CTF3 Longitudinal Beam Dynamics Issues

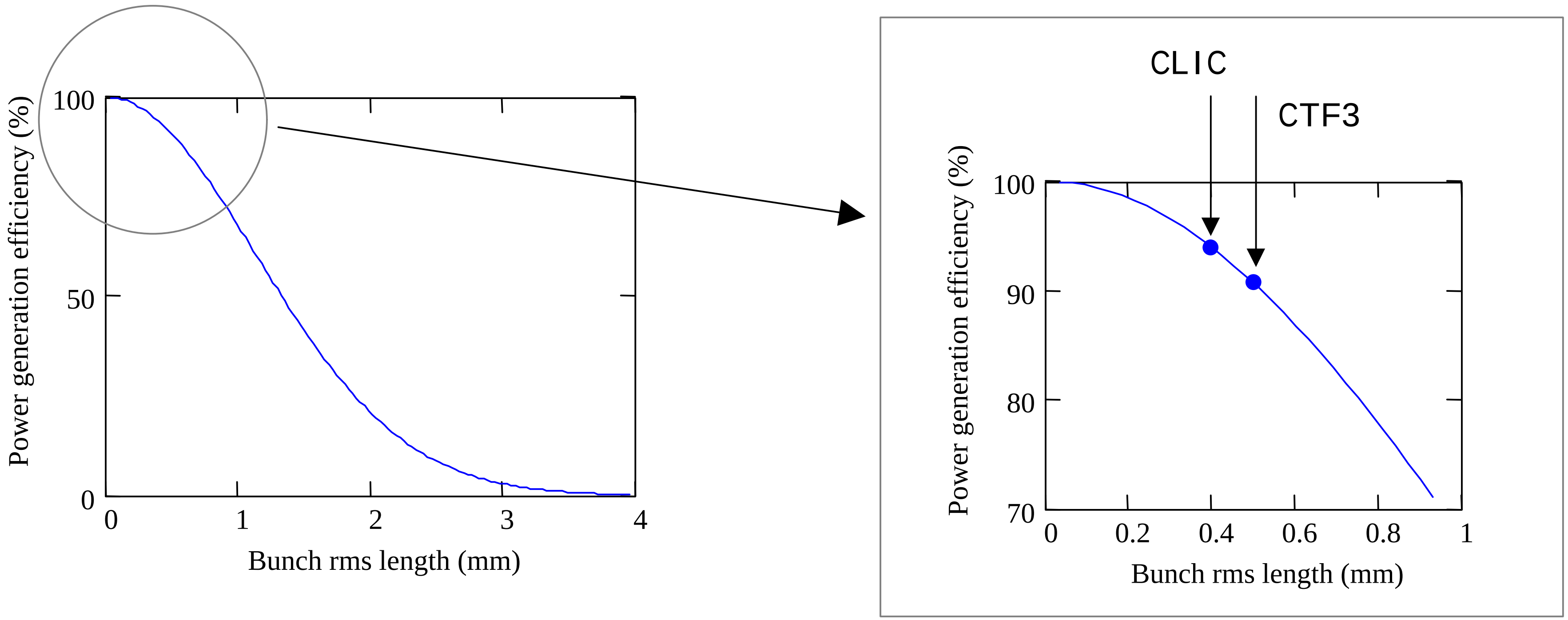
- Bunch length & phase requirements
- Bunch length gymnastics in CTF3 - effects & constraints
  - Coherent Synchrotron Radiation (CSR)
  - Ring longitudinal impedance
  - Isochronicity - momentum compaction
  - Bunch length limitations at ring injection
- Longitudinal phase space evolution - simulations
- Idle cavity option

$$P_{PETS} \propto F^2 \, q_B^2 \quad \text{where} \quad F = \int e^{-2ipnt} r(t)\,\mathrm{d}t \quad \Rightarrow \quad F = e^{-\frac{(2psn)^2}{2}} \quad \text{for gaussian bunches}$$

In order to efficiently produce 30 GHz power in the PETS, the bunches must be short.

In CLIC the nominal bunch length is σ ~ 0.4 mm rms

In CTF3, for efficiencies around 90% ⇒ **s ~ 0.5 mm rms**



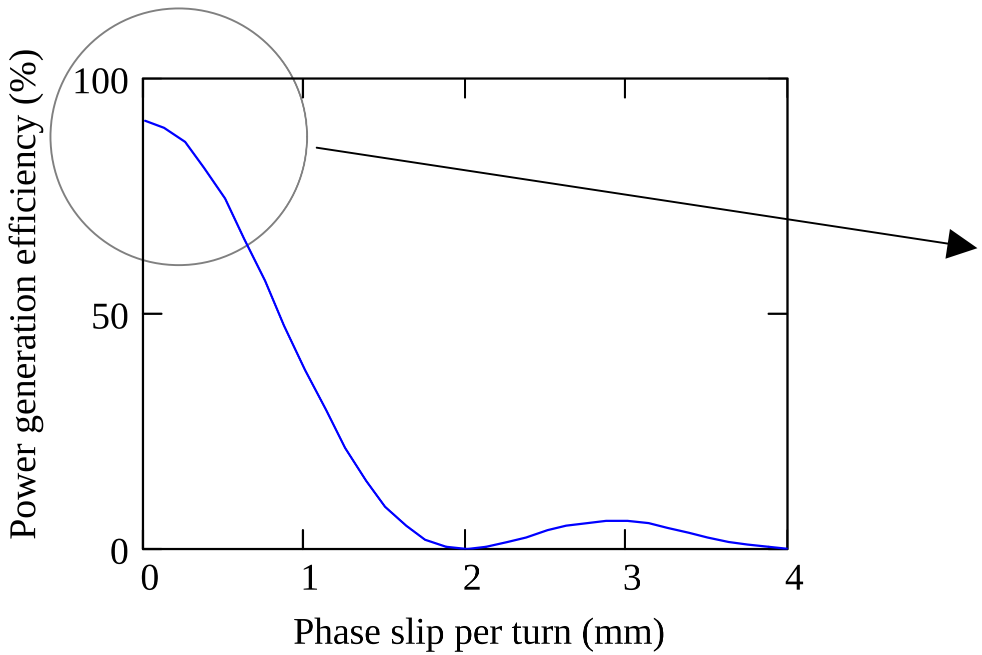
Requirements on bunch phase

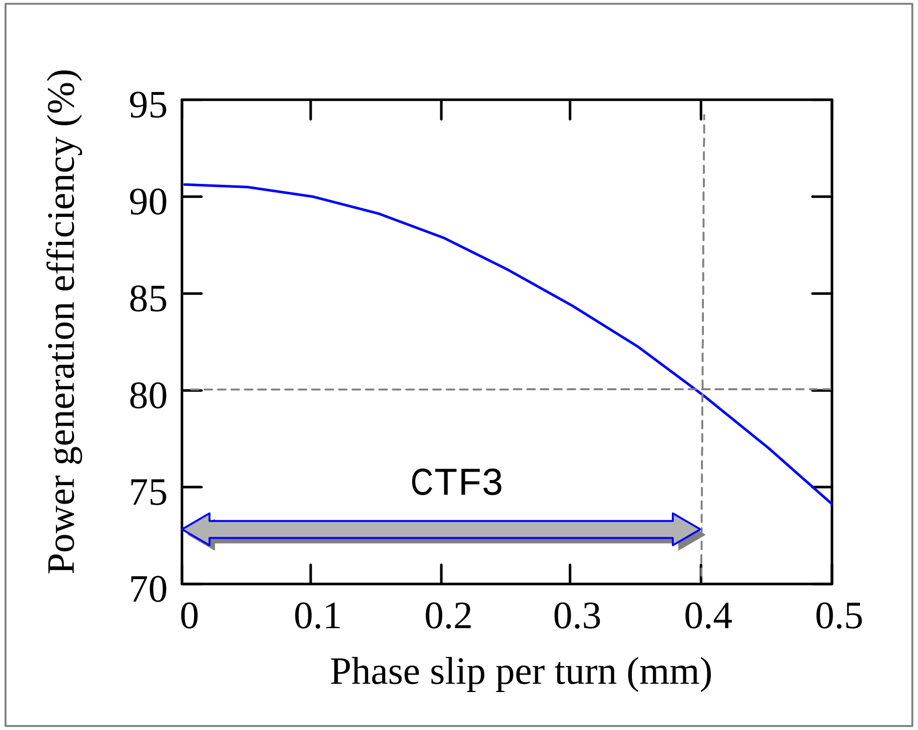
The distance between bunches after combination is 2 cm (15 GHz). Any variation in bunch-to-bunch distance corresponds to a loss of efficiency.

Below - reduction in 30 GHz power generation efficiency, for a linear phase slip of the center of the injected bunches.

For instance, in order to stay above 80% ⇒ **Ds < 0.4 mm / turn**

s ~ 0.5 mm rms





Considerations on bunch length in CTF3

- A very short bunch length is required after combination for efficient 30 GHz power production

- In order to avoid excessive bunch lengthening, the momentum compaction of the transfer lines, the delay loop and the combiner ring must be kept very small

- However, for short bunches, the longitudinal impedance as well as coherent synchrotron radiation emission become important issues:

  Energy spread & energy loss ⇒ bunch lengthening & phase errors

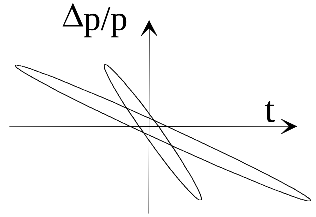
<u>Strategy:</u>

- Compress the bunches to the final value only after the combiner ring
- Optimize the bunch length in the different systems composing the CTF3

Optimizing the bunch length in CTF3

DBA

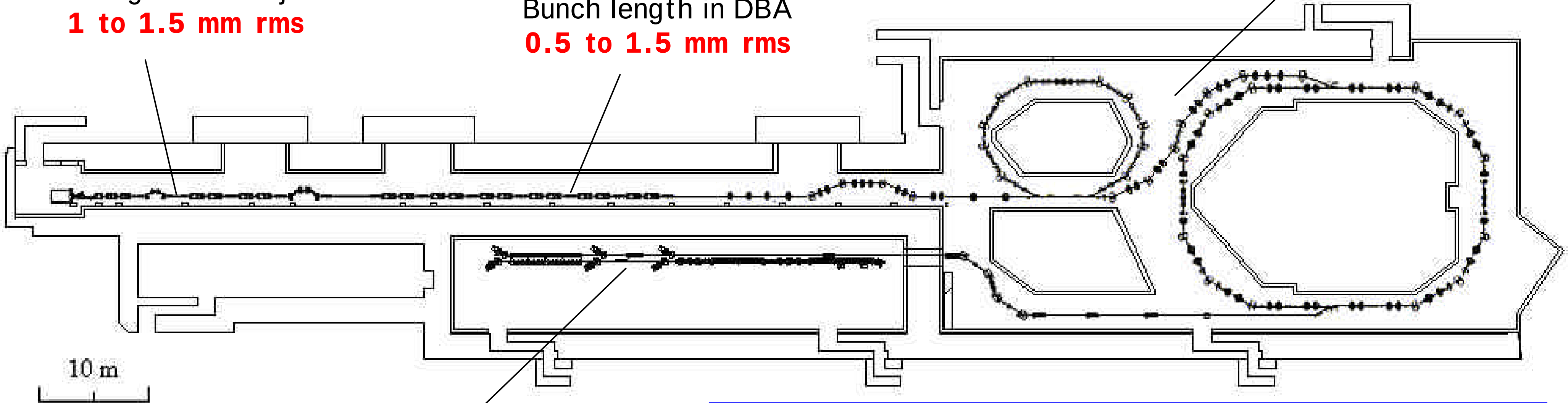
short bunches are good for transverse stability
& larger correlation for the same total energy spread



