Redesign of the CLIC Main Beam Injector Complex

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Revised version after CLIC Project Meeting

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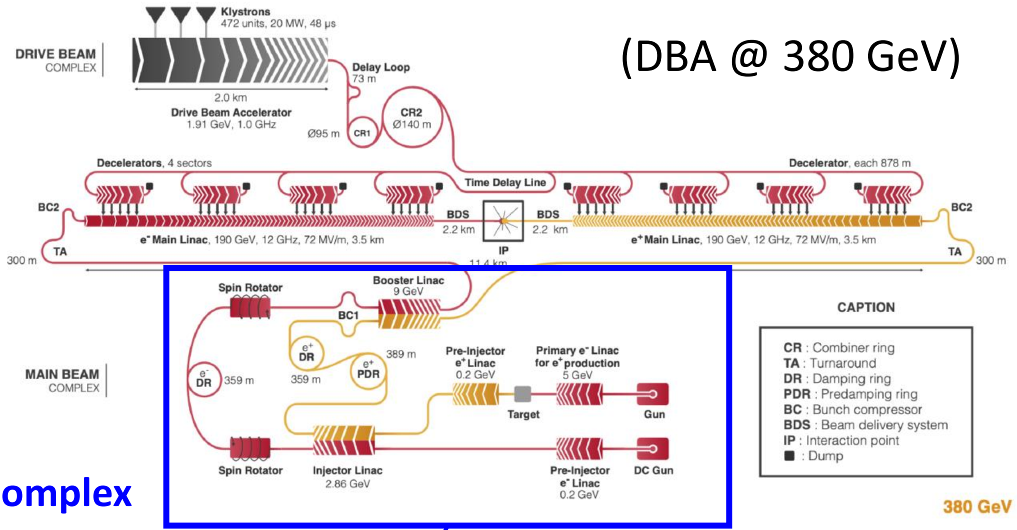
Outline

- Introduction
- New injector complex design
- Beam based alignments
- Jitter amplifications
- Conclusions

Introduction

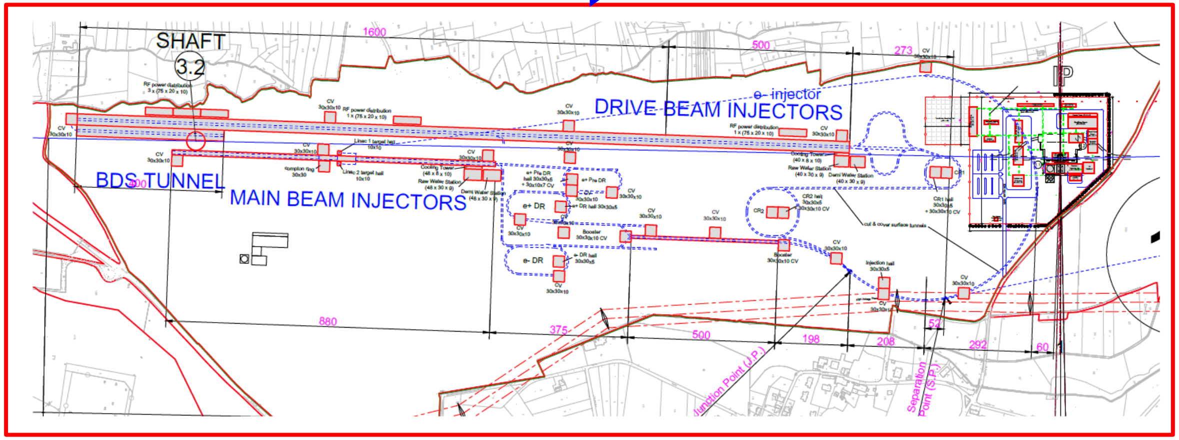
- **CLIC collider complex and Main Beam (MB) Injector complex**

(DBA @ 380 GeV)



MB Injector Complex

(Image credit: CLIC)

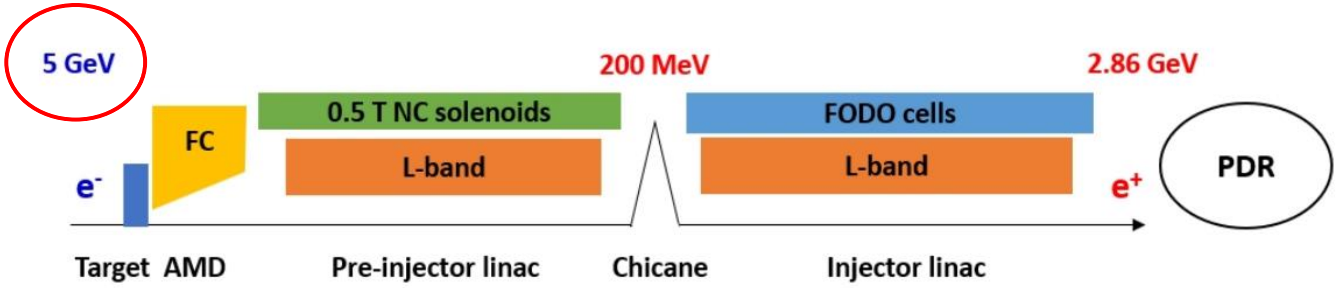


Baseline (old) design

(Image credit: CLIC)

Introduction

- Based on our latest e+ source simulation ([CLIC-Note-1200]), it is possible to reduce the e- beam energy from 5 GeV to ~2.3 GeV (assuming 1 nC max.)



