CLIC: Main Linac Beam Dynamics

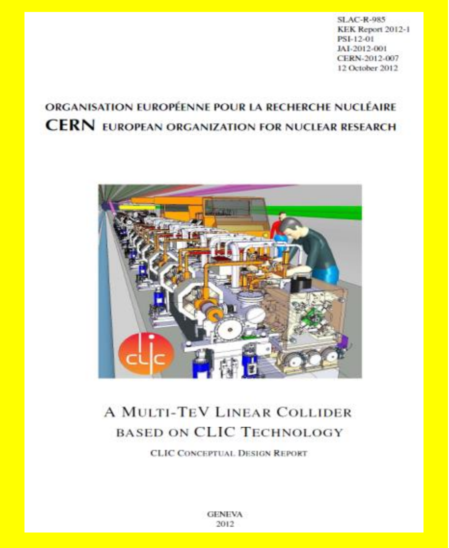
ALEGRO Workshop
CERN
March 2019

Daniel Schulte

CLIC Introduction

CLIC: **C**ompact **LI**near **C**ollider

CLIC aims to provide **multi-TeV electron-positron** collisions with high luminosity at affordable cost and power consumption



SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

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

A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

2012 CDR:
Shows feasibility of 3 TeV design

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

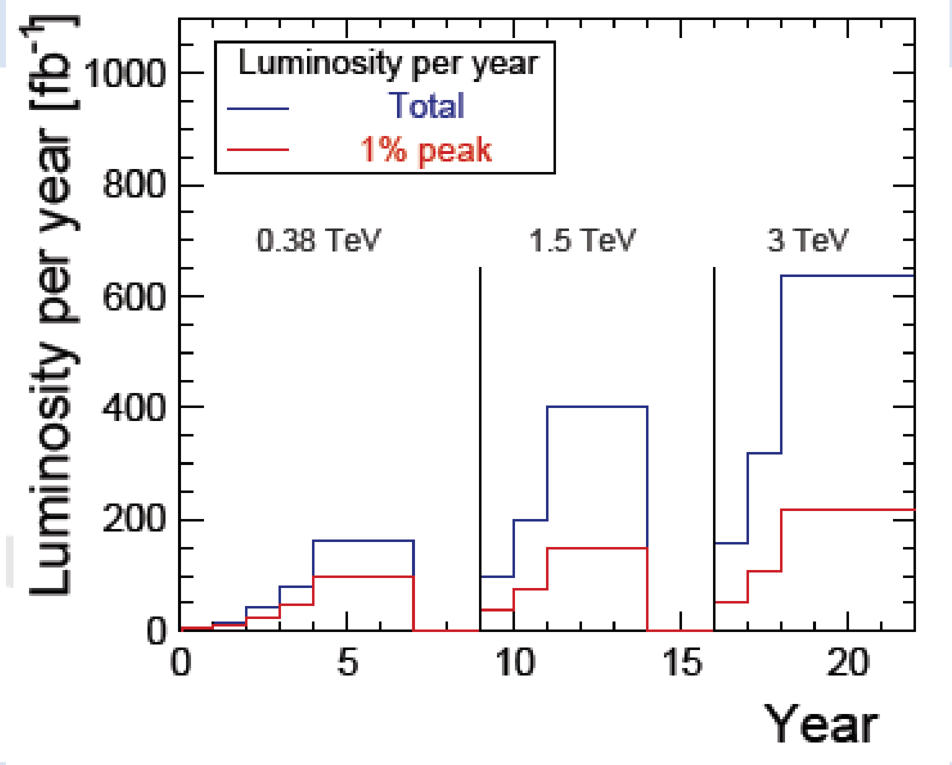
2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

CLIC Staged Scenario

Plenty of physics at low centre-of-mass energies

Energy and luminosity targets from Physics Study Group



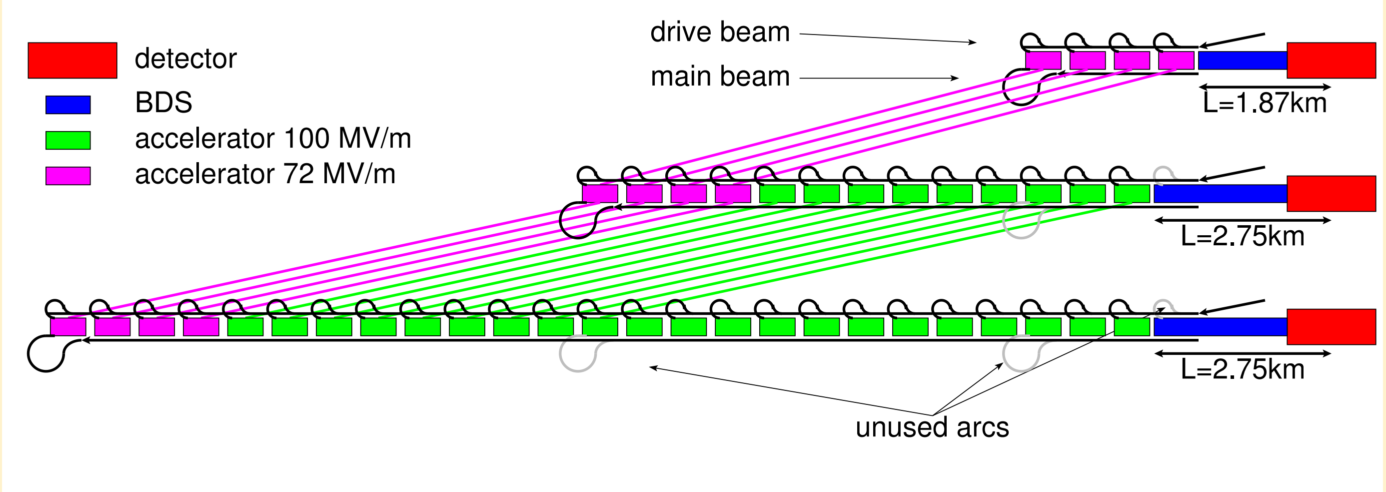
Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

Top above threshold
Higgs via Zh and WW fusion

Study top at threshold

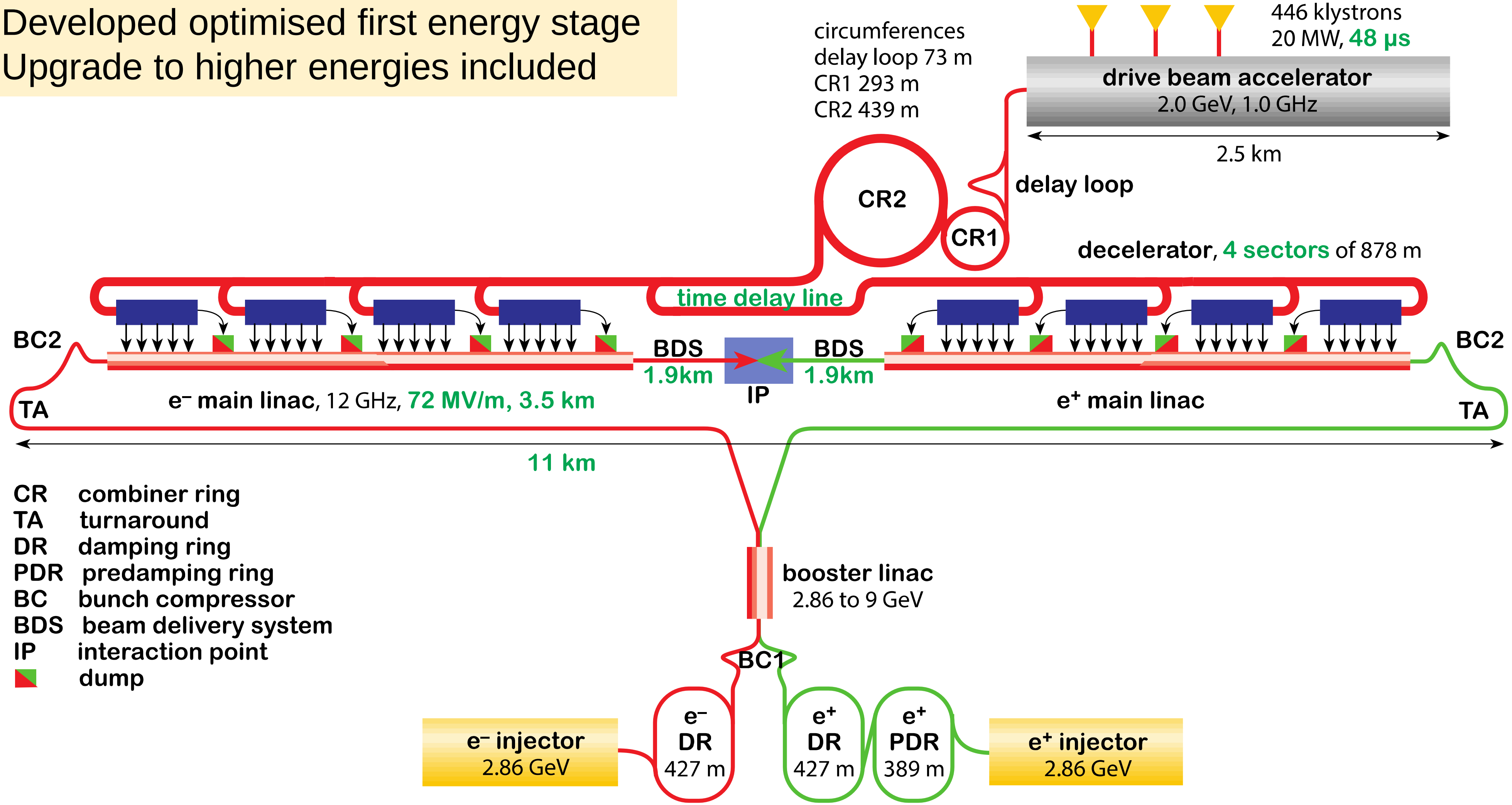
To be updated with more input from LHC and stage 1

Implementation in stages



CLIC at 380 GeV

Developed optimised first energy stage
Upgrade to higher energies included



CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
◩	dump

Key Parameters

Very small emittances required to achieve the luminosity

Bunch charge and length at IP determined by main linac

Parameter	Symbol [unit]	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	380	3000
Luminosity	L [$10^{34}cm^{-2}s^{-1}$]	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	0.9	2
Gradient	G [MV/m]	72	72 / 100
Particles per bunch	N [10^9]	5.2	3.72
Bunch length	σ_z [μm]	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	143 / 2.9	40 / 1
Emittance	$\varepsilon_{x,y}$ [μm/nm]	0.95 / 30	0.66 / 20
IP beta functions	$\beta_{x,y}$ [mm/mm]	8 / 0.1	6 / 0.07
Bunches per pulse	n_b	352	312
Bunch distance	Δz [mm]	0.5	0.5
Repetition rate	f_r [Hz]	50	50

Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

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

Luminosity spectrum

Beam current

Beam Quality (+bunch length)

Need to ensure that we can achieve each parameter

Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

The limit is the beam stability in the main linac

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

Beam current

Luminosity spectrum

Beam Quality (+bunch length)

Need to ensure that we can achieve each parameter

Luminosity Drivers at High Energy

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 (high energy)

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

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

Luminosity and Beam Quality

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}} \qquad \sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Damping ring main source of horizontal emittance
But value is OK, as we will see

	$\Delta\varepsilon_x$ [nm]	$\Delta\varepsilon_y$ [nm]		
	Total contribution	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	700	5	0	0
End of RTML	150	1	2	2
End of main linac	50	0	5	5
Interaction point	50	0	5	5
sum	950	6	12	12

Imperfections are the main source of final vertical emittance

Require 90% likelihood to meet static emittance growth target

Main Linac: Low Emittance Preservation

Beam stability

- incoming beam can jitter (have small offsets) and become unstable
- lattice design, choice of beam parameters

Static imperfections

- errors of reference line, elements to reference line, elements. . .
- excellent pre-alignment, beam-based alignment, beam-based tuning

Dynamic imperfections

- Ground motion, cooling water induced jitter, RF jitter, electronic noise,. . .
- lattice design, BNS damping, component stabilisation, feedback, re-tuning, re-alignment

- Combination of dynamic and static imperfections can be severe

- Lattice design needs to balance dynamic and static effects

Wakefields and Beam Current

Two goals:

- Maximise beam current
- But maintain good beam quality

Maximise the current by

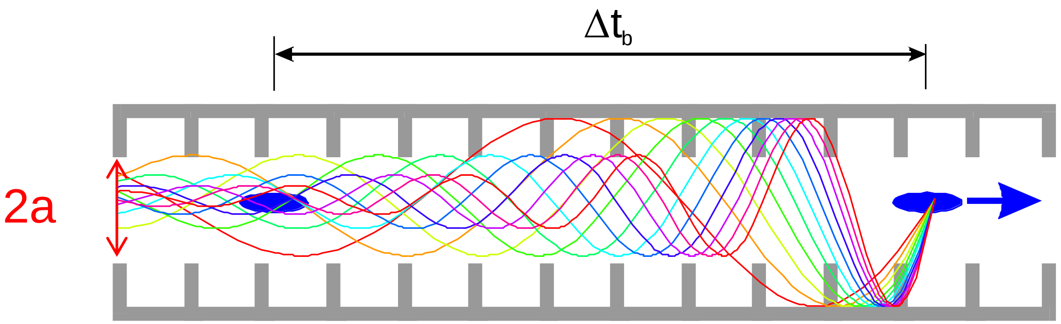
⇒ Maximising bunch charge

⇒ Minimising distance between bunches

⇒ Limit from main linac wakefields

Maximise beam quality

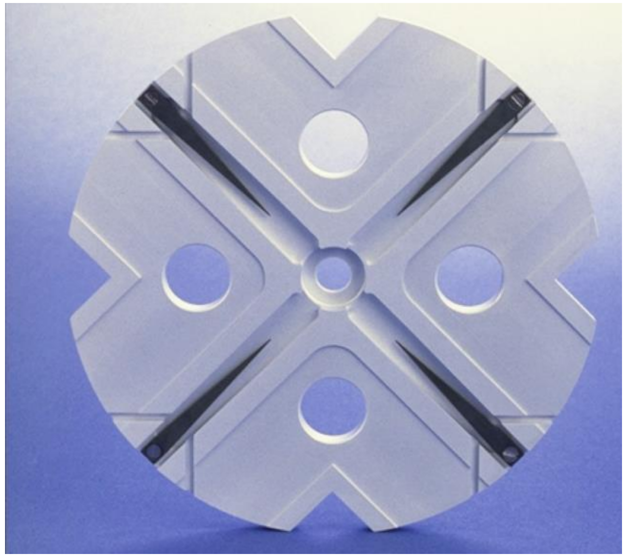
- Main linac wakefields are important component

