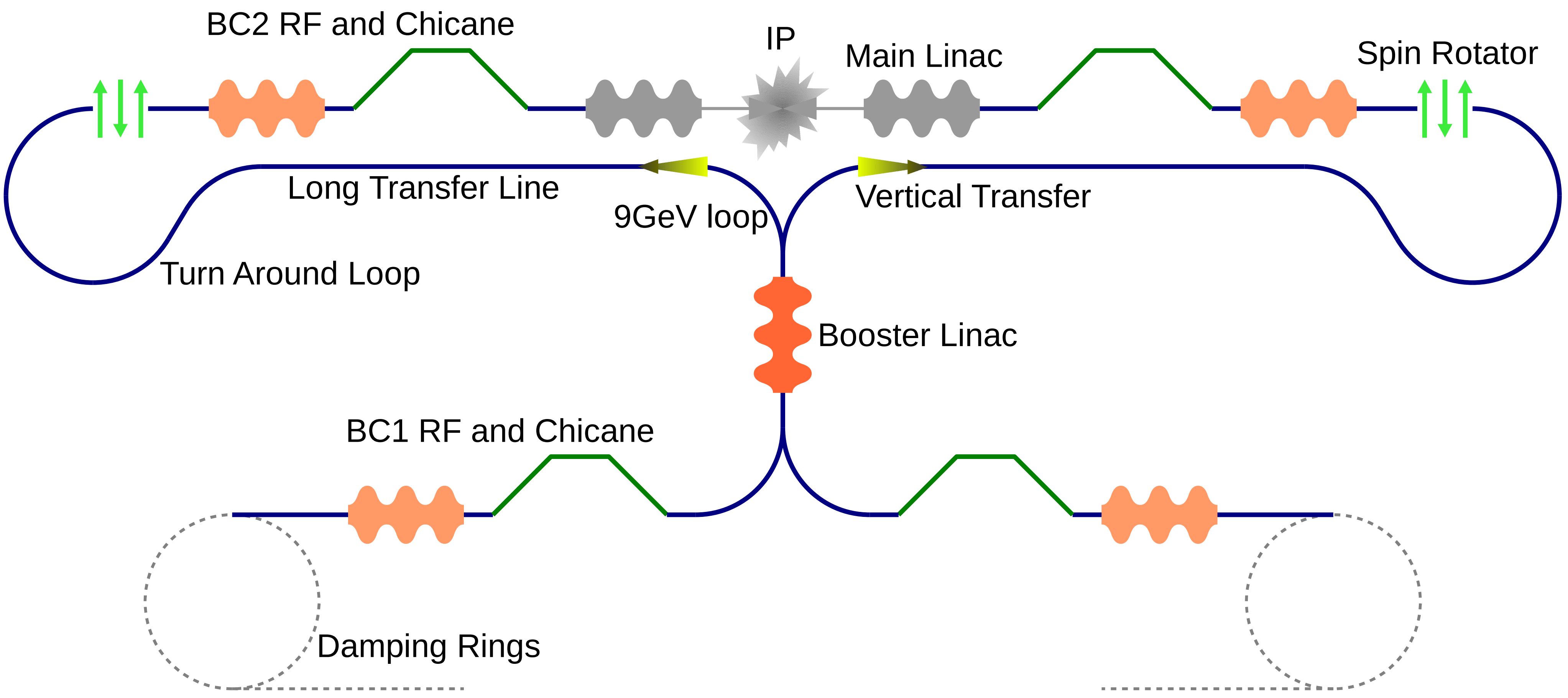
Update on the RTML

for an introduction to the RTML please see last years talks

- Overview
- Update on
  - General layout and parameters
  - Beam dynamics simulations
  - Bunch compression system
  - Booster linac
  - Long transfer line
  - Magnetic stray fields in the long transfer line
  - Turn around loop
  - Misalignment studies
  - Phase stabilization
- Other Work in Progress

Overview / Functional Layout



not shown: Diagnostics, Collimation, Dispersion Correction, Coupling Correction, Spectrometers and Dumps

General Layout / Parameters

- The general layout is unchanged.
- But in view of the CDR some open points have been decided:
  - The spin rotator will be behind the turn around loop.
  - The vertical transfer will not be included in the horizontal 9 GeV loop.
  - The lattices should be suitable for CLIC3TeV and CLIC500 parameters (e.g. double charge).
- Nominal parameters have been slightly updated:

Property	Symbol	Value	Unit
Particle energy	E_0	2.86	GeV
Bunch charge	Q_0	0.65	nC
RMS bunch length	σ_s	1400	µm
RMS energy spread	σ_E / E_0	0.1	%
Normalized emittance	$\varepsilon_{n,x}$	500	nm rad
	$\varepsilon_{n,y}$	5	nm rad

@ exit of damping rings

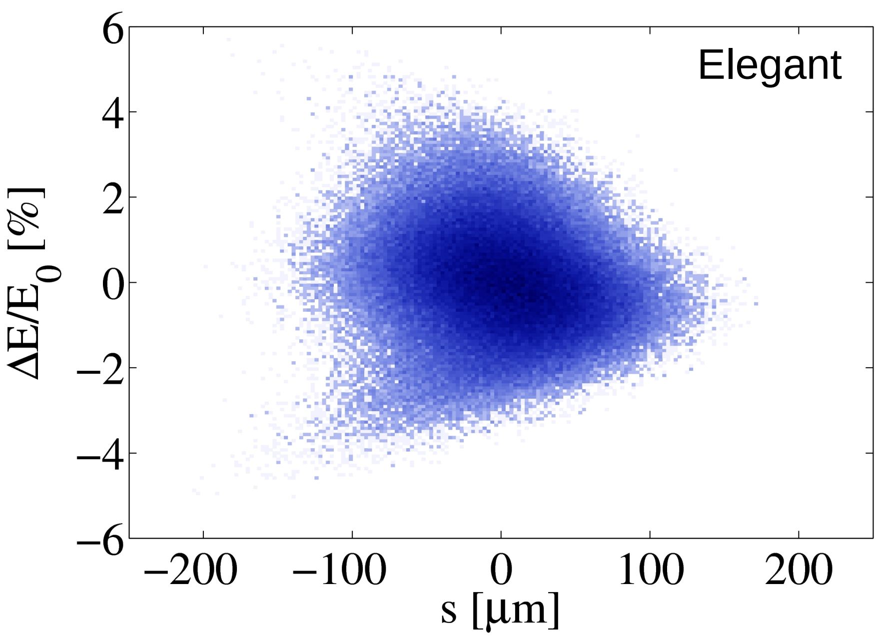
Property	Symbol	Value	Unit
Particle energy	E_0	8 (9?)	GeV
Bunch charge	Q_0	> 0.6	nC
RMS bunch length	σ_s	44	µm
RMS energy spread	σ_E / E_0	< 1.5	%
Normalized emittance	$\varepsilon_{n,x}$	< 600	nm rad
	$\varepsilon_{n,y}$	< 10	nm rad

