CLIC: The CLIC Accelerator Design and Performance

CERN Academic Training

Wednesday March 7, 2018

Daniel Schulte

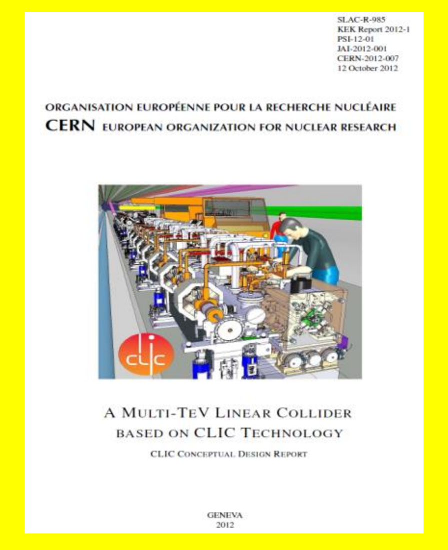
For the CLIC collaboration

No names at individual contributions, have to omit many important contributions

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

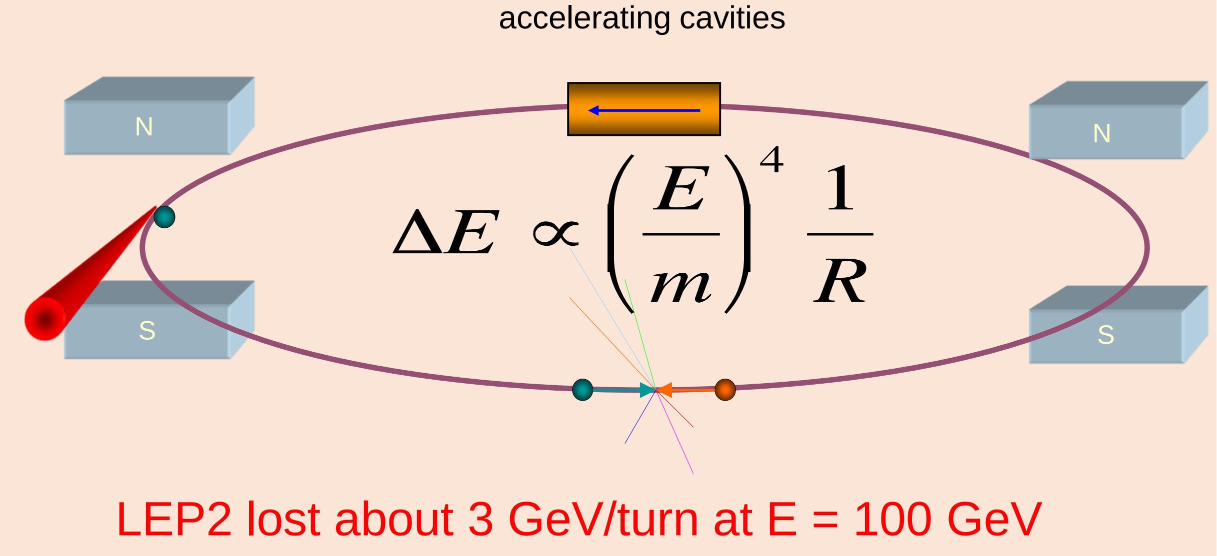
Getting ready for data taking by the time the LHC programme reaches completion

CLIC Concept

To reach multi-TeV energies:

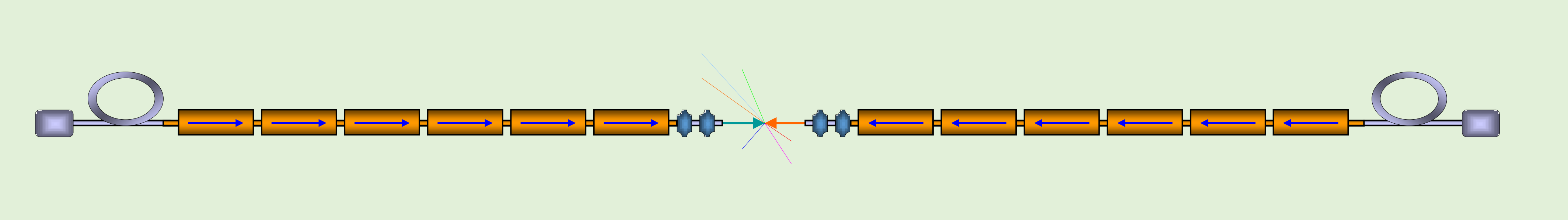
- Linear collider to avoid synchrotron radiation

- High accelerating field to achieve high energy
  - ⇒ Normal conducting accelerating structures
- High beam current and quality to achieve the luminosity
  - ⇒ High quality of components
  - ⇒ Little imperfections
  - ⇒ Fancy beam dynamics



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

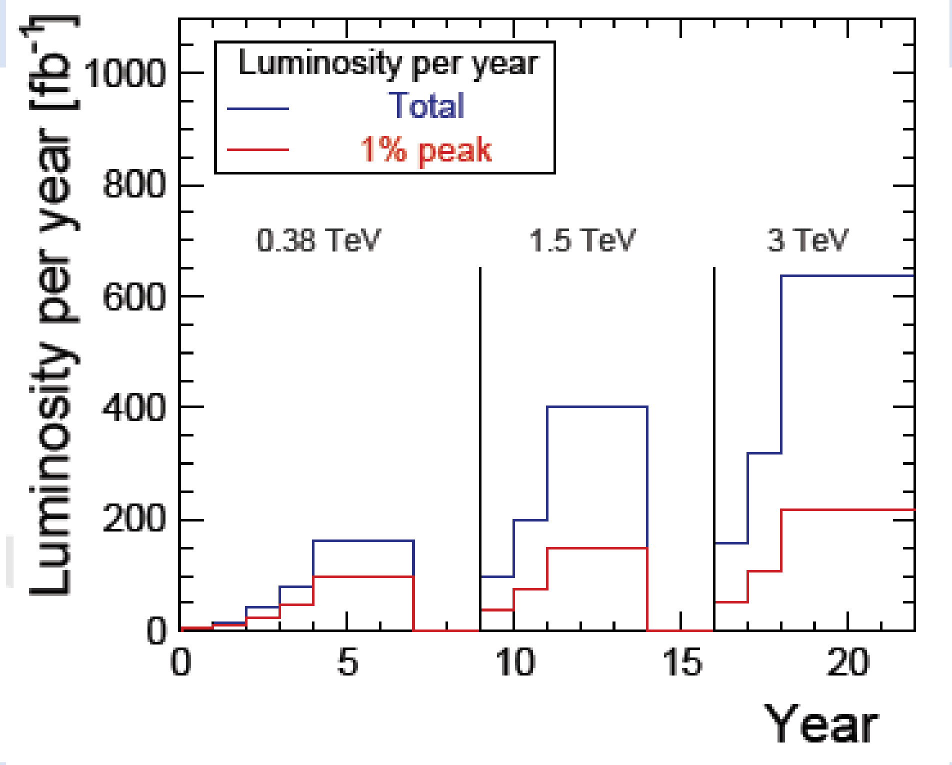
LEP2 lost about 3 GeV/turn at E = 100 GeV



CLIC Staged Scenario

Plenty of physics at low centre-of-mass energies

Energy and luminosity targets from Physics Study Group



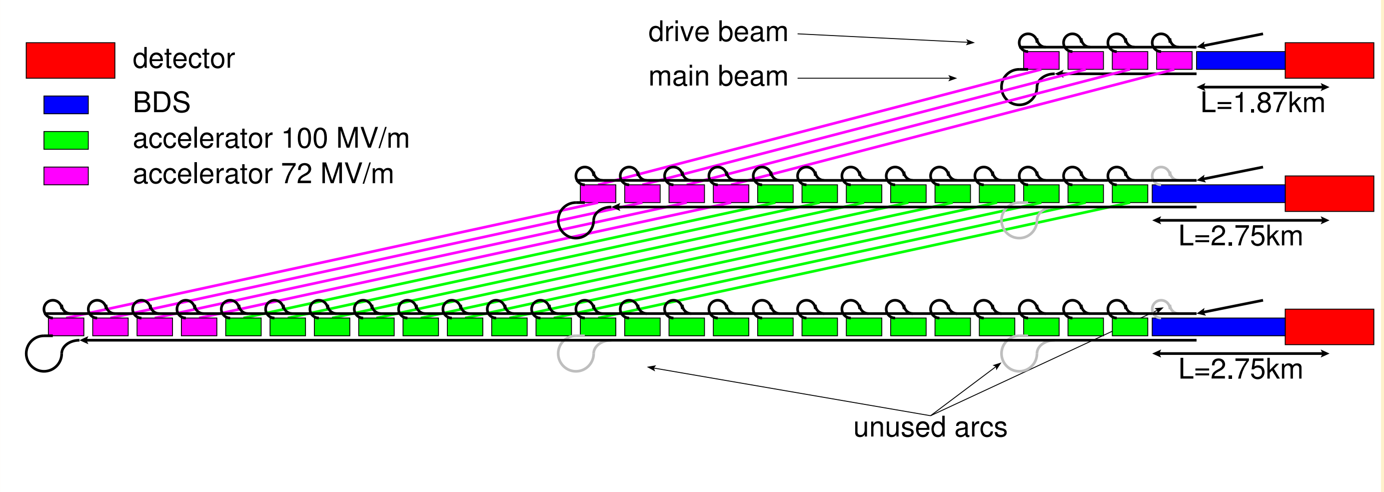
Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380 350	500 100
2	1500	1500
3	3000	3000

Top above threshold
Higgs via Zh and WW fusion

Study top at threshold

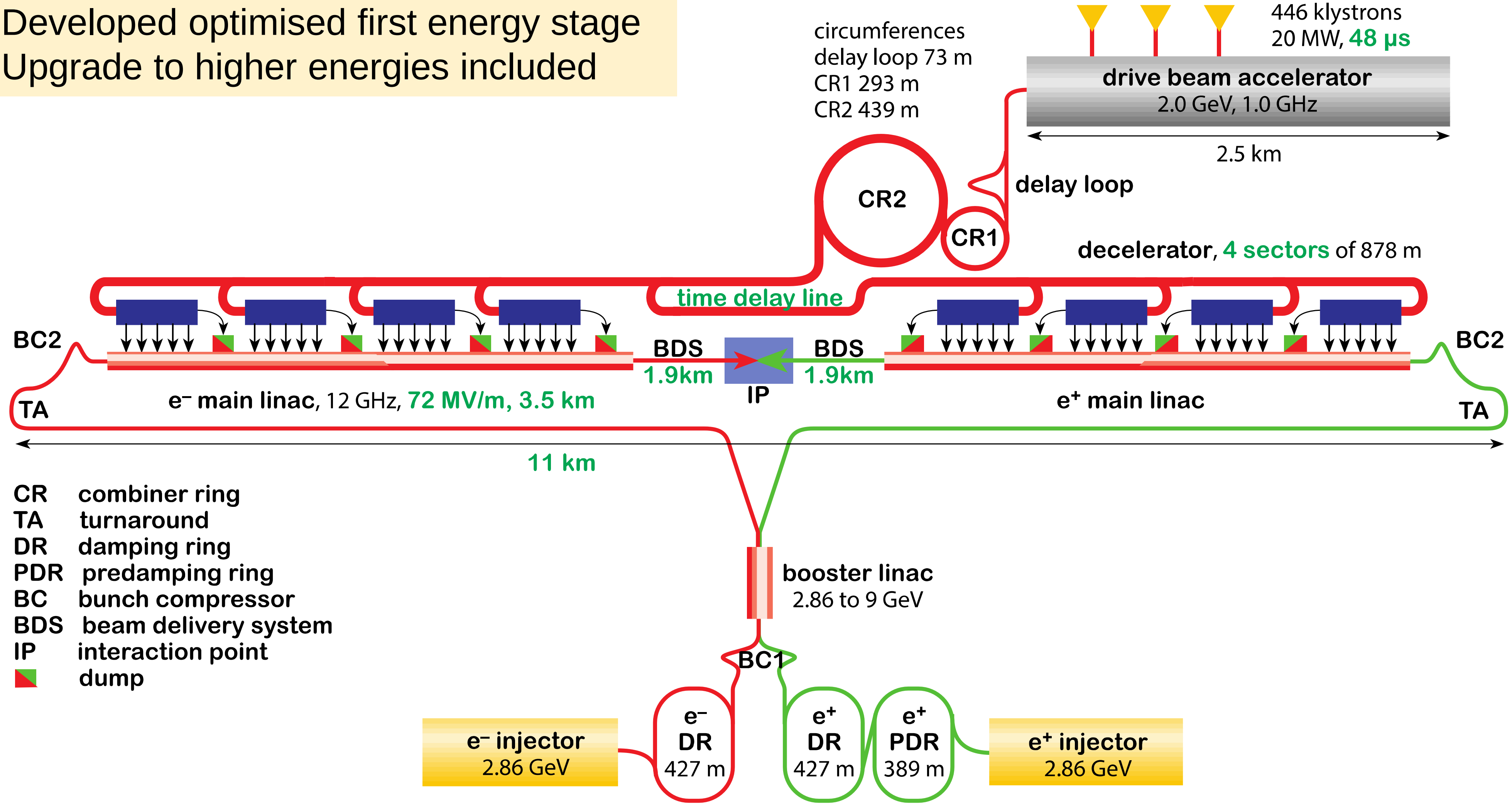
To be updated with more input from LHC and stage 1

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

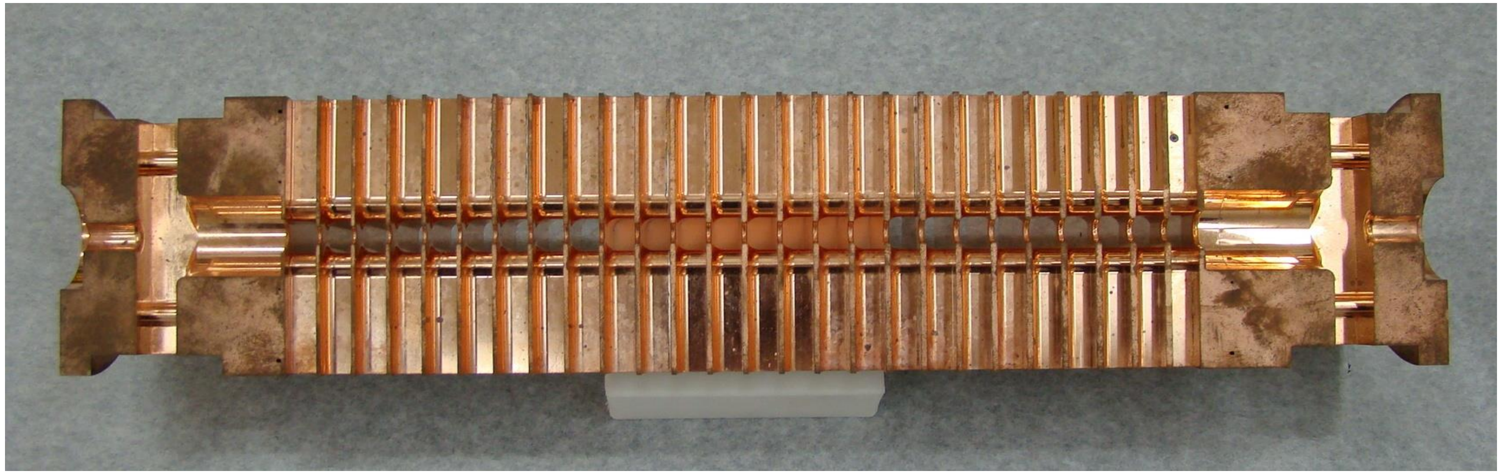
Key Parameters

Parameter	**Symbol**	**Unit**	**Stage 1**	**Stage 2**	**Stage 3**
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Charge per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

Accelerating Structure

380 GeV / 3 TeV

12 GHz
27 / 23 cm long
72 / 100 MV/m
59.5 /61.3 MW input power
244 ns RF pulses



20600 / 140,000 structures 380 GeV / 3 TeV

Total peak RF power:
1.6 TW (380 GeV) 8.5 TW (3 TeV)

But only 10^{-5} duty factor

- 50 RF bursts per second
- 244 ns long (312 bunches)
- = 12.2 μs / s

Production of peak power is a challenge
Typical 12 GHz klystrons produces O(50 MW)

Solution is drive beam

CLIC Gradient

Breakdowns (discharges during the RF pulse)

- Require $p \leq 3 \times 10^{-7}\ \mathrm{m}^{-1}\mathrm{pulse}^{-1}$

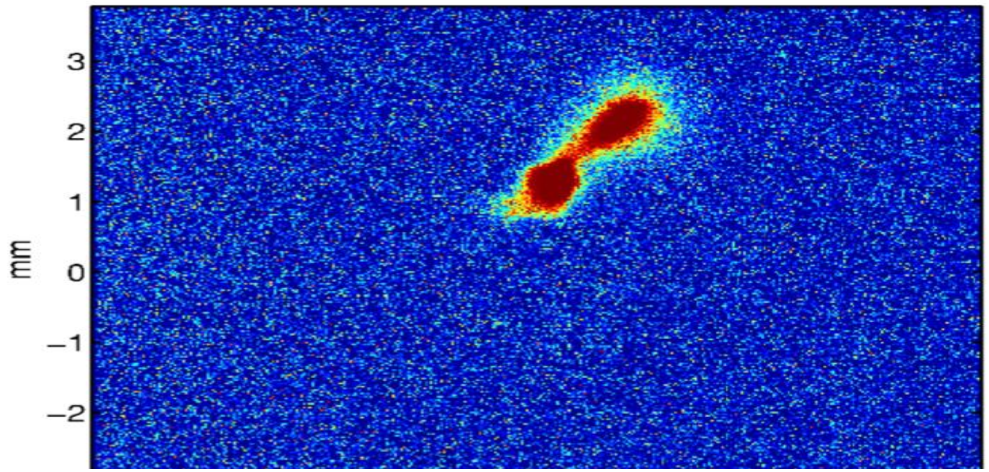
Structure design based on empirical constraints, not first principle

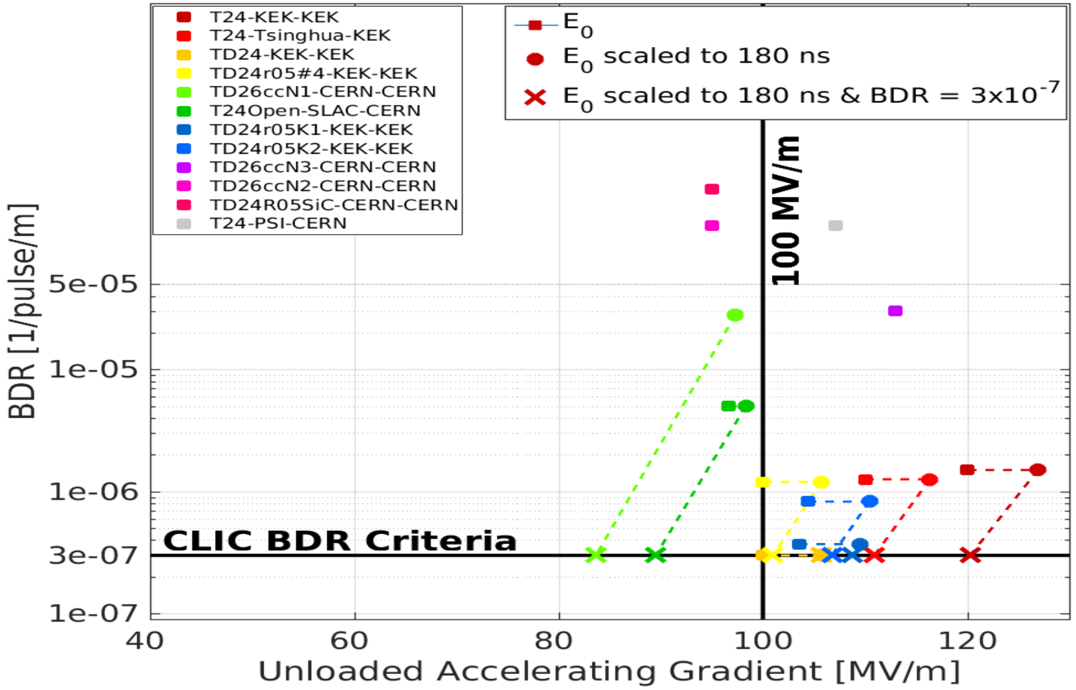
- Maximum surface field
- Maximum temperature rise
- Maximum power flow

R&D established gradient O(100 MV/m)

Structure for 380 GeV optimised for cost of first energy stage

$\Rightarrow$ 72 MV/m

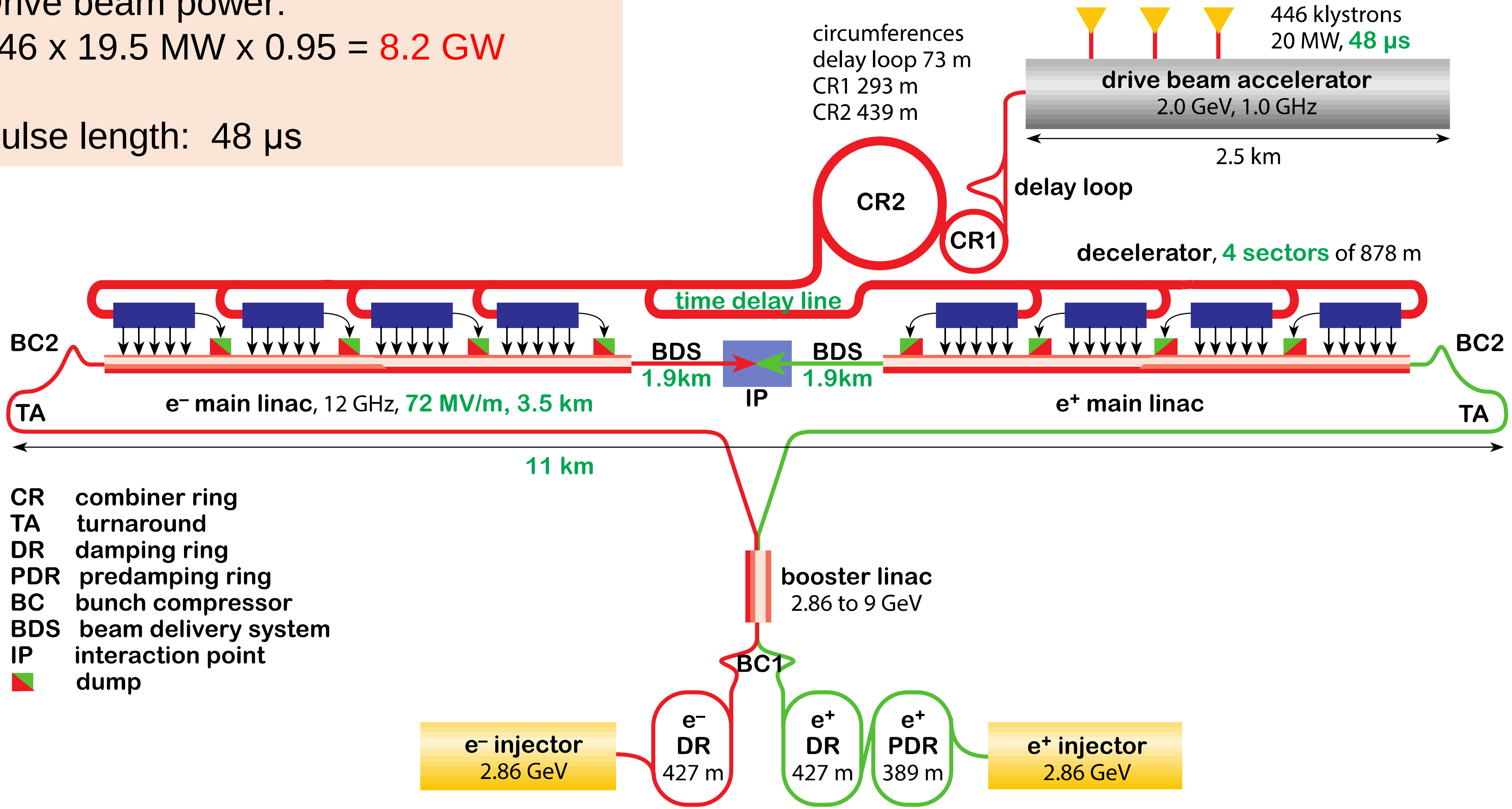




Power Production: Drive Beam Production

Drive beam power:
446 x 19.5 MW x 0.95 = 8.2 GW

Pulse length: 48 µs



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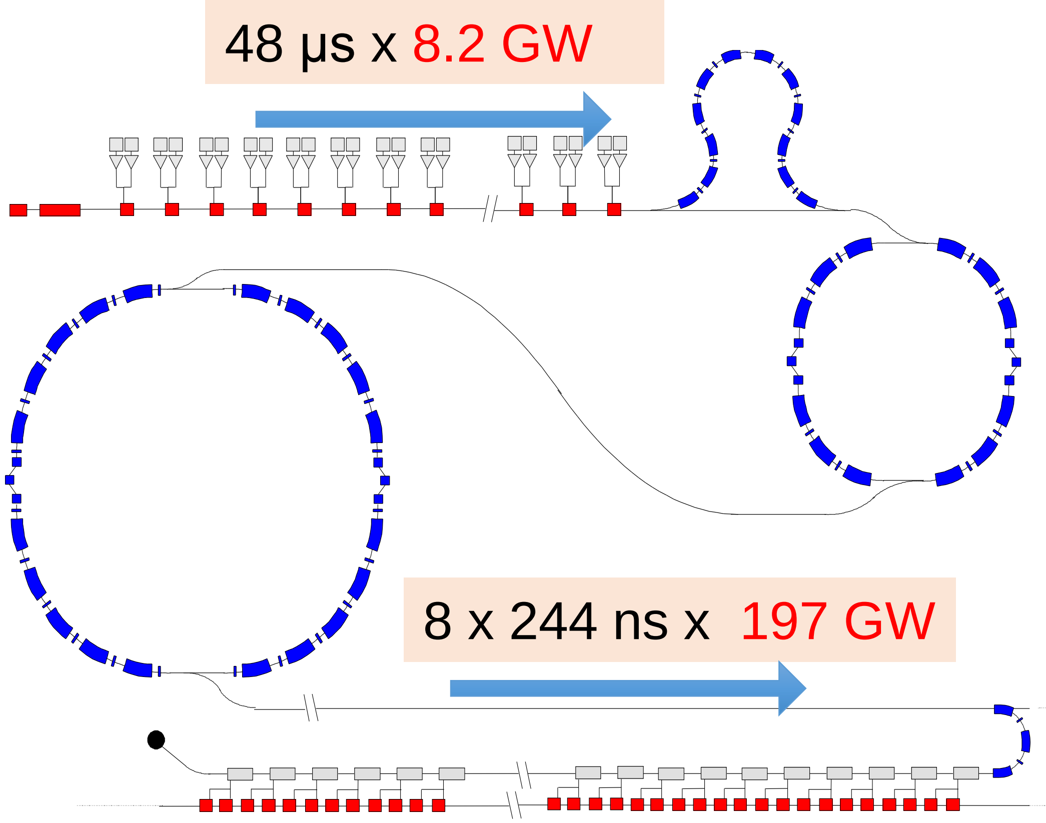
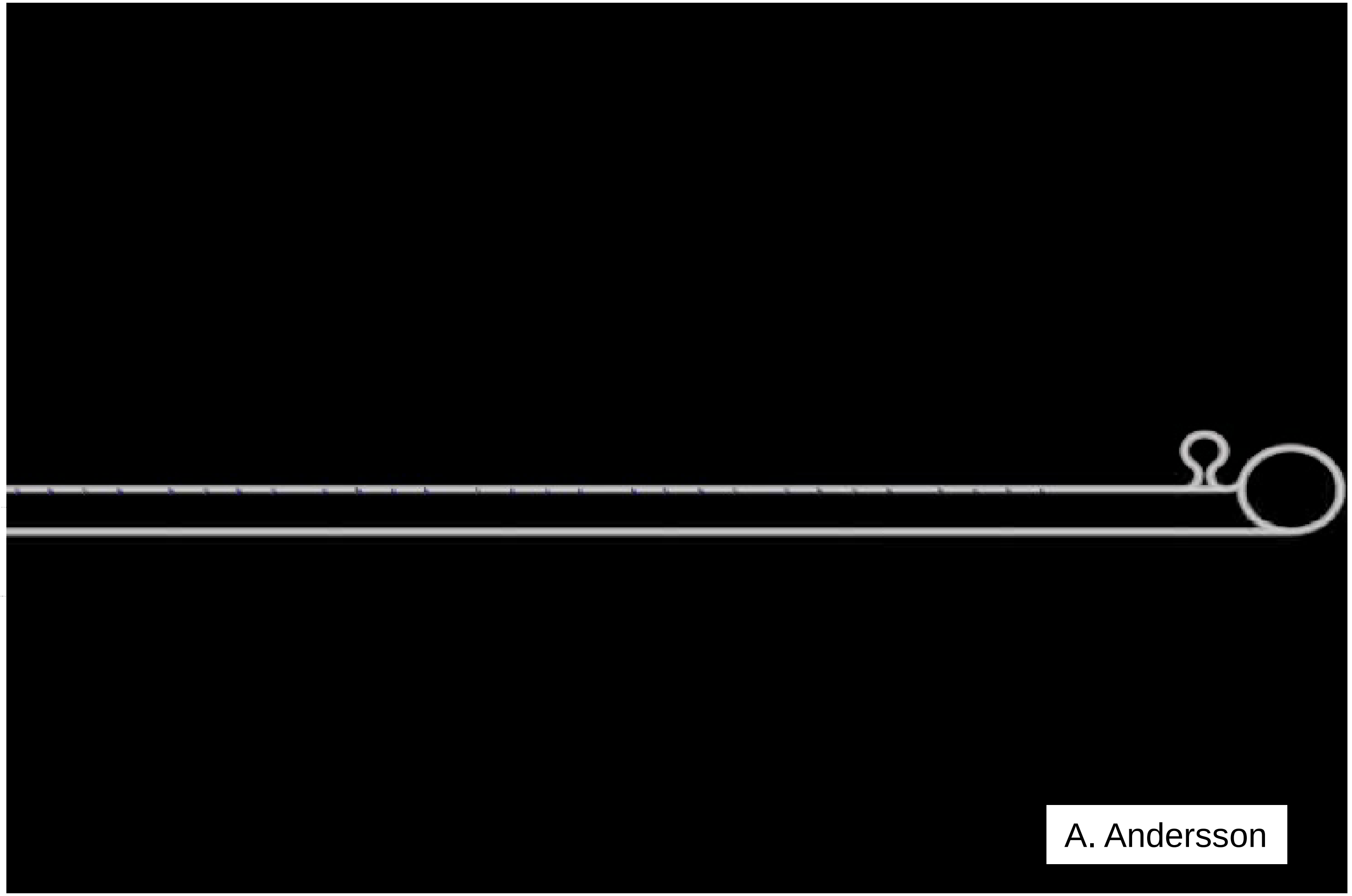
🟥	dump

Drive Beam Combination Concept


48 µs x 8.2 GW

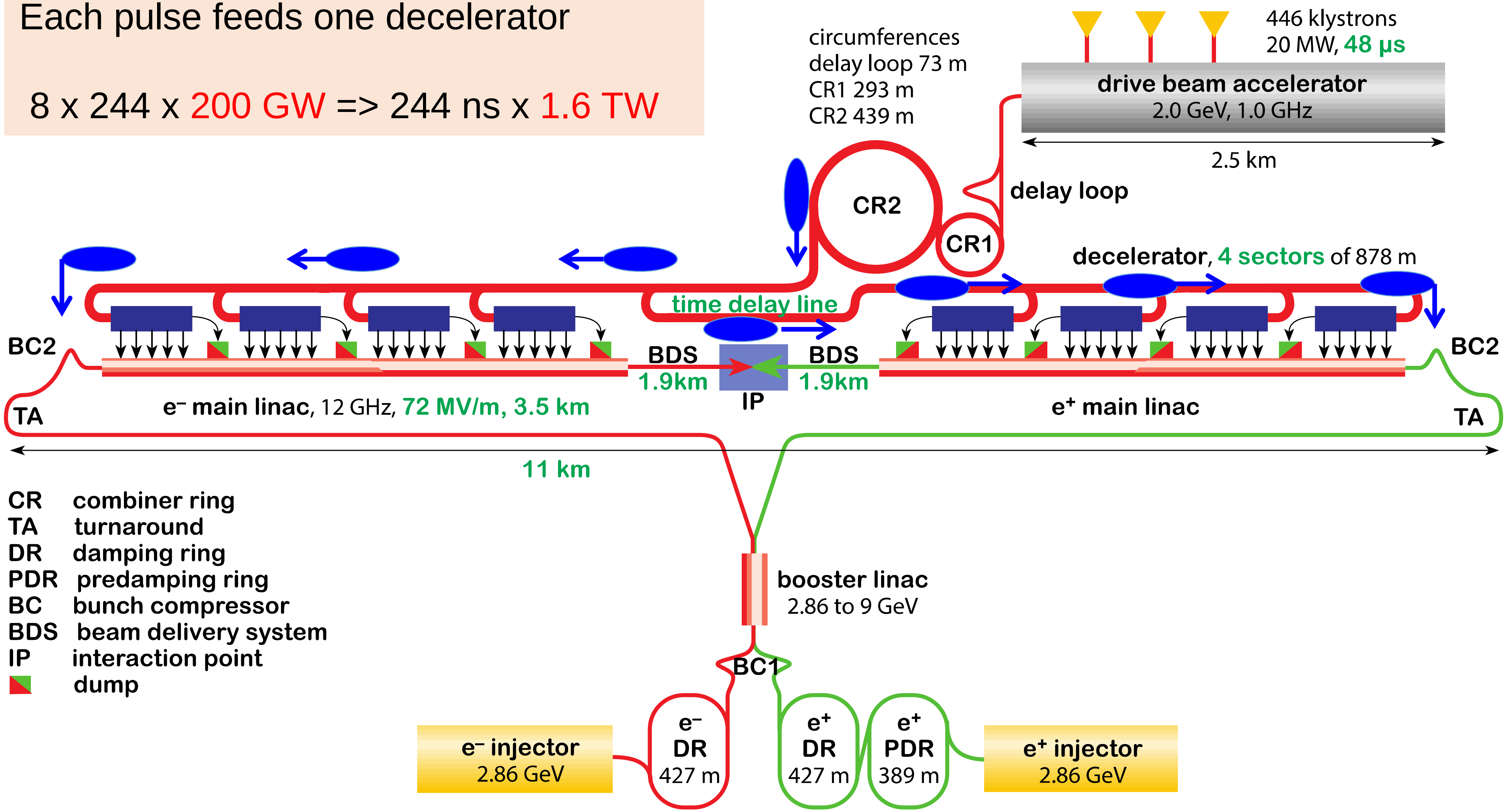
8 x 244 ns x 197 GW


A. Andersson

Power Production: Drive Beam Distribution

Each pulse feeds one decelerator

8 x 244 x 200 GW => 244 ns x 1.6 TW



circumferences
delay loop 73 m
CR1 293 m
CR2 439 m

446 klystrons
20 MW, **48 μs**

drive beam accelerator
2.0 GeV, 1.0 GHz

2.5 km

delay loop

CR2

CR1

decelerator, **4 sectors** of 878 m

time delay line

BC2

BDS
1.9km

IP

BDS
1.9km

BC2

TA

e⁻ main linac, 12 GHz, **72 MV/m, 3.5 km**

e⁺ main linac

TA

11 km

booster linac
2.86 to 9 GeV

BC1

e⁻ injector
2.86 GeV

e⁻
DR
427 m

e⁺
DR
427 m

e⁺
PDR
389 m

e⁺ injector
2.86 GeV

CR	**combiner ring**
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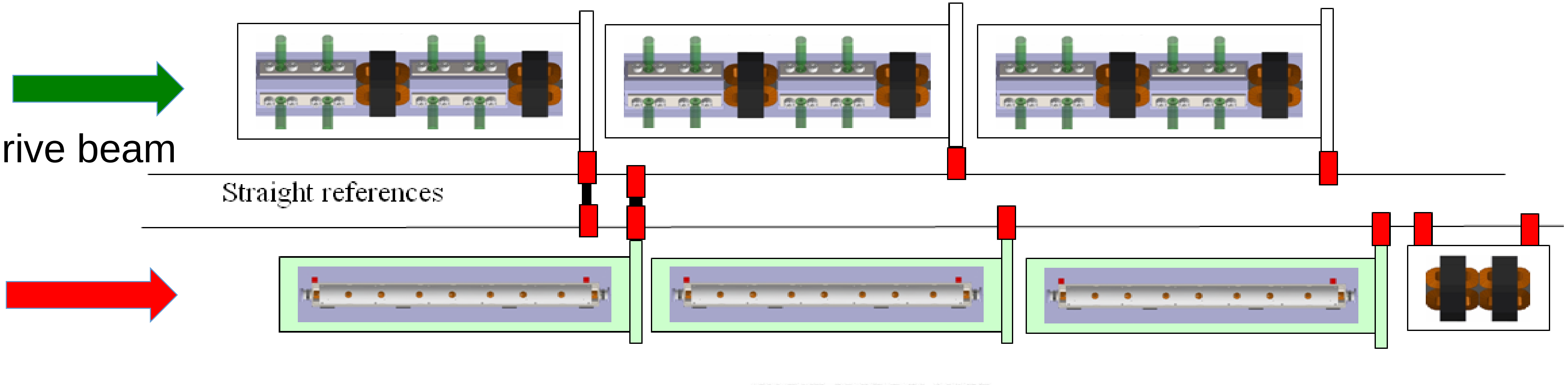
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
🟥	**dump**