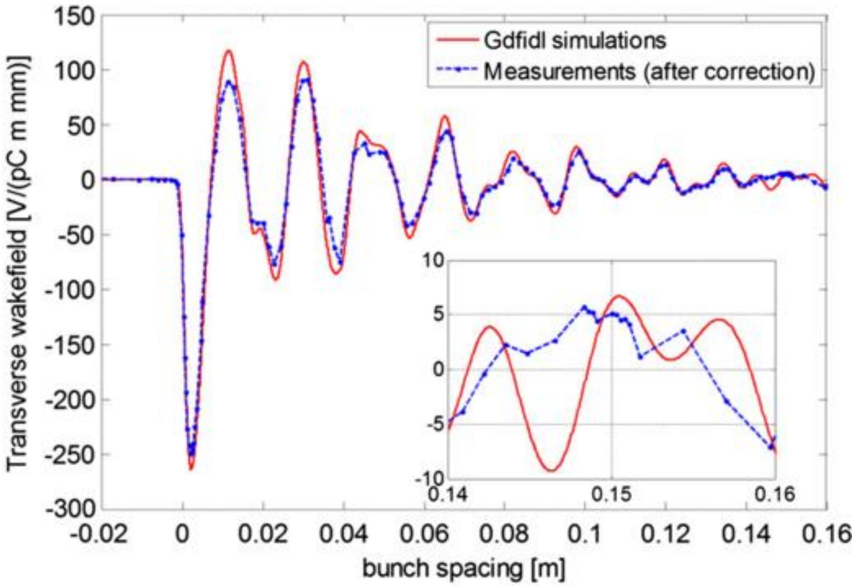


RF team loves small **a**
Less power
easier to reach gradient

Beam team hates small **a**
More wakefields
Beam less stable

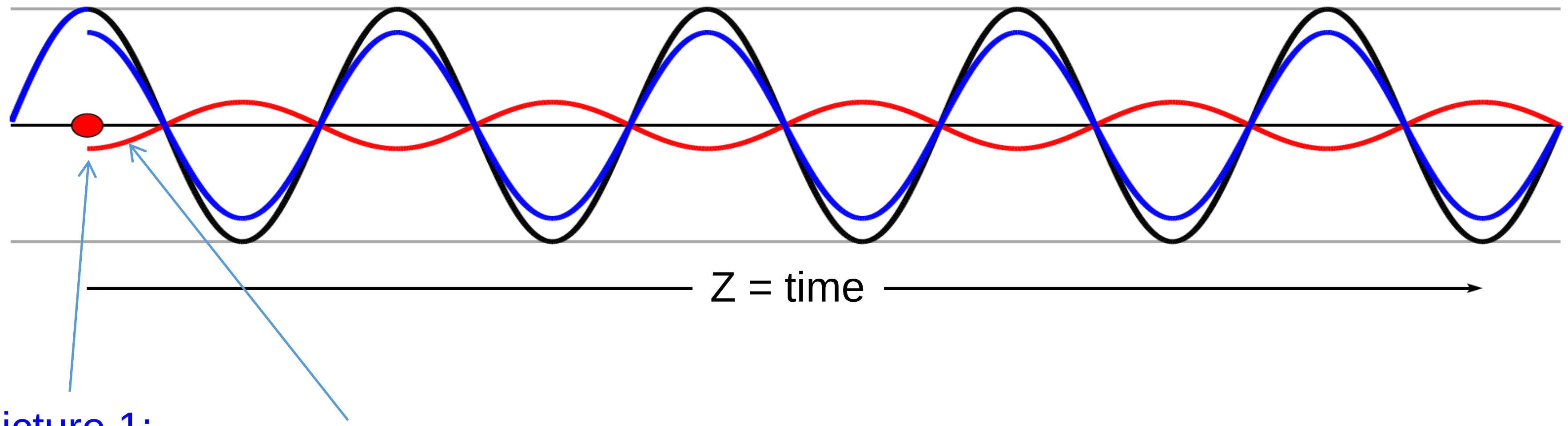
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$





Will ignore multi-bunch wakefields solved by technical means in CLIC

Longitudinal Wakefield and Energy Spread

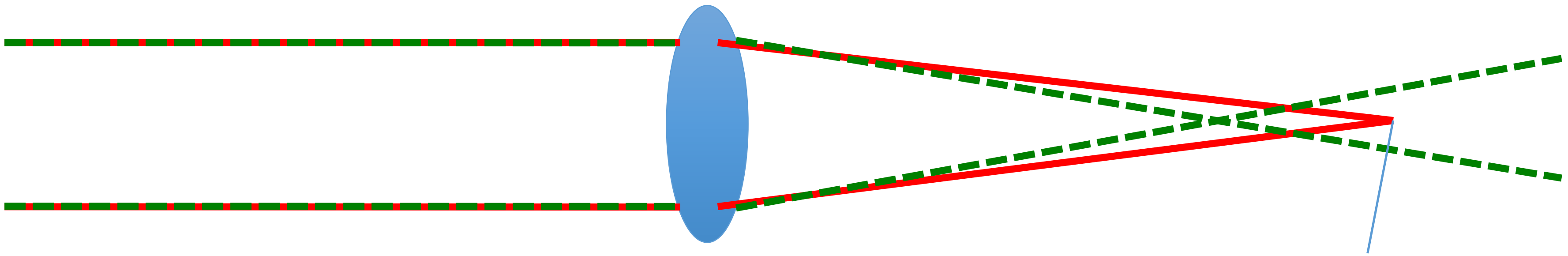


Picture 1:
Particle extracts energy

Picture 2:
Particle induces field

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

Limit arises from final focus system energy bandwidth
CLIC goal 0.35% RMS spread



Nominal particle

Lower energy particle

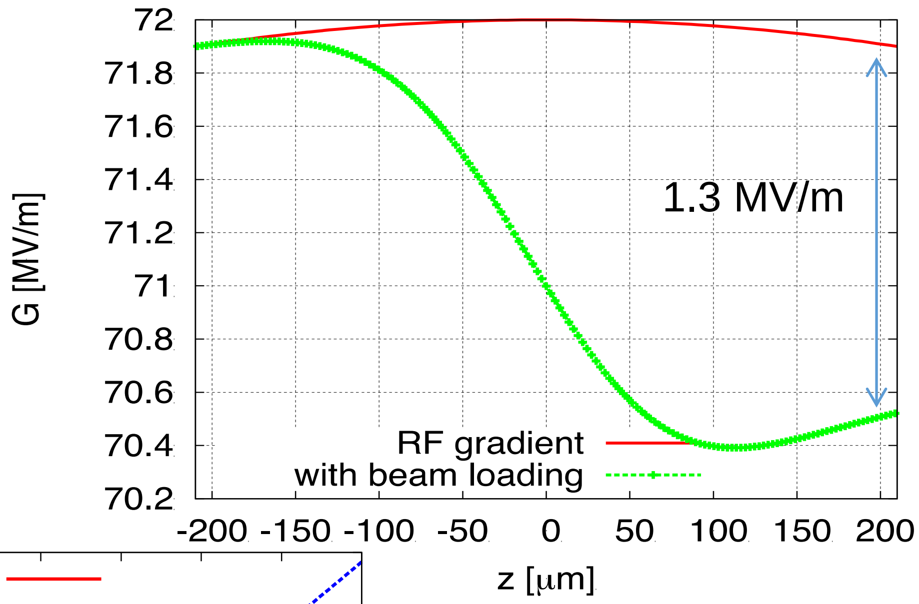
Focusing lens
Actually a doublet of quadrupoles

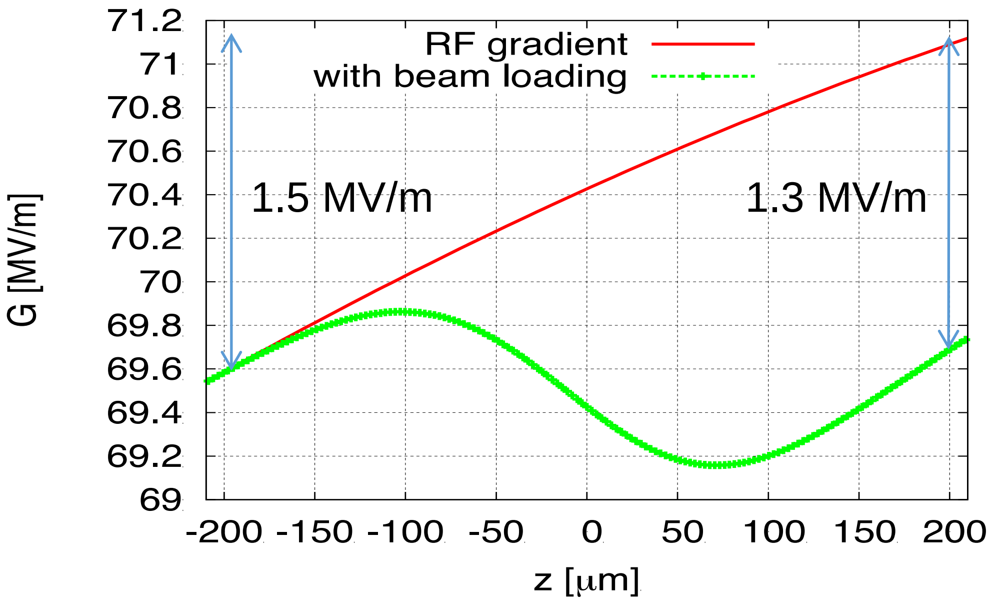
IP, i.e. focal point

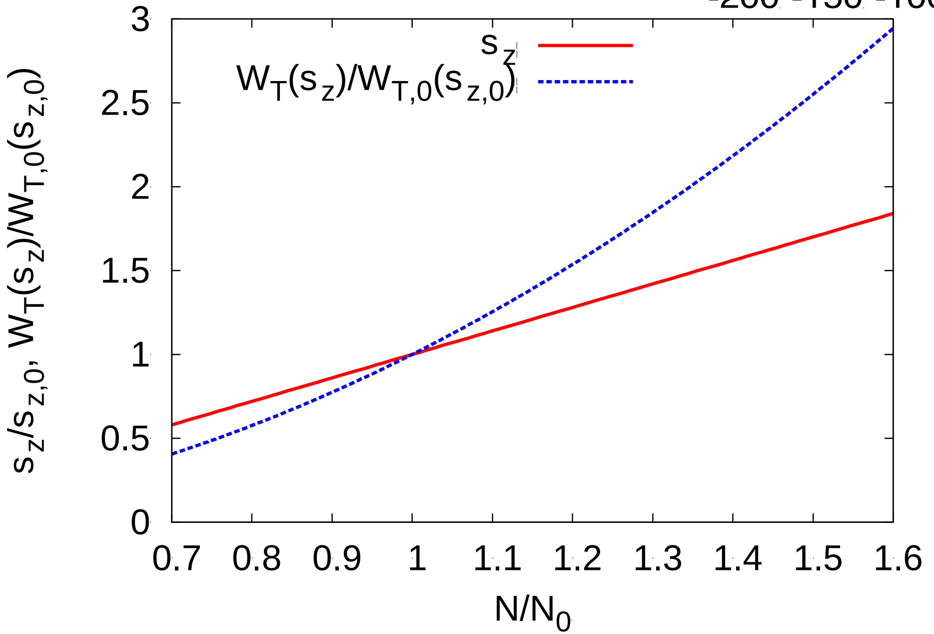
Energy Spread and Bunchlength

Energy spread can be reduced by passing beam off-crest of the RF

Reasonable limit 12°
2% gradient loss







This ties the bunch length to the charge for a given structure design

More charge requires longer bunches
The transverse wakefield effect roughly increases as length x charge

Transverse Wakefields

For short distances the wake-field rises linear

Coherent bunch offset (worst case)
The tail is deflected to the outside

- Oscillation amplitude increases
- Oscillation frequency decreases

First particle

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

Example equation of motion first particle

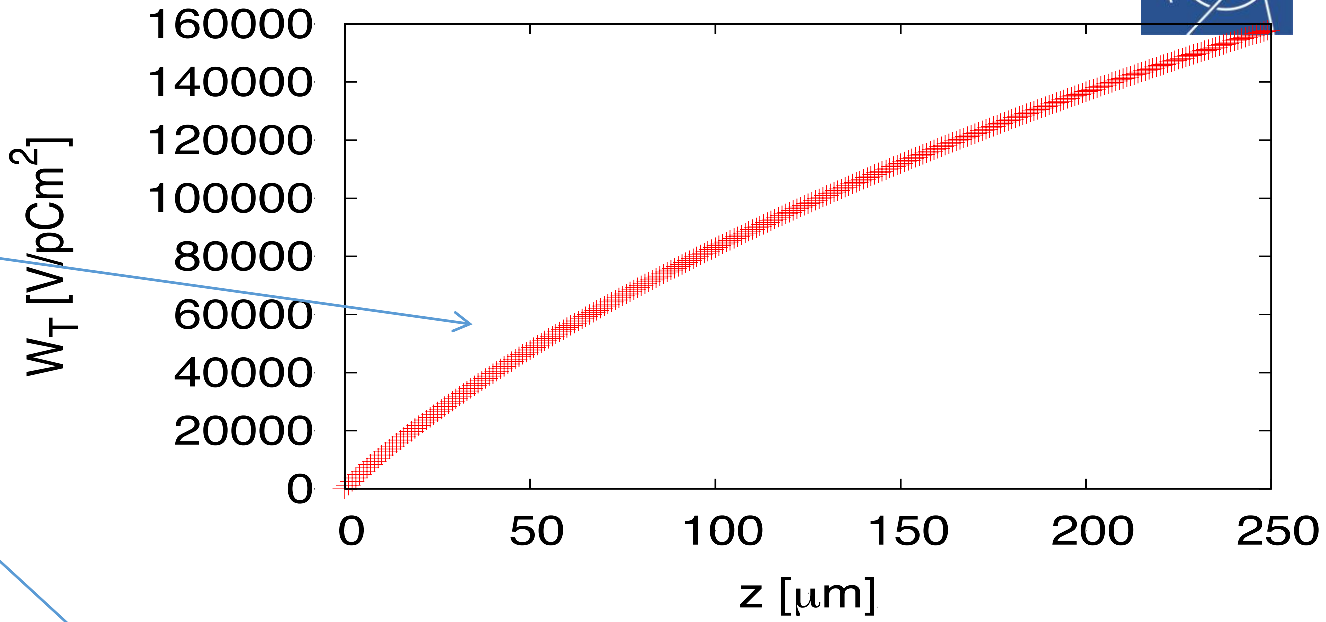
$$x_1(s) = x_0 \cos\left(\frac{s}{\beta}\right)$$

