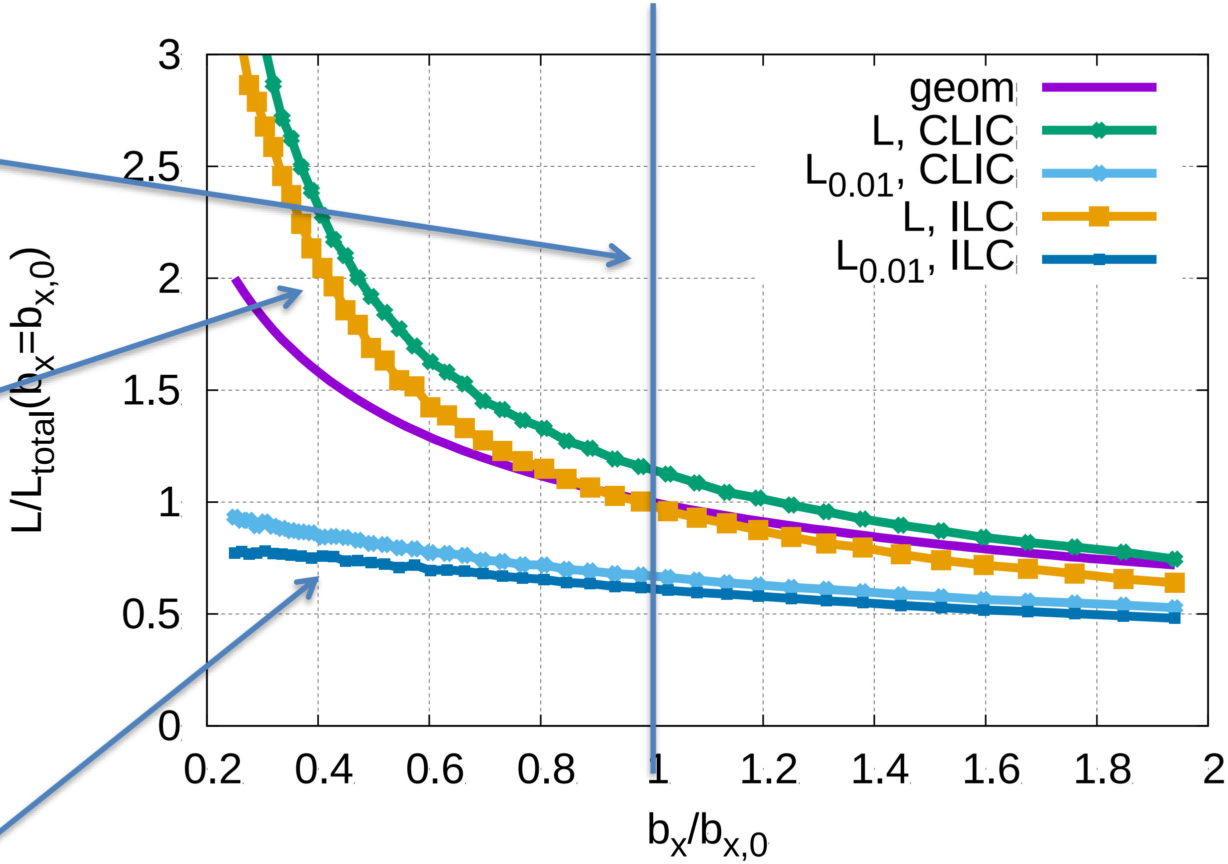
Conclusion

Many thanks for listening
To the linar collider collaborations for the work presented
and to the people from whom I stole figures: E. Adli, K. Artoos, A. Grudiev, E. Jensen, A. Latina, H. Mainaud Durand, J. Pfingstner, J. Snuverink, I. Syratchev, W. Wuensch