Bunch length in DL and CR
~ 2 mm rms

Bunch length from injector
1 to 1.5 mm rms

Bunch length in DBA
0.5 to 1.5 mm rms



Bunch length needed for 30 GHz
power production
~ 0.5 mm rms

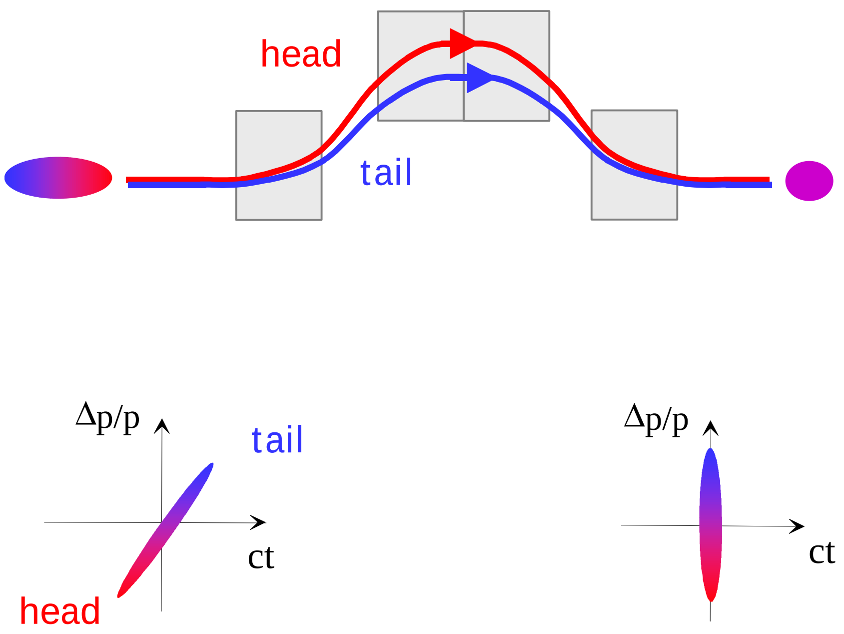
DL and CR

long bunches are good to avoid CSR and impedance effects
max bunch length limited by injection with RF deflectors
energy spread limited by the momentum acceptance of the ring and the transfer lines

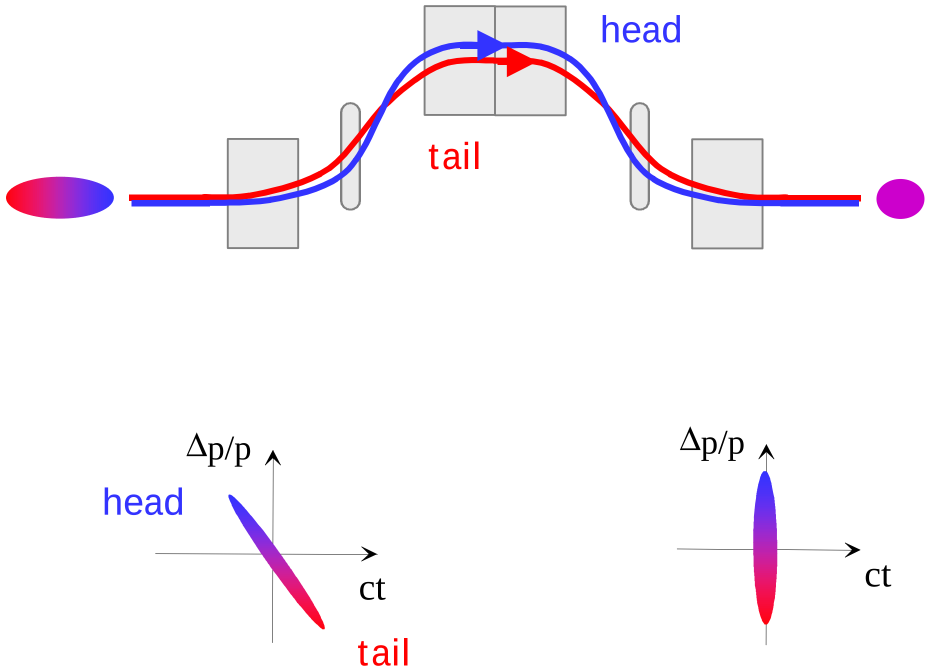
$$c\,\Delta t = R_{56}\,\Delta p/p$$

$$R_{56} = \int \frac{D}{r}\,ds$$

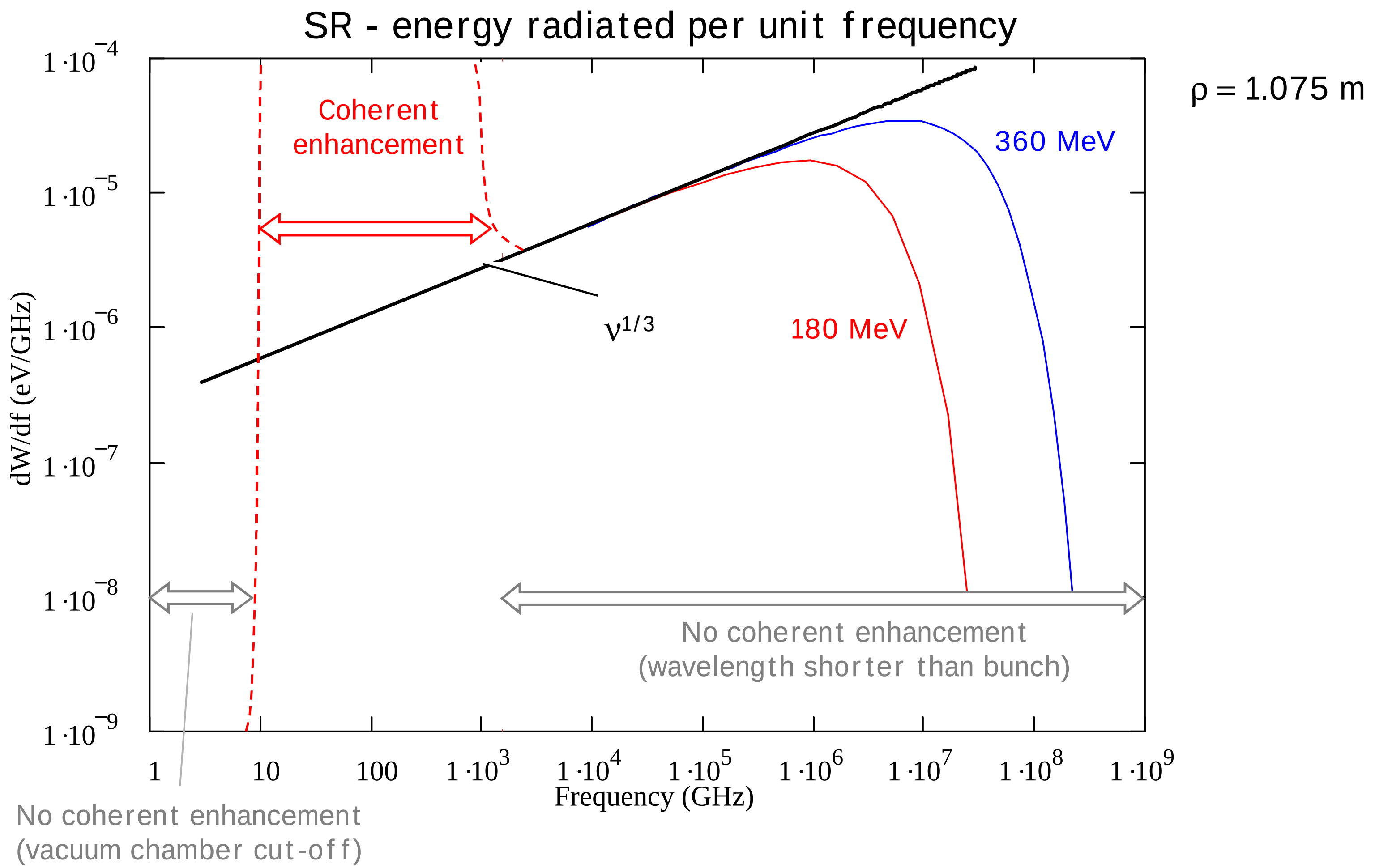
$R_{56} > 0$



$R_{56} < 0$



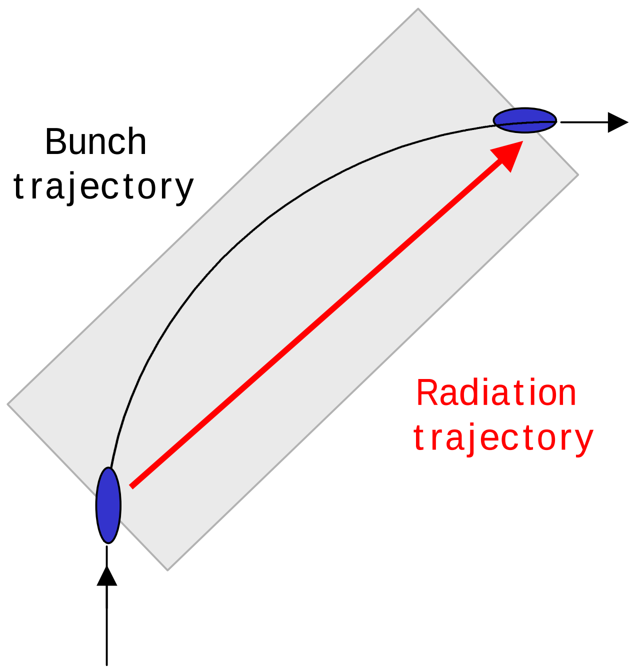
Short, high-charge electron bunches in magnetic bends radiate coherently at wavelengths larger than the bunch length. The effect is an average energy loss and an energy spread. When the vacuum chamber is small compared to the wavelength emitted, the emission is reduced (shielding)



The CSR wake-field

The CSR is similar to a longitudinal wake-field, causing an average energy loss and an energy spread whose amplitude does not depend on the beam energy.

