CLIC Magnets from a Beam Dynamics Perspective

Andrea Latina on behalf of the
CLIC Beam Physics Team

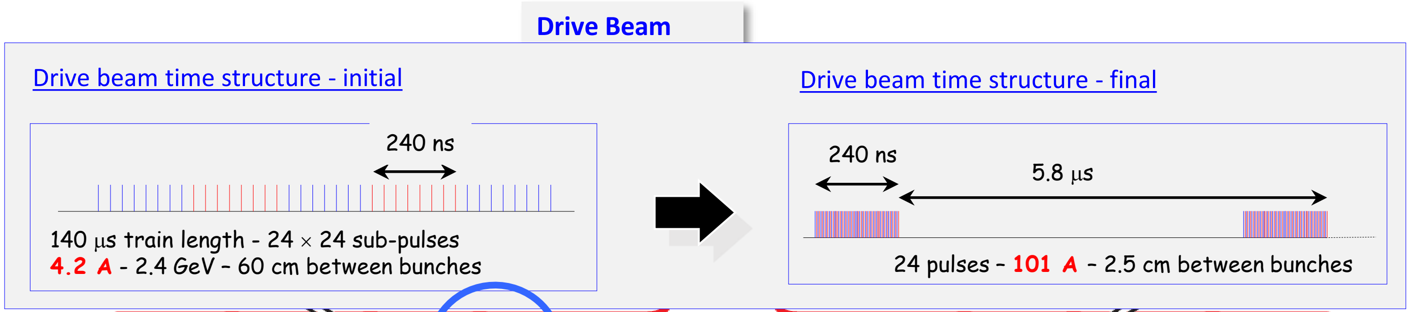
Acknowledgments:

D. Schulte, Y. Han (CERN) - J. Clarke (STFC) - J. Pfingstner (Oslo U.)

Example of Linear Colliders' Parameters

Parameter	**SLC - 92 GeV**	**ILC – 500 GeV**	**CLIC – 380 GeV**	**CLIC – 3000 GeV**	**Units**
Luminosity	0.0003	1.8	1.5	**6**	10^{34} cm^{-2} s^{-1}
Gradient	20	**31.5**	**72**	**100**	MV/m
Electrons/bunch	37	20	5.2	3.72	10^9
Bunches/train	1	1312	352	312	n_b
Bunch separation	-	554	0.5	0.5	ns
Repetition rate	120	5	50	50	Hz
Horizontal beam size	1700	474	143	40	nm
Vertical beam size	600	**5.9**	**2.9**	**1**	nm
Longitudinal beam size	1000	300	**70**	**44**	µm

CLIC Layout 3 TeV



Drive Beam

Drive beam time structure - initial

240 ns

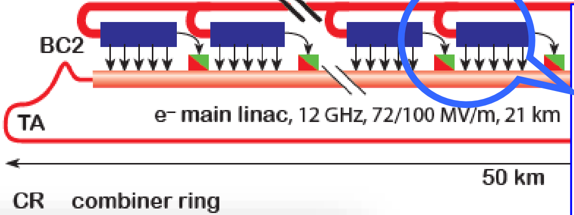
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

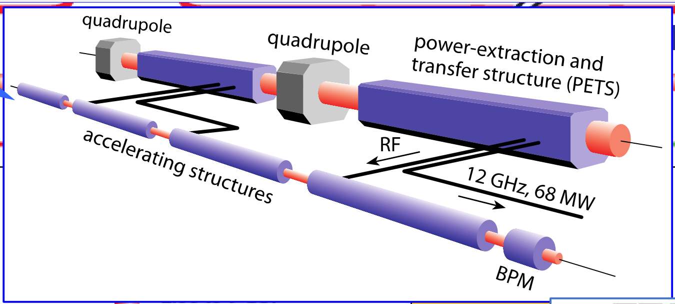
Drive beam time structure - final

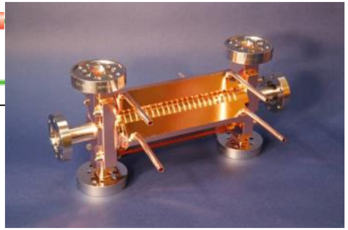
240 ns

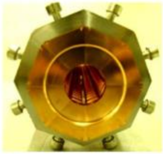
5.8 μs

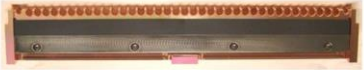
24 pulses – 101 A – 2.5 cm between bunches



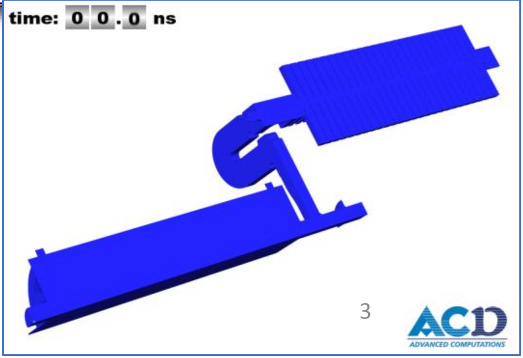








e^+
PDR
389 m

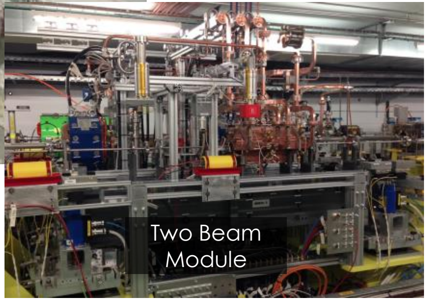


CLIC Test Facility (CTF3)

DELAY LOOP

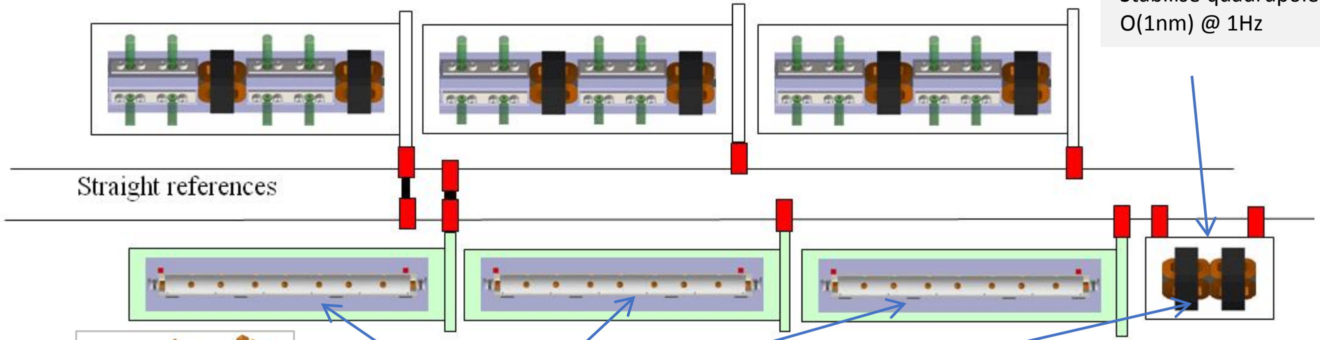
DRIVE BEAM LINAC

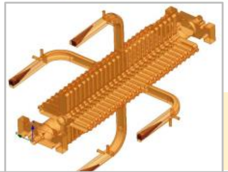
COMBINER RING



CLIC Performance Verification

Stabilise quadrupole
O(1nm) @ 1Hz

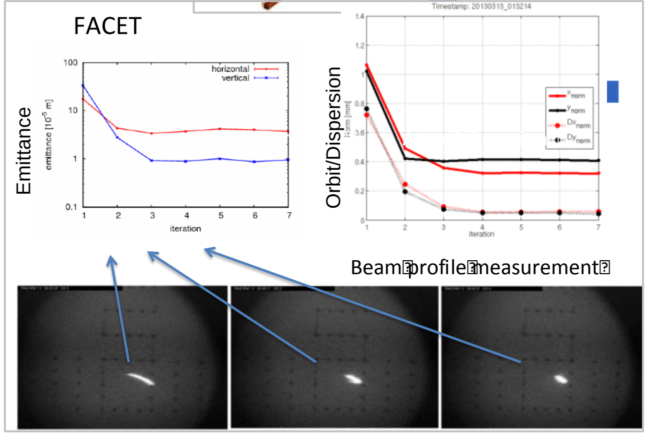




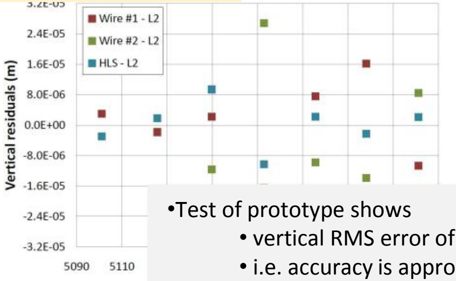
3) Use wake-field monitors accuracy O(3.5µm) – CTF3