Reserve

Beamstrahlung

Luminosity Spectrum



Design value
$L_{0.01}/L=60\%$

The total luminosity L varies strongly with beta-function

But $L_{0.01}$ does not change so much

Hard to push beta-functions
That low

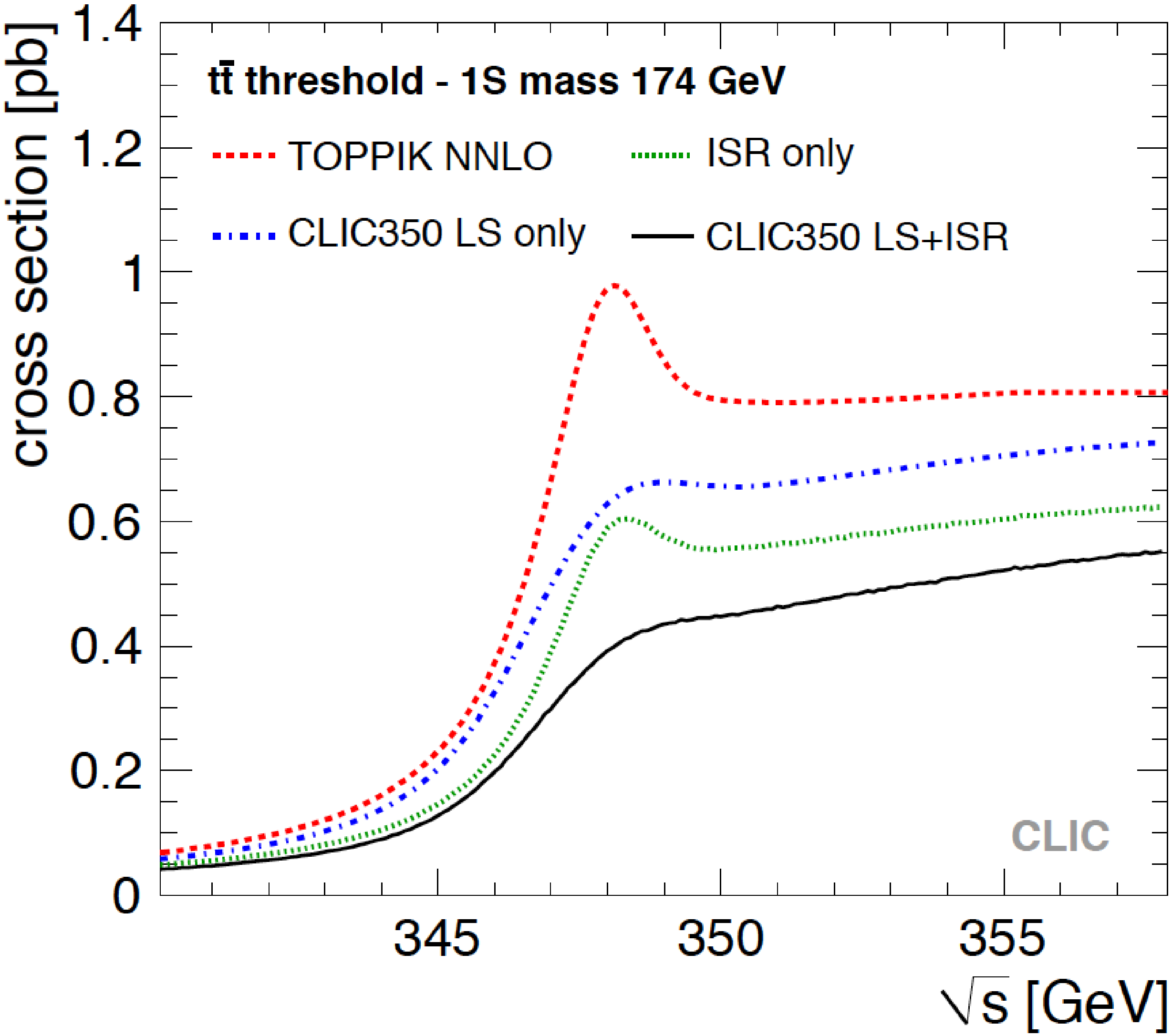
So tend to use $L_{0.01}/L=60\%$ as criterion

Reasonable compromise for most physics studies

Top Production at Threshold

K. Seidel et al. **arXiv:1303.3758**

Top production at threshold is strongly affected by beam energy spread and beamstrahlung



For $L_{0.01} > 0.6$ L impact of beamstrahlung is comparable to ISR

But depends on physics

Note: Luminosity Drivers

In the classical regime

$$\mathcal{L} \propto H_D \, n_\gamma \, \eta_{RF->beam} \frac{P_{RF}}{E_{cm}} \frac{1}{\sigma_y}$$

