Emittance Exchange and Bunch Compression

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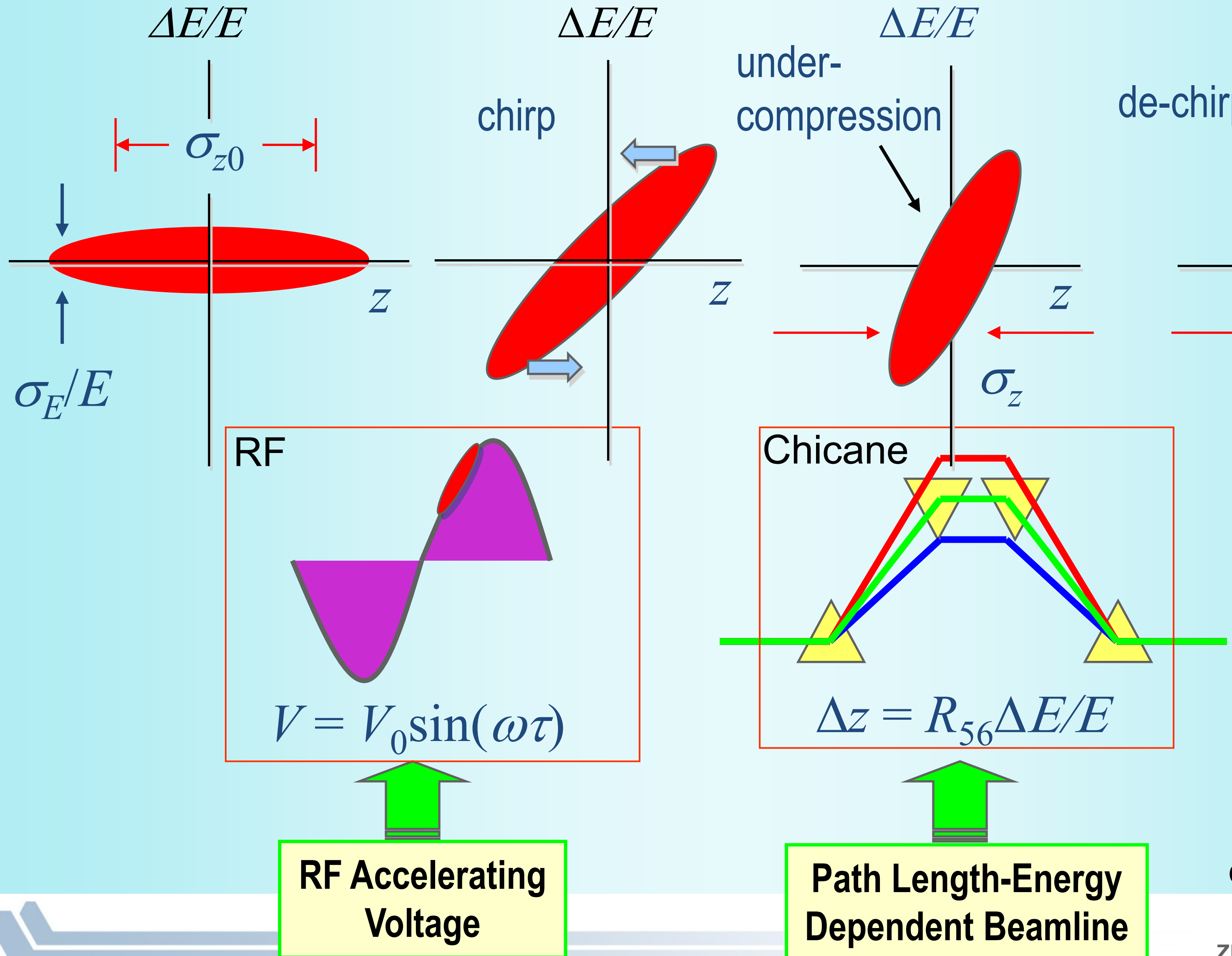
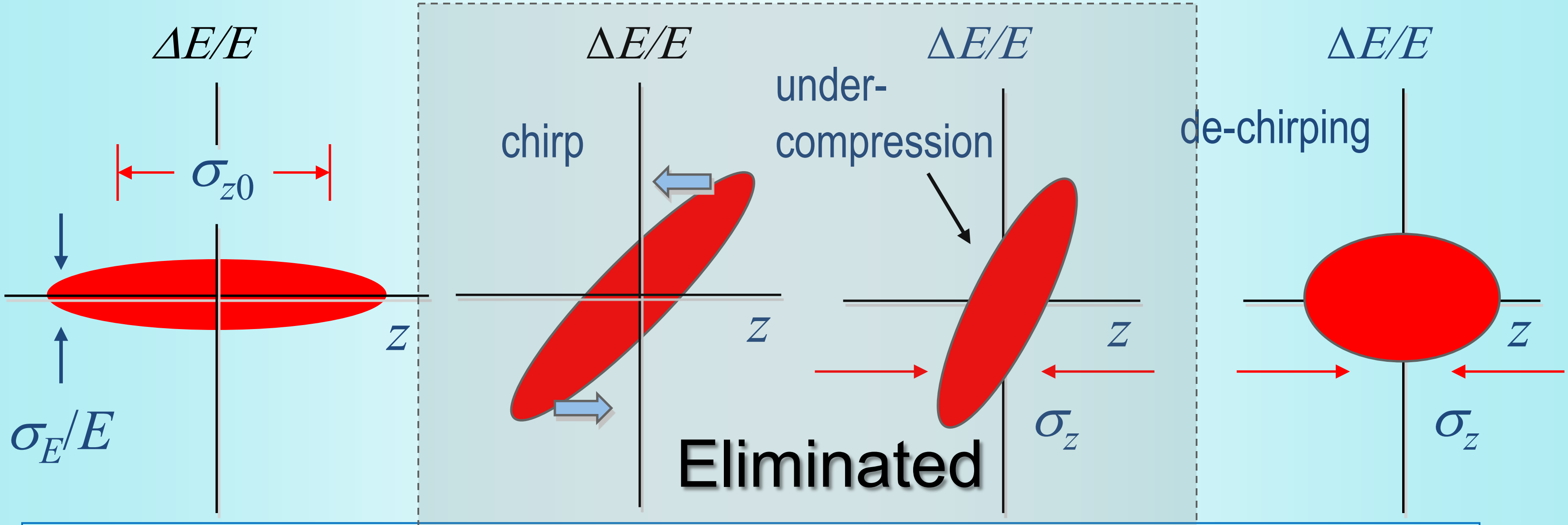
Increase peak current via rf energy modulation (chirping), magnetic bunch compression and de-chirping



