CLIC Drive Beam Linac

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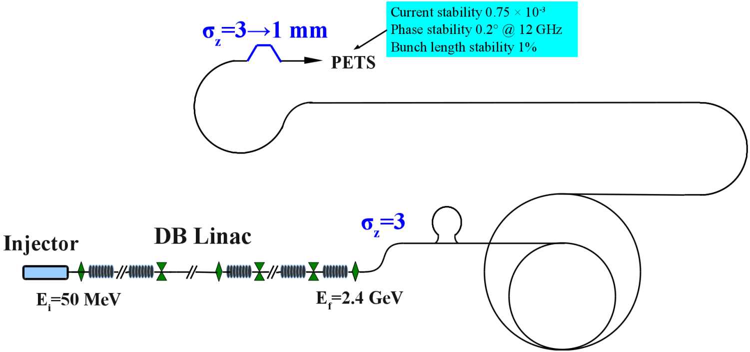
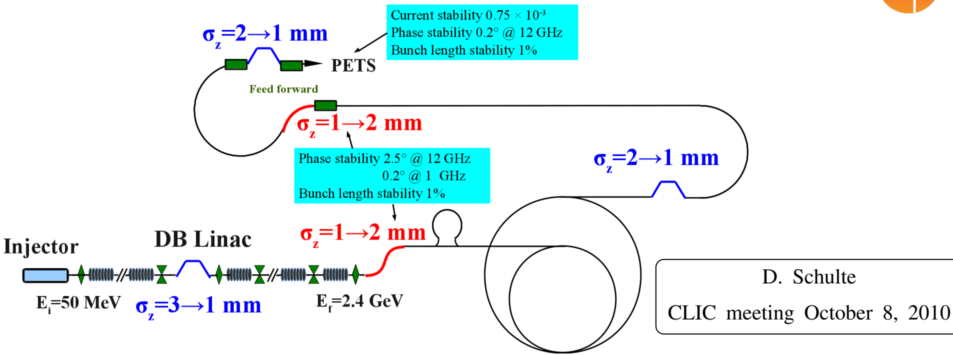
Contents

CLIC RF power production layout



- The beam pulse with 140 μs pulse length and 4.2 A current which consists of 24 × 24 sub-trains of about 120 bunches each is accelerated up to 2.4 GeV in Drive Beam Linac (DBL).
- After DBL, 24 sub-trains will be merged into a signle sub-train using delay loop (DL), combiner ring one (CR1) and combiner ring two (CR2). (Each sub train will have 100 A pulse current and 240 ns pulse length)
- CLIC requires very thight tolerances at the entrance of PETS. If the full bunch compression is performed in front of PETS one needs large R_{56} required and large R_{56} requires too small energy jitter.

CLIC RF power production layout



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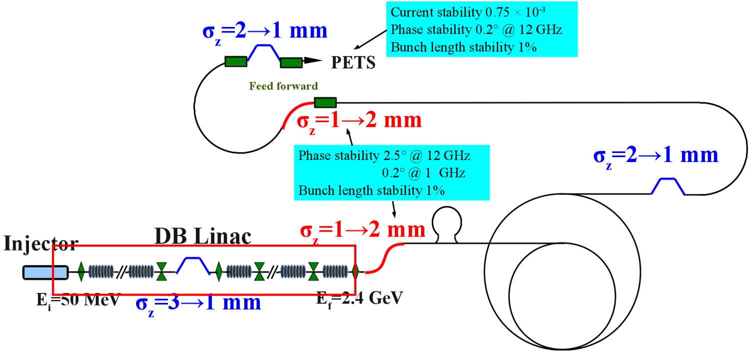

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Aim

The study aims finding solutions for beam transport through Drive Beam Linac in required tolerances...

- the transverse parameters...
  - > small emittance growth
  - > small transverse jitter amplification
  - > easy correctable lattice
  - > acceptance of large energy errors

DB Linac Beam Parameters

Initial Beam Energy(MeV)	50
Final Beam Energy(GeV)	2.4
Initial Energy Spread(%)	1
Final Energy Spread(%)	<0.35
Pulse Current(A)	4.2
Bunch Charge(nC)	8.4
Initial Bunch Length(mm)	3
Final Bunch Lenght(mm)	1
Initial Emittance (mm.mrad)	50
Emittance Growth(%)	<10
Pulse Length(μ s)	140
Bunch separation(cm)	60
No of Bunch/Pulse	70128
Bunch length variatiton(%)	<1
Bunch Phase variation(deg)	<0.2

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- the longitudinal parameters...
  - > stable beam phase
  - > stable bunch length
  - > relatively small energy spread

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- stable bunch charge

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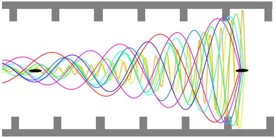
Considered instability sources

Instabilities driven by wakefields

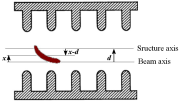
This instability generated by off-axis beam trajectories can be developed within a single-bunch or along a train of bunches.