When the beam-pipe dimensions is small compared to the wavelength emitted, the wake is reduced (shielding)

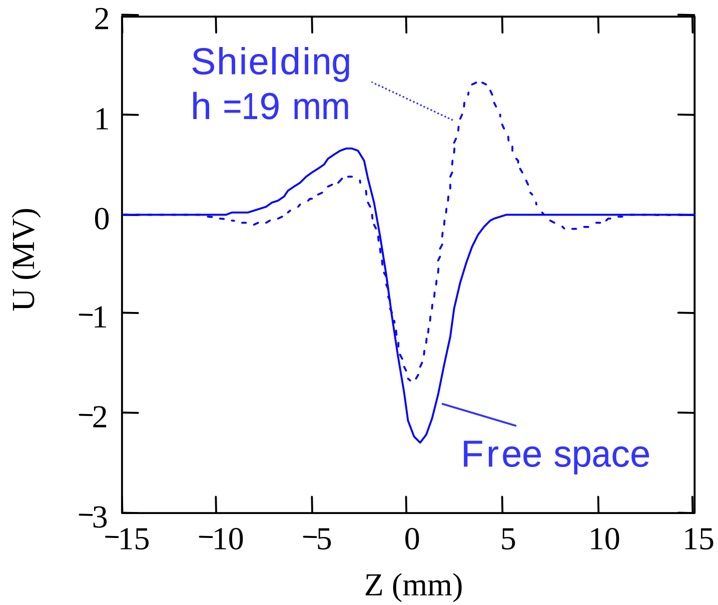


The emitted radiation can overcome the bunch along its curved path. Therefore, unlike a classical wake, the bunch head can be accelerated.

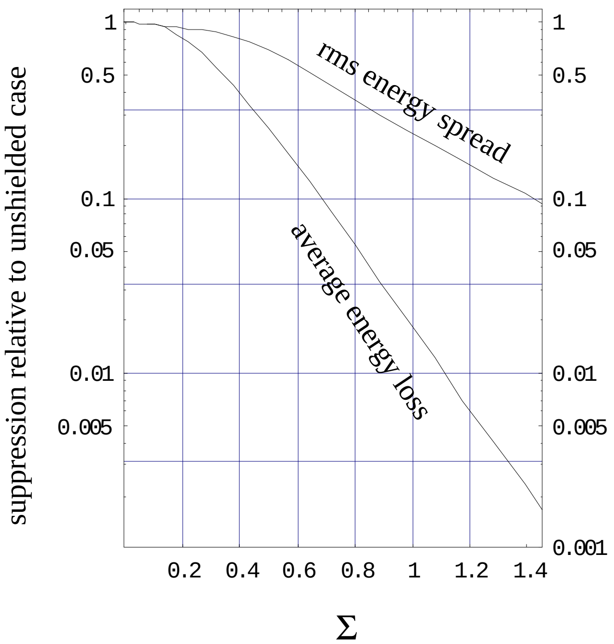
CSR Wake

$\sigma_Z = 1.5$ mm - $Q_B = 2.33$ nC

9/2 turns in CR

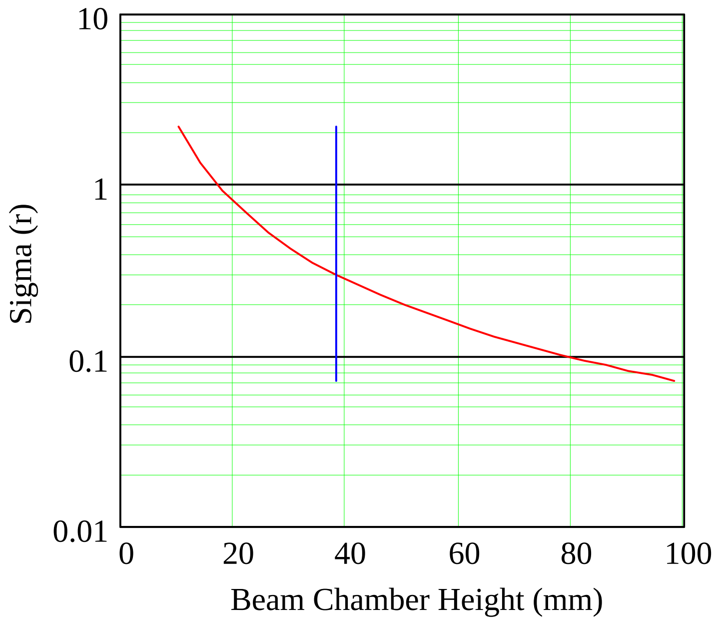


Shielding effect for CSR



Effect of shielding for CSR induced energy loss and spread, as a function of the scaling parameter **S**, defined as:

$$\Sigma(h) = \frac{\sqrt{2r}\; s_z}{h^{3/2}}$$



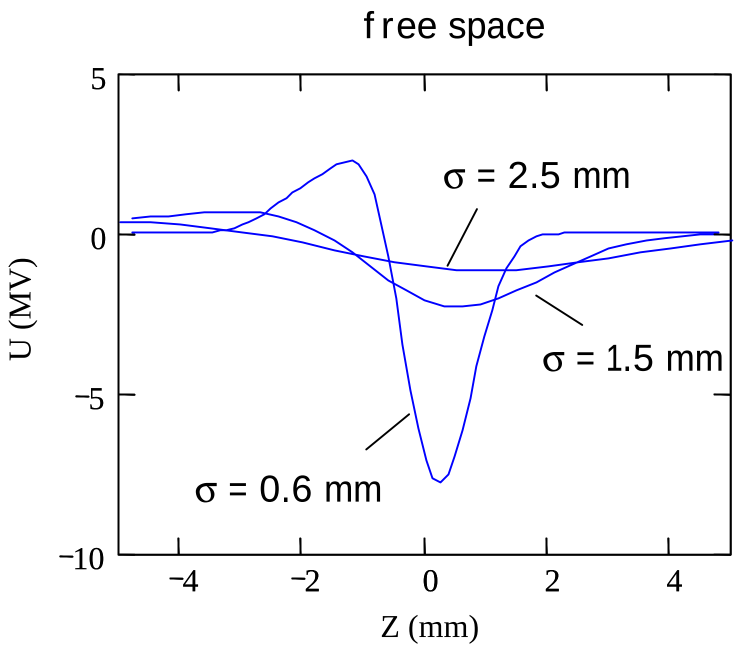
Σ parameter as a function of beam chamber height, for a bunch with **s_z** = 1.5 mm

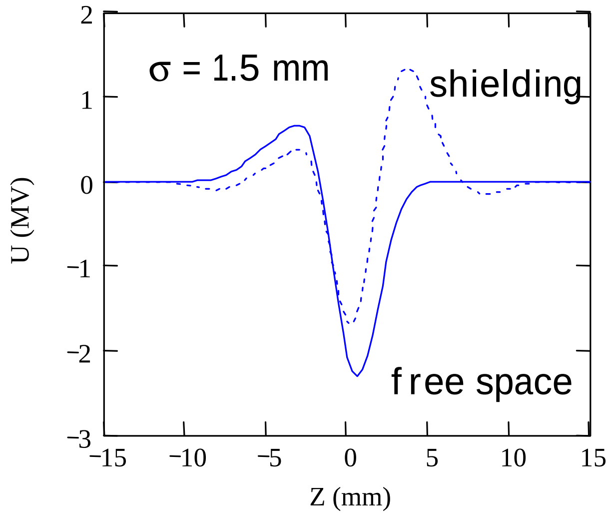
For h = 38 mm ➡ Σ = 0.3

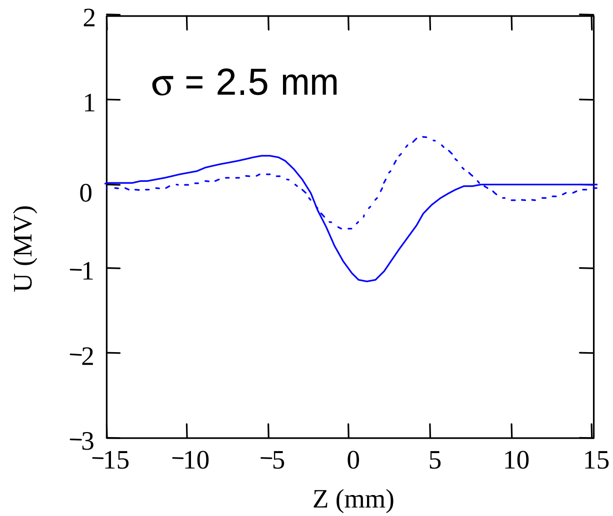
The CSR wake-field - II

CSR wake for 9/2 turns in the ring, for different bunch lengths, in free space (left) and including shielding in a h = 19 mm vacuum chamber (left)

$Q_B = 2.33$ nC







If the bunches are compressed to the final length before injection in the ring, the CSR wake would be too strong

Stretching the bunches before injection reduces the CSR wake

Ring Impedance

Besides the CSR effect, the electromagnetic interaction with the vacuum chamber can produce energy spread and energy loss.

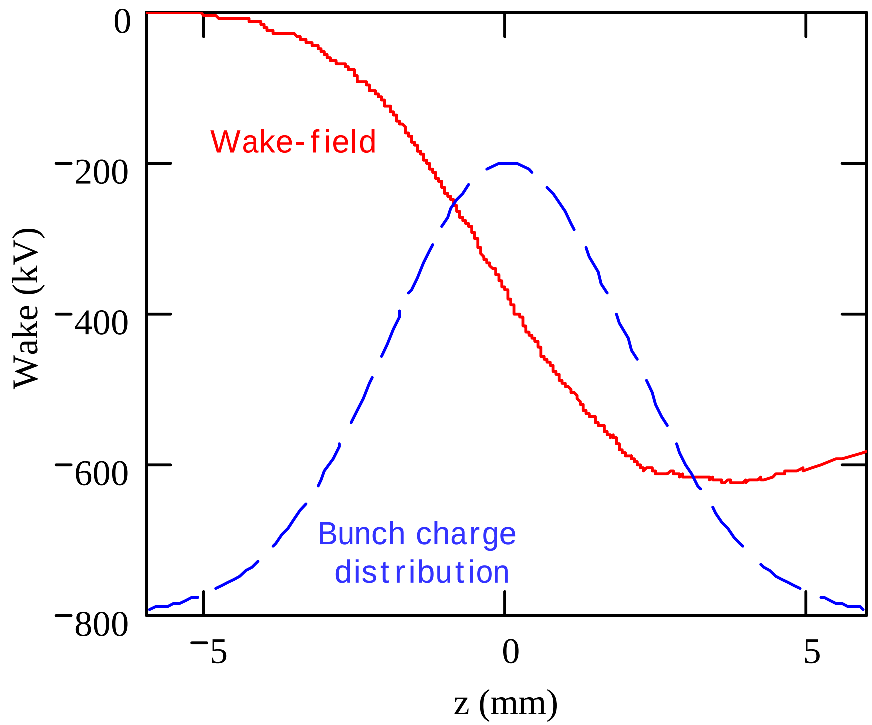
A rough evaluation of an acceptable impedance can be made by assuming a purely inductive impedance. The limit of the normalized impedance is found to be **Z/n < 0.4 W**. The estimated value compared to the impedance of other accelerator rings (for example, $Z/n \sim 21\ \Omega$ in EPA and 0.6 Ω in DAFNE) shows that a very careful design of the CTF3 combiner ring vacuum chamber is necessary.