1) Pre-align BPMs+quads
accuracy O(10µm) over about 200m

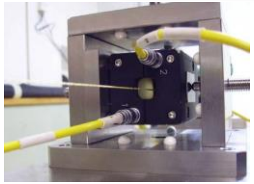
2) Beam-based alignment

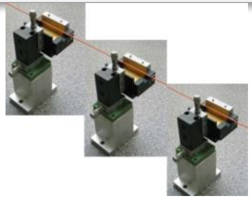


Beam profile measurement

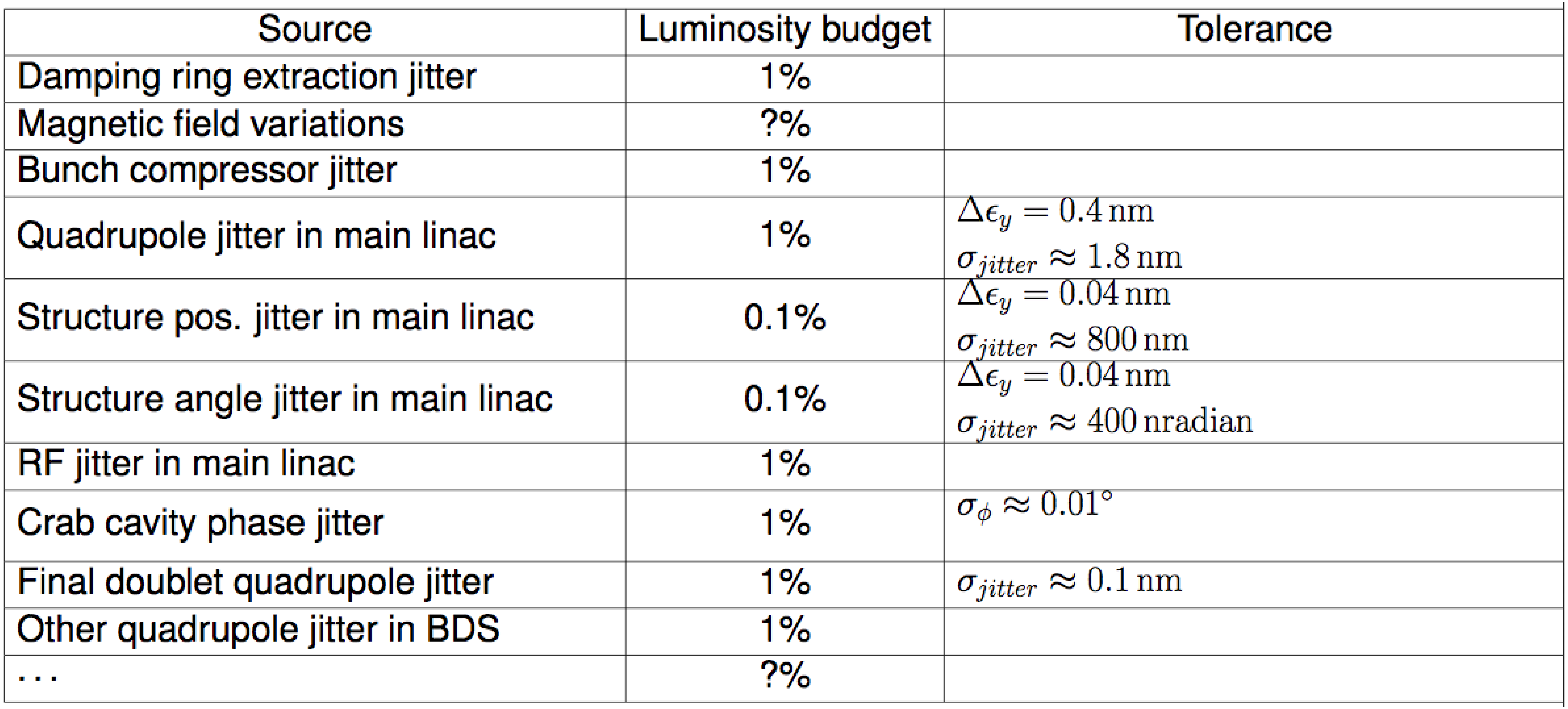


- Test of prototype shows
  - vertical RMS error of 11µm
  - i.e. accuracy is approx. 13.5µm





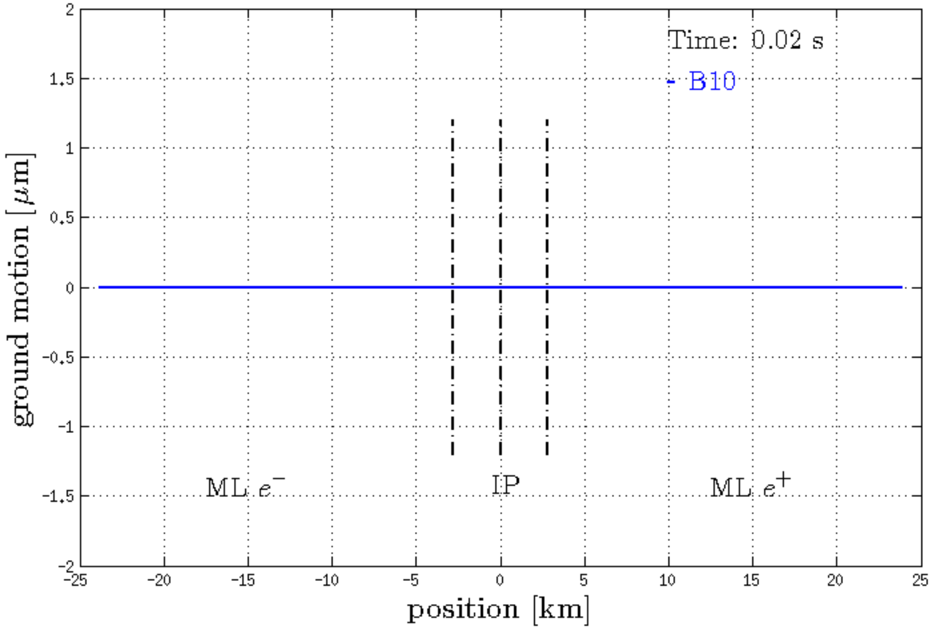
Example of CLIC Tolerance to Fast Imperfections

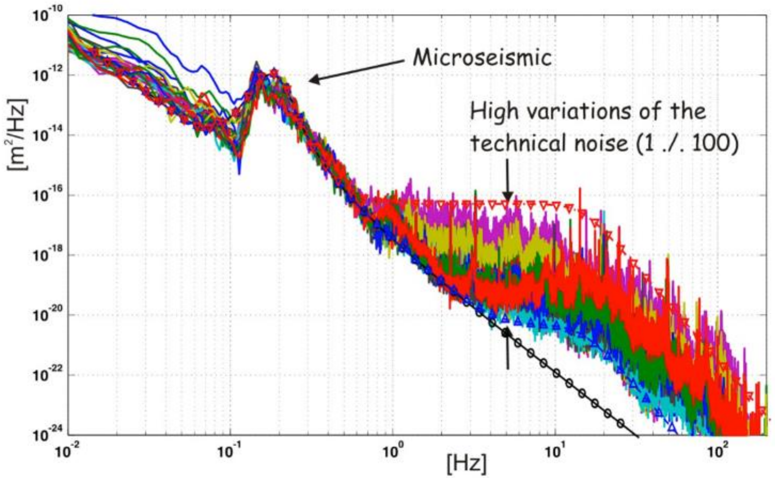


Source	Luminosity budget	Tolerance
Damping ring extraction jitter	1%	
Magnetic field variations	?%	
Bunch compressor jitter	1%	
Quadrupole jitter in main linac	1%	$\Delta\epsilon_y = 0.4\,\mathrm{nm}$ $\sigma_{jitter} \approx 1.8\,\mathrm{nm}$
Structure pos. jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 800\,\mathrm{nm}$
Structure angle jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 400\,\mathrm{nradian}$
RF jitter in main linac	1%	
Crab cavity phase jitter	1%	$\sigma_\phi \approx 0.01^\circ$
Final doublet quadrupole jitter	1%	$\sigma_{jitter} \approx 0.1\,\mathrm{nm}$
Other quadrupole jitter in BDS	1%	
...	?%	

Example Issue: Ground Motion at CLIC

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

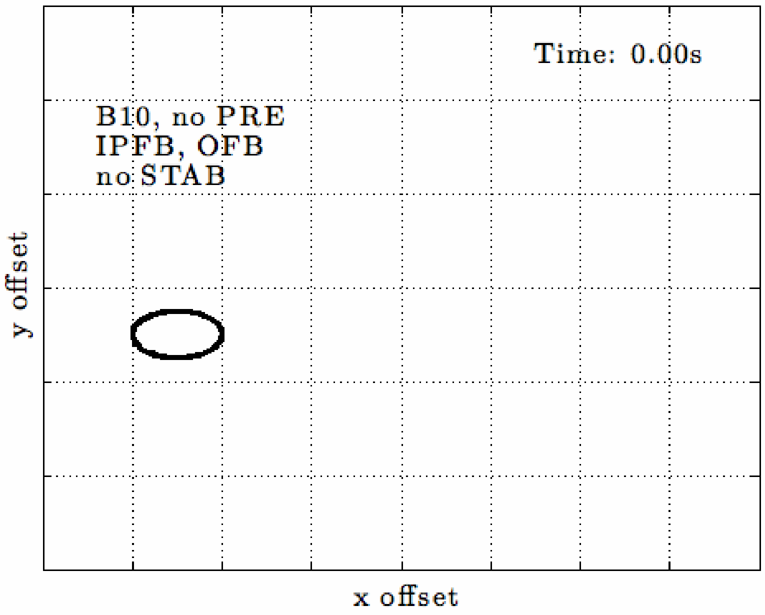




J. Pfingstner

Beams at Collision

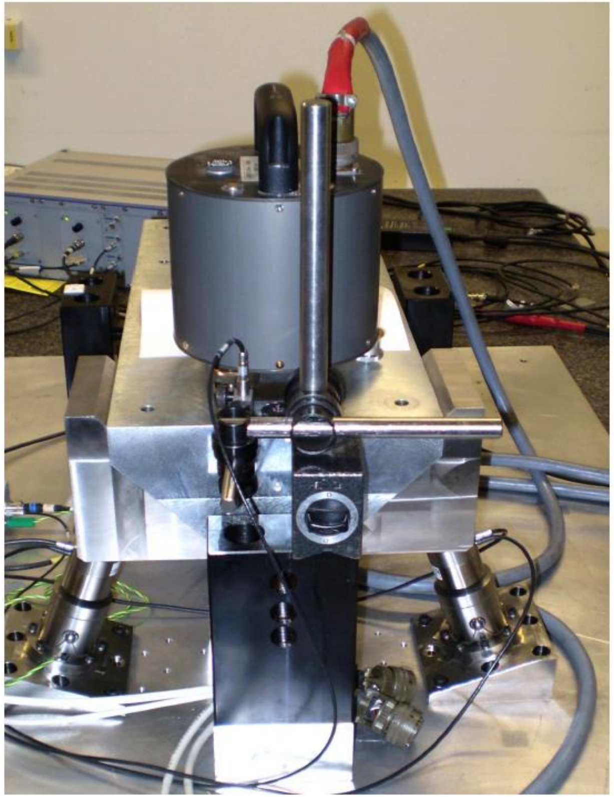
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