In the quantum regime

$$\mathcal{L} \propto H_D \, \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}} \, \eta_{RF->beam} \frac{P_{RF}}{E_{cm}} \frac{1}{\sigma_y}$$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Beamstrahlung Optimisation

For low energies (classical regime) number of emitted photons

$$\boxed{n_\gamma} \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

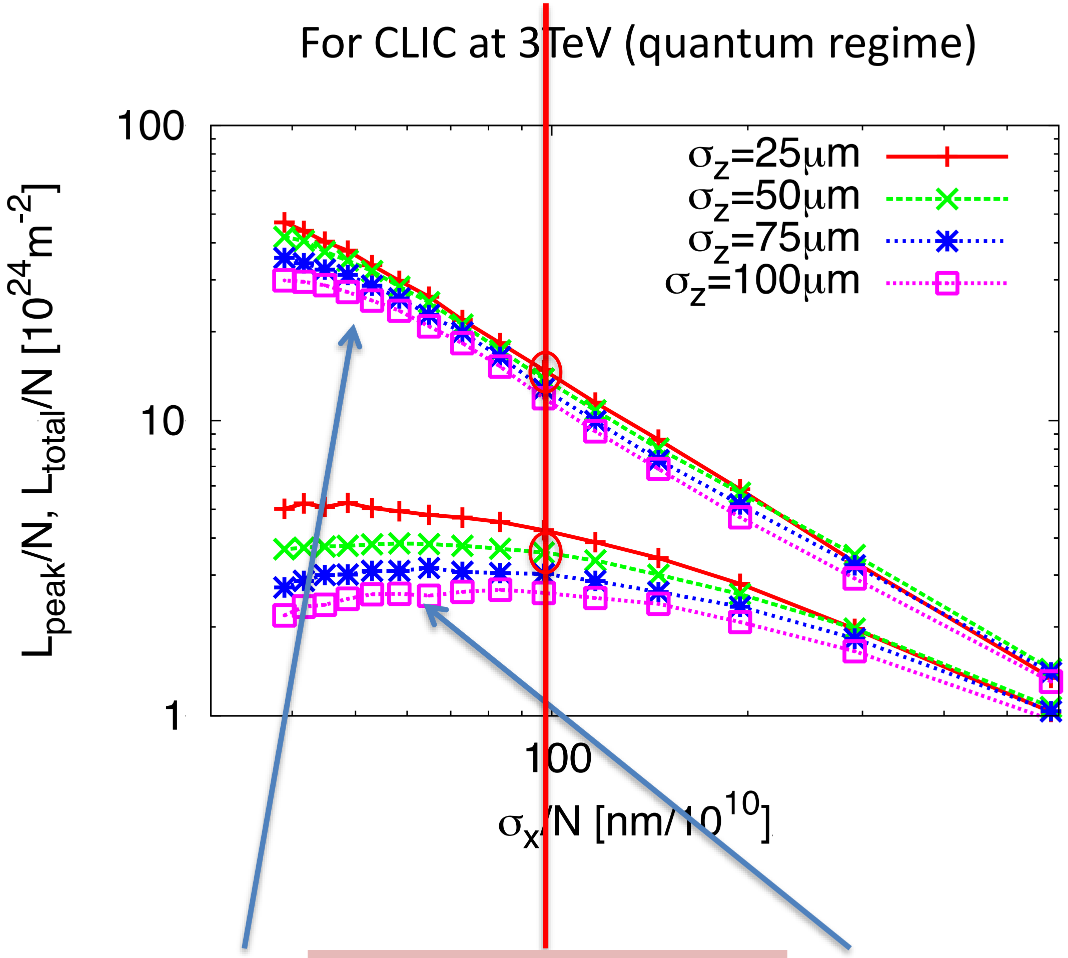
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

Hence use $\sigma_x \gg \sigma_y$

$$\sigma_x + \sigma_y \approx \sigma_x$$

$$\mathcal{L} \propto H_D \boxed{\frac{N}{\sigma_x}} N n_b f_r \frac{1}{\sigma_y}$$

For CLIC at 3TeV (quantum regime)