A more precise evaluation can be obtained by a time-domain calculation of the contributions of the different elements in the ring

Here it is shown the cumulative wake-field obtained by summing up the different contributions, for a bunch with **s_z = 2 mm**

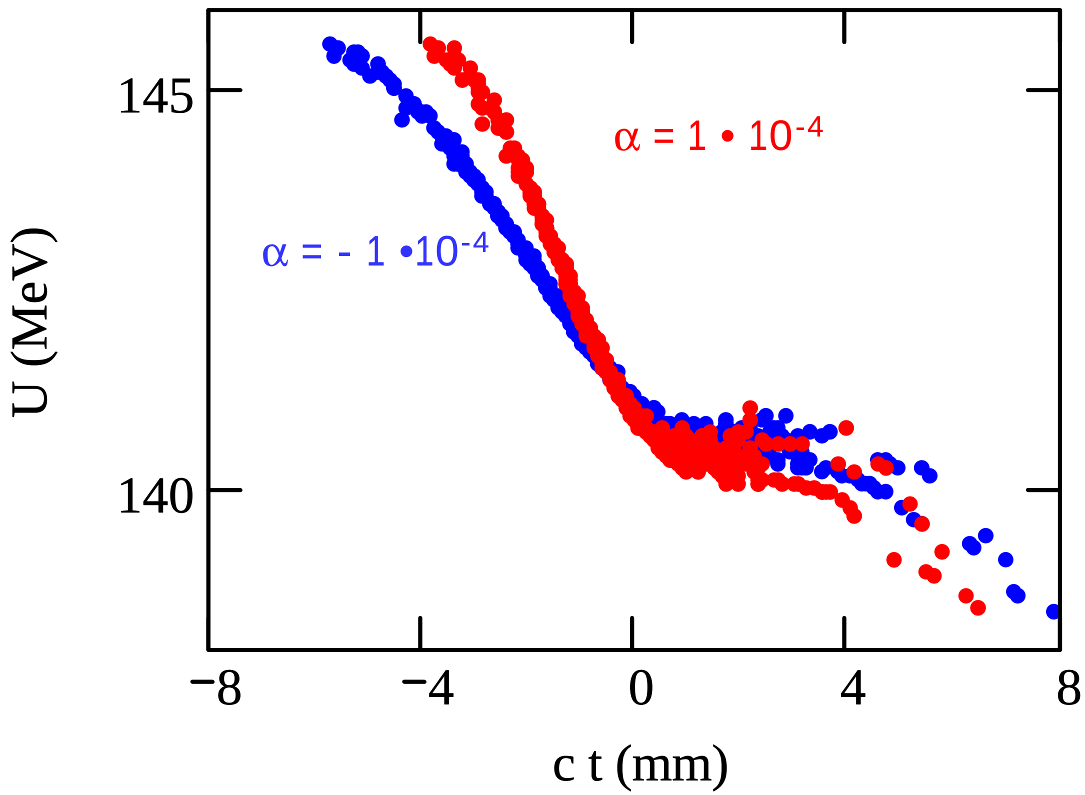
The main effects are coming from the BPMs and the RF deflectors

A. Ghigo, M. Zobov, CTF3 Note 26



Isochronicity - momentum compaction

The ring momentum compaction α causes a distortion in the longitudinal phase space

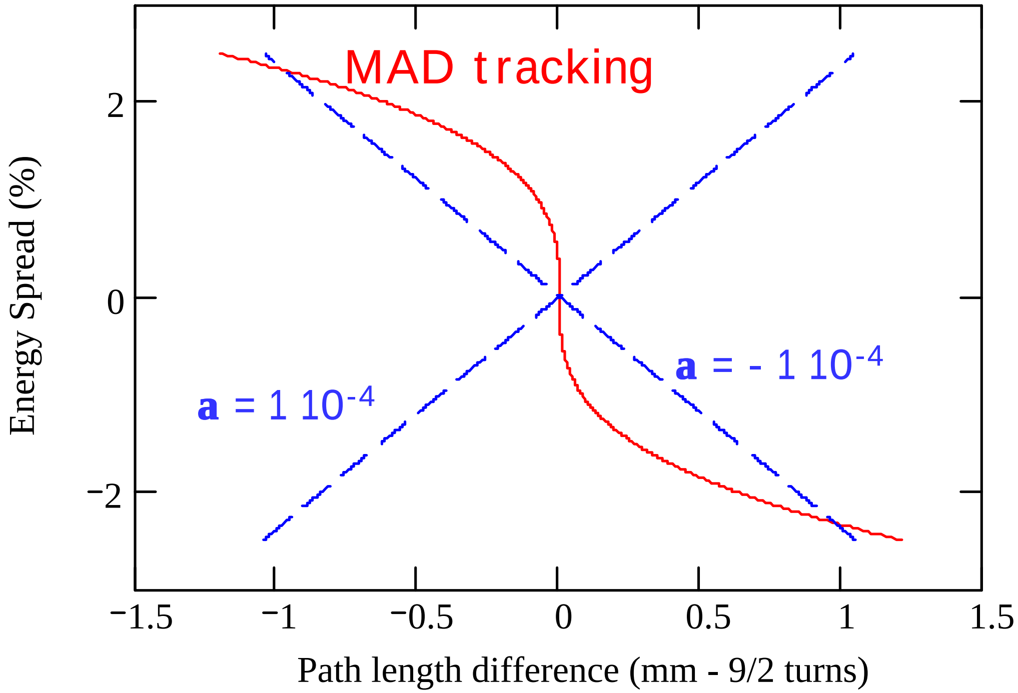


Requirement: $\alpha < 1\ 10^{-4}$

Longitudinal phase space distribution, after 9/2 turns, for two different values of the ring momentum compaction

Momentum compaction a in the combiner ring

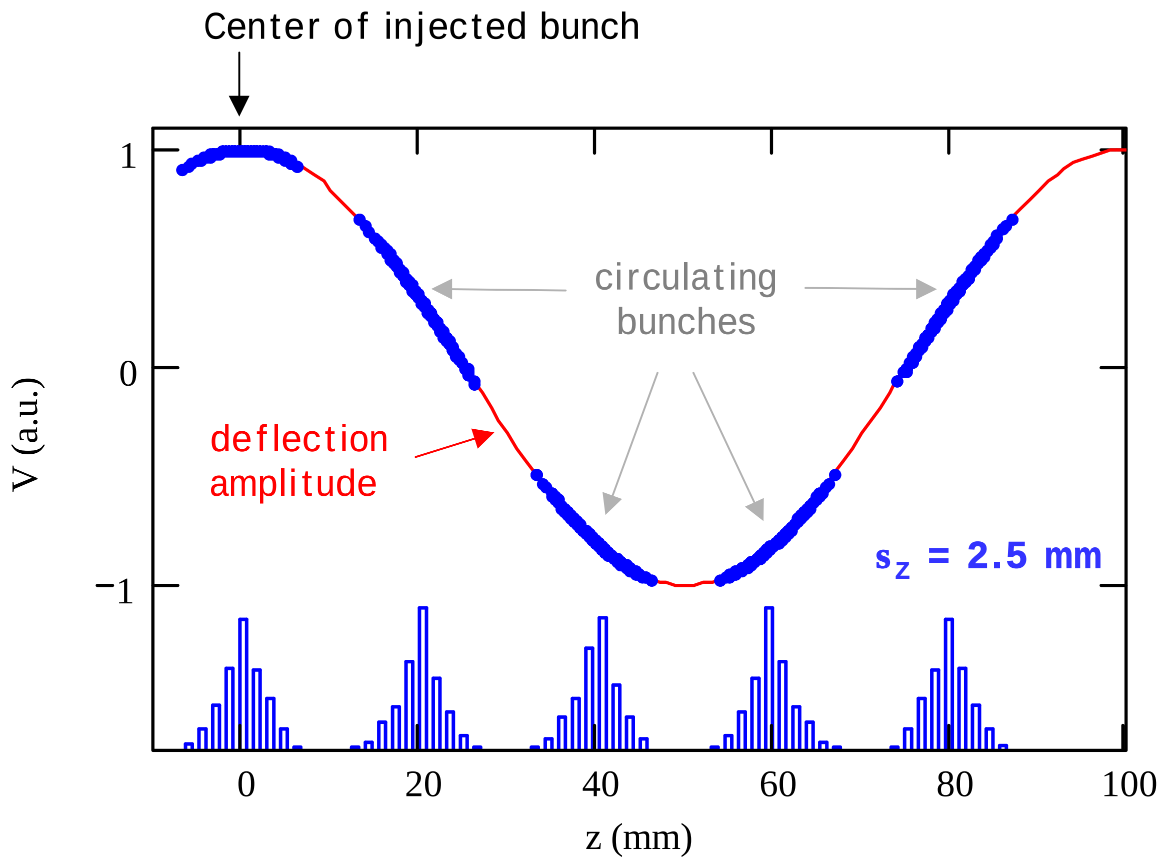
Isochronicity curve in the combiner ring - comparison between requirements and MAD tracking



C. Biscari, CTF3 Note 24

The bunch length is increased before the delay combiner and the ring, to minimize CSR and longitudinal wake-field effects.