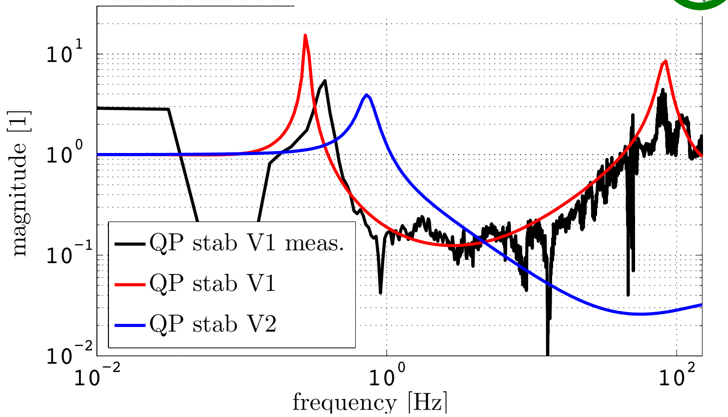
J. Pfingstner

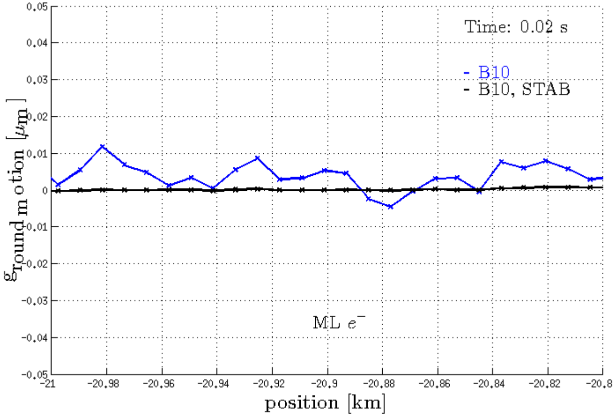
Stabilisation System

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



K. Artoos et al.

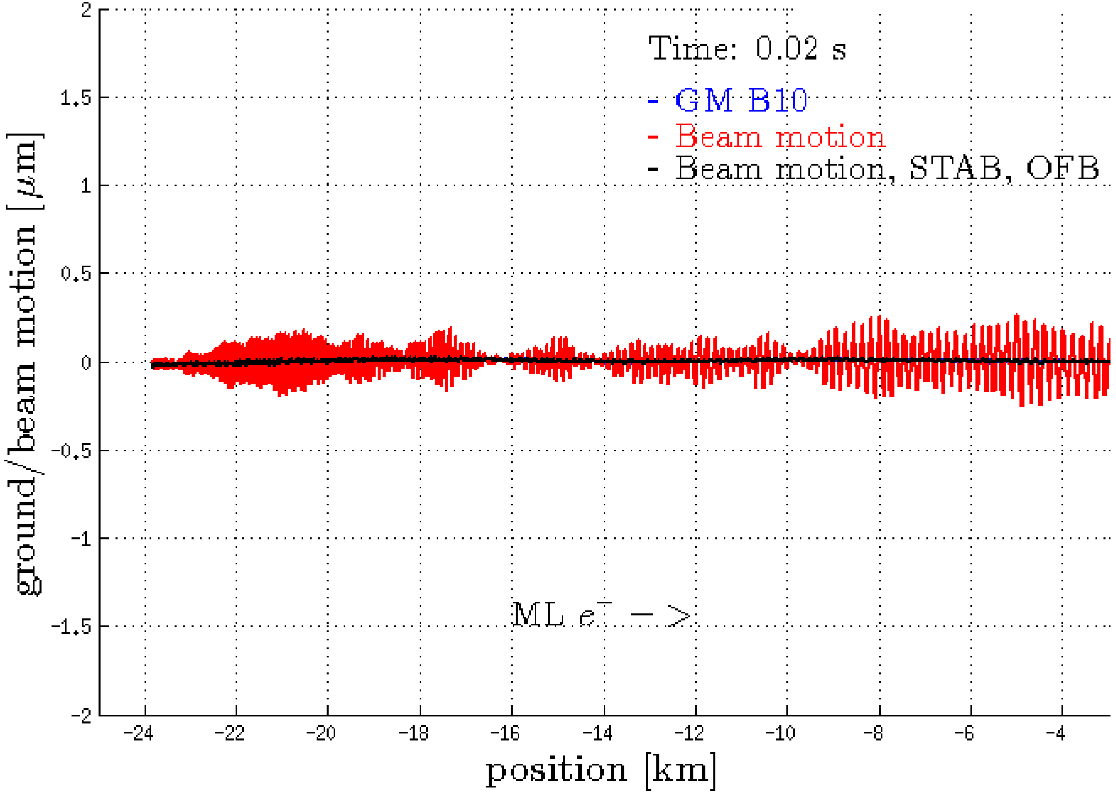




J. Snuverink, et al.

Impact of Stabilisation on Beam

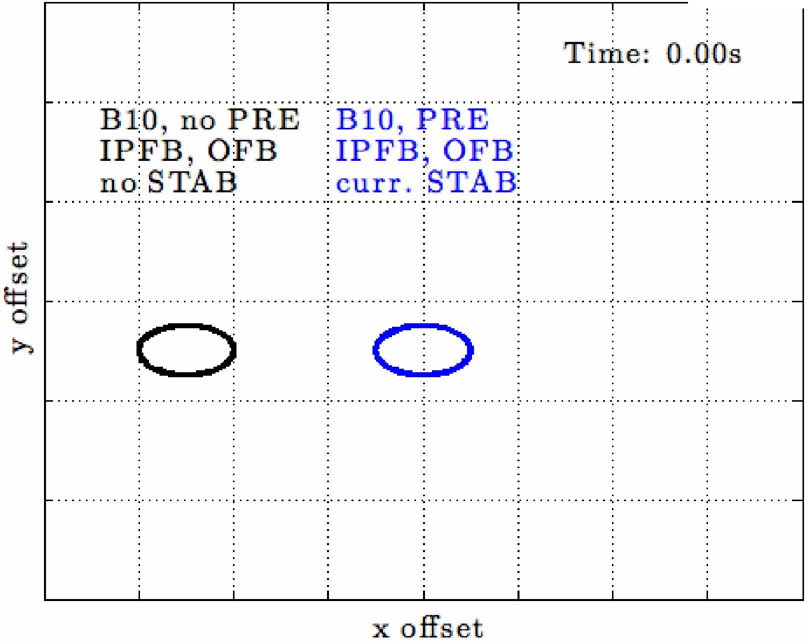
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

Beams at Collision

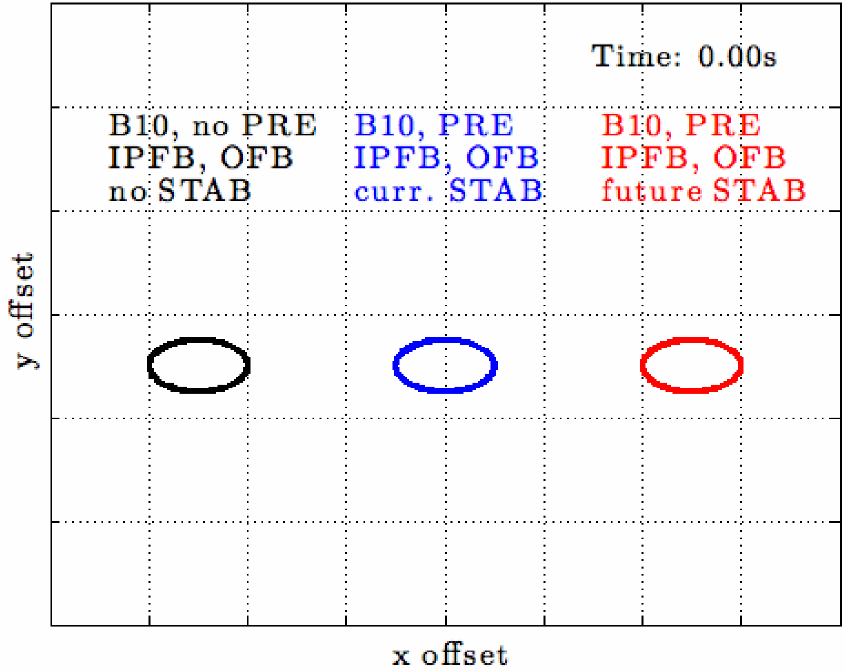
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

Beams at Collision

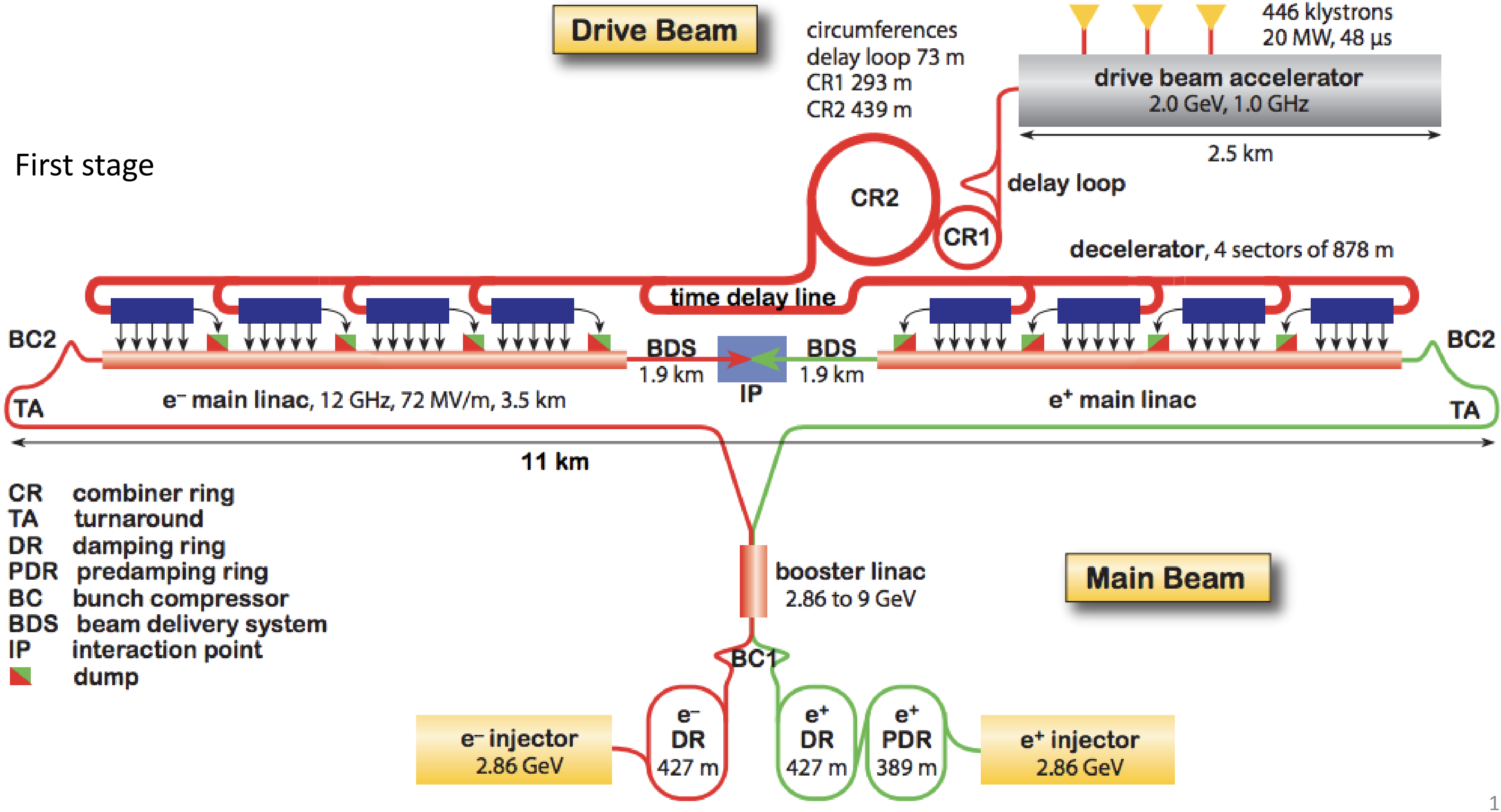
$$\mathcal{L} \propto H_D \; \frac{N}{\sigma_x} \; N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