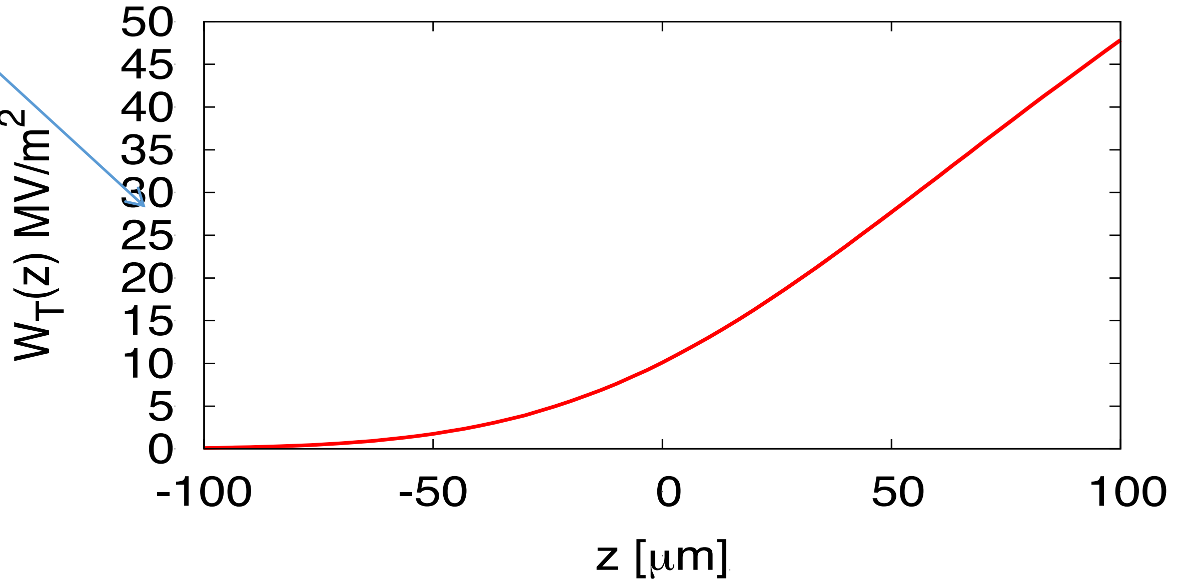
Second particle

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

Example equation of motion second particle

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

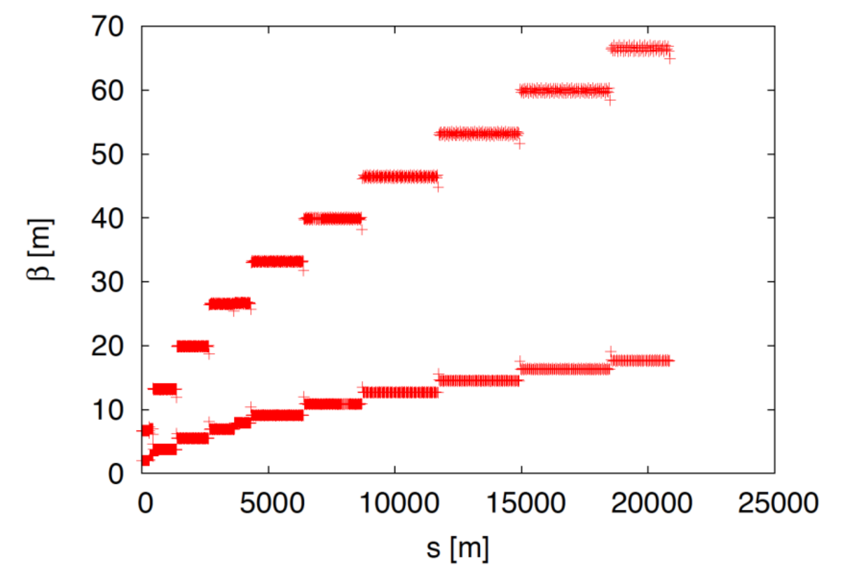




Tricks of the Beam Physics

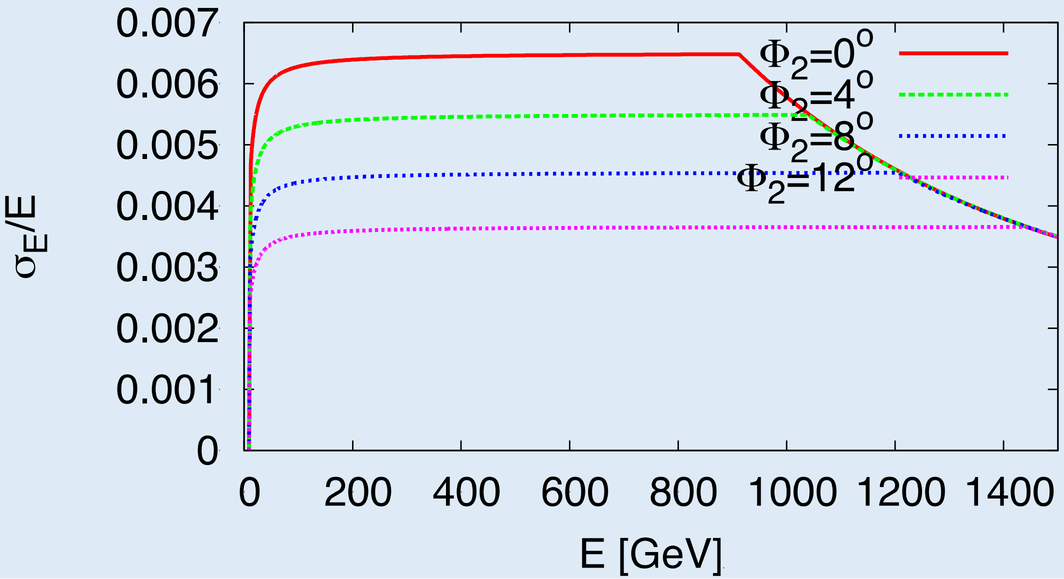
Make the focus strong again

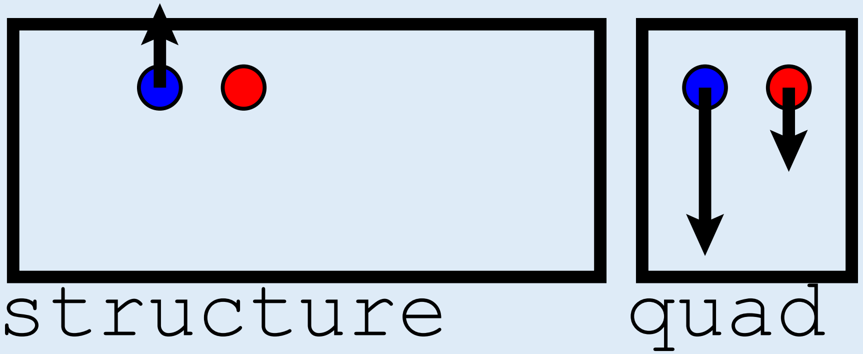
- Use O(10%) of the linac for magnets
- Leads to small beta-function
- Makes the beam stable (strong spring for an oscillator)



For single bunch use BNS damping (Balakin, Novokhatsky and Smirnov)