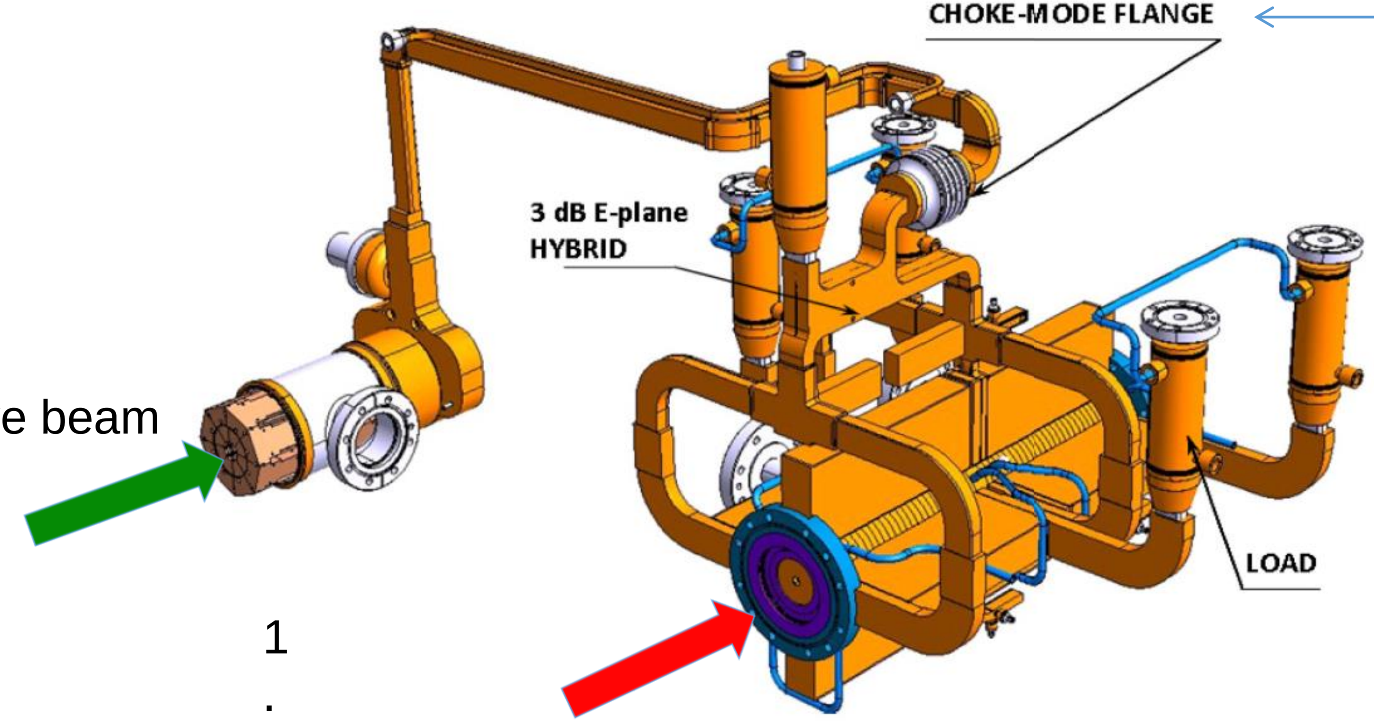
Two-beam Module Concept



100 A drive beam

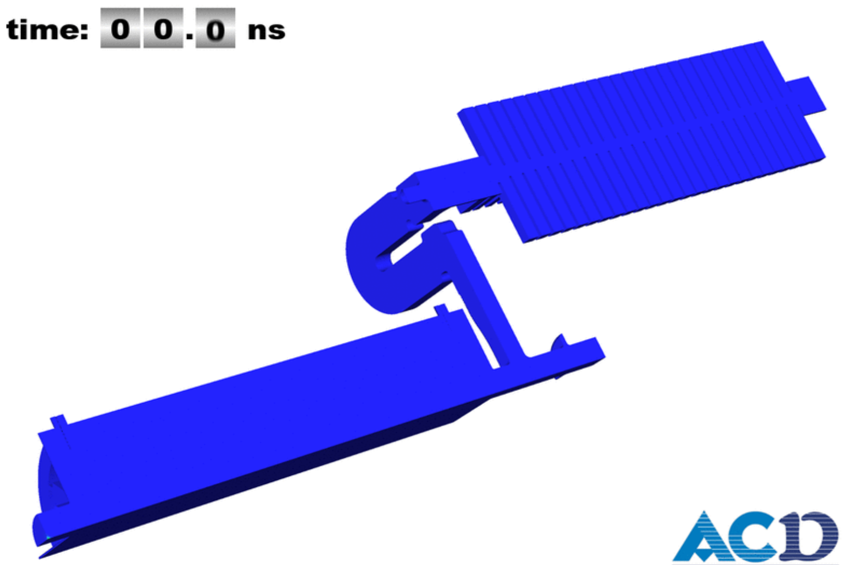
1.7 A main beam

2.2m

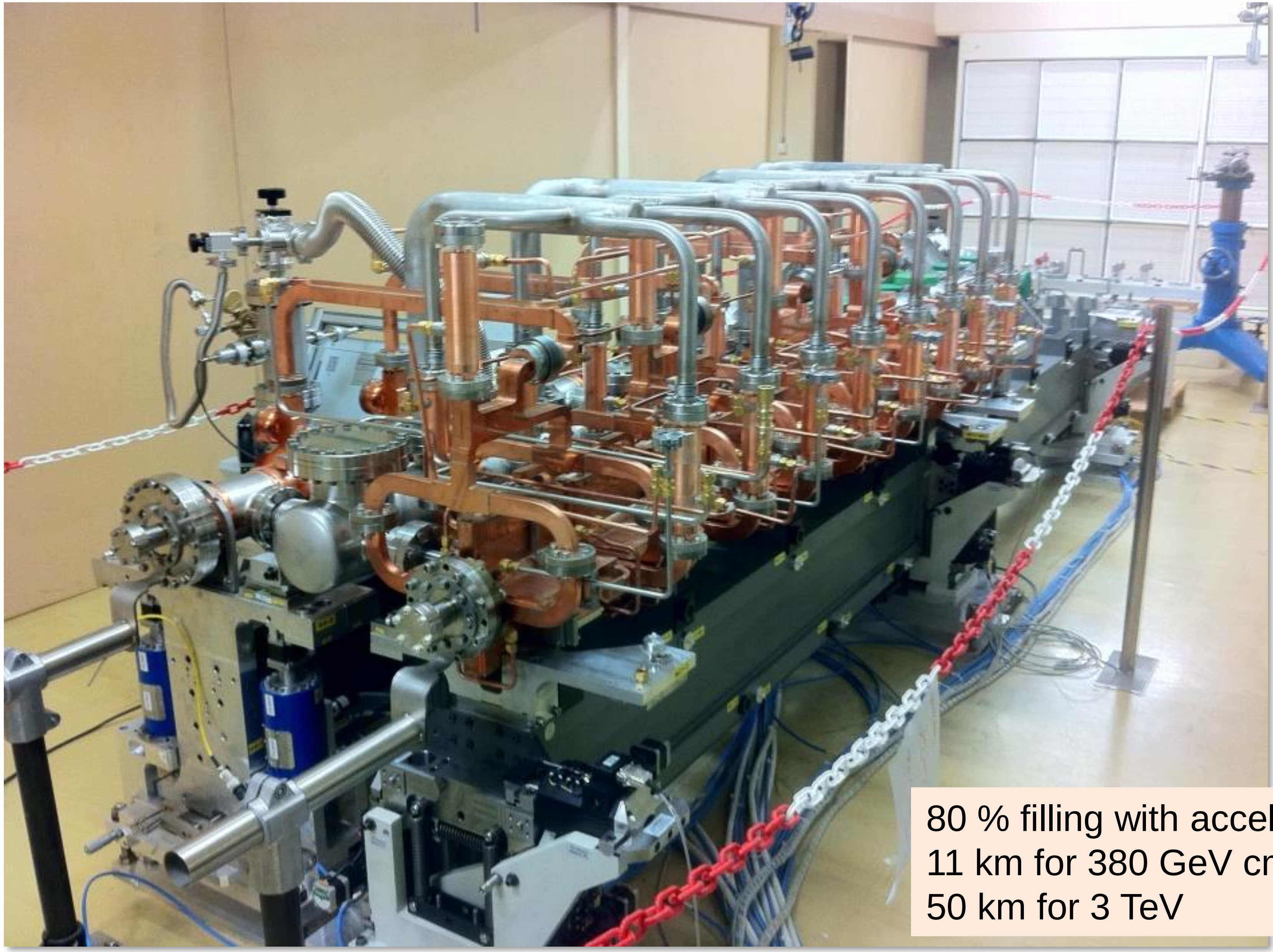


100 A drive beam

1.7

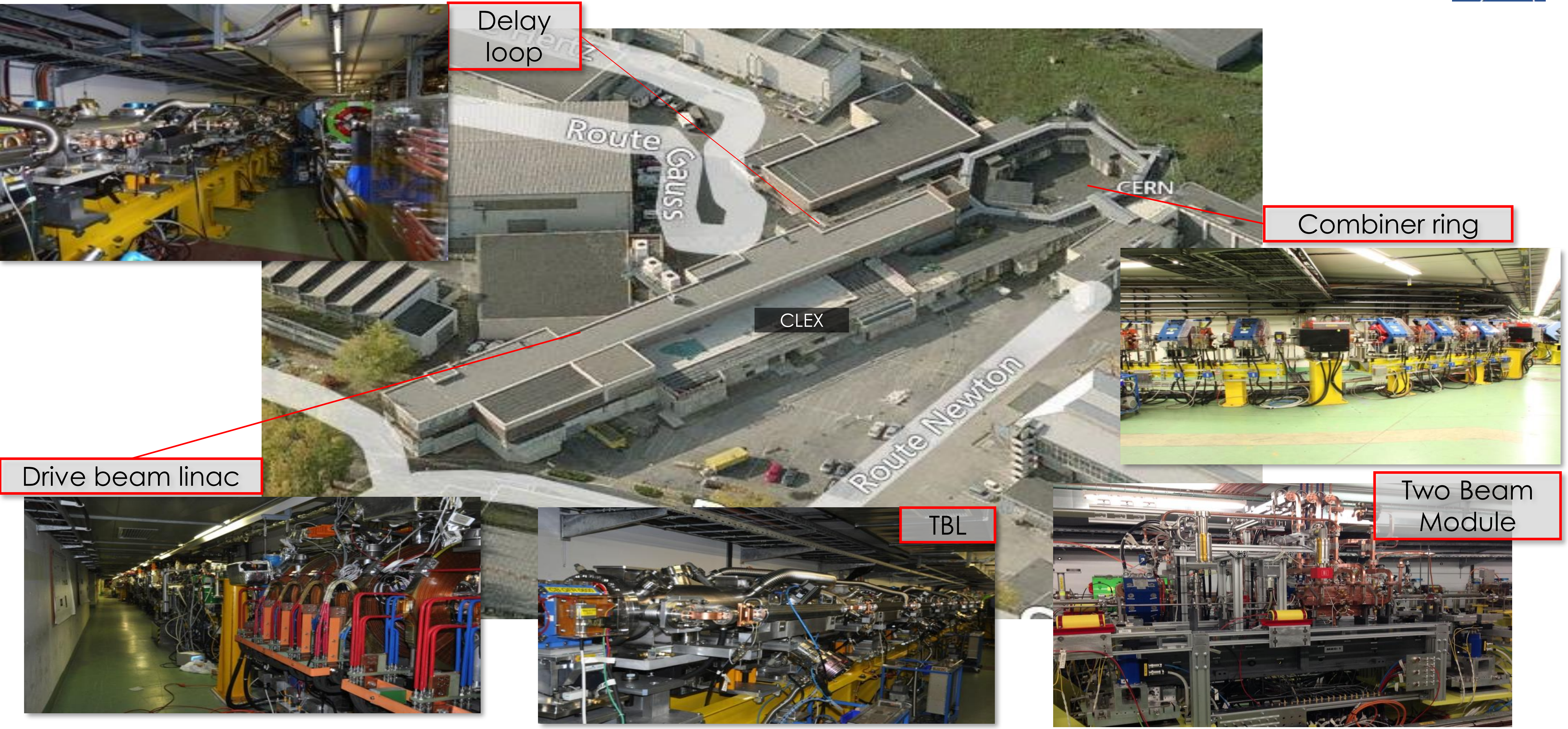


CLIC Two-beam Module



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

CLIC Test Facility (CTF3)

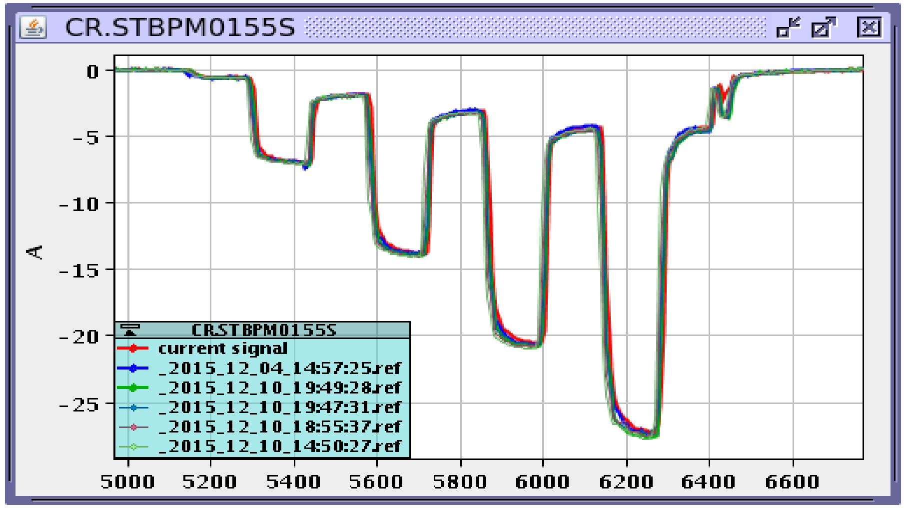


Drive Beam Scheme Performance

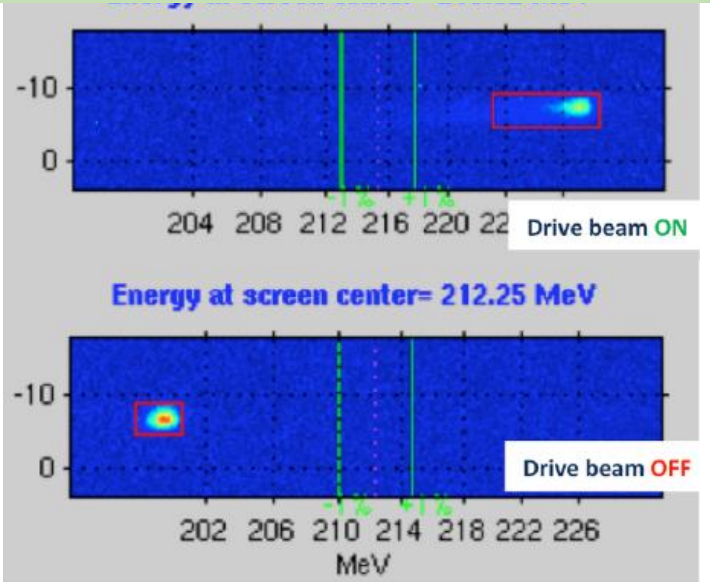
CTF3 measurements:

- RF to drive beam efficiency > 95%
- Current multiplication factor 8
- Most of beam quality
- 145 MV/m X-band acceleration

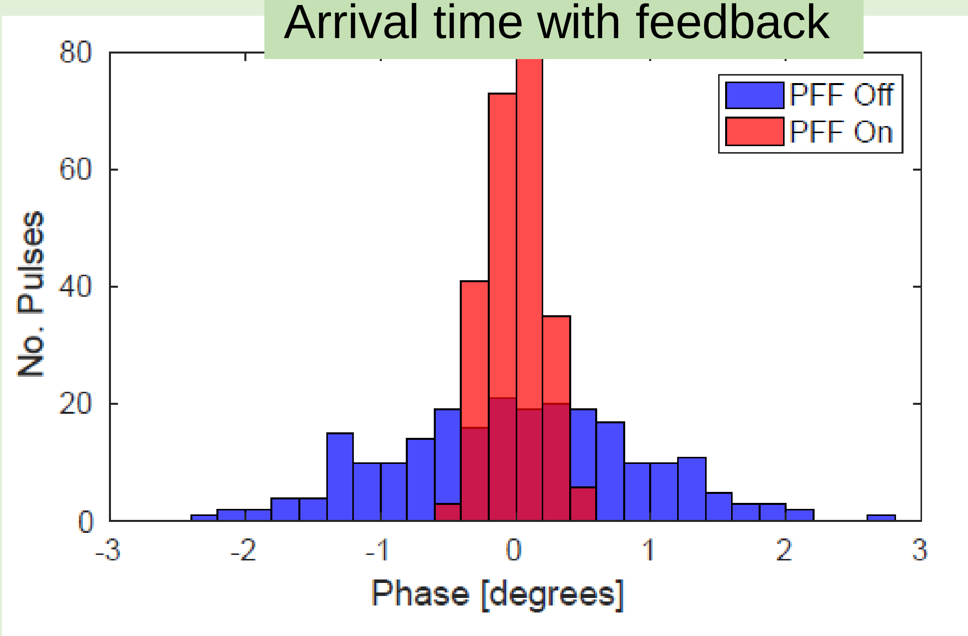
Detailed simulations of drive beam performance in CLIC



Measured 145 MV/m gradient



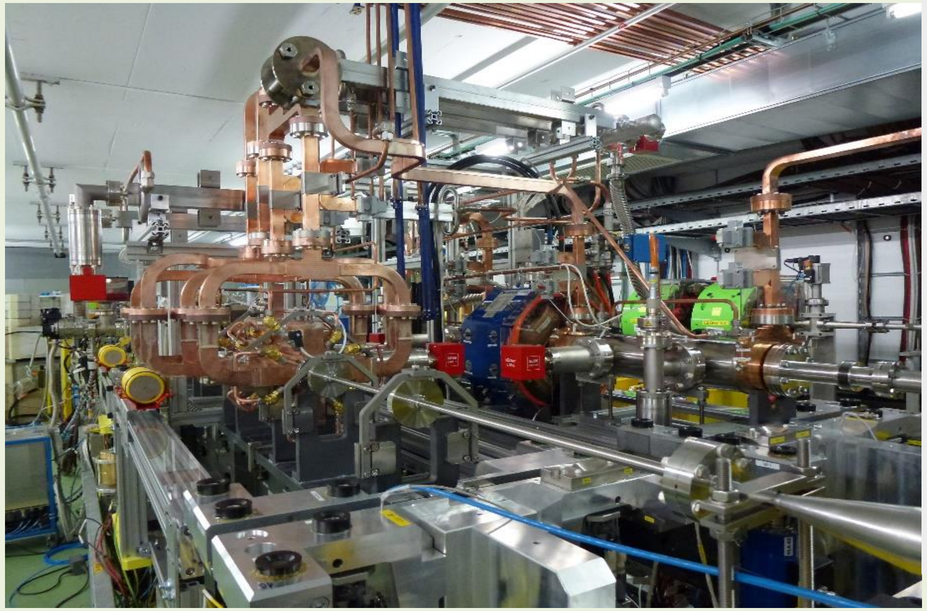
Arrival time with feedback



Current stability affected by very low CTF3 energy, 3 x larger beam and delay loop design different from CLIC

Parameter	CLIC goal	CTF3 measured
Arrival time	50 fs	50 fs
Current after linac	0.75 x 10^{-3}	0.2-0.4 x 10^{-3}
Current at end	0.75 x 10^{-3}	2-18 x 10^{-3}
Energy	1.0 x 10^{-3}	0.7 x 10^{-3}

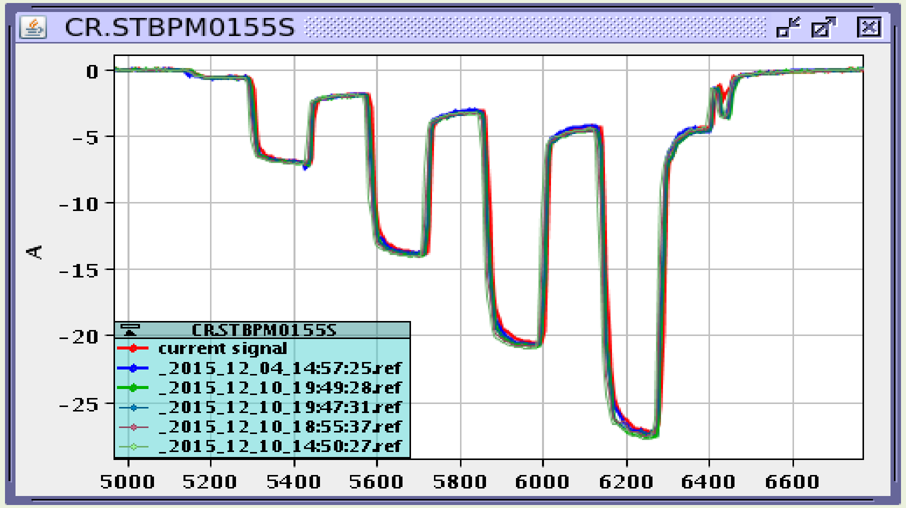
From CTF3 to CLEAR



CTF3 has demonstrated drive beam production and main beam acceleration

- Technology
- Beam quality
- Operation

Now stopped



New facility is coming online: CLEAR
CERN Linear Electron Accelerator for Research

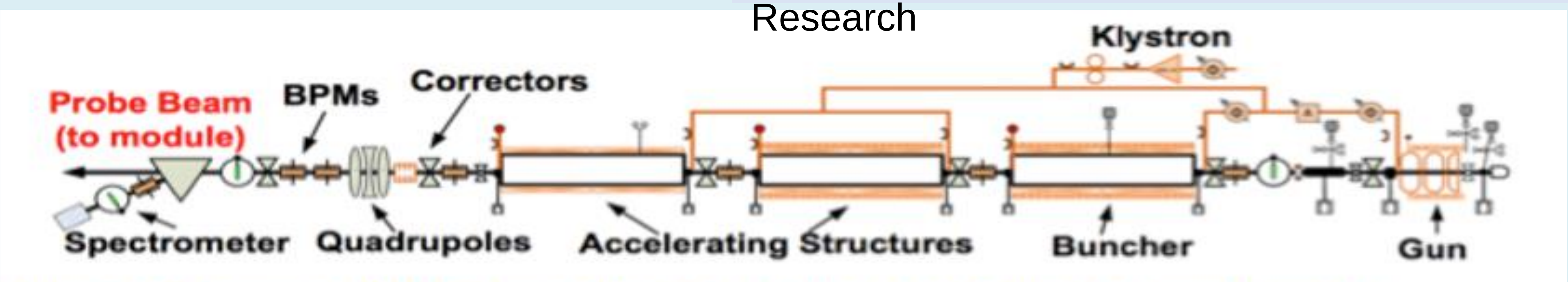


Figure 1: The current CALIFES beam line. The length of the facility (as shown) is ~20m.

Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

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

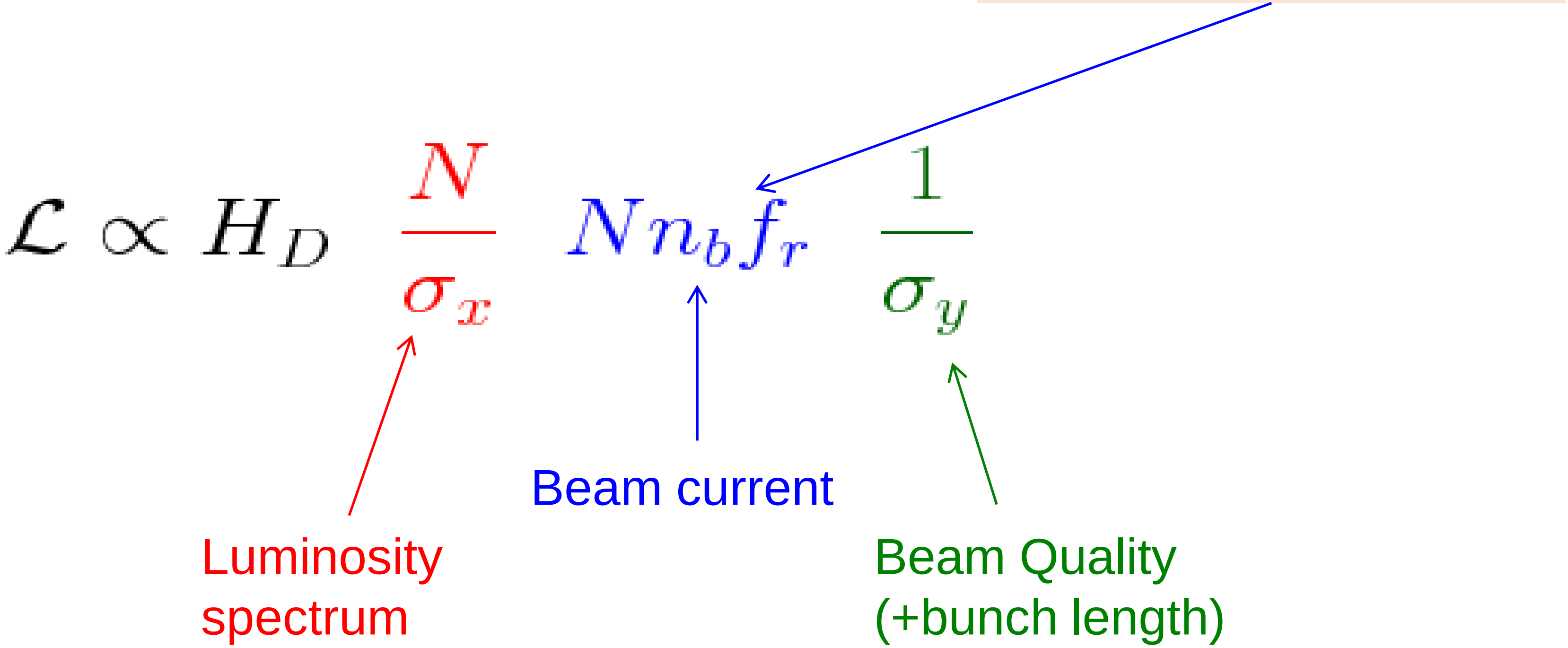
Need to ensure that we can achieve each parameter

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



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

Luminosity spectrum

Beam current

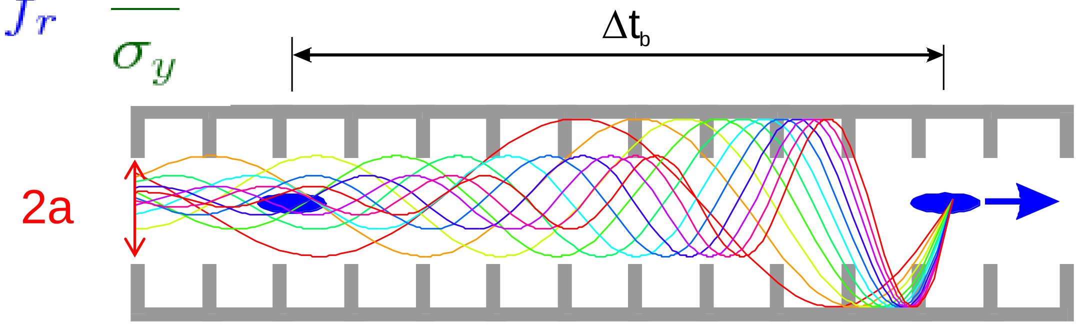
Beam Quality (+bunch length)

Need to ensure that we can achieve each parameter

Wakefields and Beam Current

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

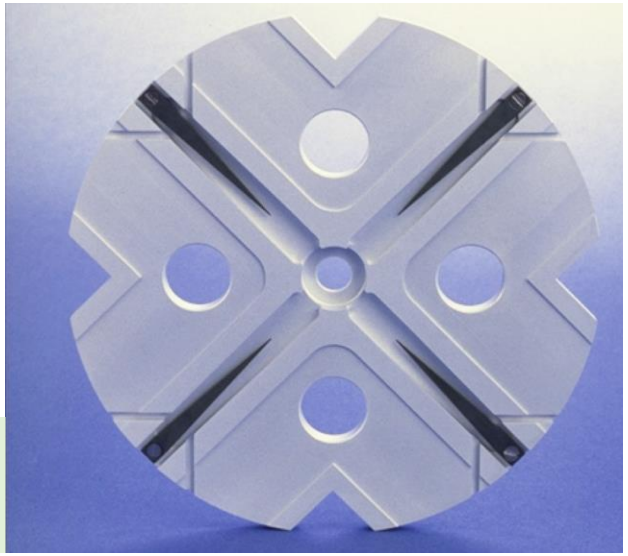
Goal: maximise beam current
⇒ Maximise bunch charge
⇒ Minimise distance between bunches



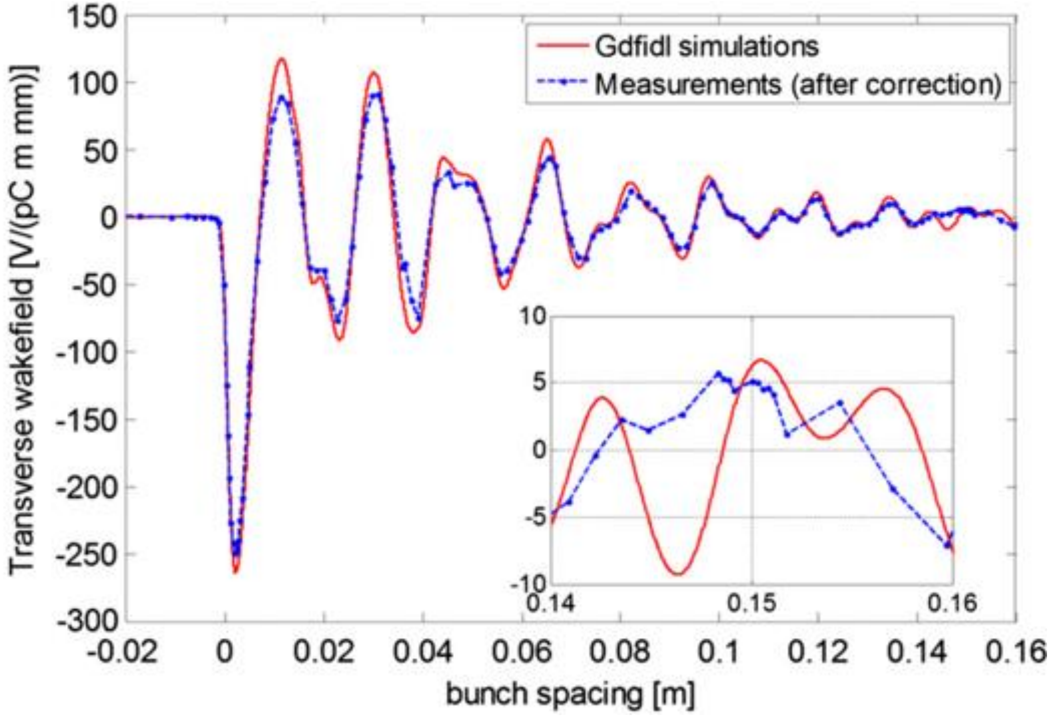
Limits are given by wakefields:
With an offset particles produce transverse wakefields
⇒ The head kicks the tail, force is defocusing
⇒ Can render beam unstable

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

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



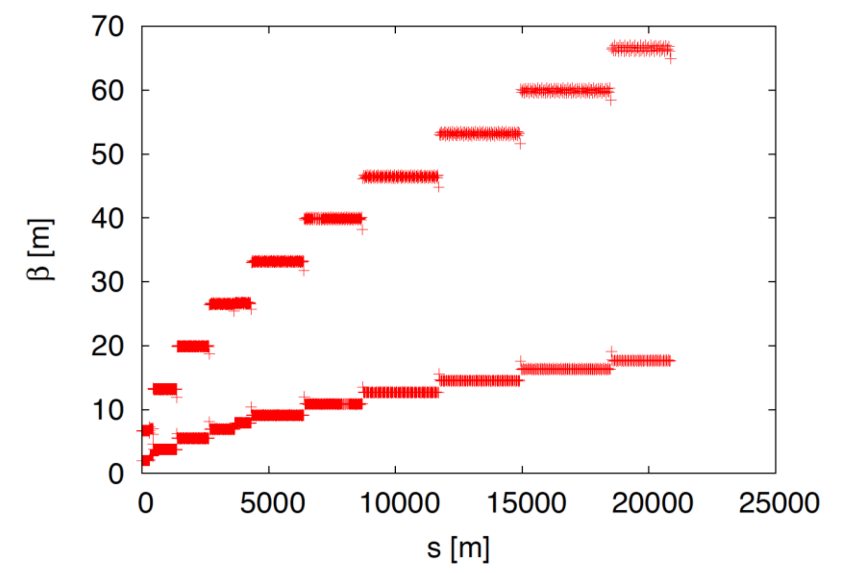
Multi-bunch wakefields minimised by damping and detuning