5 GeV

200 MeV

2.86 GeV

e-

FC

0.5 T NC solenoids

L-band

FODO cells

L-band

e+

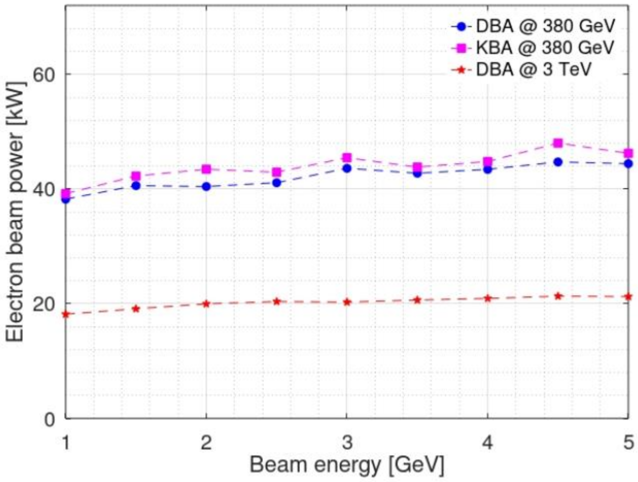
PDR

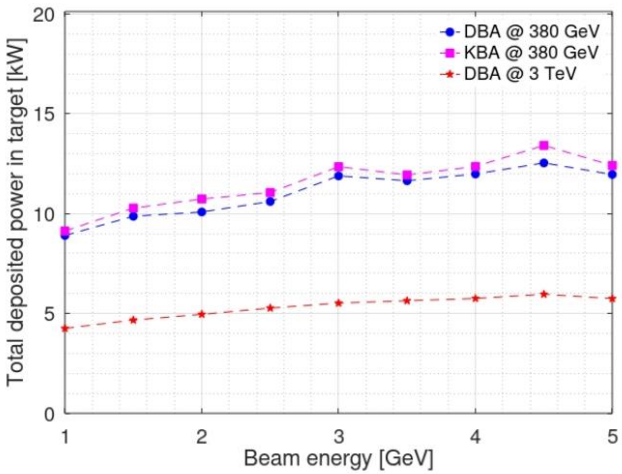
Target AMD

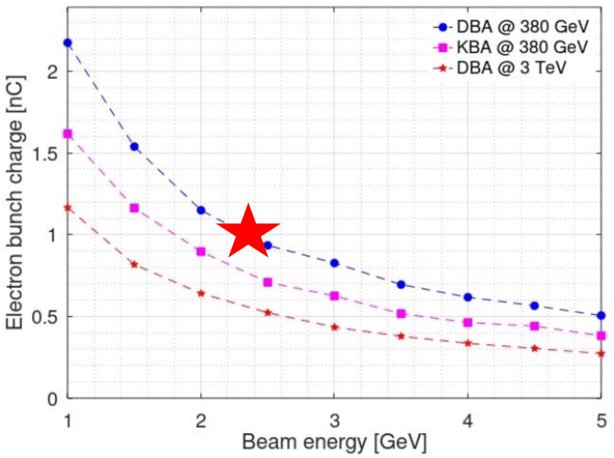
Pre-injector linac

Chicane

Injector linac

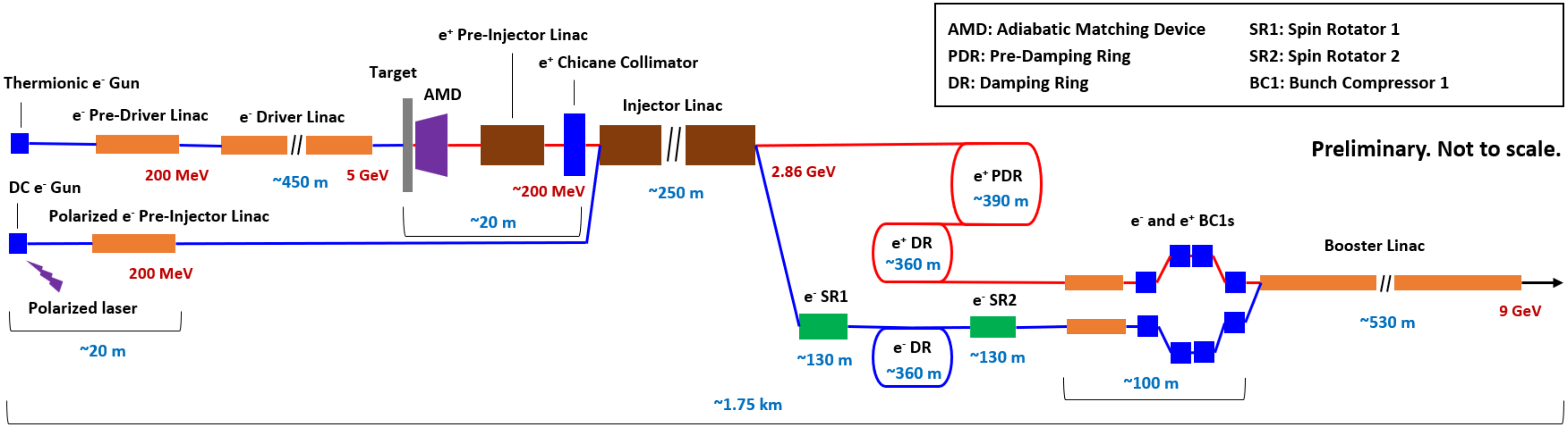






New injector complex design

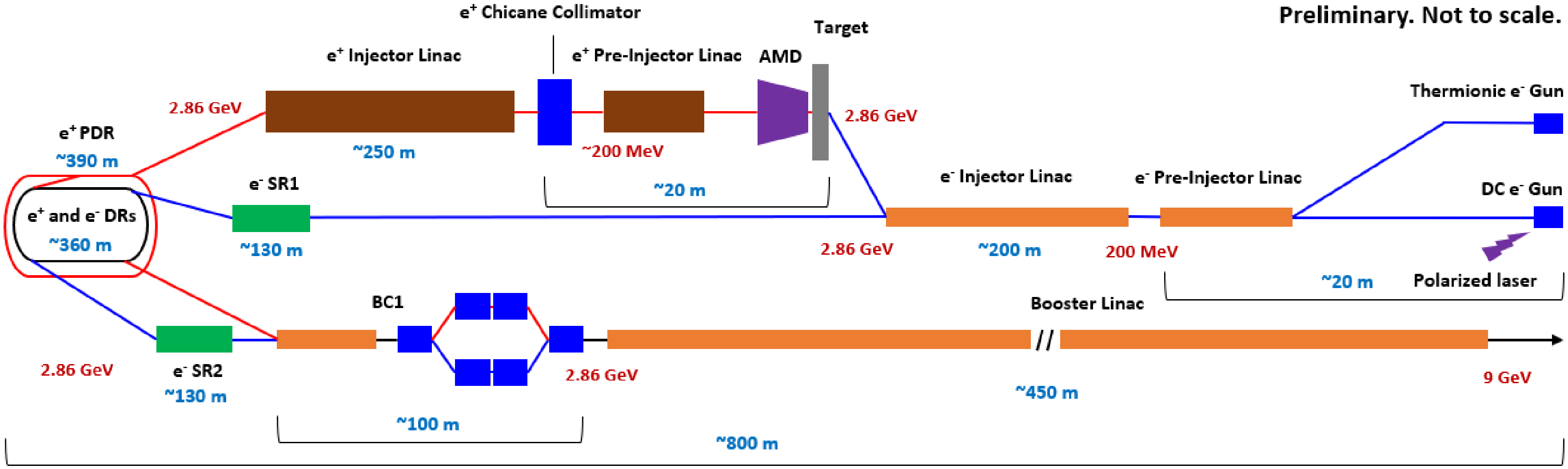
- **Baseline (old) design schematic layout**


AMD: Adiabatic Matching Device
PDR: Pre-Damping Ring
DR: Damping Ring
SR1: Spin Rotator 1
SR2: Spin Rotator 2
BC1: Bunch Compressor 1

Preliminary. Not to scale.