- Introduce energy chirp that compensates transverse wakefields

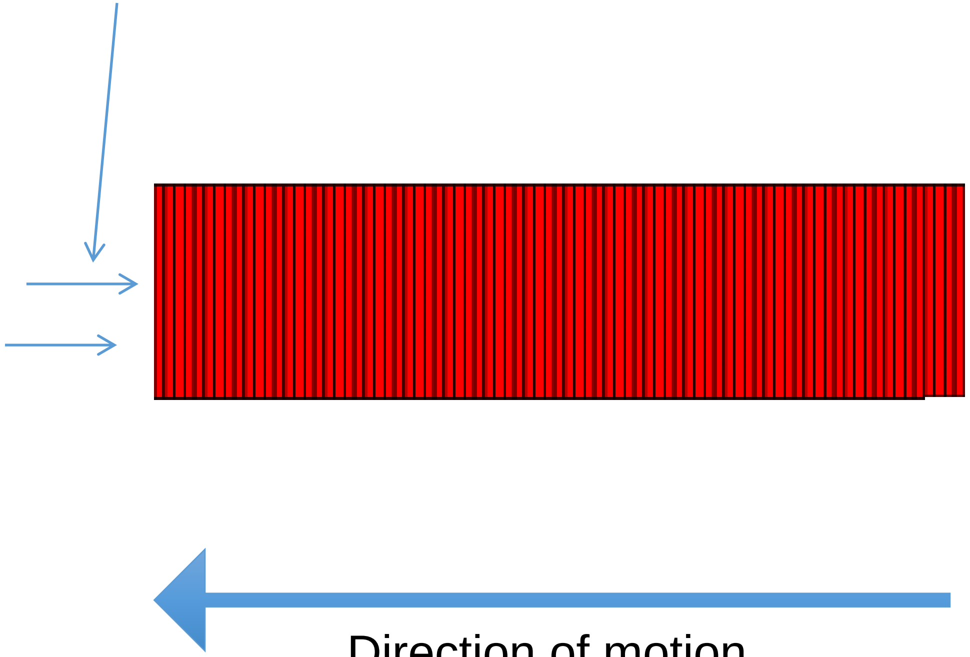




Beam Stability, With BNS

No BNS damping

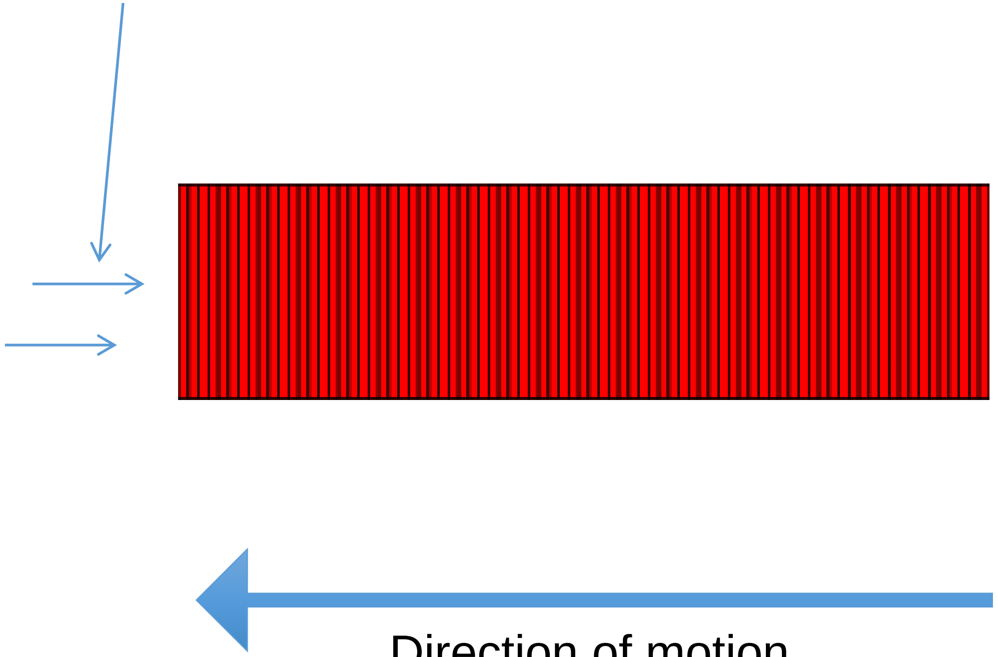
Offset beam centre at injection



Direction of motion

With BNS damping

Offset beam centre at injection

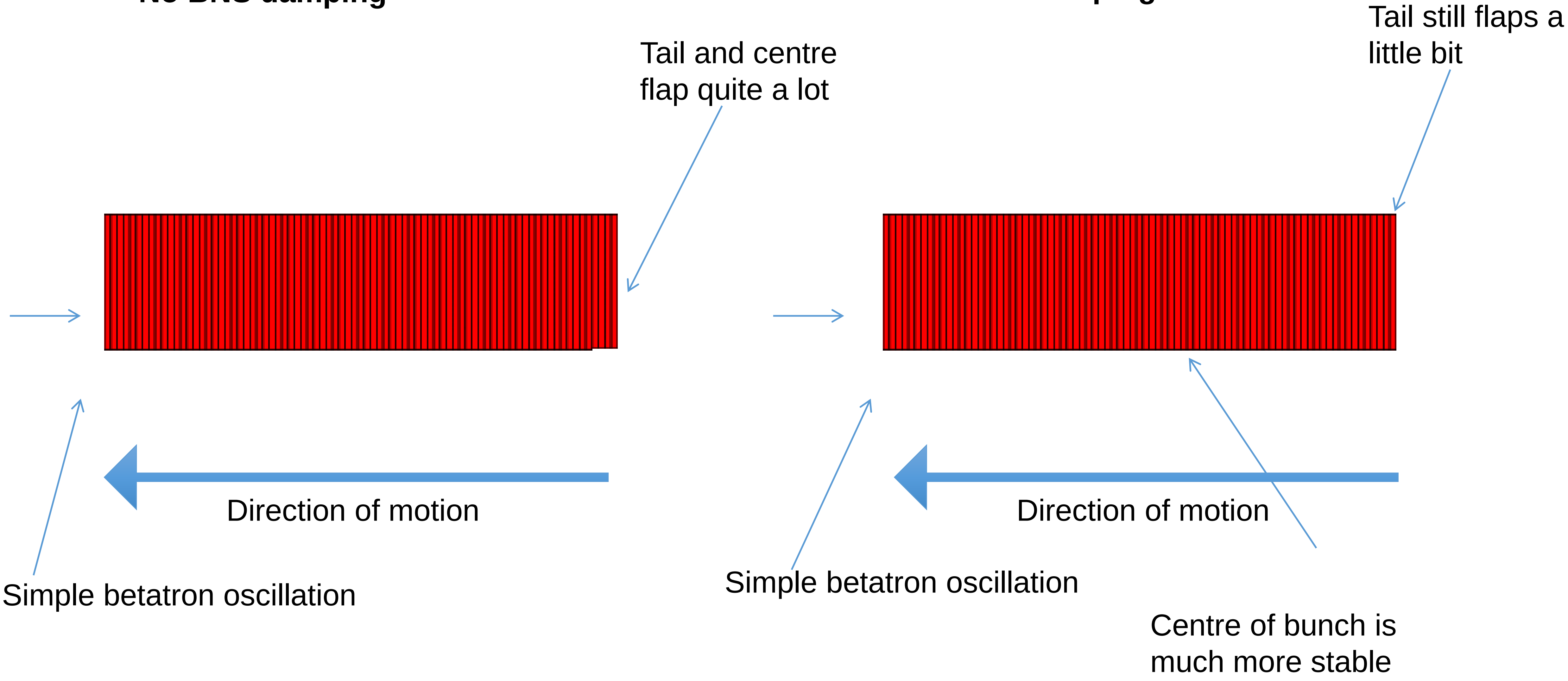


Direction of motion

Beam Stability, With BNS

No BNS damping

With BNS damping



Tail and centre flap quite a lot

Direction of motion

Simple betatron oscillation

Tail still flaps a little bit

Direction of motion

Simple betatron oscillation

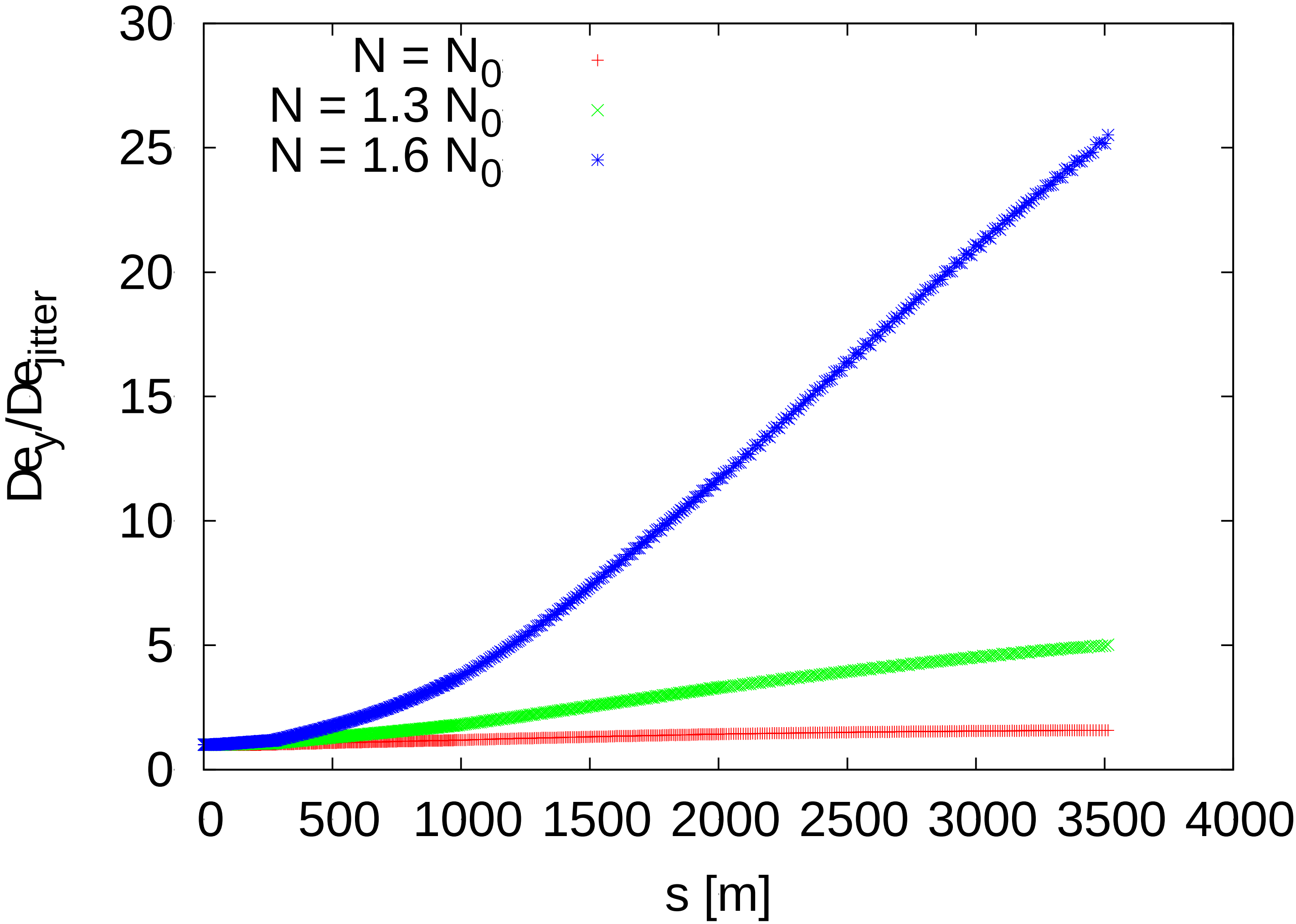
Centre of bunch is much more stable

Impact of Charge

If one increases the charge the beam stability will be compromised

30% more charge are still reasonable
But keep a bit away to as a margin

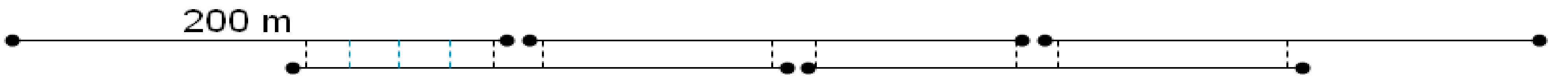
60% more charge leads to unstable beam

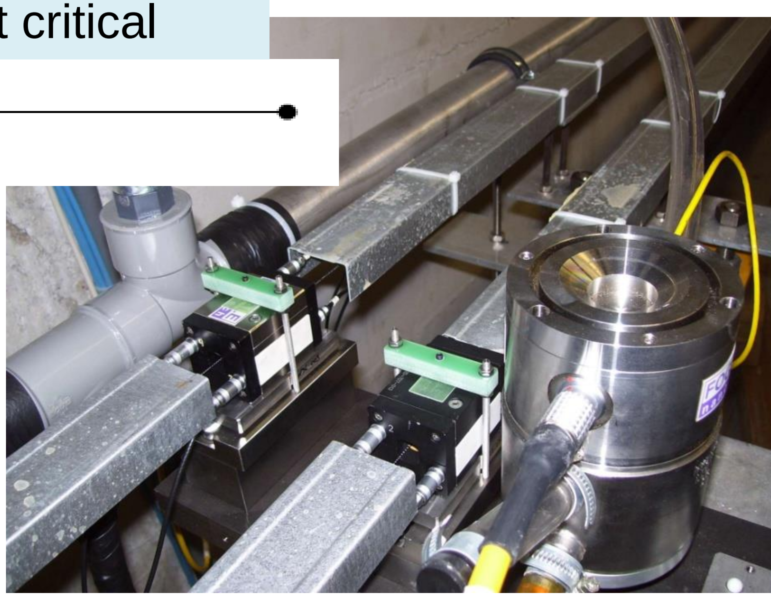


Static Imperfections: Main Linac Alignment

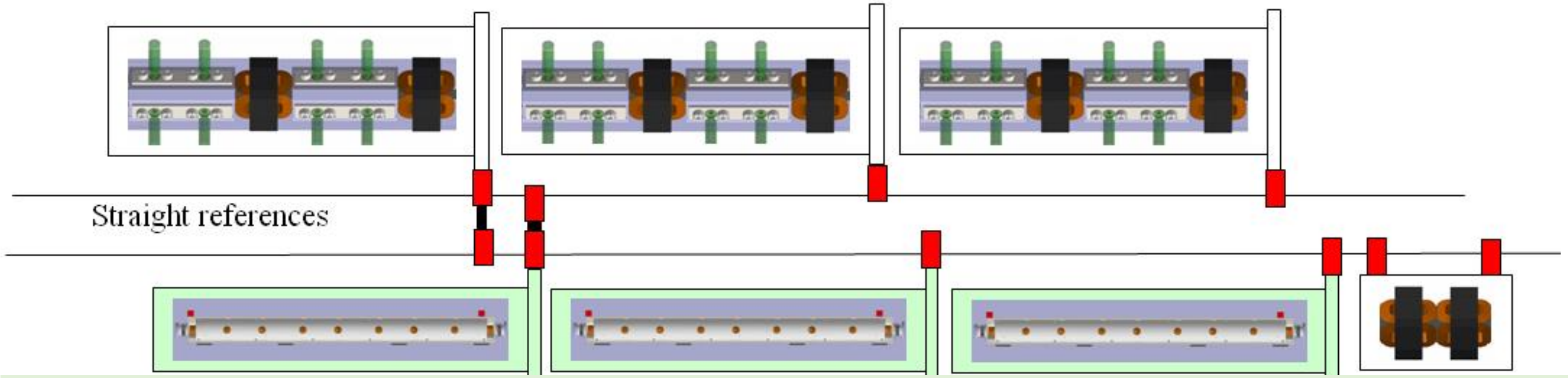
1) Align components accurately on the supporting girders

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





3) Align modules remotely to the wires using their sensors and movers

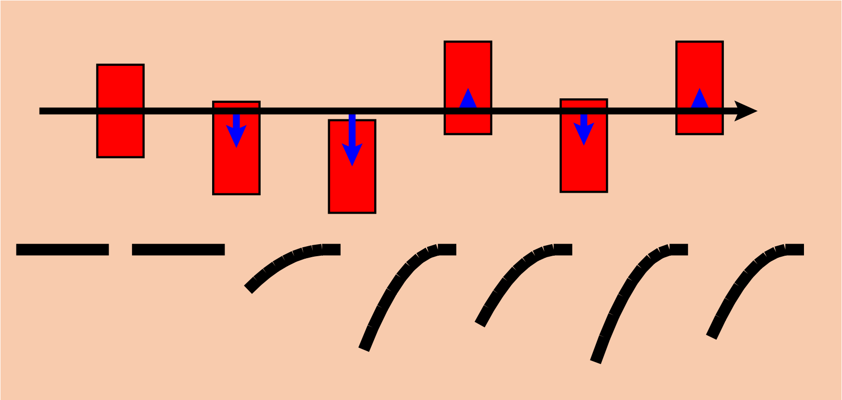


The error for this is most critical misalignment of components is of the order O(10µm)

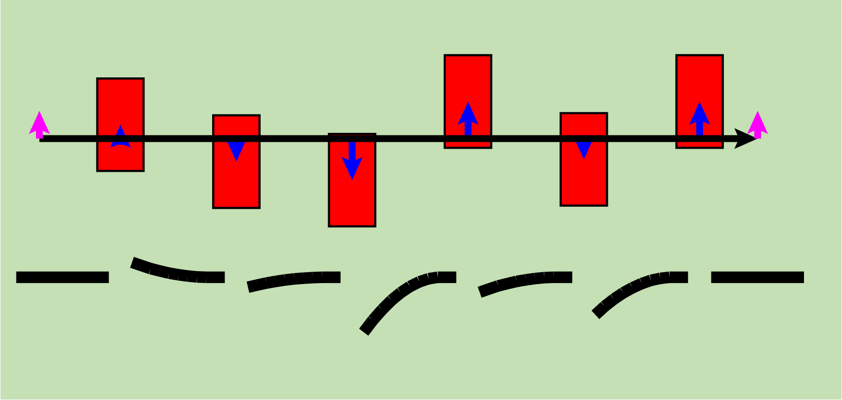
4) Use sophisticated beam-based alignment such as dispersion free steering (DFS, i.e. different energy beams) to align components
In particular to align BPMs

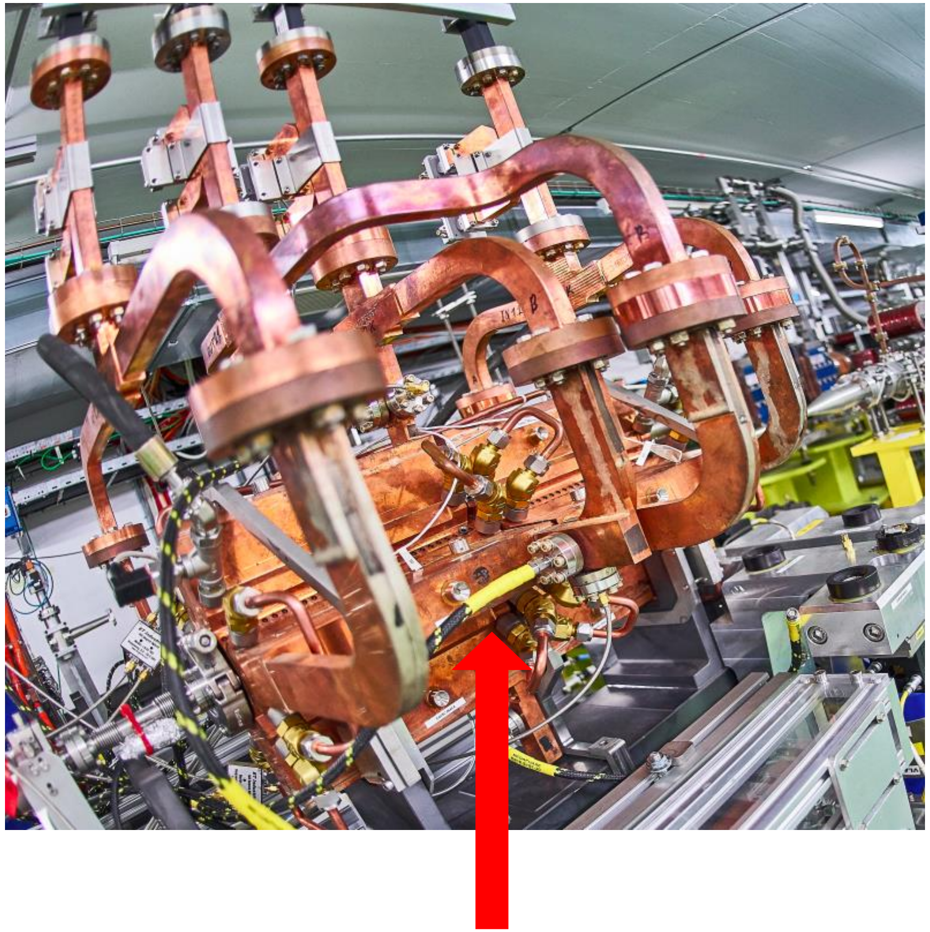
RF Alignment

Structures scattered on girder
⇒ Wakefield kick



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





Wakefield monitor:
Measure wakefield in damping waveguide

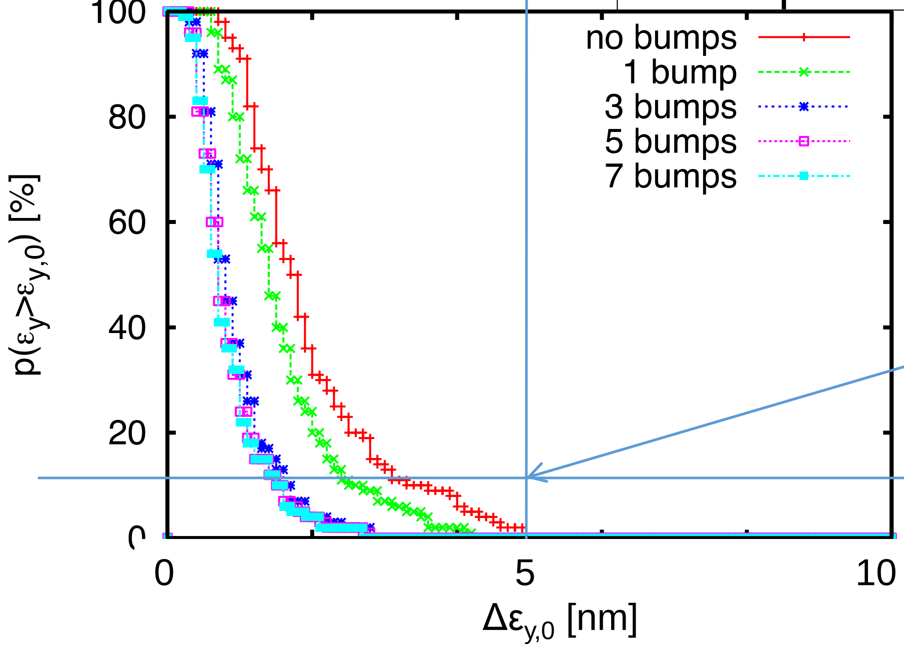
Limit mainly from
- wakefield monitor accuracy (3.5 μm)
- reproducibility of wakefield
- tiny variation of betatron phase along girder