CLIC Layout 380 GeV

First stage



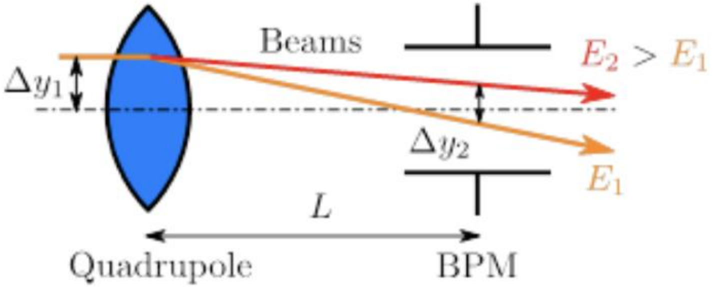
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
◪	dump

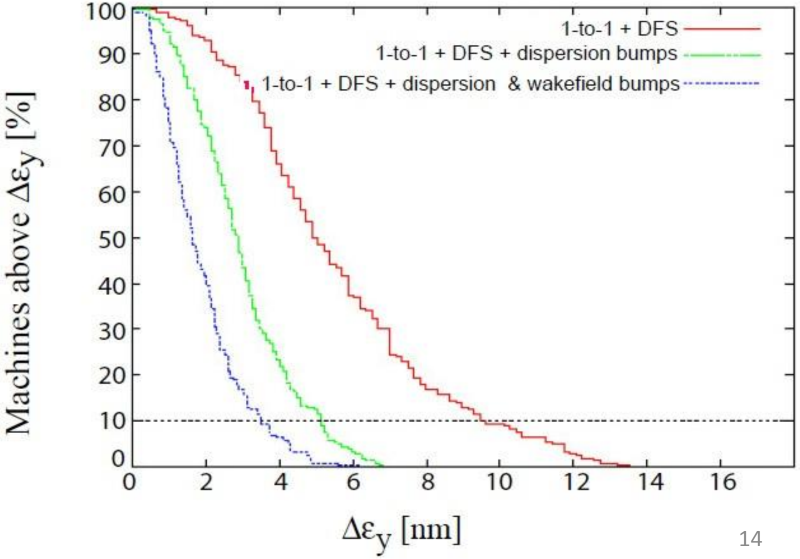
Tuning strategy

- Excellent pre-alignment is not enough
- Beam-based correction: simpler
    - one-to-one correction
- More sophisticated beam-based correction
    - dispersion-free steering
    - ballistic alignment
    - kick minimisation
- Remove residual effects
    - accelerating structure alignment
    - emittance tuning bumps

\- Tune luminosity

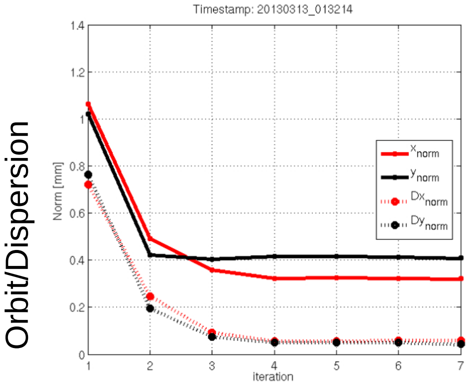
  \- tuning knobs

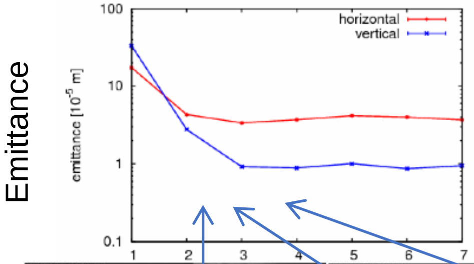




CLIC Beam-Based Alignment tests at SLAC

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

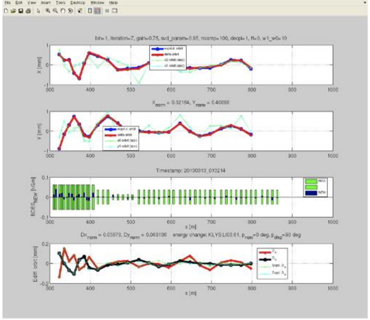




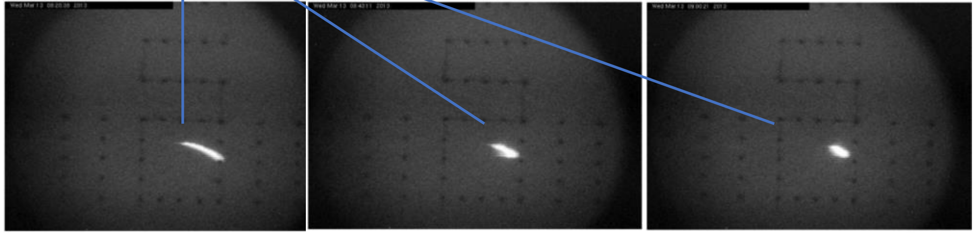
DFS correction applied to 500 meters of the SLC linac

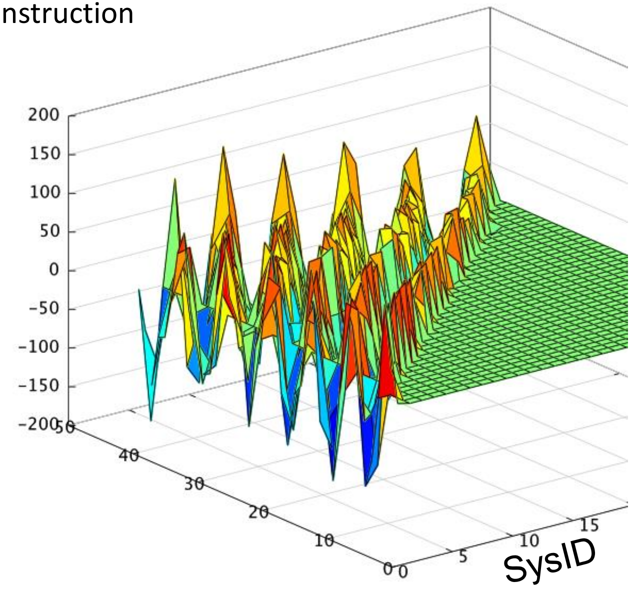
- SysID algorithms for model reconstruction
- DFS correction with GUI
- Emittance growth is measured

Graphical user interface:



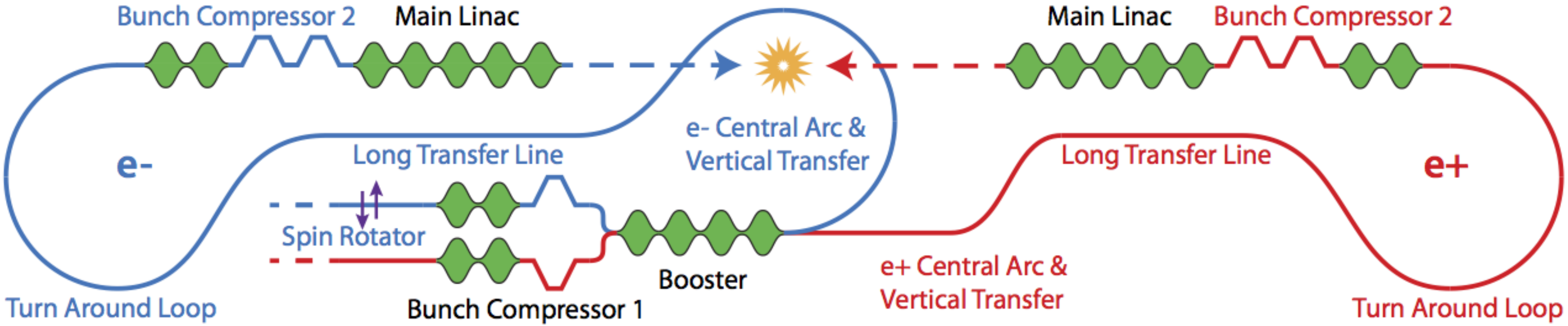
Beam profile measurement





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

Main Beam: Rings to Main Linac



Sub-systems:

- SR: spin rotator
- BC1, BC2: bunch compressors
- BOOSTER: booster linac
- **CA**, VT, **TAL**: central arc and turnaround loops
- LTL: long transfer line

Since **CA** and **TAL** are the most complex sections, the strength error requirement for those magnets is $\Delta B/B = 10^{-4}$

All the others $\Delta B/B = 10^{-3}$

<u>Dispersion-Free Steering:</u> measures response to energy changes

In BC1 and BC2, the phase of the RF cavities is changed to decrease the beam energy.

In SR, LTL and TAL, the magnetic strength of magnets is scaled by 5%.

In the other parts: BOOSTER, CA and VT, the RF cavities gradient is decreased by 5% to get the test beam.