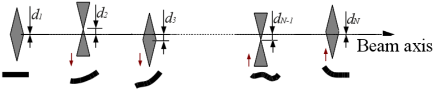
- the transverse wakefiled created by leading particles of a bunches (or bunches of a train) deflects the trialing particles of bunches (or remaining bunches of train). Minimum deflection requires strong lattice
- the longitudinal wakefield created by leading particles of a bunches decelerating effect on remaining bunches. Effect can be reduced by off-crest acceleration



instability caused by static imperfections

All elements on beamline may be scattered around a straight line. (element offsets, field errors, angle errors, qaudrupole roll errors...)



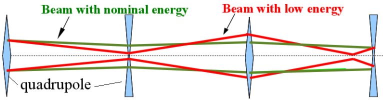


- Offsets of the structures (thus offset of the beam inside structures) causes increasing the wake field effect. Minimum deflection requires strong lattice
- Imperfection of the quadrupoles causes kick on the beam, thus leads increasing the emittance growth. Various alignment technique is used to align beam. Requires weak lattice and less number of quadrupoles

Considered instability sources

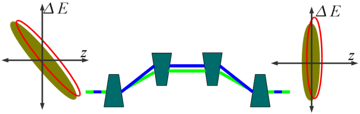
energy and gradient errors

- Any error of incoming beam energy or variation of the gradient will lead quadrupole strengths not to be adapted to the beam energy.
- These situations can cause beam amplification to grow, eventually, beam losses especially in DBL1 where the beam energy is low.



- If there is any variation on desired relative energy spread, the error will be transferred to phase or length of outgoing bunch

$$\delta_z = R_{56}\delta_E$$



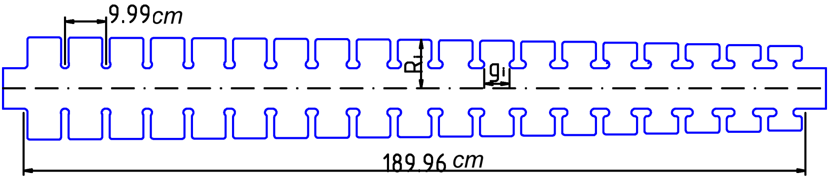
What can change energy and relative energy spread ?

- Current error of beam → changes wake field
- Incoming phase error of bunch or phase error RF
- Gradient error of linac or energy error of incoming beam

for fully loaded opr.

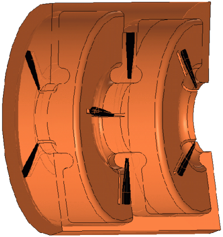
$$\frac{\delta E}{E_0} \propto \frac{2\delta G}{G_0}$$
$$\frac{\delta E}{E_0} \propto \frac{\delta N}{N_0}$$

CLIC Drive Beam Accelerating Structure



SICA (Slotted Iris-Constant Aperture) principle like CTF3

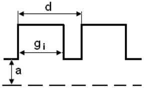
- P_{RF} = 15 MW
- Cell number = 19 Cell
- Total length = 2.4 m (including coupler & connectors)
- RBP = 49 mm
- Cell length = 99.979 mm
- Gap length = 40-80 mm
- Gradient = 3.4 MV/ per structure
- Efficiency = > 95 %