courtesy P. Emma

What is proposed?

Performing bunch compression without energy chirp



Advantages:

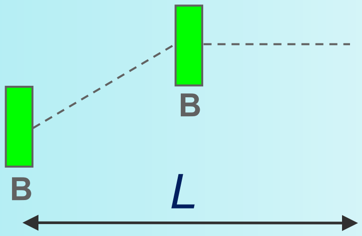
a) there is no energy chirp to remove after compression

- ❑ compression can be done at the end of the linac
  - reduced peak current in the linac
  - reduced CSR effects

b) additional benefits – to be discussed

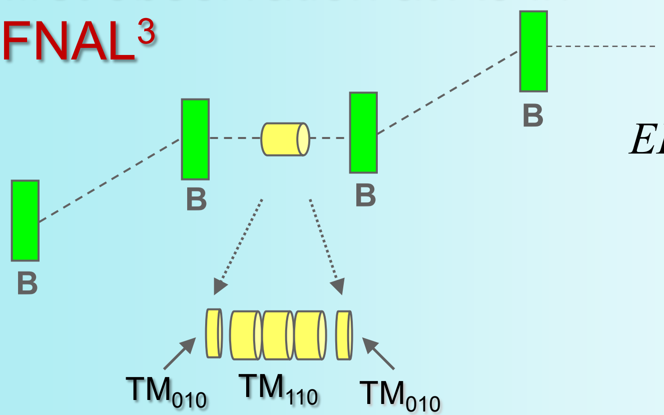
Emittance exchange[1]

First leg of EEX scheme



$$M=\begin{bmatrix}1 & L & 0 & \eta\\ 0 & 1 & 0 & 0\\ 0 & \eta & 1 & \xi\\ 0 & 0 & 0 & 1\end{bmatrix}\quad\begin{pmatrix}x\\ p_x\\ z\\ \delta\end{pmatrix}\qquad \xi\equiv R_{56}$$

Complete EEX scheme[2], first observation at A0 in FNAL[3]



Deflecting cavity

$$EEX=\begin{bmatrix}0 & 0 & \frac{1}{2}k(d+2L) & \eta+\frac{1}{2}k(d+2L)\xi\\ 0 & 0 & k & k\xi\\ k\xi & \eta+\frac{1}{2}k(d+2L)\xi & 0 & 0\\ k & \frac{1}{2}k(d+2L) & 0 & 0\end{bmatrix}$$

The following constraint was used: $k\eta=1$

1) M. Cornacchia, P. Emma, PRST-AB, **5**, (2002)
2) P. Emma, Z. Huang, K.-J. Kim, P. Piot, PRST-AB, **9**, (2006)
3) J. Ruan *et al*. http://arxiv.org/abs/1102.3155 , January 15, 2011

Emittance exchange[1]

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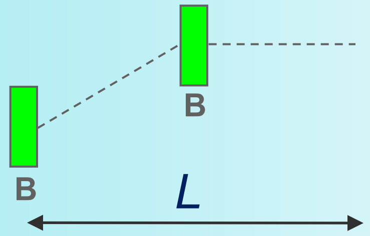

$$M = \begin{bmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \begin{pmatrix} x \\ p_x \\ z \\ \delta \end{pmatrix} \qquad \xi \equiv R_{56}$$

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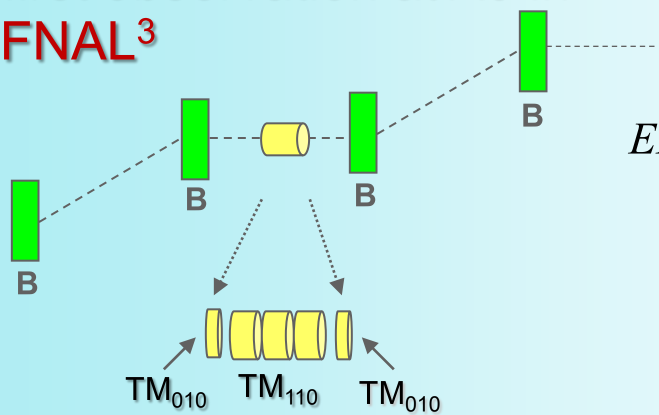

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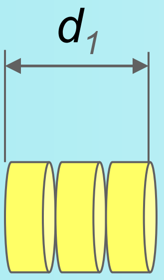
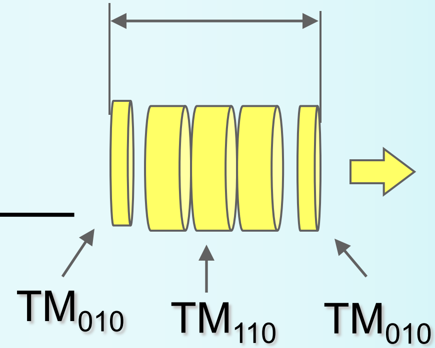
Thick deflecting cavity:



$$\begin{bmatrix} 1 & d_1 & kd_1/2 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & kd_1/2 & k^2 d_1/6 & 1 \end{bmatrix}$$