Tricks of the Beam Physics

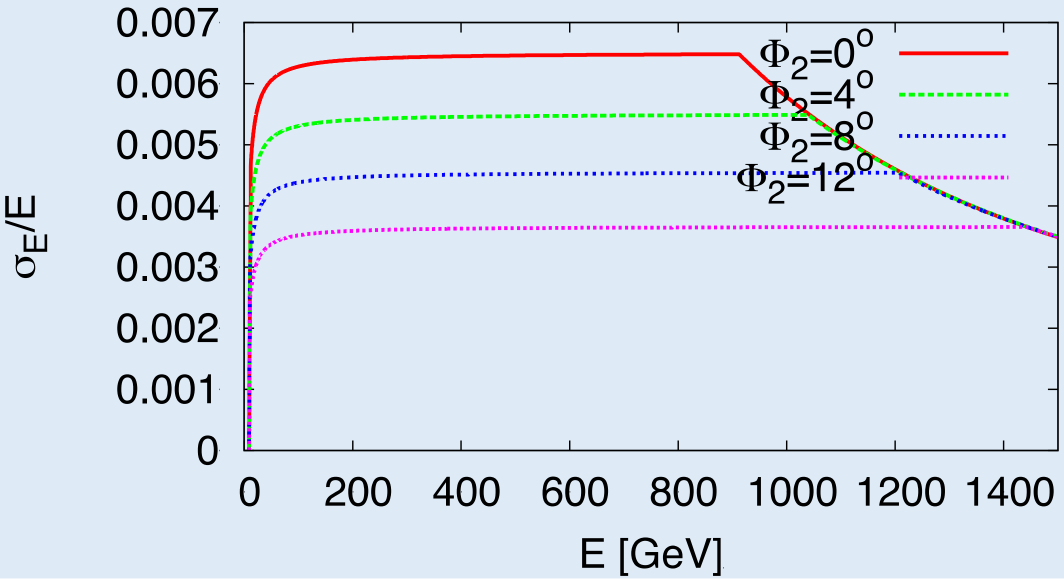
Make the focus strong again

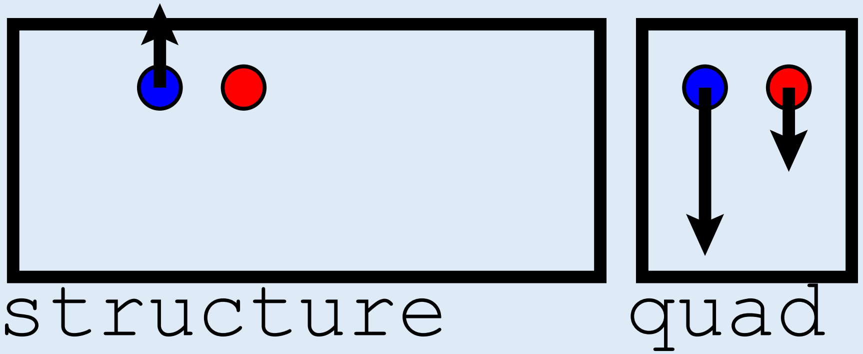
- Use O(10%) of the linac for magnets
- Leads to small beta-function
- Makes the beam stable (strong spring for an oscillator)



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

- Introduce energy chirp that compensates transverse wakefields

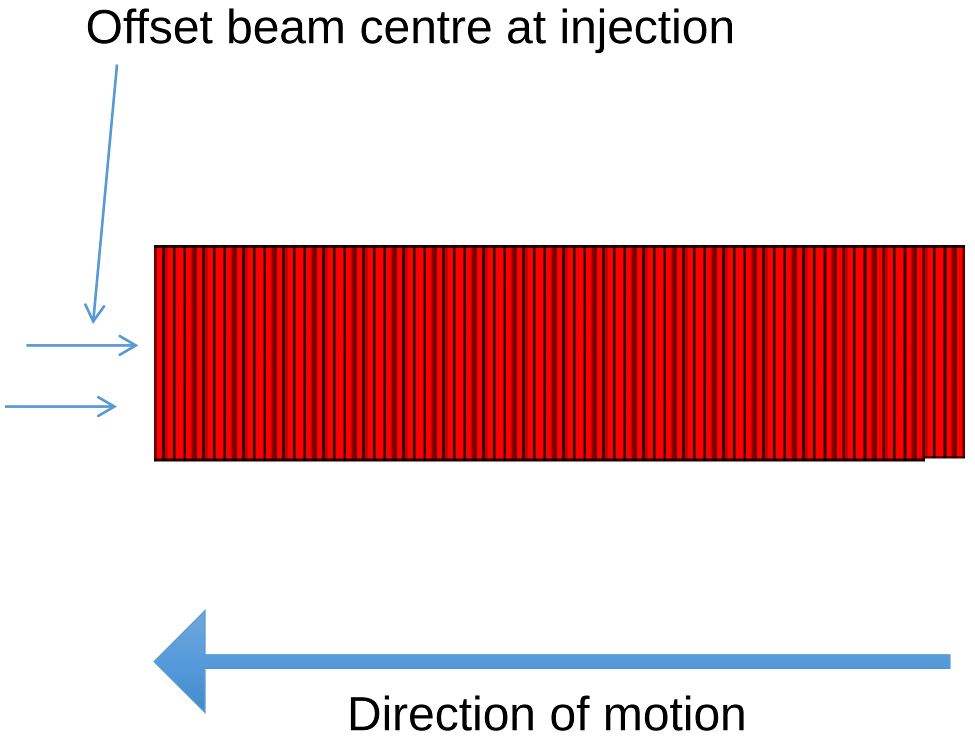


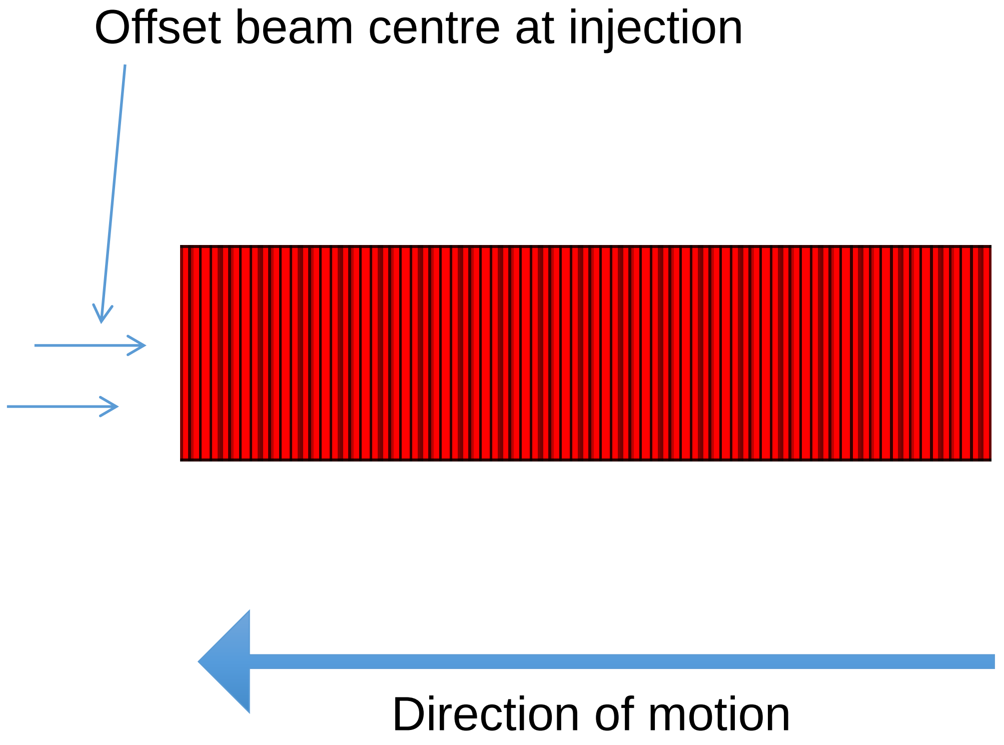


Beam Stability, With BNS

No BNS damping

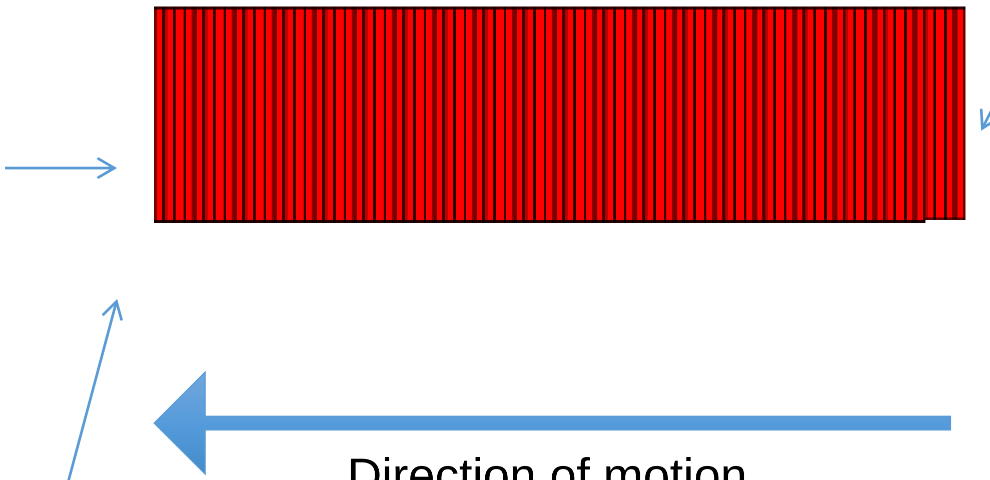
With BNS damping





Beam Stability, With BNS

No BNS damping

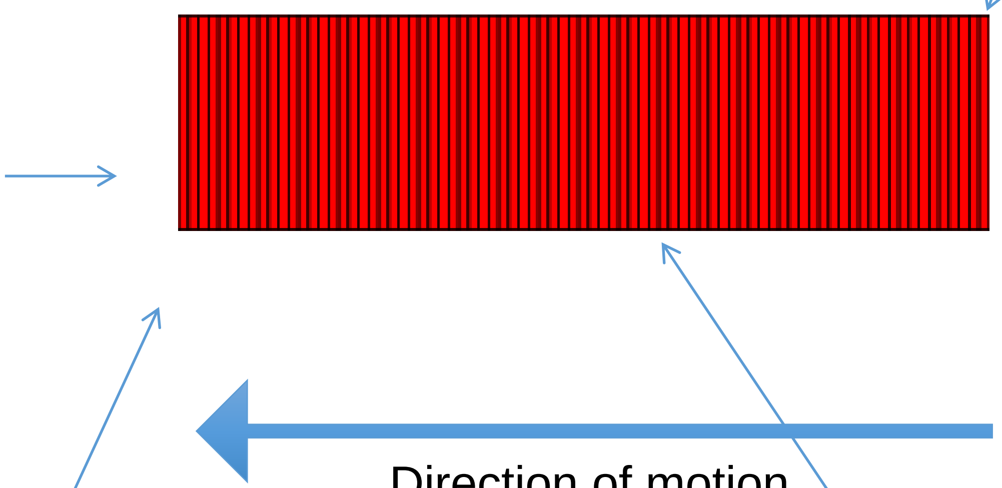


Tail and centre flap quite a lot

Direction of motion

Simple betatron oscillation

With BNS damping



Tail still flaps a little bit

Direction of motion

Simple betatron oscillation

Centre of bunch is much more stable ✓

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

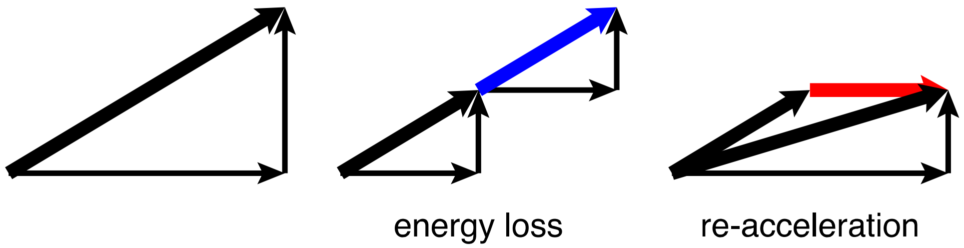
	$\Delta\epsilon_x$ [nm]	$\Delta\epsilon_y$ [nm]		
	Total contribution	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	700	5	0	0
End of RTML	150	1	2	2
End of main linac	50	0	5	5
Interaction point	50	0	5	5
sum	950	6	12	12

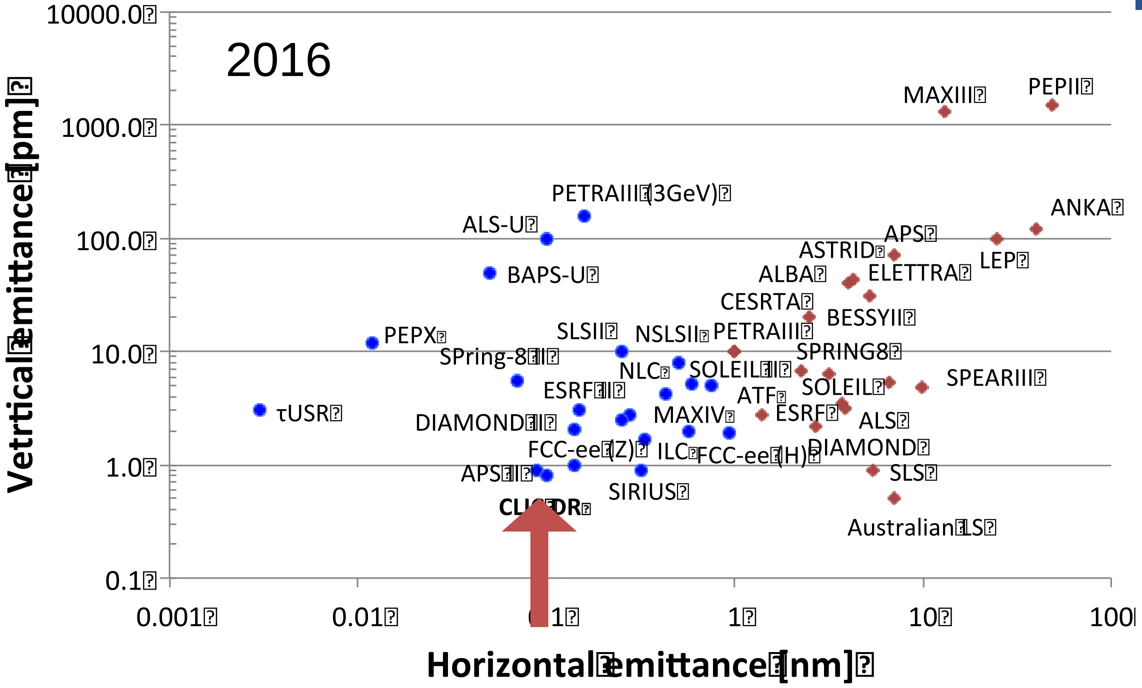
Imperfections are the main source of final vertical emittance

Require 90% likelihood to meet static emittance growth target

Damping Rings

Cool the beams from the sources





Important progress in collaboration with light source community

Studies of lattice and collective effects show that emittance targets can be reached for 3TeV

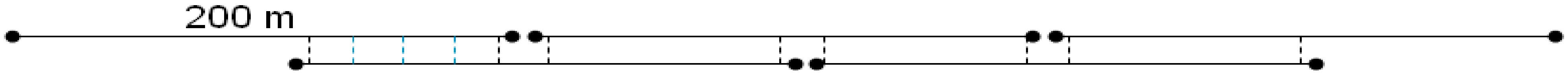
Currently optimising for 380 GeV

✓

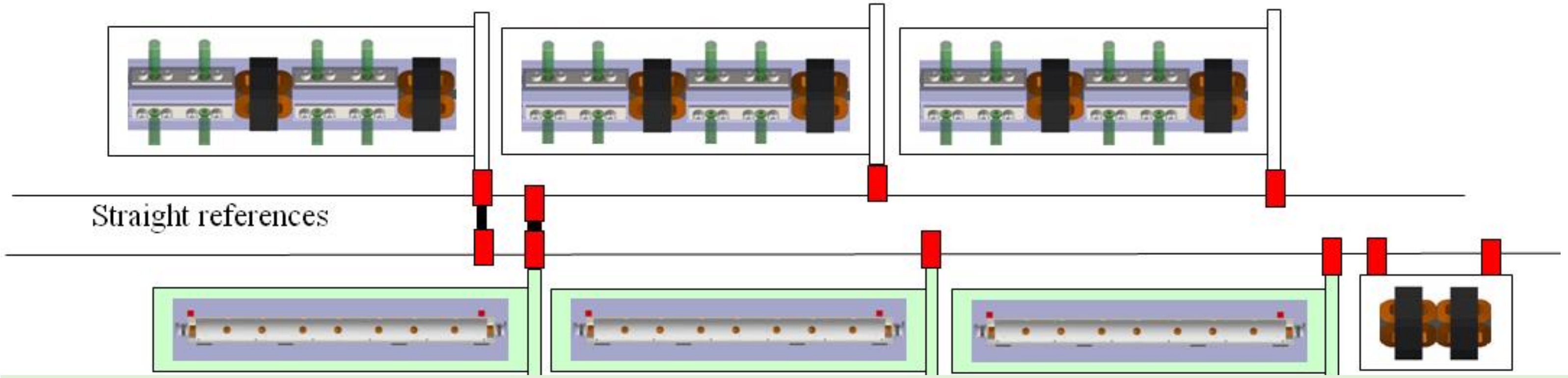
Static Imperfections: Main Linac Alignment

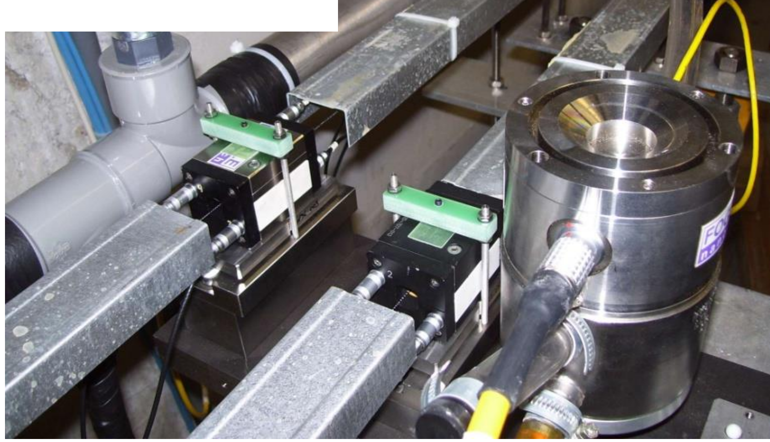
1) Align components accurately on the supporting girders

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



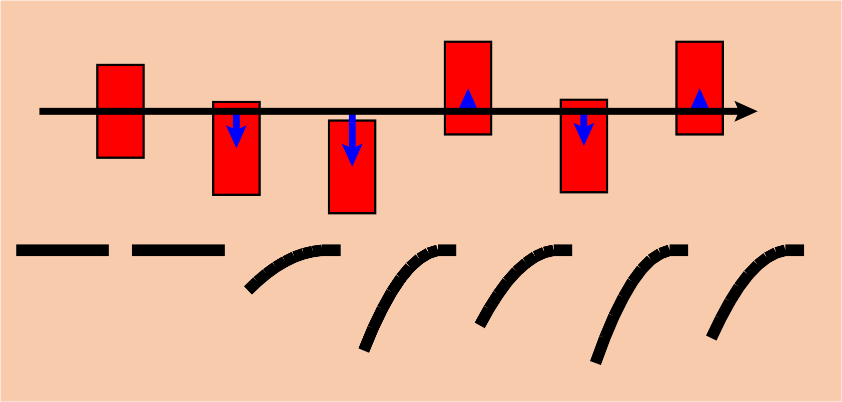


The error for this is most critical misalignment of components is of the order O(10µm)

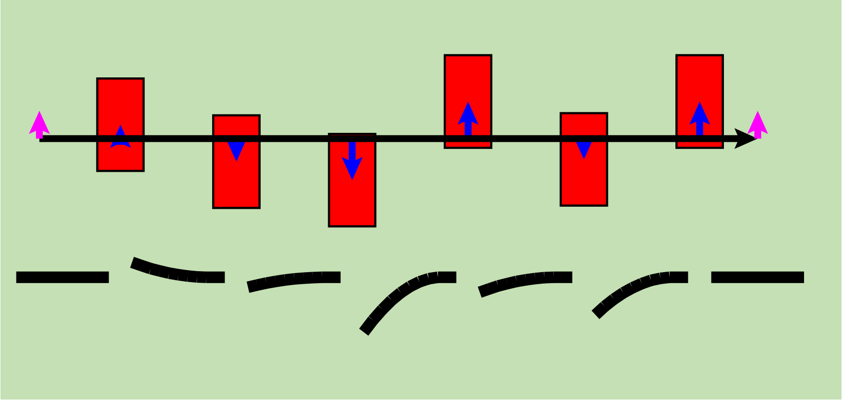
4) Use sophisticated beam-based alignment such as dispersion free steering (DFS, i.e. different energy beams) to align components
In particular to align BPMs

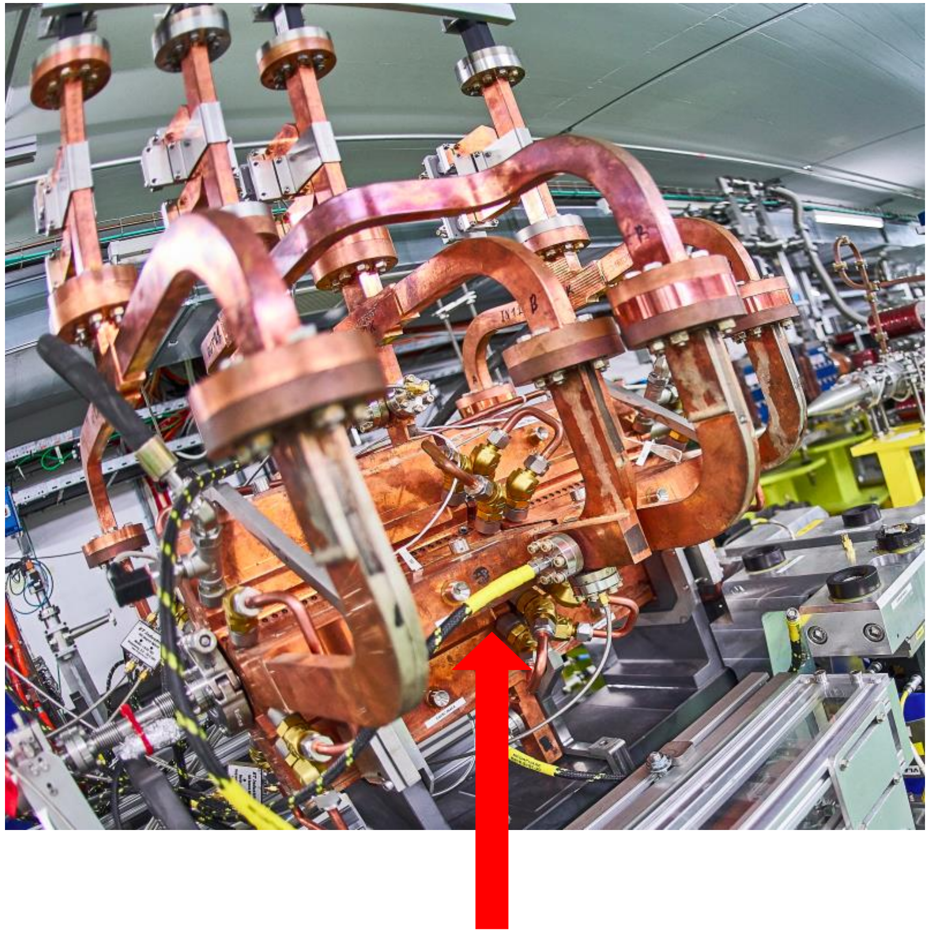
RF Alignment

Structures scattered on girder
⇒ Wakefield kick



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





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

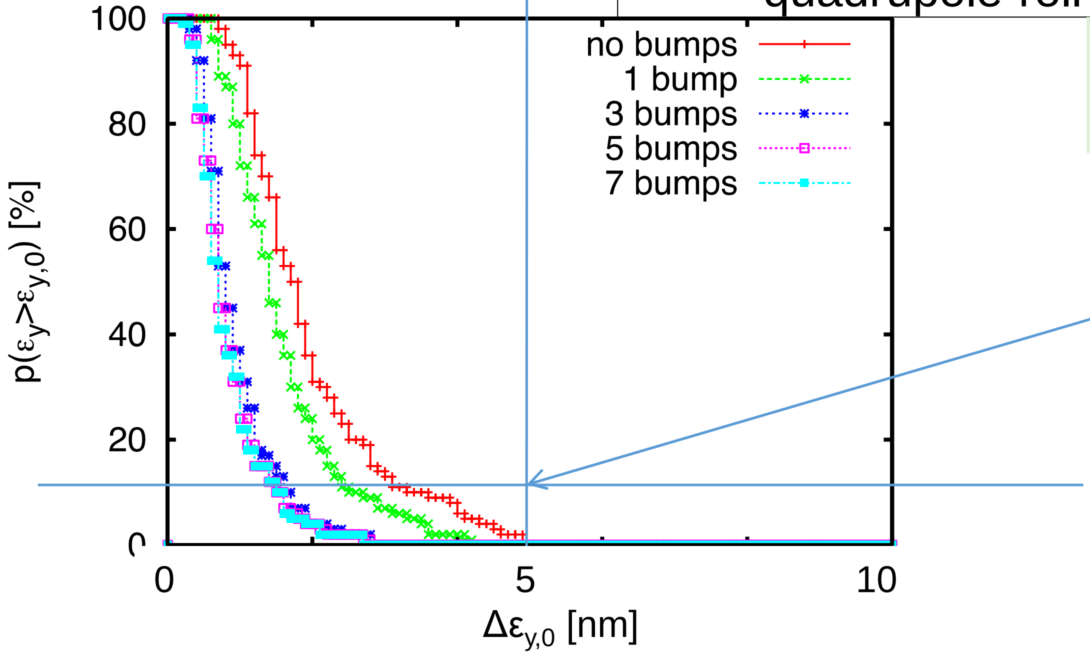
Wakefield monitor:
Measure wakefield in damping waveguide

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	$\approx$ 0.12 nm



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

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

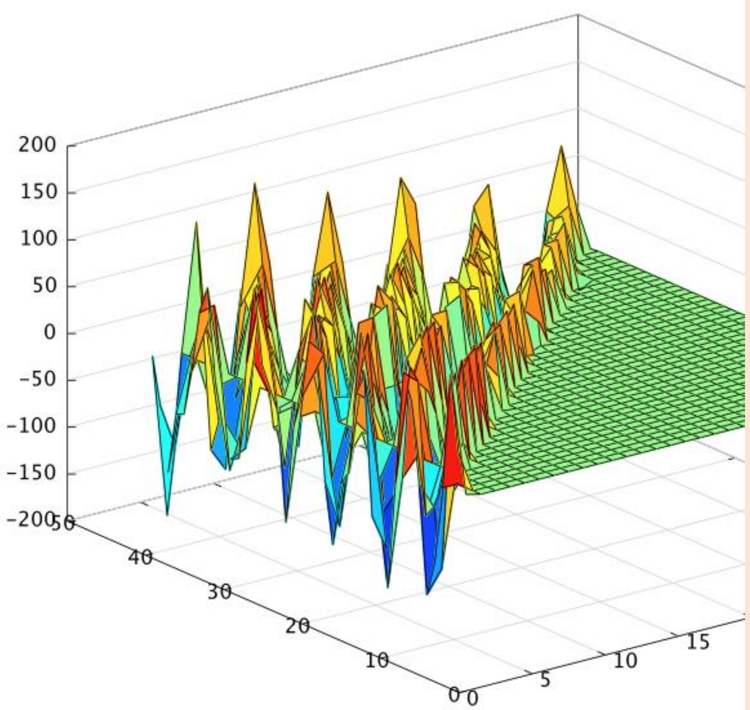
Further improvement using tuning bumps

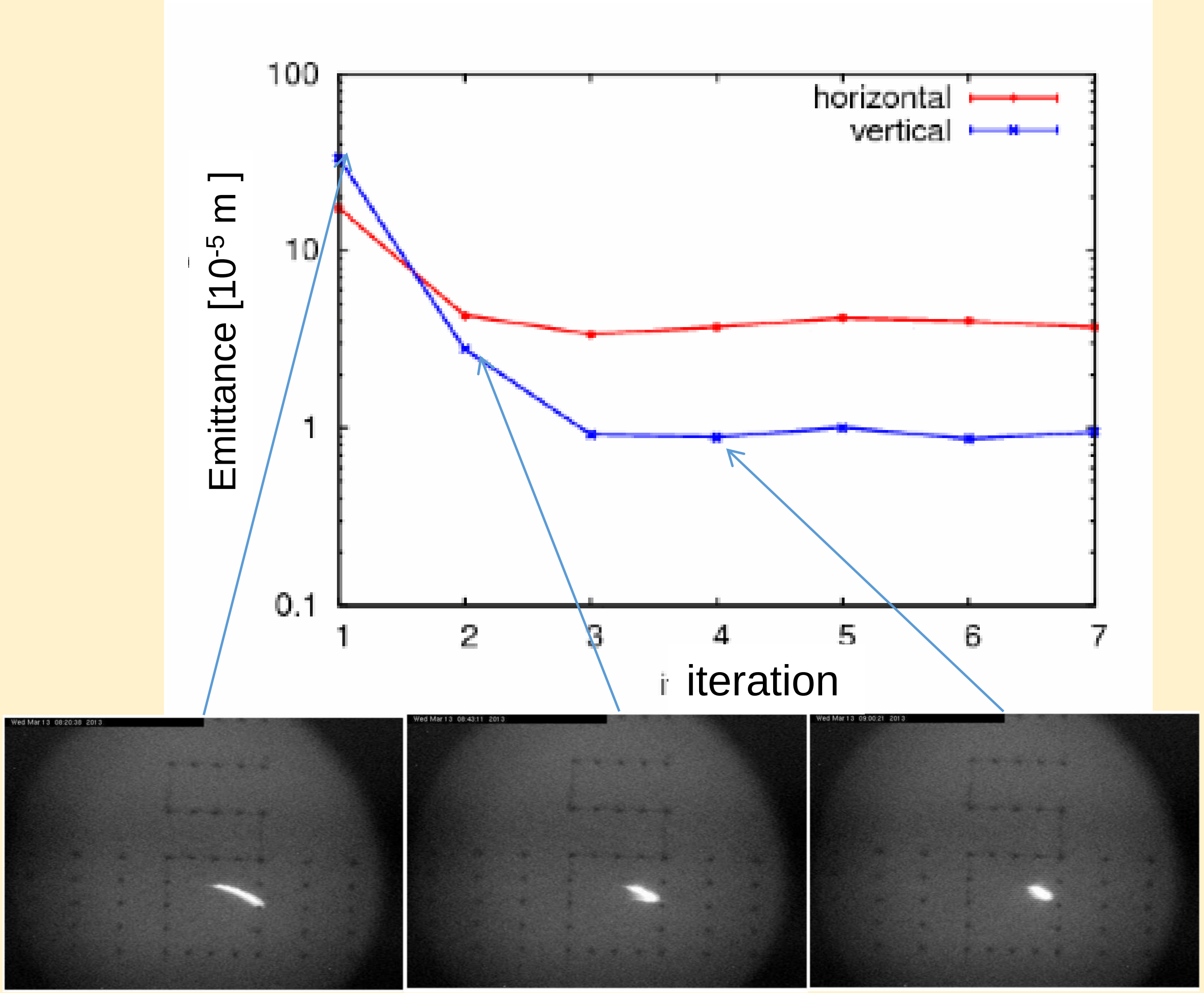
CLIC Beam-Based Alignment Tests at FACET