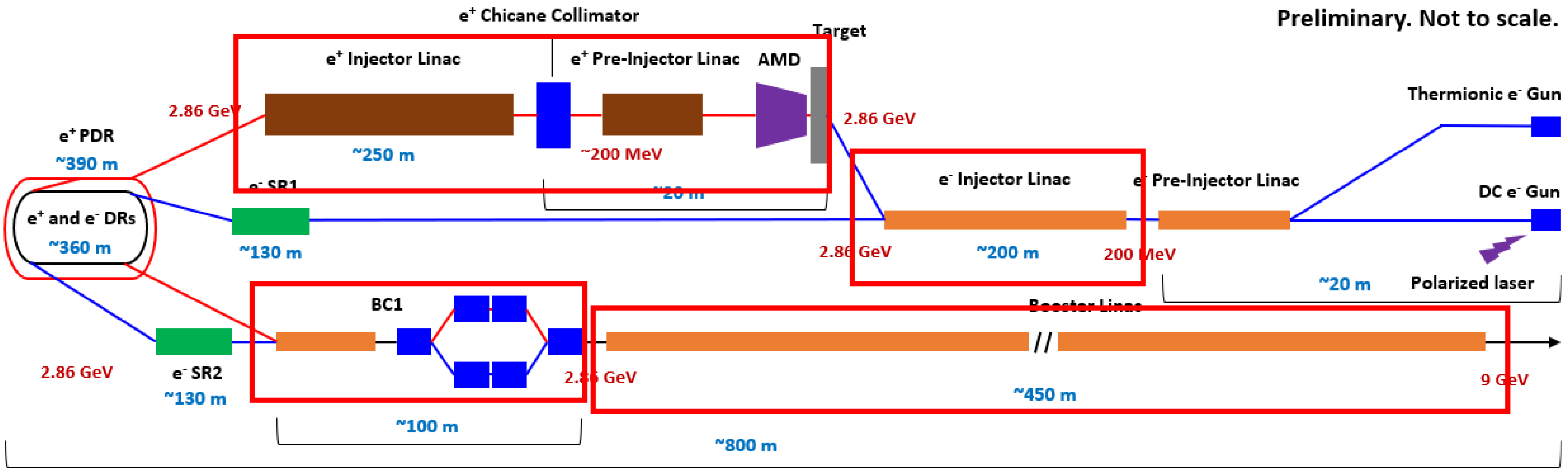
- **Alternative (new) design schematic layout – In progress**

Preliminary. Not to scale.



New injector complex design

- We currently only focus on the (re)design of:
  - **e- Injector Linac, e+ Source, BC1 Linac, Booster Linac**
- New 3 m long RF acc. structures are used (as Adnan presented), replacing the 1.5 m “CLIC L-band” structure (a = 20—14 mm)
- e+ Source linacs requires larger aperture (a ≥ 20 mm) due to large beam size. Other linacs can use smaller aperture (a < 20 mm)

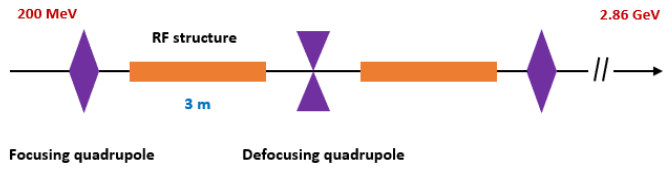


Preliminary. Not to scale.

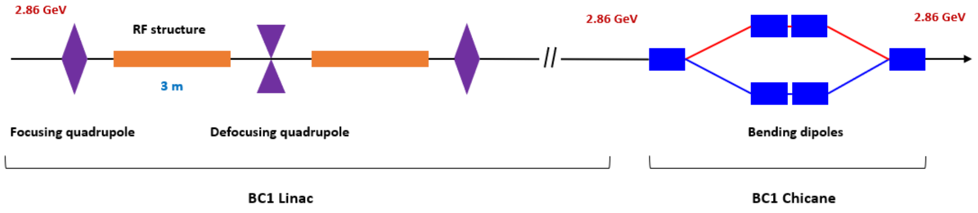
New injector complex design

- Design of e- linacs

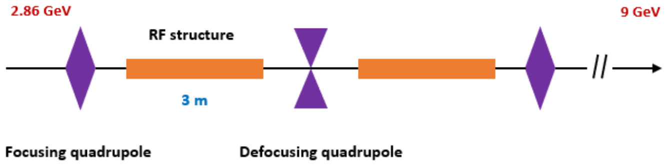
e- Injector Linac

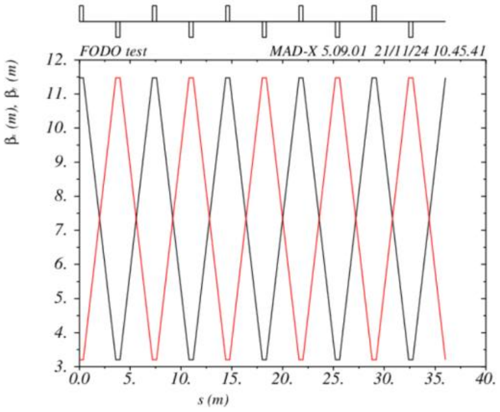


BC1 Linac



Booster Linac





FODO phase advance: 76.345°

Spacing 3.2 m, k1 ~ 0.8584 m^{-1}

- New L-band RF structure is used
  - 2 GHz, L = 3 m, **a0 = 18 mm (21—15), d0 = 3.66mm (3.26—4.06)**
  - 60 cells, 2π/3 phase advance per cell
- Doubling number of structures between quads increases jitter amplification significantly (e.g. F = 1.1 → 1.3 in Booster Linac), though misalignment effect is smaller

New injector complex design

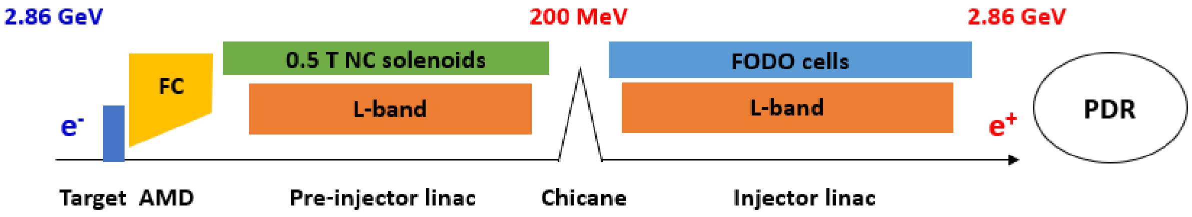
- Design parameters and results for e- linacs (DBA@380 GeV)
  - Simulation using RF-Track (Gaussian bunch w/ collective effects)
  - Voltages for BC1 and Booster Linac are from our latest RTML optimization (CLIC-Note-1199). Energy losses in arcs are compensated with higher gradient

