New type of a bunch compressor and generation of a short wave length coherent radiation

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LBNL, August 06, 2010

“Any fool with four dipoles can compress a bunch”

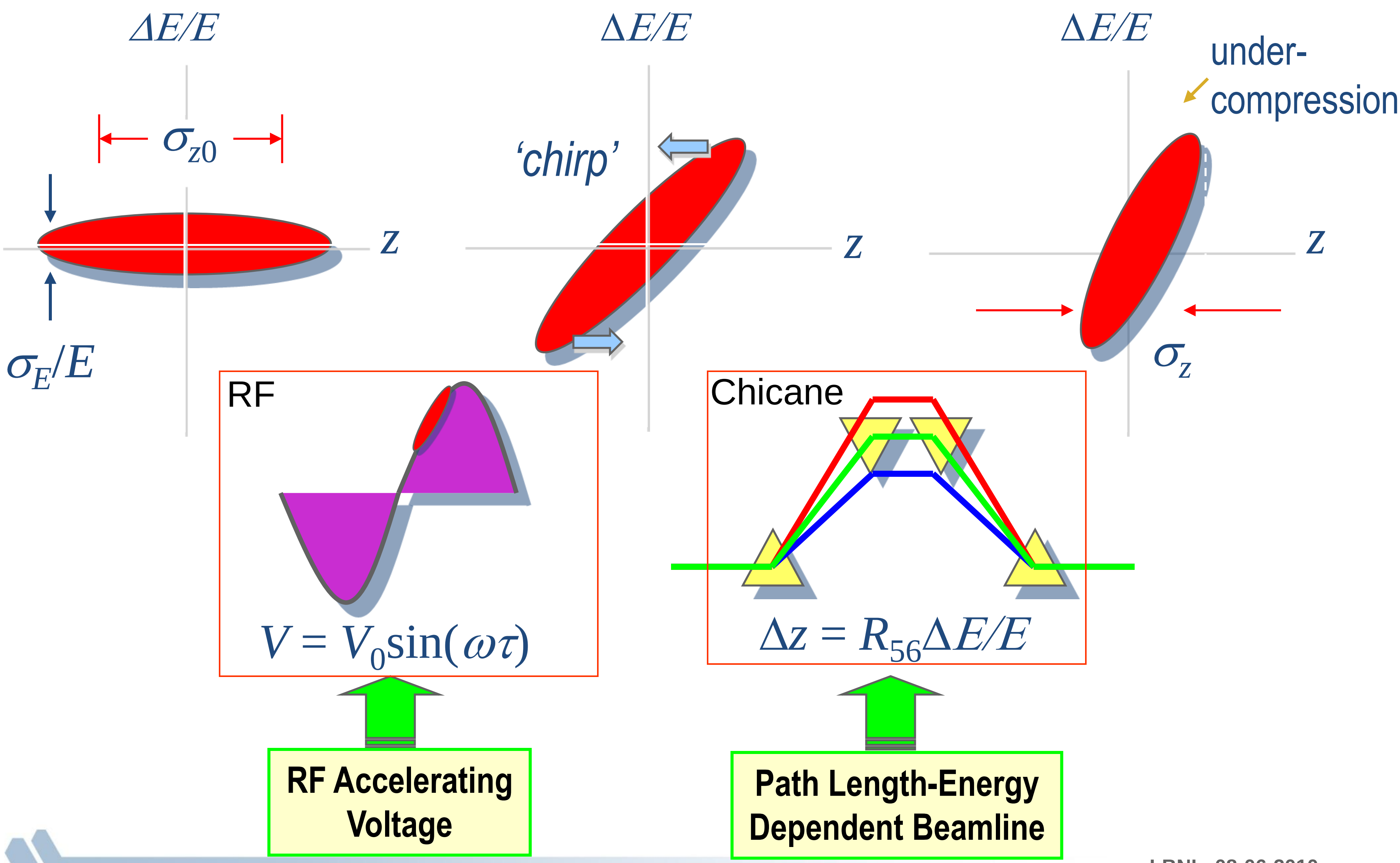
- anonymous

OK, but there may be a few details to consider…

P. Emma, ICFA Workshop, Sardinia, 2002

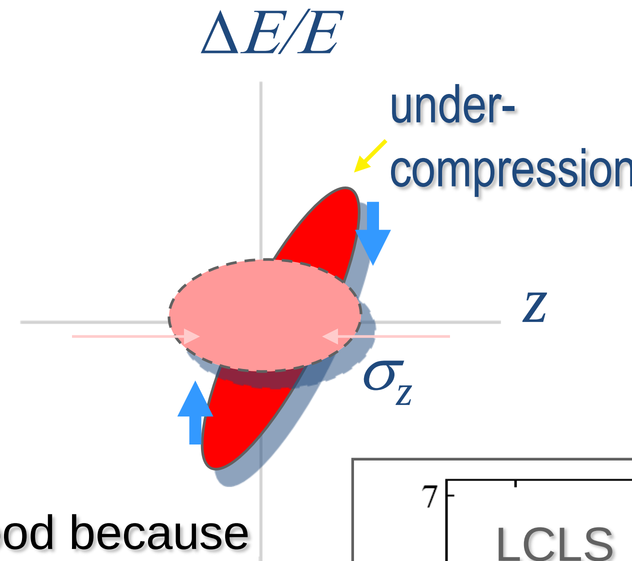
Magnetic Bunch Compression

Courtesy P. Emma



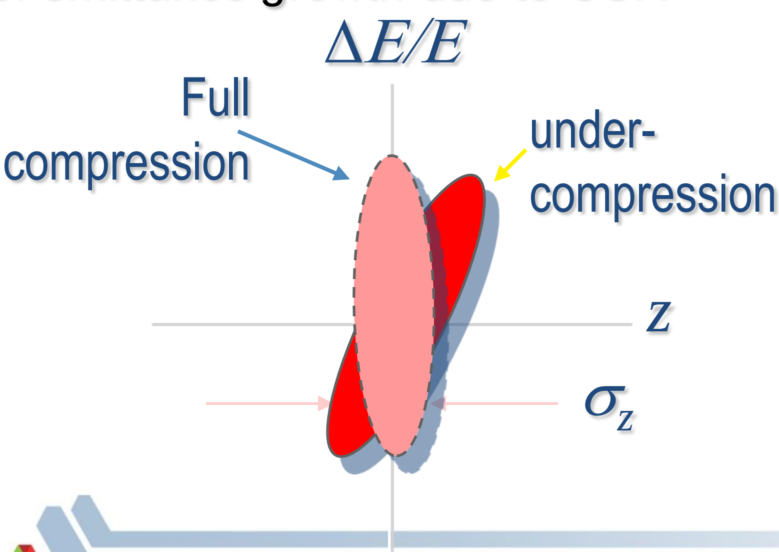
Some issues

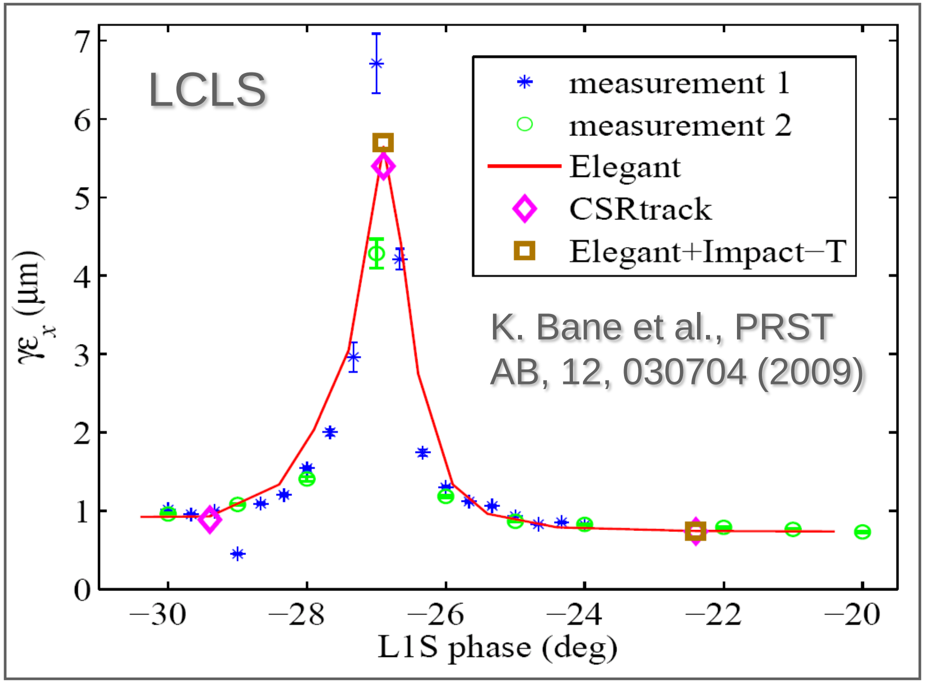
Needs:
de-chirping



De-chirping is typically done by using wake fields and/or off-crest acceleration

Full compression is not good because of emittance growth due to CSR





References

Results presented here use the idea of transverse to longitudinal emittance exchange