R. Wegler

Wakes of the Structure

Short range wake fields (Karl Bane)



$$Z_0 = 120\pi\Omega$$

$$s_{\|0,i} = 0.41\,\frac{a^{0.18} g_i^{1.6}}{d^{2.5}}$$

$$s_{\perp 0,i} = 1.69\,\frac{a^{1.79} g_i^{0.38}}{d^{1.17}}$$

$$s_{\|0,av} = \frac{1}{n}\sum_{i=1}^{n} s_{\|0,i}, \quad s_{\perp 0,av} = \frac{1}{n}\sum_{i=1}^{n} s_{\perp 0,i}$$

$$W_{\|}(s) = \frac{4Z_0 c}{\pi a^2}\exp\left(-\sqrt{\frac{s}{s_{\|0,av}}}\right)$$

$$W_{\perp}(s) = \frac{4Z_0 c s_{\perp 0,av}}{\pi a^4}\left[1 - \left(1 + \sqrt{\frac{s}{s_{\perp 0,av}}}\right) e^{-\sqrt{\frac{s}{s_{\perp 0,av}}}}\right]$$

Long range wake fields

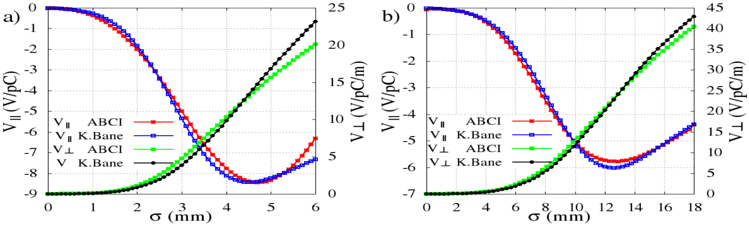
HOM's of CTF3 given in design report are scaled for 1 GHz structure

- **f:** frequency of mode
- **K:** kick factor of mode
- **Q:** Damping term of mode

$$\mathbf{f'} = \mathbf{f}\tfrac{1}{3}, \quad \mathbf{K'} = \mathbf{K}(\tfrac{1}{3})^3, \quad \mathbf{Q'} = \mathbf{Q}$$

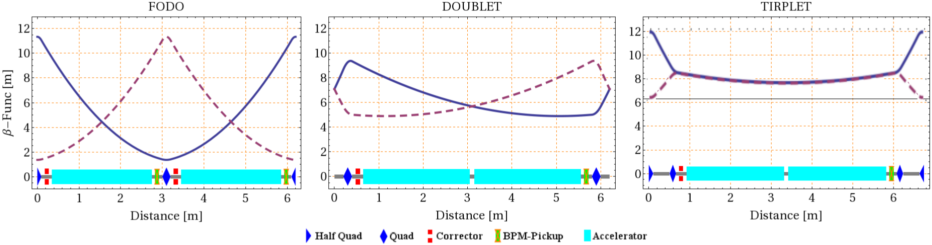
f [GHz]	Q	K [V/pC/m$_2$]
1.37	8.74	16.86
1.45	8.11	24.48
1.73	71.55	6.31
...	...	...

No long range longitudinal wake field (perfect beam loading)



Studied Lattices

$$\left.\begin{array}{l}\Delta x \propto \int \frac{\beta(s)}{E(s)} ds \\ \Delta x' \propto \int \frac{\beta(s)}{E(s)} ds\end{array}\right\} \Rightarrow$$ Minimum deflection of particles from their ideal path requires small betatron oscillations



FODO

Total length 6.2 m
Quad length 0.2 m
Quad strength 2.6 m^{-2}

DOUBLET

Total length 6.2 m
Quad length 0.2 m
Quad strength 2.86 m^{-2}

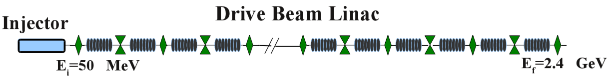
TRIPLET

Total length 6.74 m
Quad length 0.22;0.16 m
Quad strength 2.86;-2.0m^{-2}

$$\begin{array}{llll}
\text{FODO} & : \beta_x = \beta_y = 4.44\text{m}, & \alpha_x = -\alpha_y = 1.66, & \mu_{x,y} = 103^\circ \\
\text{Doublet} & : \beta_x = \beta_y = 5.69\text{m}, & \alpha_x = -\alpha_y = 0.40, & \mu_{x,y} = 58^\circ \\
\text{Triplet} & : \beta_x \approx \beta_y \approx 7.64\text{m}, & \alpha_x \approx \alpha_y \approx 0.001, & \mu_x = 46^\circ, \; \mu_x = 49^\circ
\end{array}$$

Work flow

1



- optimizing lattice
- optimizing structure

Work flow

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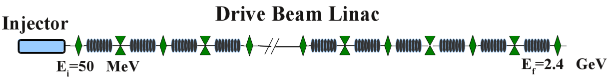
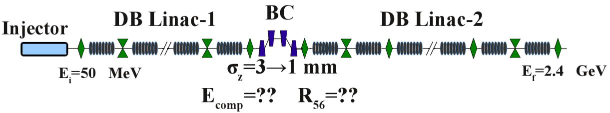