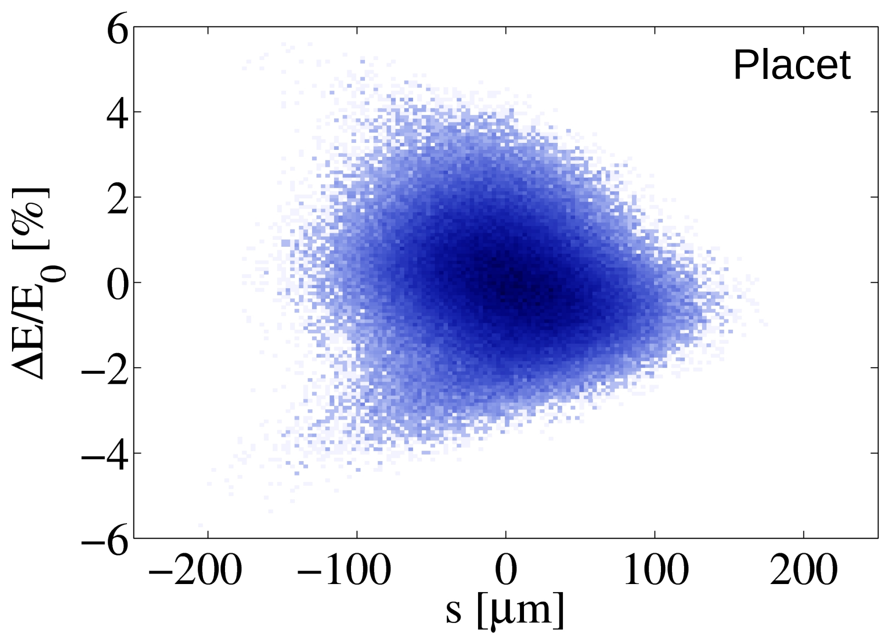
@ entrance of main linac

Tolerances (static and dynamic) need further discussions.

Beam Dynamics Simulations

- Lattice files have been created for the codes ELEGANT and PLACET.
- The sub-systems have been connected by simplified optics matching sections.
- Simulations of the full RTML, i.e. BC1, booster linac, long transfer line, turn around loop and BC2, including incoherent synchrotron radiation (ISR) and short range cavity wake fields have been performed. Later some CSR simulations were done (ELEGANT only).
- The agreement in the longitudinal plane is very good. In the horizontal plane the emittance growth is $\Delta\varepsilon_{n,x}$=44 nm rad for ELEGANT and $\Delta\varepsilon_{n,x}$=57 nm rad for PLACET. This difference seems to be due to differences in the application of wake fields.

