

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

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**“Any fool with four dipoles can compress a bunch”**

**- anonymous**

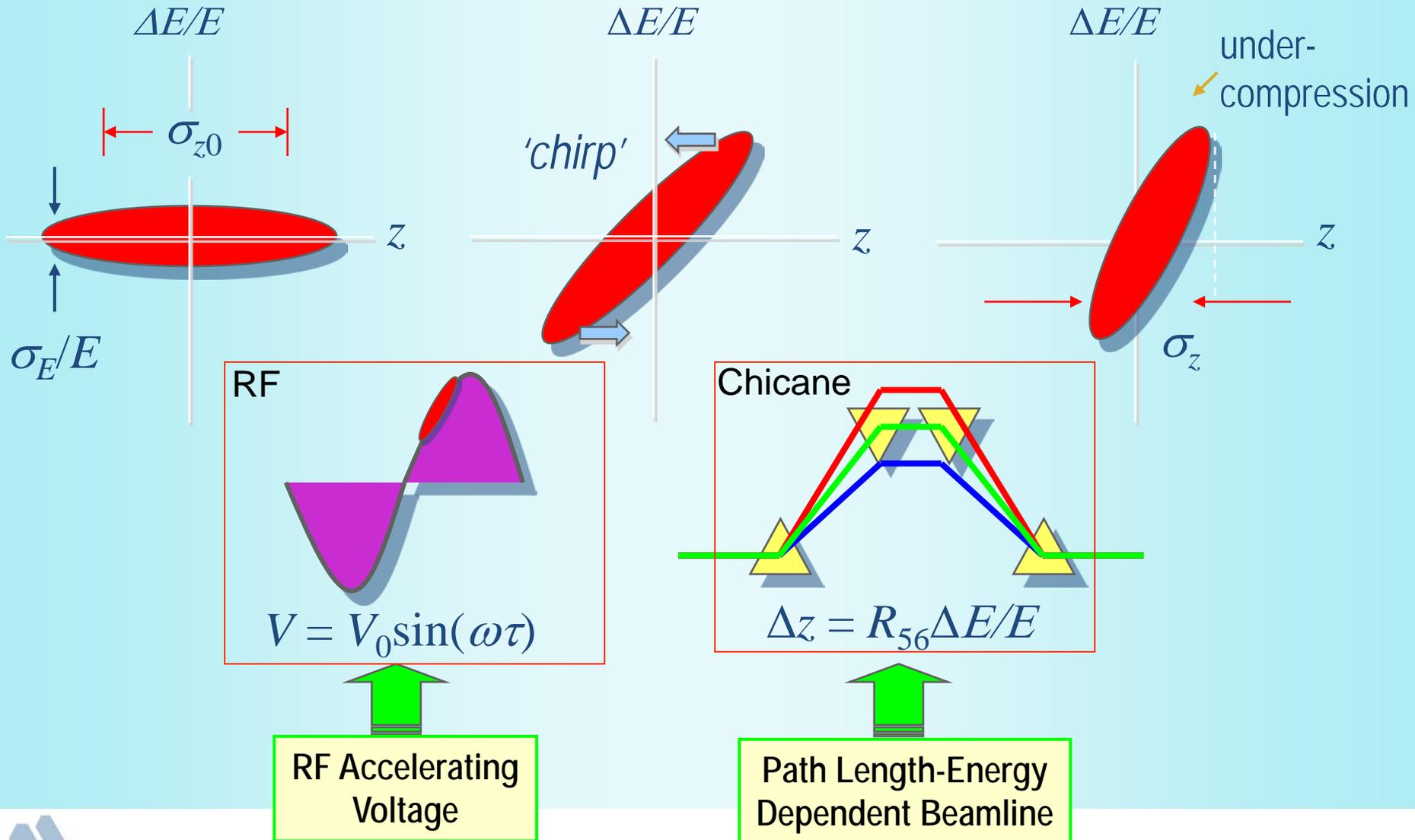


OK, but there may be a few details to consider...



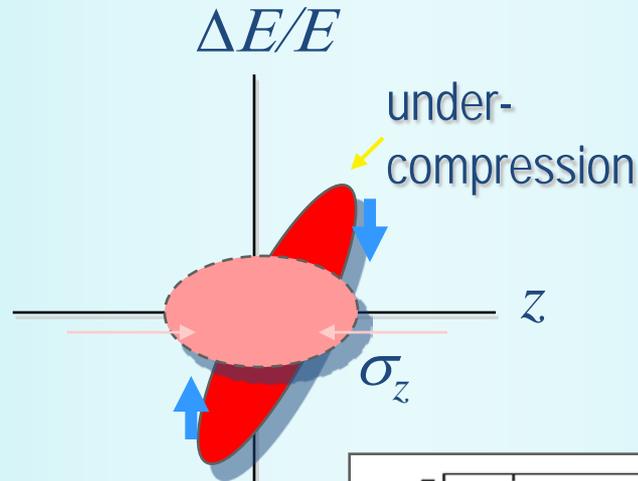
# Magnetic Bunch Compression

Courtesy P. Emma



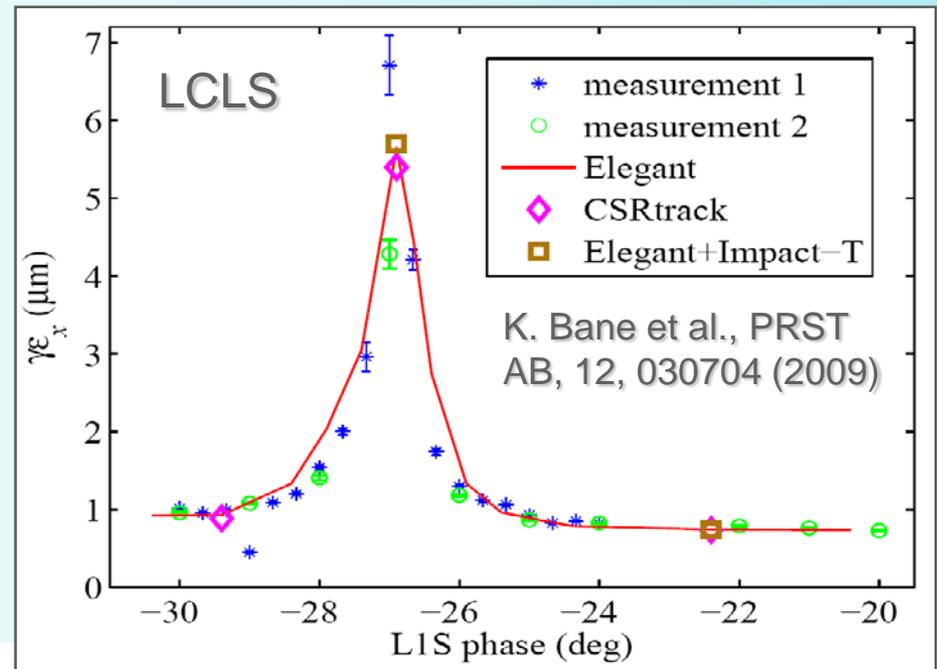
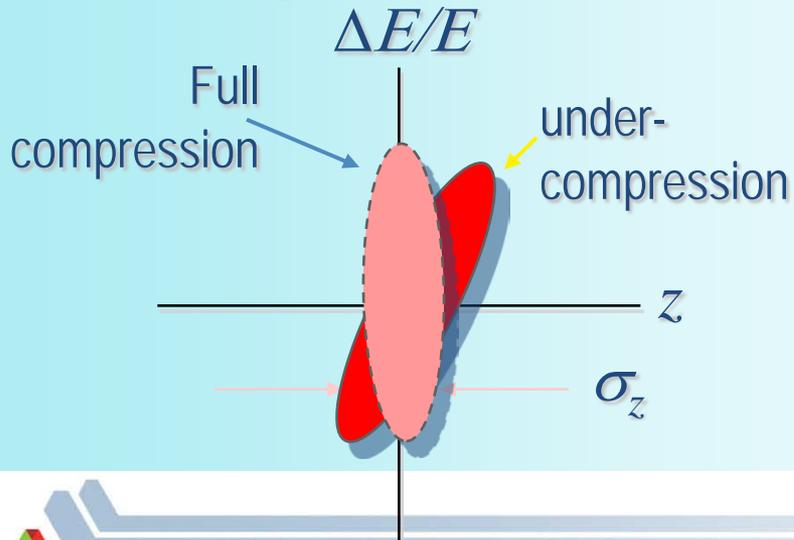
# Some issues