M. Cornacchia, P. Emma, "Transverse to longitudinal emittance exchange", Phys. Rev. ST Accel. Beams 5, 084001 (2002)

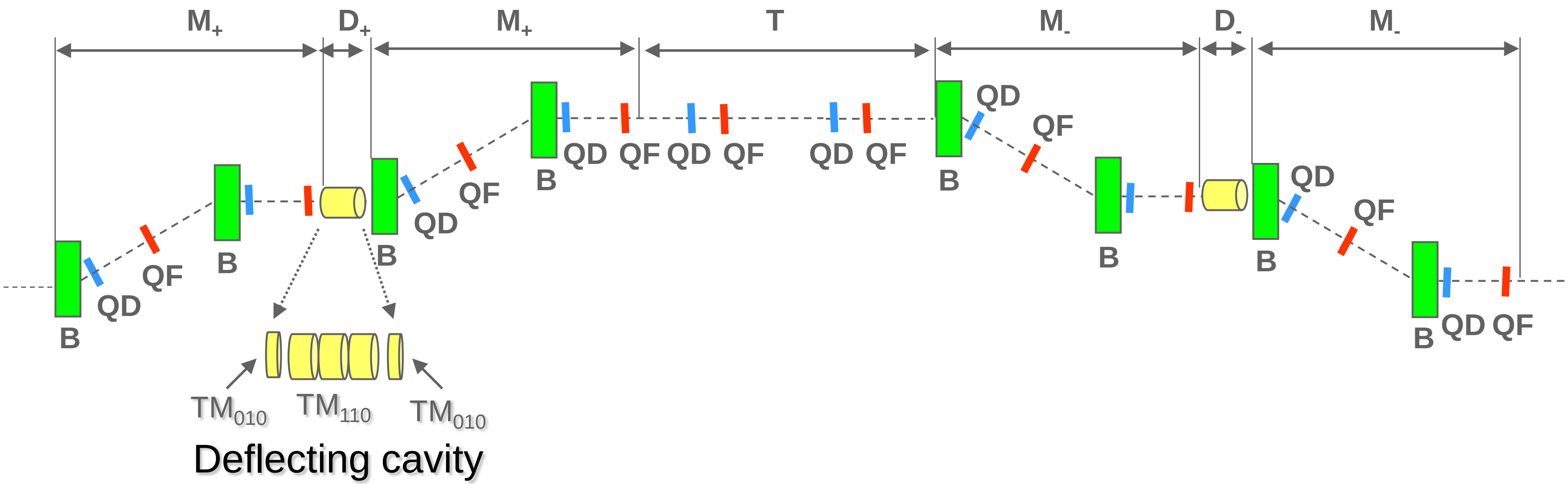
P. Emma, Z. Huang, K.-J. Kim, P. Piot, "Transverse-to-Longitudinal Emittance Exchange to Improve Performance of High-Gain Free-Electron Lasers", Phys. Rev. ST Accel. Beams 9, 100702 (2006).

R.P. Fliller, D.A. Edwards, H.T. Edwards, T. Koeth, K.T. Harkay, K.-J. Kim, "Transverse to longitudinal emittance exchange beamline at the A0 Photoinjector", Part. Acc. Conf., PAC07, (2007).

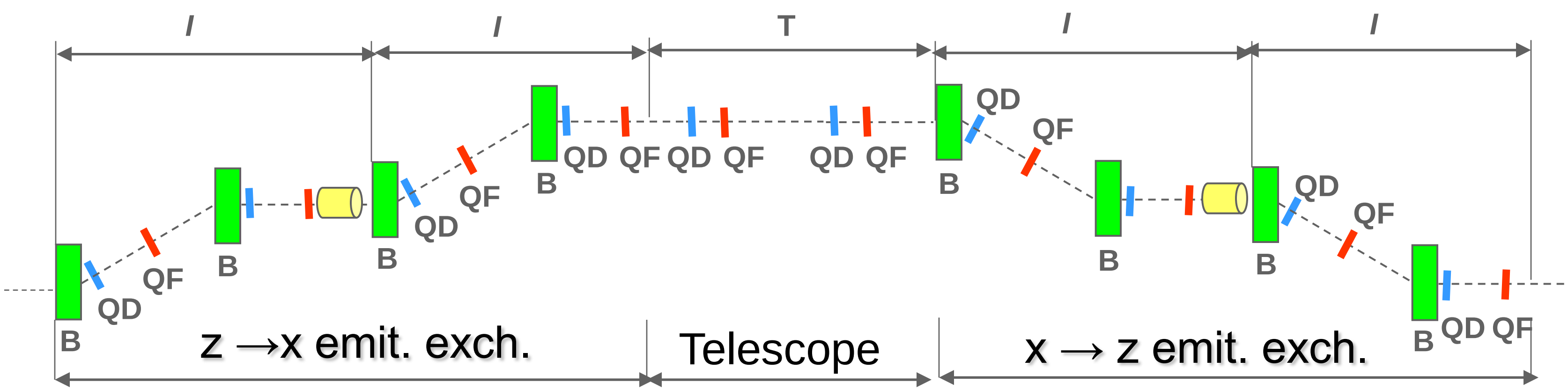
A schematic of the bunch compressor

(manipulate longitudinal phase space with ease of a transverse phase space)