One can cancel unwanted energy gain using accelerating cavities on the sides :



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

$$\frac{eV_{010}}{E} \approx -\frac{d_1}{12a}\left(\frac{eV_{110}}{E}\right)^2$$

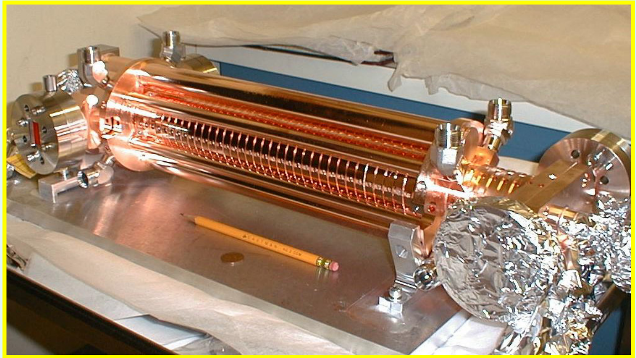
Thin cavity approximation $d_1 \rightarrow 0$:

$$\delta \approx \frac{eV_0}{Ea} x = k x$$

$$\Delta x' \approx \frac{eV_0}{Ea} ct \approx k z$$

In agreement with Panofsky – Wentzel theorem

Example: SLAC X-band LOLA cavity

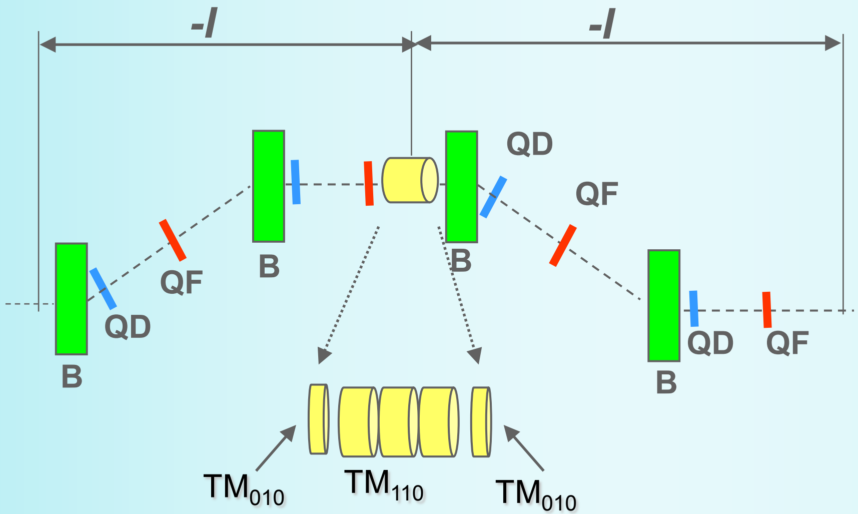


E_{beam} = 250 MeV
f_{RF} = 11.4 GHz
V_0 = 22 MV (0.5 m)
V_1 = 6.6 MV
k = 0.21 cm^{-1}

Emittance exchange (2)

Emittance exchange scheme used in this proposal

Transport matrixes of sections (ignoring cavity):