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).

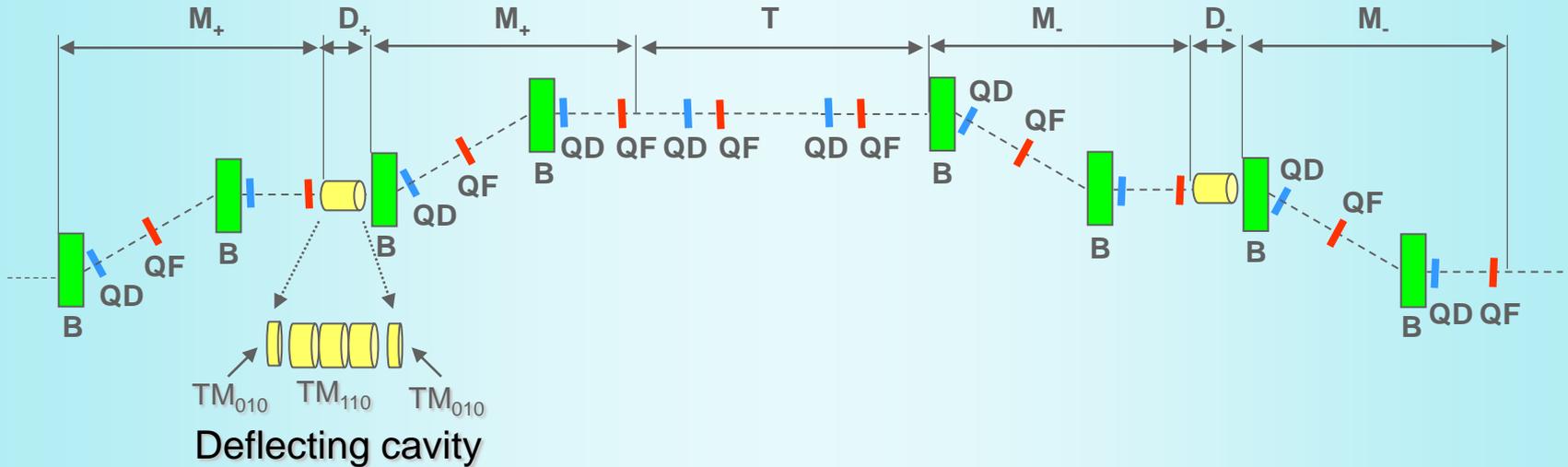
R.P. Fliller, D.A. Edwards, H.T. Edwards, T. Koeth, K.T. Harkay, K.-J. Kim, “Transverse to longitudinal emittance exchange beamline at the A0 Photoinjector”, Part. Acc. Conf., PAC07, (2007).