- optimizing lattice
- optimizing structure

2



- Finding compression energy, optimizing RF phase
- optimizing compressor

Work flow

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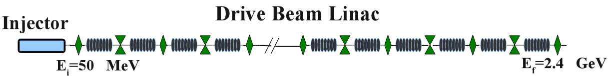
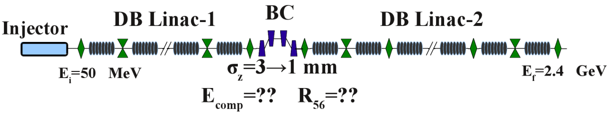


- optimizing lattice
- optimizing structure

2



- Finding compression energy, optimizing RF phase
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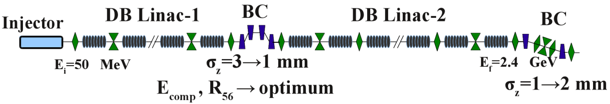
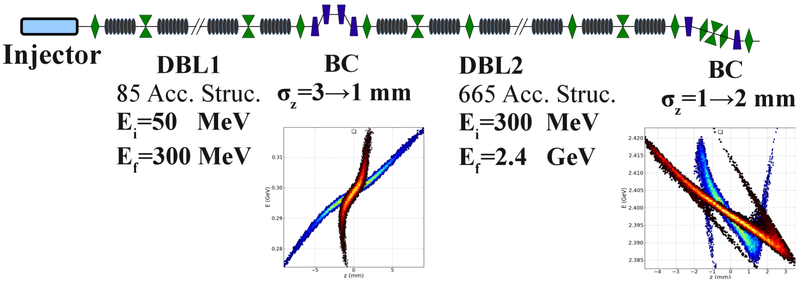
3



- optimizing lattice again
- optimizing bunch de-compressor and RF_{DBL2} phase
- . . .

Sketch of Drive Beam Linac



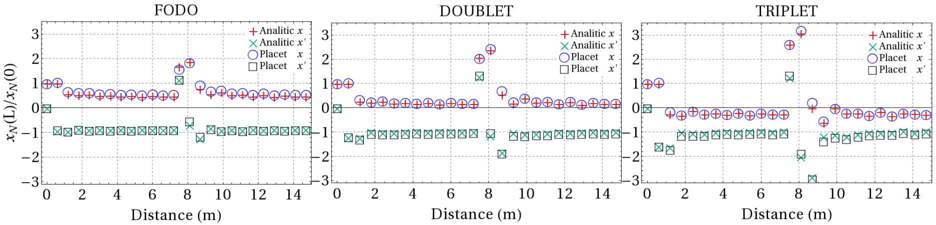
DBL-1

- Beam Energy 50-300 MeV
- No of Structure ∼ 85
- Rf Phase 20-27.5 deg

DBL-2

- Beam Energy 0.3-2.4 GeV
- No of Structure 665
- Rf Phase 18 deg

Long range wake effects (point like bunches)



$$\begin{pmatrix} x_N(s) \\ x'_N(s) \end{pmatrix} = \sqrt{\frac{\gamma(s)}{\beta_x(s)}} \begin{pmatrix} 1 & 0 \\ \alpha_x(s) & \beta_x(s) \end{pmatrix} \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix}$$

Plots shows normalized amplitudes of point like bunches of two sub-train at the end of the linac.

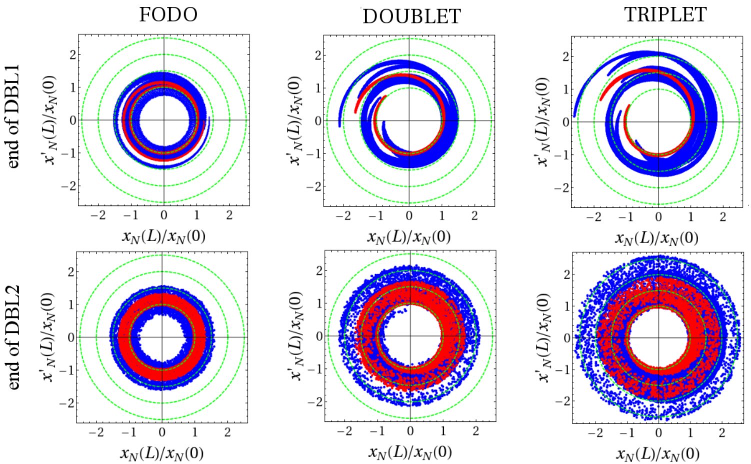
Each sub-train have 15 bunches and all bunches has same initial offset

The amplification of bunches of a single sub-train reaches steady state rapidly within this sub-train length.