Variant 1

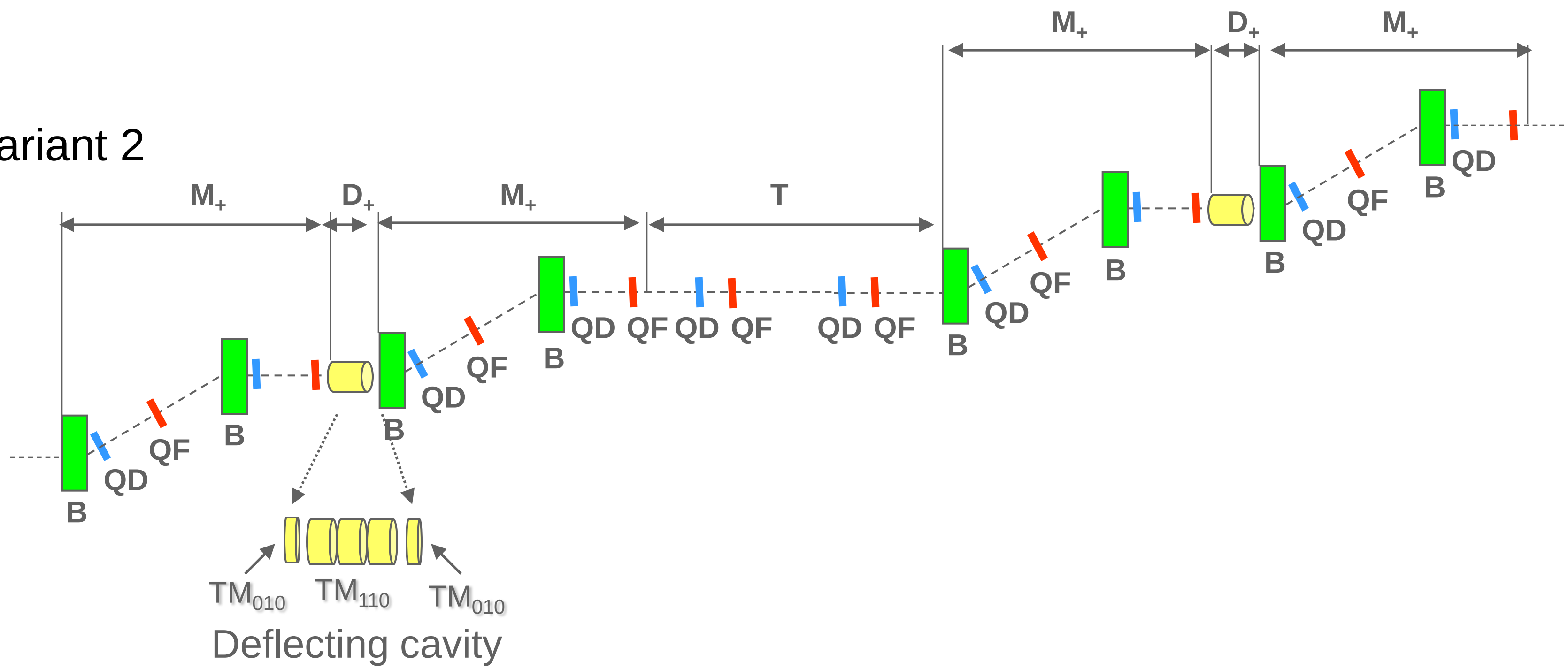


Focusing properties of individual sections

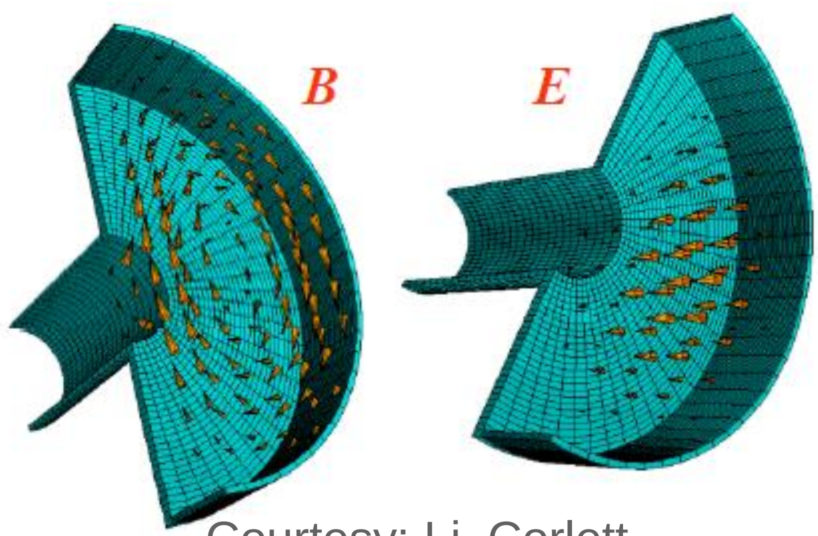


A schematic of the bunch compressor: alternative variant

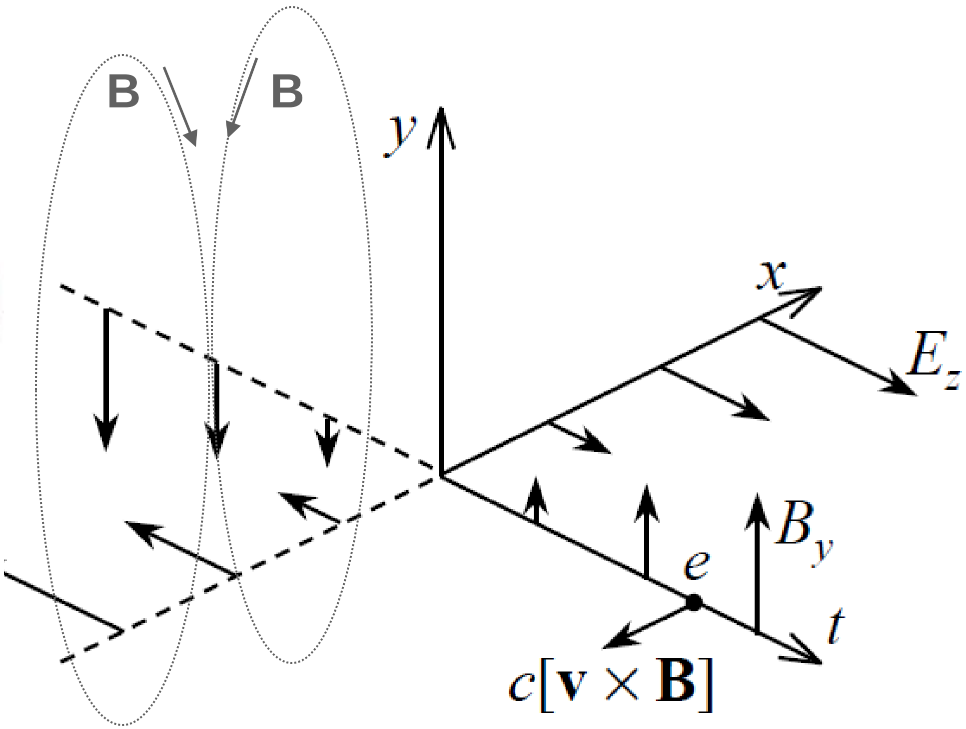
Variant 2



Deflecting cavity



Courtesy: Li, Corlett



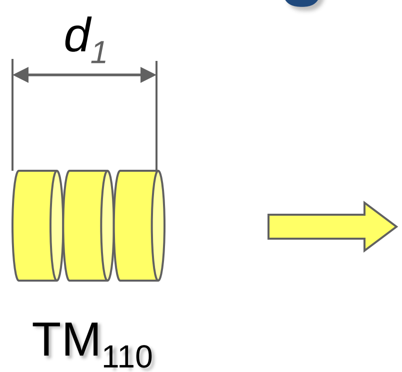
Thin cavity approximation:

$$\delta = \frac{2eV_0}{E} J_1(x/a)\cos(\omega_{rf} t) \approx \frac{eV_0}{Ea} x = k\,x$$

$$\Delta x' = \frac{2eV_0}{E}\frac{J_1(x/a)}{x/a}\sin(\omega_{rf} t) \approx \frac{eV_0}{Ea} ct \approx k\,z$$

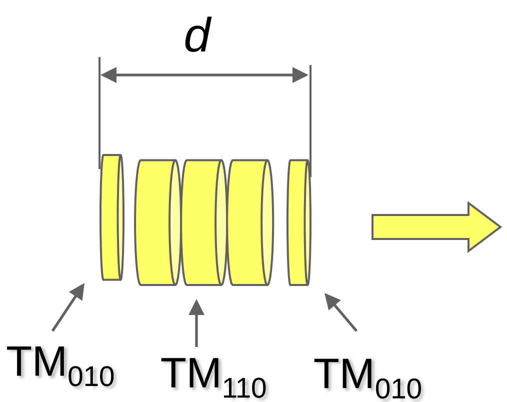
In agreement with Panofsky-Wentzel theorem

Thick deflecting cavity:



$$\begin{bmatrix} 1 & d_1 & kd_1/2 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & kd_1/2 & k^2 d_1/6 & 1 \end{bmatrix} \qquad \begin{bmatrix} x \\ x' \\ z \\ \delta \end{bmatrix}$$

One can cancel unwanted energy gain using two TM_{010} mode side cavities

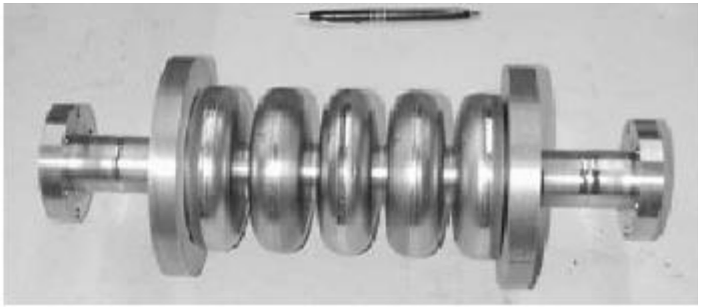


$$\begin{bmatrix} 1 & d & kd/2 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & kd/2 & 0 & 1 \end{bmatrix}$$

Required energy gain in each TM_{010} cavity

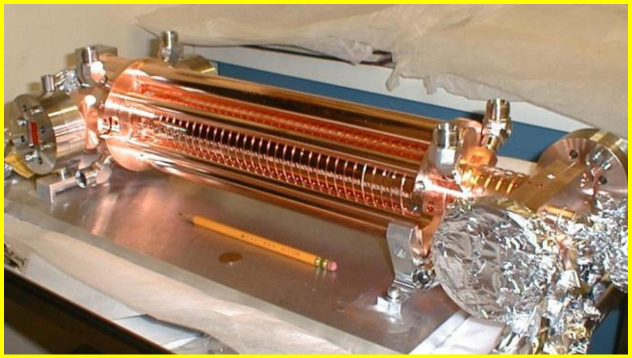
$$\frac{eV_1}{E} \approx -\frac{d_1}{12a}\left(\frac{eV_0}{E}\right)^2$$

FNAL: SRF five cell prototype



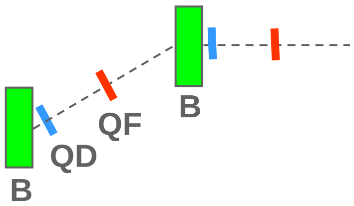
E_{beam} = 250 MeV
f_{RF} = 3.9 GHz
V_0 = 4 MV (1m, 3x7 cells: Li, Corlett)
V_1 = 0.4 MV
k = 0.013 cm^{-1}

SLAC: copper X-band LOLA



E_{beam} = 250 MeV
f_{RF} = 11.4 GHz
V_0 = 22 MV (0.5 m)
V_1 = 6.6 MV
k = 0.21 cm^{-1}

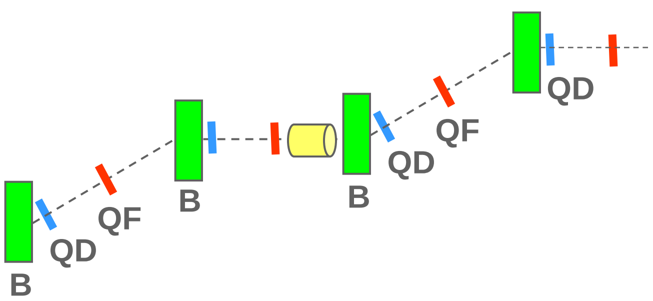
First leg of emittance exchange scheme



$$M_{+} = \begin{bmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \begin{matrix} x \\ p_x \\ z \\ \delta \end{matrix}$$

$$\xi \equiv R_{56}$$

Complete emittance exchange scheme



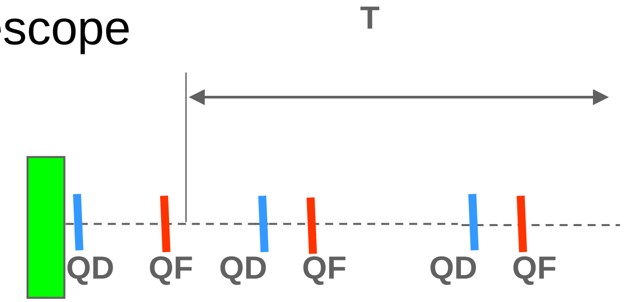
$$M_{+} \cdot D_{+} \cdot M_{+} = \begin{bmatrix} 0 & 0 & 0 & \eta \\ 0 & 0 & k & k\xi \\ k\xi & \eta & 0 & 0 \\ k & 0 & 0 & 0 \end{bmatrix} = E_{+}$$

The following constrains were used:

$$L = -d / 2$$

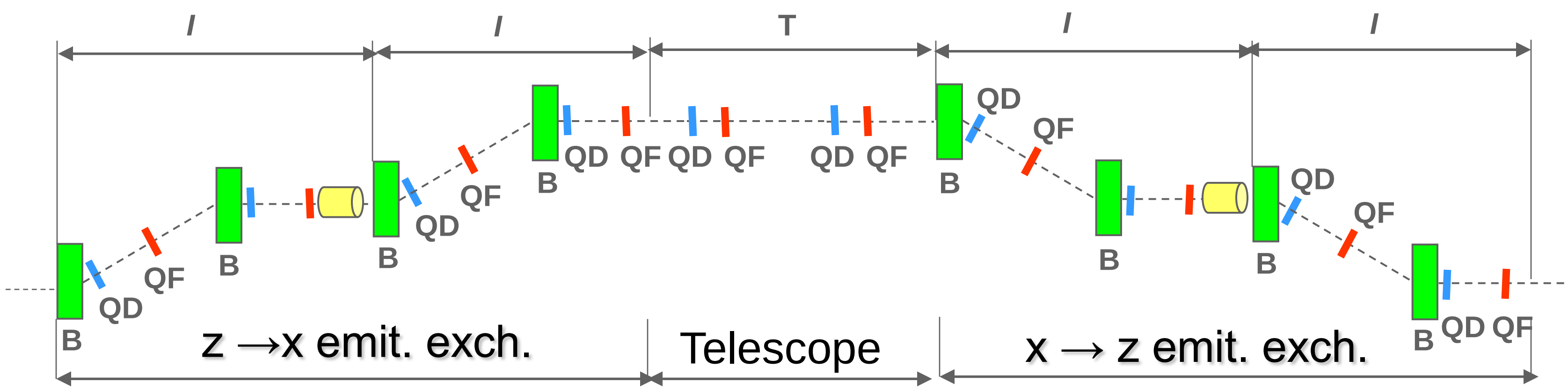
$$k\eta = -1$$

Telescope



$$T = \begin{bmatrix} -m & 0 & 0 & 0 \\ 0 & -1/m & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Total transformation



$$E_+ \cdot T \cdot E_- = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k^2\xi & 1 & 0 & 0 \\ 0 & 0 & -\frac{1}{m} & -\xi\left(\frac{1}{m} + m\right) \\ 0 & 0 & 0 & -m \end{bmatrix}$$