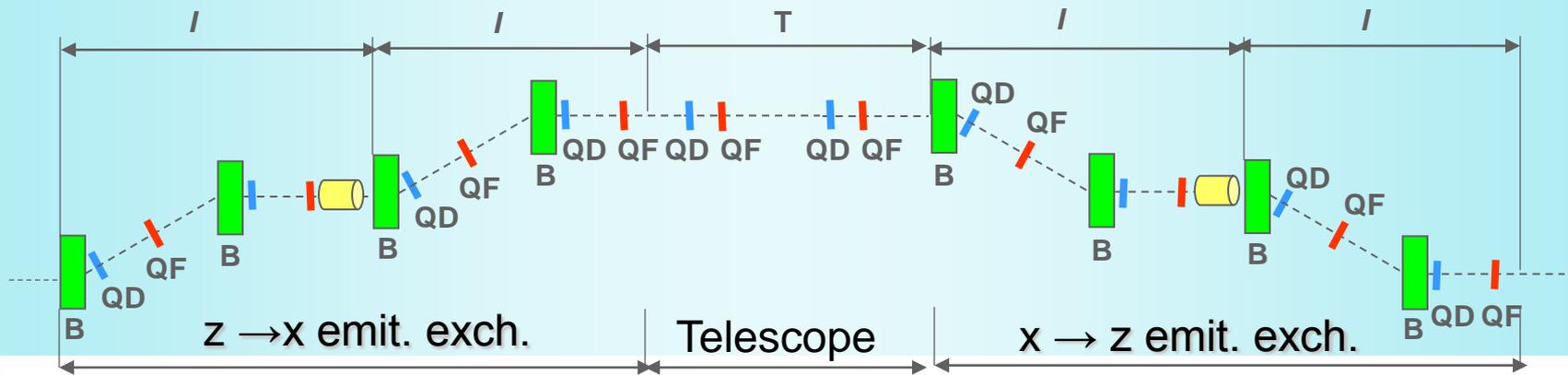
# A schematic of the bunch compressor

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

Variant 1

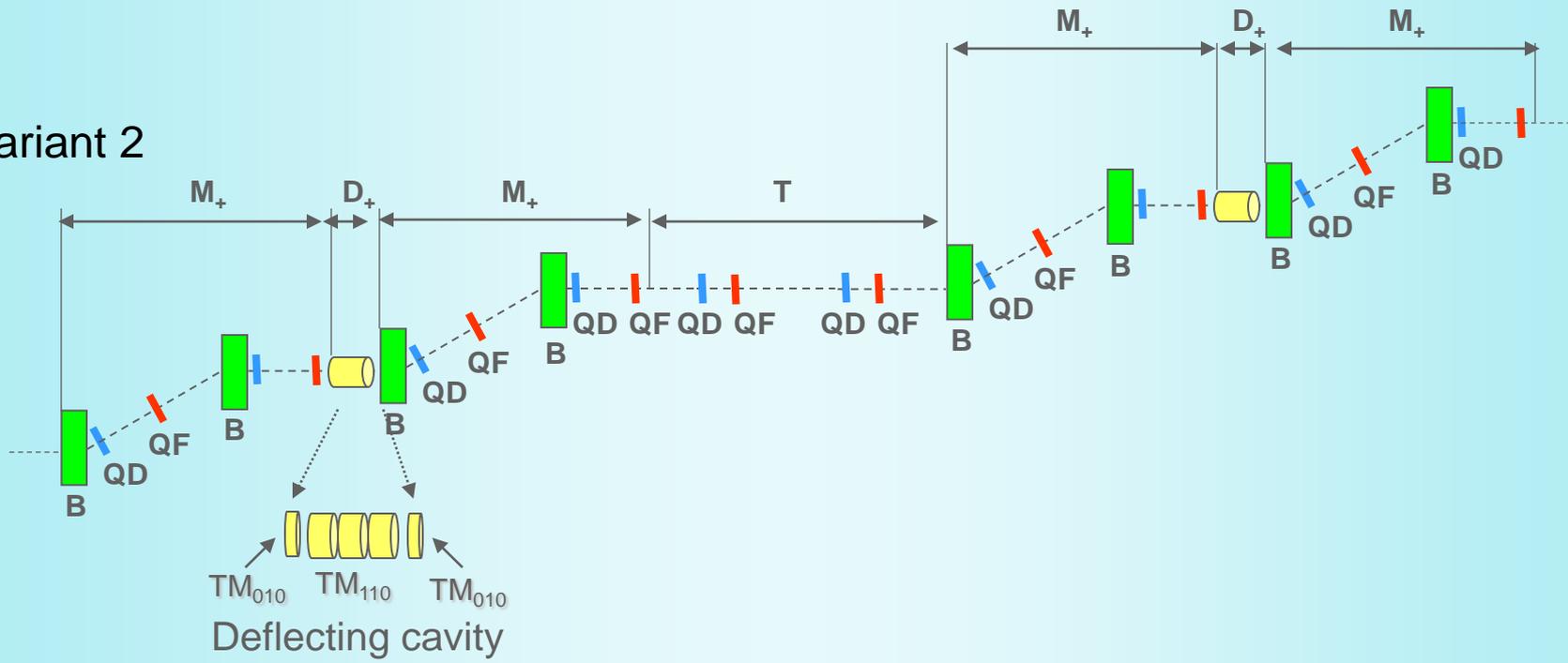


Focusing properties of individual sections

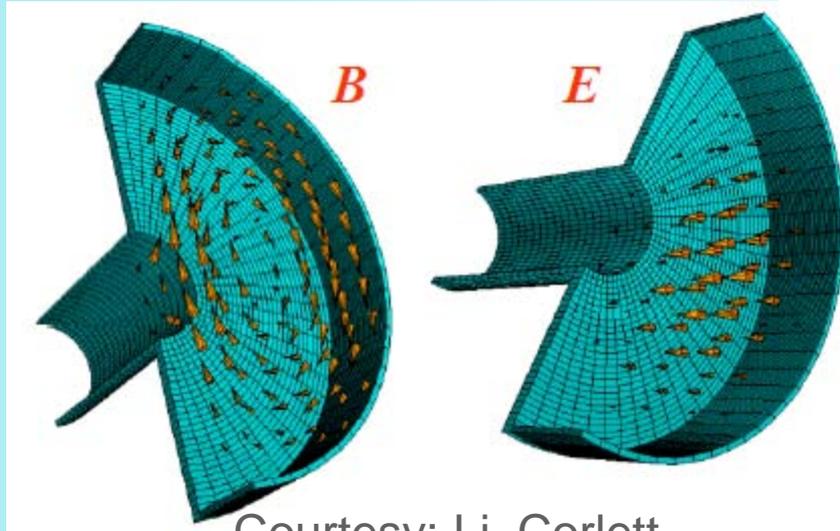


# A schematic of the bunch compressor: alternative variant

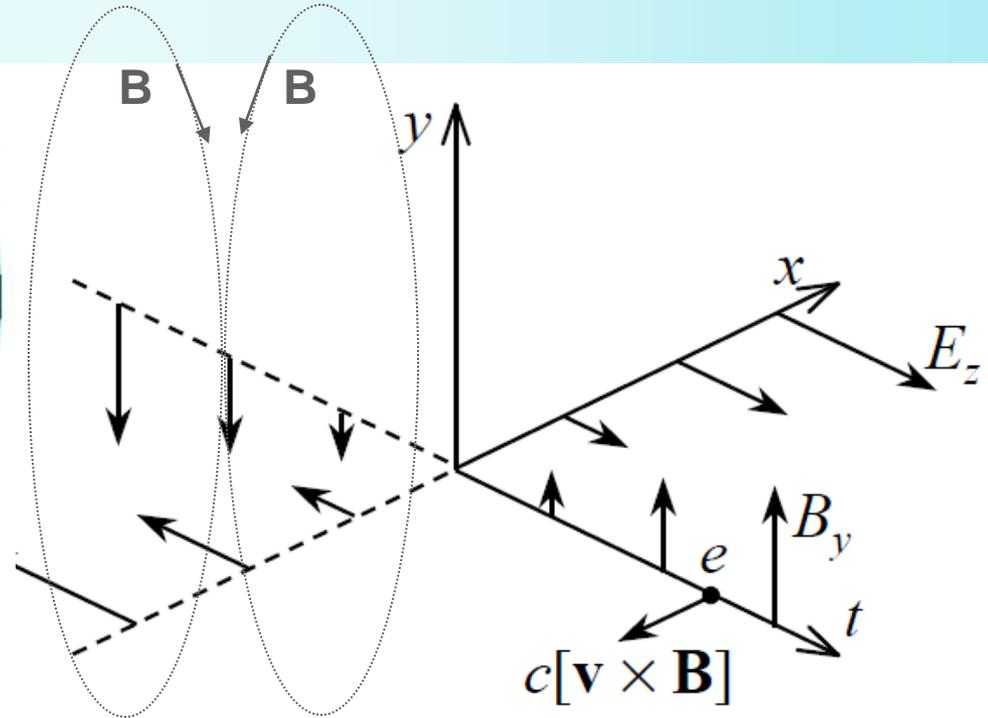
Variant 2



# Deflecting cavity



Courtesy: Li, Corlett



Thin cavity approximation:

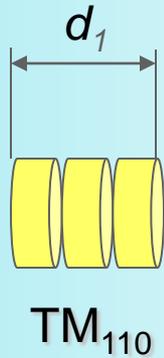
$$\delta = \frac{2eV_0}{E} J_1(x/a) \cos(\omega_{rf} t) \approx \frac{eV_0}{Ea} x = k x$$