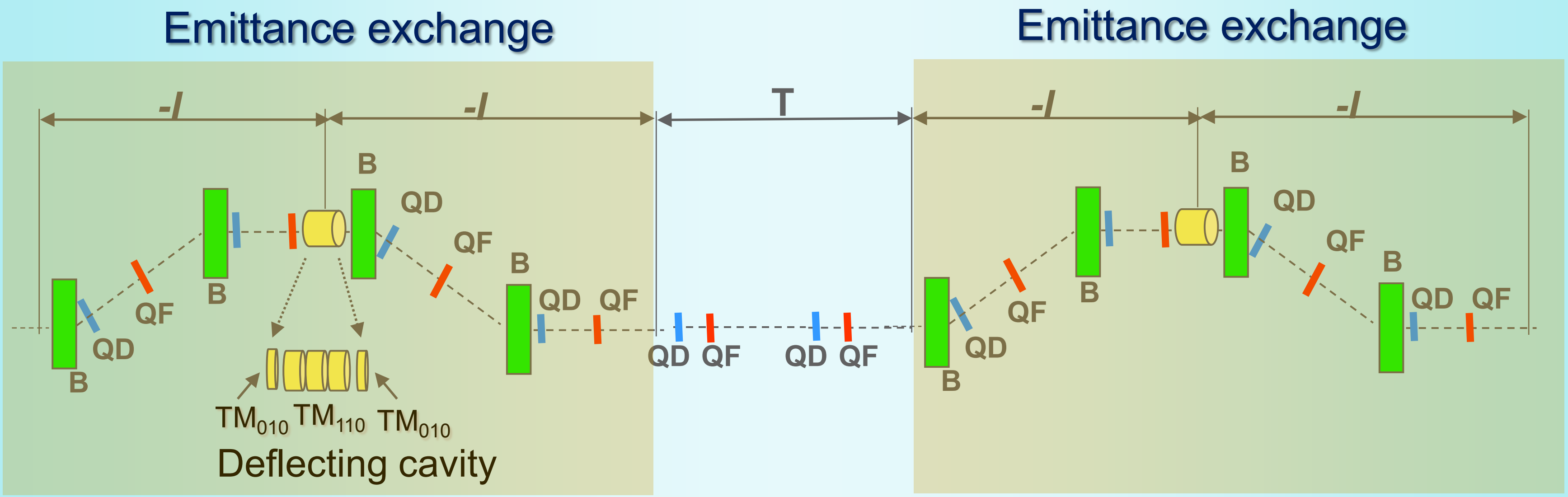


Deflecting cavity

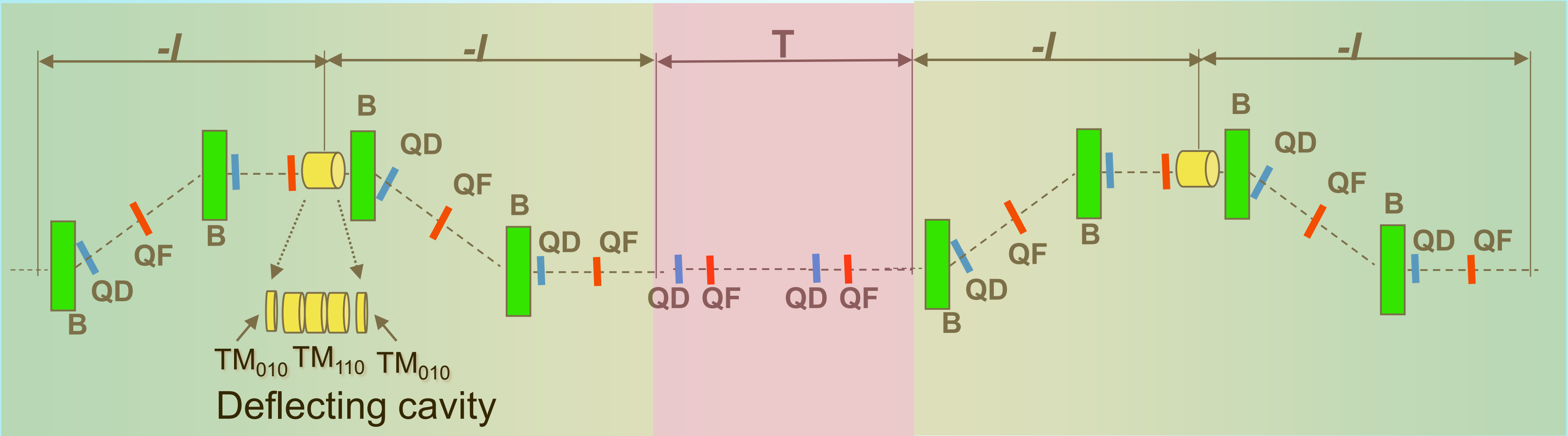
Has potential for increasing η in the deflecting cavity and reducing cavity strength, recall: $k = -1/\eta$

More emittance exchange schemes exists

A schematic of a proposed bunch compressor



A schematic of a proposed bunch compressor

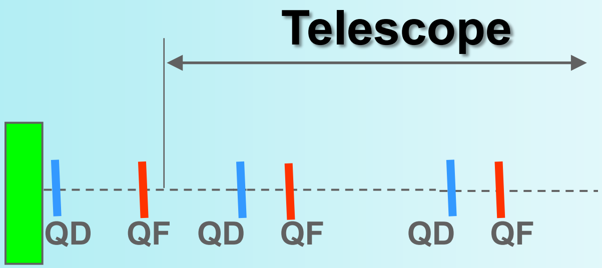


z →x emit. exch.

x → z emit. exch.

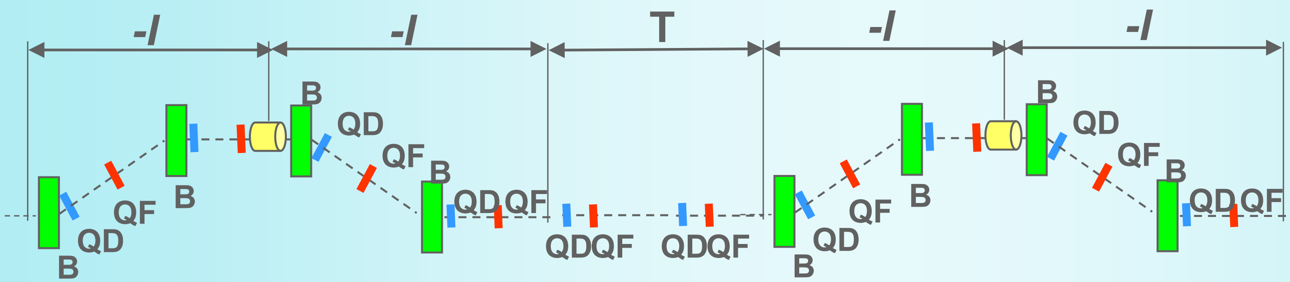
Manipulate the longitudinal phase space with ease of manipulation of the transverse phase space

A schematic of a proposed bunch compressor (2)



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

m is the de-magnification factor



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

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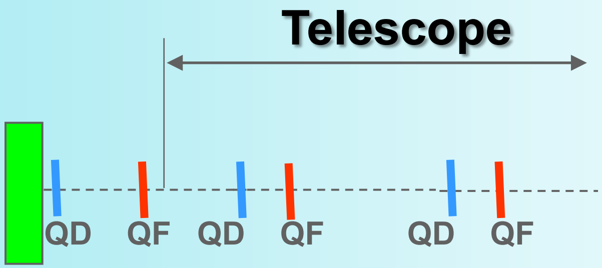