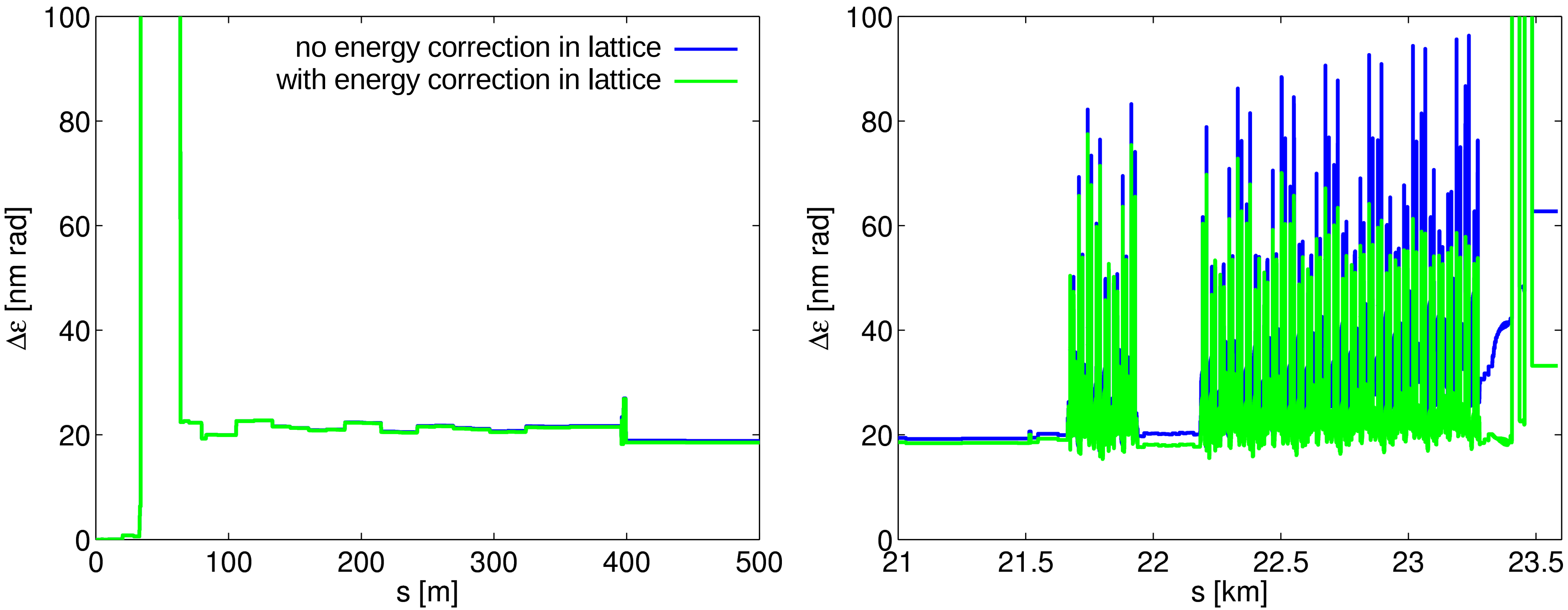




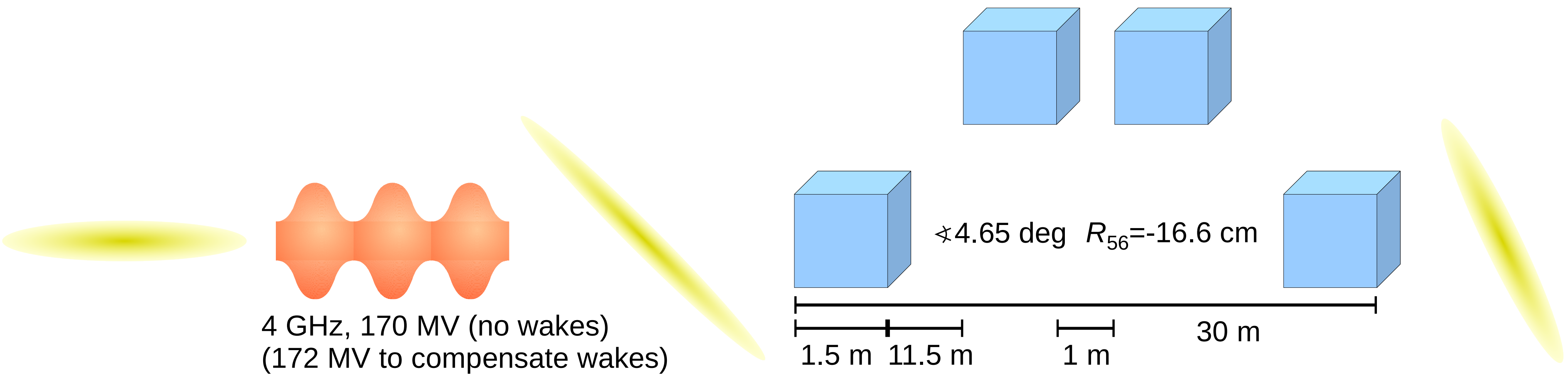
Beam Dynamics Simulations

- First simulations showed that CSR along RTML and wake fields in BC2 RF are too strong.
- To improve, the compression has been reduced in BC1 from 175µm to 300µm and the BC2 chicane has been split in two parts.
- The emittance growth induced by ISR, CSR and wakes is reduce by a factor of two and is now $\Delta\varepsilon_{n,x}$<100 nm rad.

CSR induced emittance growth $\Delta\varepsilon_{n,x}$ along RTML:



Bunch Compressor 1



E_0	2.86	GeV
σ_s	1400	µm
$\sigma_{E,unc}/E_0$	0.1	%
$1/E_0\ dE/ds$	0	1/m
$\sigma_{E,tot}/E_0$	0.1	%

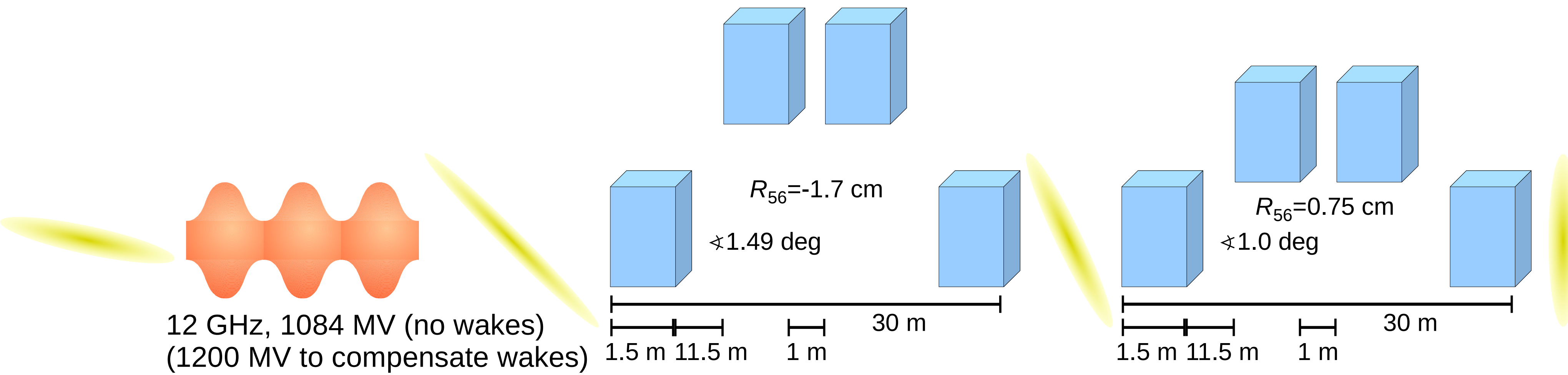
E_0	2.86	GeV
σ_s	1400	µm
$\sigma_{E,unc}/E_0$	0.1	%
$1/E_0\ dE/ds$	-4.95	1/m
$\sigma_{E,tot}/E_0$	0.7	%

E_0	2.86	GeV
σ_s	300	µm
$\sigma_{E,unc}/E_0$	0.47	%
$1/E_0\ dE/ds$	-17.4	1/m
$\sigma_{E,tot}/E_0$	0.7	%

To improve performance of BC1:

- ➔ less bunch compression (reduces CSR in all beam lines up to BC2)
- ➔ larger than necessary energy chirp (under-compression), i.e. less R_{56} => less CSR (the induced chirp would allow a compression to 200 µm)

Bunch Compressor 2



E_0	8	GeV
σ_s	300	µm
$\sigma_{E,unc}/E_0$	0.17	%
$1/E_0\ dE/ds$	-6.22	1/m
$\sigma_{E,tot}/E_0$	0.25	%

E_0	8	GeV
σ_s	300	µm
$\sigma_{E,unc}/E_0$	0.17	%
$1/E_0\ dE/ds$	-37.5	1/m
$\sigma_{E,tot}/E_0$	1.14	%

E_0	8	GeV
σ_s	100	µm
$\sigma_{E,unc}/E_0$	0.5	%
$1/E_0\ dE/ds$	-102	1/m
$\sigma_{E,tot}/E_0$	1.14	%

E_0	8	GeV
σ_s	44	µm
$\sigma_{E,unc}/E_0$	1.14	%
$1/E_0\ dE/ds$	0	1/m
$\sigma_{E,tot}/E_0$	1.14	%

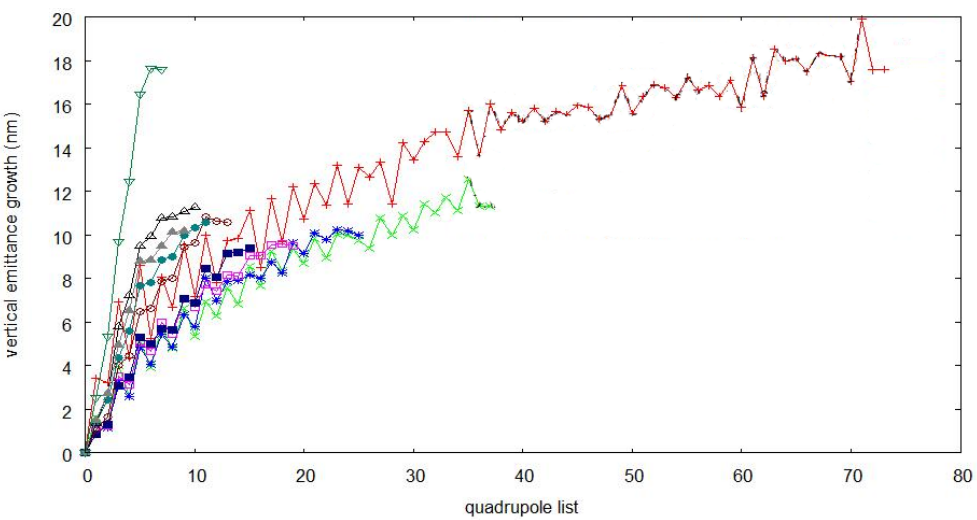
To improve performance of BC2:

- ➔ utilize double chicane
- ➔ reduce bend angles where bunches are shortest, i.e. less CSR
- ➔ gain a lot flexibility to adapt to different parameter sets
- ➔ due to longer initial bunches less RF required, i.e. less wake fields

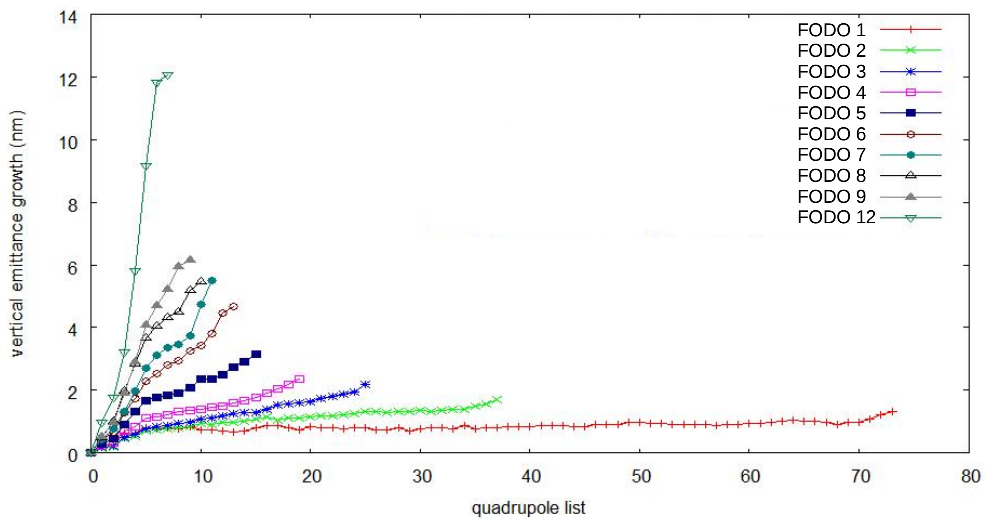
Booster Linac

by D. Wang (IHEP, Beijing)

- Optimized lattice with respect to single-bunch wake fields and misalignment tolerances.
- Compared different lattices (FODO and Triplet focusing) using different number of cavities per cell.
- 3-4 cavities of 3 m length per quadrupole in a FODO lattice seems to be a good compromise, $\Delta\varepsilon_{n,y}$=2 nm rad after orbit correction (dispersion free or wakefield free steering), sensitivity on misalignment of quadrupoles and cavities and BPM errors is rather relaxed.
- Multi-bunch wakes have been analytically estimated. They might become a challenge.



before orbit correction



after orbit correction

(Plots taken from EUROTeV-Report-2008-092)

Long Transfer Line

by B. Jeanneret (CERN)

- "Just" a simple FODO lattice. But due to its length (21 km) it has its own challenges.
- $k_1 < 0.01$ m^{-2} to reduce chromatic dilutions, huge average beta function > 600 m.
- Resistive wall wake fields and fast beam ion instability have to be taken into account.
- To mitigate resistive wall wake fields a large beam pipe of 10 cm diameter is being used.
- To mitigate fast beam ion instability the vacuum must be better than 0.1 nTorr (G. Rumolo).
- Emittace dilution and beam mis-steering due to magnetic stray fields are a huge issue.

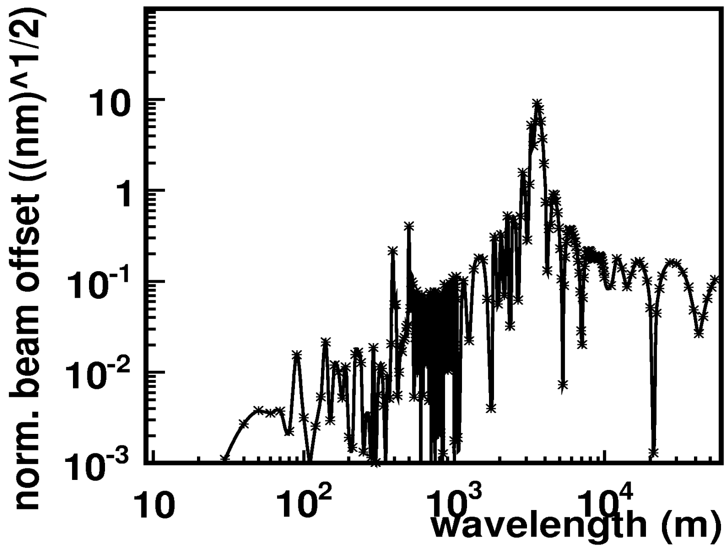
Magnetic Stray Fields

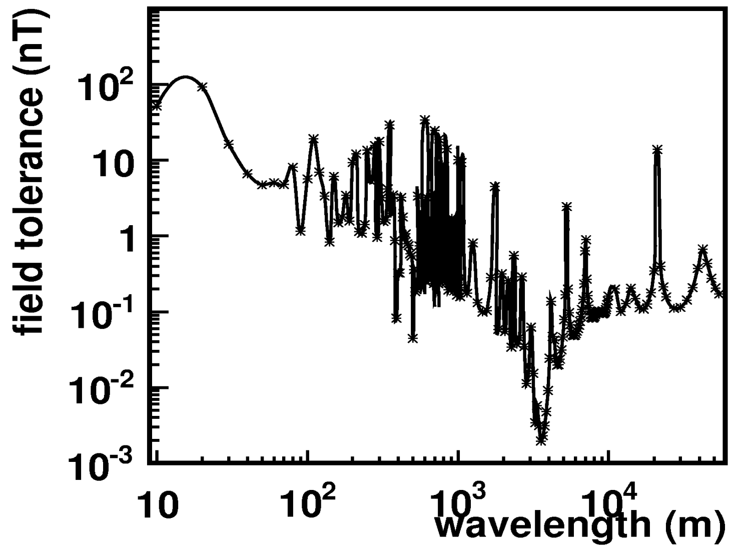
by J. Snuverink (CERN)

- Time varying, periodic stray fields are expected to be a major challenge.
- Purely random stray field should be a lot less important.
- Resonant behavior is expected at the wave length of the betatron oszillation.
- First simulations show exactly this behavior
  but also some more complex structure which at least agrees with analytical estimations.
- There is a quite strong dependence on simulation setup,
  i.e. periodic or random fields in vertical plane only or in both planes.
- We will have to continue and simulate many different cases,
  i.e. periodic, random, periodic only over a certain length, in vertical plane only,
  in horizontal plane only, both planes, different strengths,...