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

In agreement with Panofsky-Wentzel theorem

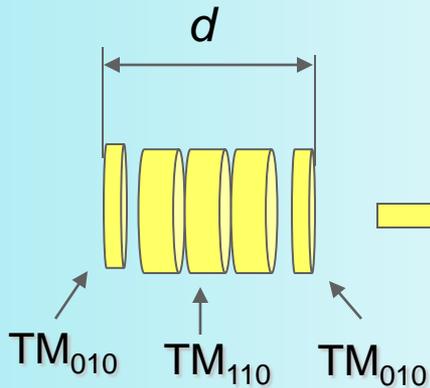


# Thick deflecting cavity:



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

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

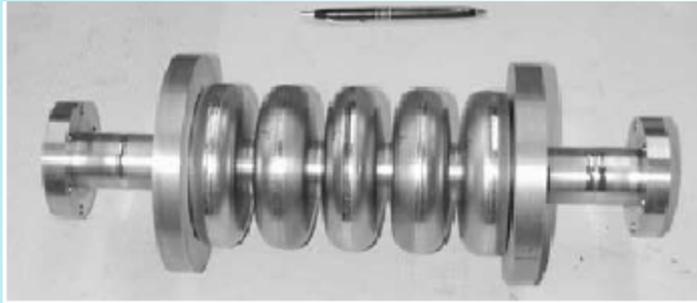


$$\begin{bmatrix} 1 & d & kd/2 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & kd/2 & 0 & 1 \end{bmatrix}$$

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



$$E_{beam} = 250 \text{ MeV}$$

$$f_{RF} = 3.9 \text{ GHz}$$

$$V_0 = 4 \text{ MV (1m, 3x7 cells: Li, Corlett)}$$

$$V_1 = 0.4 \text{ MV}$$

$$k = 0.013 \text{ cm}^{-1}$$

## SLAC: copper X-band LOLA



$$E_{beam} = 250 \text{ MeV}$$

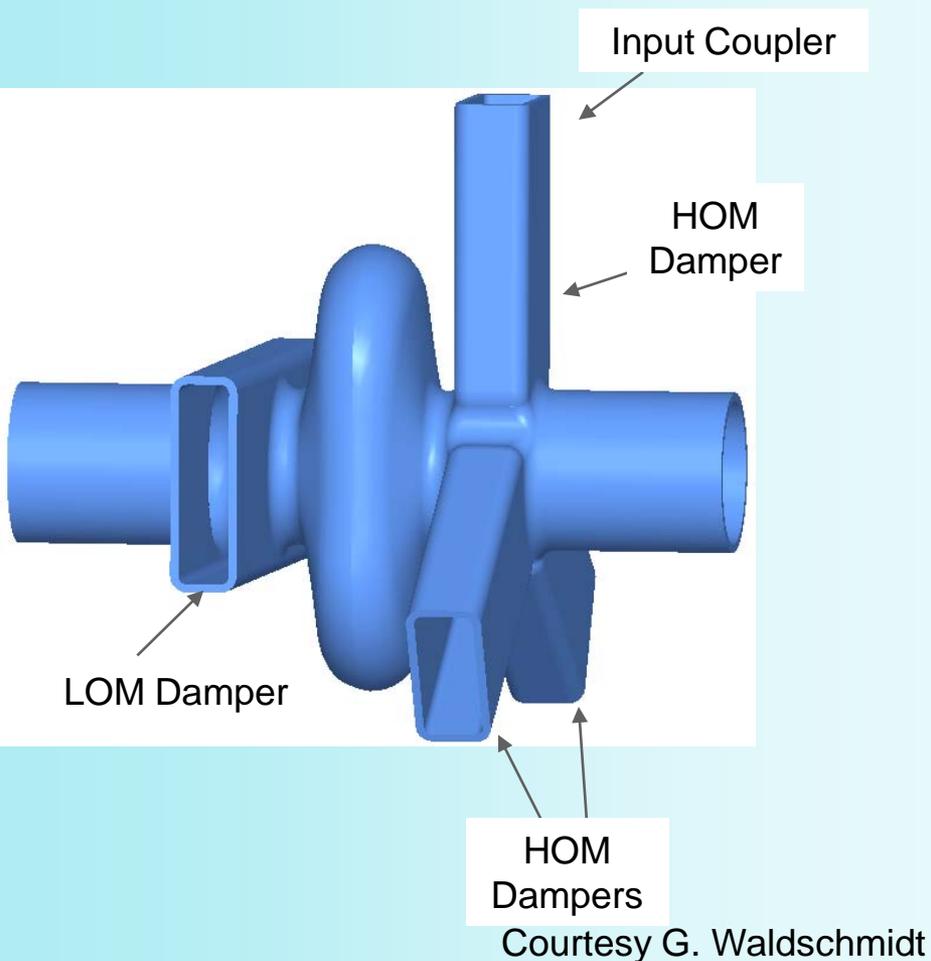
$$f_{RF} = 11.4 \text{ GHz}$$

$$V_0 = 22 \text{ MV (0.5 m)}$$

$$V_1 = 6.6 \text{ MV}$$

$$k = 0.21 \text{ cm}^{-1}$$

# Single-Cell SC Cavity



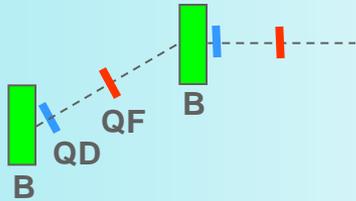
|                         |             |         |
|-------------------------|-------------|---------|
| Frequency               | 2815        | MHz     |
| $Q_U$                   | $\sim 10^9$ |         |
| $V_t$                   | 0.4         | MV      |
| Energy                  | 0.25        | J       |
| $R_t/Q$                 | 36.4        | Ohm     |
| $E_{\text{peak}} / V_t$ | 83          | 1/m     |
| $B_{\text{peak}} / V_t$ | 200         | mT / MV |
| $P_{\text{loss}}$       | $< 5$       | W       |
| $I_{\text{beam}}$       | 200         | mA      |
| No. Cavity              | $10 * 2$    |         |
| Cav. Length             | 128         | mm      |

Total length = 128 mm

Voltage gap = 53 mm

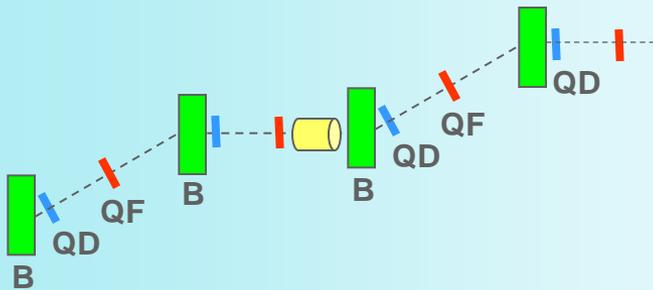
$$\frac{R_t}{Q} = \frac{V^2|_{r=r_0}}{\omega U (k r_0)^2}$$

First leg of emittance exchange scheme



$$M_+ = \begin{bmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{matrix} x \\ p_x \\ z \\ \delta \end{matrix} \quad \xi \equiv R_{56}$$

Complete emittance exchange scheme



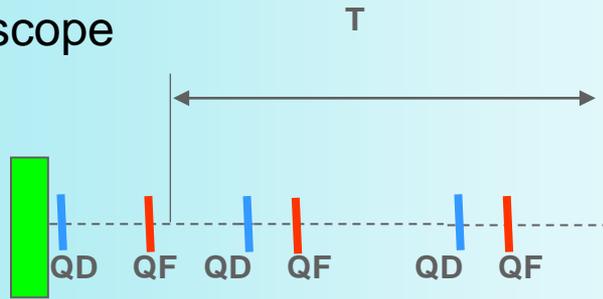
$$M_+ \cdot D_+ \cdot M_+ = \begin{bmatrix} 0 & 0 & 0 & \eta \\ 0 & 0 & k & k\xi \\ k\xi & \eta & 0 & 0 \\ k & 0 & 0 & 0 \end{bmatrix} = E_+$$