Bunch length and energy spread at the end of the scheme

Define:

σ_{z_i} - bunch length before compression,

σ_{δ_i} - uncorrelated relative energy spread before compression, and

$h = d(\ln E)/dz$ - energy chirp before compression

σ_{z_f} - bunch length after compression,

σ_{δ_f} - uncorrelated relative energy spread after compression

Using entire mapping one obtains :

$$\sigma_{z_f} = \sqrt{\left(\frac{1}{m} - h\xi\left(\frac{1}{m} + m\right)\right)^2 \sigma_{z_i}^2 + \xi^2\left(\frac{1}{m} + m\right)^2 \sigma_{\delta_i}^2}$$

$$\sigma_{\delta_f} = m\sqrt{h^2\sigma_{z_i}^2 + \sigma_{\delta_i}^2}$$

No chirp case, e.g., *h* = 0

$$\sigma_{z_f} = \sqrt{\frac{\sigma_{z_i}^2}{m^2} + \xi^2 \left(\frac{1}{m} + m\right)^2 \sigma_{\delta_i}^2}$$

$$\sigma_{\delta_f} = m \sigma_{\delta_i}$$

Case 1

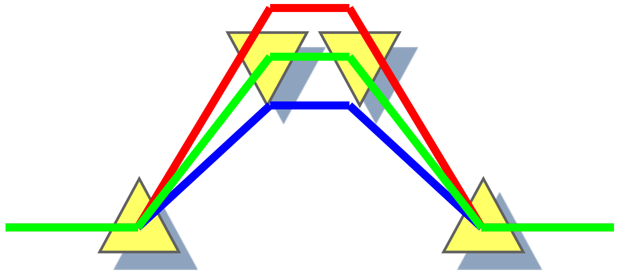
$$\xi \sigma_{\delta_i} \left(\frac{1}{m} + m\right) << \frac{\sigma_{z_i}}{m} \quad \text{then} \quad \sigma_{z_f} \approx \sigma_{z_i} / m$$

Case 2

$$\xi \sigma_{\delta_i} \left(\frac{1}{m} + m\right) >> \frac{\sigma_{z_i}}{m}$$

Then the compression is not yet finished

The last element of proposed BC is the chicane/dogleg with its R_{56} used to cancel the R_{56} accumulated upstream



$$R_{56} = -\xi(1 + 1/m^2)$$

Then, the entire mapping takes the following form:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ -k^2\xi & 1 & 0 & 0 \\ 0 & 0 & -\frac{1}{m} & 0 \\ 0 & 0 & 0 & -m \end{bmatrix}$$

… and we obtain for the final bunch length and relative energy spread:

$$\sigma_{z_f} = \frac{1}{m}\sigma_{z_i}$$

$$\sigma_{\delta_f} = m\sigma_{\delta_i}$$

… or one may prefer to wait until the electron beam gains energy from E_1 to E_2 and do the final compression at E_2

Then R_{56} for the final step should be:

$$R_{56} = -\xi(1 + 1/m^2)\frac{E_2}{E_1}$$

… and we obtain for the final bunch length and relative energy spread:

$$\sigma_{z_f} = \frac{1}{m}\sigma_{z_i}$$

$$\sigma_{\delta_f} = m\,\sigma_{\delta_i}\frac{E_1}{E_2}$$

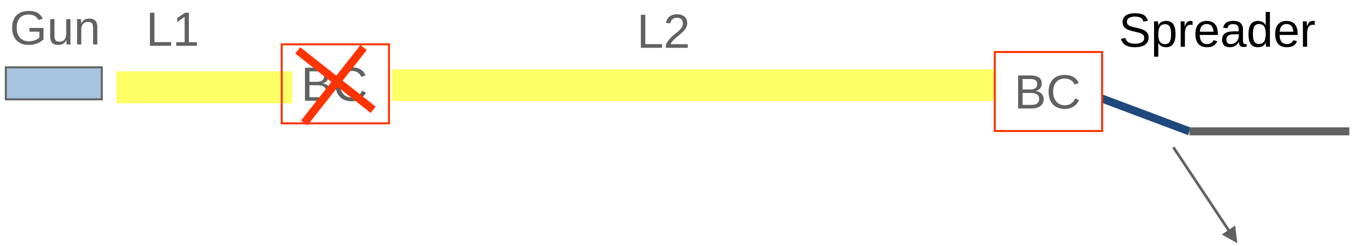
Possible advantage of a Deferred Compression is reduction of the gain of the microbunching instability and impact of other collective forces:

a) electron bunch is not yet compressed to the shortest size
b) energy spread has already grown up to the final value

Possible advantages

Because there is no need in energy chirp for compression:

a) one can use BC even after the linac and obtain final compression in a “spreader”/ “dogleg” part of the lattice leading to FEL

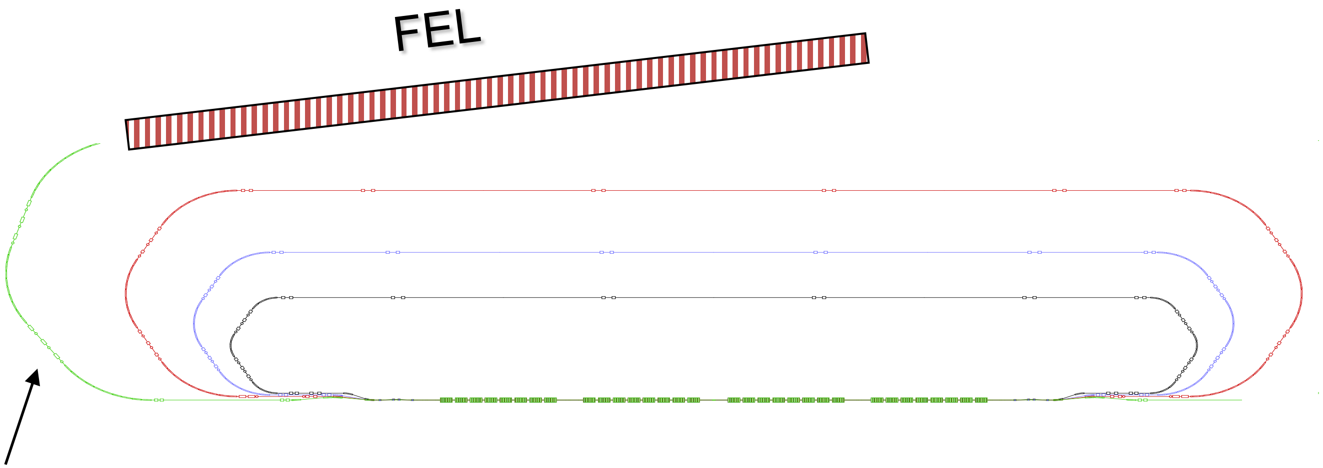


$$R_{56} = -\xi(1+1/m^2)$$

b) or use two BCs, one in usual location and one after the linac

Possible advantages (2)

Accelerate a relatively long bunch in the re-circulating linac without a chirp and compress it in the final arc.



New type of a bunch compressor

Possible cost saving

Jitter studies

No adverse jitter effects are found:
Timing jitter is compressed by a compression factor and energy jitter is increased by a compression factor:

$$\Delta t \rightarrow \Delta t / m$$

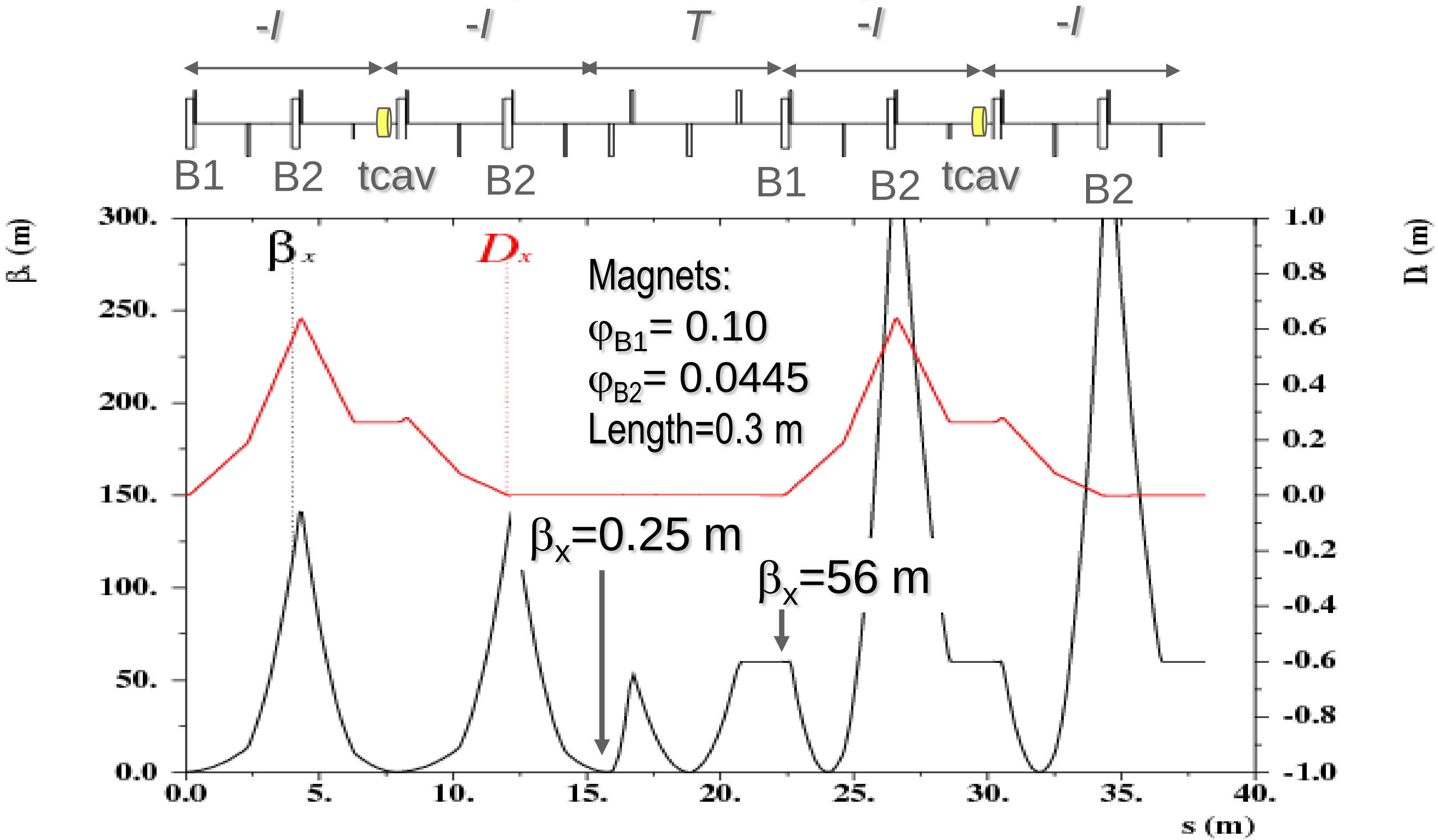
$$\Delta E \rightarrow \Delta E \cdot m$$

Illustration

In the following numerical example we use:
f_{RF} = 2.85 GHz
k=0.05 cm^{-1}
cavity length = 1 m

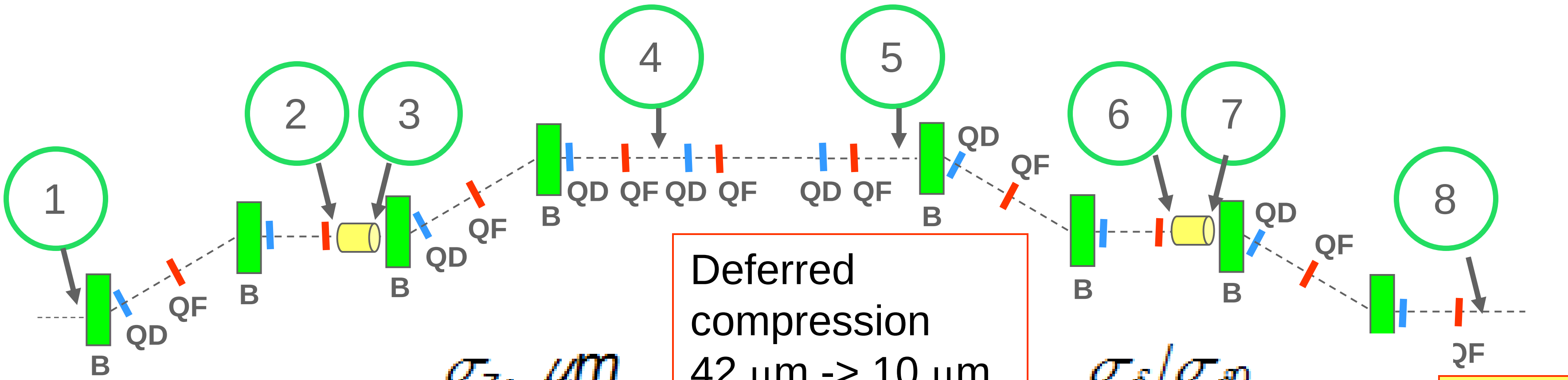
At E_b = 250 MeV this corresponds to:
V_0 = 21 MV
V_1 = -8.7 MV

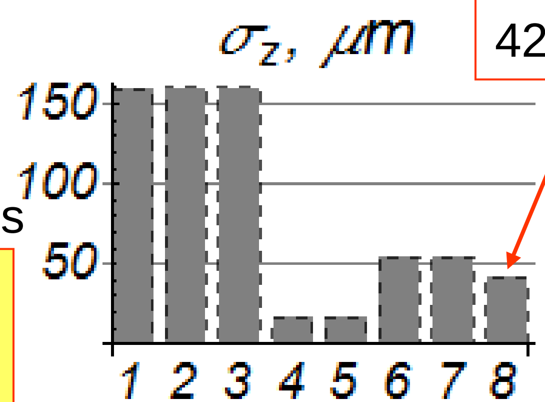
Illustration: compression by a factor of 15

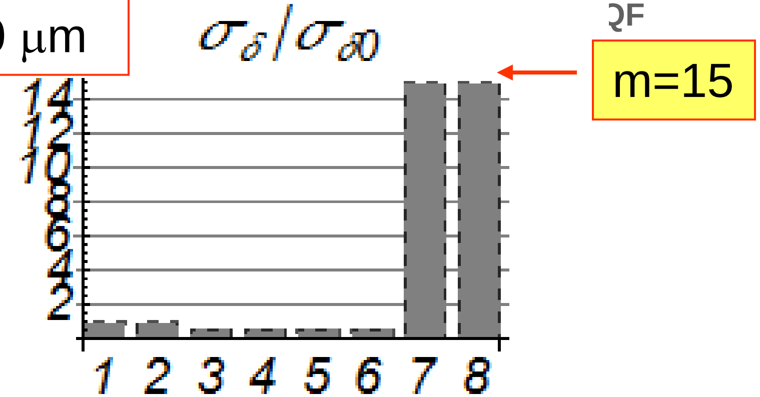


Lattice functions for a bunch compressor with a telescopic factor m=15. Note, matching of the vertical beta-function was not pursued.