Magnetic Stray Fields

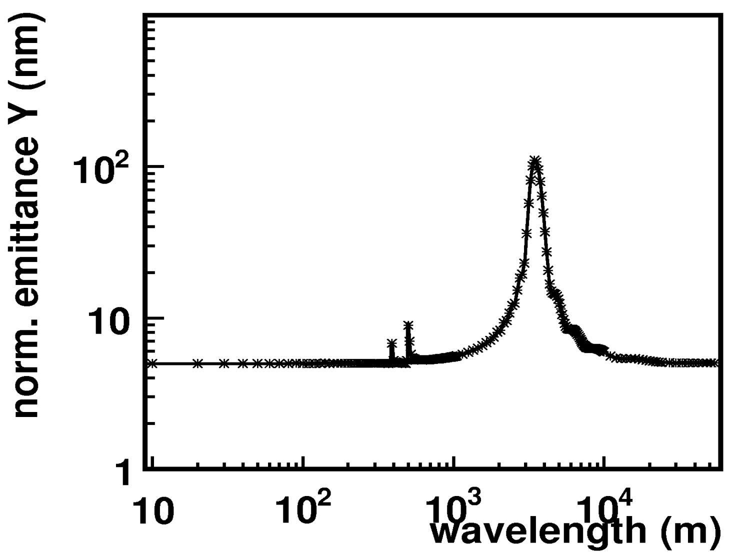
by J. Snuverink (CERN)

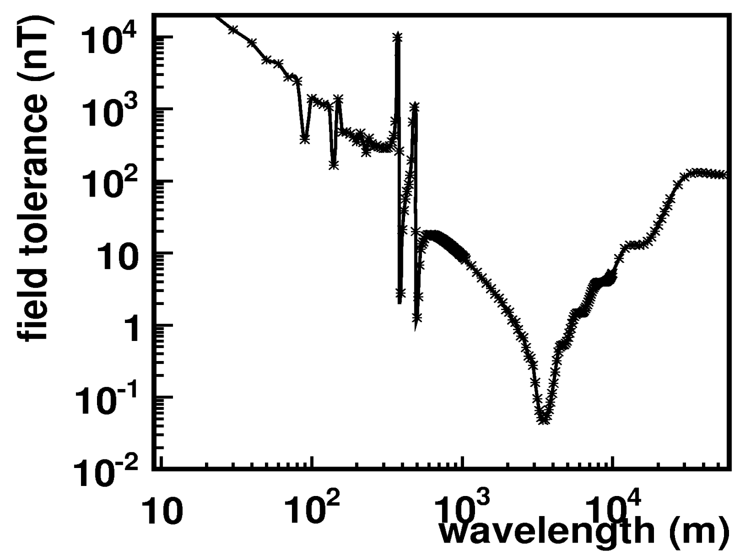




The peak corresponds to an offset of the order of millimeters.

Due to coupling also the emittance grows when horizontal and vertical fields are simulated.

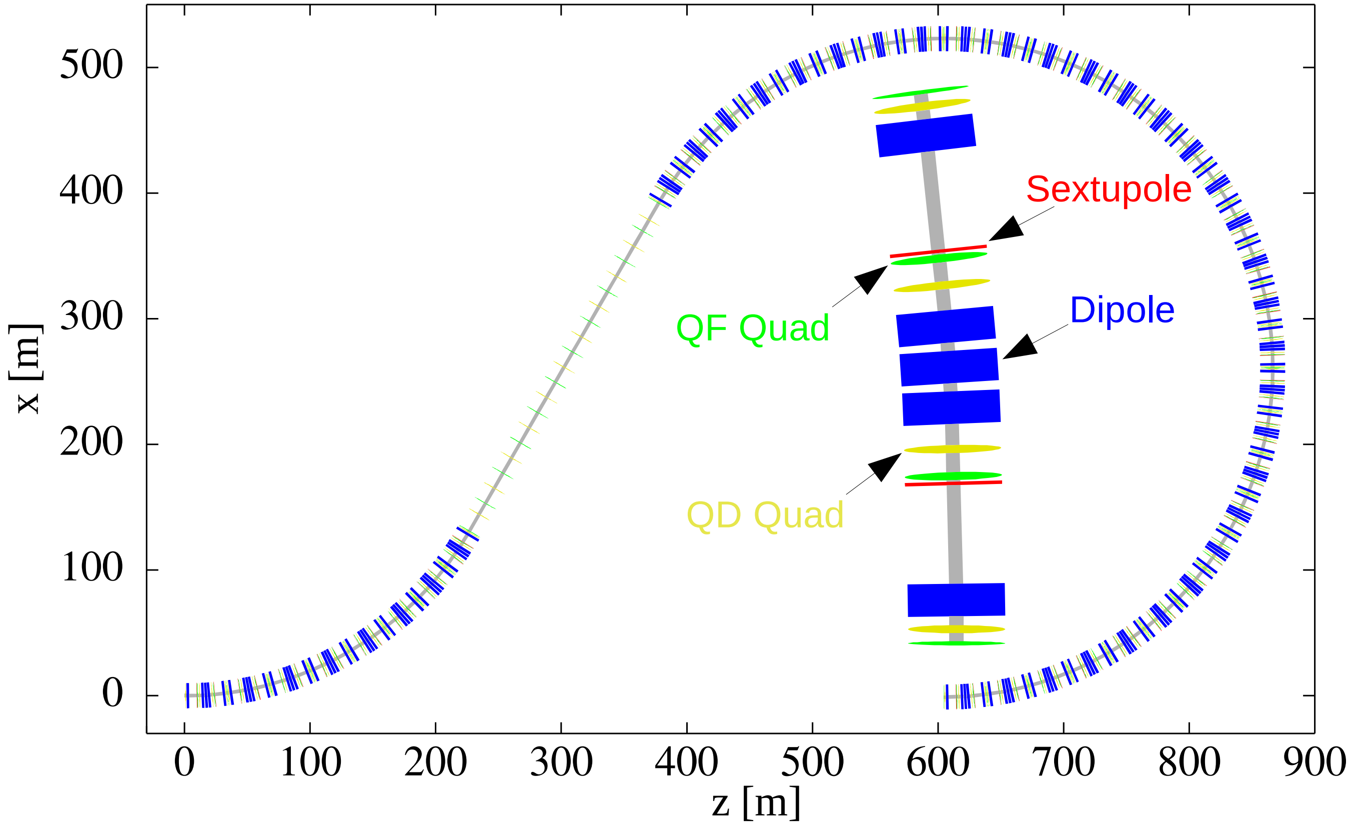




Tomorrow C. Jach will present an engineers view on this topic: “Magnetic Background Issues above 1Hz for CLIC beams”

Turn Around Loop

- Performance was already not really good and got worse with new parameters and in start-to-end simulations.
- Revised lattice to improve performance, to meet CLIC500 specifications and to lower quadrupole and sextupole gradients.
- Unfortunately, length increased to almost 1700 m.
- ISR emittance growth remained unchanged, ~30 nm rad @ 8 GeV, ~60 nm rad @ 9 GeV.
- It seems this lattice is good as a proof of principle, but not really optimum.