DFS applied to 500 meters of SLC linac

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

System model





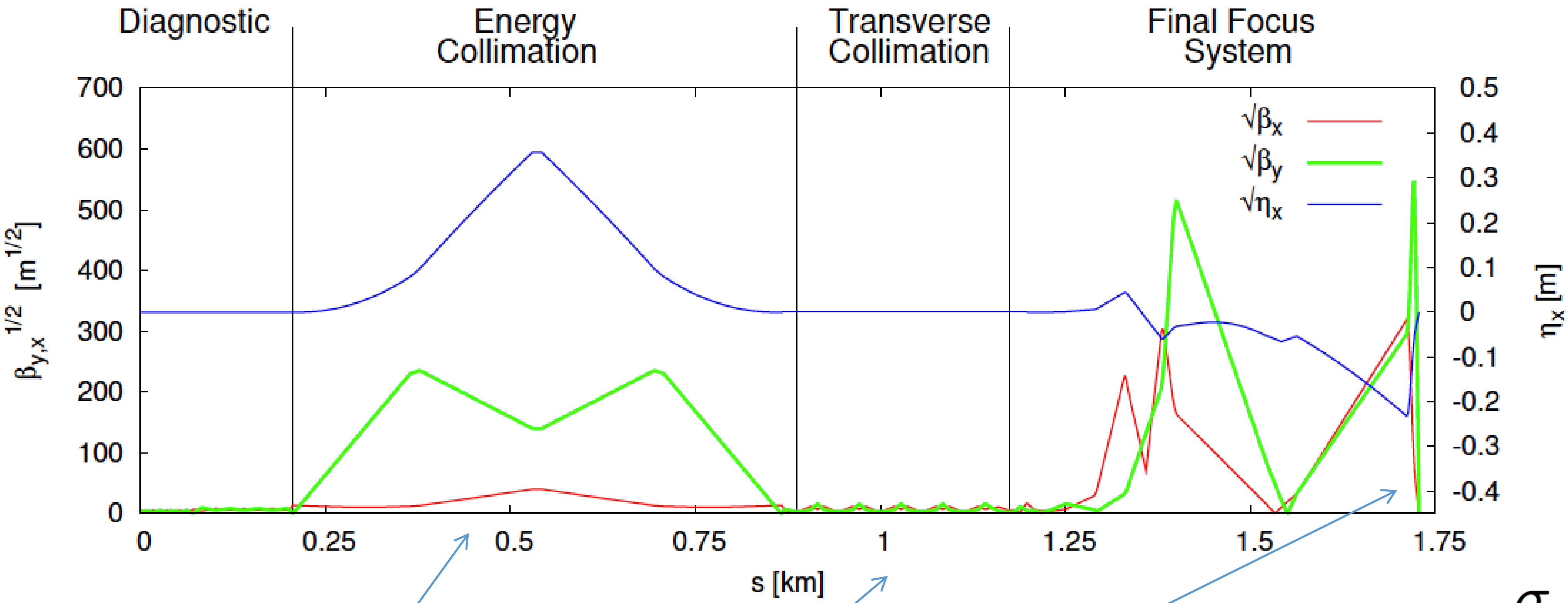
Initial beam

After 1 iteration

After 3 iterations

✓

Beam Delivery System



Removes longitudinal tails
Protection from RF failures

Cleaning transverse halo
Protection from transverse jitter

Squeezing beam to minimum size

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

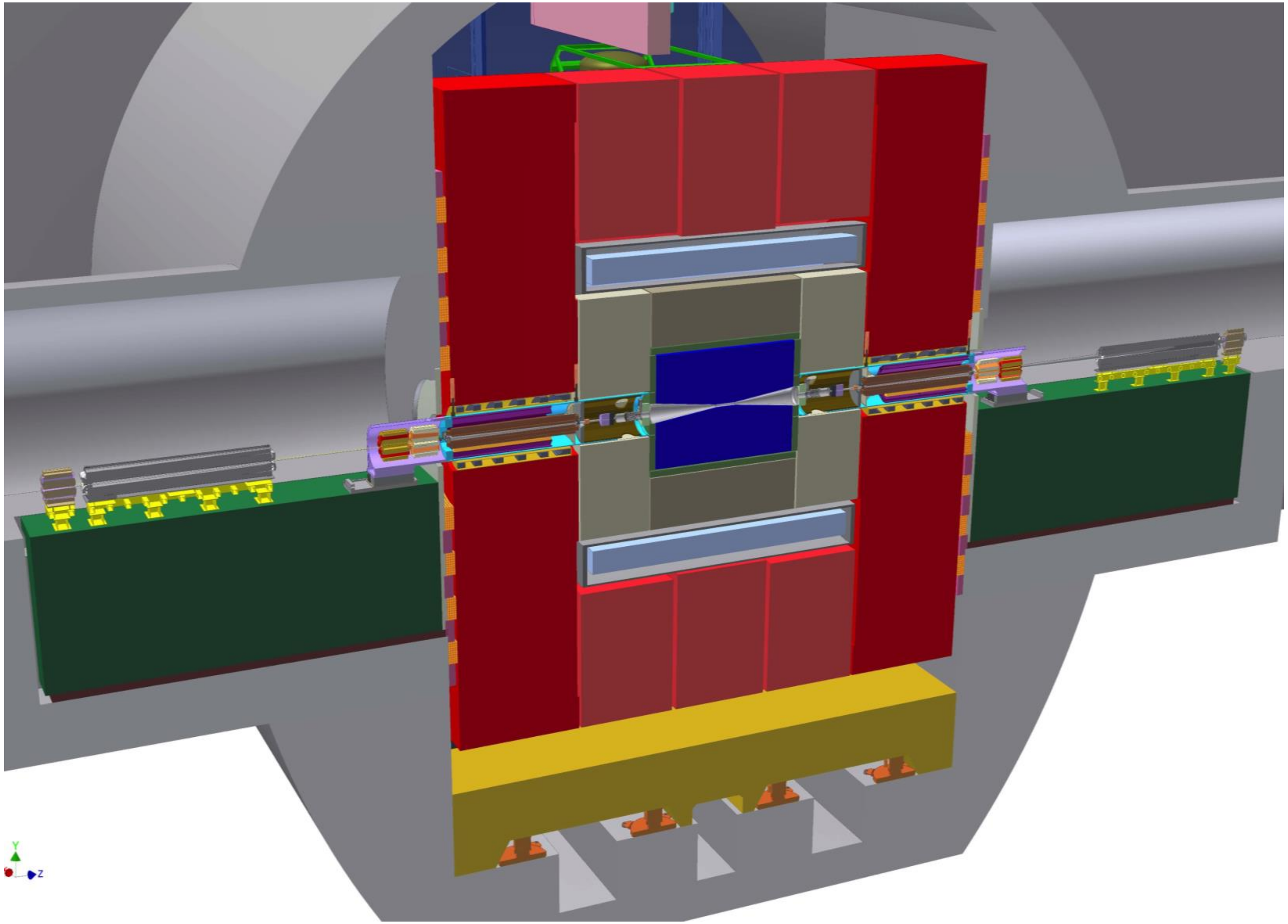
Goal 143 nm x 2.9 nm

$\beta_x = 8$ mm, $\beta_y = 0.1$ mm

Beam Delivery System

First magnet has been at L* = 3.5 m from the interaction point, inside of detector

Short L* limits chromaticity, the main challenge



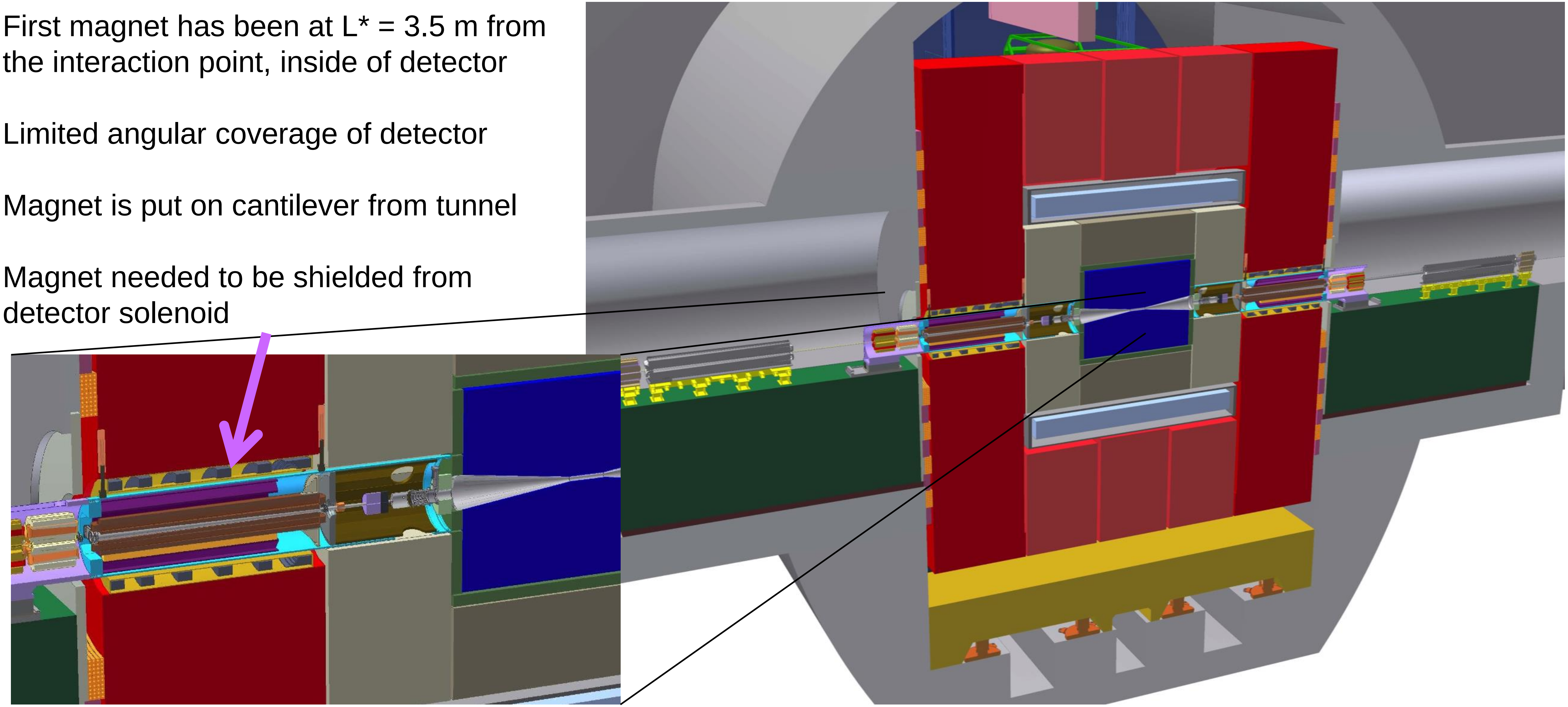
Beam Delivery System

First magnet has been at L* = 3.5 m from the interaction point, inside of detector

Limited angular coverage of detector

Magnet is put on cantilever from tunnel

Magnet needed to be shielded from detector solenoid

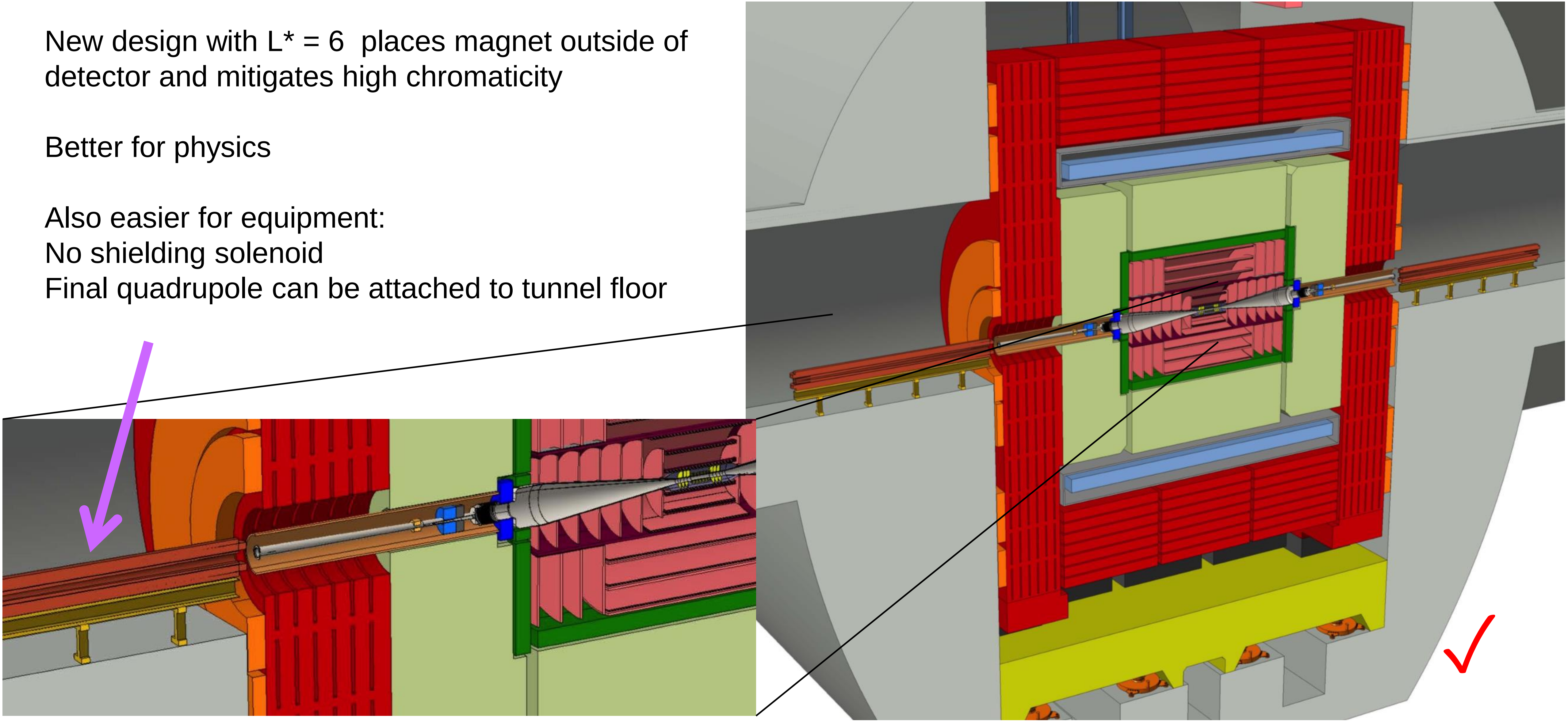


Beam Delivery System

New design with $L^* = 6$ places magnet outside of detector and mitigates high chromaticity

Better for physics

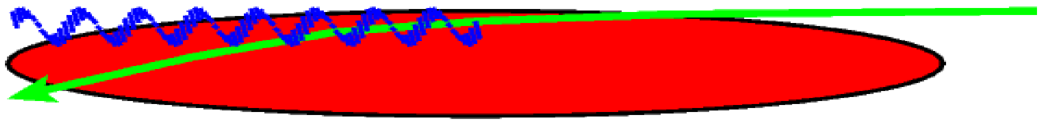
Also easier for equipment:
No shielding solenoid
Final quadrupole can be attached to tunnel floor



✓

Beam-beam Effect

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

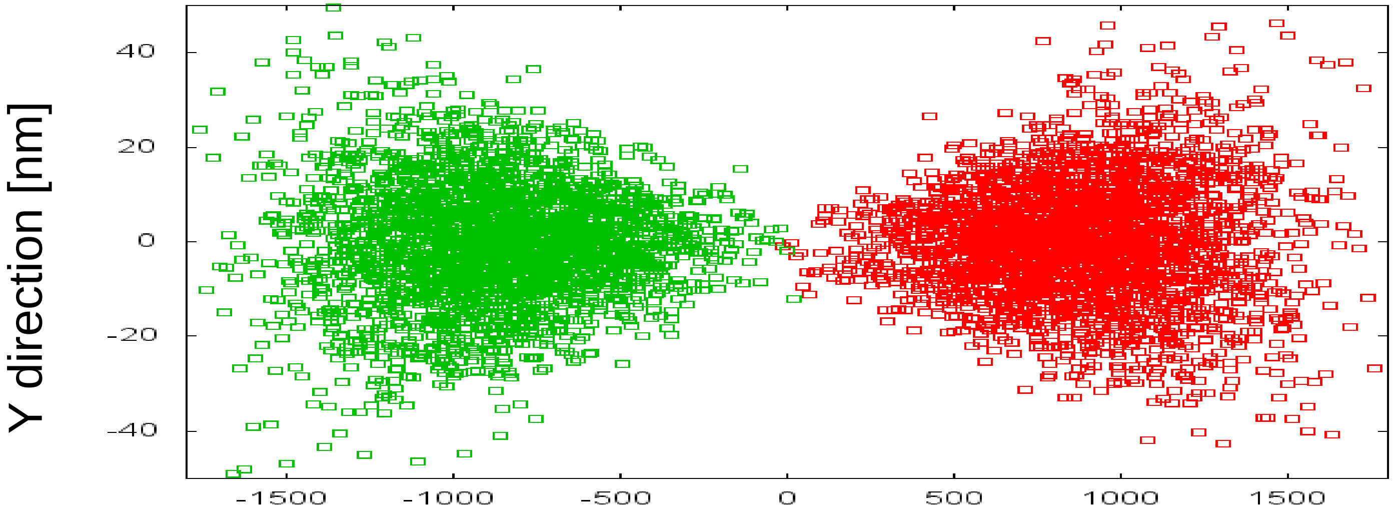


Dense beams to reach high luminosity
Beam focus each other

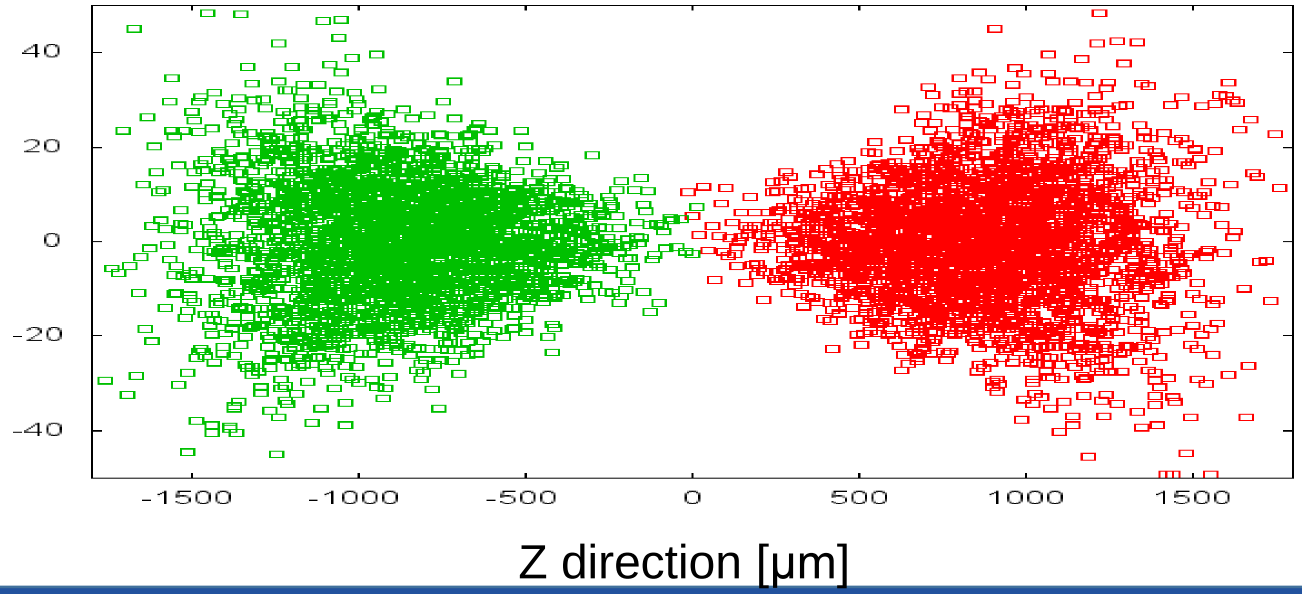
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$

Beam-beam force off

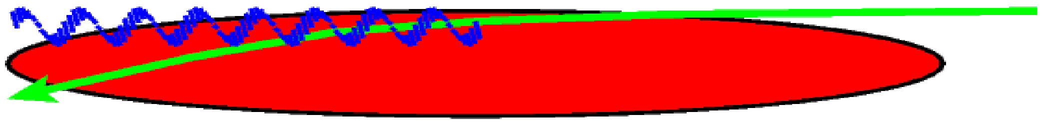


Beam-beam force on

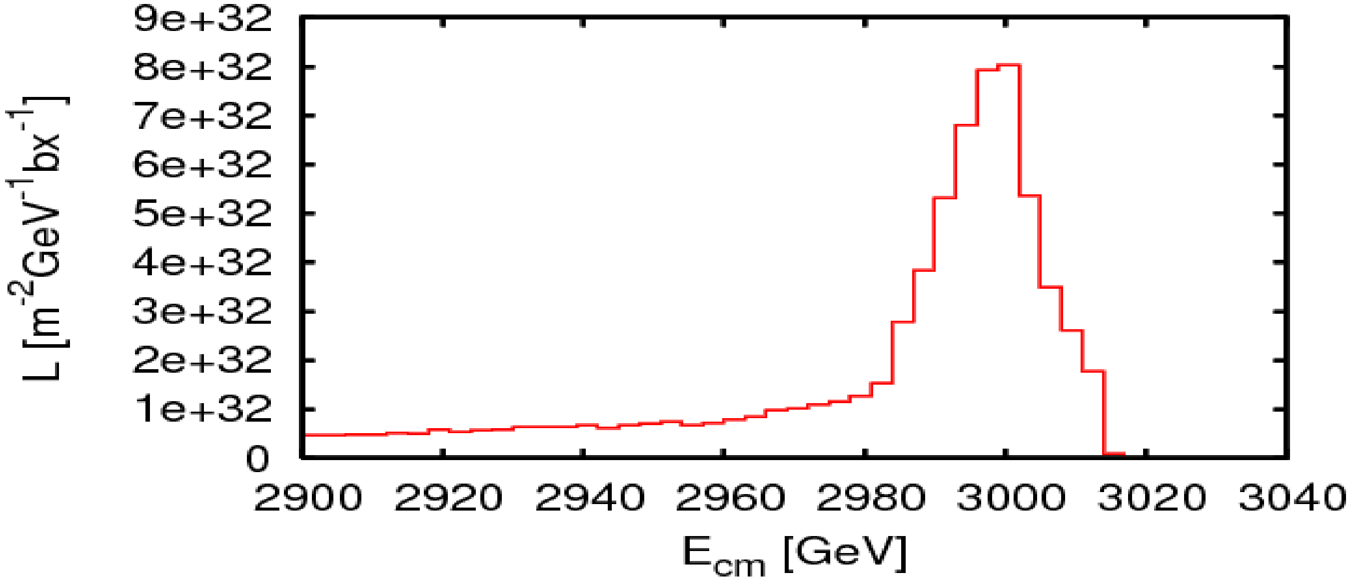


Beam-beam Effect

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



Emitt beamstrahlung
Develop luminosity spectrum

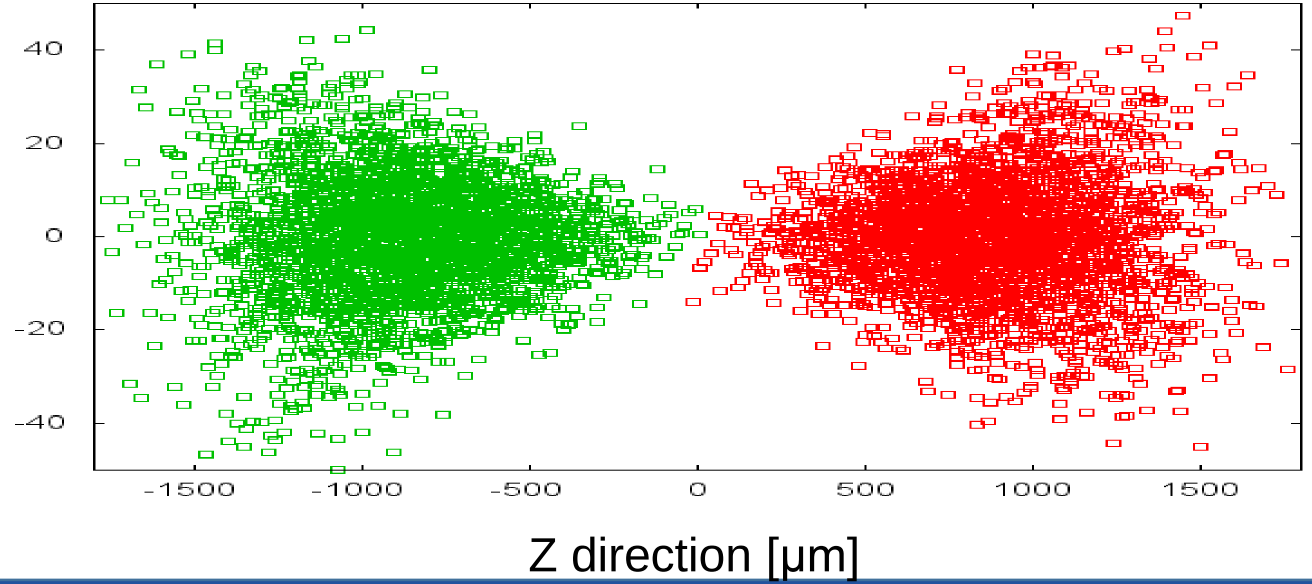


$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

Aim for O(1)
at 380 GeV

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

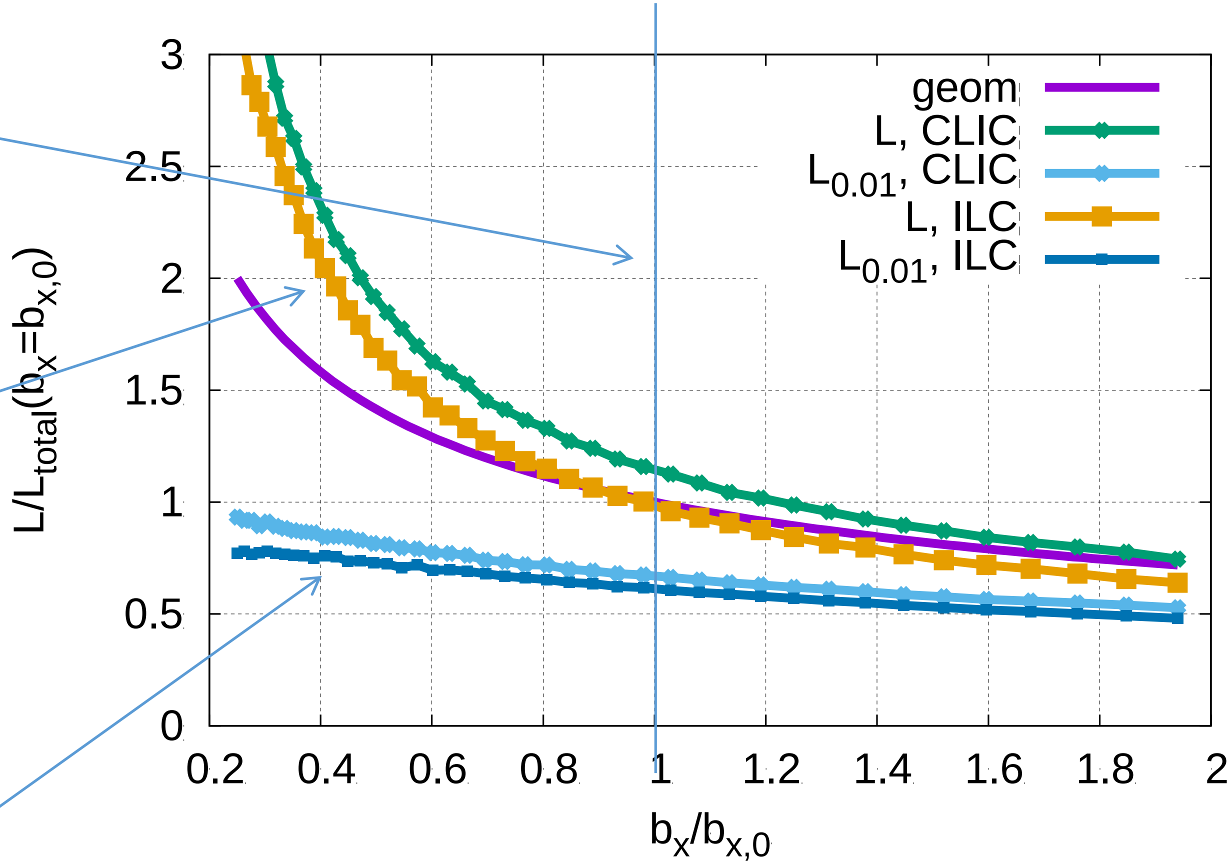
$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$



Horizontal Optimum

Design value β_x= 8 mm

Reaches $L_{0.01}/L$=60%



The total luminosity L varies strongly with beta-function

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

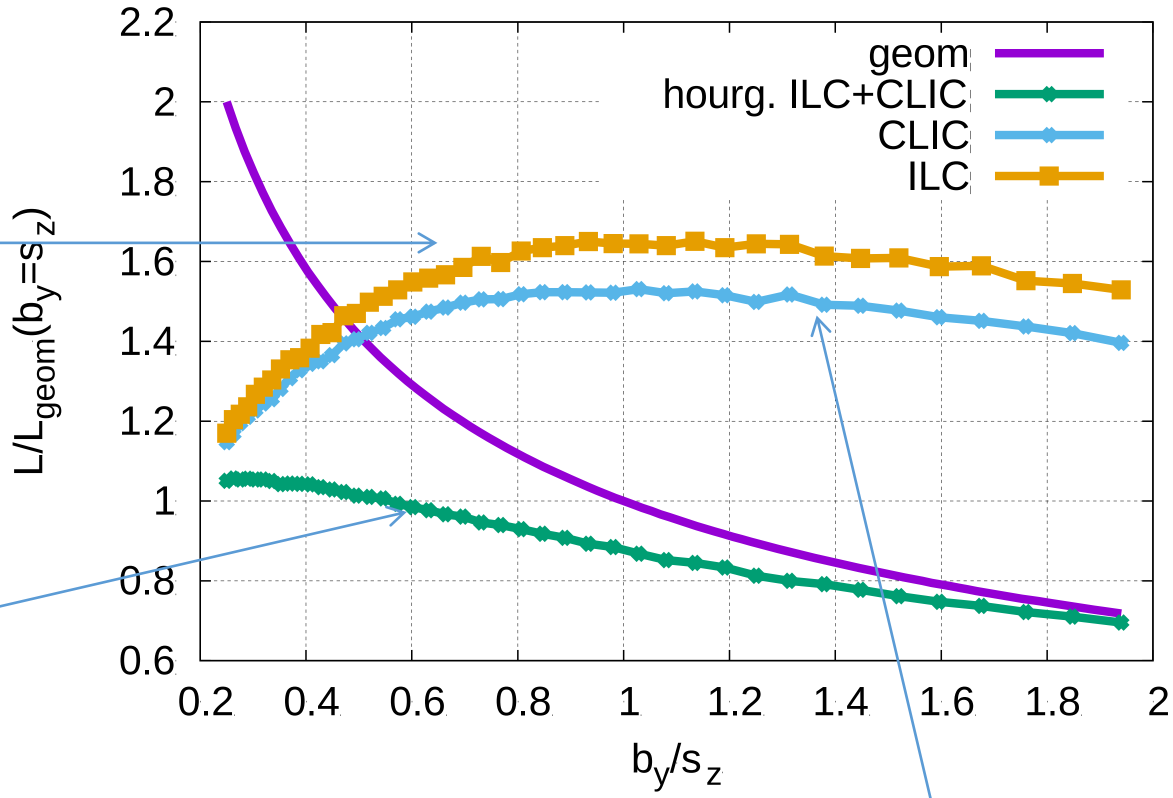
Hard to push beta-functions that low

Use $L_{0.01}/L$=60% as criterion
Reasonable compromise for most physics studies

Vertical Optimum

Including pinch effect

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



Geometric luminosity
No beam-beam forces

Somewhat above optimum because small beta-functions because it is easier for the machine

CLIC choice 100 µm,
reached by beam delivery system

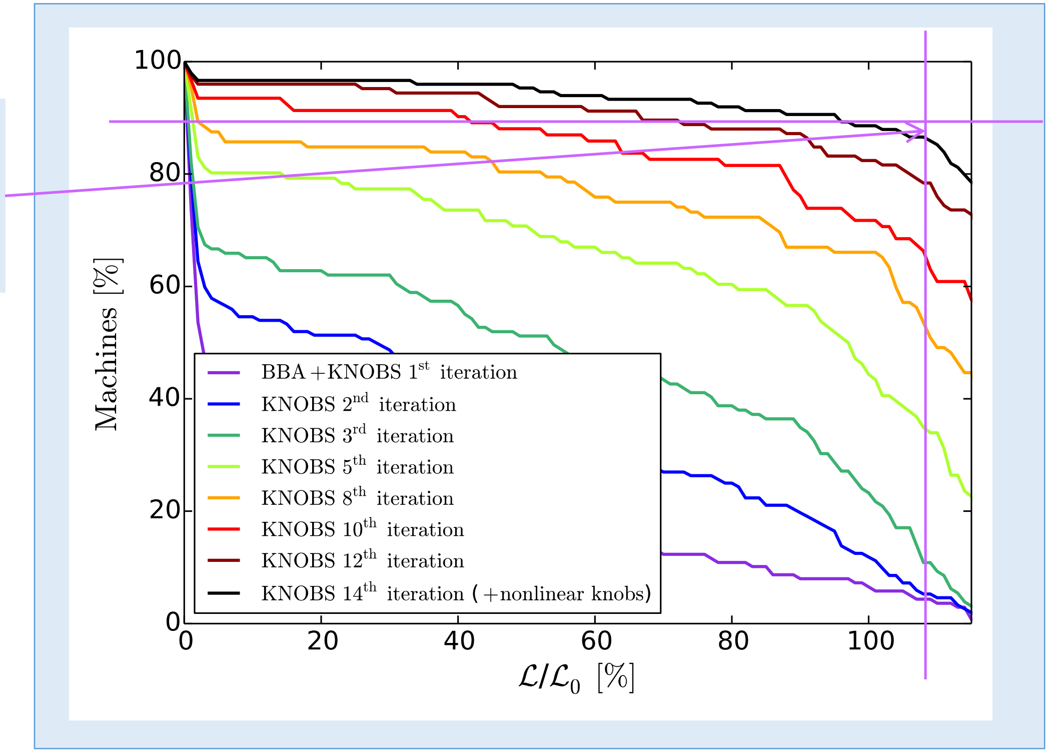
Beam Delivery System Imperfections

Realistic imperfections in BDS

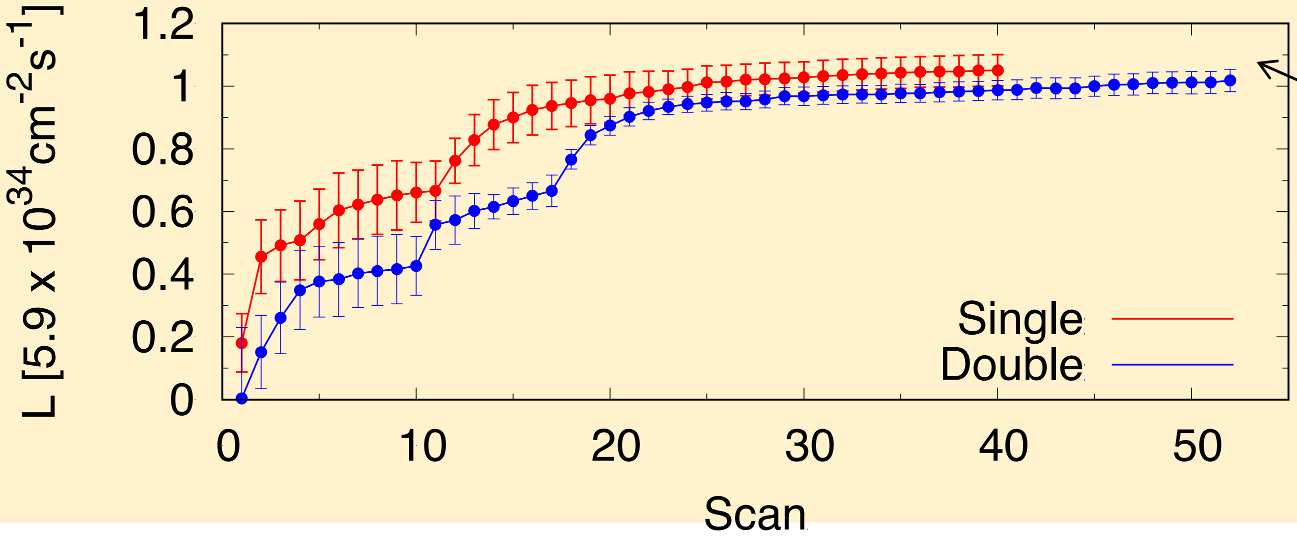
Beam-based alignment and beam size tuning is used

Aim to reach 110% of promised luminosity with 90% likelihood (10% is budget for dynamic imperfections)