Numerical values of beam sizes at key locations

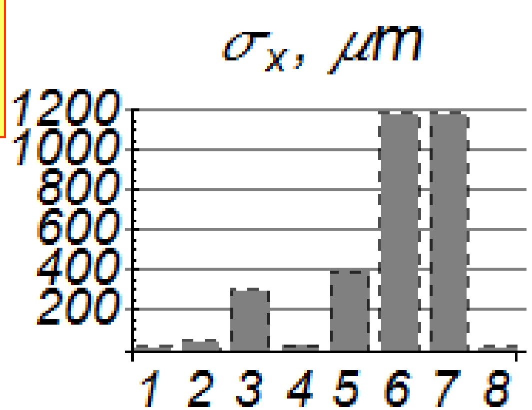


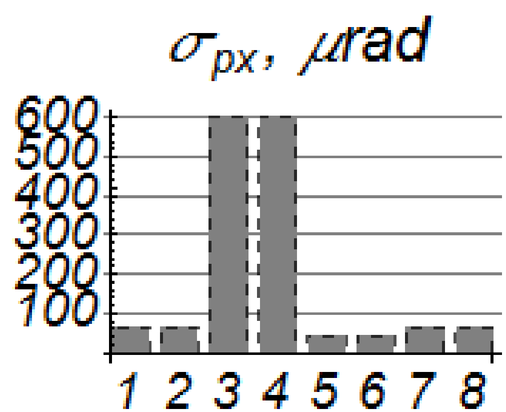




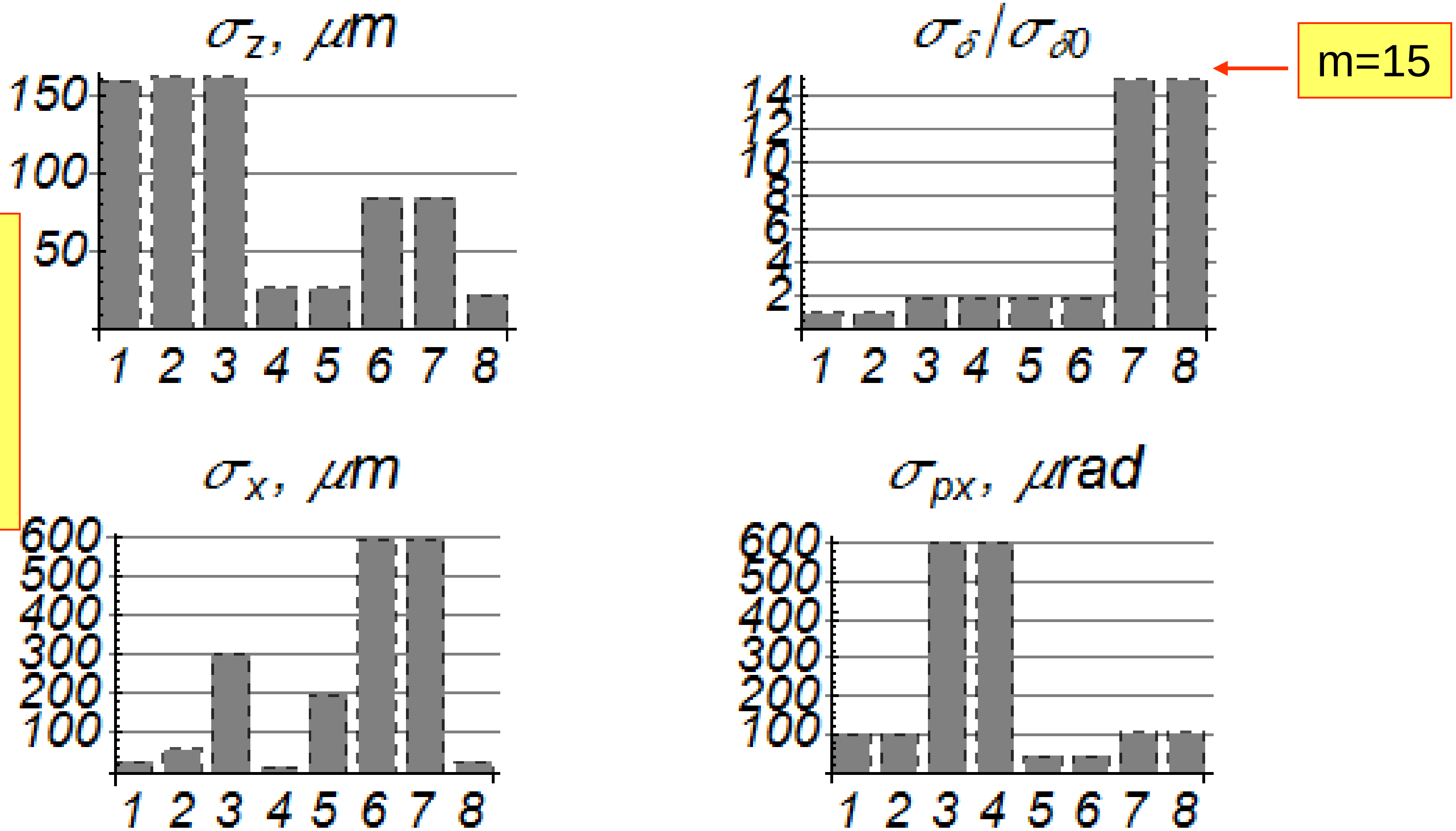
Input parameters

E_b=250 MeV
ε_x=0.5 μm
$\sigma_{\delta 0}=10^{-4}$
σ_{E0}=25 keV
σ_{z0}= 160 μm





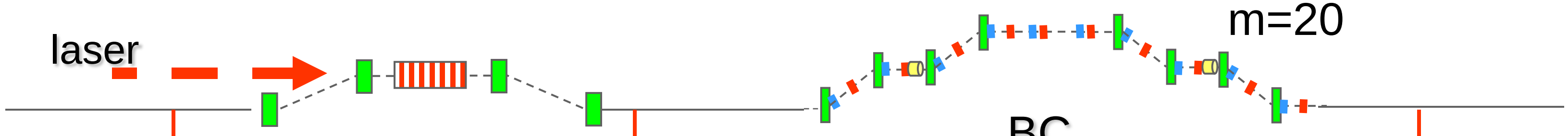
Same as before, but with a reduced beam energy to 100 MeV
This may eliminate a need in the laser heater



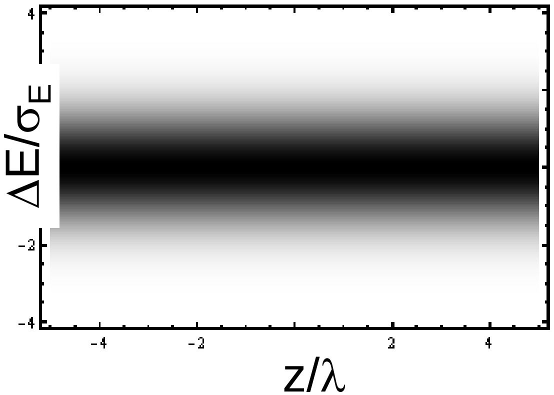
E_b=100 MeV
ε_x=0.5 μm
$\sigma_{\delta 0}=5\times10^{-5}$
σ_{E0}=5 keV
σ_{z0}= 160 μm

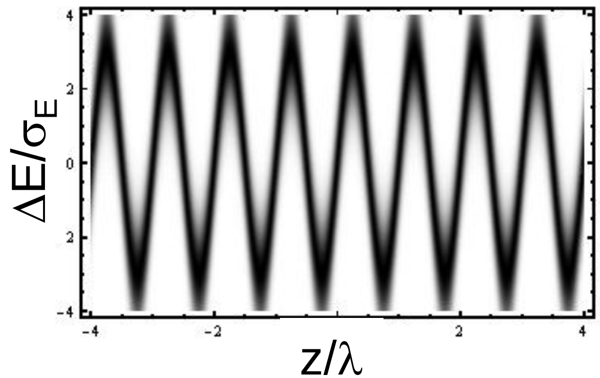
Compression of the laser induced energy modulation for microbunching at a shorter wave length

Compression factor, m=20

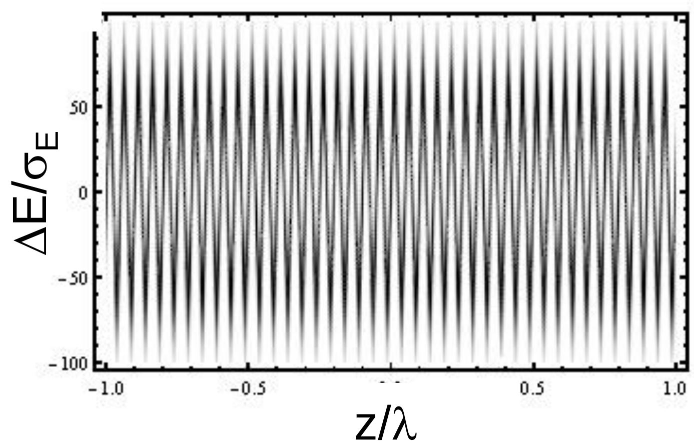


Initial modulation





Compressed modulation



Bunching efficiency at m-th harmonic of modulating frequency:

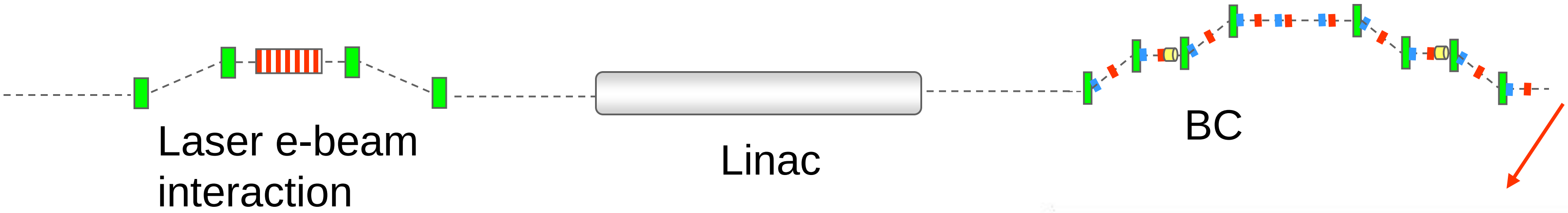
HGHG: $$|b_m| \propto e^{-\frac{1}{2}\left(\frac{m\sigma_E}{\Delta E}\right)^2}$$

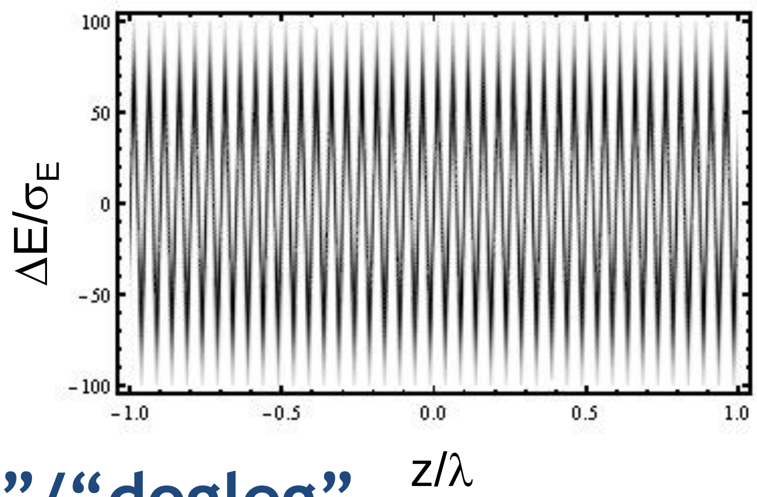
EEHG: $$|b_m| \propto m^{-1/3}\frac{\sigma_E}{\Delta E}$$

This method: $$|b_m| \propto m^0$$

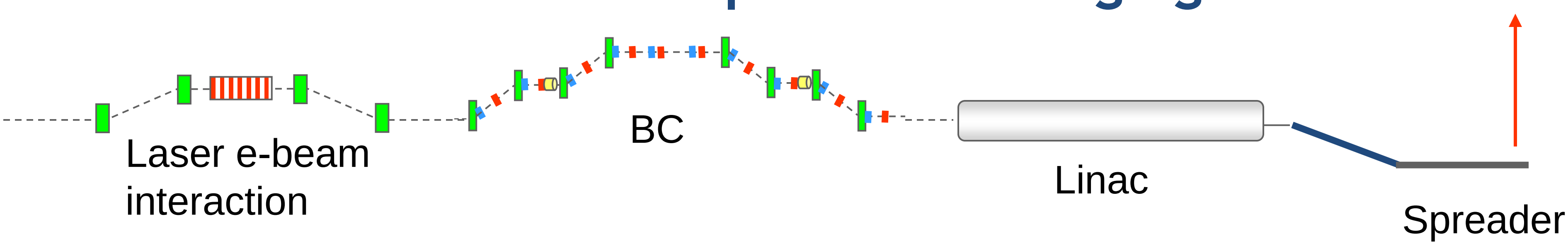
Plots of longitudinal phase space at various locations