Misalignment Studies

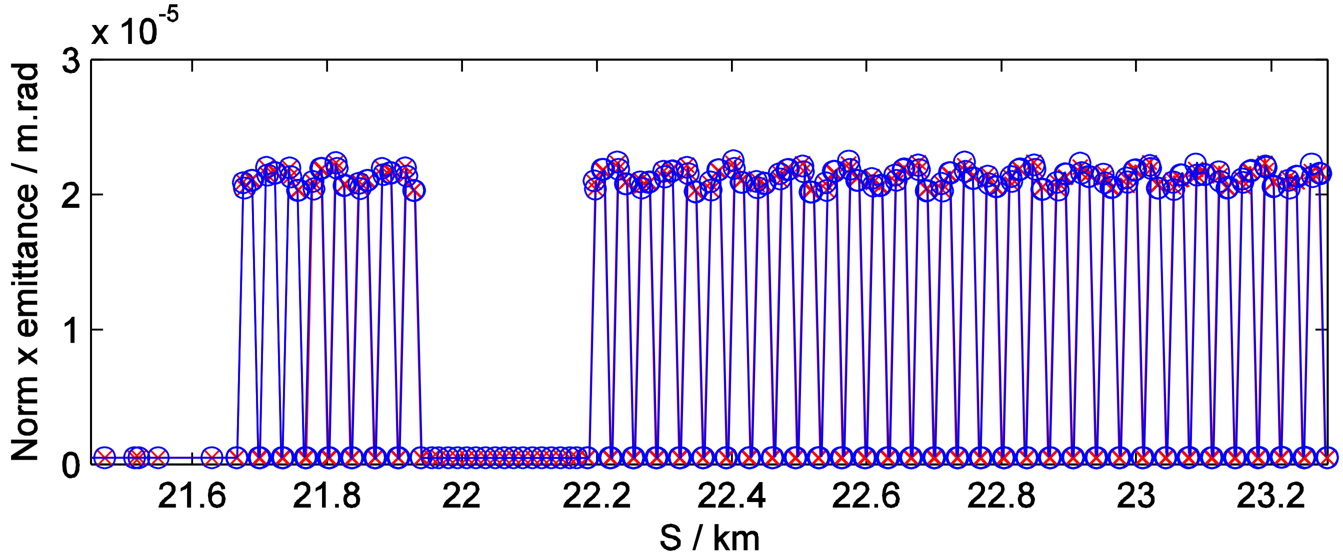
by S. Molloy (RHUL)

- Simulations done with the code LUCRETIA.
  Lattice translated partly manually and partly automatic from ELEGANT lattice.
- Random quadrupole misalignment in all 6 dimensions by 10 µm or 10 µrad rms.
- BPMs with perfect resolution and perfect alignment to quadrupole center.
- Steered beam to zero the BPM readings (matrix inversion).
- Main challenge is the turn around loop.
- Very preliminary and BPMs too idealized!

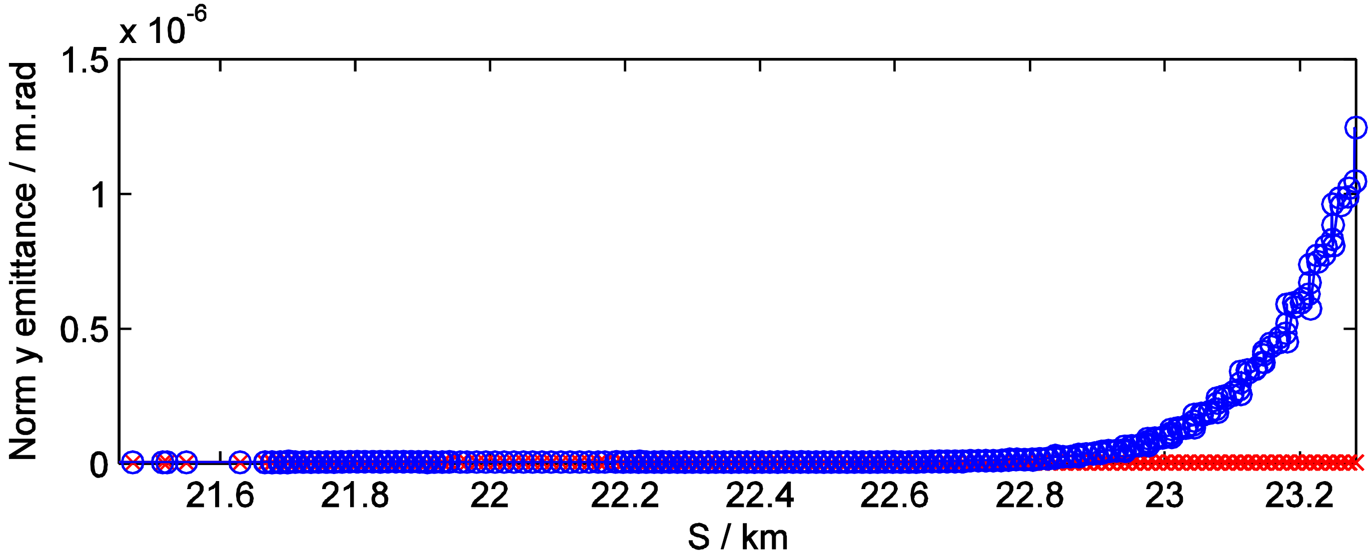
Misalignment Studies

by S. Molloy (RHUL)