Single beam tuning
85% reach 110% of promised luminosity

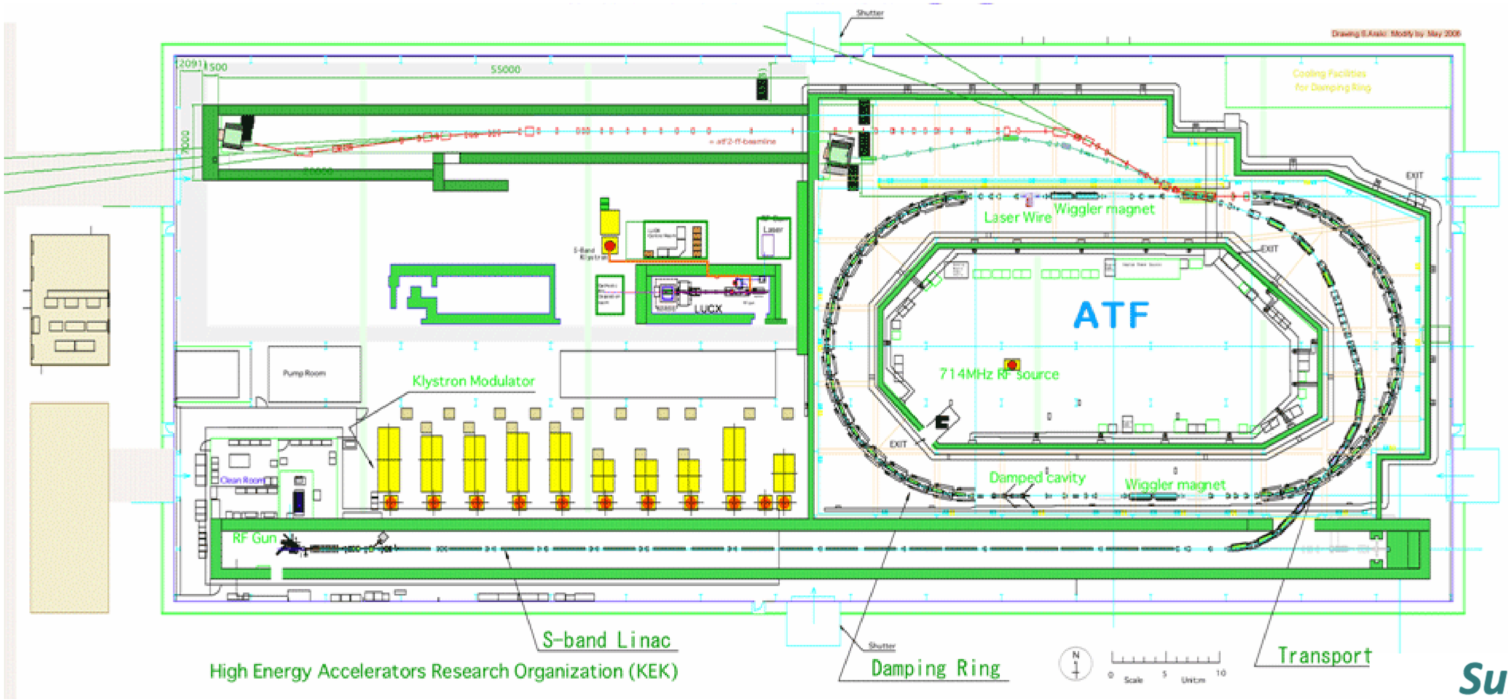


Two-beam study ongoing
Small difference in performance



Luminosity is still increasing
Simulation is very slow (much slower than reality)
Try to improve speed

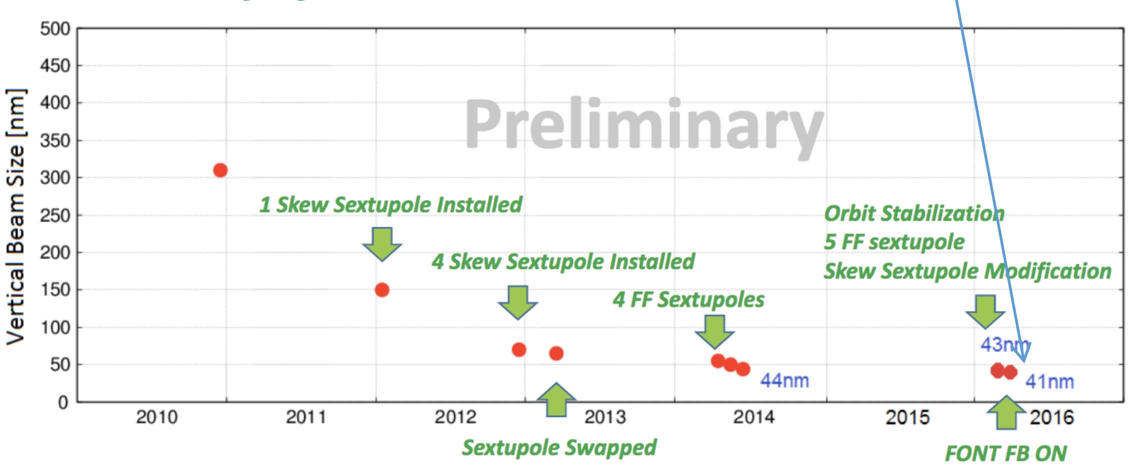
ATF 2 Results



Much learned on instrumentation, tuning, design, …
Many practical issues from reused equipment, long bunches, …

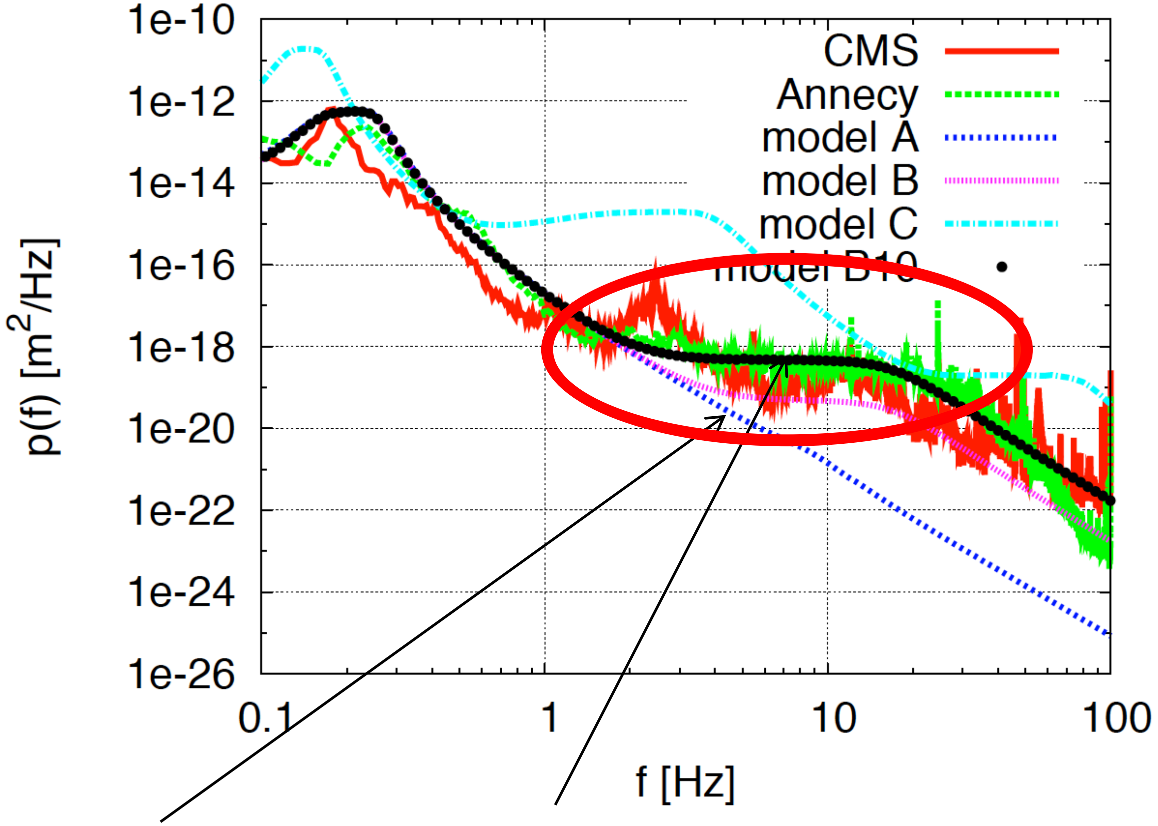
Beam size (41 nm) is close to target (37nm)

Beam jitter: 0.2 / 0.1 σ
No feedback / with feedback


Summary of the IP vertical beam size measurement

Dynamic Imperfection Example: Ground Motion

Ground motion can impact beam trajectory



LEP tunnel

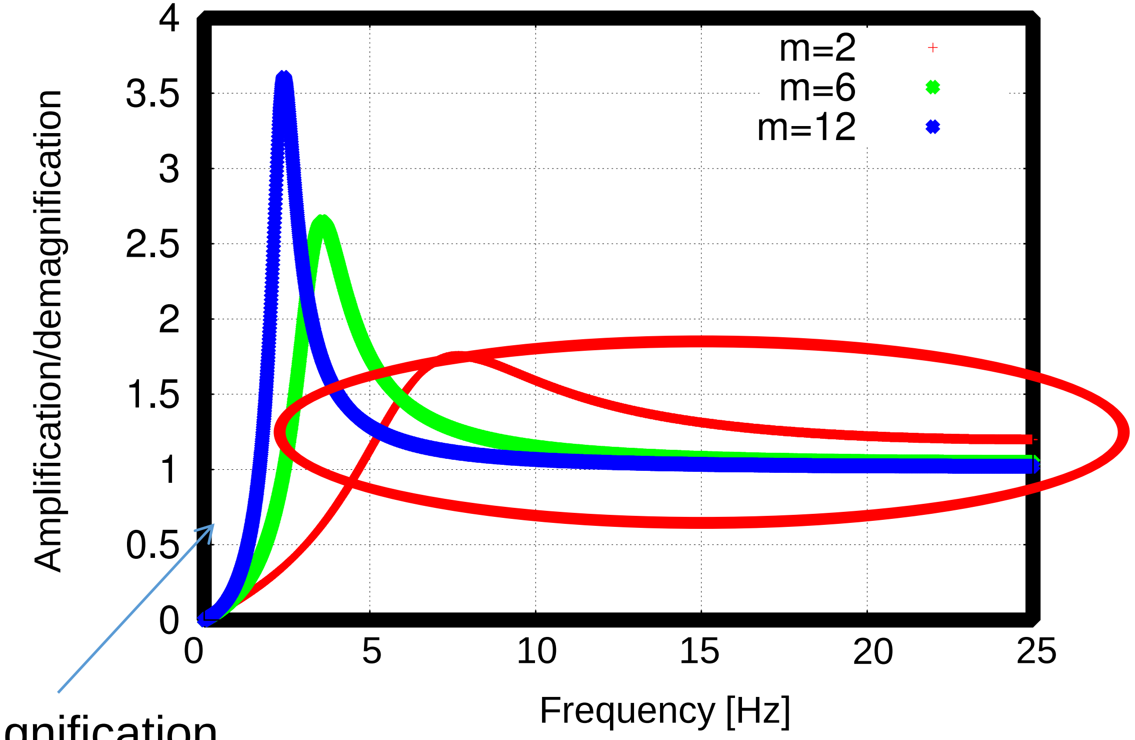
Want to be able to cope with this
(Model B10 similar to CMS hall)