Compression of the laser induced energy modulation can also be made at the end of the linac

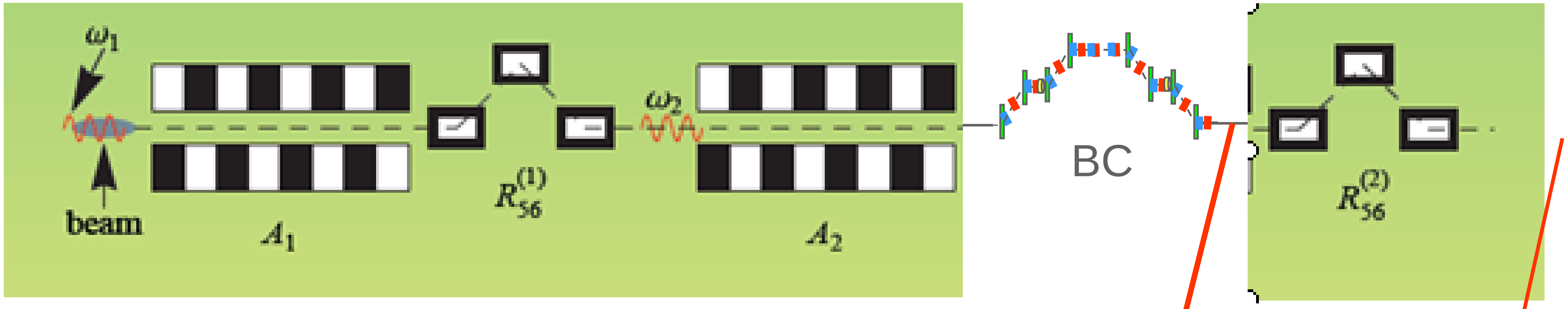




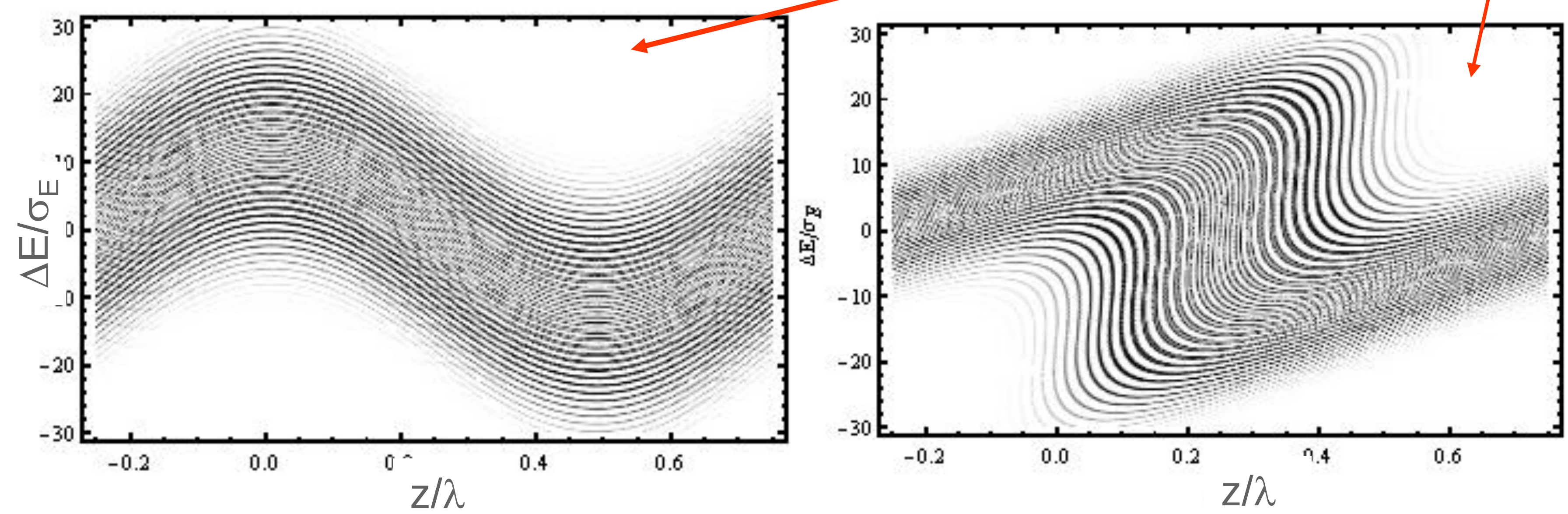
… or be deferred to a "spreader"/"dogleg"



Compression of the Echo induced microbunching

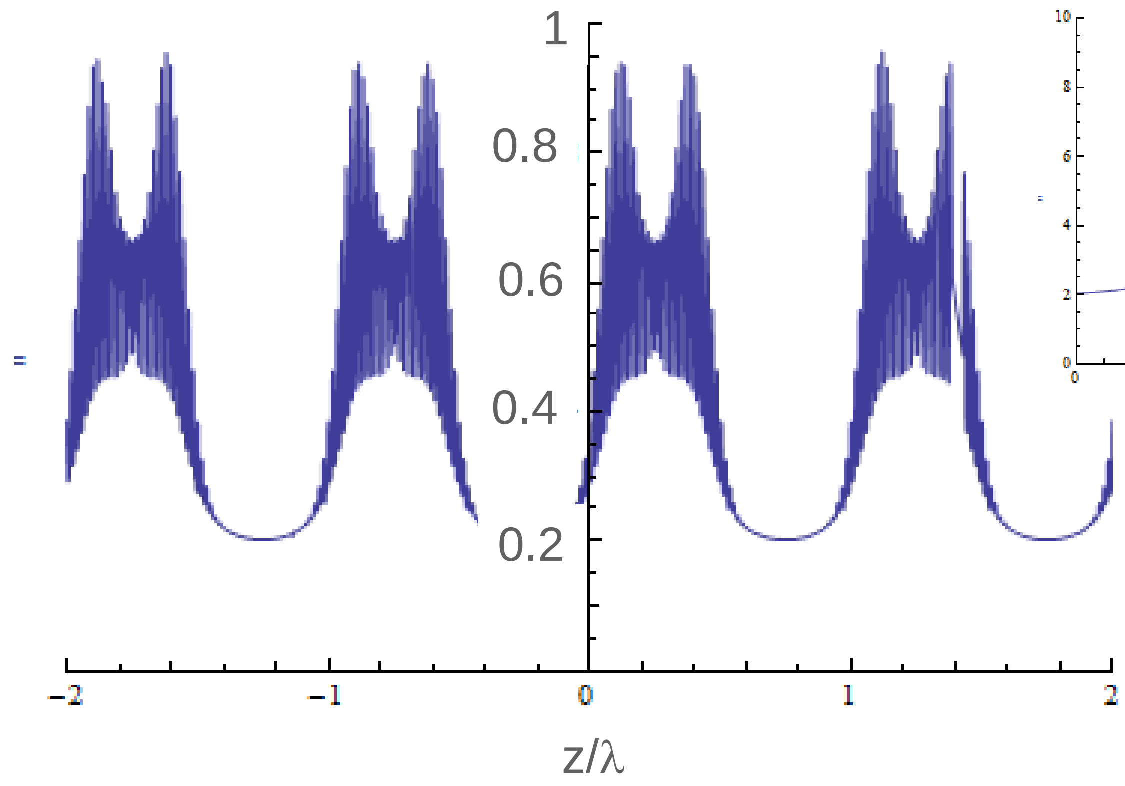


Compression factor, m=5

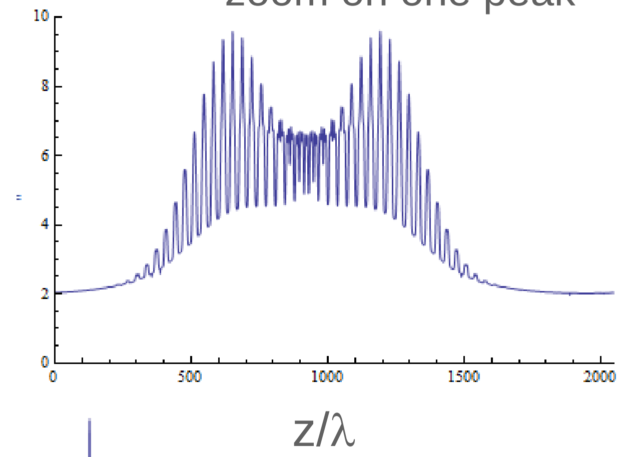


Compression of the Echo induced microbunching (2)