Main Beam: Rings to Main Linac

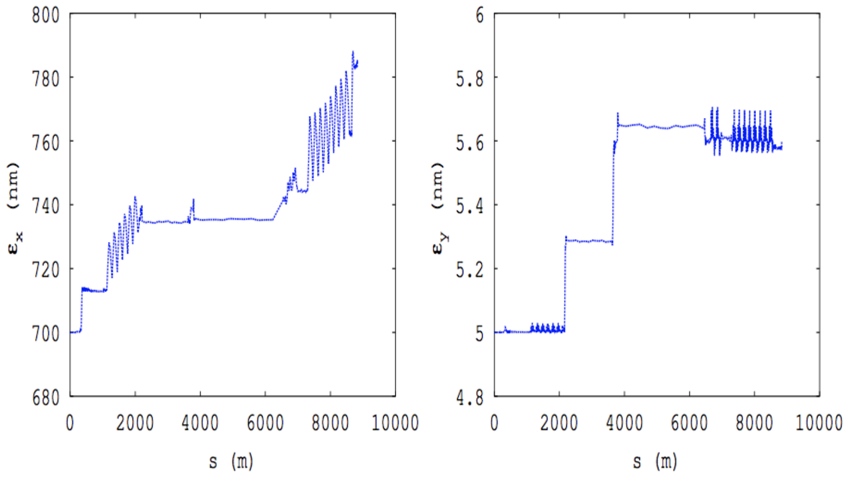


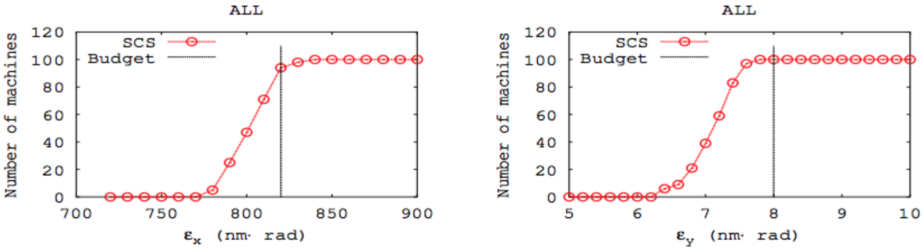
Figure: Emittance growth along the RTML

- Final emittance: $\epsilon_x < 786$ & $\epsilon_y < 5.7$ nm
- Total budget for emittance growth: $\epsilon_x < 850$ & $\epsilon_y < 8$ nm

Y. Han

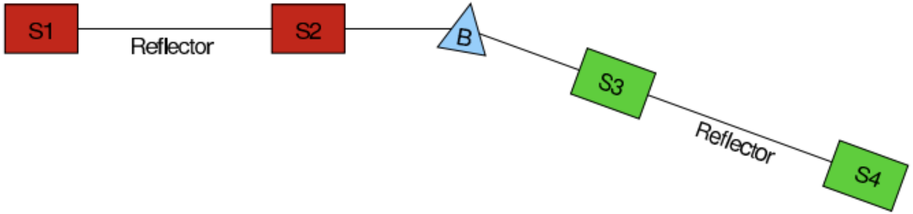
Two correction sections are used.

- The first five sextupoles in CA is used optimise the beam at the end of LTL.
- The first five sextupoles in TAL is used optimise the beam at the end of RTML.



- All dipoles, quadrupoles, sextupoles and BPMs are misaligned σ_{pos} = 30 µm σ_{roll} = 100 µrad
- BPMs resolution = 1 µm
- Magnets strength errors are considered
  - Quadrupoles in CA and TAL: 0.01%
  - All other magnets: 0.1%
  - magnet centre movement effect is considered: 5% magnets strength will induce 0.35 µm shift
- In coupling correction: sextuple moves with step size 1 µm
- 1% emittance measurement errors are considered

Spin Rotator



	Nb	∫ field strength	Length
Solenoids	4	2.9 T	2.6 m
Dipoles	6	0.38 T.m (2.3^o)	1 m
Quadrupoles	34	2.36 T	0.3 m

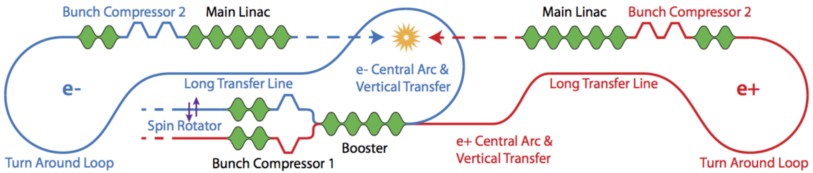
$\Delta B/B = 10^{-3}$.

We need to scale the magnetic strength to perform BBA:

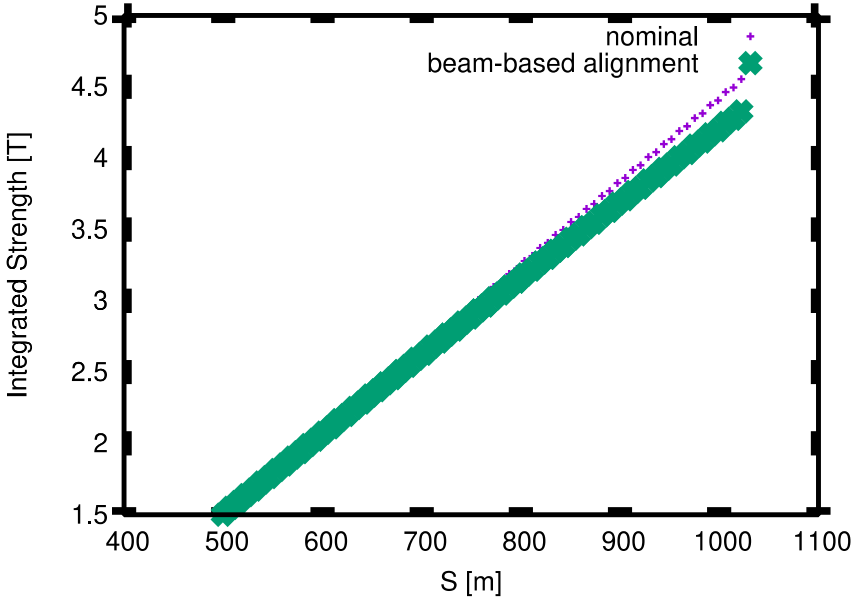
- Solenoids can be OFF
- Strength reduced by 5% in quadrupoles and bending magnets

- We assume this will induce a magnets centre shift of 0.35 μm

(based on private communications with J. Clarke)



Booster linac: quadrupole magnets



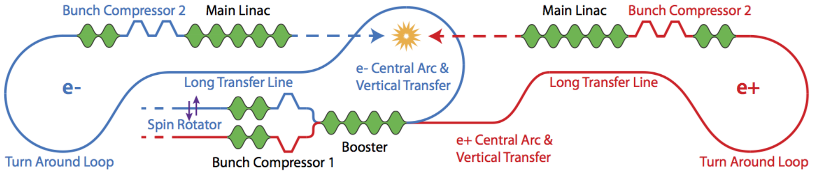
$\Delta B/B = 10^{-3}$

We need to scale the strength of magnets to perform BBA:

- We reduce the accelerating gradient by 5%
- We reduce the magnetic strength of the quadrupoles by 5%, linearly

- We assume this will induce a magnets centre shift of 0.35 µm

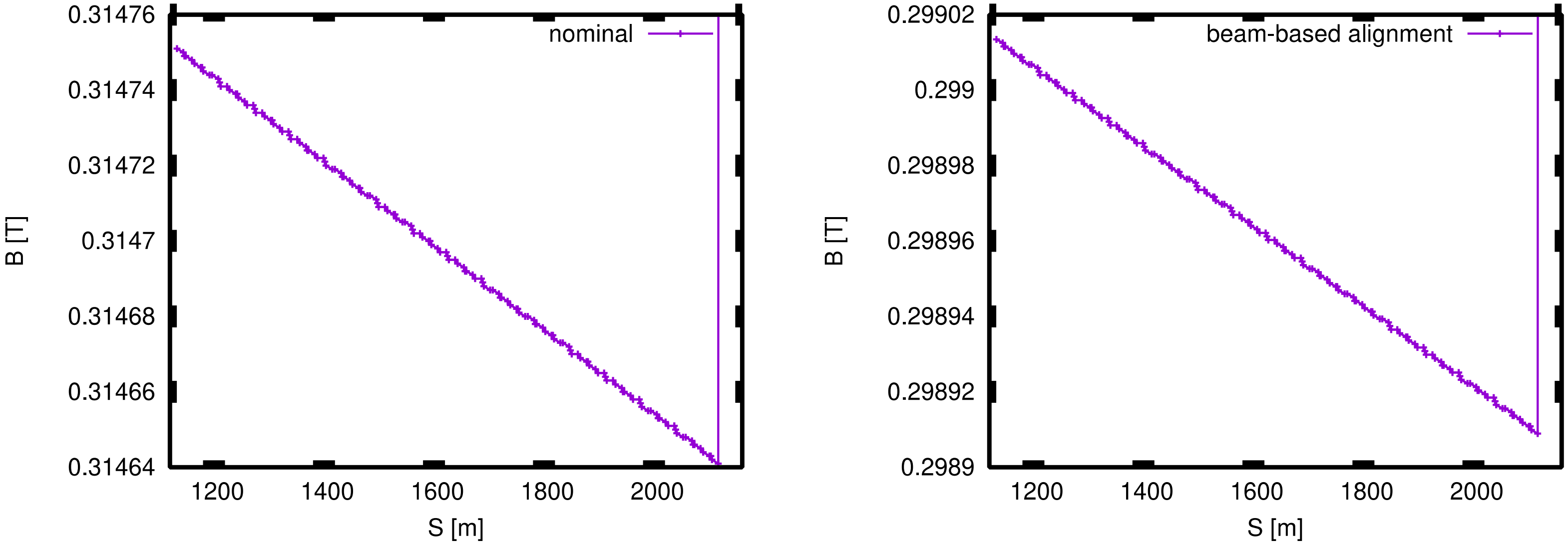
(based on private communications with J. Clarke)



Central Arc: dipole magnets

The strength must match the energy profile of the beam (decreasing because of synchrotron radiation)
The BBA setup must scale all magnetic strengths by -5%

- In dipoles, quadrupoles and sextupoles

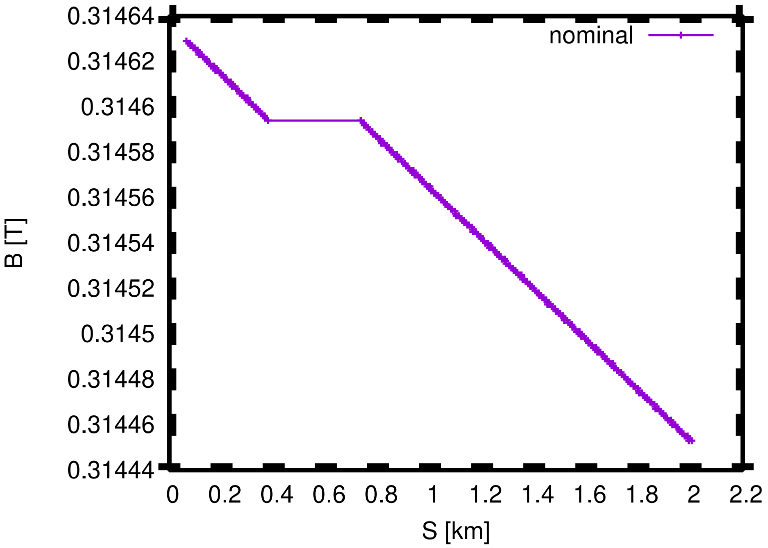


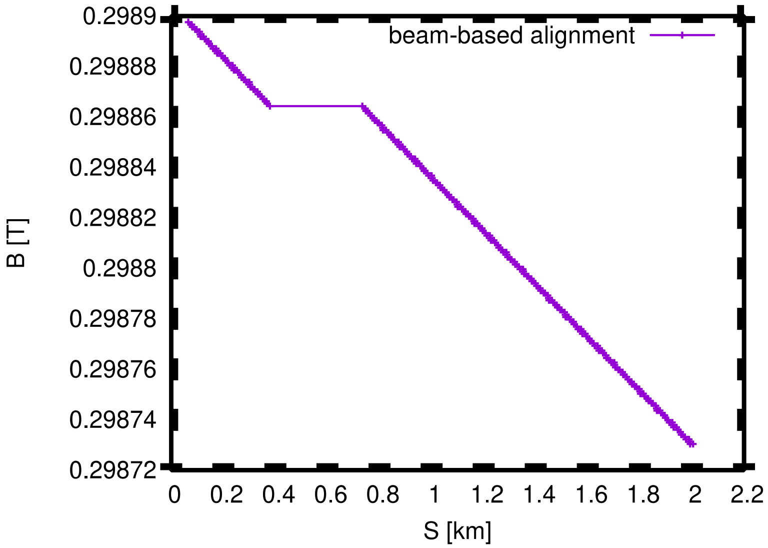
$\Delta B/B = 10^{-4}$. We assumed again a magnets centre shift of 0.35 µm in all magnets.