Total lumin

grows for smaller beams

CLIC parameter choice

ninosity in

peak starts to decrease again

CLIC Parameter Development

How CLIC Parameters Were Done

For each structure determine bunch charge and length

Determine emittance from damping ring

Add emittance growth based on detailed studies

$$\mathcal{L} \propto H_D \; \frac{N}{\sigma_x} \; N n_b f_r \; \frac{1}{\sigma_y}$$

Key CLIC Parameter Limits

Choose the maximum that main linac allows

$$\mathcal{L} \propto H_D \frac{\boxed{N}}{\sigma_x} \boxed{N} n_b f_r \frac{1}{\sigma_y}$$

Note: Choosing a different structure gives a different limit

Key CLIC Parameter Limits

Nature defines minimum beam size as function of bunch charge

$$\mathcal{L} \propto H_D \boxed{\frac{N}{\sigma_x}} N n_b f_r \frac{1}{\sigma_y}$$

Key CLIC Parameter Limits

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

Damping ring and BDS define minimum beam size
Can achieve our target but not go much below

Note: A bit of self-fulfilling prophecy

Minimum beam size is know in optimisation
Structures that require small N are removed because of low luminosity

Key CLIC Parameter Limits

Higher efficiency in main linac would allow for more beam current

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} \boxed{N n_b f_r} \frac{1}{\sigma_y}$$

Key CLIC Parameter Limits

Note: A bit of self-fulfilling prophecy
Structures that allow only small N are good for RF
But the luminosity is low so the are not liked by the optimisation

$$\mathcal{L} \propto H_D \; \frac{N}{\sigma_x} \; N n_b f_r \; \frac{1}{\boxed{\sigma_y}}$$

If we could do better, we would

All system contribute to vertical emittance
Mainly due to imperfections

BDS defines beta-function limit (some contribution from main linac)

Equivalence of Power and Field Picture

Note: Equivalence of Wakefield and Power Picture

- Why can a wakefield model be used for the beam loading?
  - i.e.

$$\Delta G(q) = \text{const } q$$

- The energy stored per unit length in the accelerating structure is

$$E'(s) = \frac{G(s)^2}{(R'/Q)(s)\omega}$$

- The reduction of acclerating field due to the passing charge q is $-\Delta G(s)$
- This yields for the energy lost by the structure

$$\Delta E'_{lost}(s) = \frac{G^2(s) - (G(s) - \Delta G(s))^2)}{(R'/Q)(s)\omega} \qquad \Rightarrow \Delta E'_{lost}(s) = \frac{2G(s)\Delta G(s) - (\Delta G(s))^2}{(R'/Q)(s)\omega}$$

- The beam extracts an energy

$$\Delta E'_{beam}(s) = q\left(G(s) - \frac{1}{2}\Delta G(s)\right)$$

hence

$$q\left(G(s) - \frac{1}{2}\Delta G(s)\right) = \frac{2G(s)\Delta G(s) - (\Delta G(s))^2}{(R'/Q)(s)\omega}$$

$$\Rightarrow \Delta G(s) = \frac{(R'/Q)(s)\omega}{2}q$$

$\Rightarrow$ The gradient change depends only on the charge not the initial gradient, as expected

- Note: I simplified a bit (sorry, but this is easier with cheating)

Single Bunch Energy Spread Simple Model

Simplified Treatment of Single Bunch Energy Spread

Assume

- $W_z(s) = W_z = \mathrm{const}$
- uniform bunch with length $L \ll \lambda$
- and use linear approximation

Field seen by first particle

$$G_H = G\cos\left(\phi - \frac{L}{2}\frac{2\pi}{\lambda}\right) \approx G\left(\cos(\phi) - \frac{L}{2}\frac{2\pi}{\lambda}\sin(\phi)\right)$$

Field seen by last particle

$$G_T = G\cos\left(\phi + \frac{L}{2}\frac{2\pi}{\lambda}\right) \approx G\left(\cos(\phi) + \frac{L}{2}\frac{2\pi}{\lambda}\sin(\phi)\right) - NeW_z$$