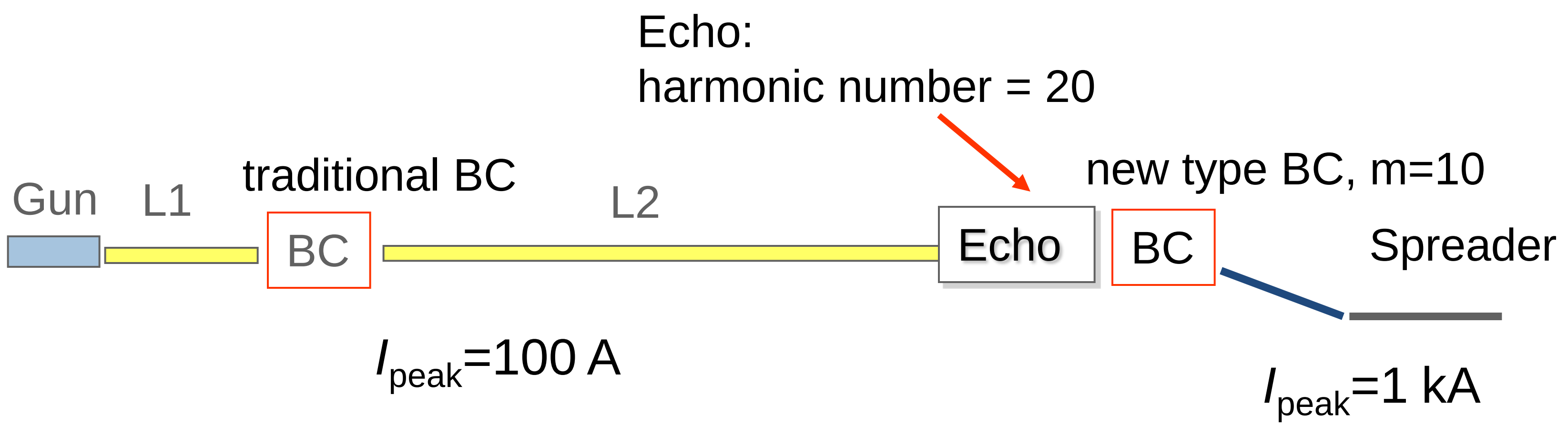
Peak current after compression, kA



zoom on one peak



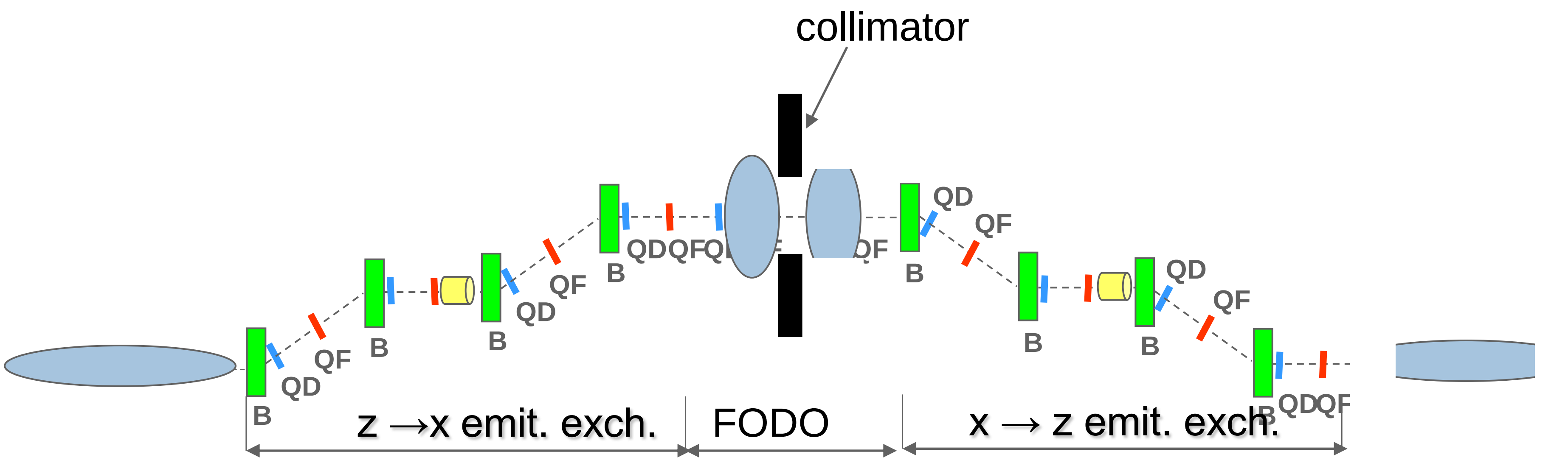
Producing 1 nm seeding beginning from 200 nm laser modulation



Total harmonic number = 20x10 = 200 !

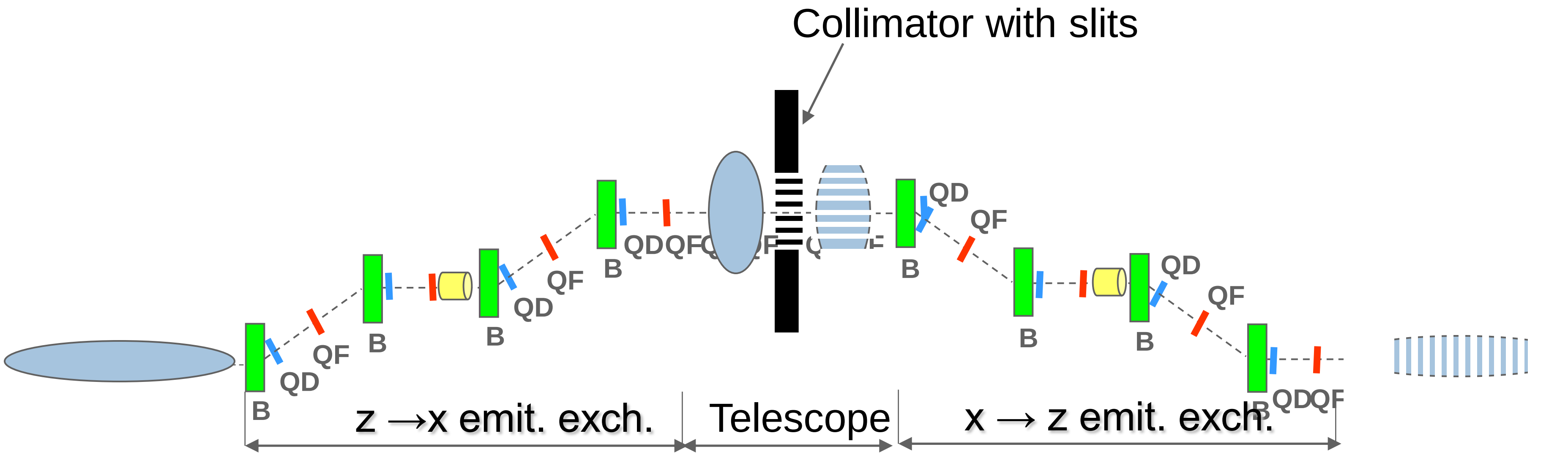
Other uses

It is often desirable to get rid off the tails in longitudinal distribution and proposed scheme can be used as efficient tail cutter



Other uses (2)

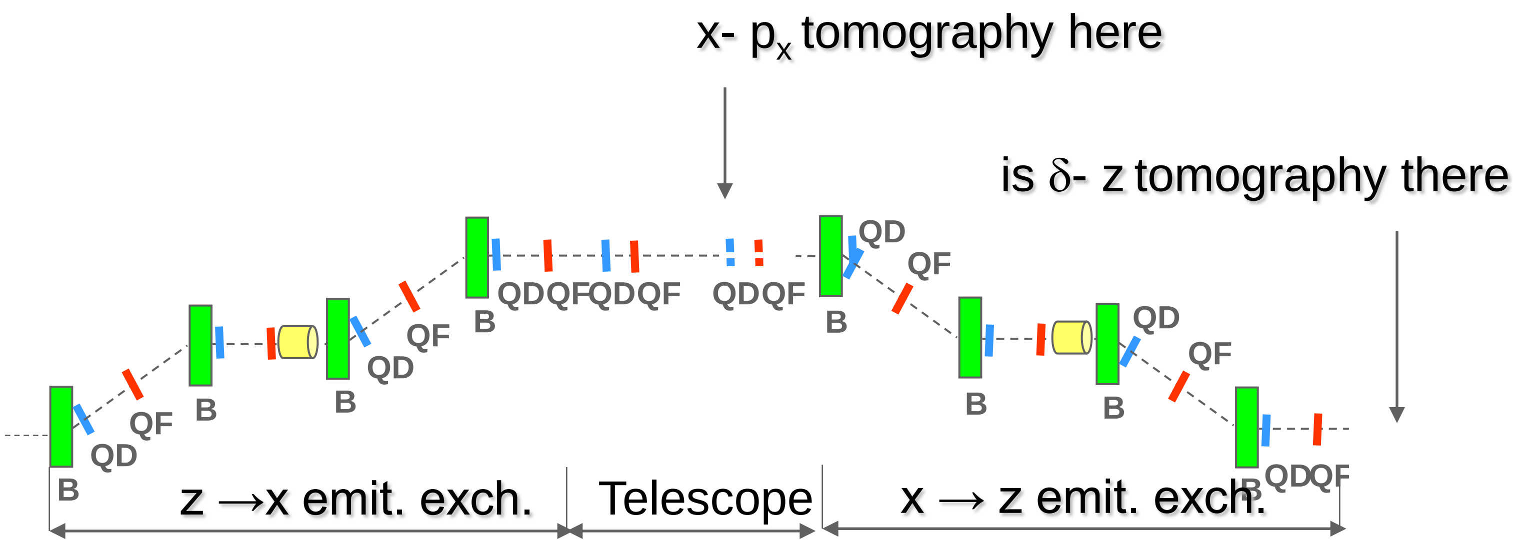
It is possible to create a sequence of a tightly spaced microbunches using a sequence of slits



Using demagnification of the beam size before slits and magnification after the slits can help to obtain a real tight spacing of microbunches

Other uses (3)

Longitudinal phase space tomography



Summary

1. Efficient electron bunch manipulation in the longitudinal phase space can be accomplished by first exchanging longitudinal and transverse emittances, manipulating electrons in the transverse phase space and finally exchanging emittances back to their original state.

2. One application is bunch compressor that does not need energy chirp
   - This can also be used for a compression of any features introduced to the electron bunch, like, for example energy modulation produced in interaction with the laser.

3. Proposed techniques for a bunch compression allows *deferred compression* that might be useful to mitigate possible adverse effects caused by collective forces.