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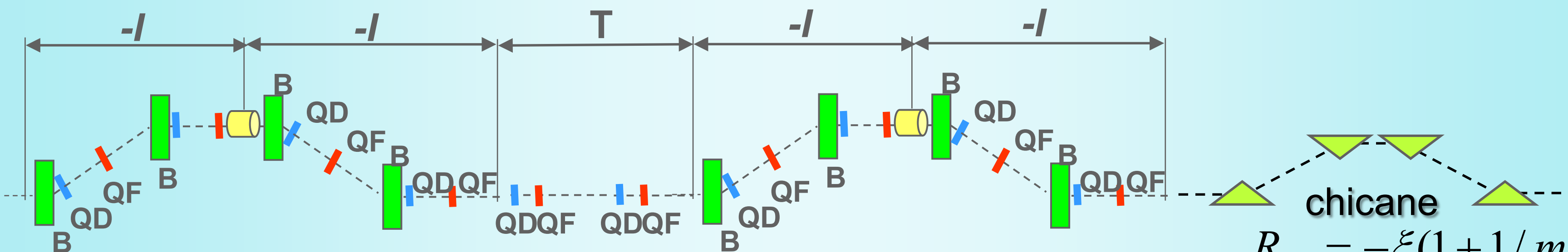


$$R_{56} = -\xi(1 + 1/m^2)$$

$$\sigma_z = \sigma_{z0}/m$$

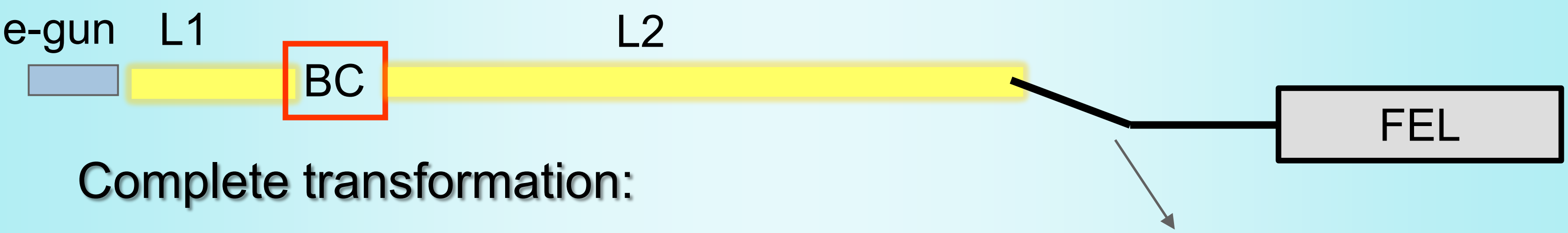
$$EEX \cdot T \cdot EEX = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k^2\xi & 1 & 0 & 0 \\ 0 & 0 & -\frac{1}{m} & -\xi(\frac{1}{m} + m) \\ 0 & 0 & 0 & -m \end{bmatrix}$$

Deferred compression:
e-bunch is not compressed to the shortest size

$$\sigma_\delta = m\sigma_{\delta 0}$$

Exploring "Deferred Compression"

one can cancel remaining R_{56} in a "dogleg" part of the lattice leading to FEL and obtain final compression right in front of the FEL



"Dogleg" transport line

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

Complete transformation:

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

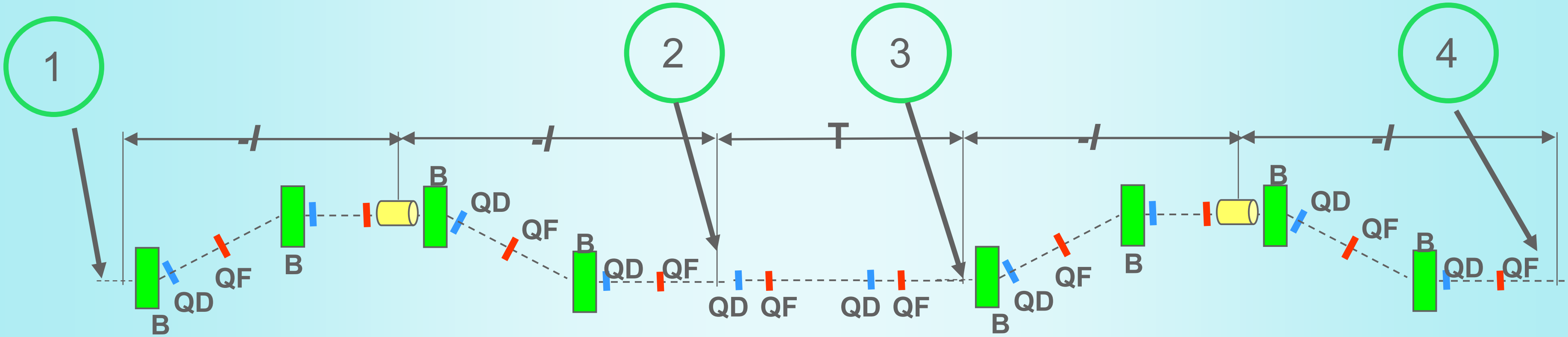
$$\sigma_z = \frac{1}{m}\sigma_{z_0}$$

$$\sigma_\delta = m\sigma_{\delta_0}$$

Benefits:

- reduced peak current in the linac, weaker space charge effect
- cure/mitigate microbunching instability:
  - less peak current
  - increased energy spread

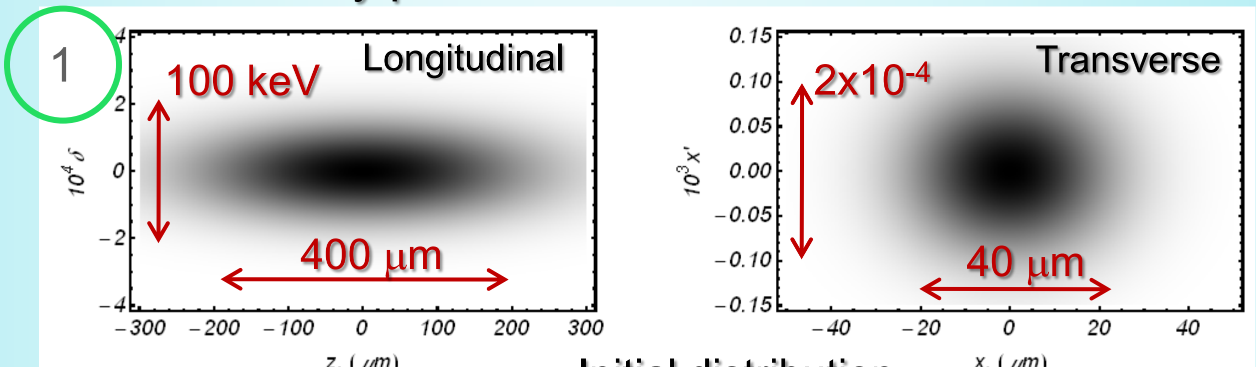
Evolution of the electron beam distribution, *m* =15