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

⇒ Cures low frequency ground motion

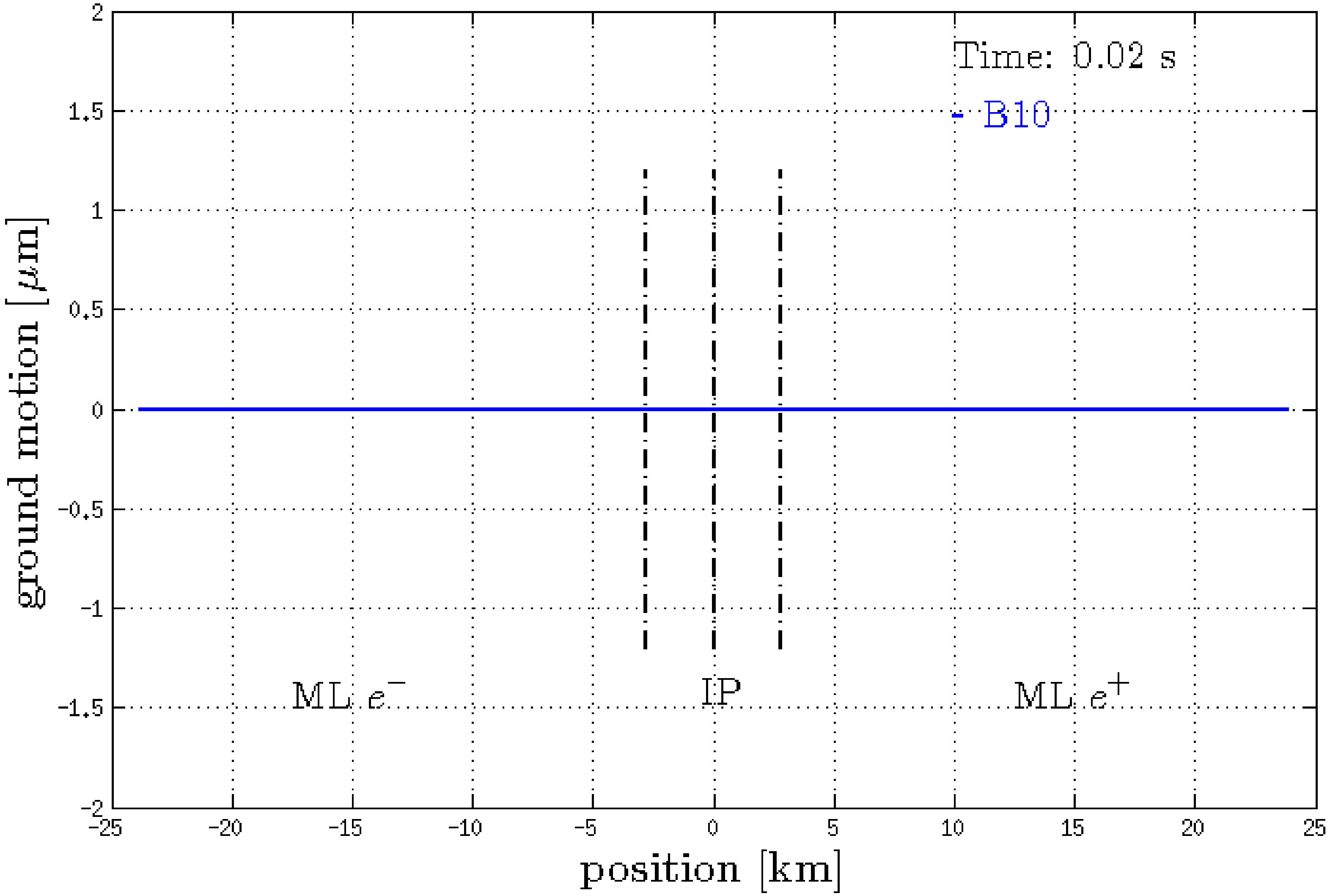
⇒ But not higher frequencies

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

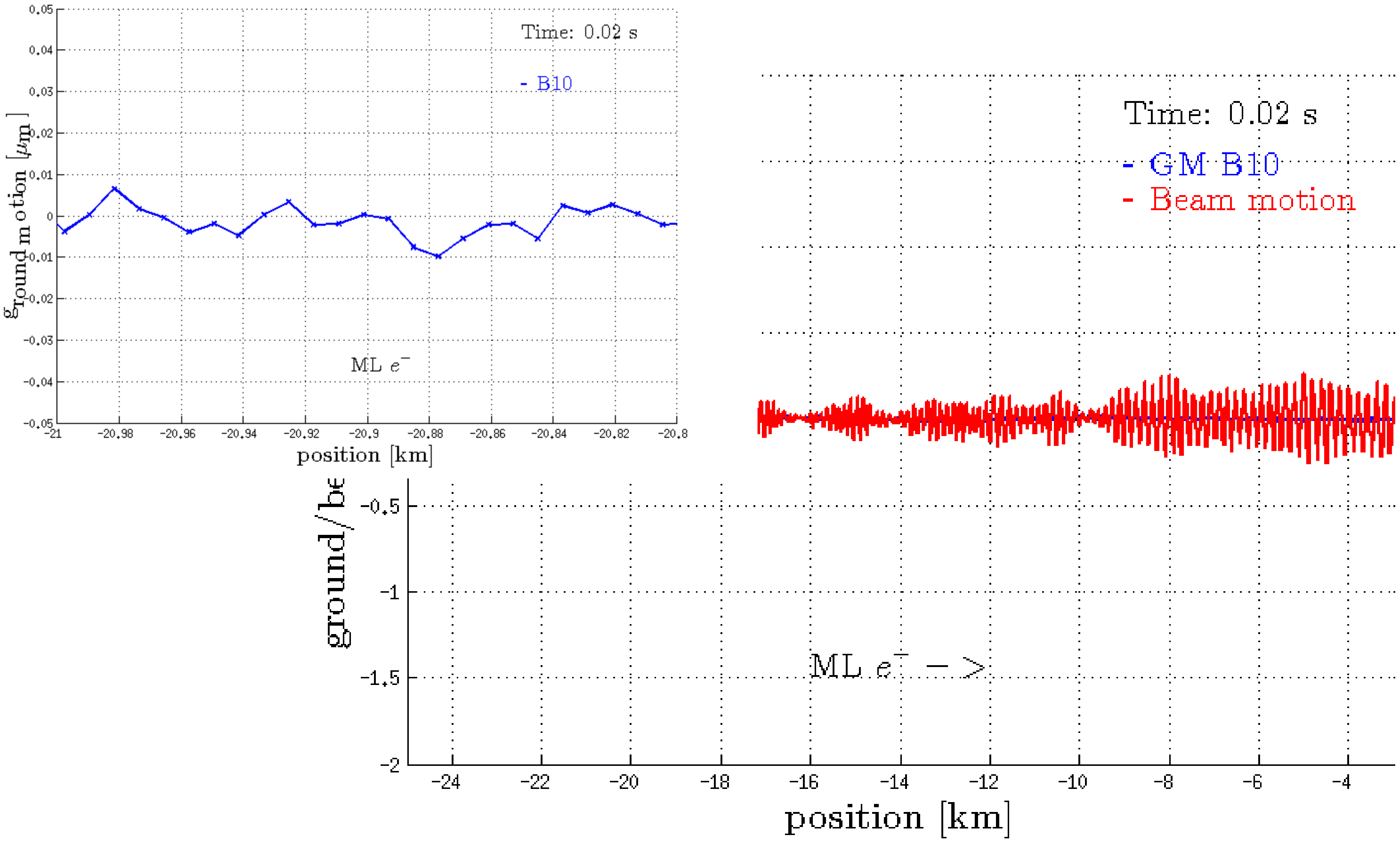


demagnification

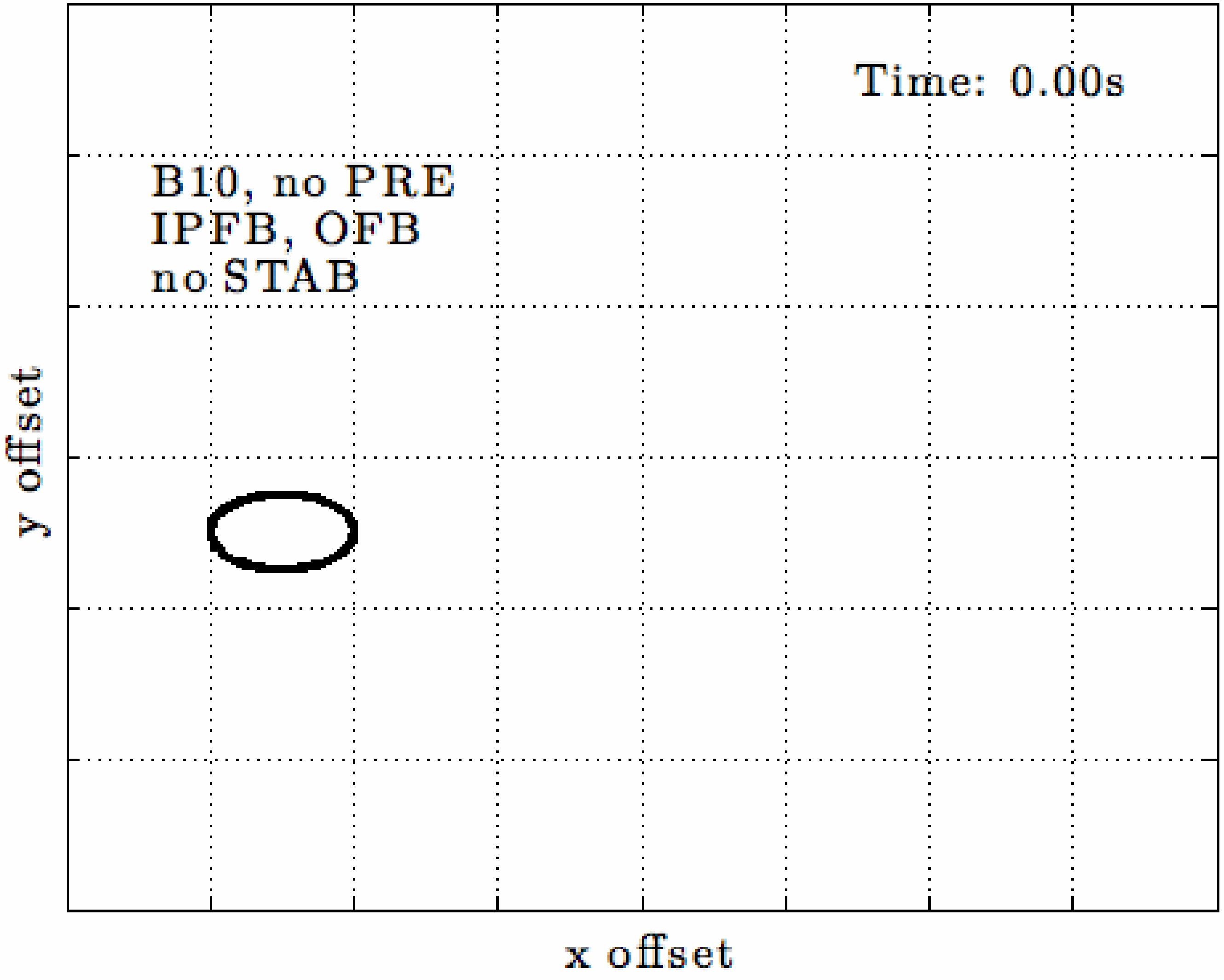
Ground Motion



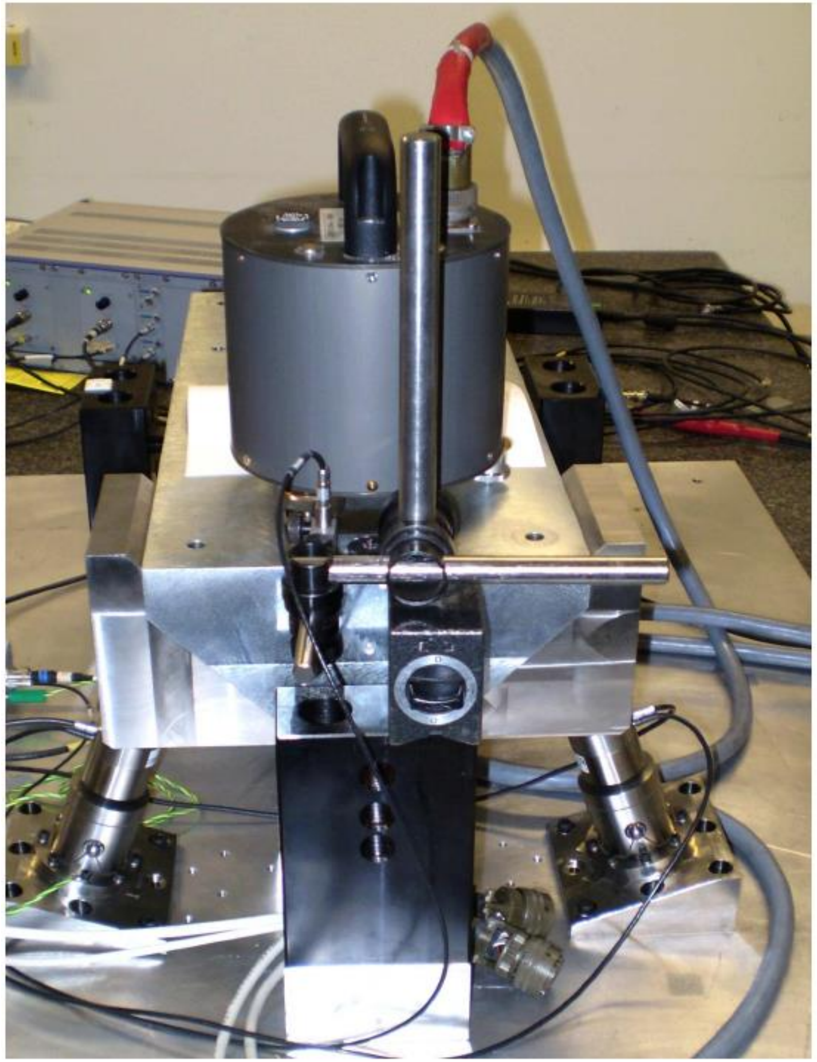
Beam Motion with Beam Feedback Only



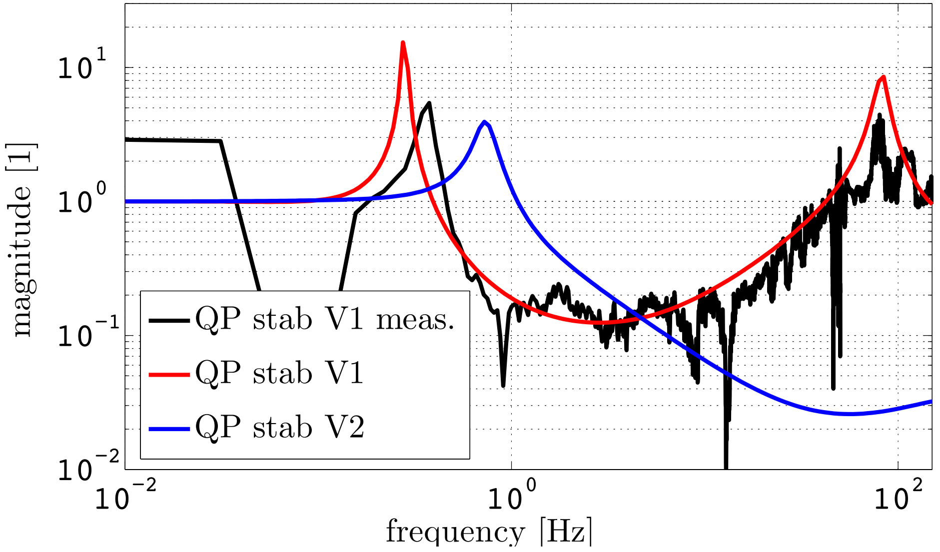
Jitter at IP

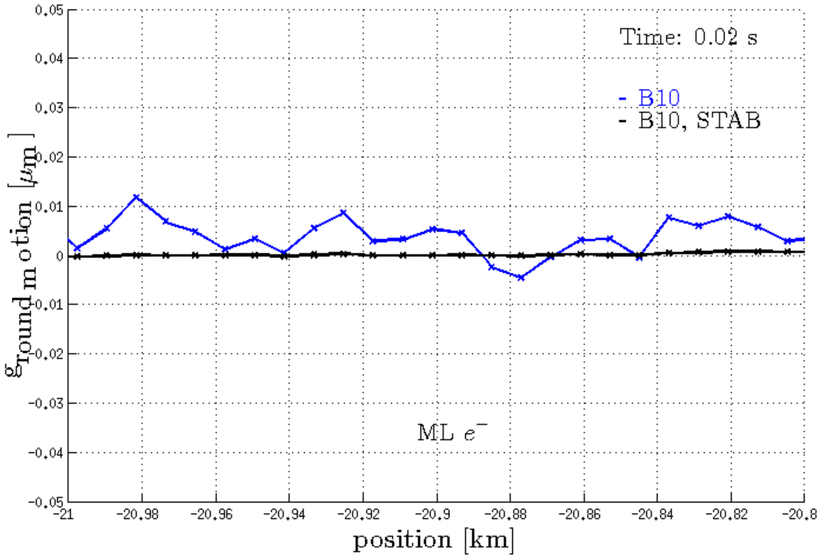


The Stabilisation System

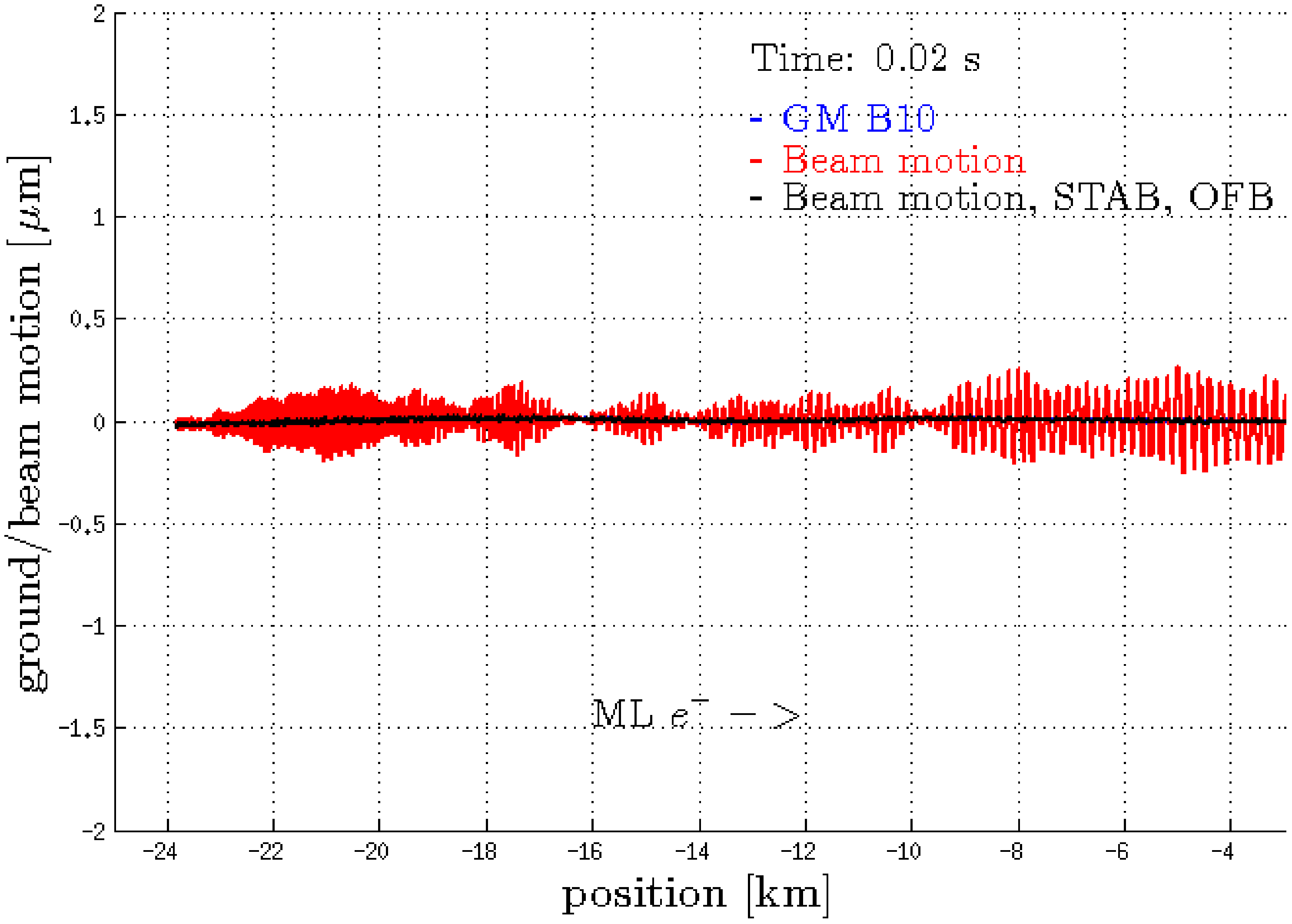


K. Artoos et al.

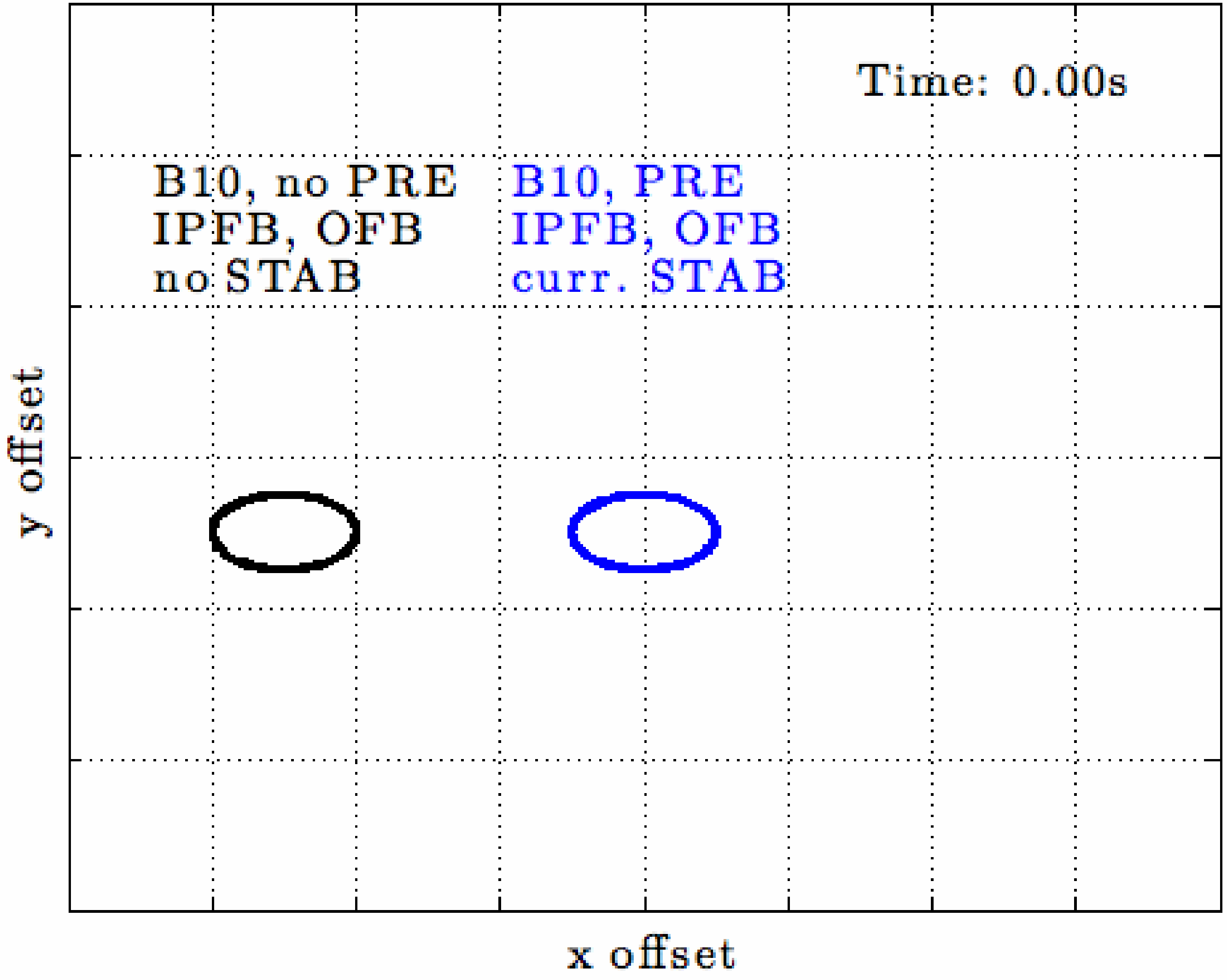




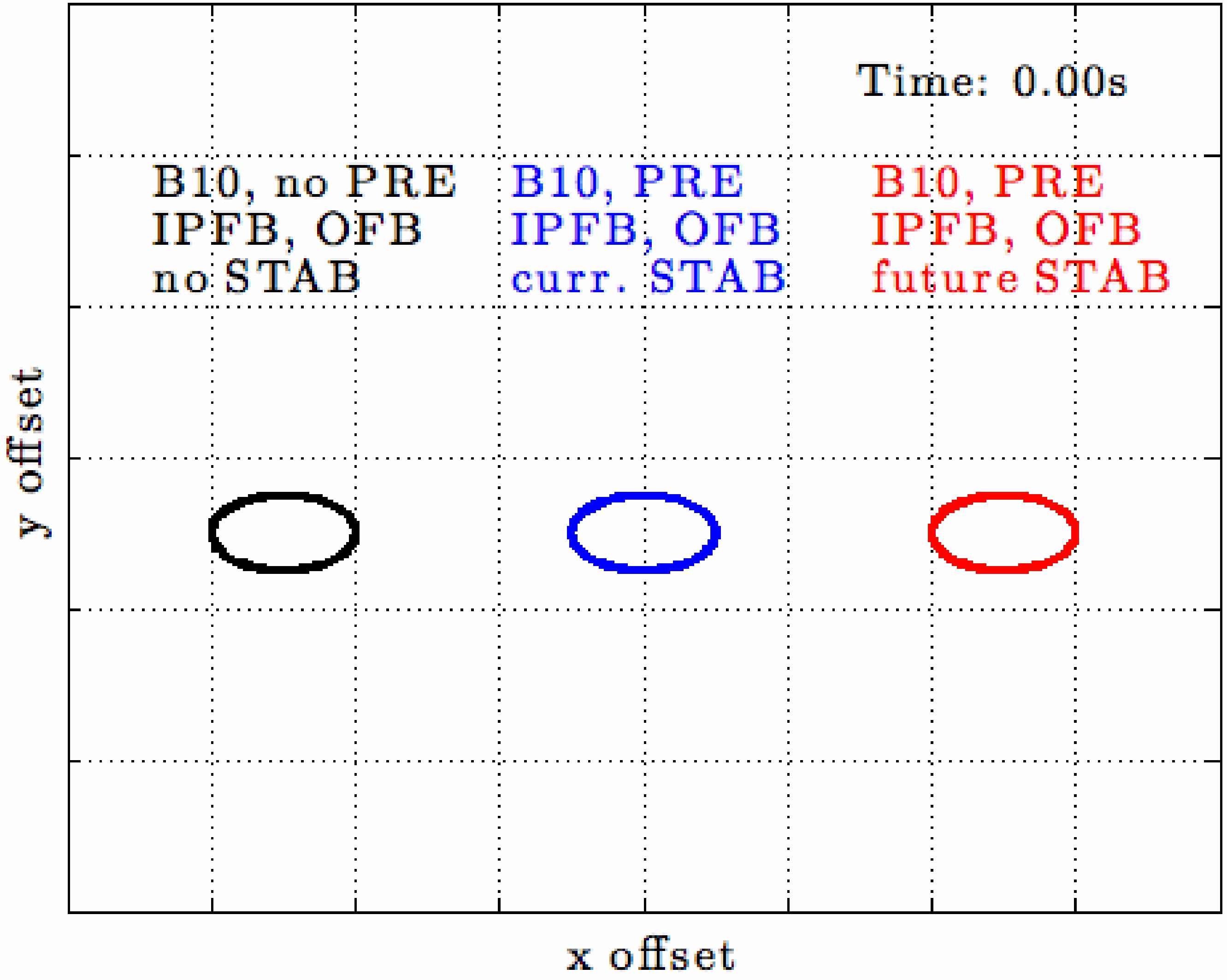
Beam Trajectory Jitter



Beam Jitter at IP



Beam Jitter at IP



Target achieved
Well within budget

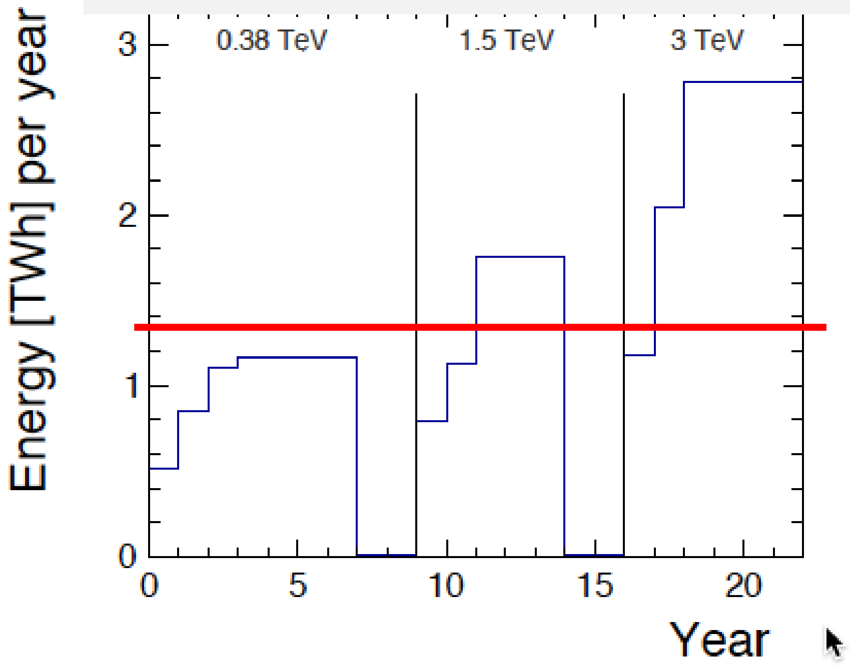
Tests at ATF 2

✓

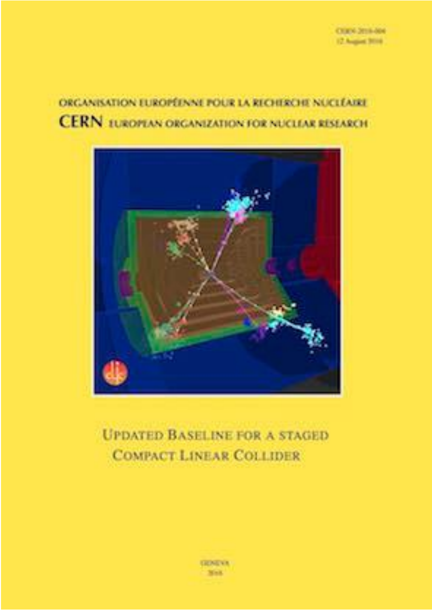
Cost and Power

Goals bring cost and power consumption down:
“reasonable cost”: O(6 GCHF)
Power < O(200 MW)

CERN energy consumption 2012: 1.35 TWh



Preliminary
Estimate 252 MW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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

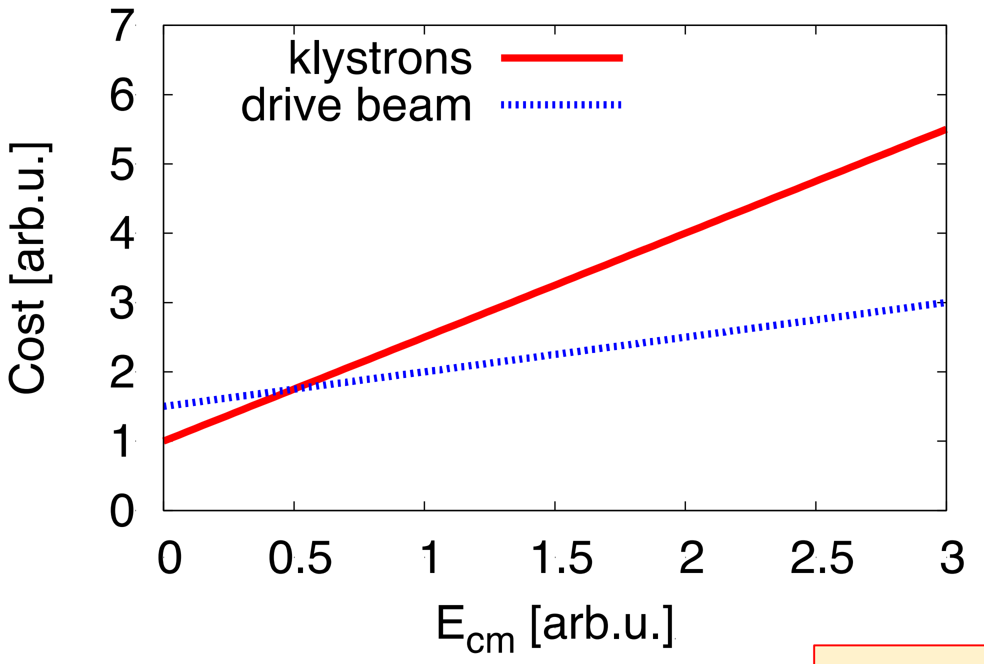
Preliminary value for 380 GeV
(MCHF of Dec 2010)

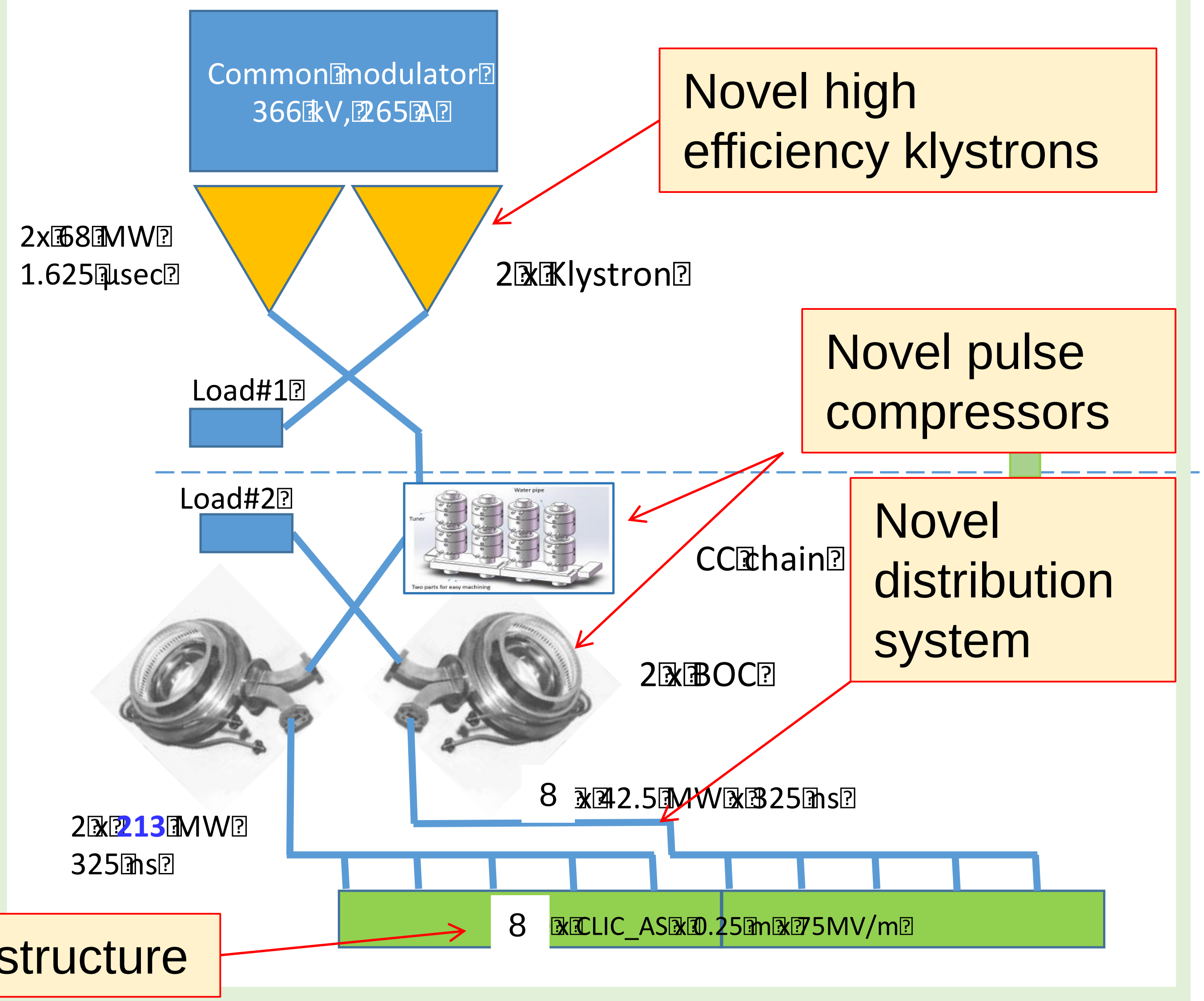
Main beam production	1245
Drive beam production	974
Two-beam accelerator	2038
Interaction region	132
Civil engineering etc.	2112
Control & operation	216
TOTAL	**6690**

Improvement of cost and power is ongoing
Detailed bottom up estimate
Already savings

Klystron-based Alternative

Develop klystron-based alternative
Expect comparable cost for first energy stage
But increases faster for high energies





Novel high efficiency klystrons

Novel pulse compressors

Novel distribution system

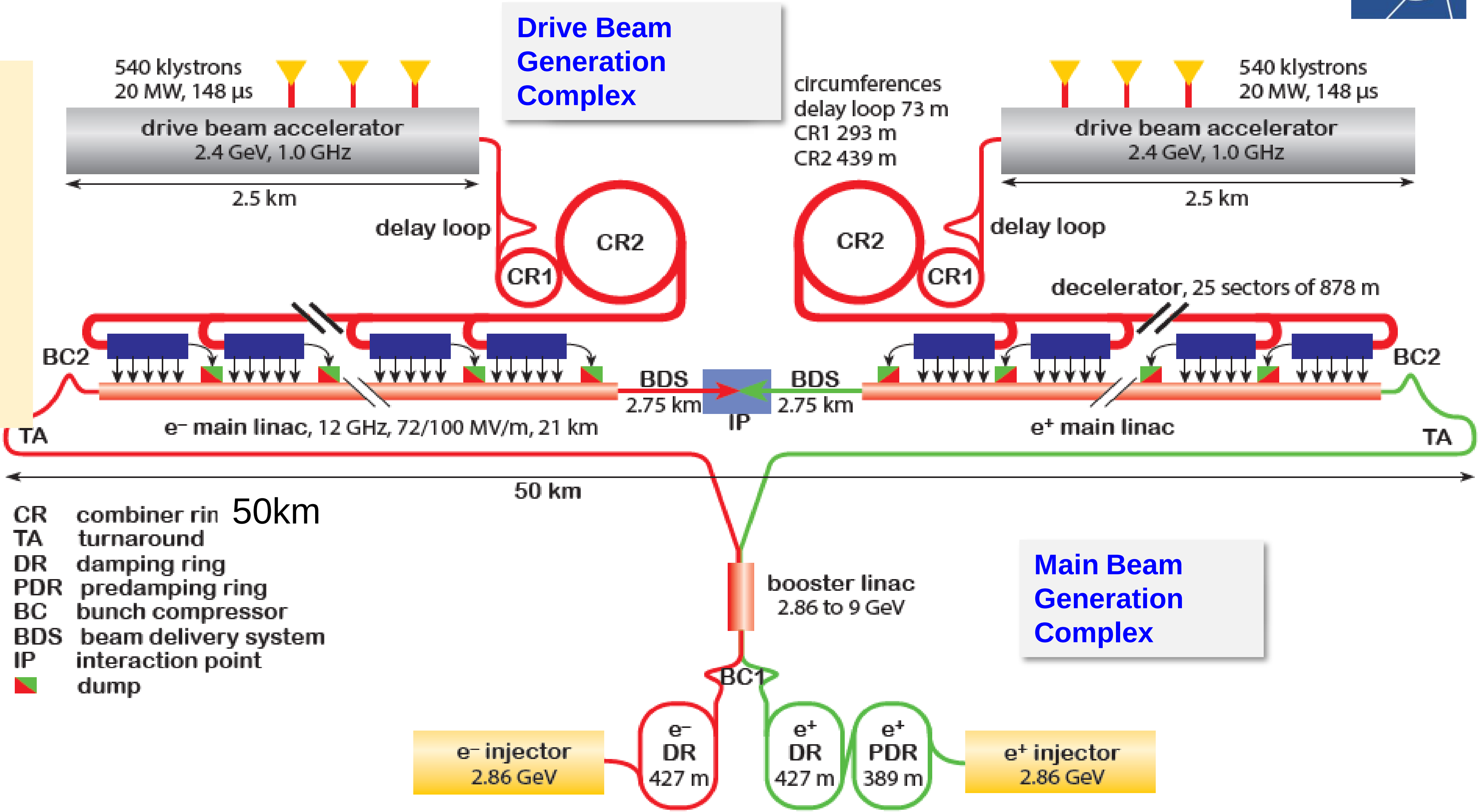
Optimised structure

CLIC at 3 TeV

Can re-use previous systems and components

Just add more linac and drive beam pulse length

At 3 TeV add one drive beam

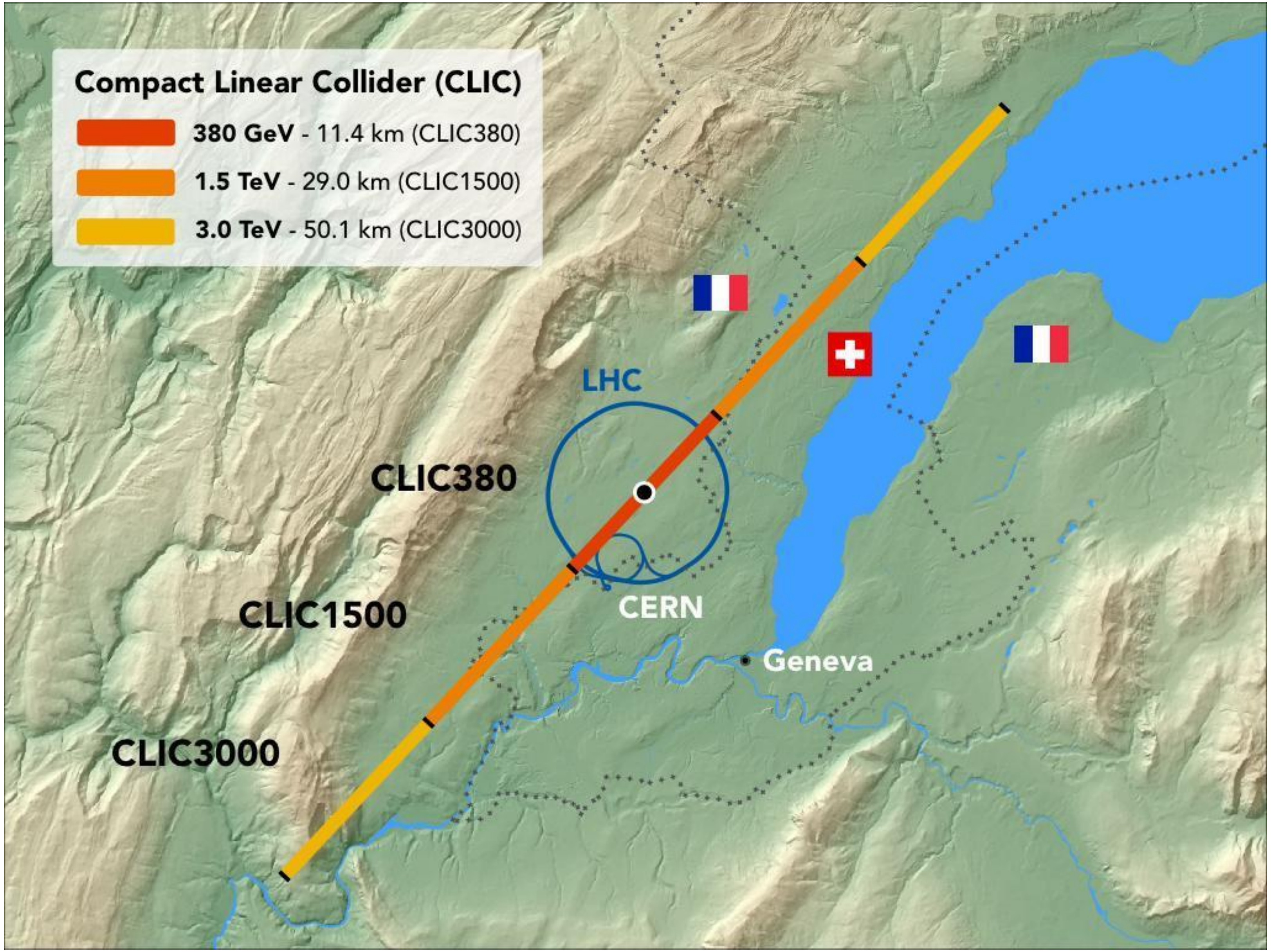


Drive Beam Generation Complex

50km

Main Beam Generation Complex

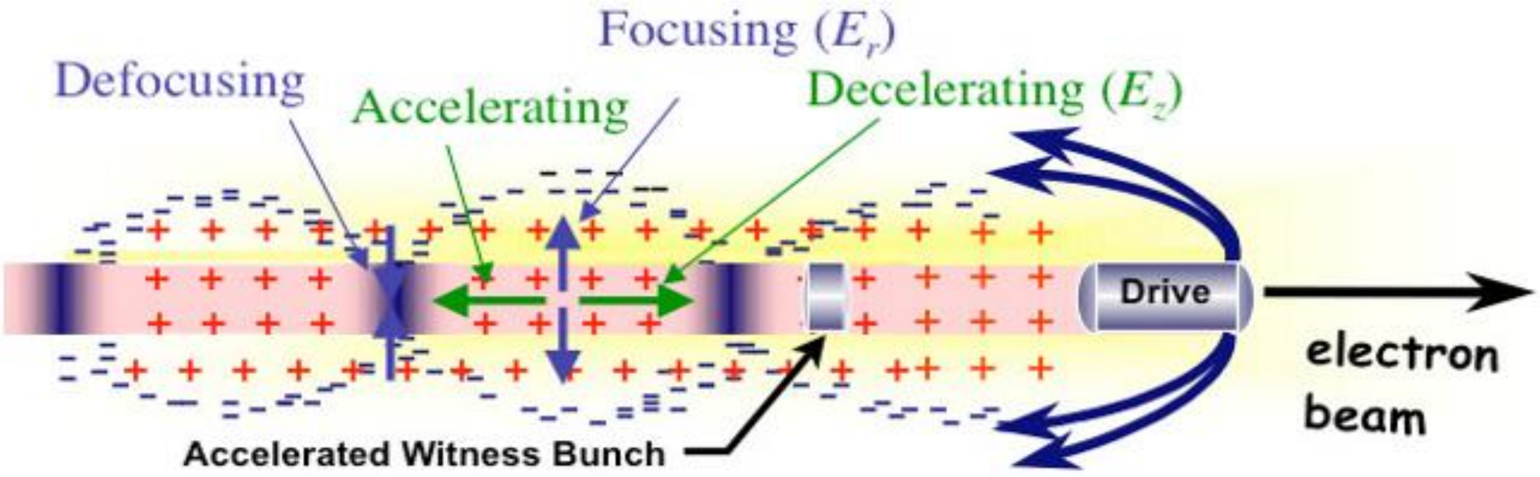
Site Near Geneva



Exploration of Future Upgrades

Exploration of novel acceleration methods for lepton collider has started

- Dielectric accelerating structures
- Laser driven plasma
- Beam driven plasma



Plasma-based acceleration demonstrated gradients of 50 GV/m

Application of novel technologies to colliders

- Started a working group for CLIC to understand potential
- Plasma community started a working group on colliders

Main challenge

- Beam quality preservation has to be explored theoretically and experimentally

Conclusion

A staged design for CLIC has been developed

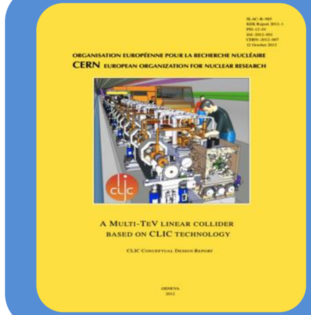
- First energy stage at 380 GeV optimised for performance, cost and power
  - Meet the physics performance targets
  - Cost roughly comparable to LHC
  - Power O(200 MW)
- Further energy stages can reuse components
  - Site available for 3 TeV
- In the long run novel acceleration methods may become available

High gradients and high peak power are key to CLIC

Great control of imperfections is second key

- Technical solutions have been demonstrated, see tomorrow
- Beam-based methods have been established

Note: CLIC CDR



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A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Vol 1: The CLIC accelerator and site facilities

- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- https://edms.cern.ch/document/1234244/

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PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Vol 2: Physics and detectors at CLIC

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- http://arxiv.org/pdf/1202.5940v1

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THE CLIC PROGRAMME:
TOWARDS A STAGED e^+e^- LINEAR COLLIDER
EXPLORING THE TERASCALE
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Vol 3: "CLIC study summary"

- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

Input documents to Snowmass 2013 has also been submitted: http://arxiv.org/abs/1305.5766 and http://arxiv.org/abs/1307.5288

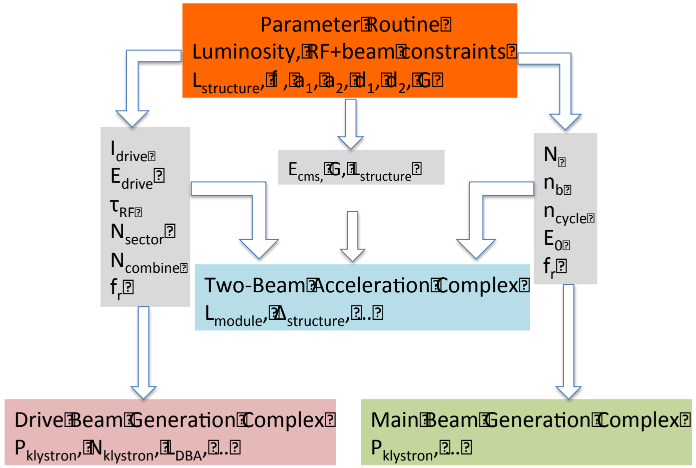
Note: CLIC Optimisation

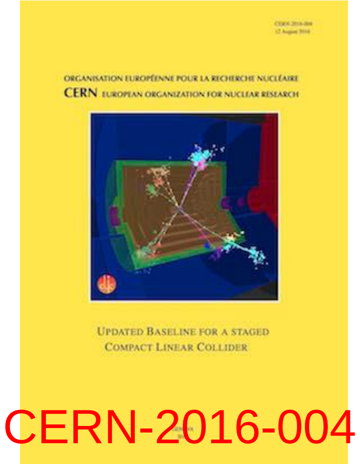
Scan 1.7 billion cases:

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)

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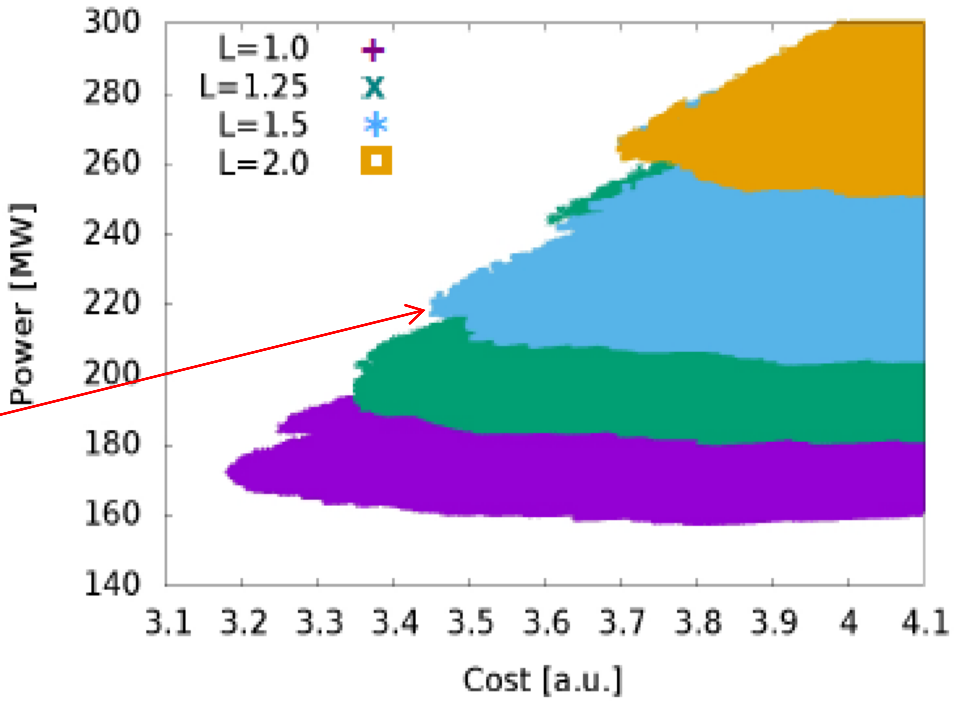
UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

CERN-2016-004

Resulting designs:
Colors indicate luminosities



This is the one that we picked

Reserve

Cost

Goal set as “reasonable cost”: 6 GCHF

Preliminary cost estimate from rebaselining

Performing bottom-up cost estimate

Also optimise the cost

- Module design is being improved
- Injector cost has been relatively high, is being reduced substantially by about halving number of klystrons
- Drive beam injector has already been optimised
- Civil engineering is being reviewed
- …

Preliminary value for 380 GeV
(MCHF of Dec 2010)

Main beam production	1245
Drive beam production	974
Two-beam accelerator	2038
Interaction region	132
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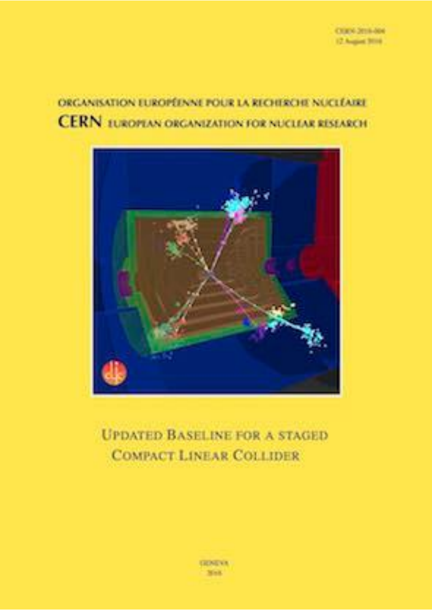

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UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

Power

Goal set as “reasonable power”: 200 MW

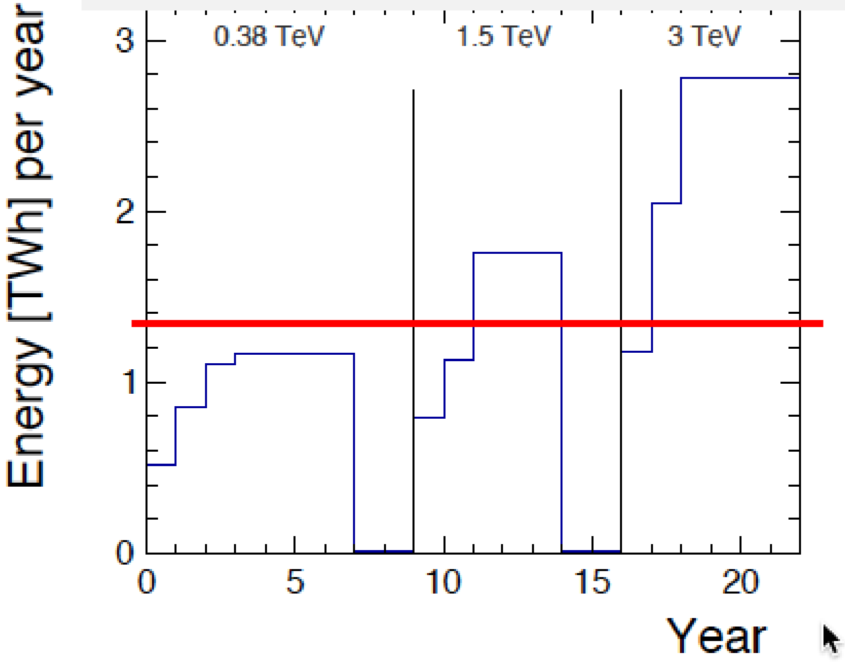
Preliminary Estimate 252 MW

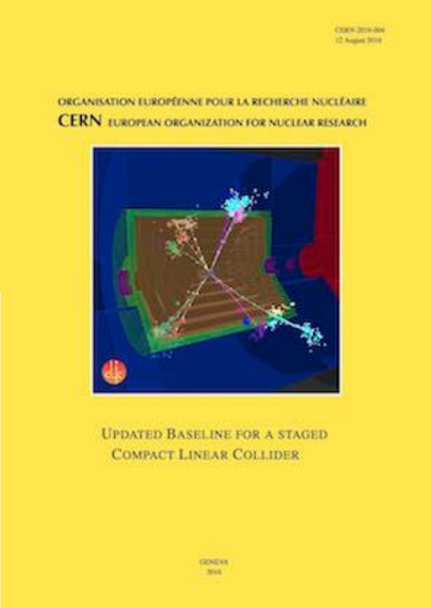
Preliminary power estimate from rebaselining

Performing bottom-up power estimate

Also optimise the power
- Use of permanent magnets
- Reduction of injector power
- More efficient klystrons
- Use of green power: Ability to switch o and off to follow electricity availability
- …

CERN energy consumption 2012: 1.35 TWh

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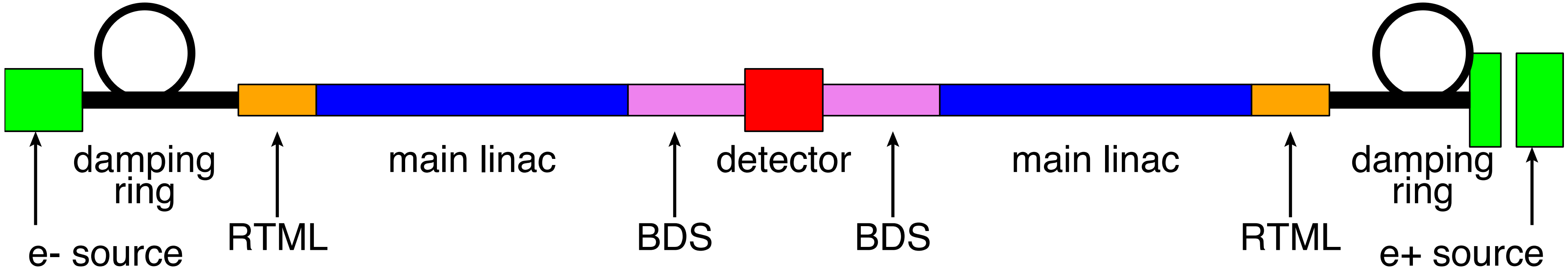
UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