Parameter	e- Injector Linac	BC1 Linac	Booster Linac
Bunch charge	~1.0 nC	~0.83 nC	~0.83 nC
E	0.200—2.86 GeV	2.86 GeV	2.86—9.01 GeV
E spread	1%—0.15%	0.12%—1.2%	1.2%--0.4%
Bunch length	1 mm	1.8 mm	~410 um
Emittance [X, Y]	Ploar.: [10, 10] um Unpol.: [50, 50] um	[700, 5] nm	[~704, 5] nm
Structures (w/ spare modules)	**58+2**	**10+2**	**124+4**
Length (w/ spare modules)	**~249 m**	**~50 m**	**~531 m**
Gradient	**15.347 MV/m**	**15.017 MV/m**	**16.579 MV/m**

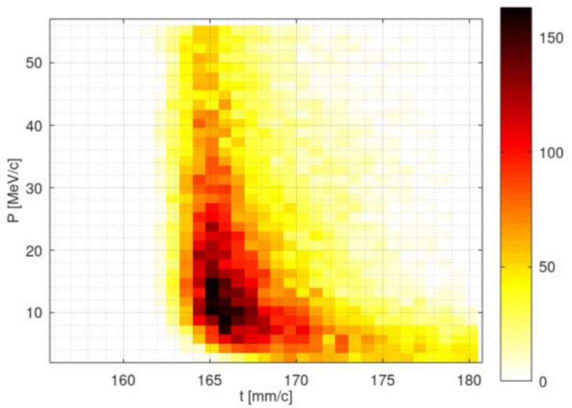
New injector complex design

- New **e+ Source** design is much more complicated and is **in progress**

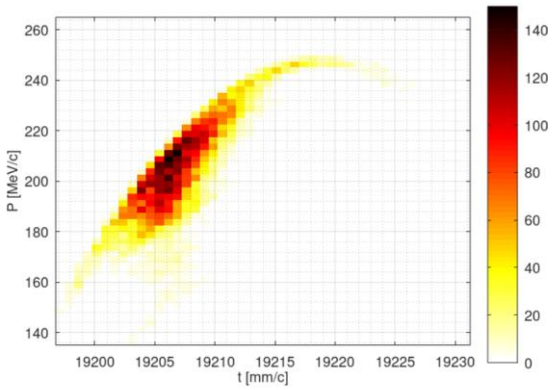
New e- E spread (rms)	**0.15%**
New e- spot size (rms)	**2.5 mm**
New target thickness	**16.5 mm**


2.86 GeV
200 MeV
2.86 GeV
FC
0.5 T NC solenoids
L-band
FODO cells
L-band
e^-
e^+
PDR
Target AMD
Pre-injector linac
Chicane
Injector linac

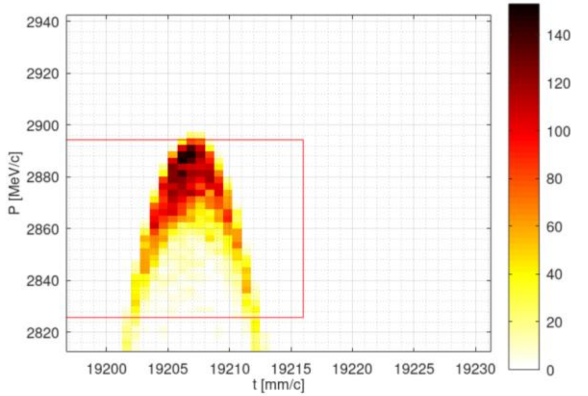
- Preliminary test (6D simulation to 200 MeV) shows expected results, that, assuming a 10% loss in the Injector Linac and a 20% loss in PDR & DR:
  - **PDR accepted e+ yield ~ 1.0, Electron bunch charge ~ 1.0 nC, PEDD ~ 33 J/g (required: < 35 J/g)**