Since the distance between bunches at switching point from odd buckets to even (or v.v.) is half of the others, the amplification at that point is slightly high due to strong kick caused by closer bunches.

FODO lattice compensates transverse deflections and worst one occurs on triplet.

Short Range wake effects



Plots show normalized amplifications of bunches of two sub-train at the end of DBL1 and DBL2. Each train consist of 15 bucn and each bunch has same initial offset (red points first bunch, blue points trailing bunches)

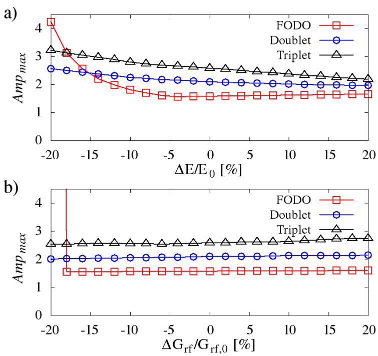
The long range kicks are dumped due to energy spread within each individual bunches

At FODO lattice amplification is acceptable. Triplet lattice is worse one

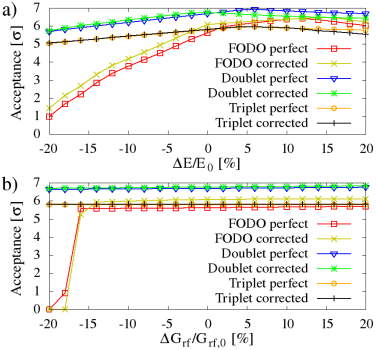
Energy and gradient acceptance of lattices

Variations of incoming beam energy or the gradient of structures will lead quadrupole strengths not to be adapted to the beam energy.

It can cause beam amplification to grow, and/or beam losses especially in DBL1 where the beam energy is low.



Beam amplification in DBL1, a) for different initial beam energy, b) for different accelerating gradient

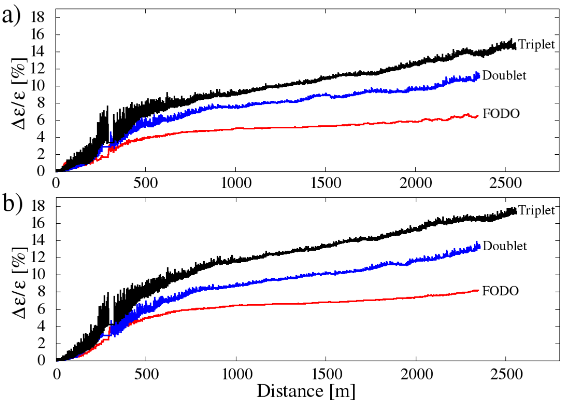


Acceptance of the lattices for $R_{beam\ pipe} = 20$mm, a) for different initial beam energy, b) for different accelerating gradient

Doublet lattice is less sensitive to the variations of beam energy and structure strengths. FODO lattice is worst one.

However still FODO lattice can be chosen since DBL requires small energy and gradient errors.

Emittance Growth



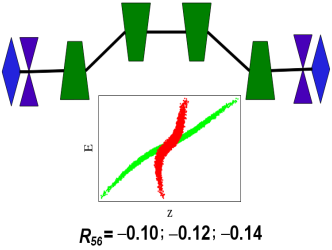
Emittance growth along the beamline. a)wakefield-free steering, b) one-to-one correction

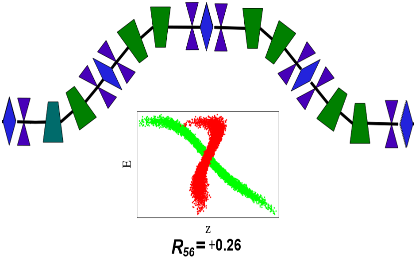
Plot shows the emittance growth along the beamline consisting of DBA1 and DBA2.
FODO and triplet lattice type emittance growth is quite small while for doublet it is above 10%.