The main limitation to the maximum bunch length acceptable in the ring comes from the injection by RF deflectors

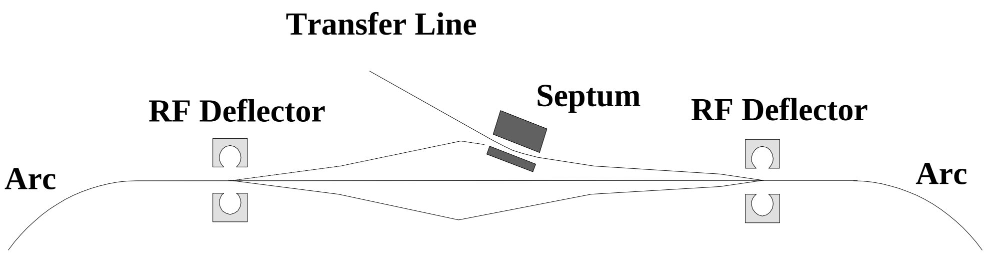


A long bunch has a large phase extension in the 3 GHz deflector, so the kick experienced by the bunch tails is different from the one experienced by the bunch center:

- Reduction of "useful" kick to avoid septum
- Effective emittance growth (only at injection)

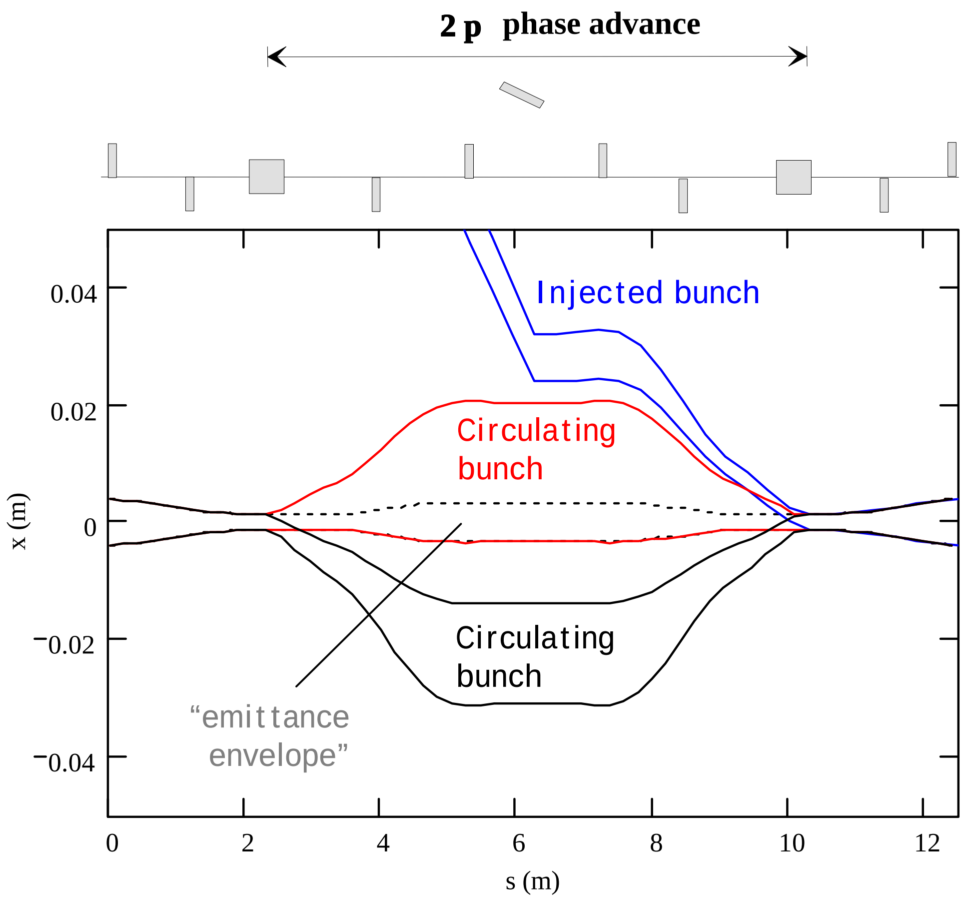
- Max bunch length ~ **2.5 mm rms**

Bunch length limitation at injection II



Layout of injection region

C. Biscari, CTF3 Note 24



Beam envelopes (2 σ longitudinal and horizontal) for injected and circulationg bunches, **s_z = 2.5 mm**.

The space available for the septum is ~7 mm, the kick from the RF deflector is 10 mrad (6 MW at 150 MeV)

Longitudinal phase space evolution - simulations

- A model of the single-bunch longitudinal phase space evolution in the complex, based on the use of macroparticles, has been used.

- The starting point is a longitudinal phase space distribution at the exit of the injector obtained from PARMELA.

- The evolution in the drive beam accelerator is calculated taking into account the RF field in the accelerating structures and the longitudinal short-range wake-fields.

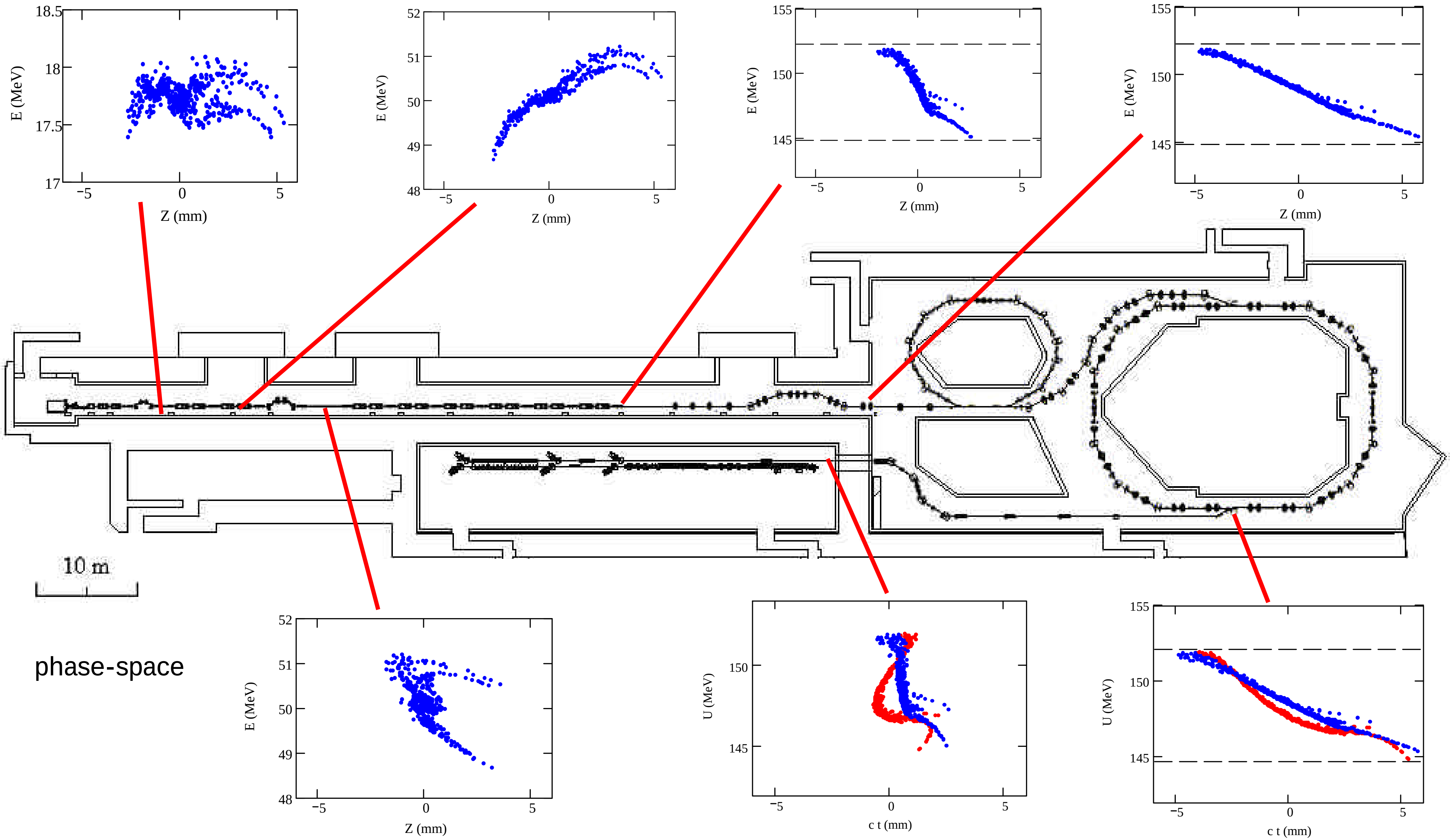
- The short-range wake-fields are modeled applying to the macro-particle distribution delta wake-fields of the form:

$$W_Z = w_1 \exp\left(w_2 \sqrt{z/\mathrm{mm}}\right)$$

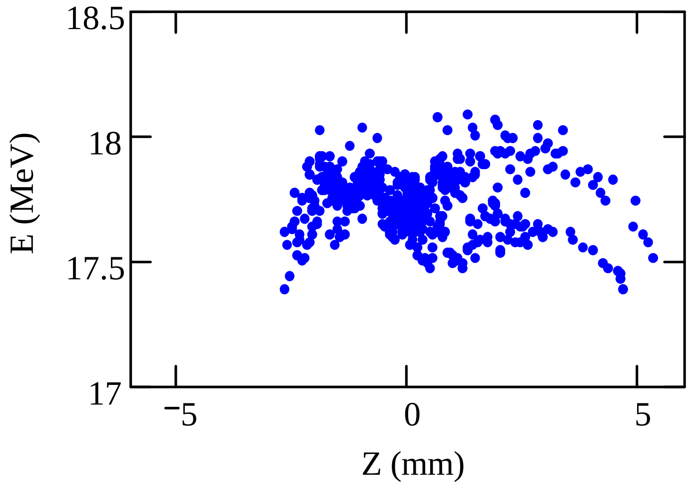
- The evolution in the ring has been calculated taking into account CSR, conventional wakes and momentum compaction. An analytical model has been used for CSR, with the approximation of considering a Gaussian longitudinal distribution for the bunches.

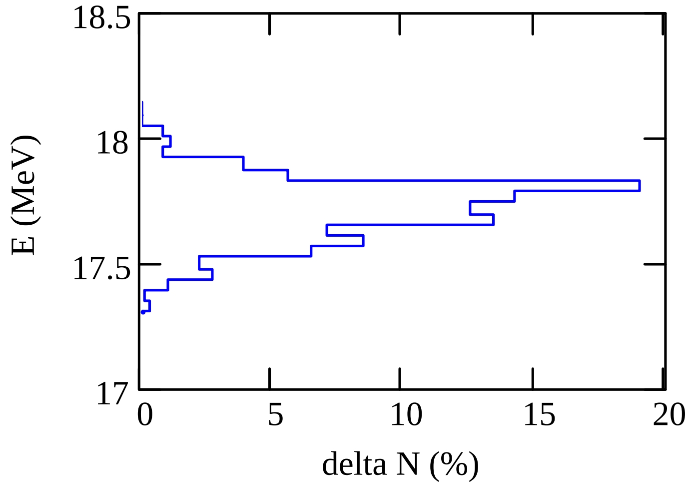
- The conventional wake-fields have been treated using a delta wake model similar to the one used in the linac.