AMD exit



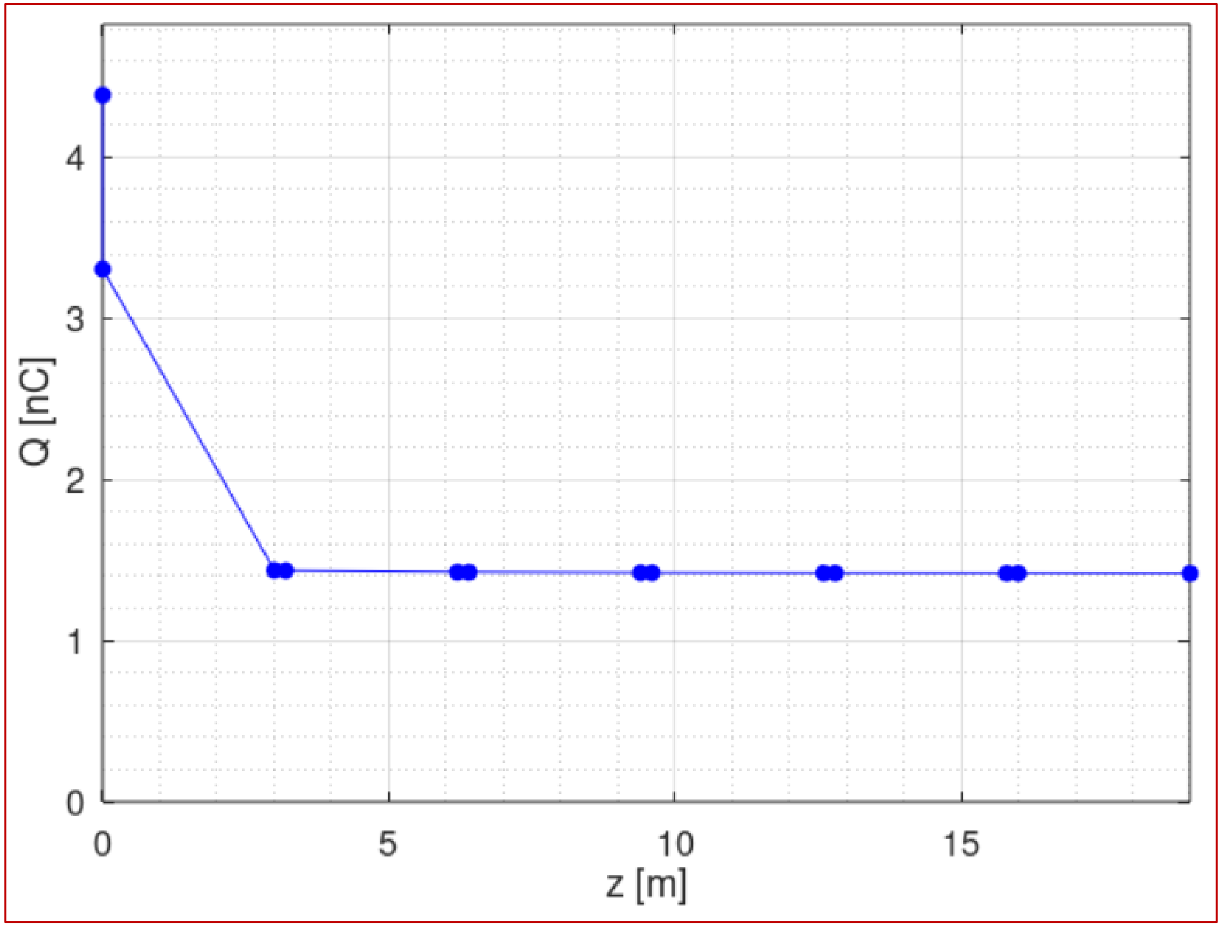
Pre-Injector Linac exit



Injector Linac exit

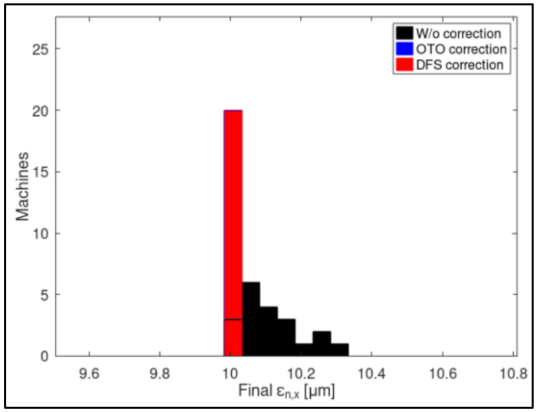
New injector complex design

- **e+ bunch charge evolution in Pre-Injector Linac**
  - **Assuming a 1 nC e- beam**



Beam based alignments

- Beam based alignment (BBA) for **e- Injector Linac**
- Misalignments
  - **Position** error (x, y): σ = 100 um (Quads, RFs, BPMs)
  - **Angular** error (roll, pitch, yaw): σ = 100 urad (Quads, RFs, BPMs)
  - **BPM** resolution: σ = 1 um
  - More in progress

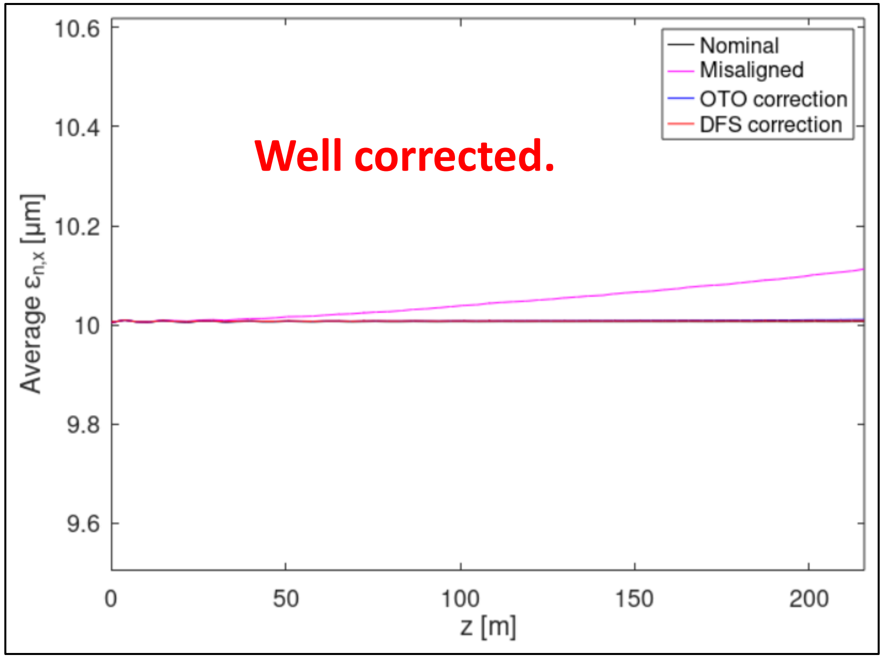


- BBA methods (typical approches)
  - One-To-One (OTO) orbit correction

$$\begin{pmatrix}-\mathbf{x}\\ \mathbf{0}\end{pmatrix} = \begin{pmatrix}\mathbf{R}\\ \beta_0\mathbf{I}\end{pmatrix}\cdot\begin{pmatrix}\theta_1\\ \vdots\\ \theta_{\mathbf{m}}\end{pmatrix}$$

  - Dispersion-Free Steering (DFS) correction

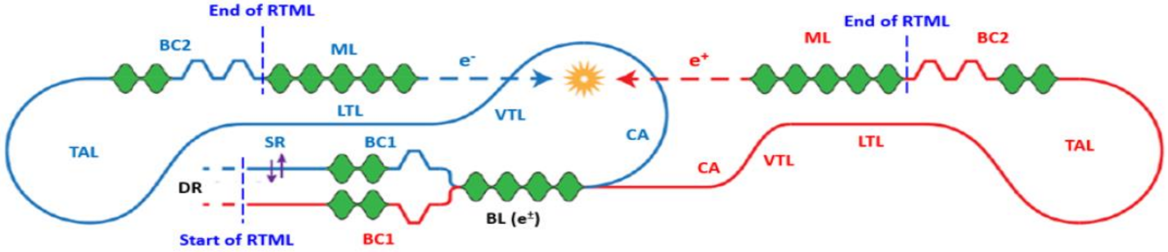
$$\begin{pmatrix} & -\mathbf{x}\\ \omega_d & (\eta_0-\eta)\\ & \mathbf{0}\end{pmatrix} = \begin{pmatrix} & \mathbf{R}\\ \omega_d & \mathbf{D}\\ \beta_1 & \mathbf{I}\end{pmatrix}\cdot\begin{pmatrix}\theta_1\\ \vdots\\ \theta_{\mathbf{m}}\end{pmatrix}$$



Well corrected.