The following constraints were used:

$$L = -d / 2$$

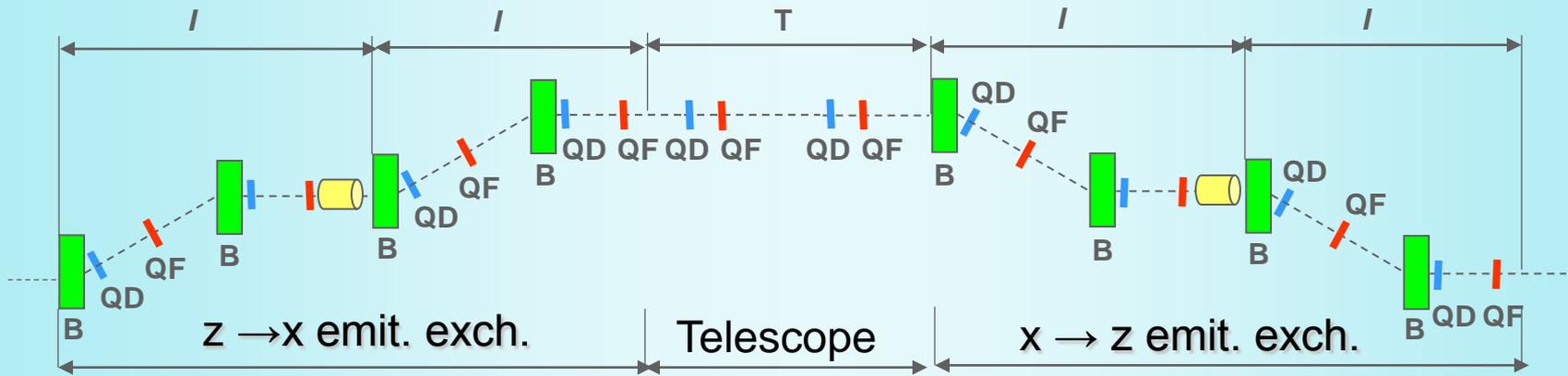
$$k\eta = -1$$

# 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:

$\sigma_{z_i}$  - bunch length before compression,

$\sigma_{\delta_i}$  - uncorrelated relative energy spread before compression, and

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

$\sigma_{z_f}$  - bunch length after compression,

$\sigma_{\delta_f}$  - 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

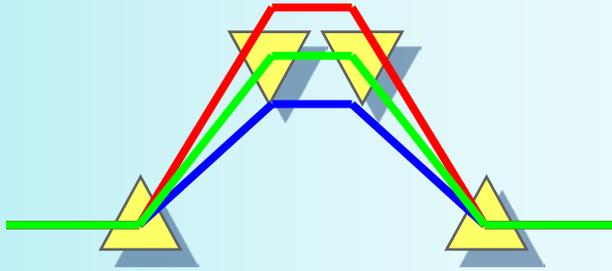
$$\xi\sigma_{\delta_i} \left(\frac{1}{m} + m\right) \ll \frac{\sigma_{z_i}}{m} \quad \text{then} \quad \sigma_{z_f} \approx \sigma_{z_i} / m$$

Case 2

$$\xi\sigma_{\delta_i} \left(\frac{1}{m} + m\right) \gg \frac{\sigma_{z_i}}{m} \quad \text{Then the compression is not yet finished}$$



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:

$$\begin{aligned} \sigma_{z_f} &= \frac{1}{m} \sigma_{z_i} \\ \sigma_{\delta_f} &= m \sigma_{\delta_i} \end{aligned}$$

... 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:

$$\begin{aligned} \sigma_{z_f} &= \frac{1}{m} \sigma_{z_i} \\ \sigma_{\delta_f} &= m \sigma_{\delta_i} \frac{E_1}{E_2} \end{aligned}$$

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:

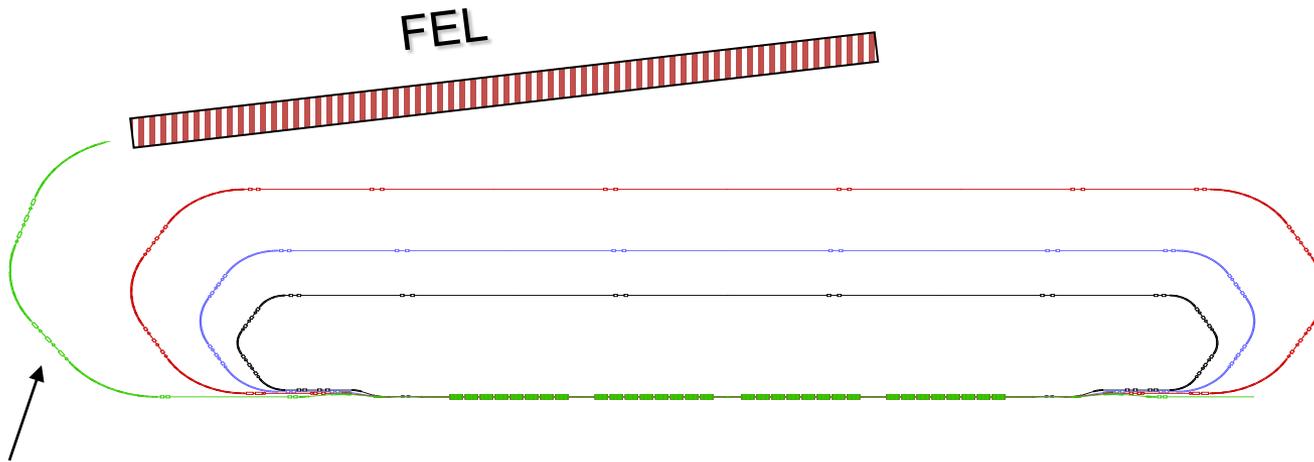
- a) one can use BC even after the linac and obtain final compression in a “spreader”/ “dogleg” part of the lattice leading to FEL