Main Linac Emittance Growth (3 TeV)

Emittance growth for different imperfections

Using sophisticated beam-based methods

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	≈ 0.12 nm



Note: The tight tolerances are the price for the strong focusing, Which allowed high beam current

Goal: less than 10% above $\Delta\varepsilon_y = 5$ nm

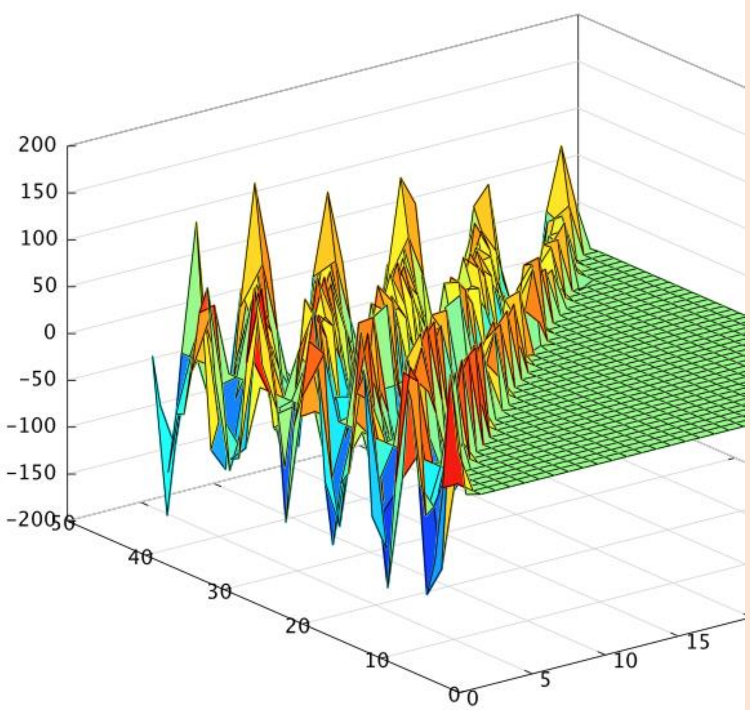
Further improvement using tuning bumps

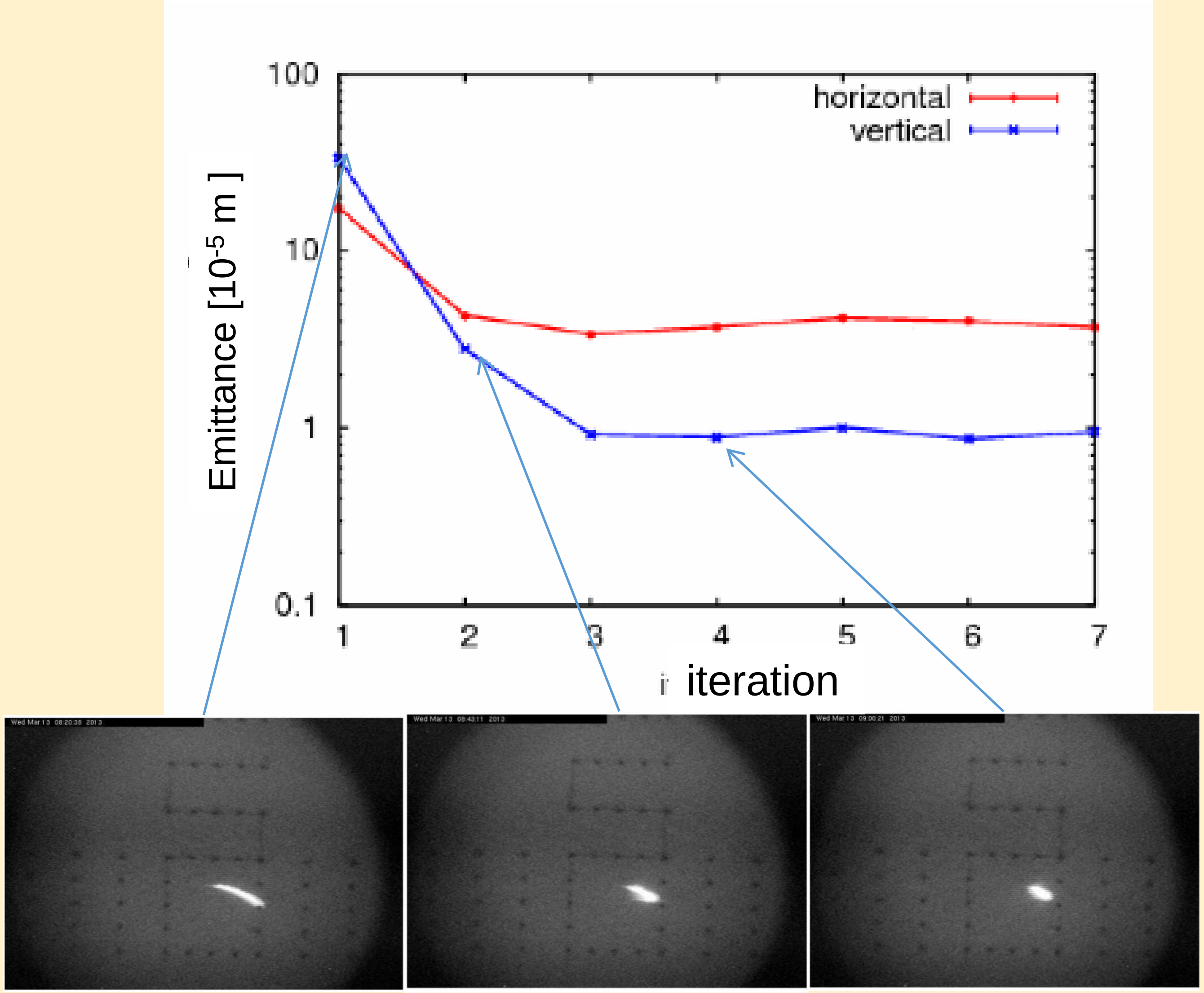
CLIC Beam-Based Alignment Tests at FACET

DFS applied to 500 meters of SLC linac

- System identification algorithms to construct model
- DFS correction with GUI
- Emittance growth is measured

System model





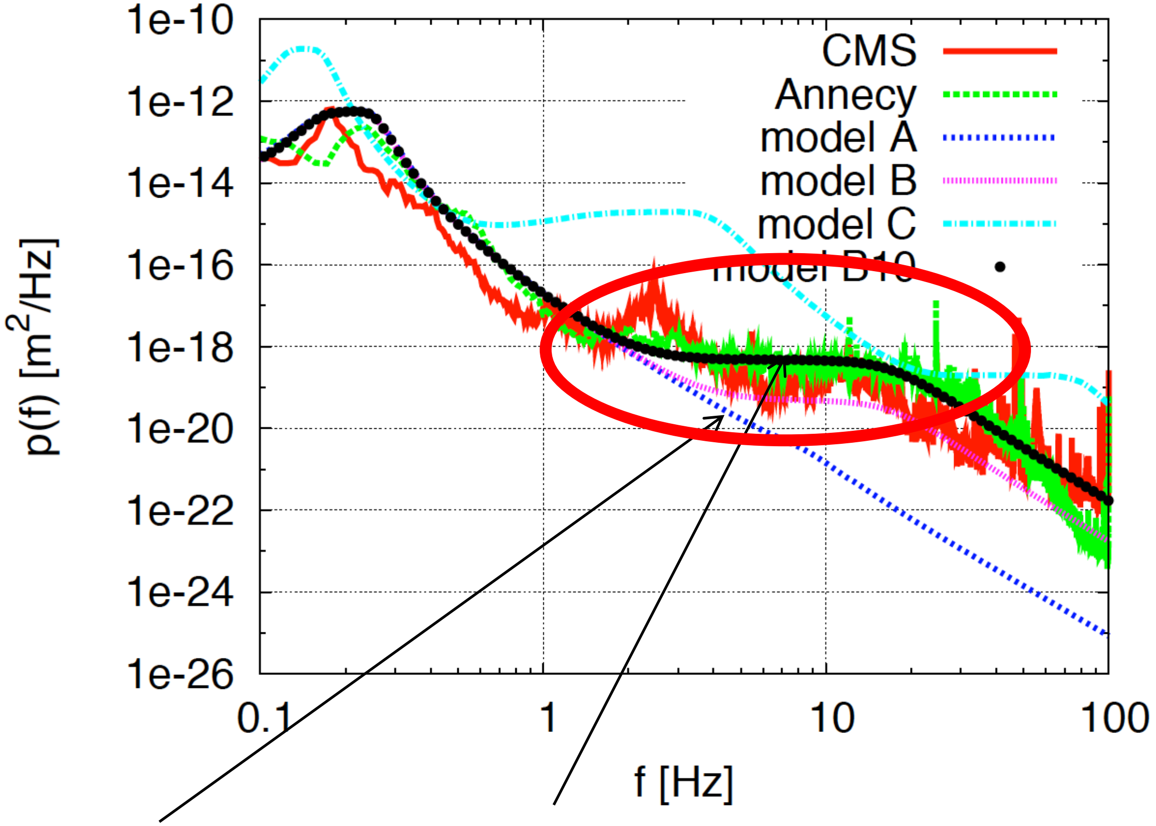
Initial beam

After 1 iteration

After 3 iterations

Dynamic Imperfection Example: Ground Motion

Ground motion can impact beam trajectory



LEP tunnel

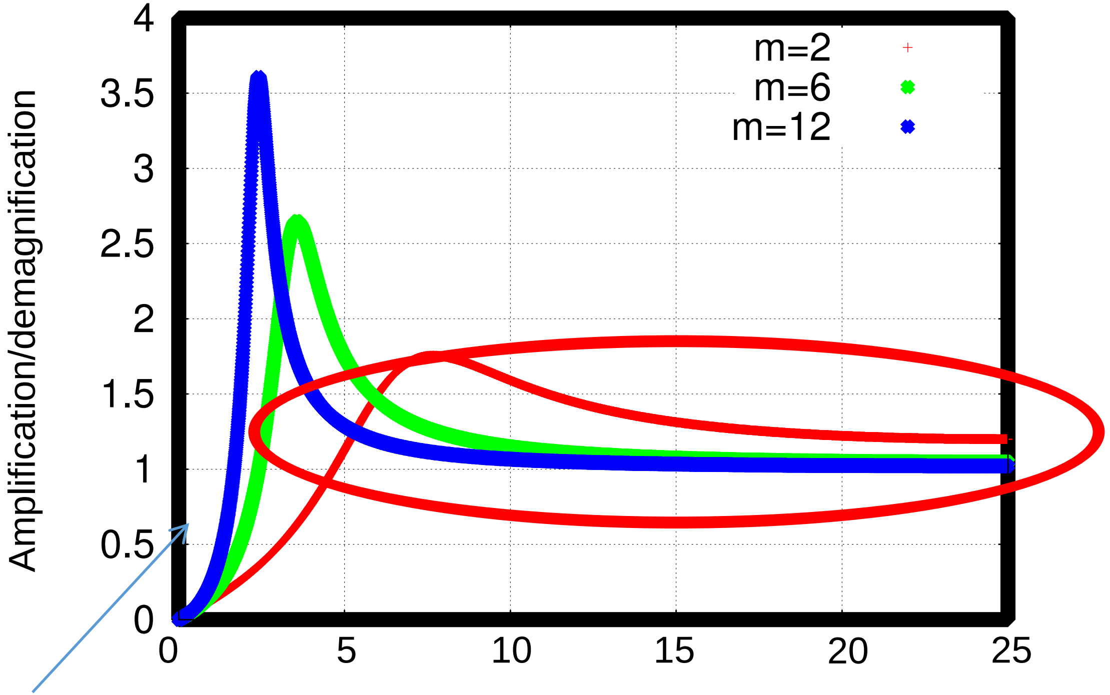
Want to be able to cope with this
(Model B10 similar to CMS hall)

Beam-trajectory feedback corrects pulse-to-pulse (20 ms)

⇒ Cures low frequency ground motion

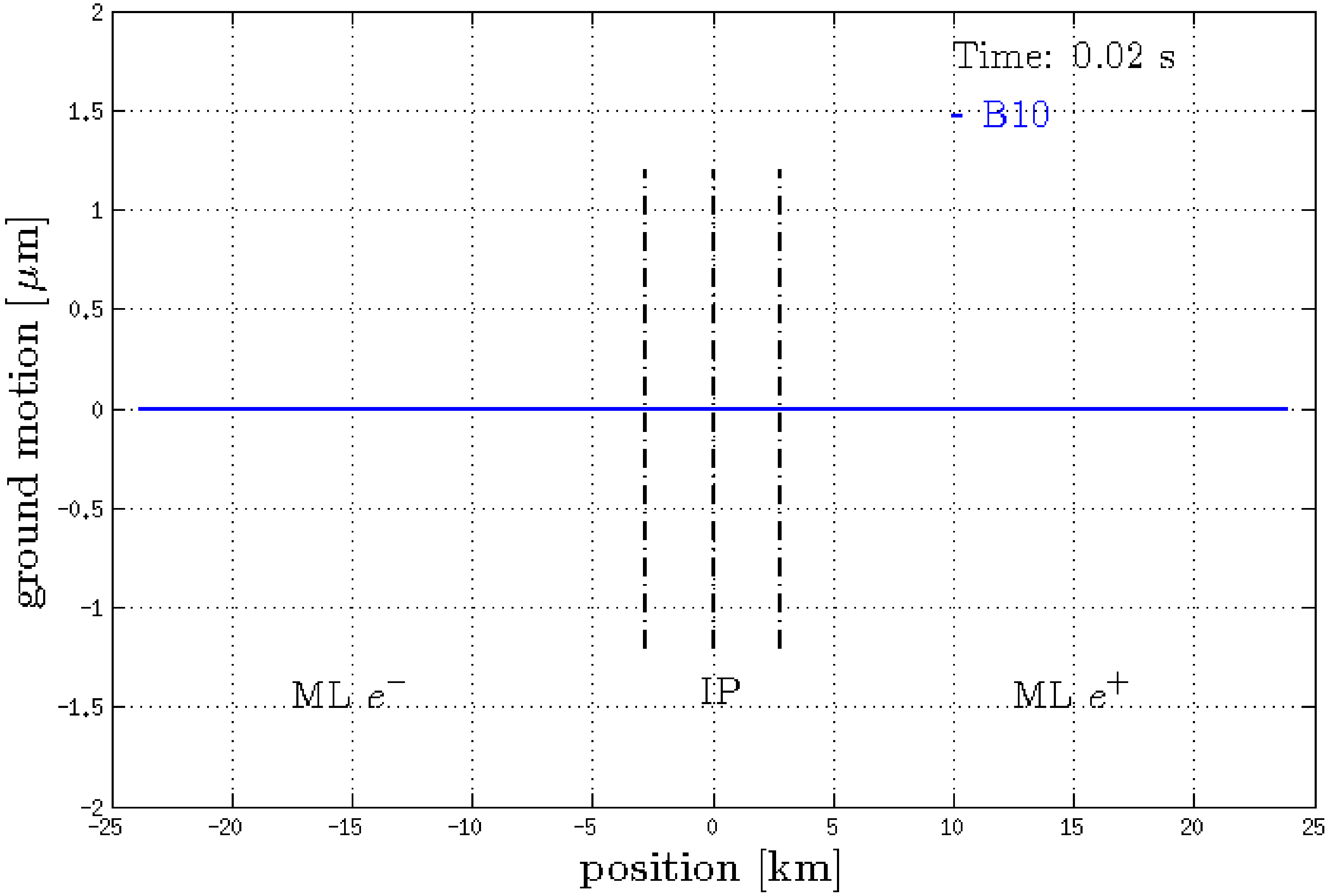
⇒ But not higher frequencies

Beam-trajectory feedback:
Example transfer curve (recursive filter)