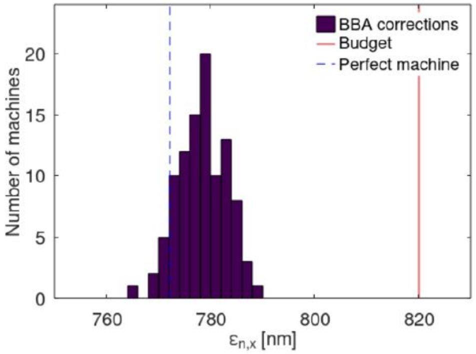
Beam based alignments

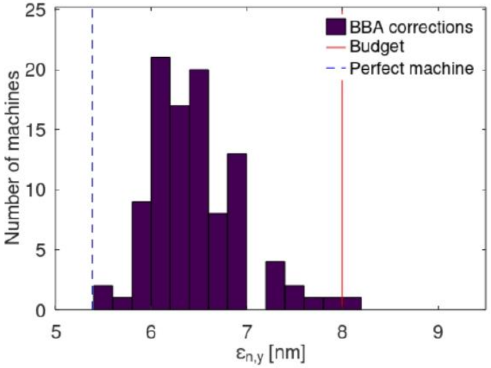
- BBA for **BC1** and **Booster Linac** is not particularly studied, as they are already included in the **Rings-To-Main-Linac (RTML)** beamline, where a complicated start-to-end BBA is applied with tight emittance growth budgets in RTML (CLIC-Note-1199)



Emittance budgets	$\epsilon_{n,x}$	$\epsilon_{n,y}$
Perfect machine	< 800	< 6
Static imperfections	< 820	< 8
Static and dynamic imperfections	< 850	< 10

- Required: ≥ 90% good machines
- Achieved: 99% (1% ε measurement error)
- Achieved: 94% (10% ε measurement error)





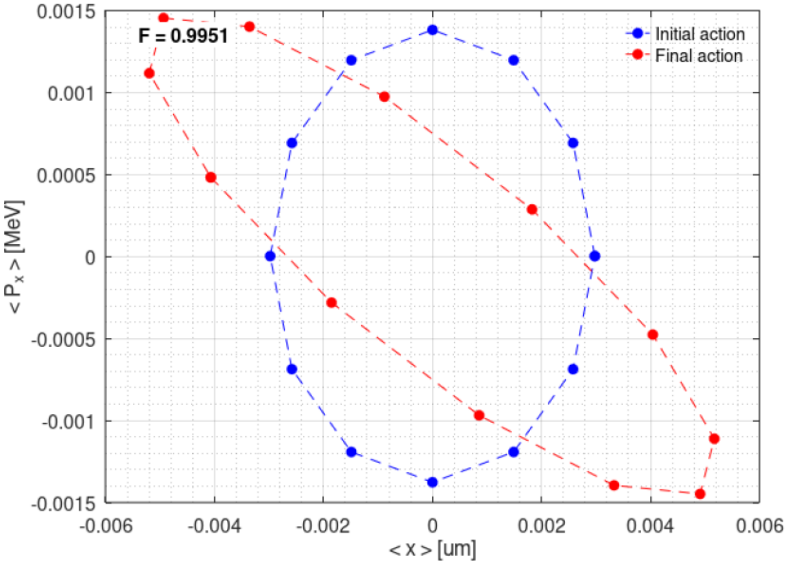
- Preliminary tests show that BBA could still work with structure aperture for BC1 and Booster Linac reduced from a0 = 17 mm to even a0 = 11 mm

Jitter amplifications

- Jitter amplification due to short-range wakefield (SRWF) is studied for Booster Linac (old design). Simulation using RF-Track
- Initial jitter assumed: 10%*σ(X, Px). Amplification independent on initial jitter
- Jitter amplification factor definition:

$$\boldsymbol{F_s = \frac{F_{W\neq 0}}{F_{W=0}}} \quad \textbf{, where} \quad \boldsymbol{F = \frac{J_{\text{final}}}{J_{\text{initial}}} = \sqrt{\frac{A_{\text{final}}}{A_{\text{initial}}}}}$$

J: jitter, A: Action (ellipse area)



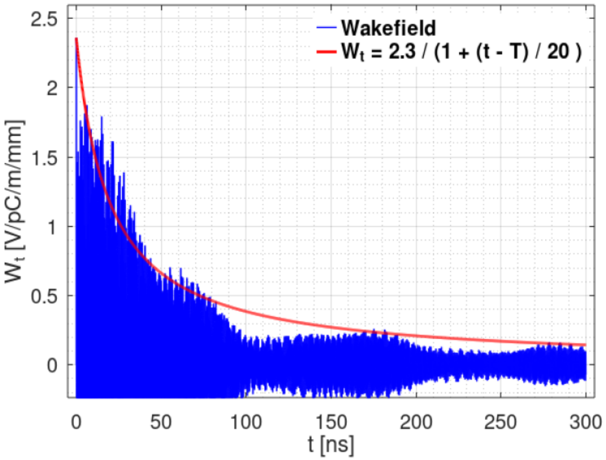
Jitter amplification factor (Fs)	Value
W/o SRWF	0.986
W/ SRWF	0.995
Due to SRWF	1.01

✓ Fs < 1 even w/o SRWF, due to the BNS damping effect (when E spread > 0)

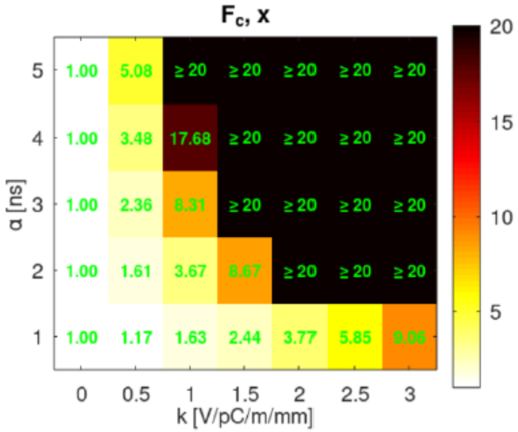
Jitter amplifications

- Jitter amplification due to long-range wakefield (LRWF) is studied in steps:
    1. Definition of wake criteria from jitter amplification study, using an approximate wake envelope function (though effect is overestimated with envelope). A 2D scan is performed with different parameters (k, α), with single particle simulation (similar to full bunch simulation)