GENEVA

Systems



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

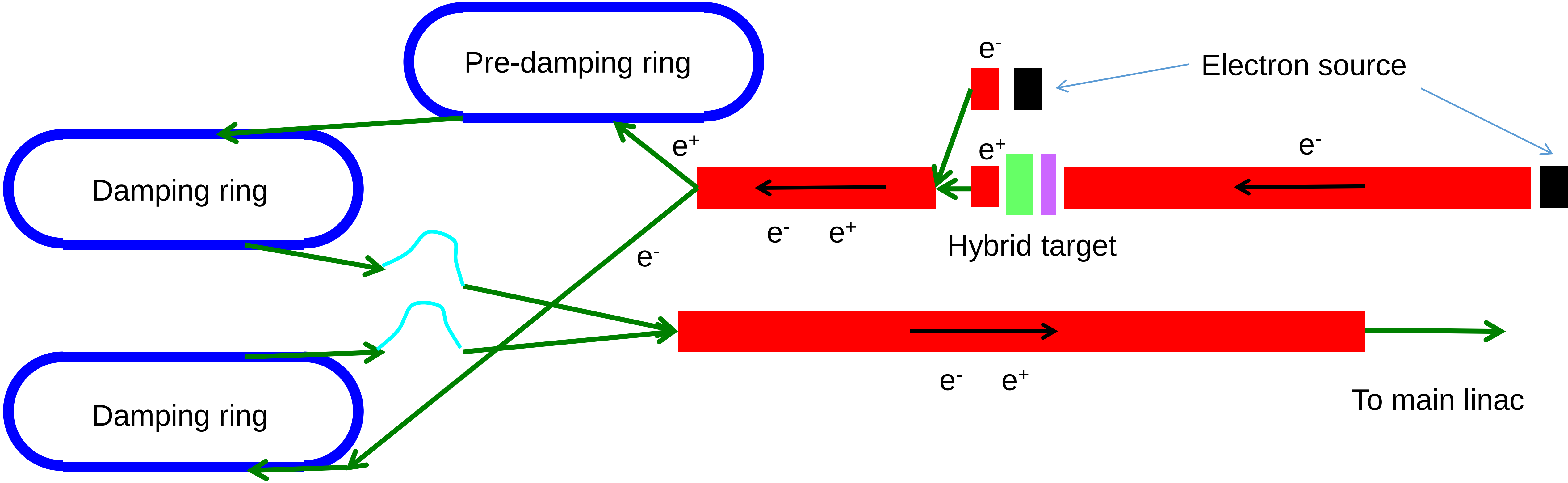
Bunch energy defined by main linac

All systems contribute to vertical emittance

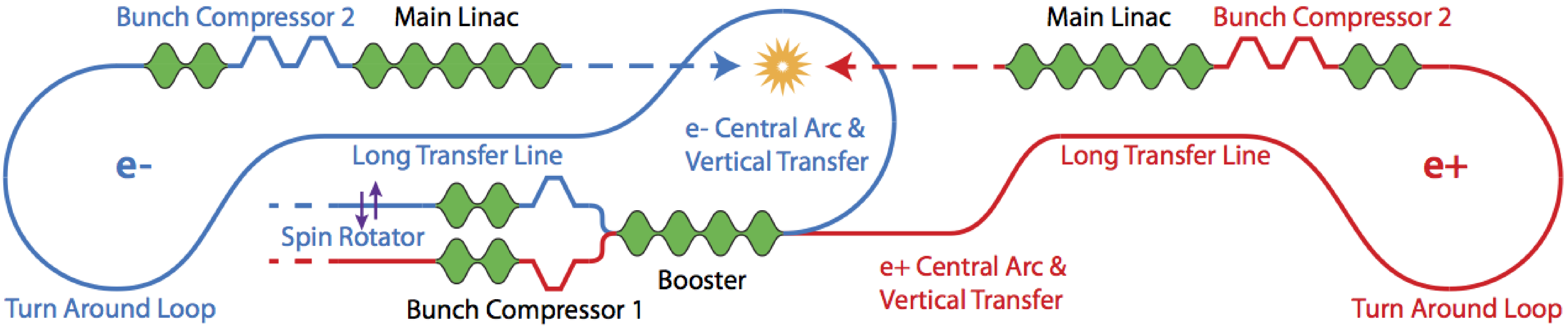
Final bunch length defined by main lina

Bunch charge defined by main linac

Main Beam Production (Schematic)



Ring To Main Linac Transport (RTML)



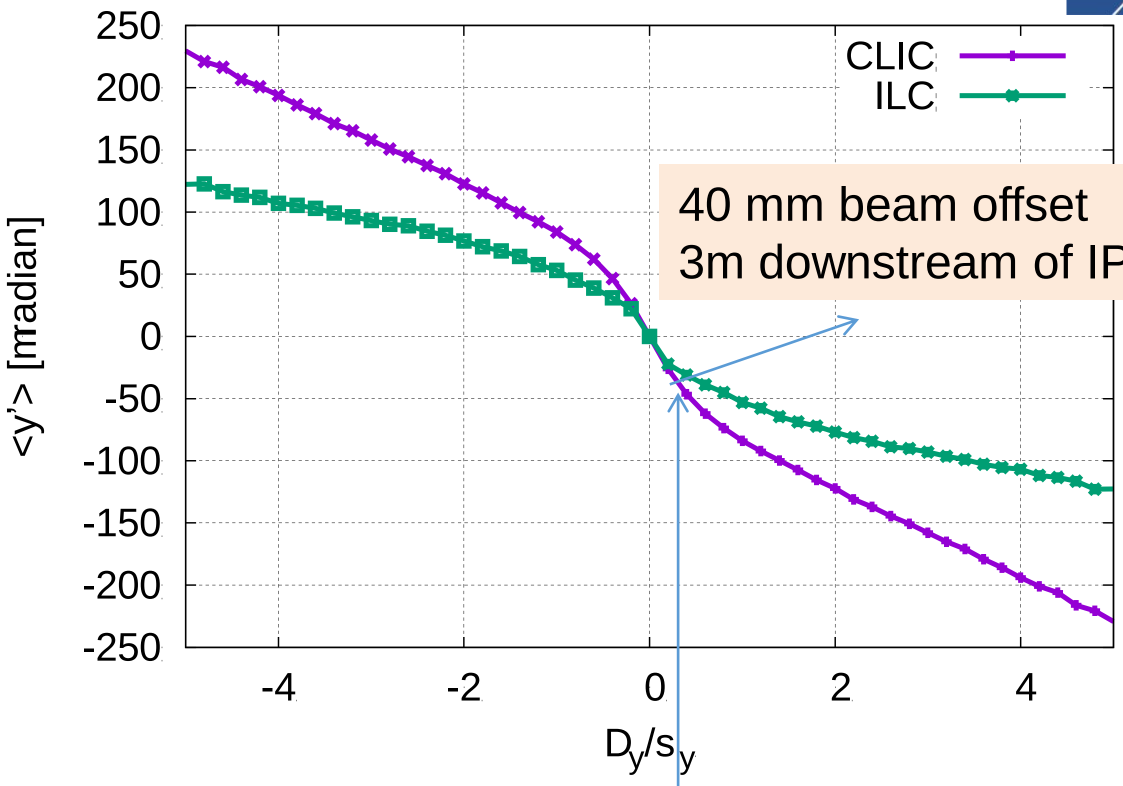
Transports the beam from the damping rings to the main linacs

Shortens the long bunch from the damping ring

Beam-beam Feedback

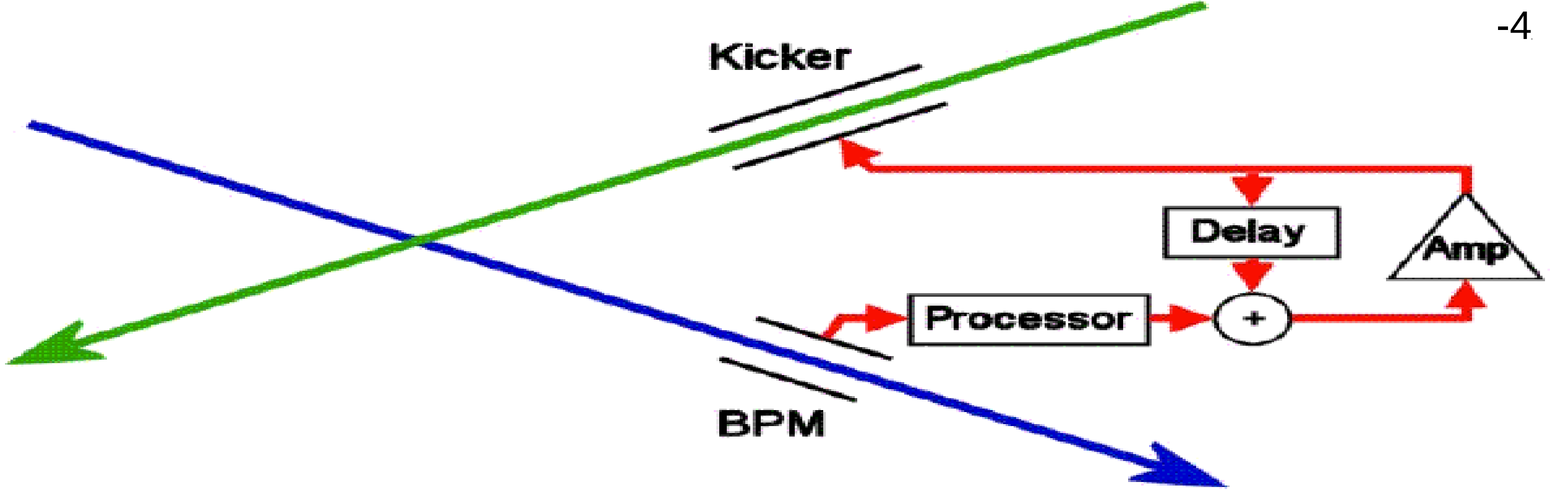
Strong deflection allows to easily measure and correct offset

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



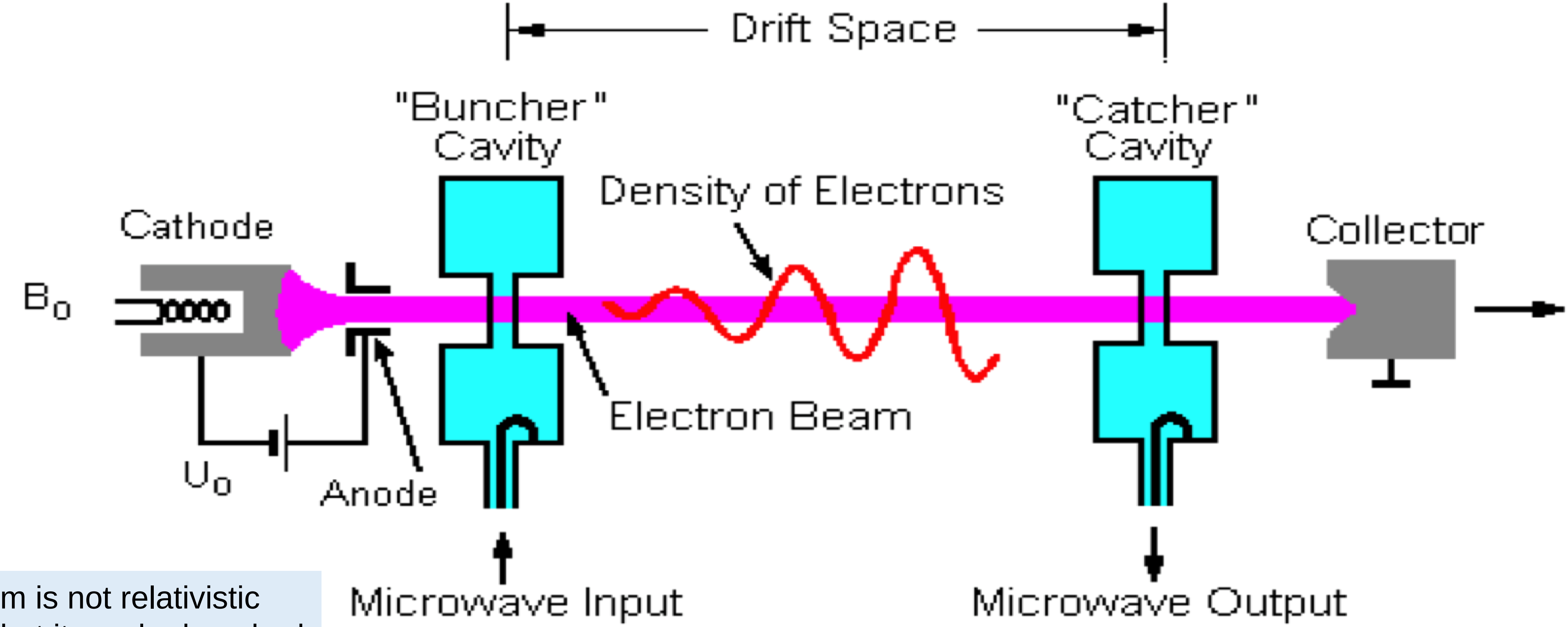
40 mm beam offset
3m downstream of IP

$\Delta_y = 0.1\sigma_y = 0.3$nm



FONT system (Oxford)
tested in ATF 2: 13 ns

Note: Klystron



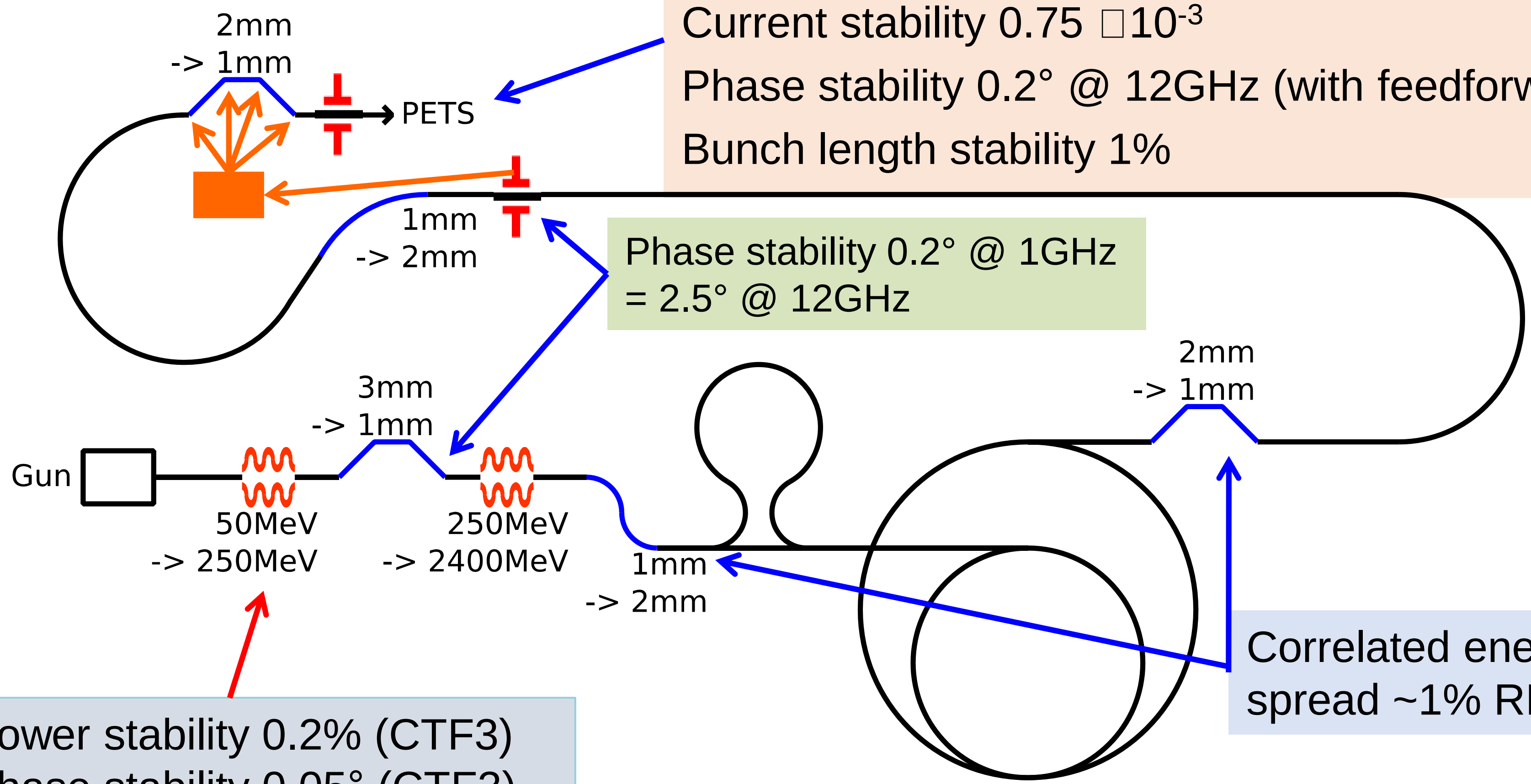
Beam is not relativistic
So that it can be bunched

Performances

Drive Beam Tolerances

Feedforward (test in CTF3)
Timing reference (FEL)

Emittance $\epsilon_{x,y} \leq 150\mu m$
Transverse jitter ≤ 0.3σ
Current stability 0.75 □10^{-3}
Phase stability 0.2° @ 12GHz (with feedforward)
Bunch length stability 1%



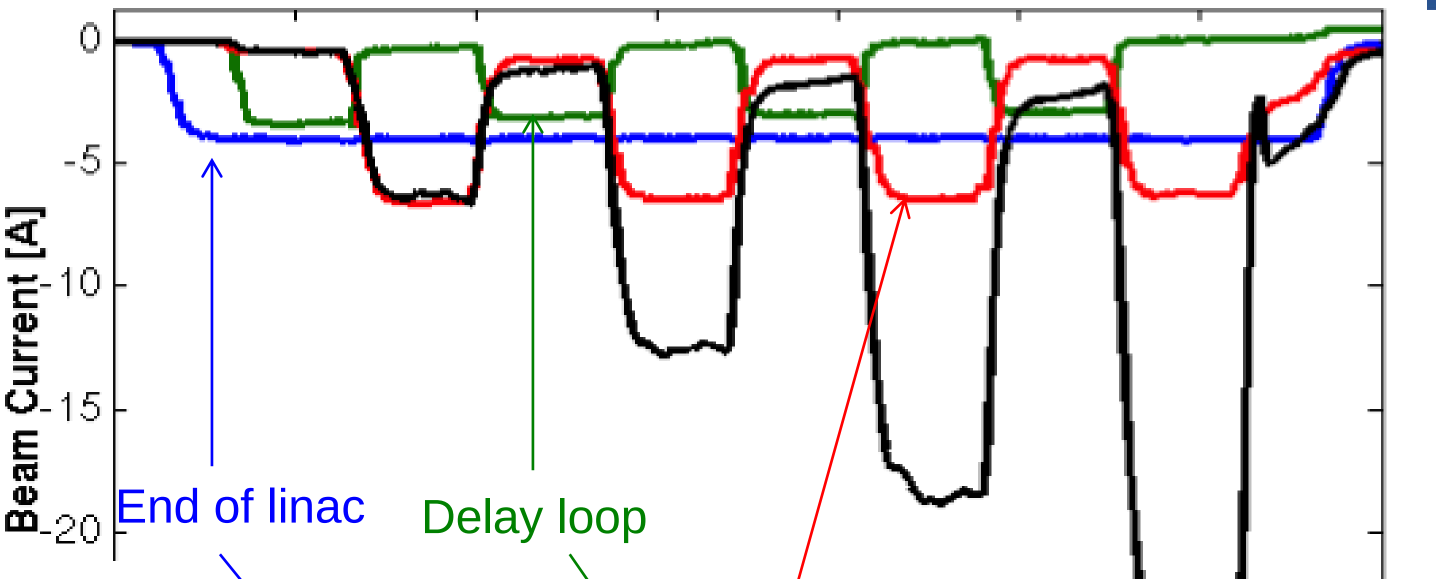
Phase stability 0.2° @ 1GHz
= 2.5° @ 12GHz

Correlated energy
spread ~1% RMS

RF power stability 0.2% (CTF3)
RF phase stability 0.05° (CTF3)

Drive Beam Combination in CTF3

RF to drive beam efficiency > 95%

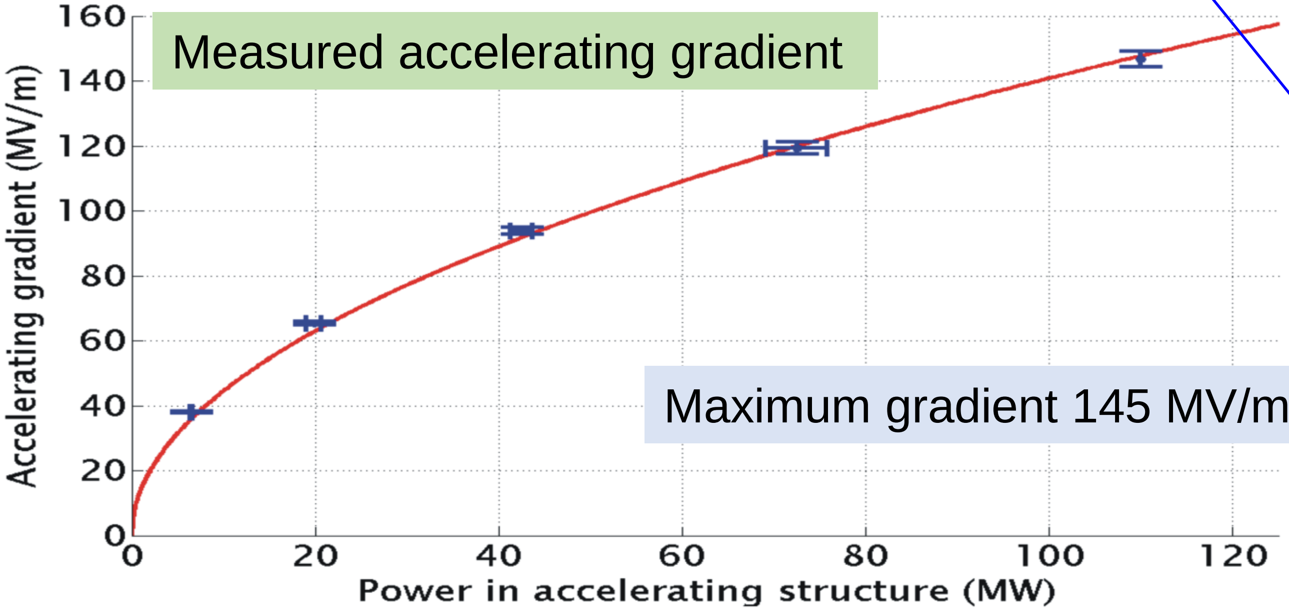


End of linac

Delay loop

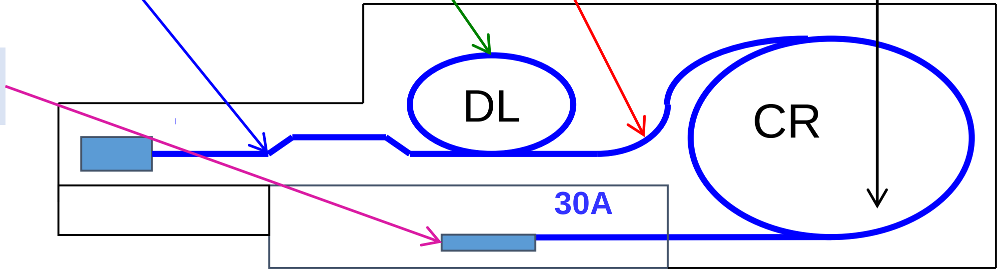
After delay loop

In combiner ring



Measured accelerating gradient

Maximum gradient 145 MV/m

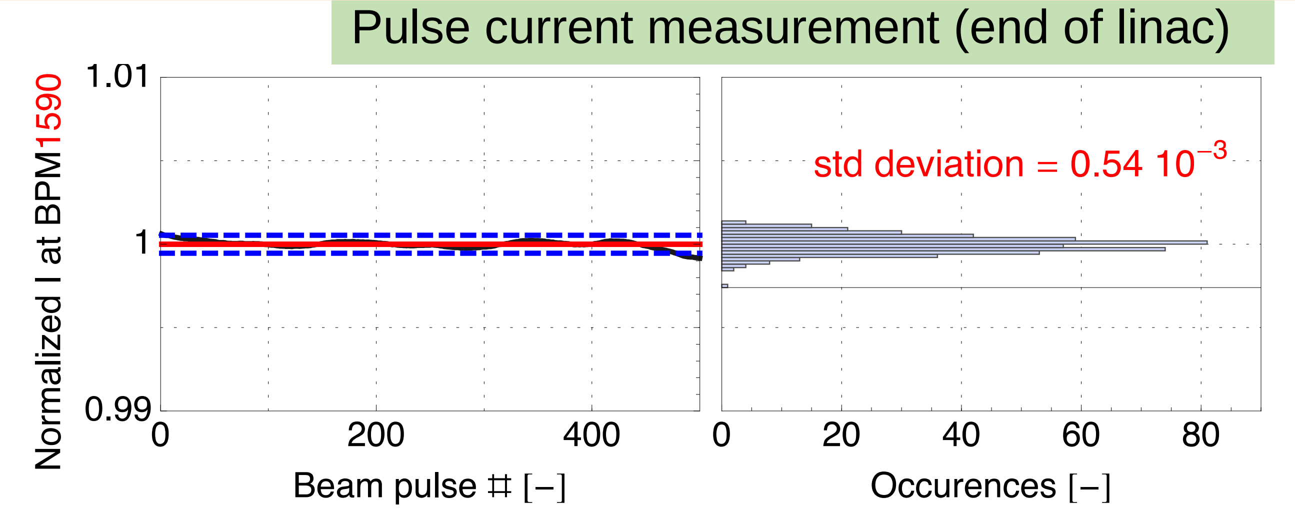


✓

Drive Beam Quality

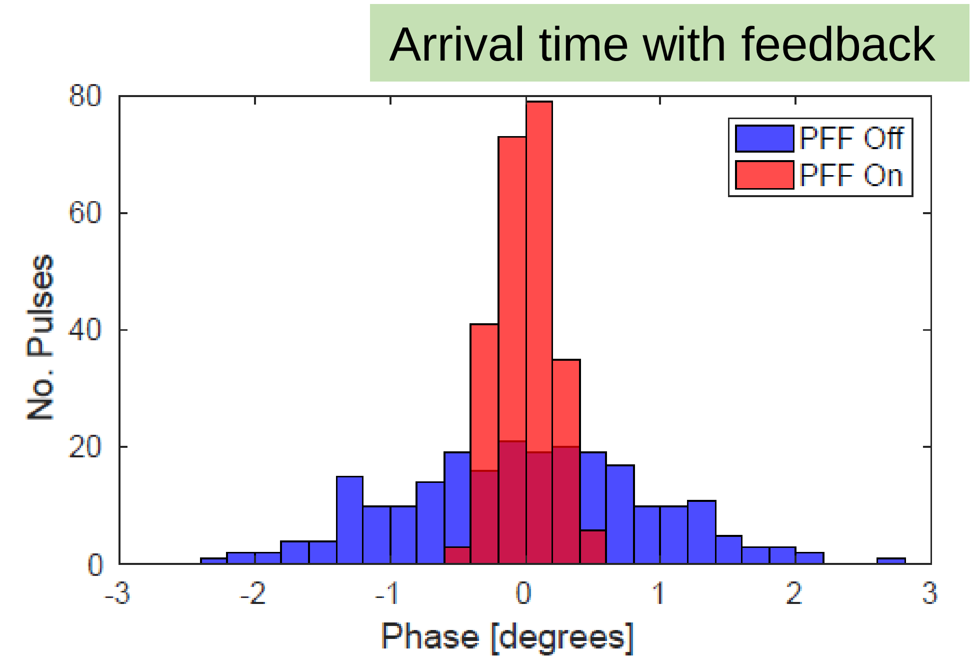
Current stability and phase stability are key

Errors lead to wrong main beam energy



Pulse current measurement (end of linac)

Losses in the delay loop, different design than in CLIC due to space
3 x smaller beam in CLIC should help



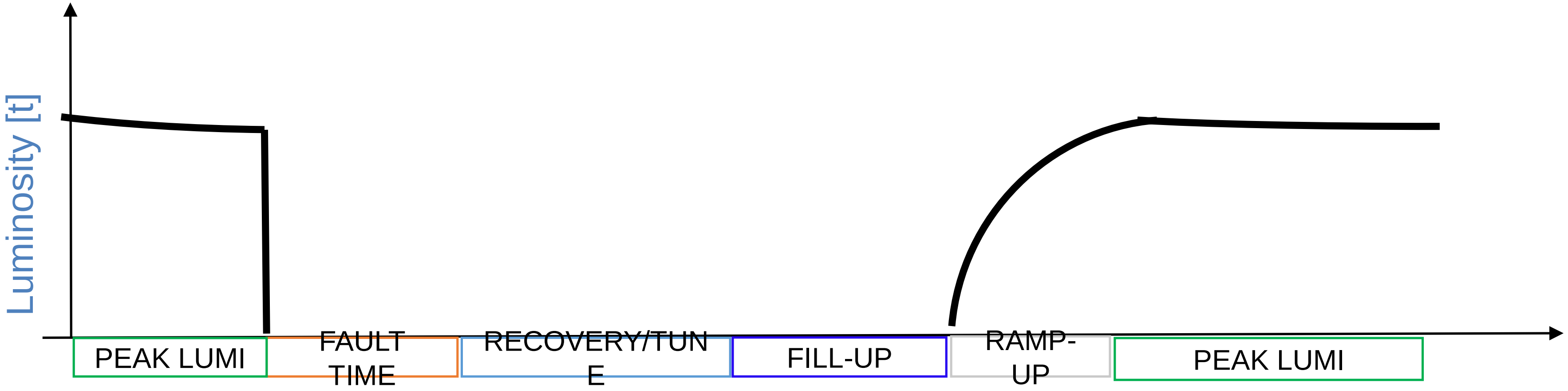
Arrival time with feedback

Parameter	CLIC goal	CTF3 measured
Arrival time	50 fs	50 fs
Current after linac	0.75 x 10^{-3}	0.54 x 10^{-3}
Current at end	0.75 x 10^{-3}	2-18 x 10^{-3} (✓)
Energy	1.0 x 10^{-3}	0.7 x 10^{-3}

Availability

Aim for 80% availability during scheduled physics runs

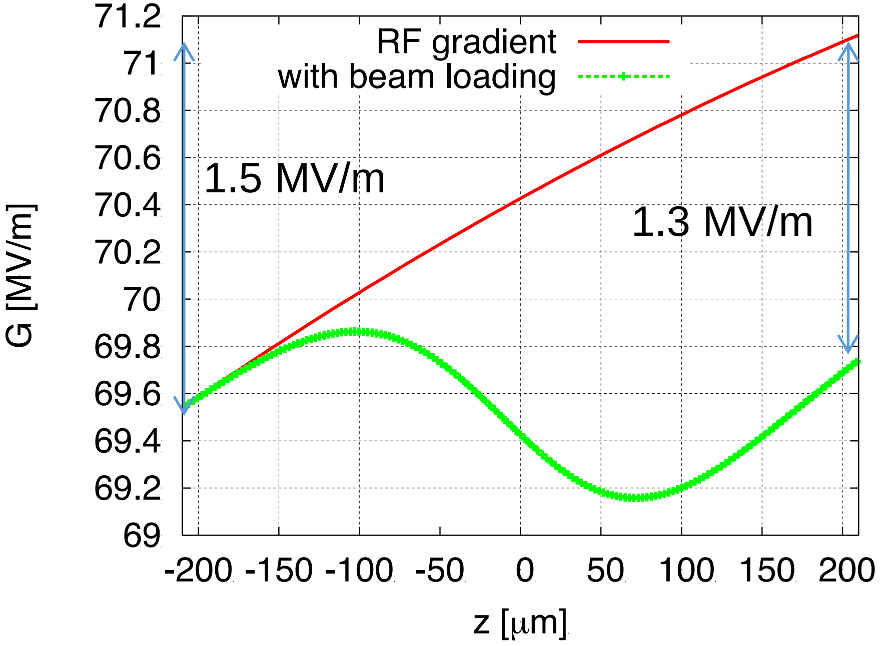
- Identifying the most important failures
- Mitigation concepts
- Repair time
- Operation schedule to optimise timing of stops

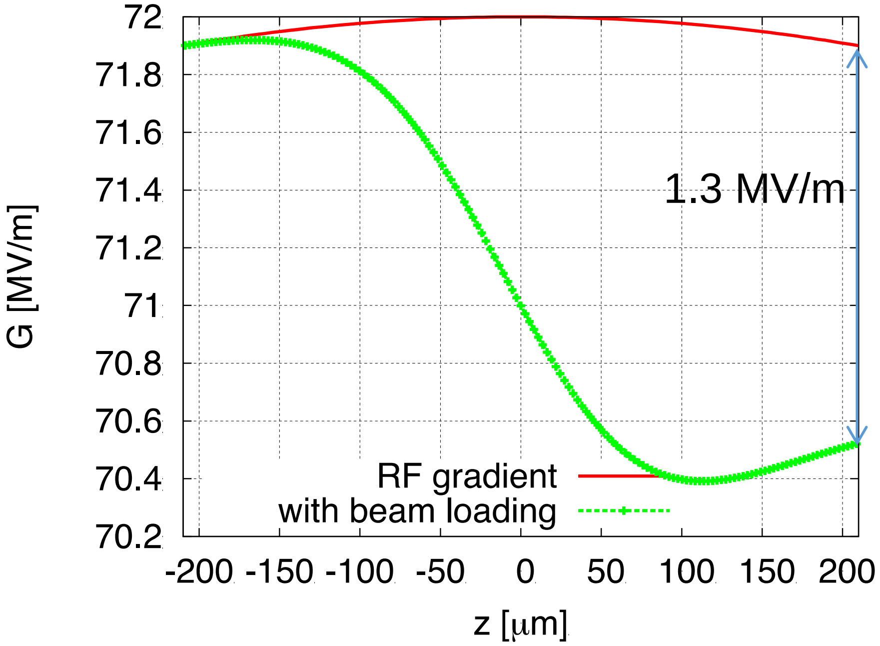


Longitudinal Wakefields and Energy Spread

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

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

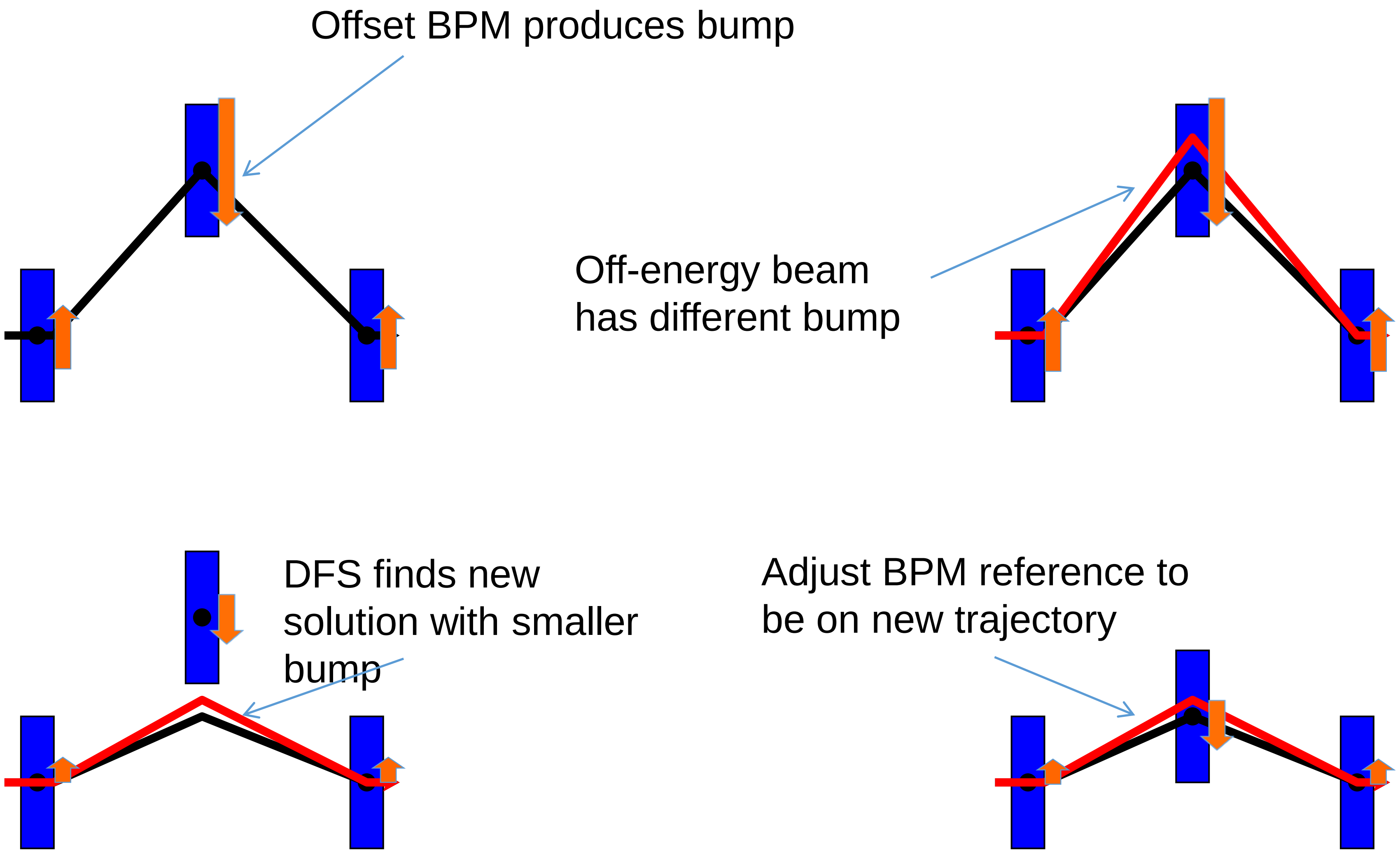
- Lattice design needs to balance dynamic and static effects