- 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:

$$f_{RF} = 2.85 \text{ GHz}$$

$$k = 0.05 \text{ cm}^{-1}$$

cavity length = 1 m

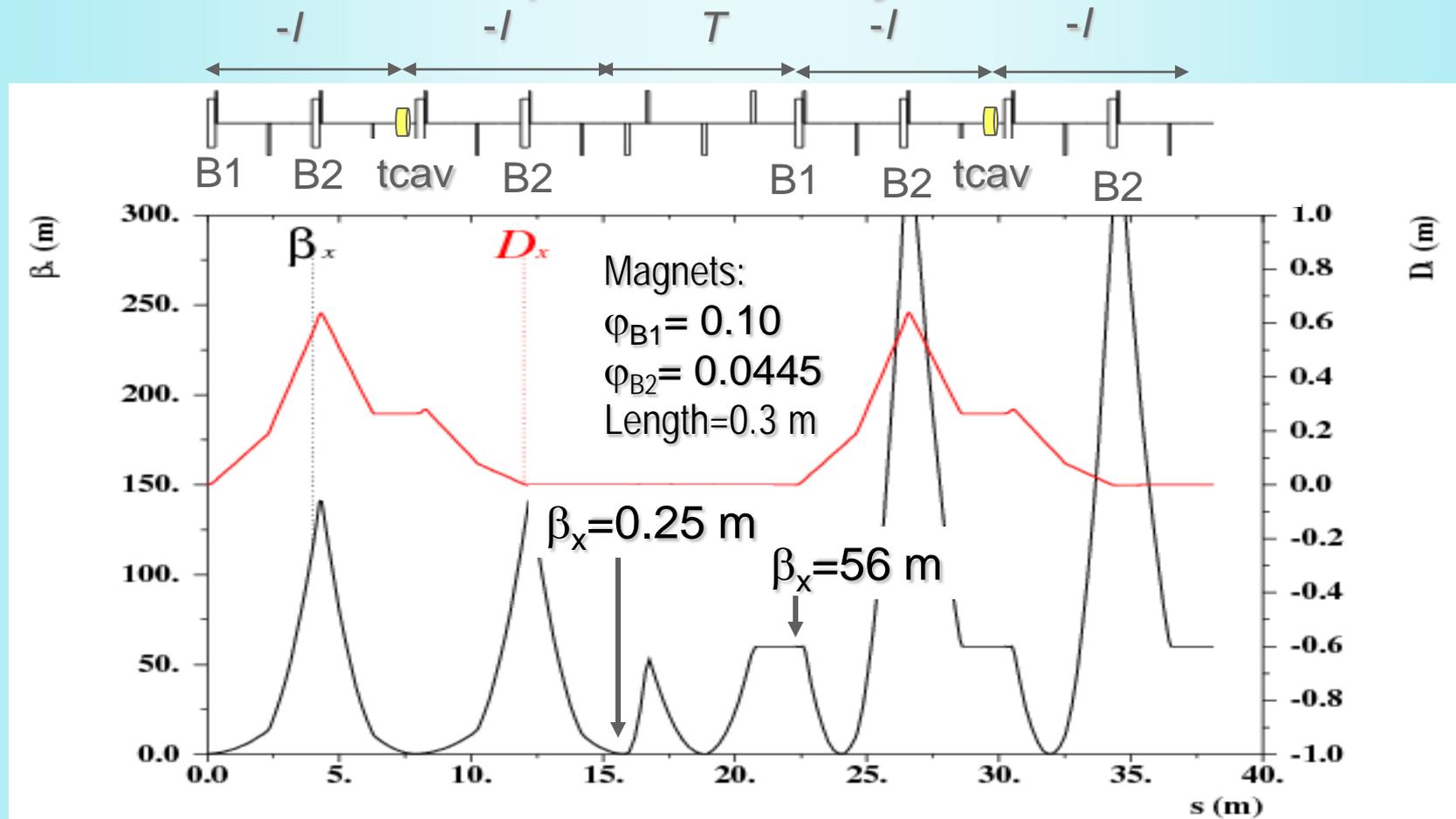
At  $E_b = 250 \text{ MeV}$  this corresponds to:

$$V_0 = 21 \text{ MV}$$

$$V_1 = -8.7 \text{ MV}$$



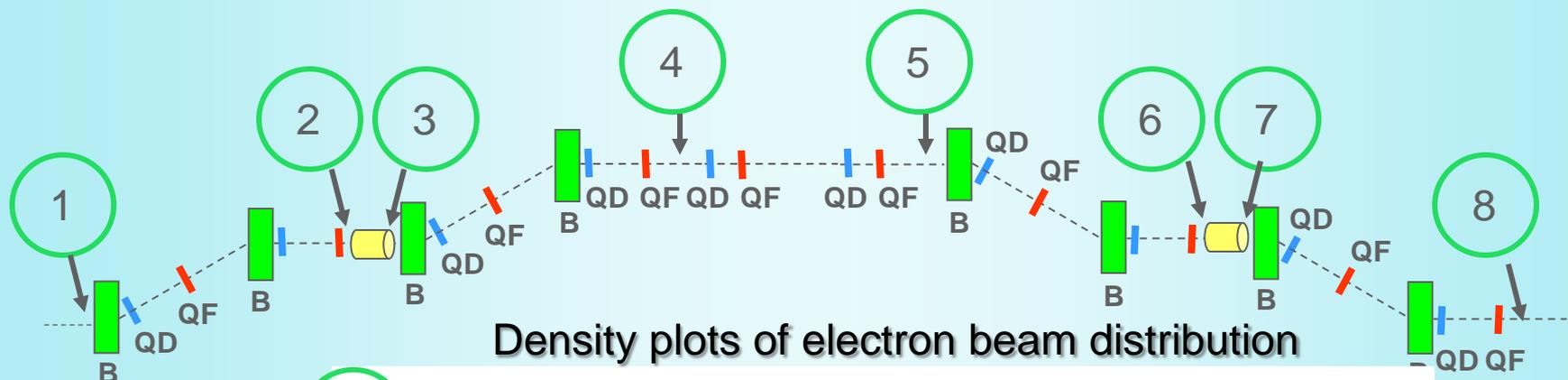
# Illustration: compression by a factor of 15



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



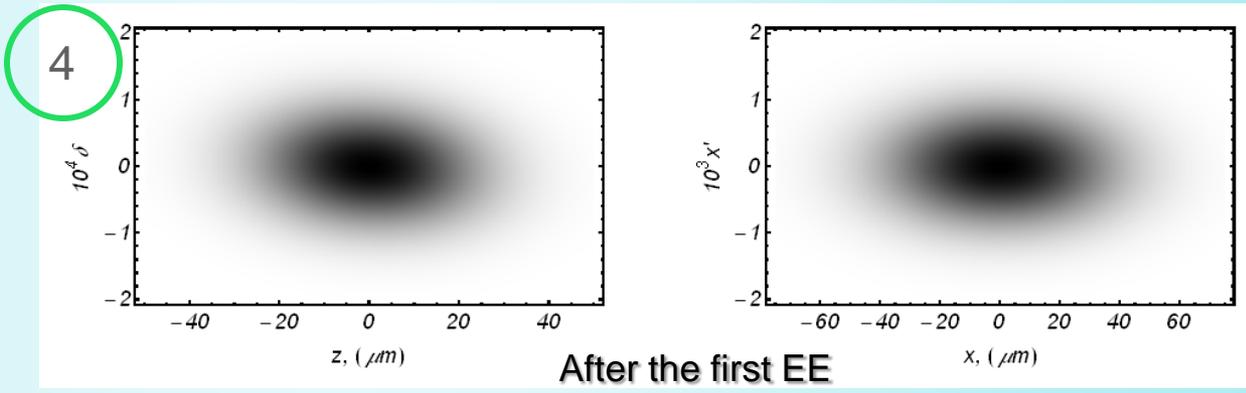
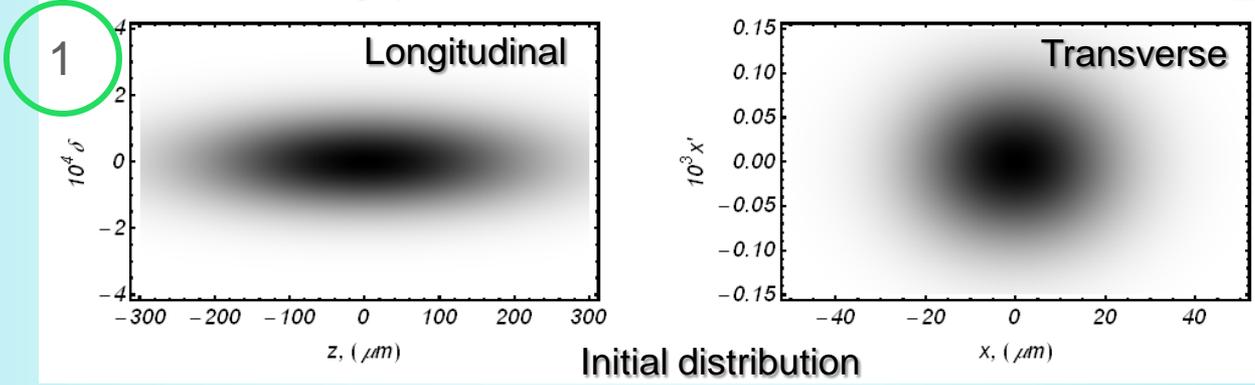
# Evolution of the electron beam distribution