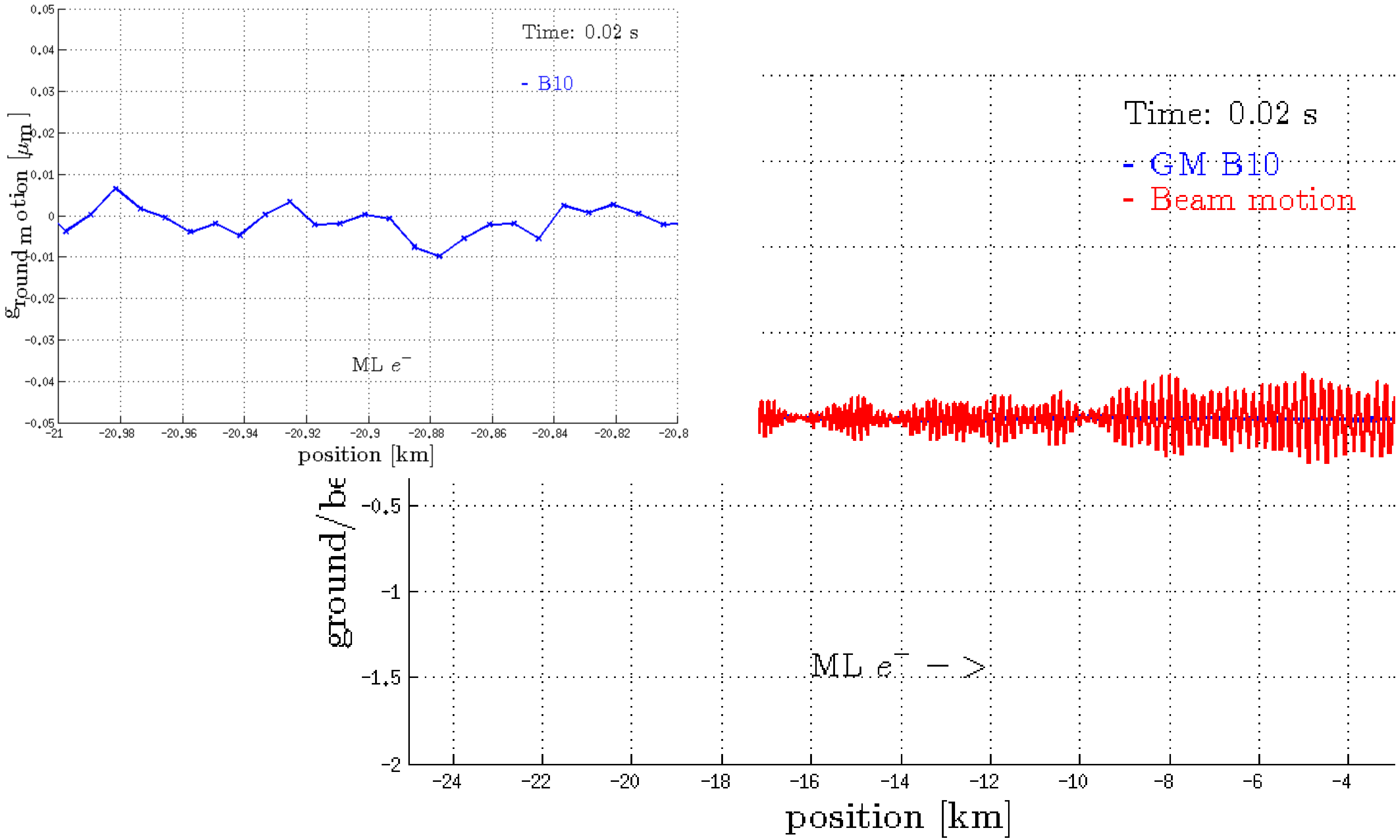


demagnification

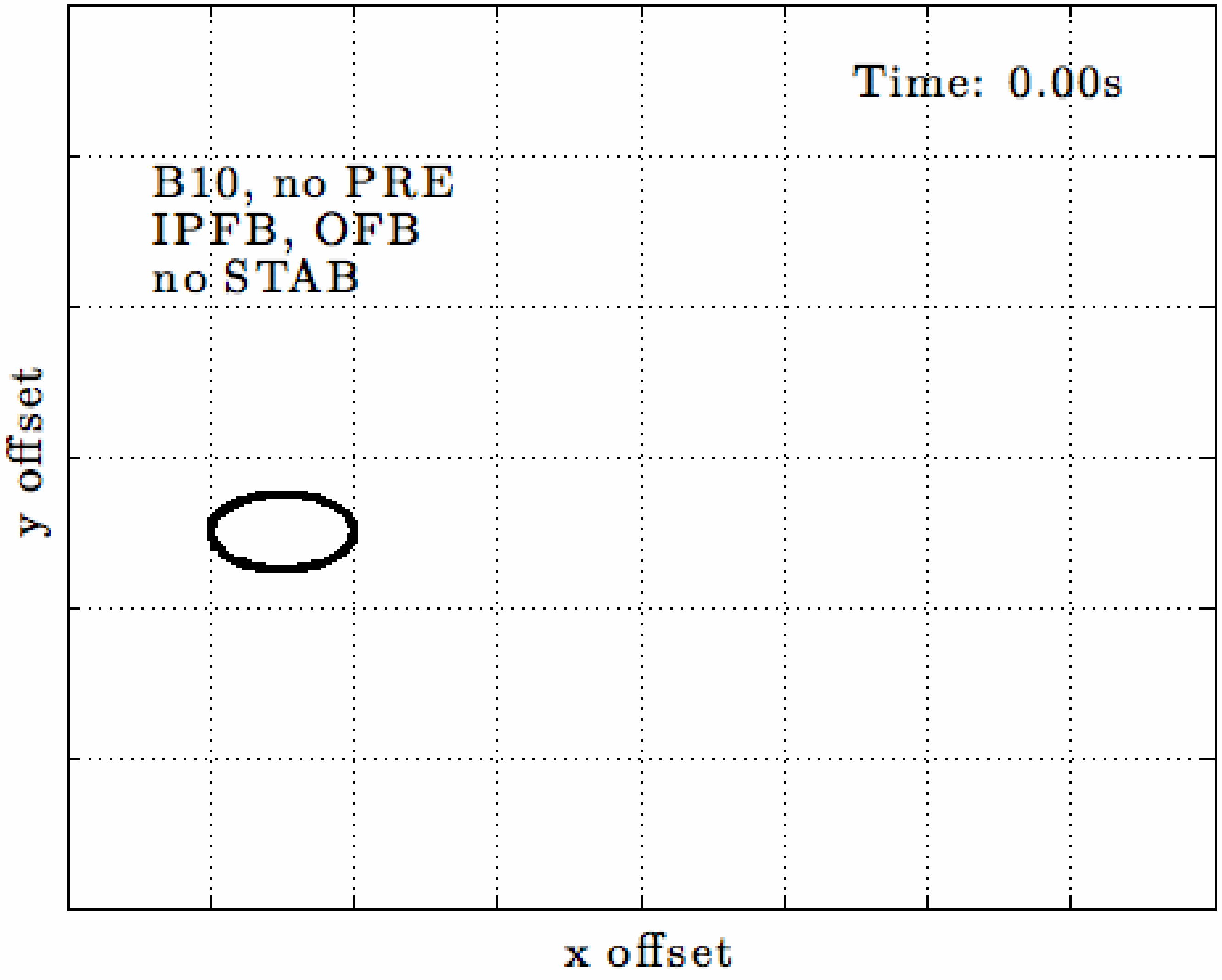
Ground Motion



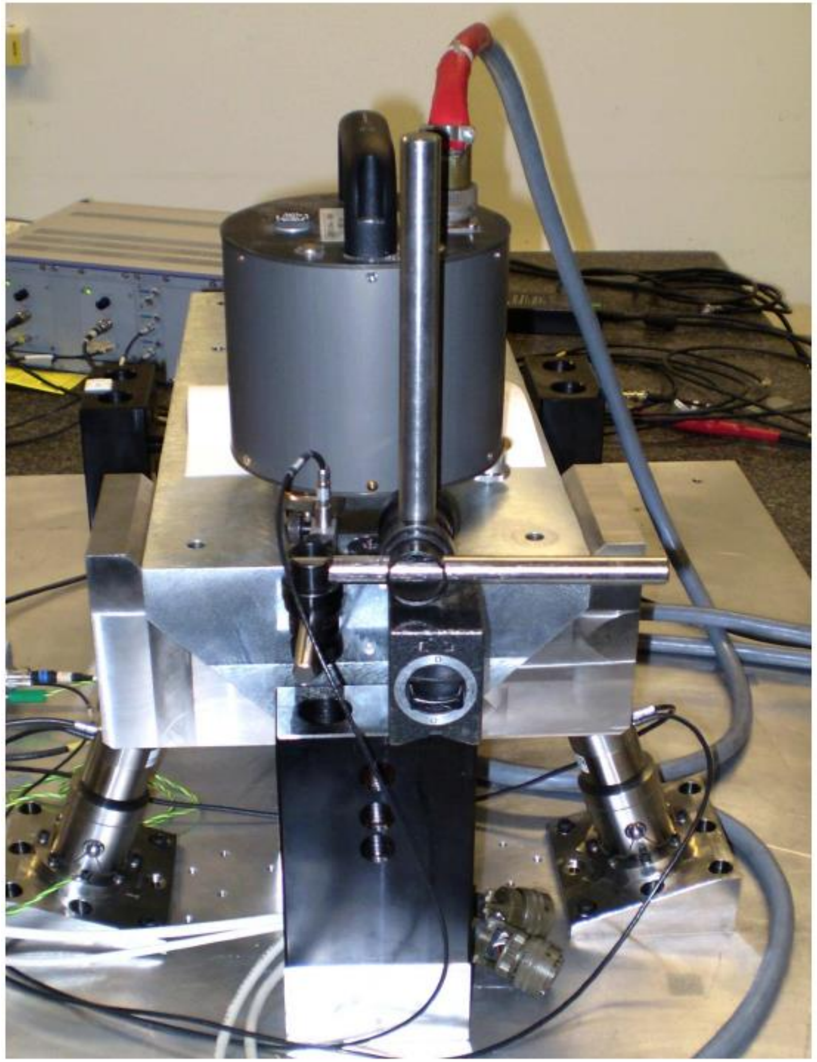
Beam Motion with Beam Feedback Only



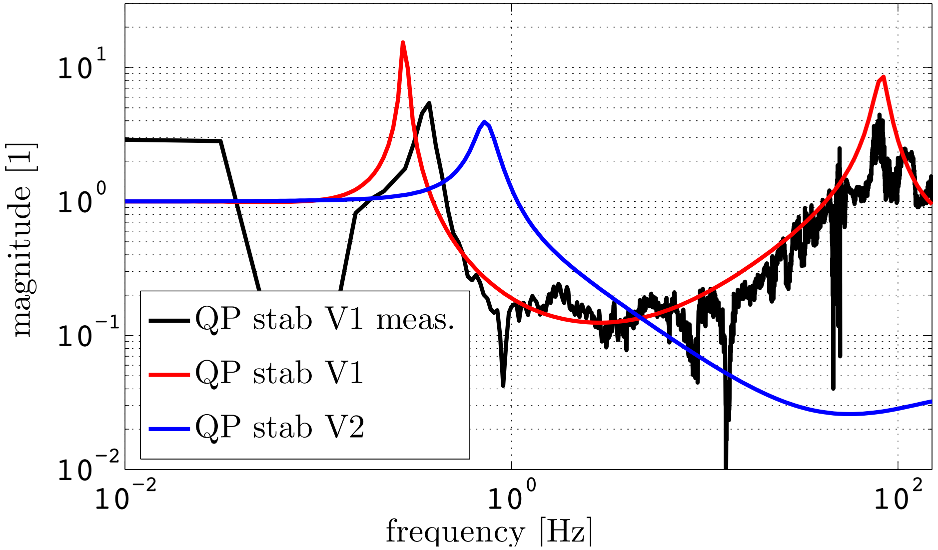
Jitter at IP

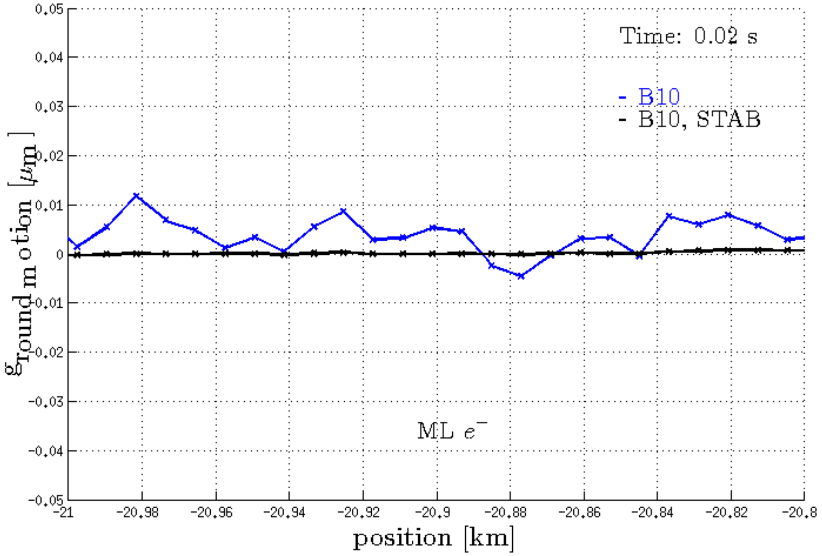


The Stabilisation System

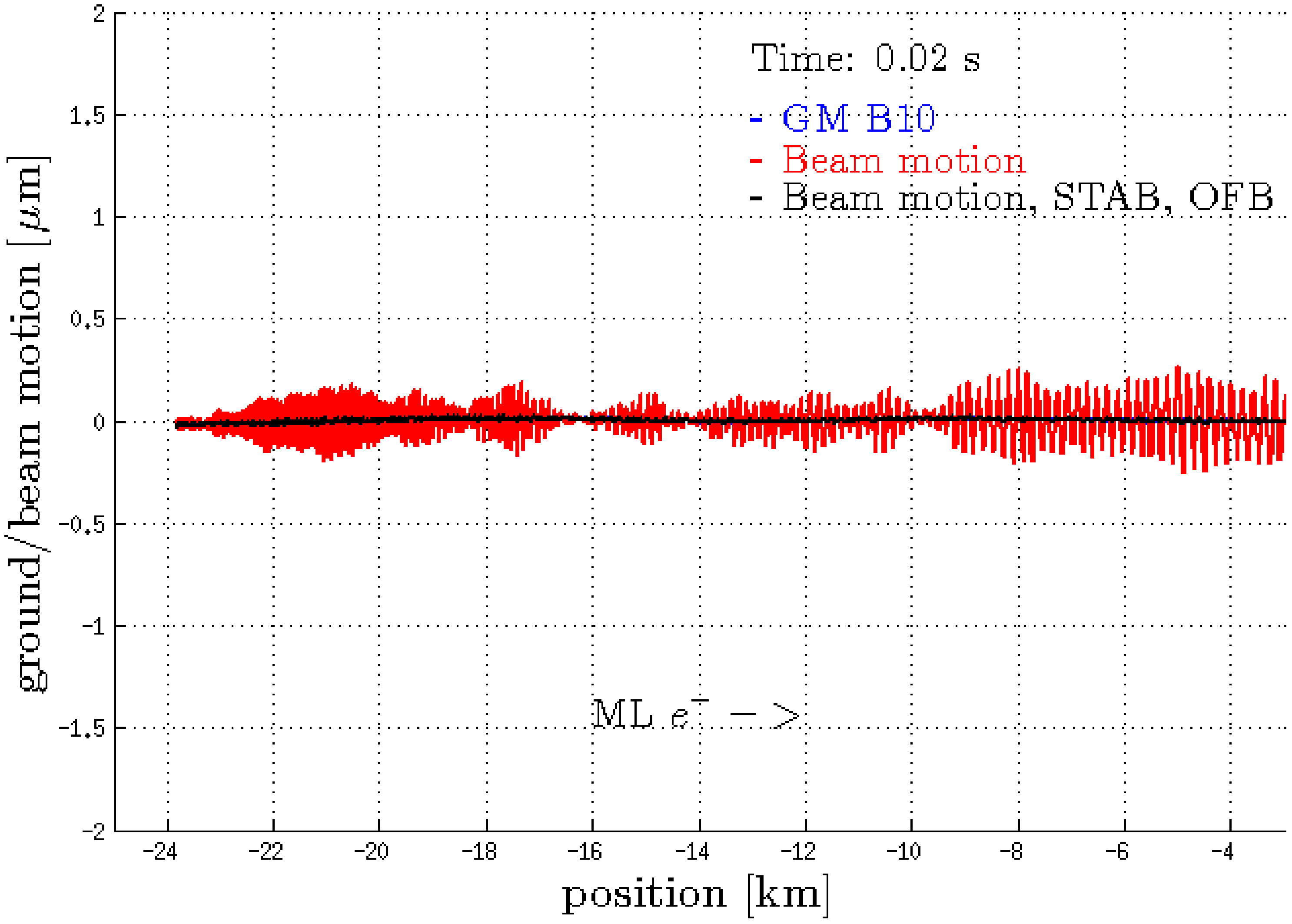


K. Artoos et al.

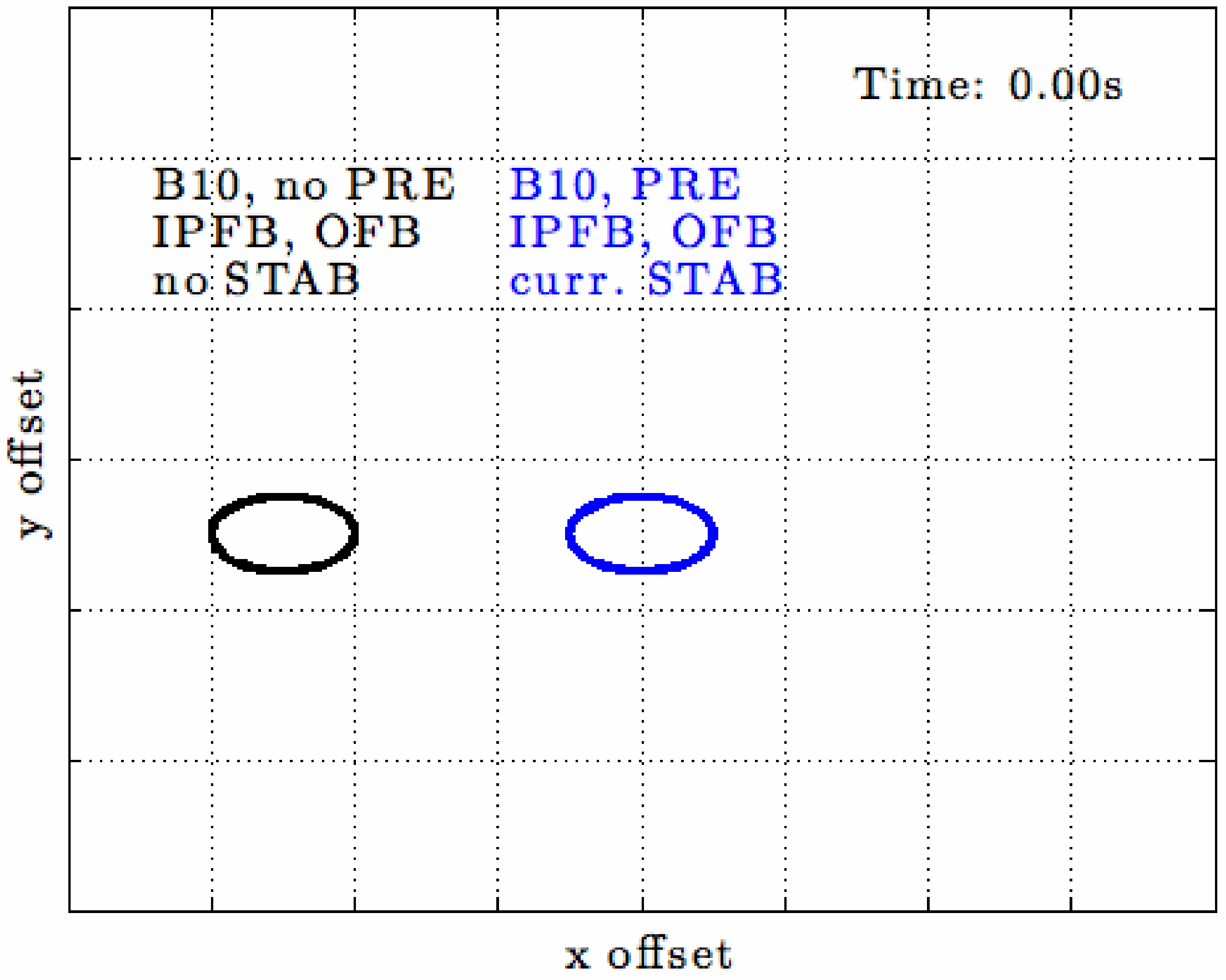




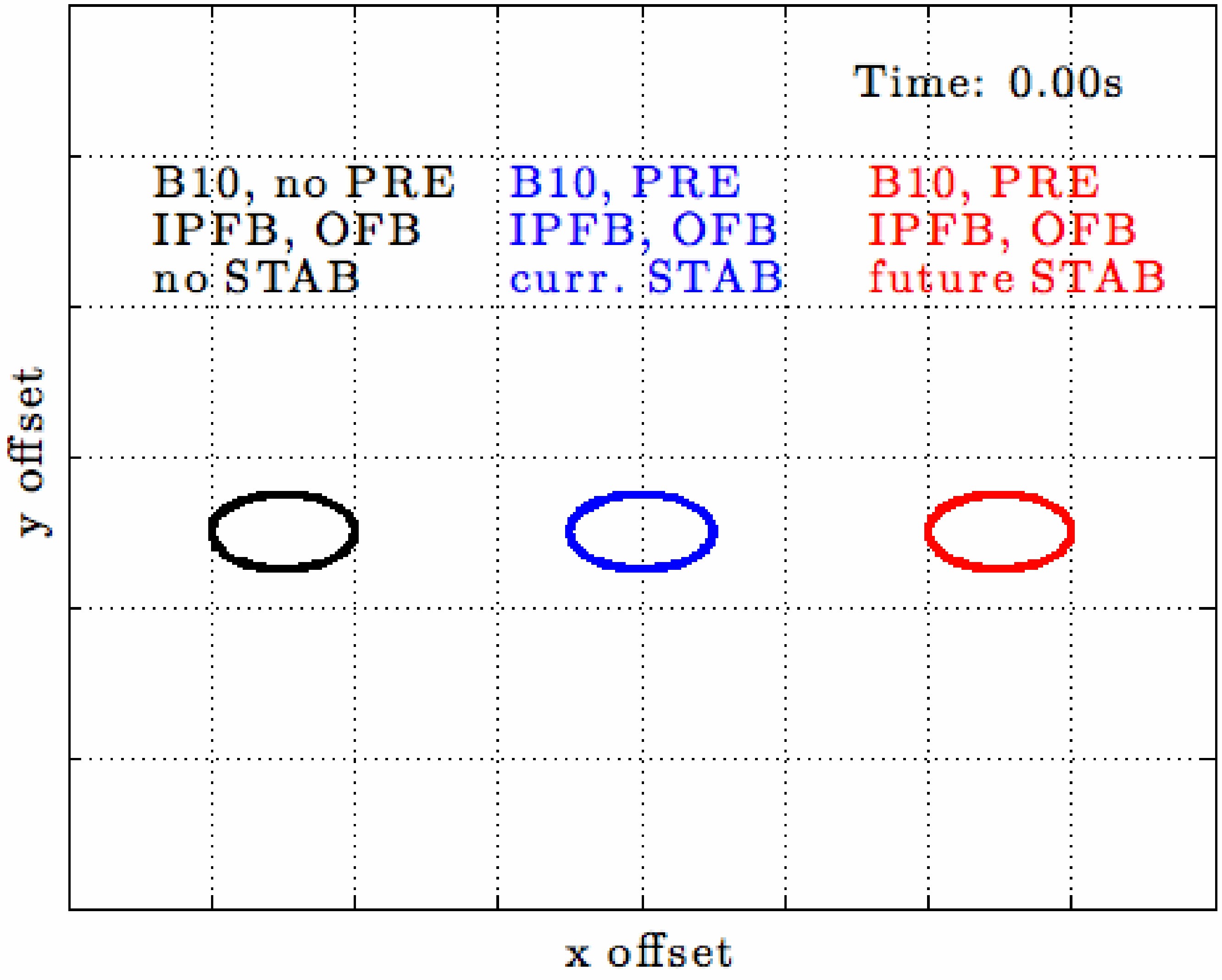
Beam Trajectory Jitter



Beam Jitter at IP



Beam Jitter at IP



Conclusion

The main linac beam dynamics is a key parameter driver in CLIC

- It defines the charge and collision bunch length and impacts the vertical emittance