Horizontal



Vertical

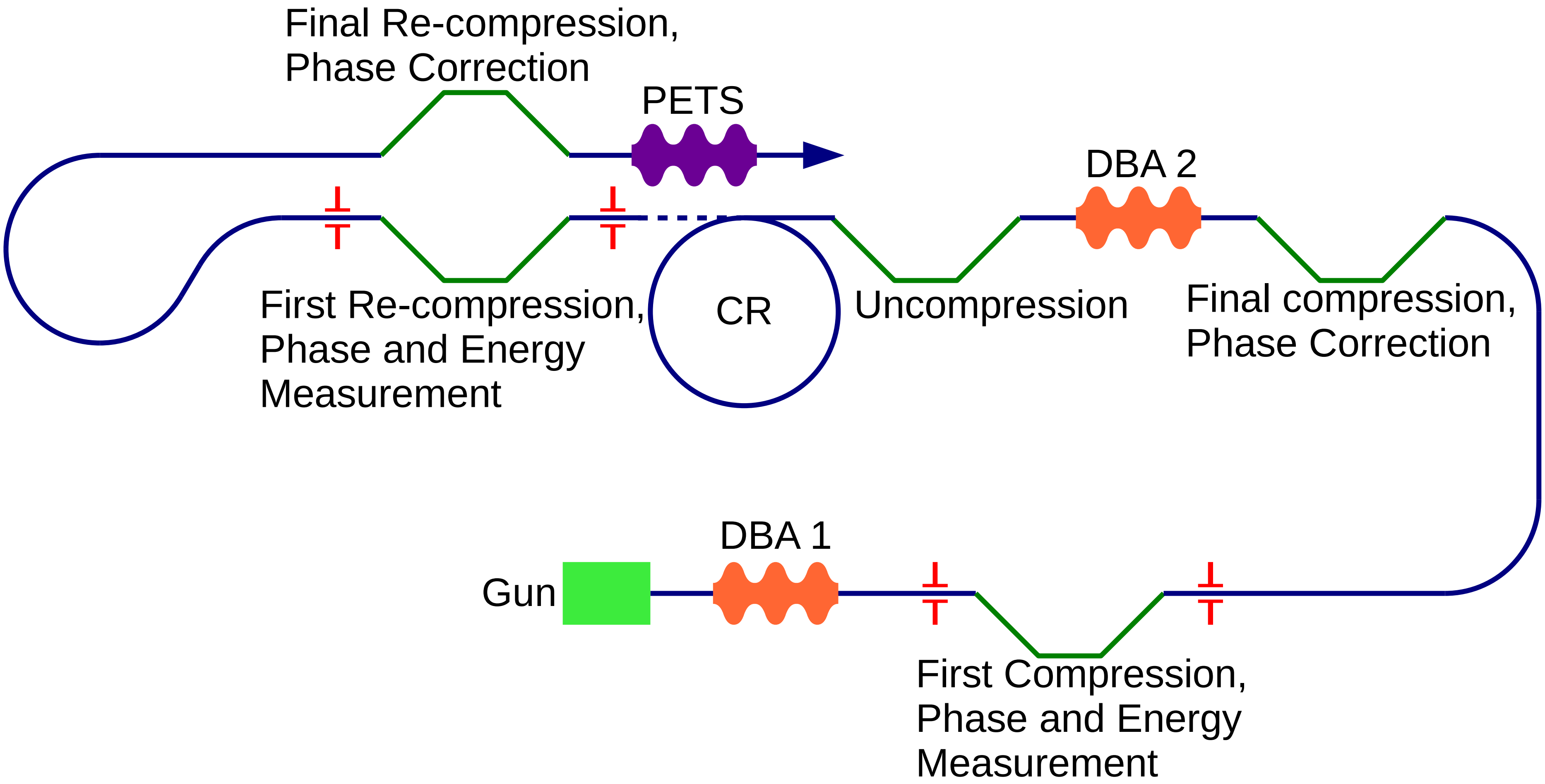


Phase Stabilization

- In the current RTML layout $R_{56,BC2}$ = 2.5 cm. Requiring a phase stability in front of the main linac of $\Delta\varphi$ < 0.1 deg (= Δl < 7 µm) means the energy stability after the booster linac must be $\Delta E/E_0 < \Delta l \,/\, R_{56,BC2} = 3 \times 10^{-4}$ in case there is no phase feed-forward.
- To mitigate this very tight requirement we can build in a feed-forward system.
- Or can we prevent energy jitter from converting into phase jitter, e.g. by clever beam line design?
- Such a beam line would require R_{56} = 0 but still has to compress the bunches.

Phase Stabilization

- For the second stage of the drive beam feedforward we foresee a scheme with R_{56} = 0 but no compression of the bunches.



Phase Stabilization

In general: $$\begin{pmatrix} s_f \\ \frac{\Delta p_f}{p_0} \end{pmatrix} = M \begin{pmatrix} s_i \\ \frac{\Delta p_i}{p_0} \end{pmatrix} \qquad M = \begin{pmatrix} R_{55} & R_{56} \\ R_{65} & R_{66} \end{pmatrix}$$

$$\sigma_{sf} = \sqrt{\sigma_{si}^2 R_{55}^2 + \frac{\sigma_{pi}^2}{p_0^2} R_{56}^2} \qquad < s_f > = R_{55} < s_i > + R_{56} < \frac{\Delta p_i}{p_0} >$$

$$\frac{\sigma_{pf}}{p_0} = \sqrt{\sigma_{si}^2 R_{65}^2 + \frac{\sigma_{pi}^2}{p_0^2} R_{66}^2} \qquad < \frac{\Delta p_f}{p_0} > = R_{65} < s_i > + R_{66} < \frac{\Delta p_i}{p_0} >$$

Longitudinal Transfer Matrix

To mimic part of the RTML we need four matrices:

BC2 chicane (M_4), BC2 RF (M_3), Turn Around Loop (M_2),
some RF to add a variable momentum chirp to the incoming beam (M_1)

$$M_4 = \begin{pmatrix} 1 & -R_{56,2} \\ 0 & 1 \end{pmatrix} \qquad M_3 = \begin{pmatrix} 1 & 0 \\ u_2 & 1 \end{pmatrix} \qquad M_2 = \begin{pmatrix} 1 & -R_{56,1} \\ 0 & 1 \end{pmatrix} \qquad M_1 = \begin{pmatrix} 1 & 0 \\ u_1 & 1 \end{pmatrix}$$

$$M = M_4 M_3 M_2 M_1$$

$$M = \begin{pmatrix} 1 - u_1 R_{56,1} - u_2 R_{56,2} - u_1 R_{56,2} + u_1 u_2 R_{56,1} R_{56,2} & -R_{56,1} - R_{56,2} + u_2 R_{56,1} R_{56,2} \\ u_1 + u_2 - u_1 u_2 R_{56,1} & 1 - u_2 R_{56,1} \end{pmatrix}$$

u_1 = momentum chirp behind the booster linac
u_2 = additional momentum chirp induced in the BC2 RF
$R_{56,1}$ = momentum-compaction factor of the turn around loop
$R_{56,2}$ = momentum-compaction factor of the BC2 chicane

in general : $u = \frac{1}{p_0} \frac{dp}{ds}$

Decouple Momentum and Phase

We assume a correct phase at the entrance, i.e. $<s_i> = 0$.
We request $<s_f> = 0$ for any initial momentum offset:

$$<s_f> = R_{55} <s_i> + R_{56} <\frac{\Delta p_i}{p_0}> = 0 \qquad \forall <\frac{\Delta p_i}{p_0}> \in \mathbb{R}$$

$$\Rightarrow R_{56} = 0$$

$$\Rightarrow -R_{56,1} - R_{56,2} + u_2 R_{56,1} R_{56,2} = 0$$

$$\Leftrightarrow R_{56,1} = \frac{R_{56,2}}{u_2 R_{56,2} - 1}$$

$$\Rightarrow M = \begin{pmatrix} 1 - u_2 R_{56,2} & 0 \\ u_2 + \frac{u_1}{1 - u_2 R_{56,2}} & \frac{1}{1 - u_2 R_{56,2}} \end{pmatrix}$$

$$\Rightarrow \sigma_{sf} = \sigma_{si} (1 - u_2 R_{56,2}) \qquad u_2 = \frac{\sigma_{si} - \sigma_{sf}}{\sigma_{si} R_{56,2}} \qquad R_{56,1} = -R_{56,2} \frac{\sigma_{si}}{\sigma_{sf}}$$