Main Linac: Dispersion-free Steering

Method reduces dispersion

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

Compromise between offset and difference



Offset BPM produces bump

Off-energy beam has different bump

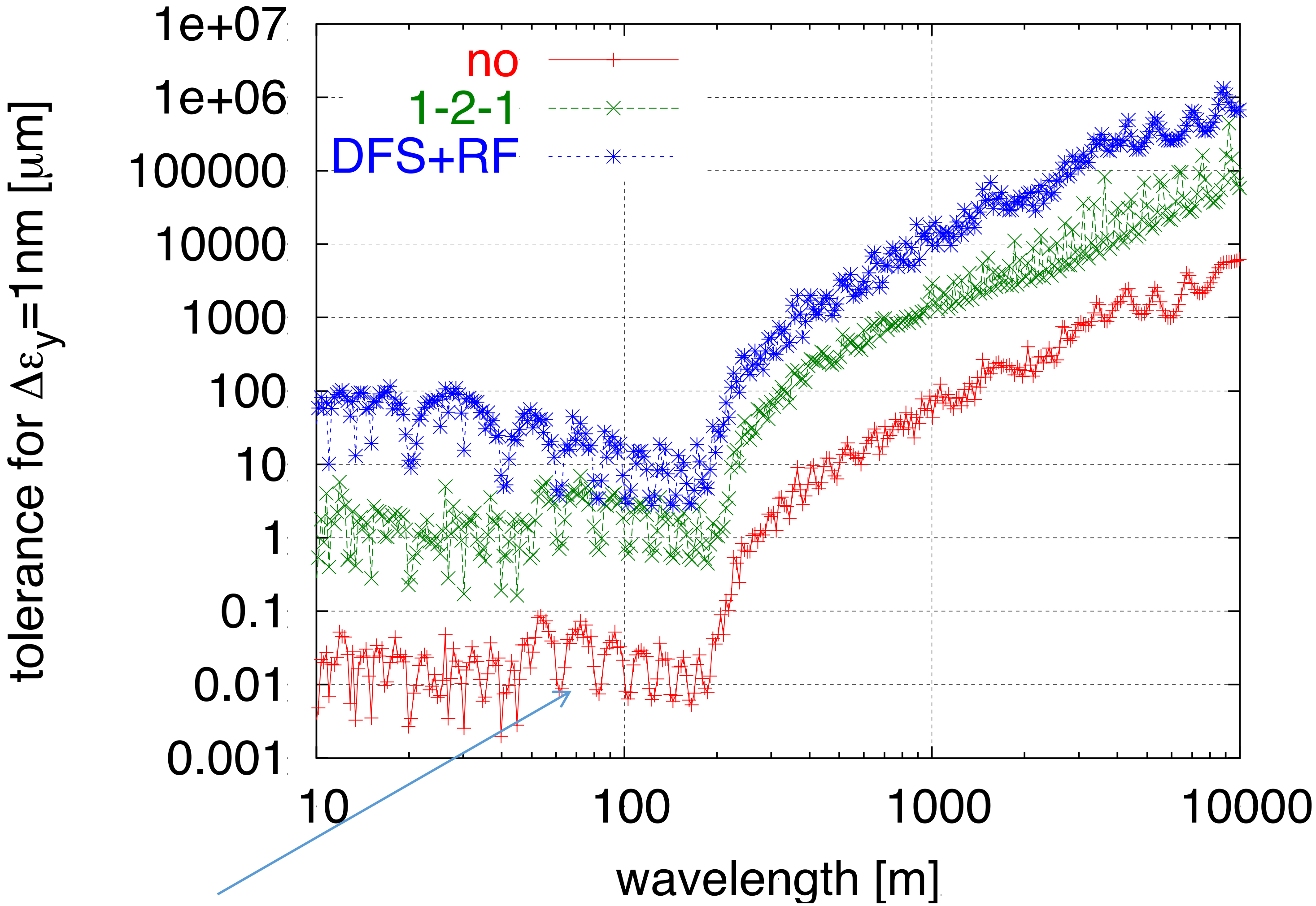
DFS finds new solution with smaller bump

Adjust BPM reference to be on new trajectory

Dispersion:
Different energy particles take different trajectories

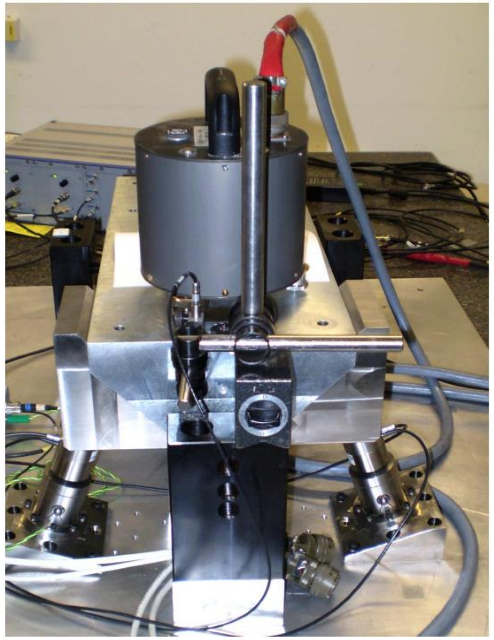
Pre-alignment Wavelength

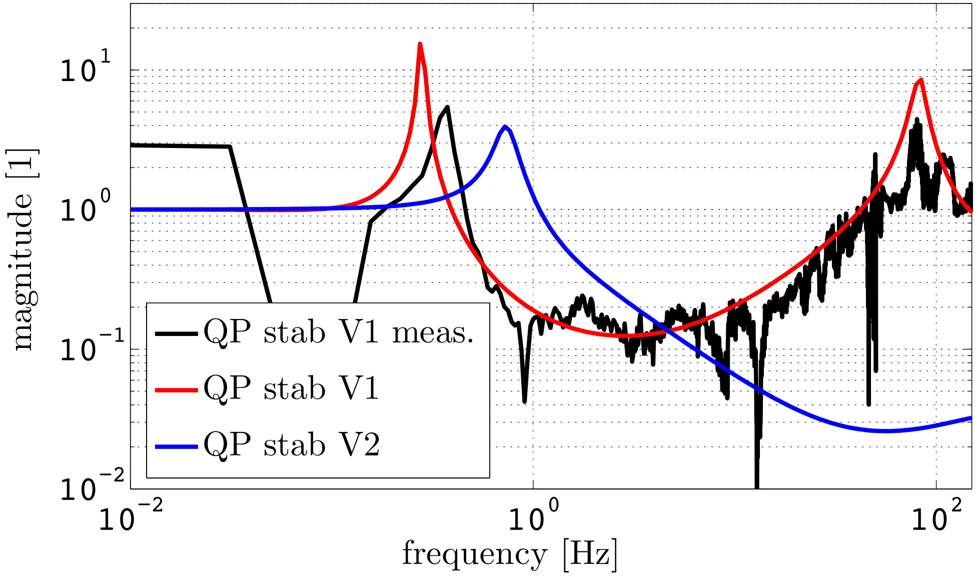
Reference line error with given wavelength

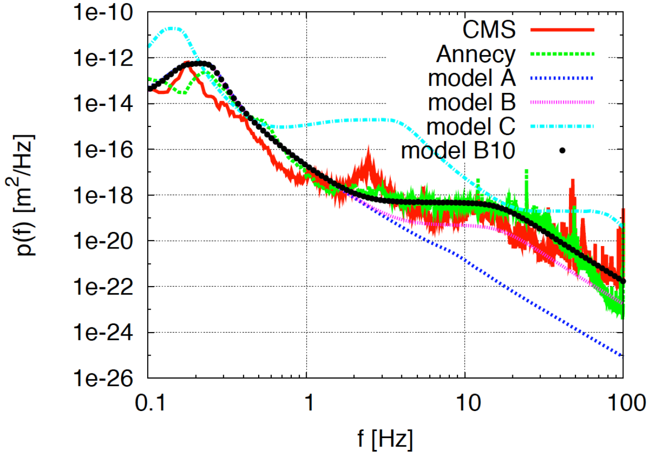


Betatron wavelengths of the different sectors

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%

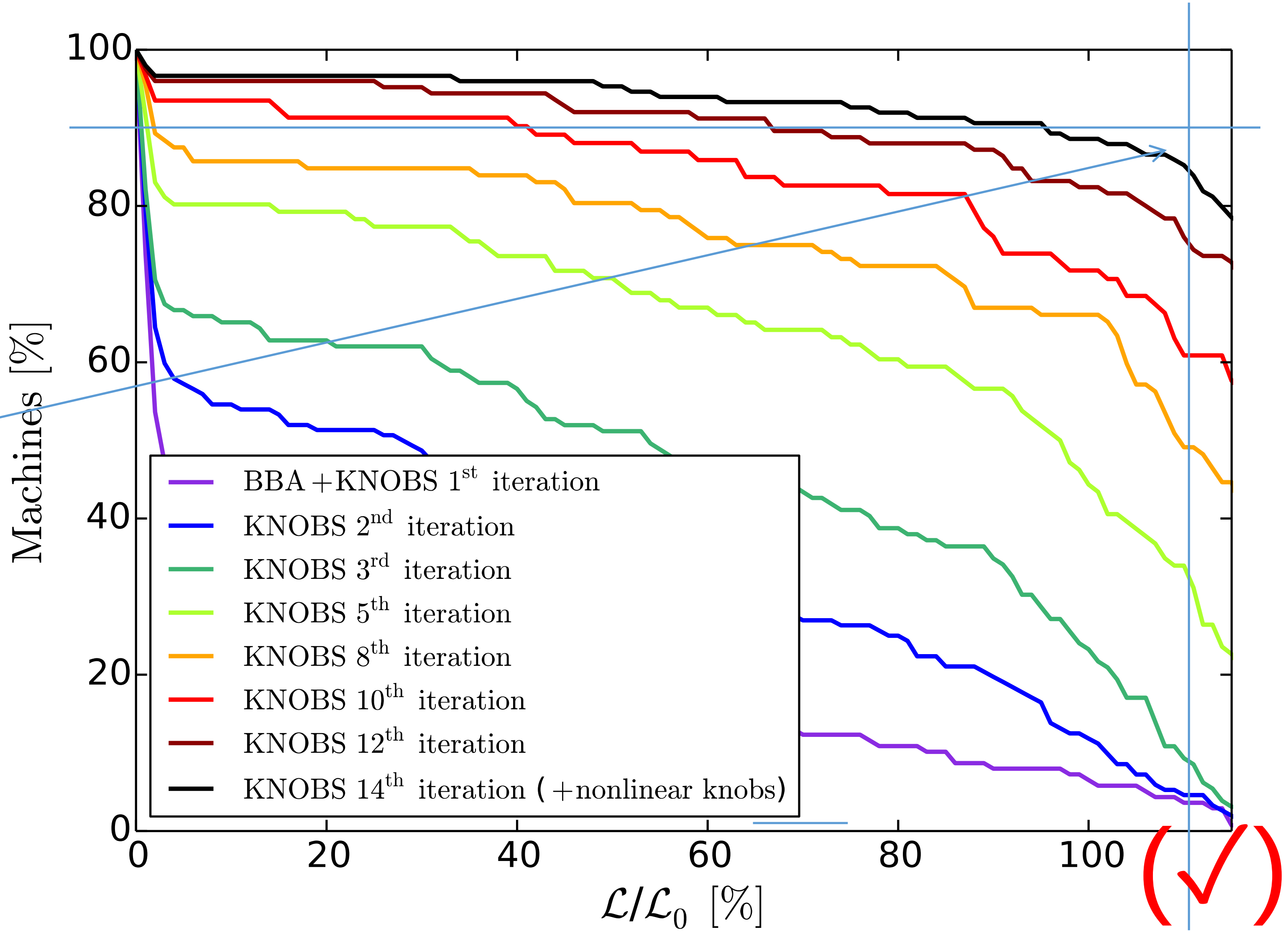
Close to/better than target

Beam Delivery System Tuning

Aim to reach 110% of promised value
(10% is budget for dynamic imperfections)

Single beam study

85% reach 110% of promised luminosity



Two-beam study ongoing

Small difference in performance

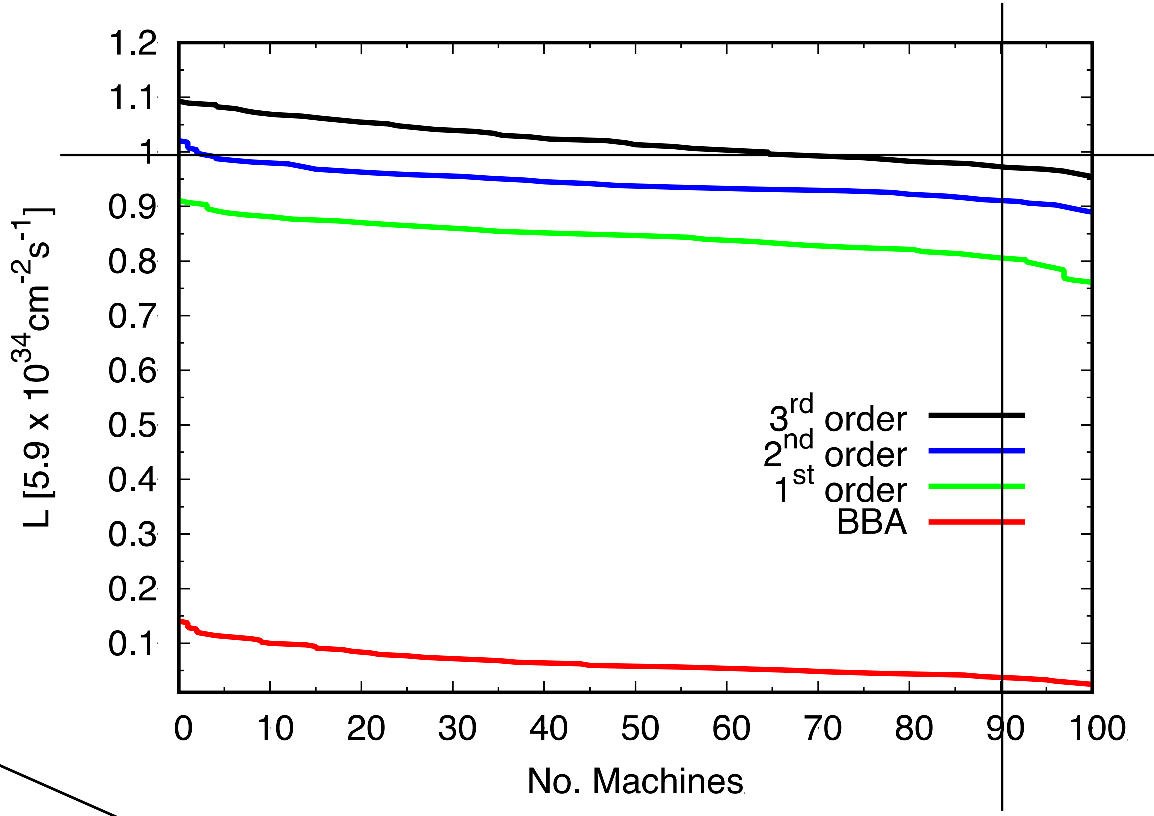
Beam Delivery System Tuning

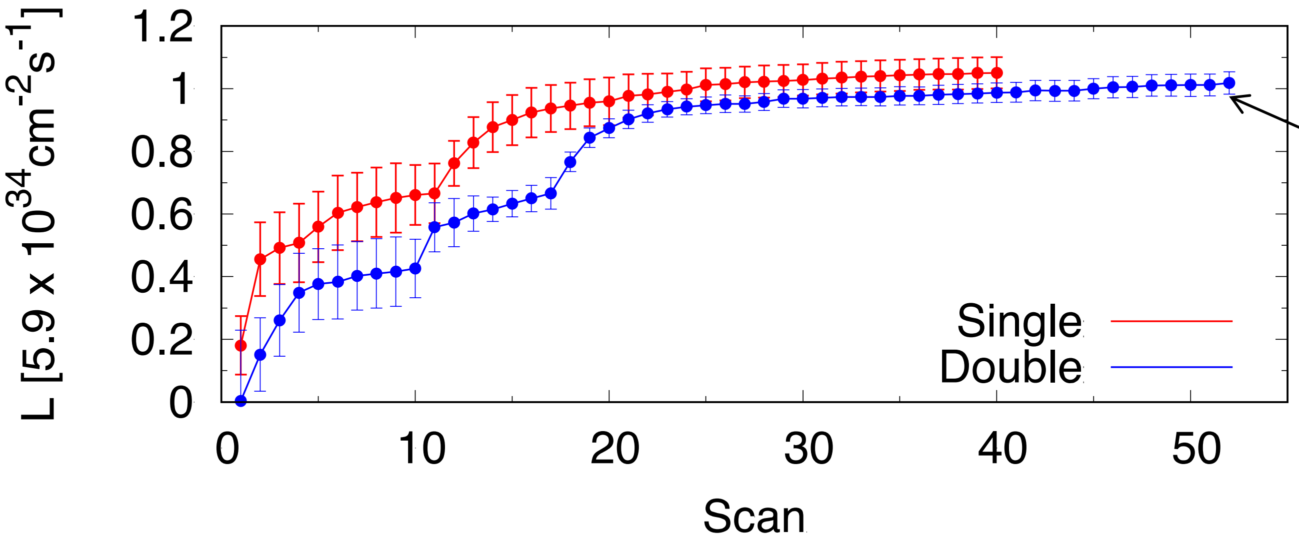
Most demanding case: Full two-beam tuning at 3 TeV

90% of machines achieve more than 97% of promised luminosity

Working on pushing this to 110% of promised luminosity

15000 luminosity measurements required





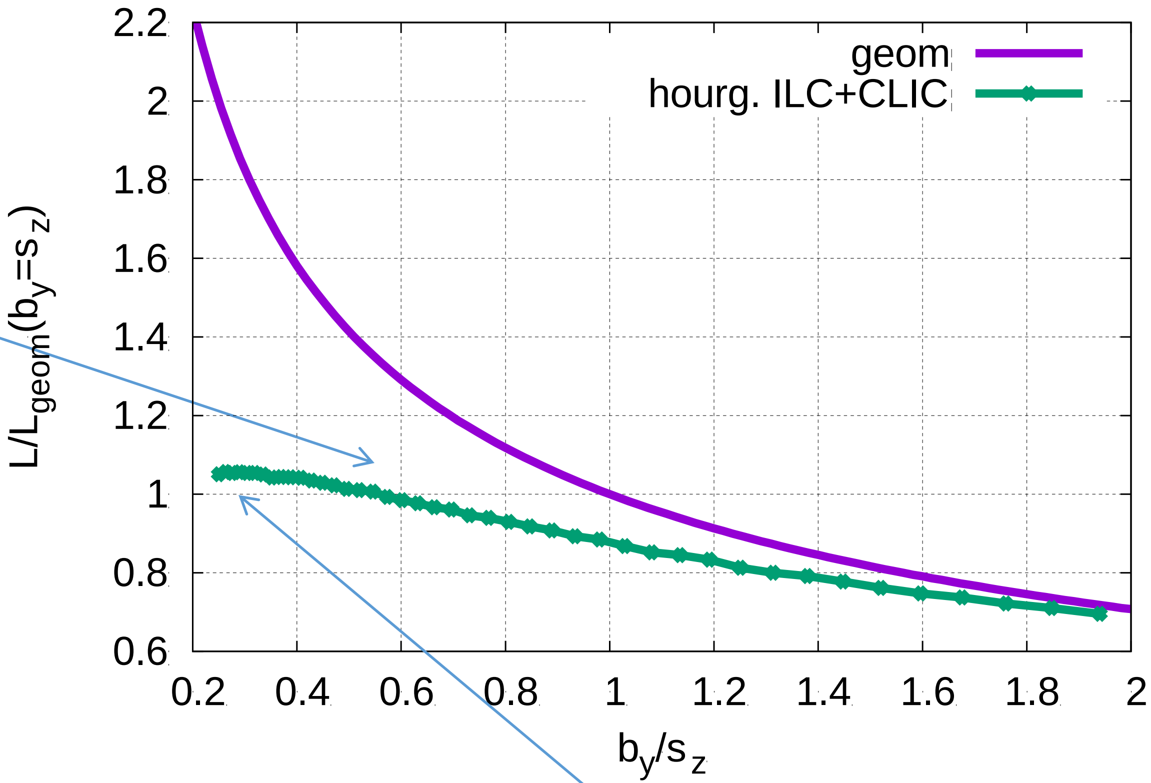
Luminosity is still increasing
Simulation is very slow (much slower than reality)
Good luminosity

(✓)

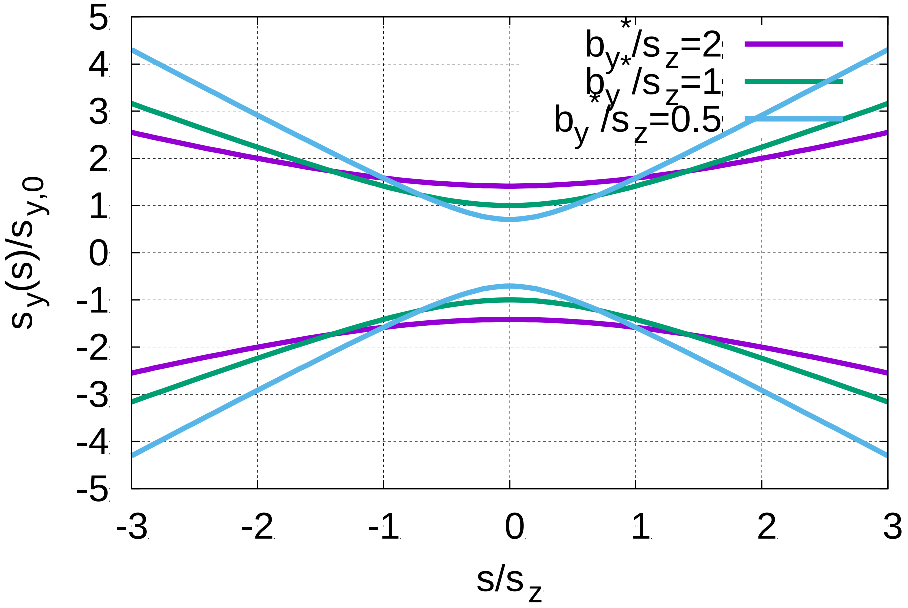
Hourglass Effect

Taking into account
hourglass effect

$$\beta(s) = \sqrt{\beta(0) + \frac{s^2}{\beta(0)}}$$



Luminosity does not improve much below $\beta_y < \sigma_z$



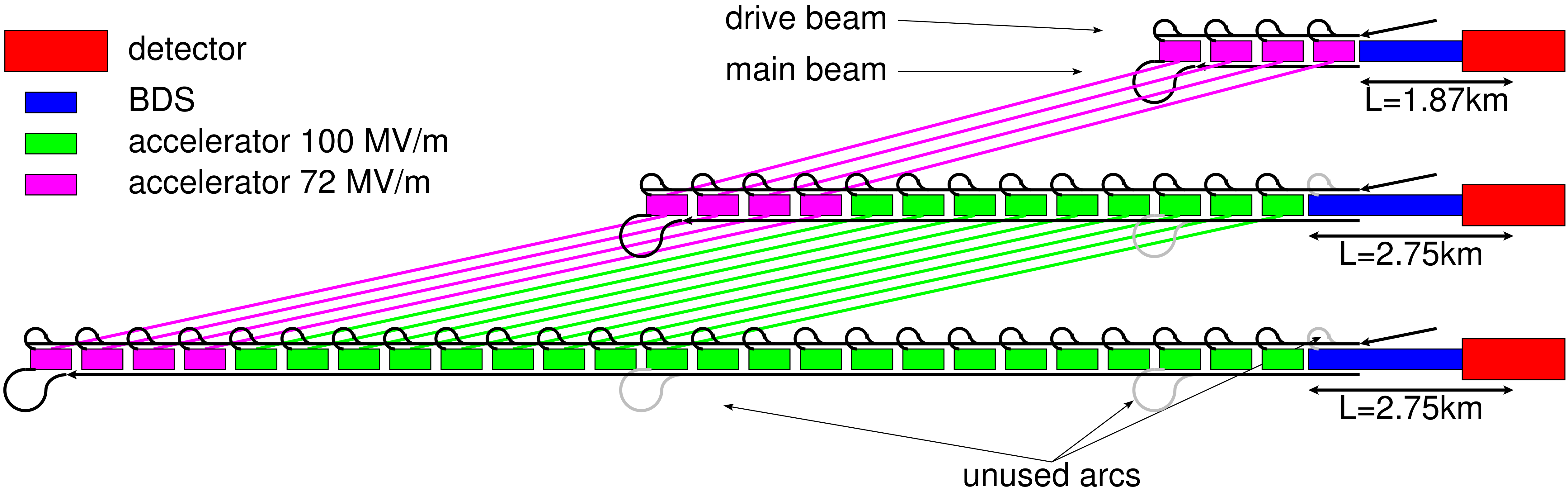
For flat beams, the optimum is around $\beta_y = 0.25 \times \sigma_z$

Note: This is different for round beams

Upgrade

The Approach

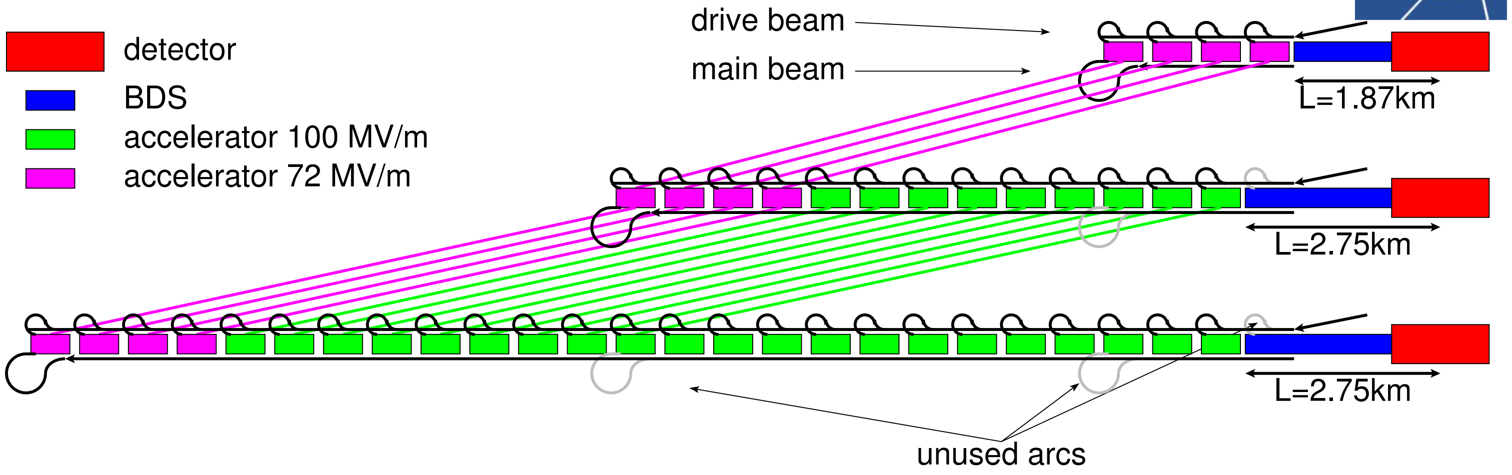
Build a linac that can be extended for further energy stages

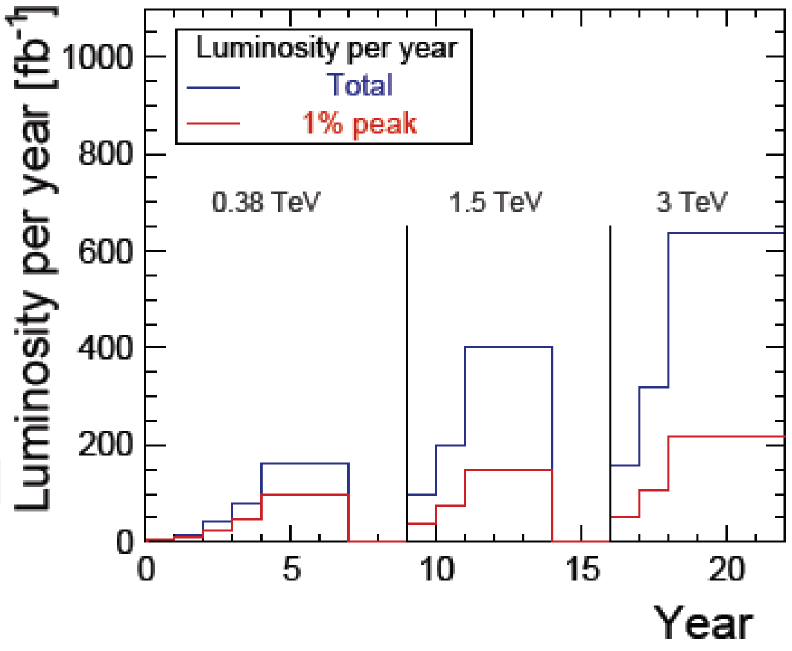


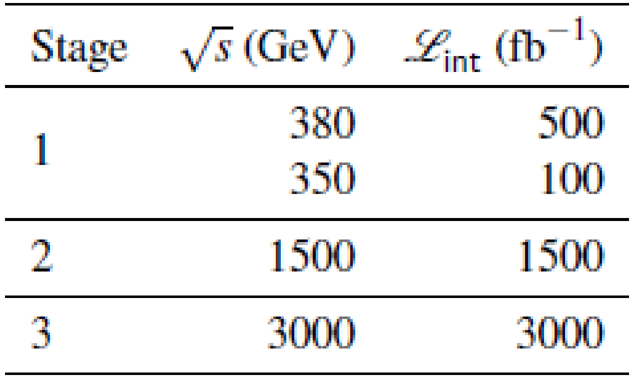
Higher gradient will beneficial for upgrade

CLIC Staged Design

Optimised first energy stage
380 GeV: HZ, WW fusion, top, …
Further stages re-use infrastructure and equipment



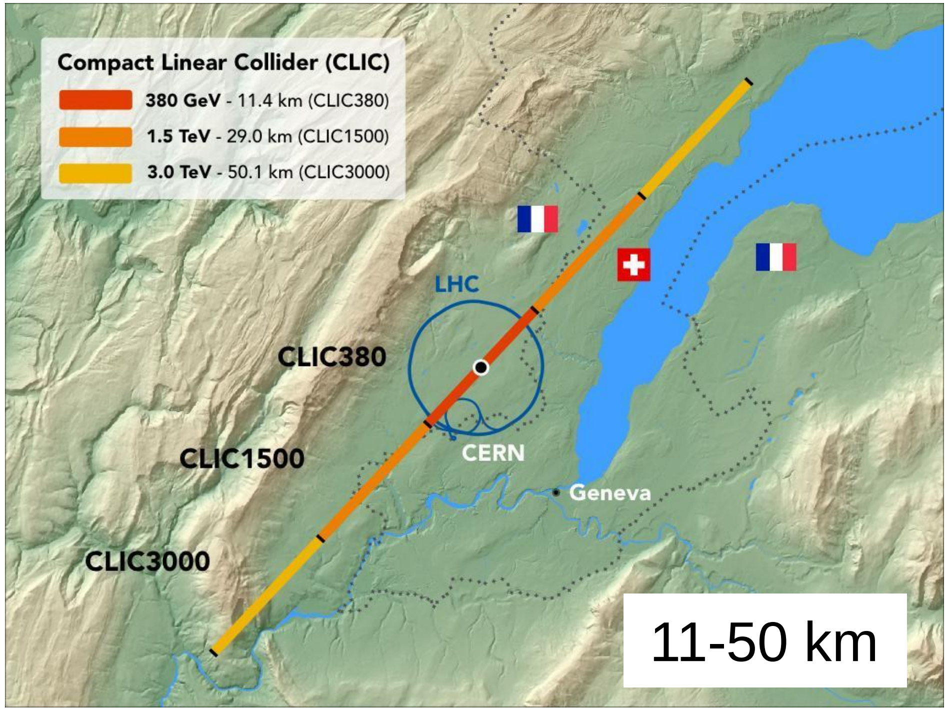




Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380 350	500 100
2	1500	1500
3	3000	3000

Preliminary value of first stage 6690 MCHF

Further optimisation ongoing



BDS and Energy Stages

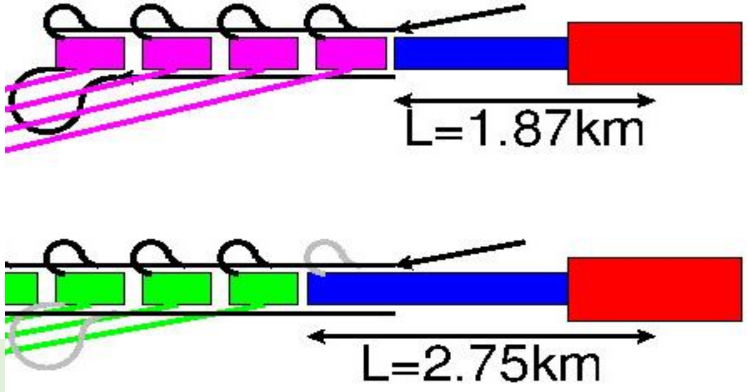
Hardware will be modified, but try to minimise changes

At high energy smaller number of bunches and bunch charge

- Should be acceptable in most systems

But have to allow for longer pulses

- Upgrade of injector and RTML RF systems



Example: BDS takes energy stages into account