For each accelerating structure design there is an optimum beam parameter set

- The highest charge that is acceptable in each bunch

Strong focusing is used to mitigate transverse wakefield effects

Imperfections and their mitigation are critical for the emittance growth and luminosity

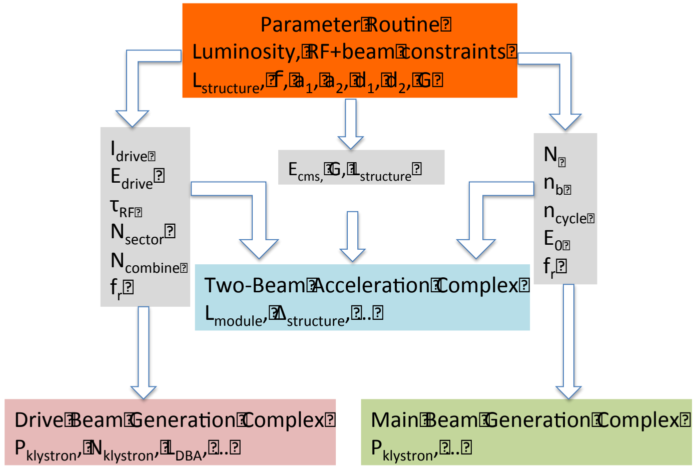
Note: CLIC Optimisation

Scan 1.7 billion cases:

Fix structure design parameters:
a_1,a_2,d_1,d_2,N_c,f,G

$\Rightarrow$ key beam parameters

$\Rightarrow$ 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

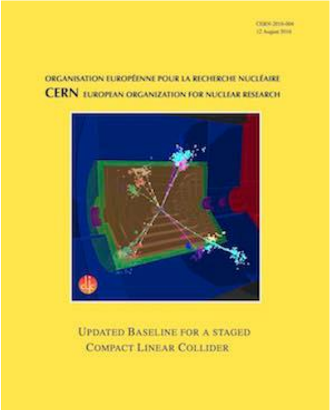
E_{cms}, G, $L_{structure}$

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
$P_{klystron}$, ...