Turnaround loops: dipole magnets

The strength matches the energy profile of the beam (decreasing because of synchrotron radiation)
The BBA setup must scale all magnetic strengths by -5%

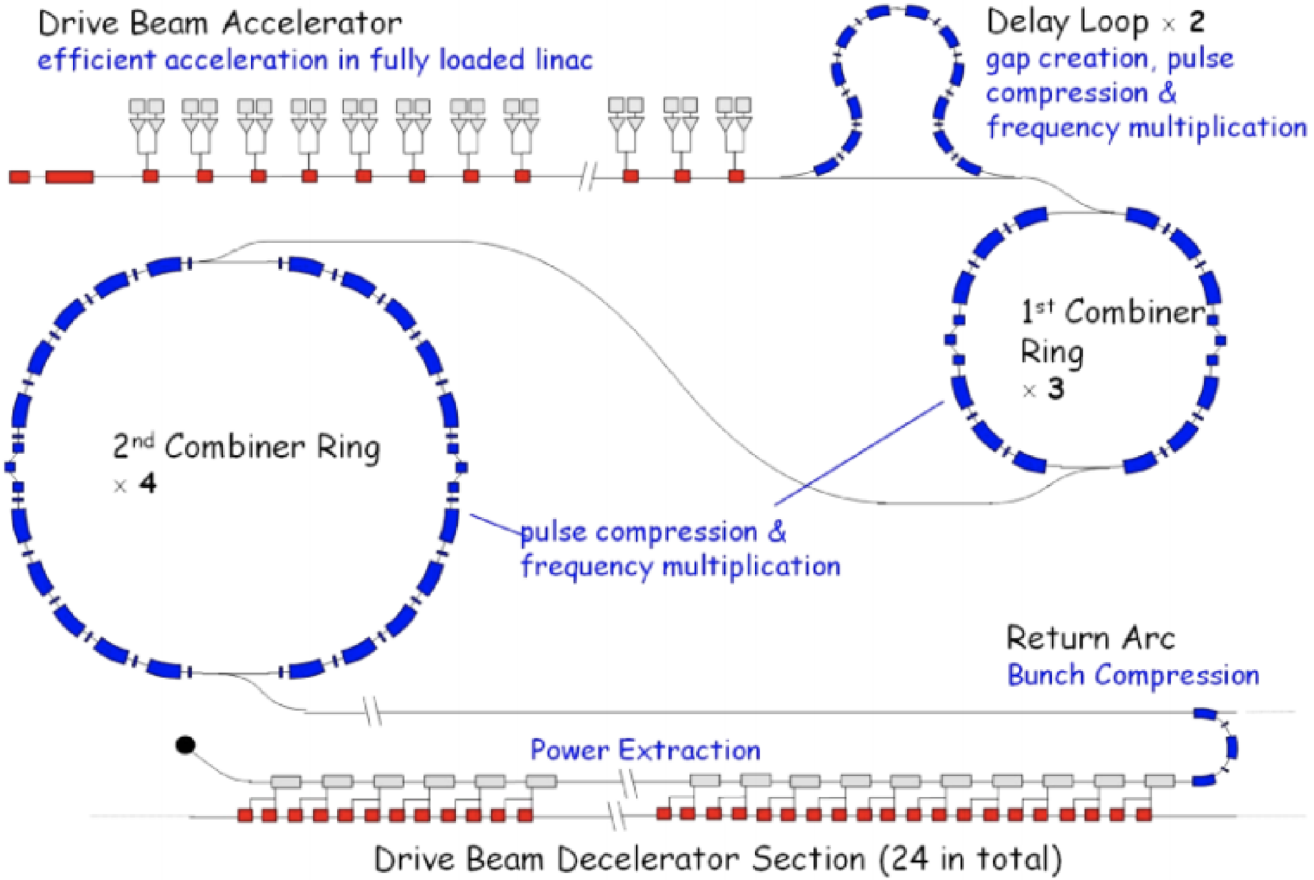
- In dipoles, quadrupoles and sextupoles



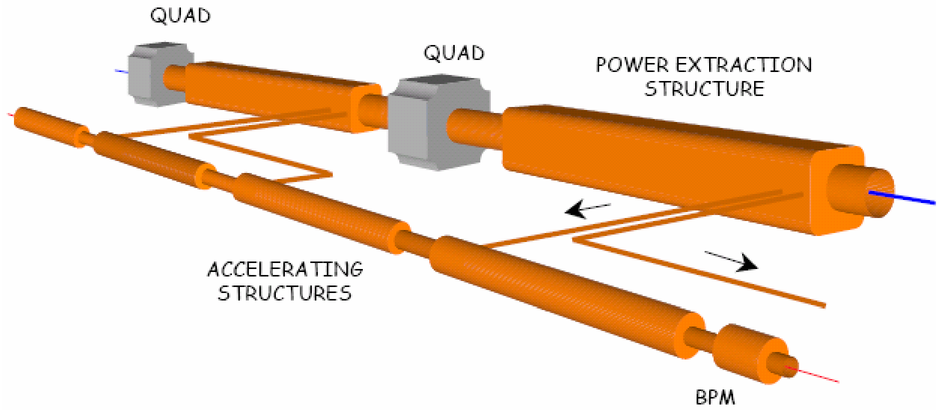


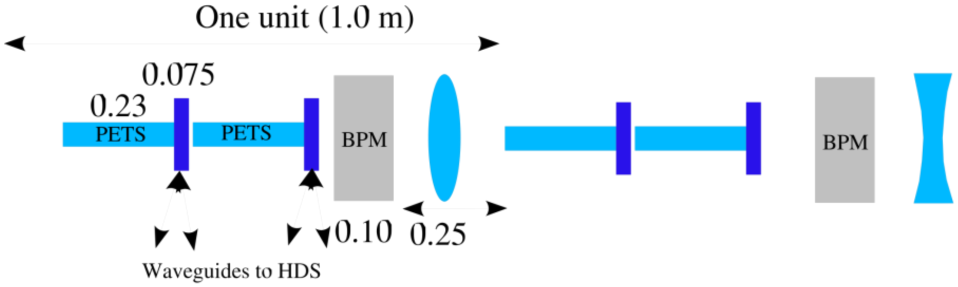
$\Delta B/B = 10^{-4}$. Magnetic strength for beam-based alignment is 5% lower than nominal.

Drive Beam Lines



Drive Beam Decelerators

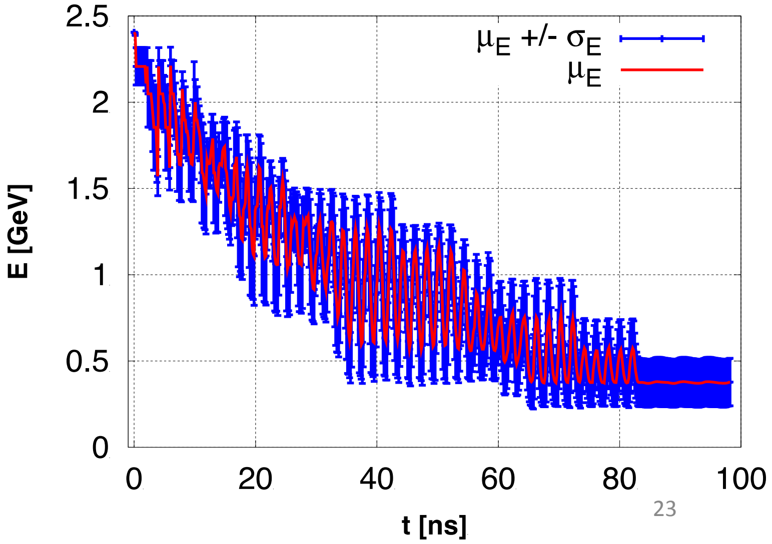




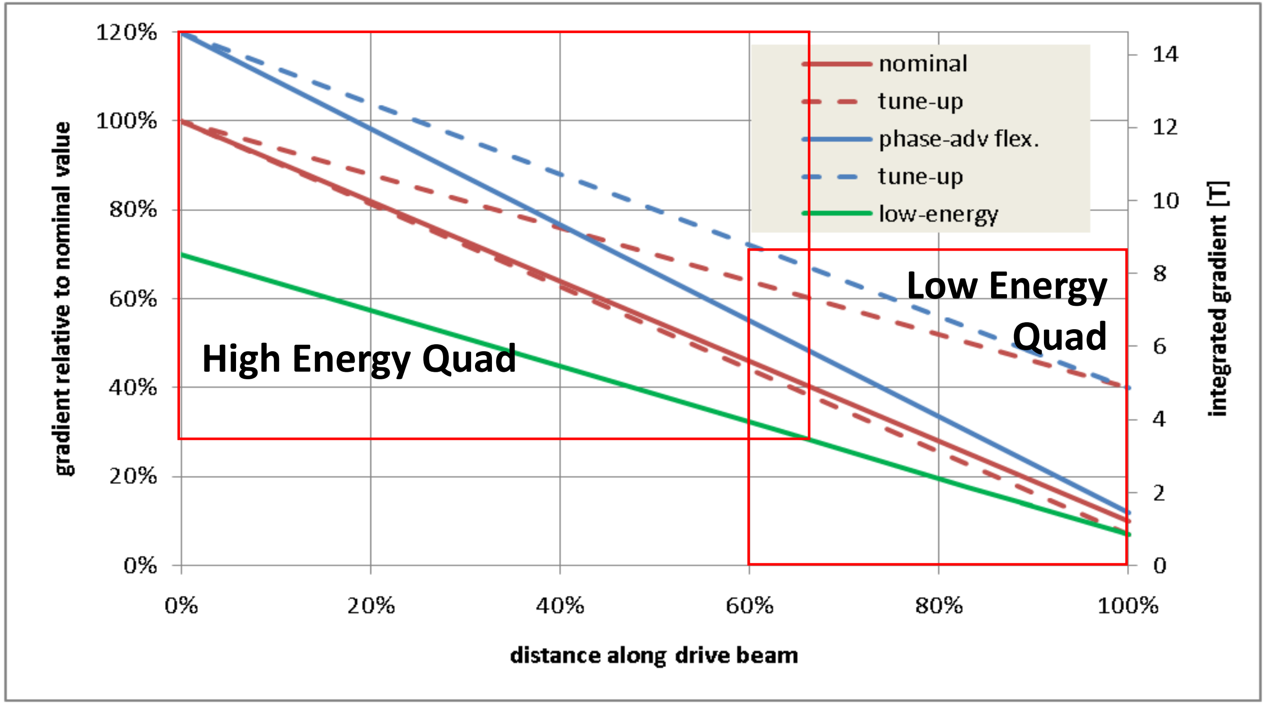
Each decelerator sector contains:
- 1492 PETS
- Up to 1050 quadrupoles