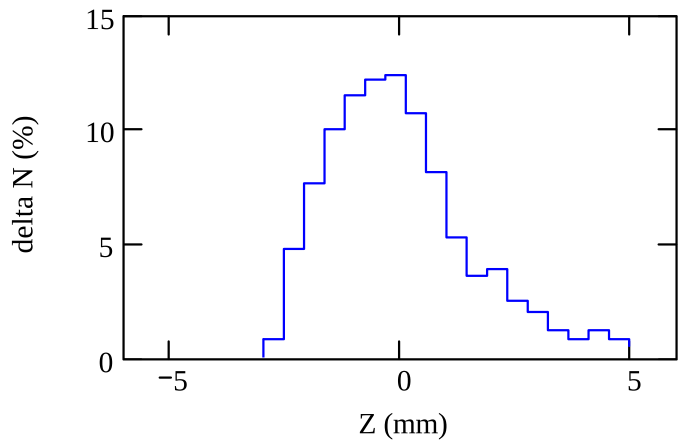
Bunch length evolution in CTF3 - II



Longitudinal phase space at the injector exit







Particle distribution in longitudinal phase-space, bunch shape and momentum spectrum after the cleaning chicane

s_z = 1.5 mm

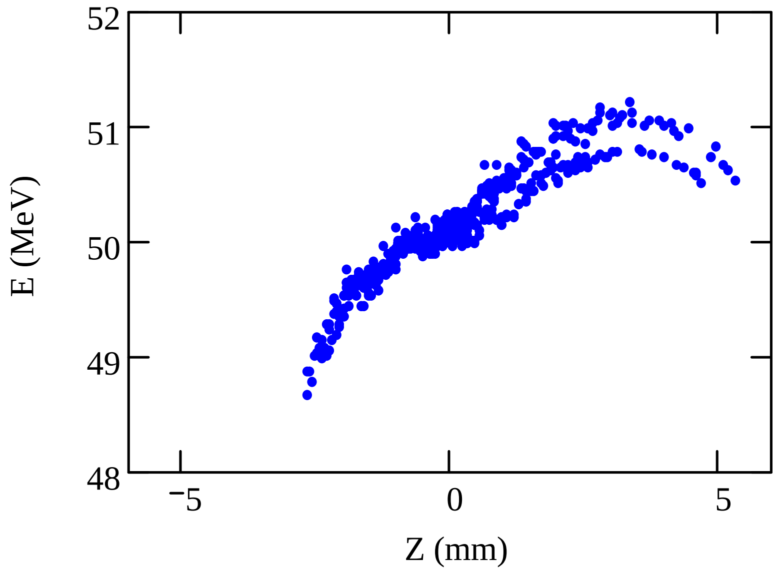
s_p = 0.12 MeV

D. Yeremian

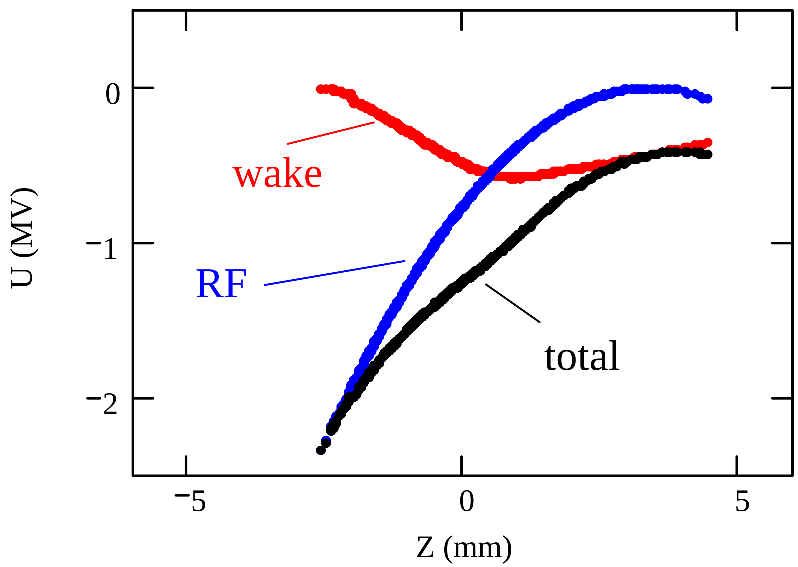
Phase space before the compression chicane

2

The beam is accelerated in a first linac section. A correlated energy spread is introduced by the combination of off-crest acceleration and short-range wake-field.



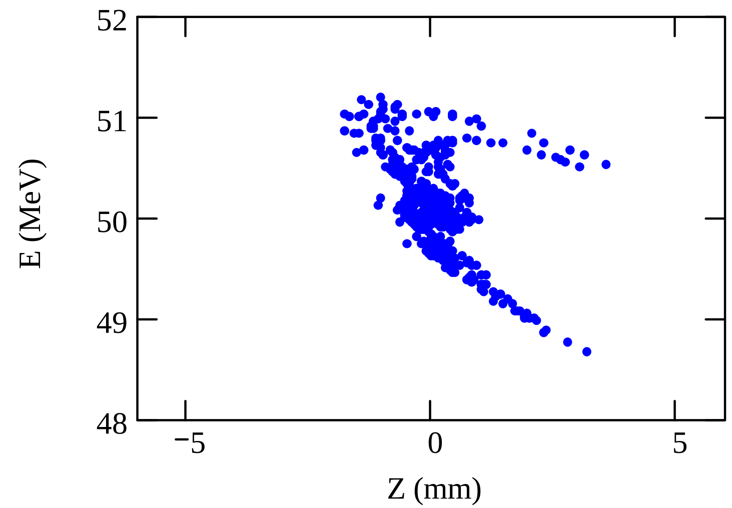
Longitudinal phase space distribution before the compression chicane

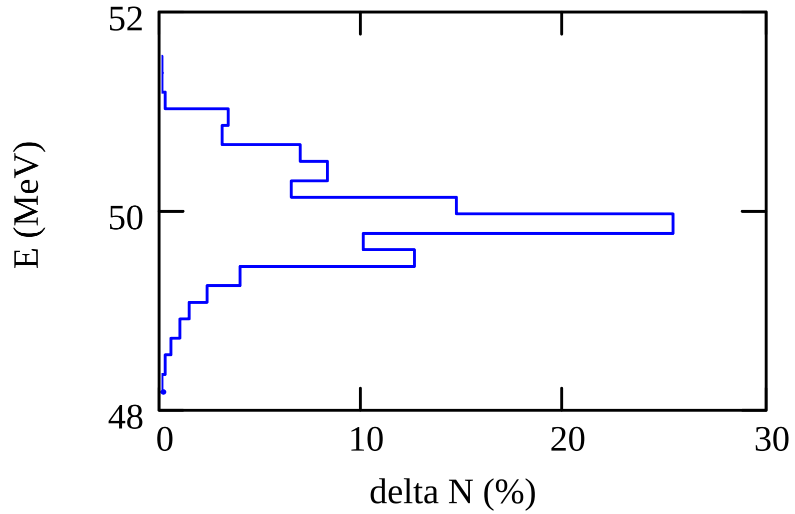


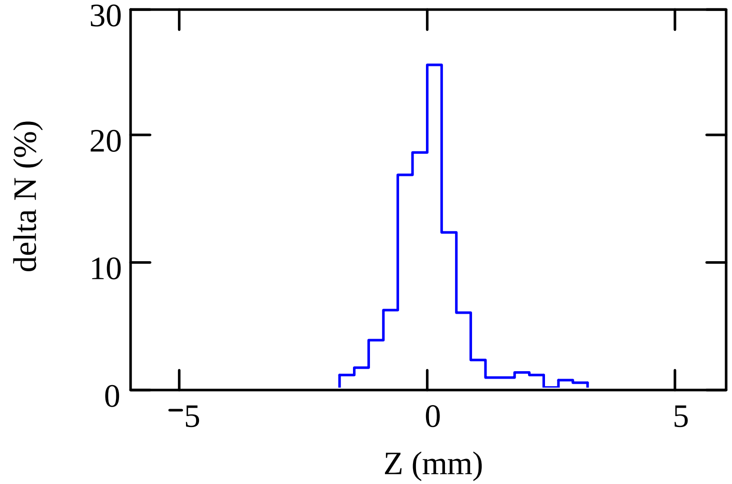
Longitudinal short-range wake-field in the linac and RF field

(-11° off-crest)

3 The bunches are compressed in the compression chicane.







Particle distribution in longitudinal phase-space, bunch shape and momentum spectrum after the compression chicane

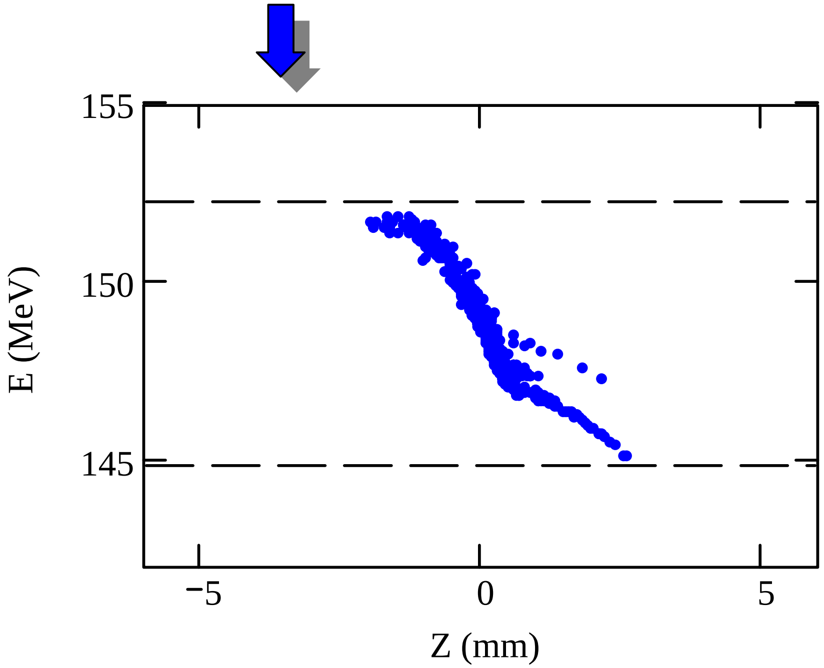
s_z = 0.7 mm

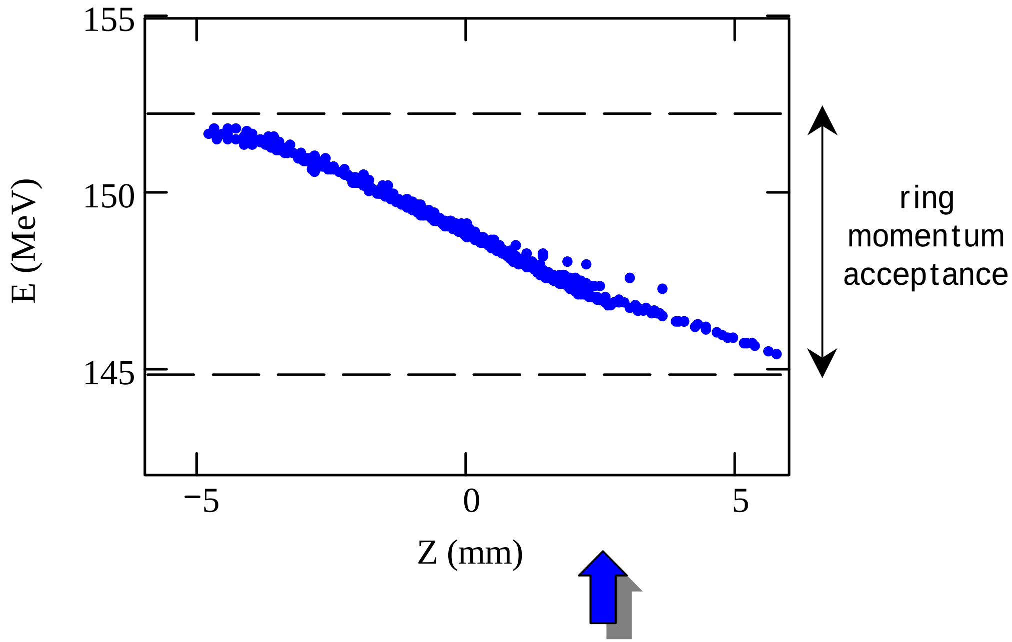
s_p = 0.45 MeV

Phase space after the DBA

④

The beam is further accelerated in the second part of DBA. A correlated energy spread (opposite sign) is introduced. The total energy spread must be within the ring acceptance