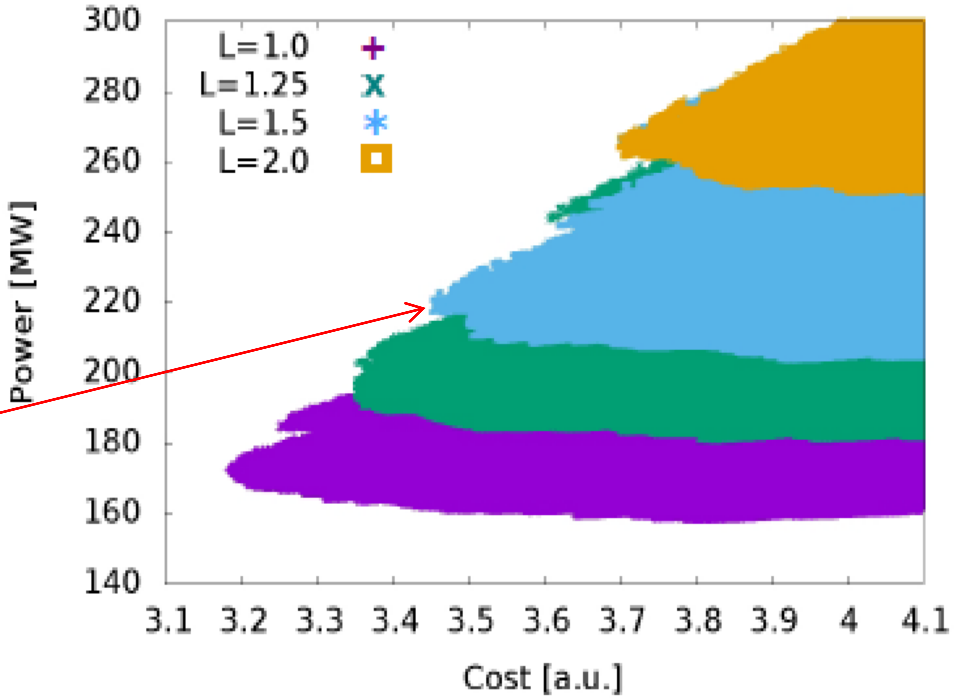
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

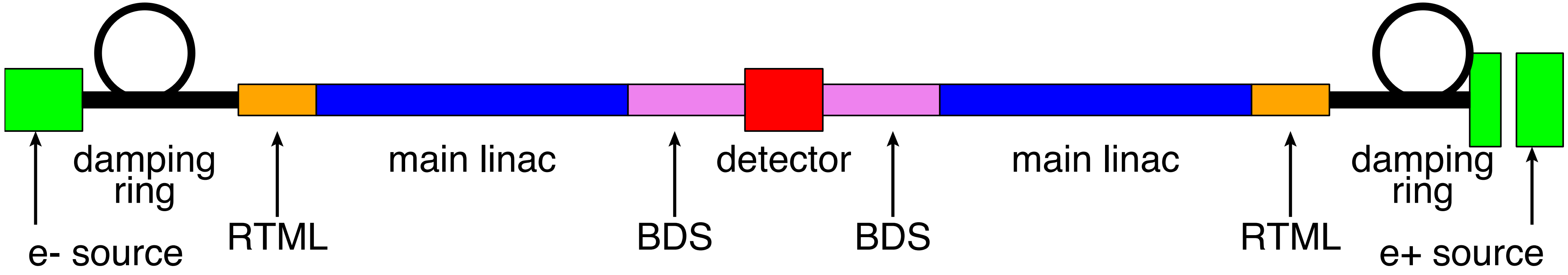
CERN-2016-004

Resulting designs:
Colors indicate luminosities

This is the one that we picked



Reserve



Damping ring makes flat beams

	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

All systems contribute to vertical emittance

Final bunch length defined by main lina

Bunch charge defined by main linac

Bunch energy defined by main linac

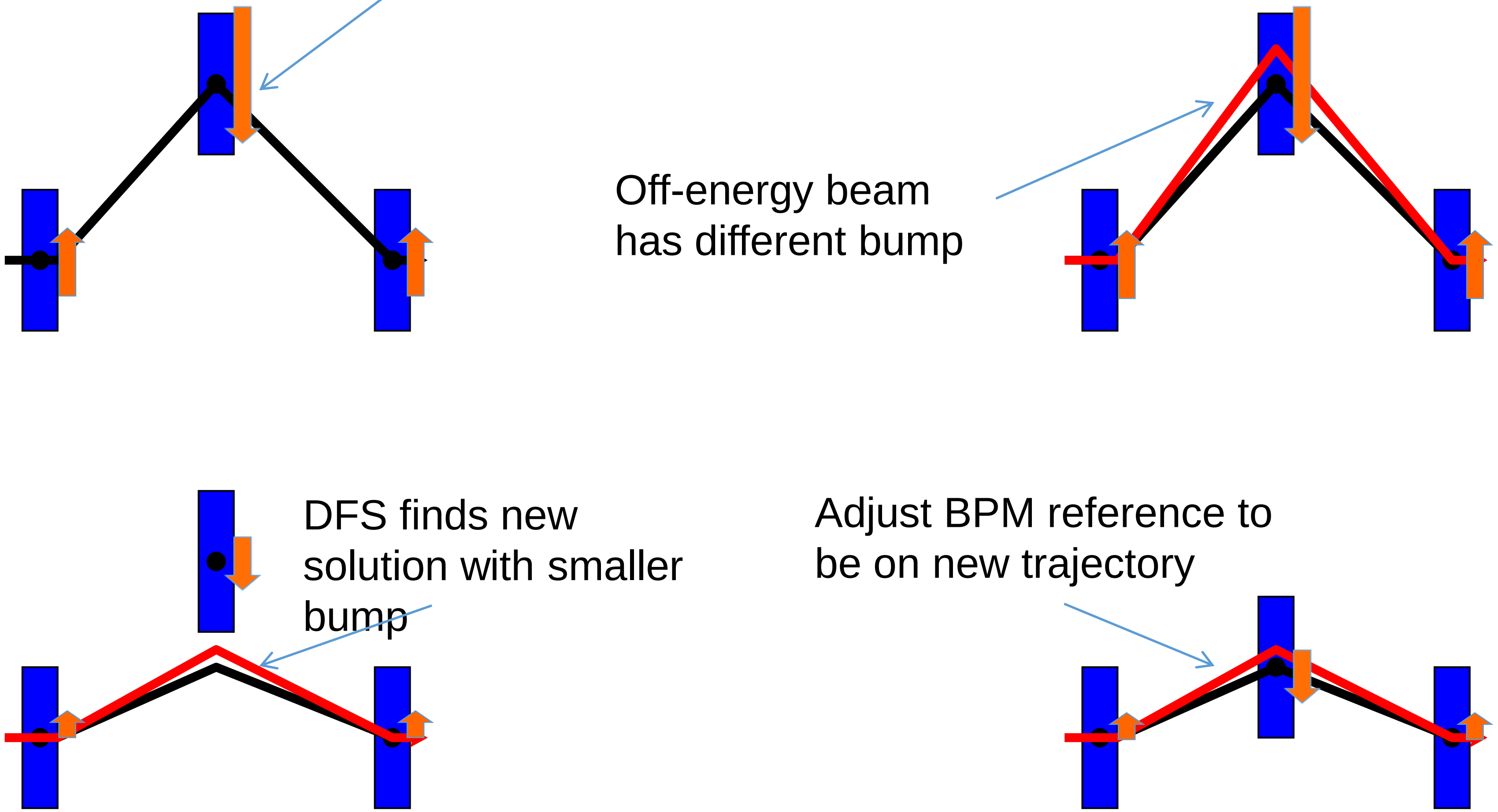
Main Linac: Dispersion-free Steering

Method reduces dispersion

Use beams of **different energy** to identify offset BPMs

Compromise between offset and difference

Dispersion:
Different energy particles take different trajectories



Offset BPM produces bump

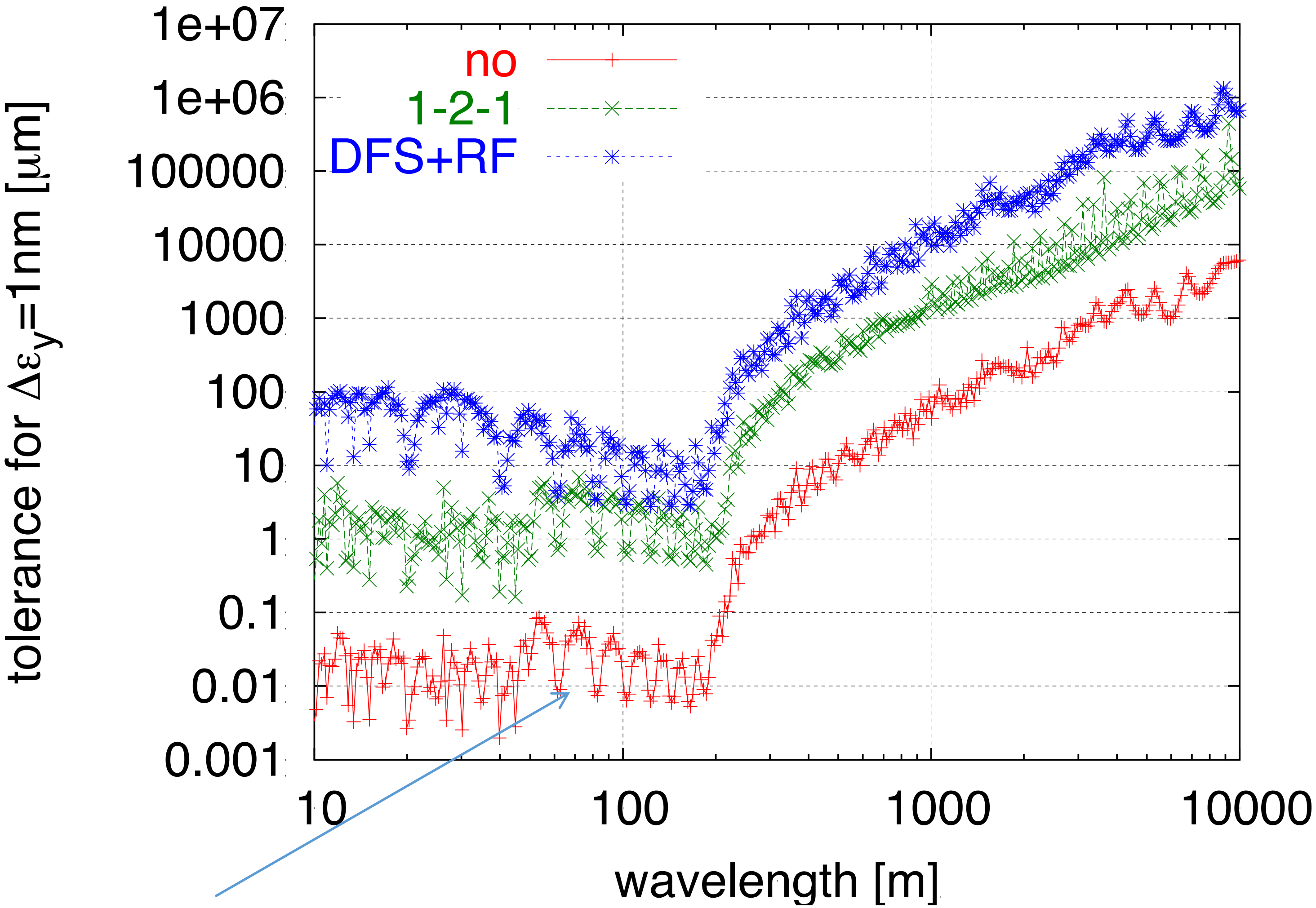
Off-energy beam has different bump

DFS finds new solution with smaller bump

Adjust BPM reference to be on new trajectory

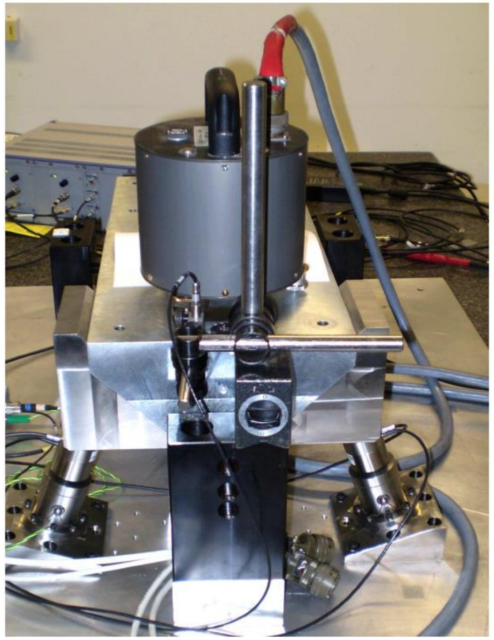
Pre-alignment Wavelength

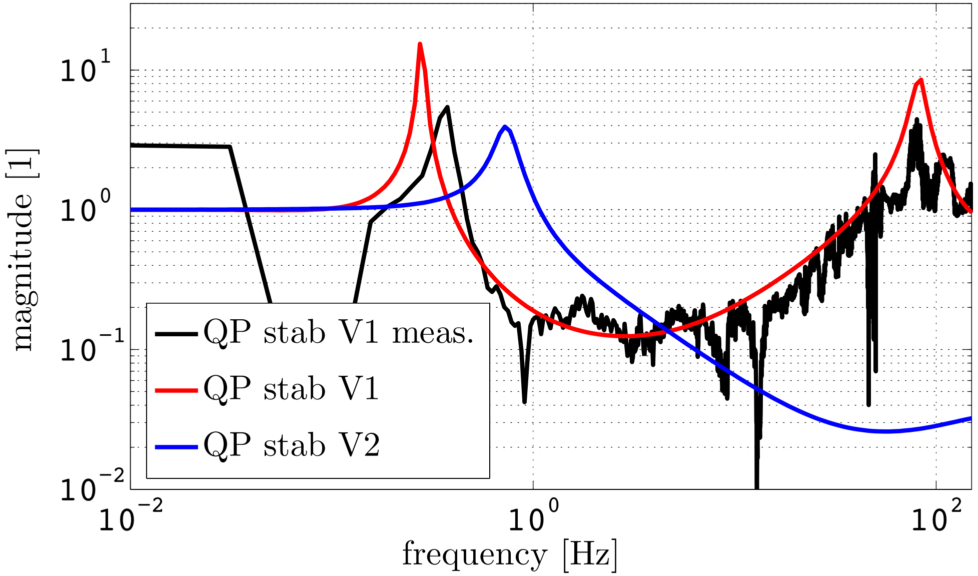
Reference line error with given wavelength

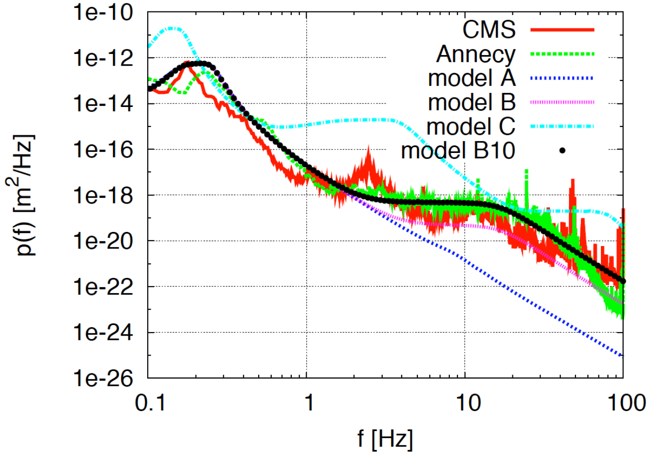


Betatron wavelengths of the different sectors

Ground Motion Summary







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