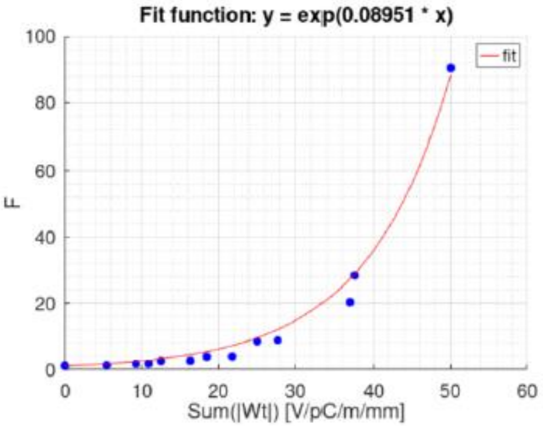
$$W_{\perp(t)} = \frac{k}{1+\frac{t-T}{\alpha}}, \qquad t \geq T = 0.5 \text{ ns}$$



Arbitrary LRWF (from a test design)



α [ns] \ k [V/pC/m/mm]	0	0.5	1	1.5	2	2.5	3
5	1.00	5.08	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20
4	1.00	3.48	17.68	≥ 20	≥ 20	≥ 20	≥ 20
3	1.00	2.36	8.31	≥ 20	≥ 20	≥ 20	≥ 20
2	1.00	1.61	3.67	8.67	≥ 20	≥ 20	≥ 20
1	1.00	1.17	1.63	2.44	3.77	5.85	9.06



✓ **F grows with Sum(|Wt|) over bunches exponentially**

✓ **Finally, Sum(|Wt|) over bunches < 10 V/pC/m/mm is used as the wake criteria for RF design**

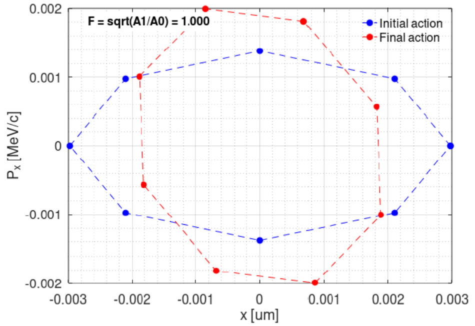
Jitter amplifications

- Jitter amplification due to long-range wakefield (LRWF) is studied in steps:
  1. Definition of wake criteria
  2. RF structure optimization (see Adnan's presentation)
  3. Wake test for jitter amplification

➢ **Coherent jitter:** trains evenly distributed on the ellipse (bunches have the same position in transverse phase space)

$$F_c = \frac{F_{W\neq 0}}{F_{W=0}}\ , \text{ where } F = \frac{J_{\text{final}}}{J_{\text{initial}}} = \sqrt{\frac{A_{\text{final}}}{A_{\text{initial}}}}$$

Action of last bunch, wakefield not used

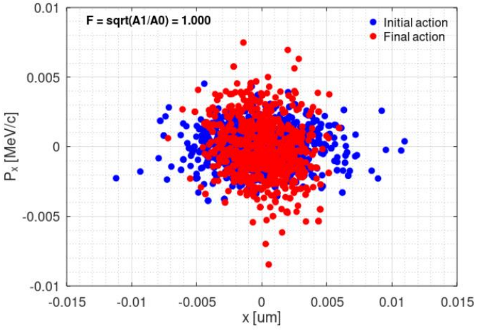


A: action (area of ellipse)

➢ **Incoherent jitter:** trains randomly distributed in transverse phase space (bunch positions are also random)

$$F_{rms} = \frac{F_{W\neq 0}}{F_{W=0}}\ , \text{ where } F = \frac{J_{\text{final}}}{J_{\text{initial}}} = \sqrt{\frac{A_{\text{final}}}{A_{\text{initial}}}}$$

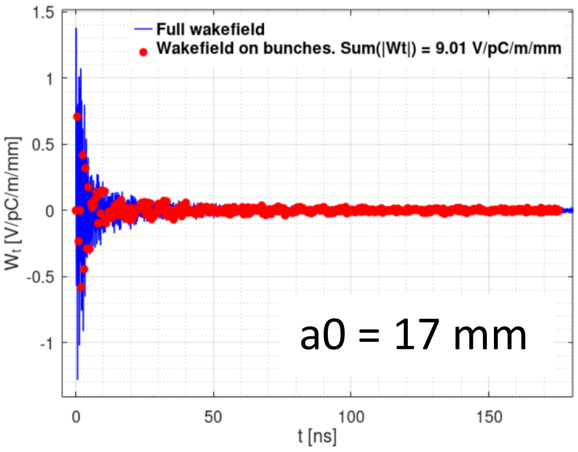
Action of last bunch, wakefield not used

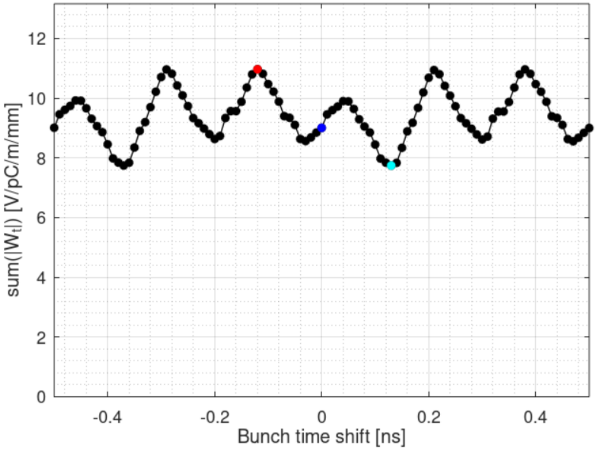


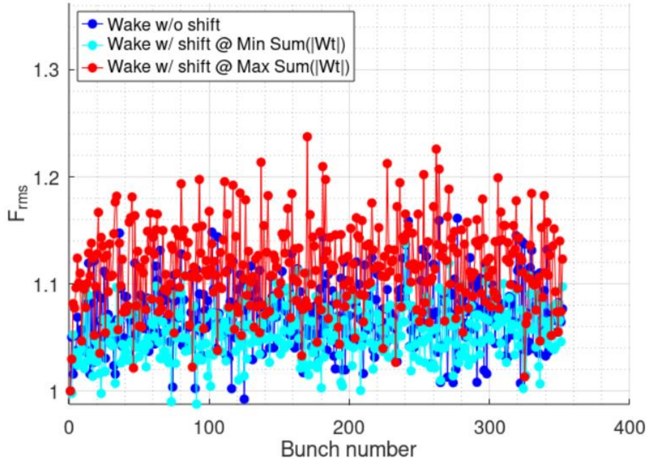
A: action (area of ellipse)

Jitter amplifications

- For stability, we shift the wakefield by ±0.5 ns, and take the worst wake (maximum sum(|Wt|)), which proves to be the worst jitter amplification