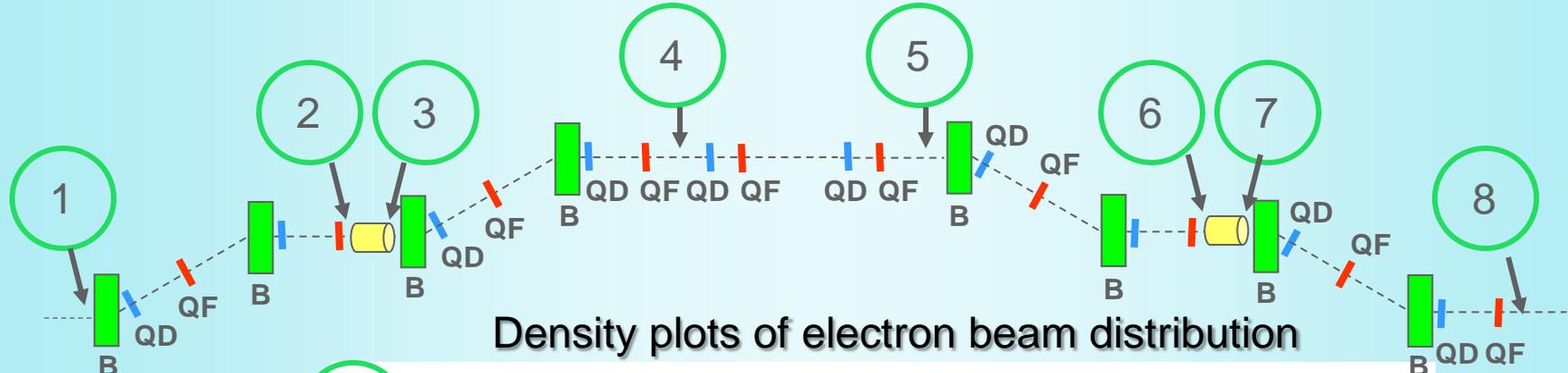
Density plots of electron beam distribution

## Input parameters

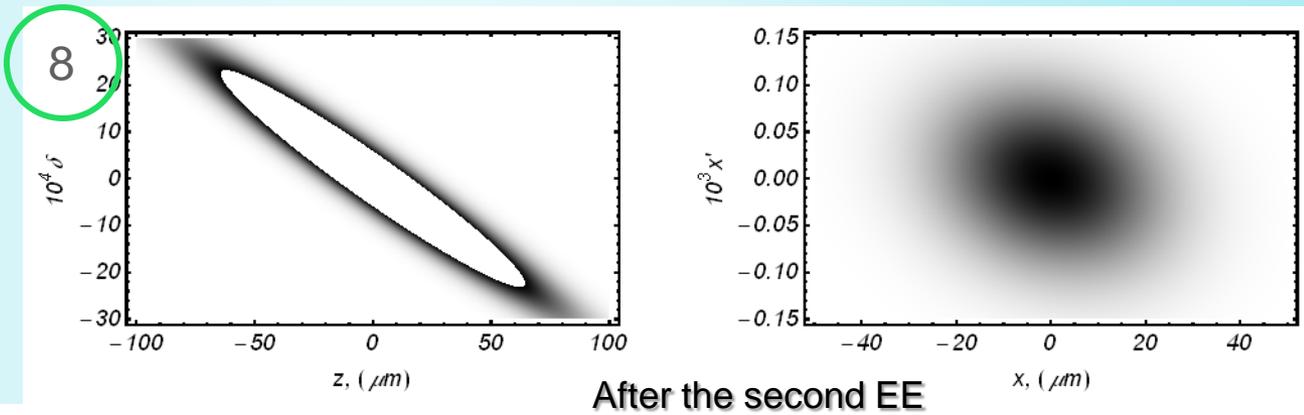
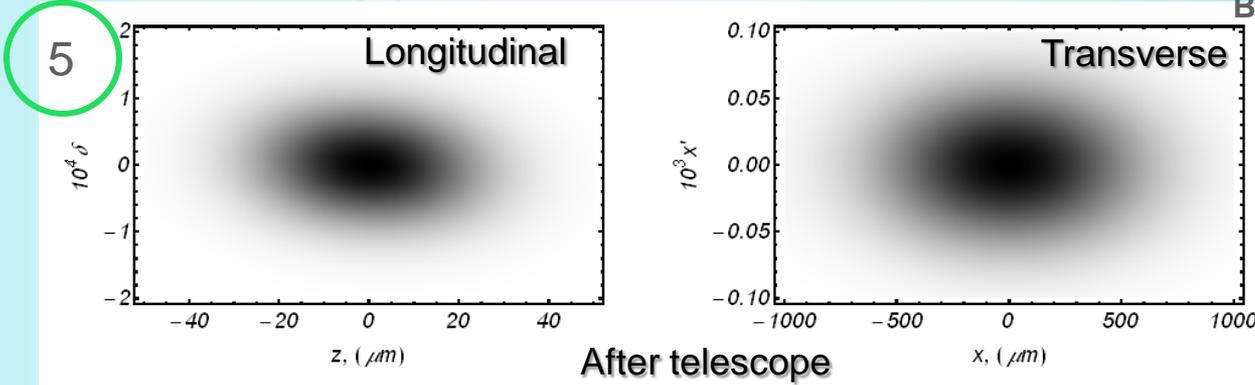
- $E_b = 250 \text{ MeV}$
- $\epsilon_x = 0.5 \text{ } \mu\text{m}$
- $\sigma_{\delta 0} = 10^{-4}$
- $\sigma_{E0} = 25 \text{ keV}$
- $\sigma_{z0} = 160 \text{ } \mu\text{m}$