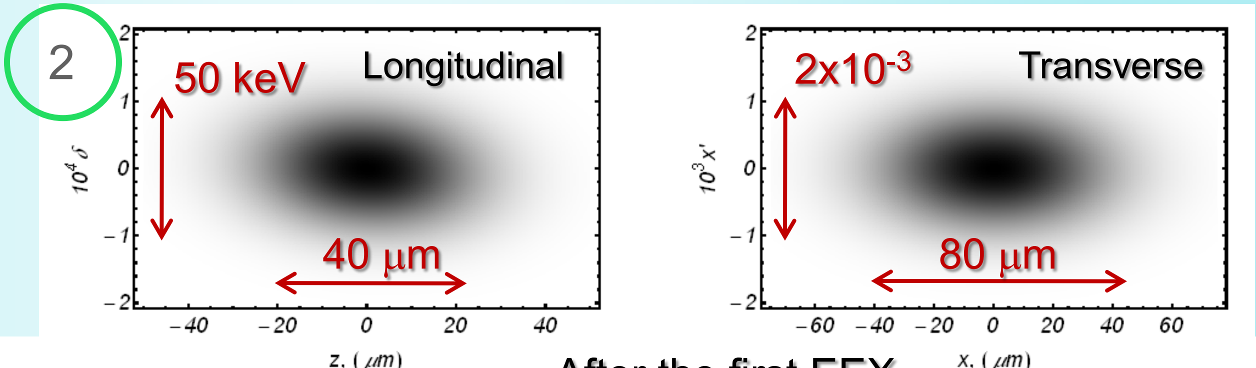
Density plots of electron beam distribution

Input parameters

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

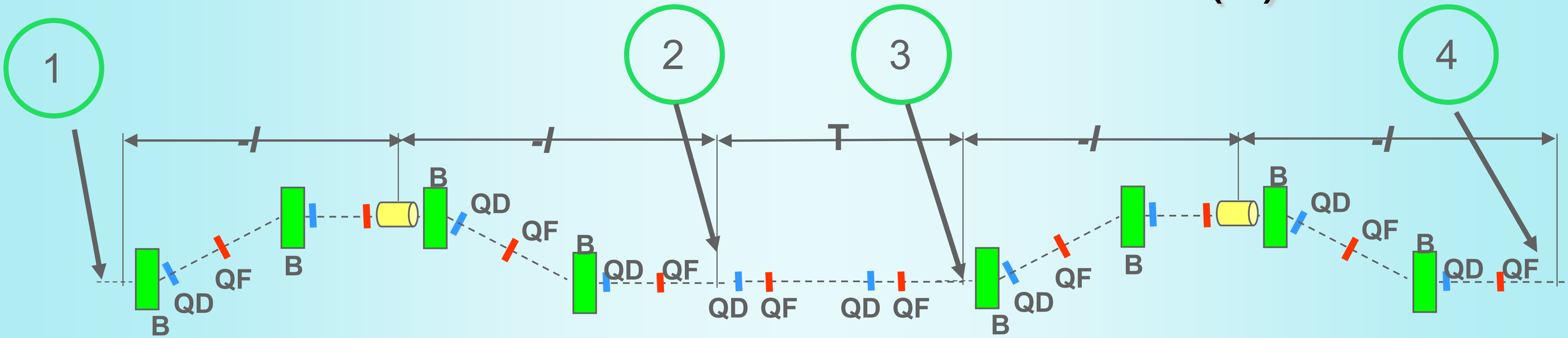


Initial distribution



After the first EEX

Evolution of the electron beam distribution (2)