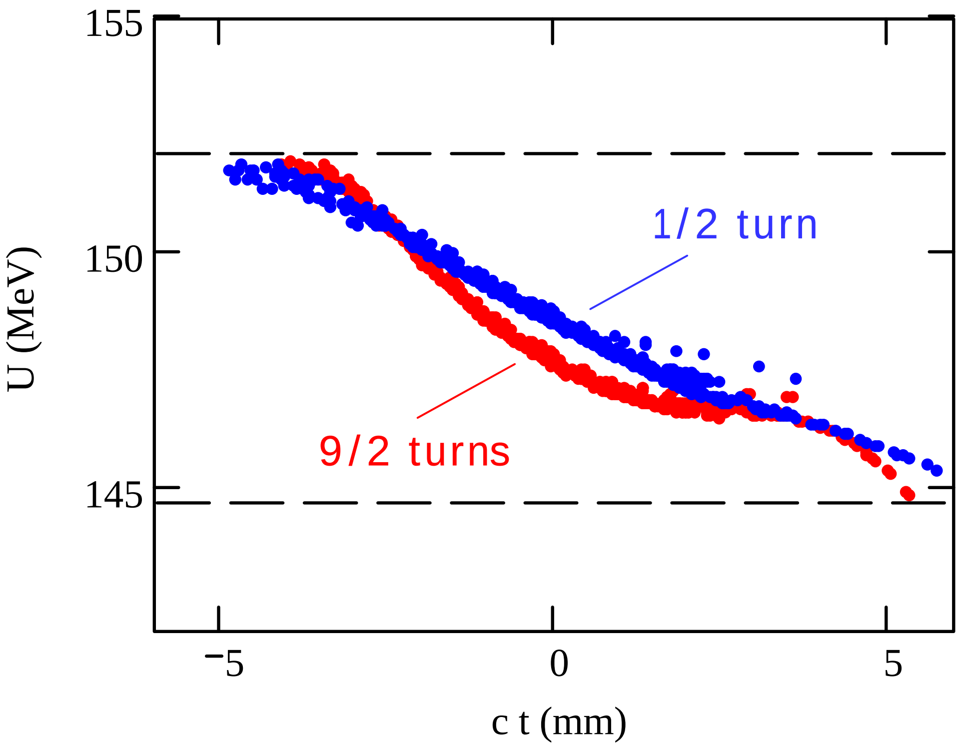
⑤

The bunches are stretched in a 4 bends achromat to **$s_z \sim 2$ mm**

Phase space after the Combiner Ring

6

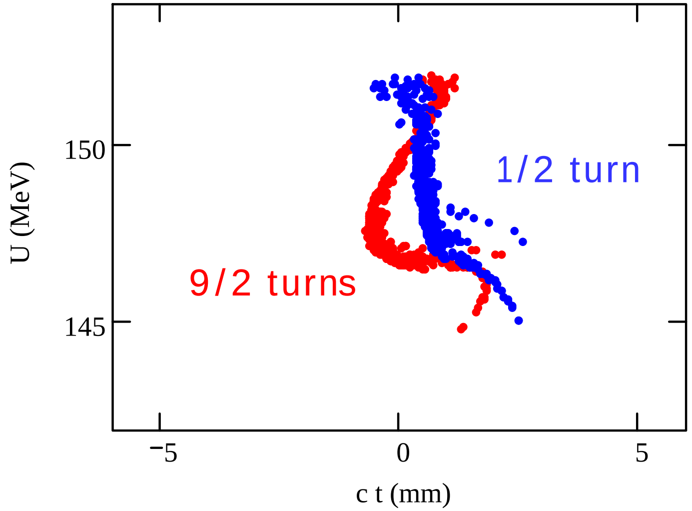
The particle distribution is distorted by CSR, wake-fields and residual momentum compaction. Bunches belonging to different pulses make different numbers of turns (from 1/2 to 9/2) in the Combiner Ring, and will have different phase-space distributions.

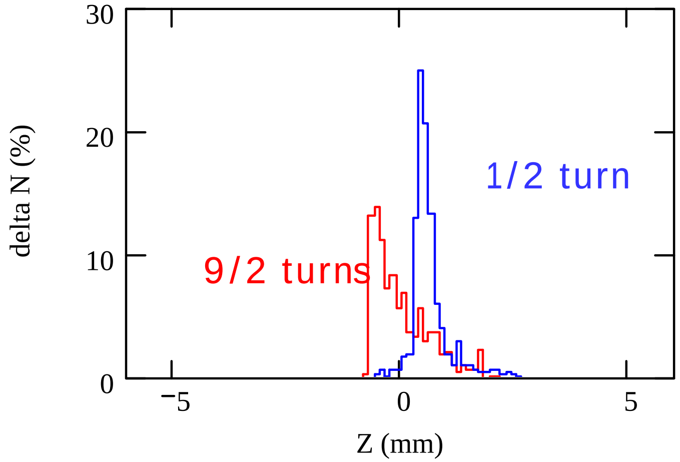


Final bunch compression

6

During the final compression, bunch-to-bunch energy differences are converted in phase errors, and differences in phase space distribution prevent optimum compression

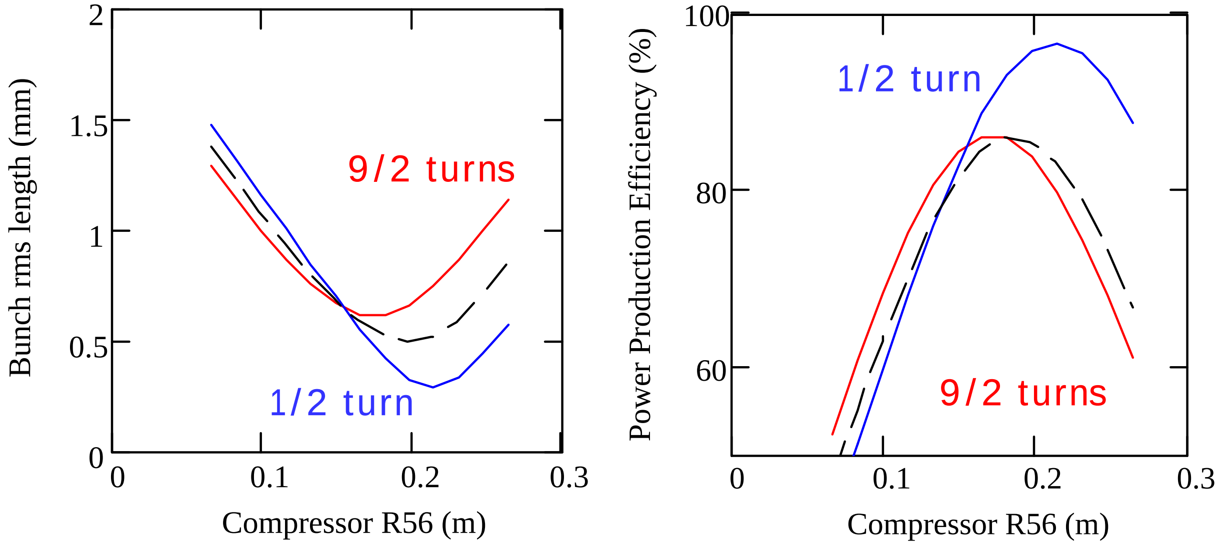




$420\ \mu m < \sigma_Z < 620\ \mu m$

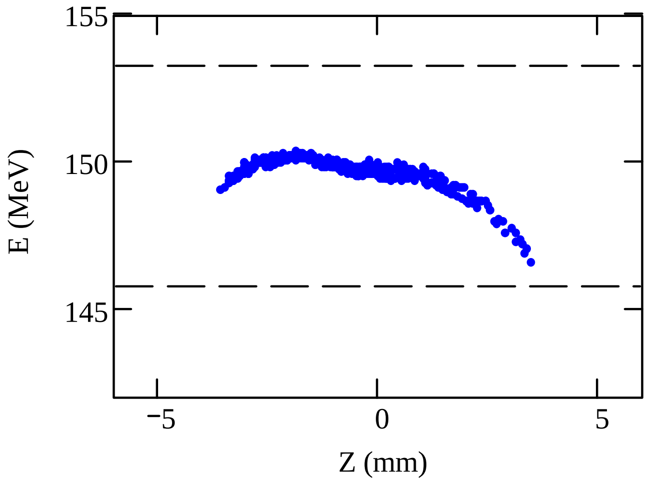
$\eta_{RF} \gtrsim 86\ \%$

Bunch length and corresponding power production efficiency as a function of the compression strength