- **Quadrupoles**
  - $\sigma_{x,y} = 300\ \mu$m position errors
  - $\sigma_{x',y'} = 300\ \mu$rad angle errors
  - $\sigma_\theta = 1$ mrad roll errors
- **Structures**
  - $\sigma_{x,y} = 300\ \mu$m position errors
  - no angle errors
  - no tilting effect
- **BPMs**
  - $\sigma_{x,y} = 300\ \mu$m position errors
  - no angle errors
  - resolution 10 μm
- the beamline on bunch compression section is perfectly aligned
- the beam is injected without any offset to DBL1 and DBL2
- test beams used for wakefield-free steering
  $E_{in,1} = 40$ MeV and $E_{in,2} = 60$ MeV initial energies
  $Q_1 = 9$ nC and $Q_2 = 8$ nC bunch charges
  $V_1 = 0.93V_0$ and $V_2 = 1.05V_0$ accelerating gradients

Studied bunch compressors

Four different bunch compressor has been taken into account



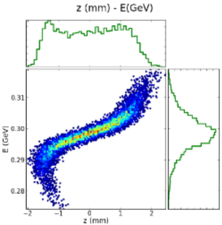


- Bunch compressor is located at 300 MeV for both type
- For chicane phase of Rf of DBL1 = 23 ; 27.5 degree
- For arc phase of Rf of DBL1 = – 7.5 degree
- For all bunch compressors only single bunch case has been computed
- CSR effect and imperfections have not been included. First order tracking code has been used..

Phase Spaces at the end of compressor and DB Linac-2

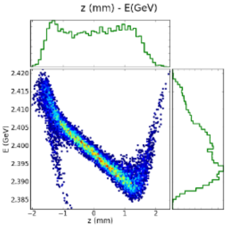
$R_{56} = -10$cm

End of bunch compressor



σ_{zrms}	=	1.00	(mm)
ϵ_{xrms}	=	49.0	(μm.rad)
ϵ_{yrms}	=	50.4	(μm.rad)
ϵ_{zrms}	=	2.59	(MeV.mm)
$<E>$	=	298.7	(MeV)
$\Delta E/E$	=	2.06	(%)
ΔE	=	45.0	(MeV)
$<\Delta E>$	=	6.16	(MeV)

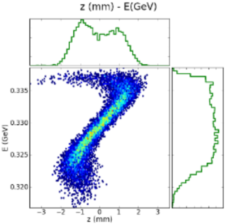
End of DBL2



σ_{zrms}	=	1.00	(mm)
ϵ_{xrms}	=	49.3	(μm.rad)
ϵ_{yrms}	=	50.3	(μm.rad)
ϵ_{zrms}	=	3.78	(MeV.mm)
$<E>$	=	2399.	(MeV)
$\Delta E/E$	=	0.313	(%)
ΔE	=	38.8	(MeV)
$<\Delta E>$	=	7.50	(MeV)

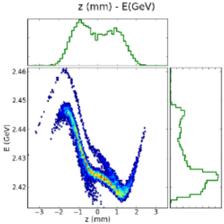
$R_{56} = +26$cm

End of bunch compressor



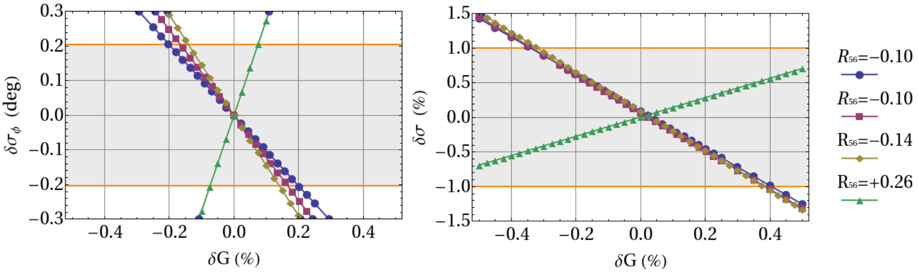
σ_{zrms}	=	1.00	(mm)
ϵ_{xrms}	=	49.0	(μm.rad)
ϵ_{yrms}	=	50.3	(μm.rad)
ϵ_{zrms}	=	2.66	(MeV.mm)
$<E>$	=	329.3	(MeV)
$\Delta E/E$	=	1.42	(%)
ΔE	=	21.8	(MeV)
$<\Delta E>$	=	4.67	(MeV)