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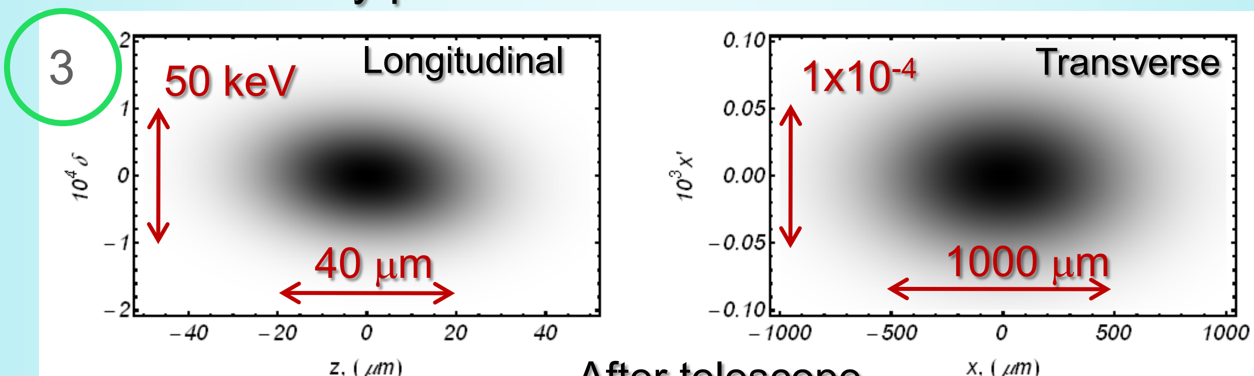
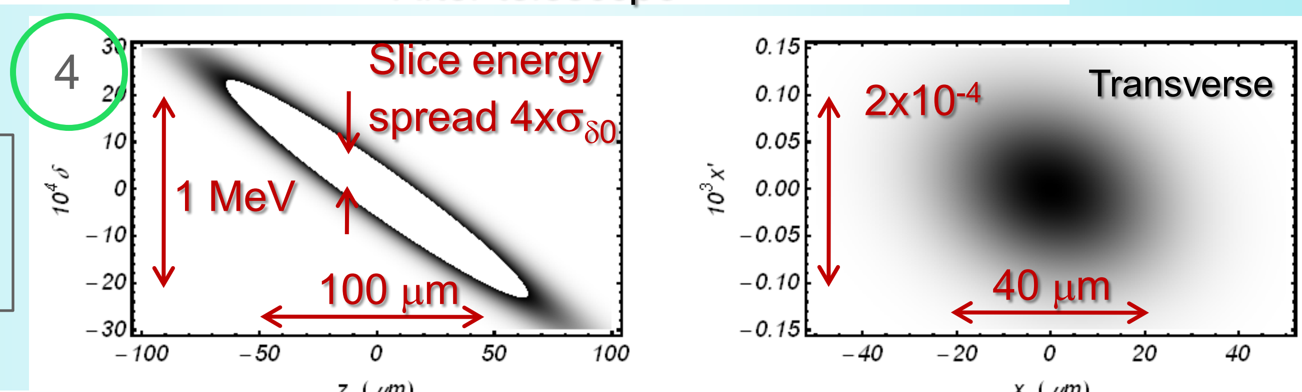


After telescope

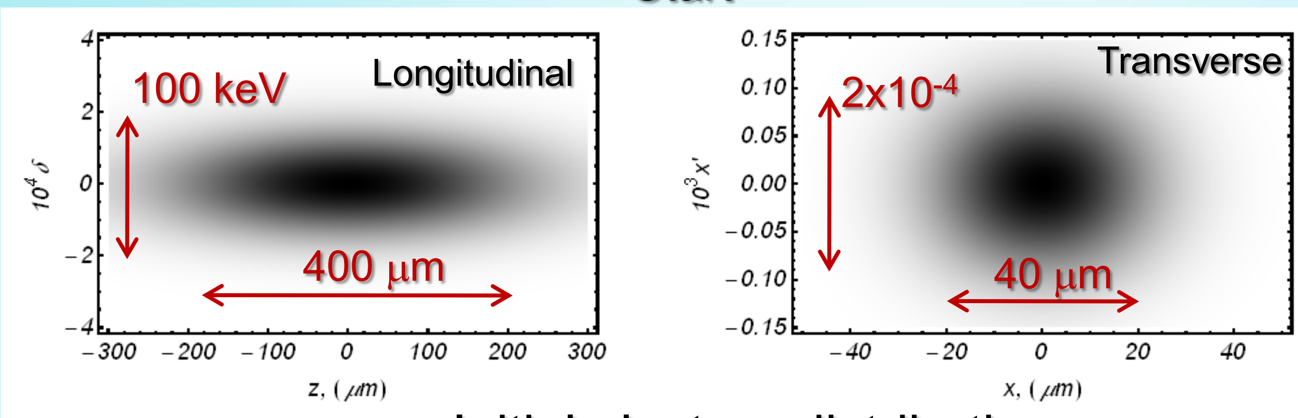


After the second EEX

$$\frac{d\delta}{dz} = -\frac{1}{\xi}\frac{m^2}{1+m^2}$$

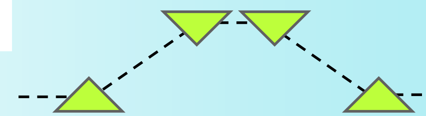
Evolution of the electron beam distribution (3)