@ 3 TeV : About 42’000 quadrupoles are required for the 48 sectors of the decelerator.
@ 380 GeV: About 8’000 quadrupoles

Below: beam energy profile after deceleration



Drive Beam Decelerators

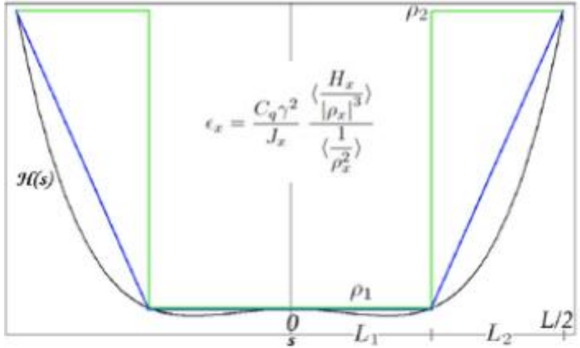


High energy quad – Gradient very high
Low energy quad – Very large dynamic range

Damping Rings: longitudinally variable magnets

The CLIC Damping Rings baseline design aims to reach an ultra-low horizontal normalised emittance of 500 nm-rad at 2.86 GeV, based on the combined effect of TME arc cells and high-field super-conducting damping wigglers, while keeping the ring as compact as possible. Design based on TME cells with longitudinally variable bends and an optimized Nb_3Sn high-field wiggler.

Papadopoulou
F. Antoniou



$$\rho_{st}(s) = \begin{cases} \rho_1, & 0 < s < L_1 \\ \rho_2, & L_1 < s < L_1 + L_2 \end{cases}$$

$$\rho_{tr}(s) = \begin{cases} \rho_1, & 0 < s < L_1 \\ \rho_1 + \frac{(L_1 - s)(\rho_1 - \rho_2)}{L_2}, & L_1 < s < L_1 + L_2 \end{cases}$$

Bending radii ratio

$$\rho = \frac{\rho_1}{\rho_2}$$

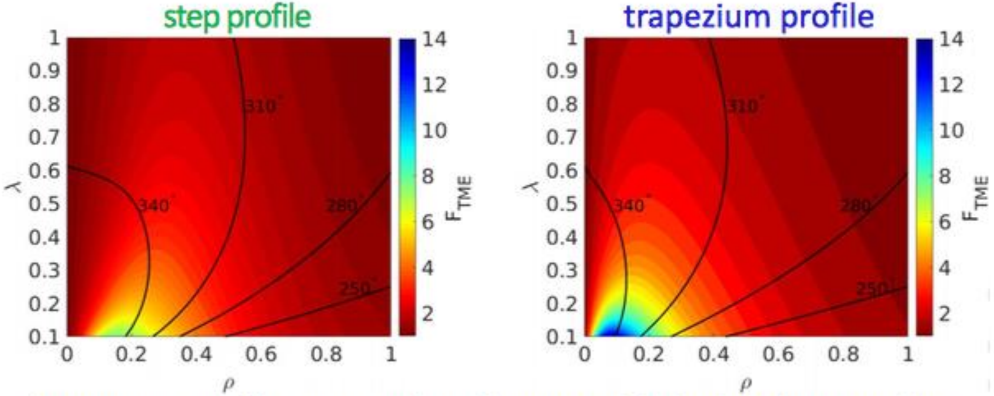
Lengths ratio

$$\lambda = \frac{L_1}{L_2}$$

Emittance reduction factor

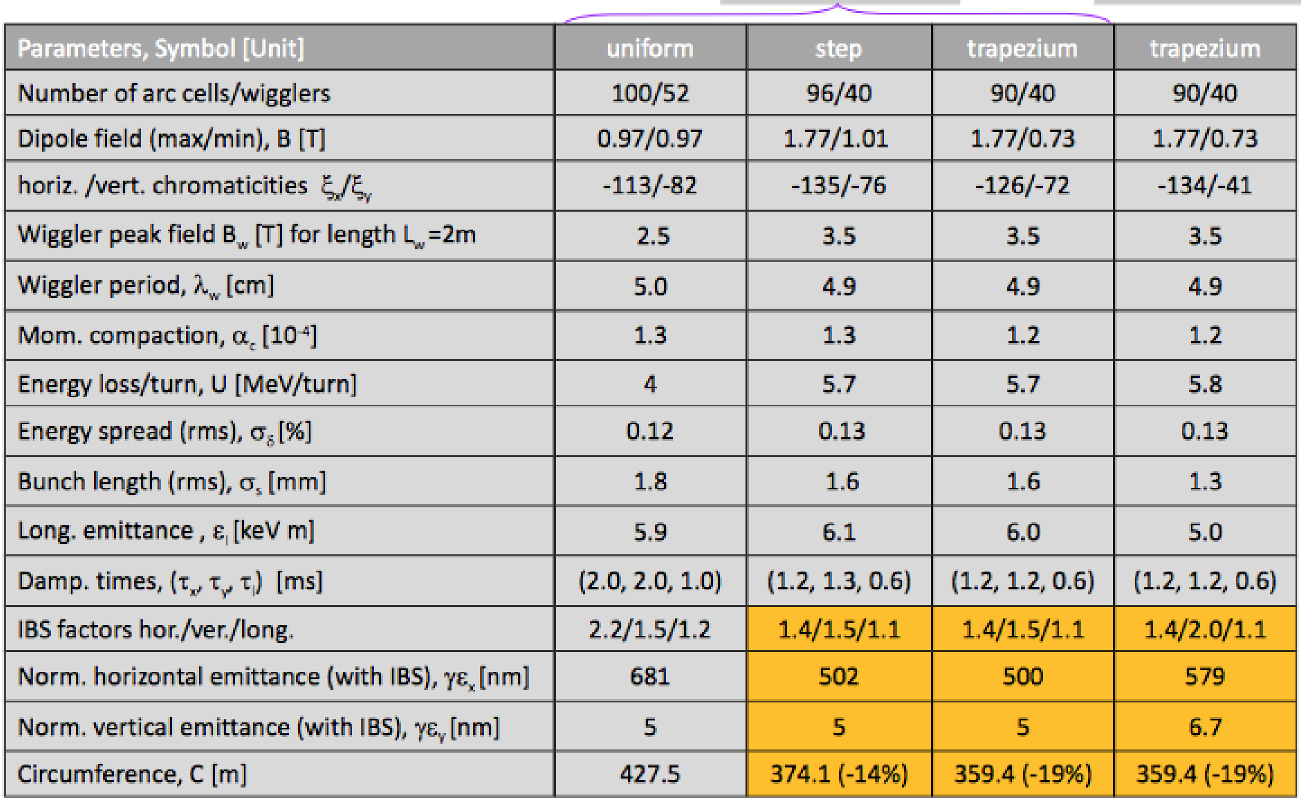
$$F_{TME} = \frac{\epsilon_{TME_{uni}}}{\epsilon_{TME_{var}}}$$

$$F_{TME} > 1$$



The parameterization of the emittance reduction factor F_{TME} with the bending radii ratio ρ and the lengths ratio λ, always for λ>0.1.

DR: design parameters



	Nb=4.07e+09			Nb=5.7e+09
Parameters, Symbol [Unit]	uniform	step	trapezium	trapezium
Number of arc cells/wigglers	100/52	96/40	90/40	90/40
Dipole field (max/min), B [T]	0.97/0.97	1.77/1.01	1.77/0.73	1.77/0.73
horiz. /vert. chromaticities ξ_x/ξ_y	-113/-82	-135/-76	-126/-72	-134/-41
Wiggler peak field B_w [T] for length L_w=2m	2.5	3.5	3.5	3.5
Wiggler period, λ_w [cm]	5.0	4.9	4.9	4.9
Mom. compaction, α_c [10^{-4}]	1.3	1.3	1.2	1.2
Energy loss/turn, U [MeV/turn]	4	5.7	5.7	5.8
Energy spread (rms), σ_δ [%]	0.12	0.13	0.13	0.13
Bunch length (rms), σ_s [mm]	1.8	1.6	1.6	1.3
Long. emittance , ε_l [keV m]	5.9	6.1	6.0	5.0
Damp. times, (τ_x, τ_y, τ_l) [ms]	(2.0, 2.0, 1.0)	(1.2, 1.3, 0.6)	(1.2, 1.2, 0.6)	(1.2, 1.2, 0.6)
IBS factors hor./ver./long.	2.2/1.5/1.2	1.4/1.5/1.1	1.4/1.5/1.1	1.4/2.0/1.1
Norm. horizontal emittance (with IBS), $\gamma\varepsilon_x$ [nm]	681	502	500	579
Norm. vertical emittance (with IBS), $\gamma\varepsilon_y$ [nm]	5	5	5	6.7
Circumference, C [m]	427.5	374.1 (-14%)	359.4 (-19%)	359.4 (-19%)

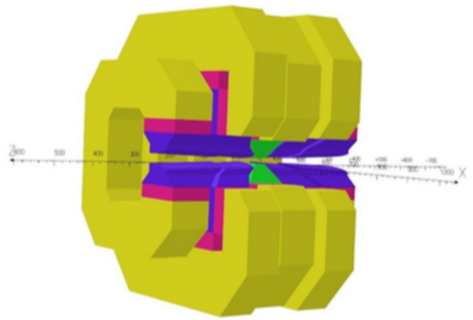
- S. Papadopoulou, F. Antoniou and Y. Papaphilippou, Alternative optics design of the CLIC Damping Rings with variable dipole bends and high-field wigglers, proc. of IPAC'15

-H. Ghasem et al. , "Nonlinear Optimization of CLIC DRS New Design with Variable Bends and High Field Wigglers", proc. of IPAC'16

Magnet design based on the characteristics of the variable bends for the CLIC DRs

-Based on the trapezium profile, the designed dipole has a total length of 56 cm and bends the beam by 4 degrees.