End of DBL2



σ_{zrms}	=	1.00	(mm)
ϵ_{xrms}	=	49.0	(μm.rad)
ϵ_{yrms}	=	50.2	(μm.rad)
ϵ_{zrms}	=	4.79	(MeV.mm)
$<E>$	=	2428.	(MeV)
$\Delta E/E$	=	0.374	(%)
ΔE	=	48.5	(MeV)
$<\Delta E>$	=	9.09	(MeV)

RF Gradient Tolerance

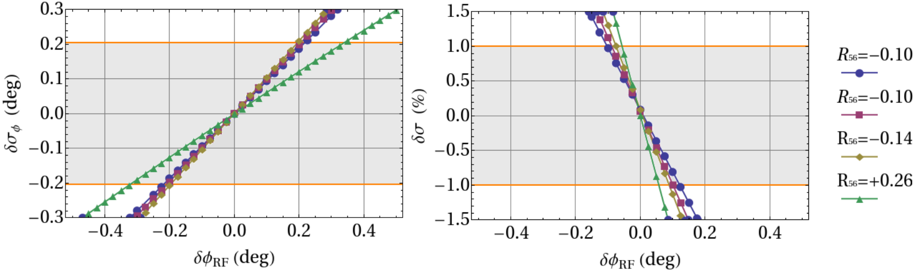


The RF amplitude tolerance is limited by the phase error of the bunches, the length variations are small

The amplitude tolerance of the effective gradient is 0.2%

- for the accelerating power amplitude the tolerance is 0.1% → it will be 0.2% for the klystron power
- for beam current it is 0.2%

RF Phase Tolerance

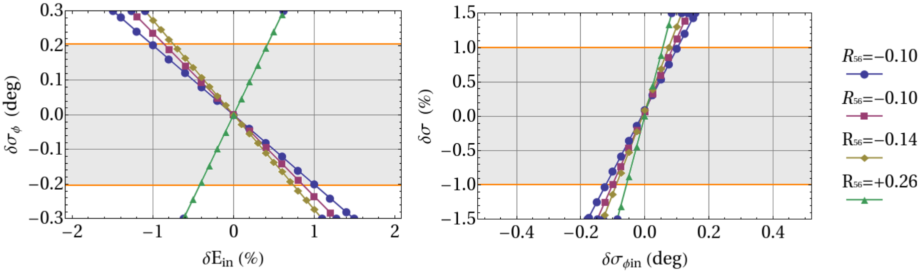


The phase tolerance is limited by the bunch length variation. Largest tolerance is given with $R_{56} = -0.1$

The phase tolerance for the effective gradient is 0.1°

- for klystron phase it is 0.05°
- for the beam phase it is 0.1°

Incoming bunch energy and phase tolerance



incomin energy tolerance is limited by phase error,

incoming phase tolerance is limited by bunch length variation

The incoming energy tolerance is 1%

Incoming energy 50 MeV $\rightarrow$ 0.5MeV $\approx$ 0.2% gradient tolerance over 85 structure

Incoming phase tolerance is 0.1°

It is identical to the phase tolerance of the effective gradient

Conclusion

- Three type of lattices has been studied
  - FODO lattice yields best results in terms of transverse wakefield effect and the triplet is worst
  - although FODO and doublet has same number of quadrupoles FODO gives smallest emittance growth
  - Additionally FODO type of lattice has low cost easy operation feature..
  - Doublet type has smallest sensitivity to energy errors FODO has largest. Nevertheless, too large errors should not be important because of the tight tolerance of energy error in bunch compressor.
  - In order to have weaker lattice one can use two accelerating structure per half FODO cell after 1.5 GeV. That wouldn't change wakefield effects much since integration along beamline will not change much.
- Four type of bunch compressor have been studied
- The bunch compressor section has been simulated with neglecting the impact of imperfections. Also coherent synchrotron radiation has not been included.
- Although arc compressor is better about saving RF power (about 10 structure), larger tolerances are achieved with chicane that has $R_{56} = -0.1\text{m}$.
- Computed longitudinal tolerances can be summarized as

RF power error	(%)	0.2
Beam current error	(%)	0.2
RF phase error	(deg)	0.05
Incoming beam phase error	(deg)	0.1

- Obviously these tolerances can be tighter for multibunch beam loading case since there can exist bunch-to-bunch energy spread and phase shift.

Thank you

Special thanks to Daniel Schulte …