Start



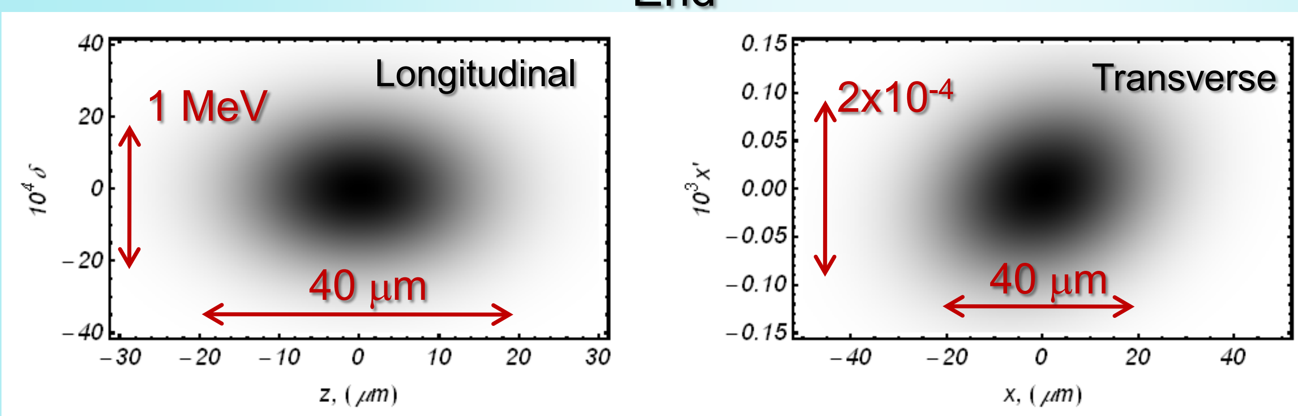
Initial electron distributions

chicane



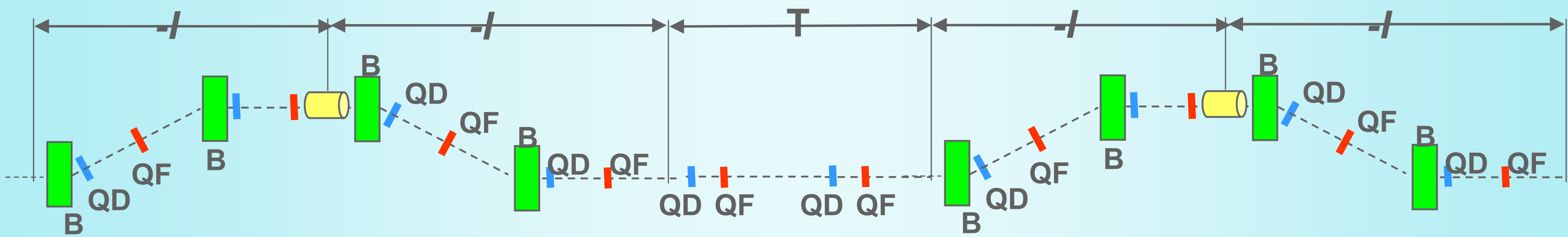
$$R_{56} = -\xi(1+1/m^2)$$

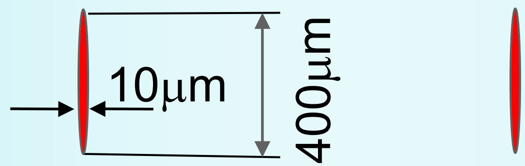
End



Final: after completion of deferred compression

Coherent Synchrotron Radiation





Intensity of bend magnet synchrotron radiation

$$W_N \approx N^2 W_1 f(k)$$

k is the wave number, W_1 is single electron emission

$$f(k) \propto \left| \iint dx dz \rho(x,z) e^{-ikx\sin\theta + ikz\cos\theta} \right|^2 = e^{-(k\sigma_x \sin\theta)^2 - (k\sigma_z\cos\theta)^2}$$

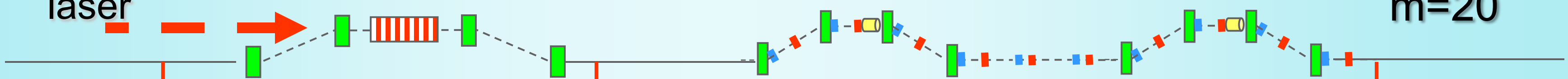
For given σ_z and σ_x , when $k\sigma_z \leq 1$, then $k\theta\sigma_x \geq 1$

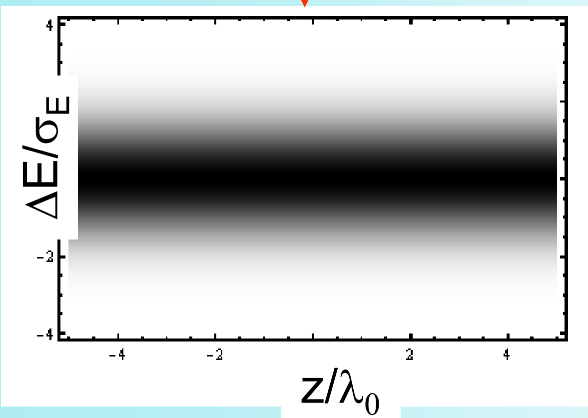
where $\theta \approx \frac{0.8}{\gamma}\left(\frac{1}{k\lambdabar_{crit}}\right)^{1/3}$; $\lambdabar_{crit} \approx 10\,\text{nm}$

CSR is partially suppressed by a large transverse beam size

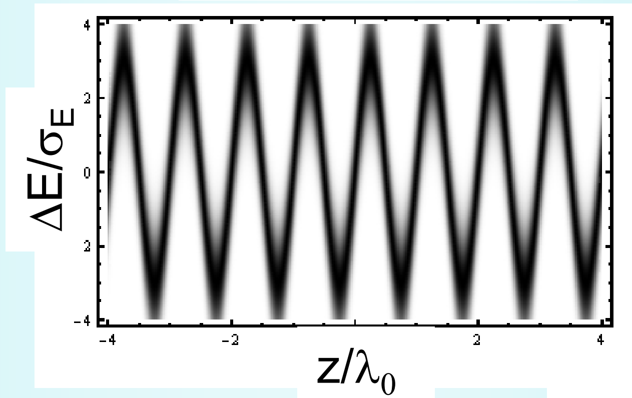
Compression of the laser induced energy modulation for microbunching at a shorter wave length

Compression factor, m=20

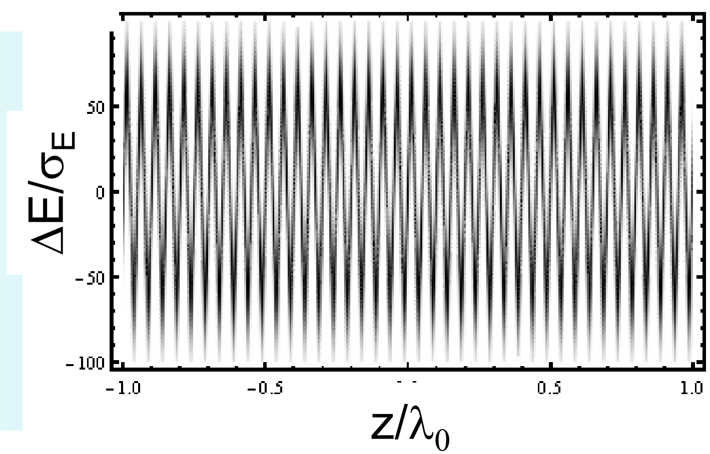




Initial modulation



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

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

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.