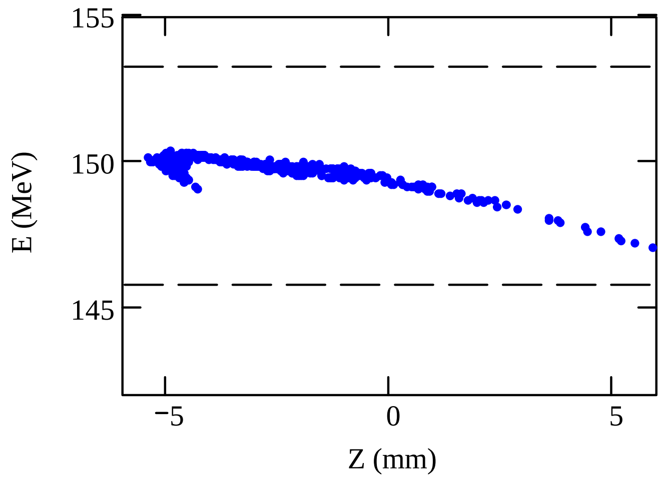


Idle cavity option - I

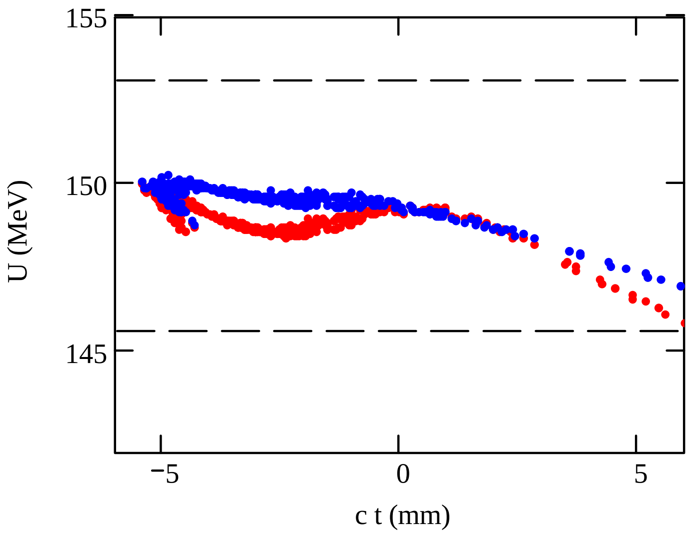
Longitudinal phase space distribution at the end of DBA



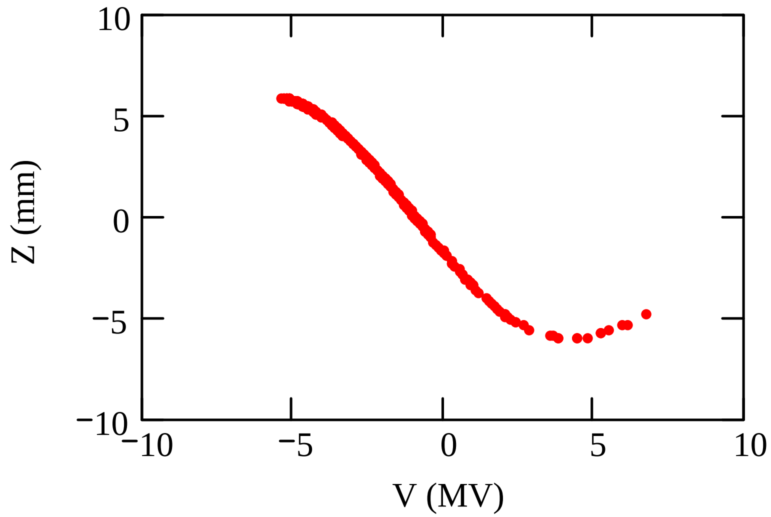
Bunch stretching to ~ 2 mm rms



Longitudinal phase space distribution after the combiner ring



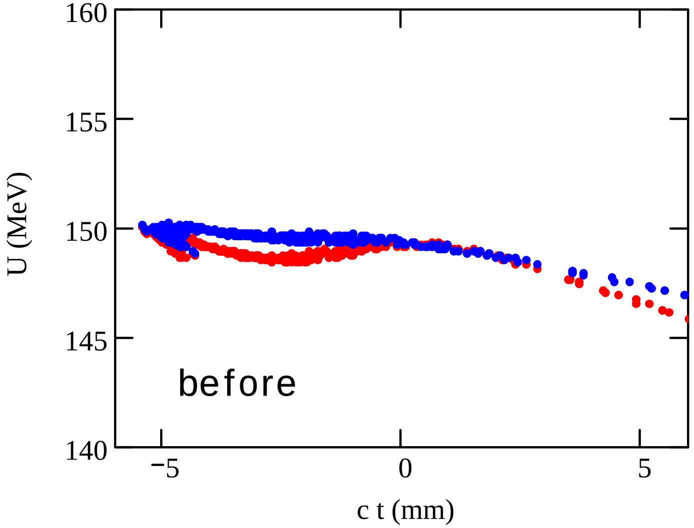
Idle cavity option - II

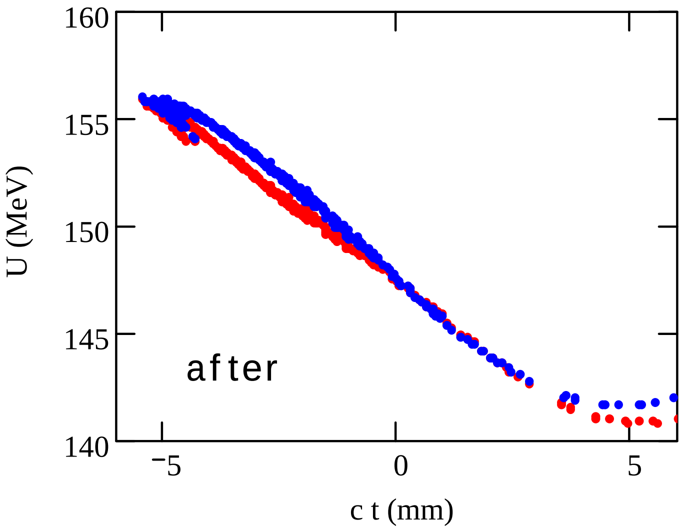


Steady state longitudinal field in idle cavity, over the bunch extension

peak integrated voltage	6 MV
de-phasing	60 degrees

Longitudinal phase space distributions, before and after the idle cavity

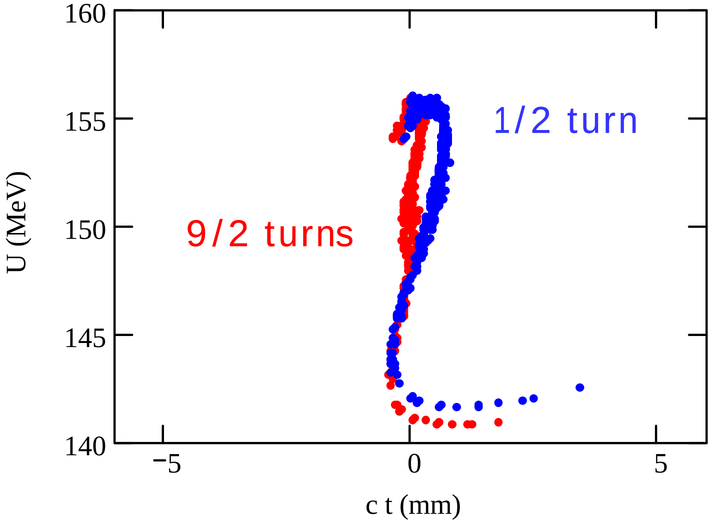


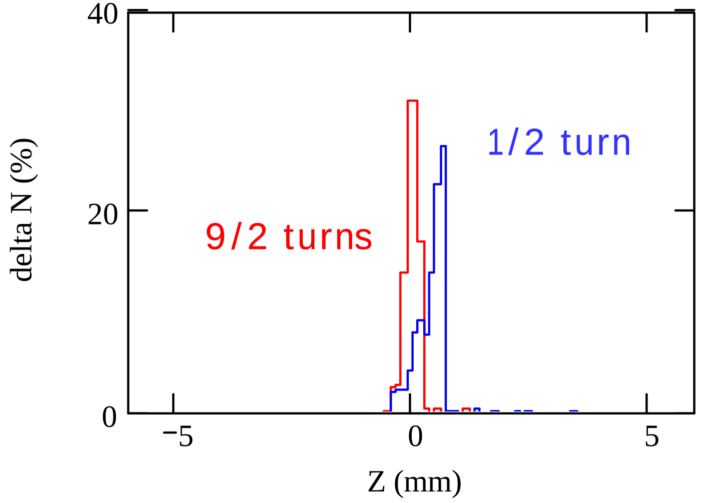


Idle cavity option - final compression

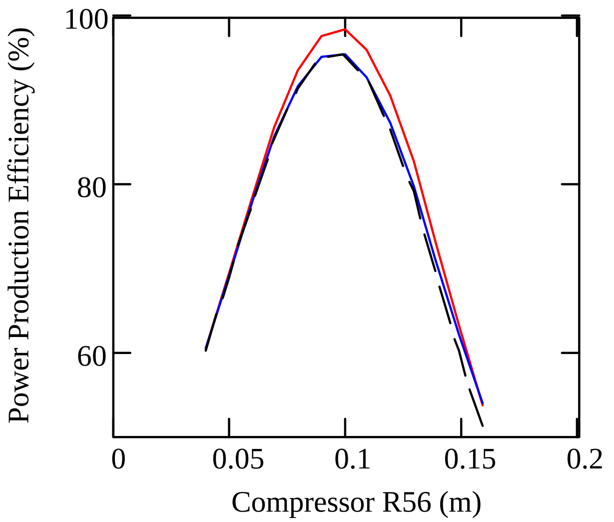
$200\ \mu m < \sigma_Z < 330\ \mu m$

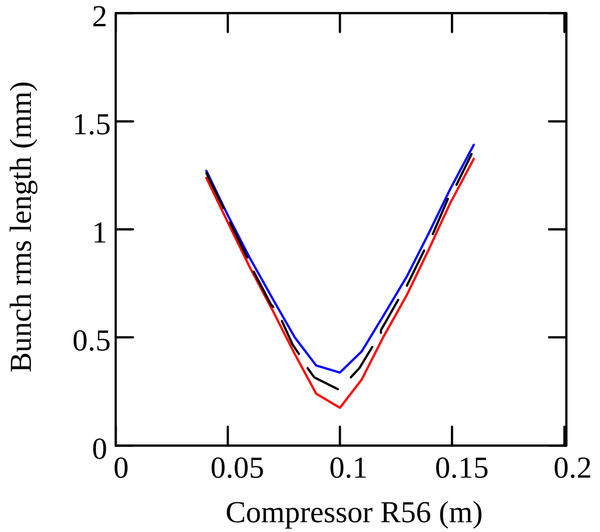
$\eta_{RF} \gtrsim 95\ \%$





Bunch length and corresponding power production efficiency as a function of the compression strength





SUMMARY

- A very short bunch length is required in CTF3 after recombination for efficient 30 GHz power production
- The rms bunch length is changed along the complex in order to minimize distortions to the phase space distribution.
- In particular, the rms bunch length is maximized to ~ 2 mm in the Delay Loop and the Combiner Ring.
- By a careful design of the components it is possible to keep the conventional wake-fields contribution within the design limits.
- The Delay Loop and the Combiner Ring are isochronous to 2nd order.
- The bunches are finally compressed to ~ 500 μm.
- A simplified model, based on macro-particle distribution and analytical calculations has been developed to evaluate the evolution of the longitudinal phase space in the CTF3 complex, taking into account CSR and conventional wake-fields.

- The results show that the desired bunch length and 30 GHz power production efficiency can be obtained after final compression with the assumptions made above.