We require (this automatically solves the equation for all other particles)

$$G_H = G_T$$

which leads to

$$L = \frac{NeW_z}{G}\frac{\lambda}{2\pi\sin(\phi)}$$

Speed of Deconeherence in Simple Model

Beam Offset and Decoherence

Solve equation of motion for particle with different energy

$$x_2(0) = x_0 \quad x_2'(0) = 0$$

$$x_2''(s) + \frac{1}{\beta_2^2} x_2(s) = x_2''(s) + \frac{1}{(1+\delta)\beta^2} x_2(s) = 0$$

Solution has the same amplitude (small difference in maximum angle) but different frequency
Particle will decohere from the nominal energy

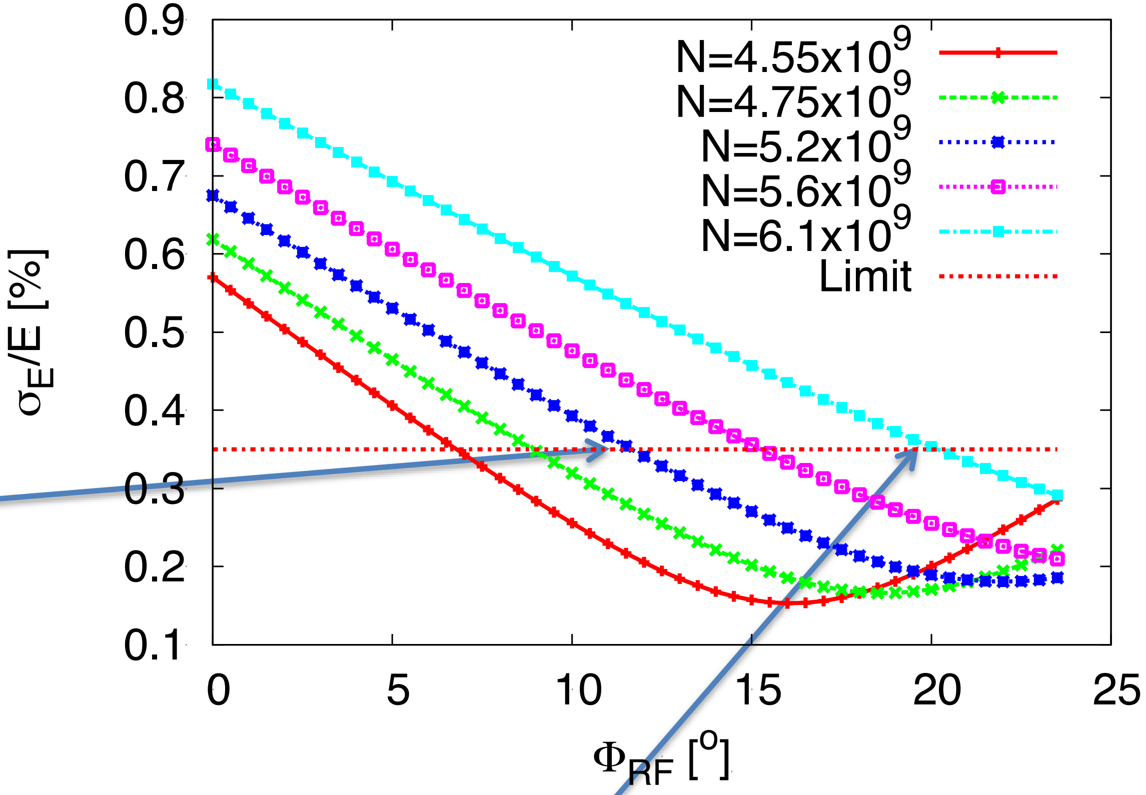
$$x_2(s) = x_0 \cos\left(\frac{s}{\beta_2}\right) = x_0 \cos\left(\frac{s}{\sqrt{1+\delta}\beta}\right) \approx x_0 \cos\left(\frac{s}{(1+0.5\delta)\beta}\right)$$

With energy spread beam offset will turn into beam size growth

Choice of Mean RF Phase in CLIC

Note: Choice of Average RF Phase

Examples of beams with the same transverse wakefield effects
i.e. larger N means shorter bunch



CLIC bunch at 380 GeV
Running at 12°
2% gradient loss

12° is a good compromise

17% more charge requires 20°
6% gradient loss
More sensitive to phase jitter

Emittance Bumps in ILC

Some Old Example for ILC