Full Compression

We assume that the initial momentum spread is purely uncorrelated.
We request that the final momentum spread is purely uncorrelated:

$$\frac{\sigma_{pf}}{p_0} = \sqrt{u_f^2 \sigma_{sf}^2 + \frac{\sigma_{pfu}^2}{p_0^2}} = \frac{\sigma_{pfu}}{p_0}$$

$$\Rightarrow u_f = 0$$

Since longitudinal emittance must be preserved:

$$\sigma_{pf} \sigma_{sf} = \sigma_{pi} \sigma_{si}$$

$$\Leftrightarrow \frac{\sigma_{pf}^2}{p_0^2} \sigma_{sf}^2 = \frac{\sigma_{pi}^2}{p_0^2} \sigma_{si}^2$$

$$\Leftrightarrow \left(\sigma_{si}^2 R_{65}^2 + \frac{\sigma_{pi}^2}{p_0^2} R_{66}^2 \right) \sigma_{si}^2 R_{55}^2 = \frac{\sigma_{pi}^2}{p_0^2} \sigma_{si}^2$$

$$\Leftrightarrow \frac{\sigma_{pi}^2}{p_0^2} \sigma_{si}^2 \left(1 - R_{66}^2 R_{55}^2 \right) = \sigma_{si}^4 R_{55}^2 R_{65}^2$$

Note that $R_{55} = \frac{1}{R_{65}}$ (see previous slide)!

$$\Leftrightarrow R_{65} = 0$$

Full Compression

$$R_{65}=0$$

$$\Leftrightarrow 0=u_1+u_2-u_1 u_2 R_{56,1}$$

taken from original *M*

$$\Leftrightarrow 0=\frac{\sigma_{si}\sigma_{sf}-\sigma_{sf}^2+u_1\sigma_{si}^2 R_{56,2}}{\sigma_{si}\sigma_{sf}R_{56,2}}$$

plugged in what we know already

$$\Leftrightarrow 0=\sigma_{si}\sigma_{sf}-\sigma_{sf}^2+u_1\sigma_{si}^2 R_{56,2}$$

$$\Leftrightarrow R_{56,2}=\frac{\sigma_{sf}^2-\sigma_{si}\sigma_{sf}}{u_1\sigma_{si}^2}$$

$$\Rightarrow R_{56,1}=\frac{\sigma_{si}-\sigma_{sf}}{u_1\sigma_{si}}=-\frac{\sigma_{si}}{\sigma_{sf}}R_{56,2}$$

$$\Rightarrow u_2=-\frac{u_1\sigma_{si}}{\sigma_{sf}}$$

Since bunch lengths are given by specifications only a single free parameter is left over, here it is u_1!

$$\Rightarrow M=\begin{pmatrix}\frac{\sigma_{sf}}{\sigma_{si}} & 0 \\ 0 & \frac{\sigma_{si}}{\sigma_{sf}}\end{pmatrix}$$

not strictly isochronous since isochronicity requires R_{55} = 1 and R_{56} = 0 (see K. Brown: R_{51} = R_{52} = R_{56} = 0 and implicitly R_{55} = 1).

But often R_{55} is forgotten and only R_{51} = R_{52} = R_{56} = 0 is asked for...

Phase Stabilization

- The calculations have show that to first order one can decouple incoming energy jitter and outgoing phase while still achieving full bunch compression.
- The second stage of the drive beam feed-forward is a special case with no compression.
- Beam lines and bunch parameters have to fulfill strict requirements.
- There must exist a momentum chirp u_1 in front of the turn around loop. It has to have the opposite sign of $R_{56,2}$ of BC2.
- $R_{56,1}$ of the turn around loop must have the opposite sign of $R_{56,2}$.
- The additional momentum chirp u_2 induced in the BC2 RF must have the opposite sign of u_1.
- One solution would be:

  u_1 = 4.0 m^{-1}, u_2 = -27.3 m^{-1}, $R_{56,1}$ = 21.3 cm, $R_{56,2}$ = -3.13 cm

  These values could be achieved with proper lattice design. To get a positive u_1 either BC1 has to over-compress or the booster linac has to run off-crest.
- Simulations using the code ELEGANT show that non-linearities, i.e. RF curvature and higher-order transfer matrix elements, limit the applicability to 10^{-3} relative energy stability behind the booster linac.

Phase Stabilization

- Only the phase jitter is mitigated.
- Incoming (i.e. after booster linac) phase jitter will be reduced by a factor σ_{sf} / σ_{si}.
- Incoming (i.e. after booster linac) energy jitter will be amplified by a factor σ_{si} / σ_{sf}. This could become a limiting factor.
- Only requirements on accelerating cavities upstream are relieved. The BC2 RF still has to fulfill tight tolerances ($\Delta\phi_{BC2RF}$ < 0.05 deg).
- The setup is inflexible. Whenever one parameter changes all others have to be adjusted.
- BC1 is not discussed at all. Since it has a huge $R_{56,BC1}$ = 23 cm we require $\Delta E/E_0 < \Delta l \,/\, R_{56,BC1} = 3 \times 10^{-5}$ after BC1 RF. If we consider the factor σ_{sf} / σ_{si} = 44/300 = 1/7 still $\Delta E/E_0 < 2 \times 10^{-4}$ (= 600 keV) is required!
- For the energy stability behind the damping rings Yannis says this is o.k.
- But what about stability of BC1 RF?
- Fortunately, BC1 RF is weak (170 MeV) and we run at zero-crossing, i.e. 0.2 deg @ 4 GHz required.

Other Work in Progress

- Vertical transfer:
  Main concern are ISR and CSR since the vertical emittance is so small.
  For the CDR a civil engineering concept must be found how to layout vertical transfer and 9GeV loop.
- 9GeV loop (K. Zengin, Ankara University):
  For civil engineering reasons this might become a real loop not just an arc.
  It should be similar to the turn around loop due to similar requirements (or will the turn around loop become similar to this loop?).
- Diagnostics:
  Positions and specifications are existing but might need some revisions.
  Some of the systems should be studied in detail, e.g. emittance measurement
- Spin rotator (hopefully N. Solyak, Fermilab):
  Nothing has been done in the past. We hope that Fermilab collaborates. If not and we don't find another collaborator we will not have it for the CDR.
- More work we have to do:
  Collimation, Feedback and Feedforward, Field error tolerances, ...