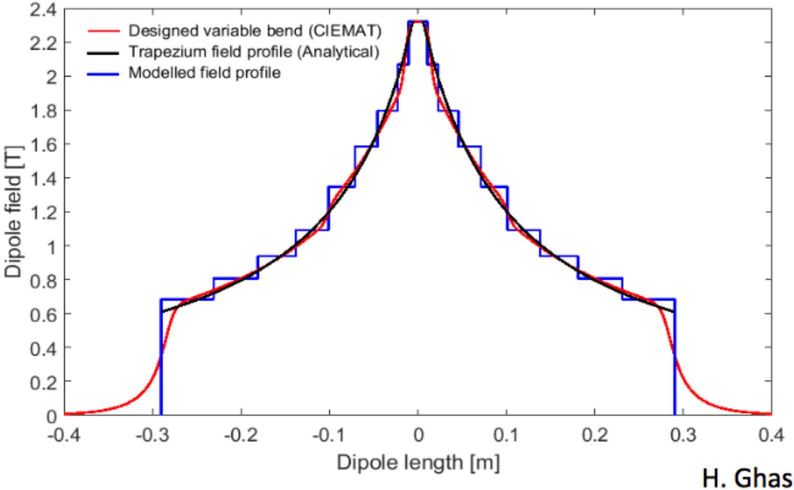
- A maximum field of 2.3 T is reached. The λ and ρ values achieved are 0.04 and 0.29 respectively, corresponding to a F_{TME}=7.



Opera

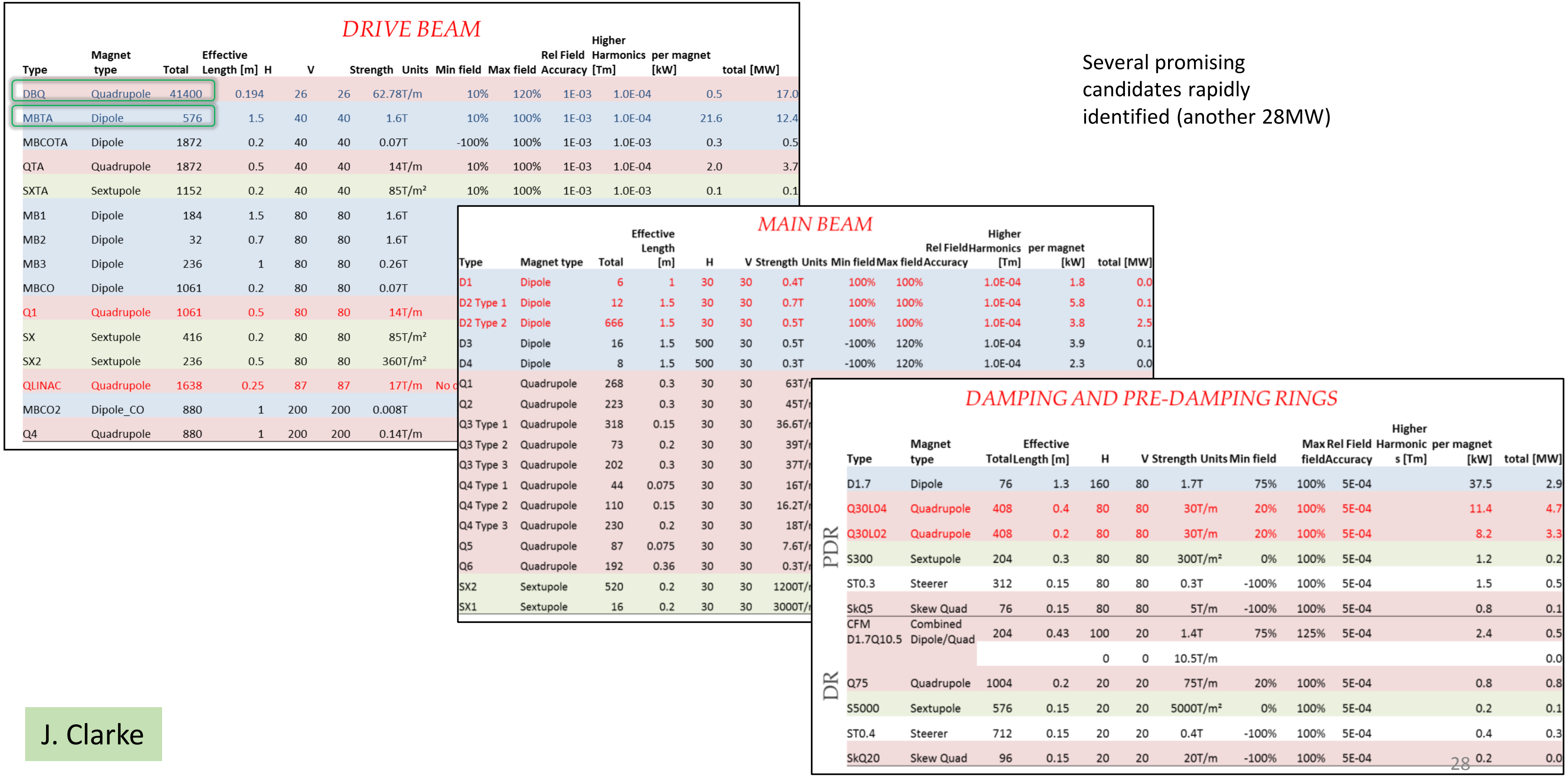
M. A. Domínguez, F. Toral (CIEMAT, Spain)

see "Design of a Dipole with Longitudinally Variable Field using Permanent Magnets for CLIC DRs"



H. Ghasem

Quick Assessment May 2016



DRIVE BEAM

Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
DBQ	Quadrupole	41400	0.194	26	26	62.78T/m		10%	120%	1E-03	1.0E-04	0.5	17.0
MBTA	Dipole	576	1.5	40	40	1.6T		10%	100%	1E-03	1.0E-04	21.6	12.4
MBCOTA	Dipole	1872	0.2	40	40	0.07T		-100%	100%	1E-03	1.0E-03	0.3	0.5
QTA	Quadrupole	1872	0.5	40	40	14T/m		10%	100%	1E-03	1.0E-04	2.0	3.7
SXTA	Sextupole	1152	0.2	40	40	85T/m²		10%	100%	1E-03	1.0E-03	0.1	0.1
MB1	Dipole	184	1.5	80	80	1.6T							
MB2	Dipole	32	0.7	80	80	1.6T							
MB3	Dipole	236	1	80	80	0.26T							
MBCO	Dipole	1061	0.2	80	80	0.07T							
Q1	Quadrupole	1061	0.5	80	80	14T/m							
SX	Sextupole	416	0.2	80	80	85T/m²							
SX2	Sextupole	236	0.5	80	80	360T/m²							
QLINAC	Quadrupole	1638	0.25	87	87	17T/m		No c					
MBCO2	Dipole_CO	880	1	200	200	0.008T							
Q4	Quadrupole	880	1	200	200	0.14T/m							

MAIN BEAM

Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
D1	Dipole	6	1	30	30	0.4T		100%	100%		1.0E-04	1.8	0.0
D2 Type 1	Dipole	12	1.5	30	30	0.7T		100%	100%		1.0E-04	5.8	0.1
D2 Type 2	Dipole	666	1.5	30	30	0.5T		100%	100%		1.0E-04	3.8	2.5
D3	Dipole	16	1.5	500	30	0.5T		-100%	120%		1.0E-04	3.9	0.1
D4	Dipole	8	1.5	500	30	0.3T		-100%	120%		1.0E-04	2.3	0.0
Q1	Quadrupole	268	0.3	30	30	63T/							
Q2	Quadrupole	223	0.3	30	30	45T/							
Q3 Type 1	Quadrupole	318	0.15	30	30	36.6T/							
Q3 Type 2	Quadrupole	73	0.2	30	30	39T/							
Q3 Type 3	Quadrupole	202	0.3	30	30	37T/							
Q4 Type 1	Quadrupole	44	0.075	30	30	16T/							
Q4 Type 2	Quadrupole	110	0.15	30	30	16.2T/							
Q4 Type 3	Quadrupole	230	0.2	30	30	18T/							
Q5	Quadrupole	87	0.075	30	30	7.6T/							
Q6	Quadrupole	192	0.36	30	30	0.3T/							
SX2	Sextupole	520	0.2	30	30	1200T/							
SX1	Sextupole	16	0.2	30	30	3000T/							

DAMPING AND PRE-DAMPING RINGS

	Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
PDR	D1.7	Dipole	76	1.3	160	80	1.7T		75%	100%	5E-04		37.5	2.9
	Q30L04	Quadrupole	408	0.4	80	80	30T/m		20%	100%	5E-04		11.4	4.7
	Q30L02	Quadrupole	408	0.2	80	80	30T/m		20%	100%	5E-04		8.2	3.3
	S300	Sextupole	204	0.3	80	80	300T/m²		0%	100%	5E-04		1.2	0.2
	ST0.3	Steerer	312	0.15	80	80	0.3T		-100%	100%	5E-04		1.5	0.5
	SkQ5	Skew Quad	76	0.15	80	80	5T/m		-100%	100%	5E-04		0.8	0.1
DR	CFM D1.7Q10.5	Combined Dipole/Quad	204	0.43	100	20	1.4T		75%	125%	5E-04		2.4	0.5
					0	0	10.5T/m							0.0
	Q75	Quadrupole	1004	0.2	20	20	75T/m		20%	100%	5E-04		0.8	0.8
	S5000	Sextupole	576	0.15	20	20	5000T/m²		0%	100%	5E-04		0.2	0.1
	ST0.4	Steerer	712	0.15	20	20	0.4T		-100%	100%	5E-04		0.4	0.3
	SkQ20	Skew Quad	96	0.15	20	20	20T/m		-100%	100%	5E-04		0.2	0.0

Several promising candidates rapidly identified (another 28MW)

J. Clarke