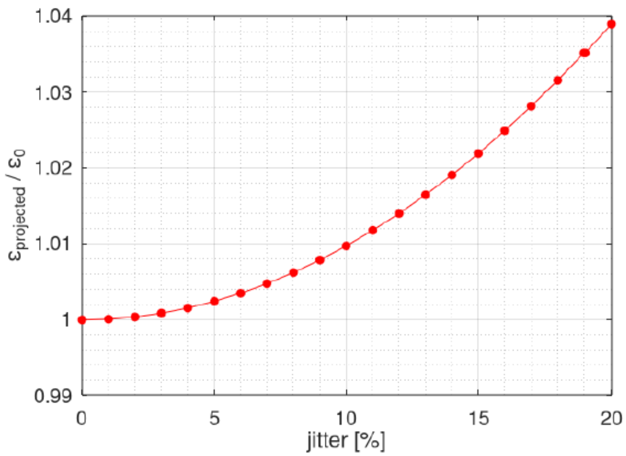


- Jitter amplification is taken to be the average of the last 200 bunches
  - ✓ For incoherent jitter, 100 trains are simulated (average is similar to 1000 or more trains)

Jitter amplification	**e- Injector Linac**	**e+ Injector Linac**	**BC1 Linac**	**Booster Linac**
Fc	**1.01**	**In Progress**	**1.00**	**1.00**
Frms	**1.53**		**1.00**	**1.12**

Jitter amplifications

- From incoherent jitter amplification to projected emittance growth (full train)
  - Taking the average projected emittance of randomly jittered trains



$$\frac{\varepsilon_{\text{projected}}}{\varepsilon_0} \approx 1 + \mathrm{J}^2, \qquad J \approx \sqrt{\frac{\varepsilon_{\text{projected}}}{\varepsilon_0} - 1}$$

$$F = \frac{J_{\text{final}}}{J_{\text{initial}}} \approx \sqrt{\frac{\varepsilon^{\text{final}}_{\text{projected}} - \varepsilon_0}{\varepsilon^{\text{initial}}_{\text{projected}} - \varepsilon_0}}$$

$$\Delta\varepsilon_{\text{projected}} \approx \varepsilon_0 \cdot J^2_{\text{initial}} \cdot \left(F^2 - 1\right)$$

- So the projected emittance growth can be estimated (e.g. 10% initial jitter):

Normalized emittance	**e- Injector Linac**	**e+ Injector Linac**	**BC1 Linac**	**Booster Linac**
Single bunch ε_0^n [x, y]	**Polar.: 10 um** **Unpol.: 50 um**	**~10 mm**	**[700, 5] nm**	**[~704, 5] nm**
$\Delta\varepsilon^n_{\text{projected}}$ [x, y]	**~0.1 um** **~0.7 um**	**In progress**	**~0**	**~[1.8, 0.01] nm**

Conclusions

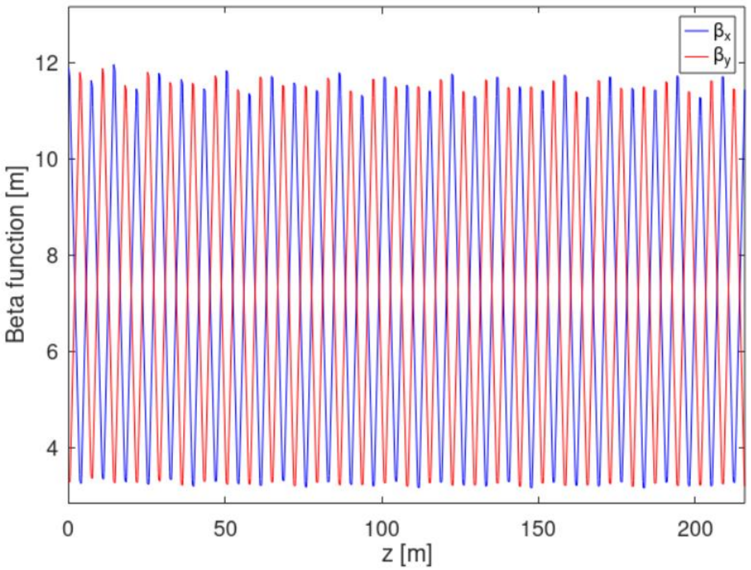
- CLIC **Main Beam Injector complex** redesigned with **simplified** layout. Much **shorter total length** and e- Injector Linac length
- Study focused on Drive beam-Based Acceleration (**DBA**) mode @ **380 GeV**
- Preliminary study of **misalignments**. **Well corrected** with **BBA**
- **Jitter amplifications** in the linacs estimated, that are small and **acceptable**
- Work in progress
  - Reoptimise **e+ source**, including e+ Injector Linac redesign
  - Update **RTML** design and BBA study using new BC1 Linac and Booster Linac
  - RTML e+ beam transfer lines redesign for **Civil Engineering consistency**, though not included in the Injector Complex

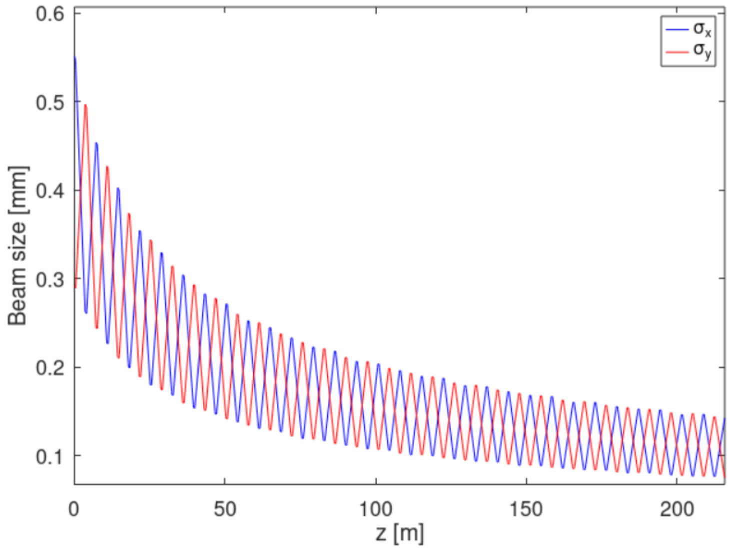
BACKUP

New e- Injector Linac design

- Results from RF-Track

Parameter	Unit	Value
Final E	GeV	2.860
Final E spread	%	0.15
Emittance growth	um	0





New Booster Linac design

- Results from RF-Track

Parameter	Unit	Value
Final E (energy losses in RTML considered)	GeV	9.010
Final E spread	%	0.39
Emittance growth	nm	0