# Evolution of the electron beam distribution (2)

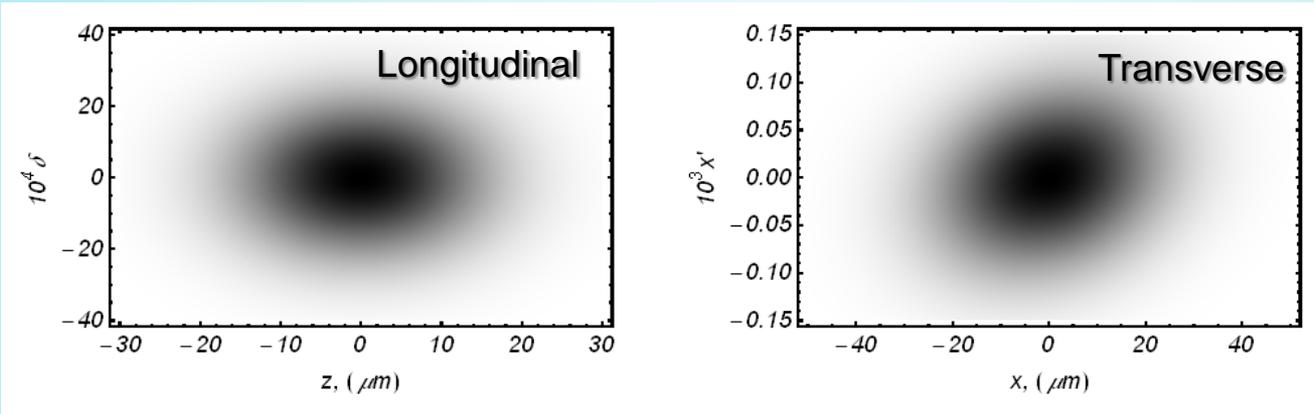


Density plots of electron beam distribution

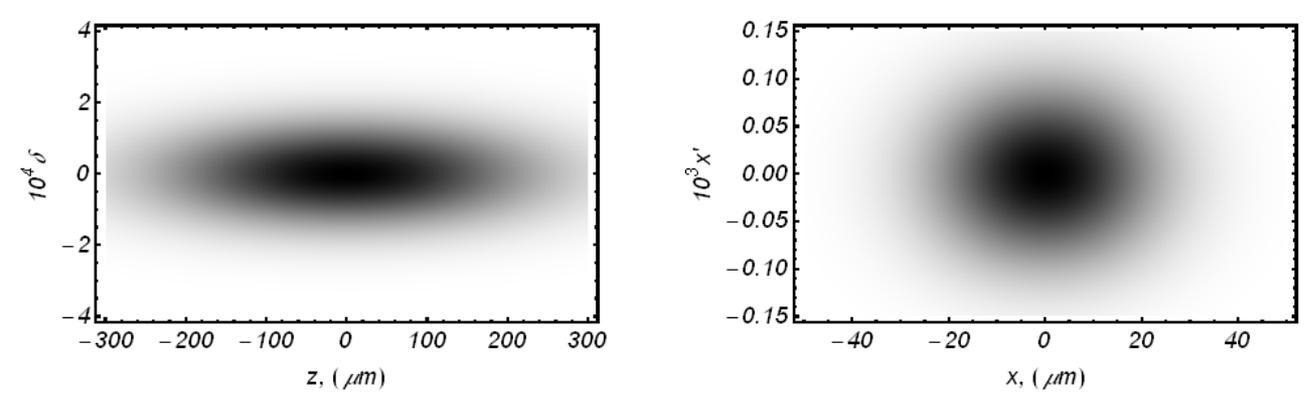


# Evolution of the electron beam distribution (3)

Density plots of electron beam distribution

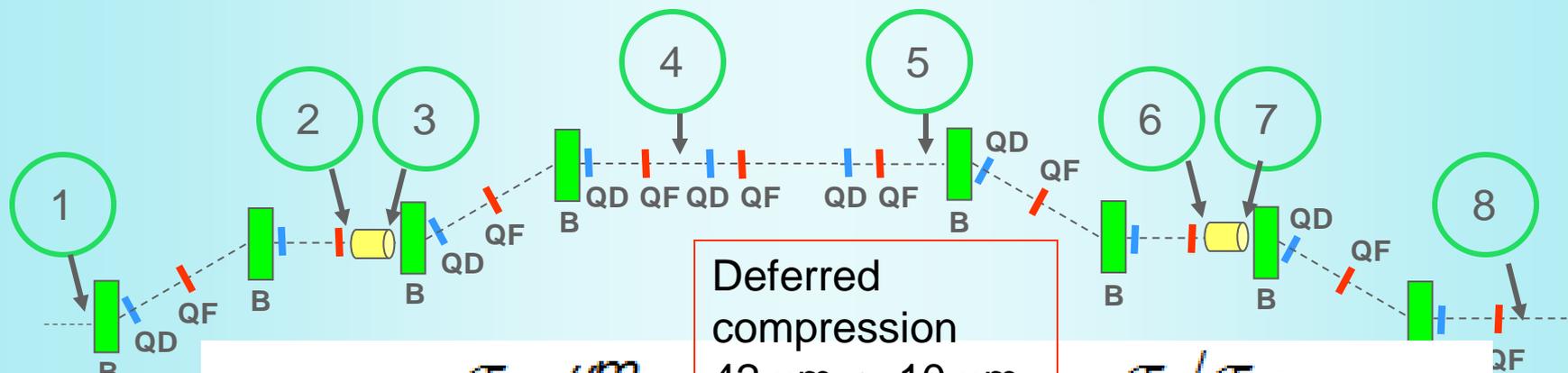


Final: after completion of deferred compression



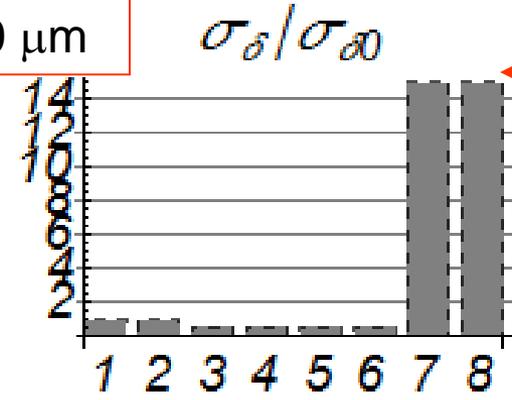
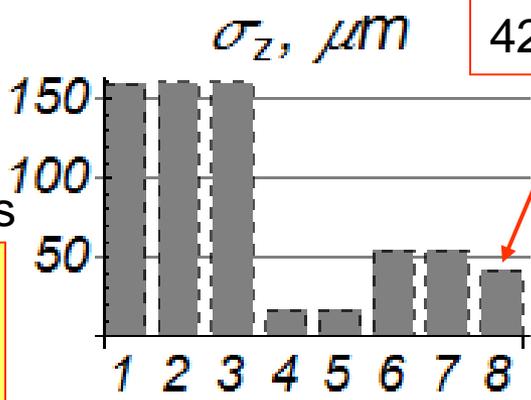
Initial: compare with the final

# Numerical values of beam sizes at key locations

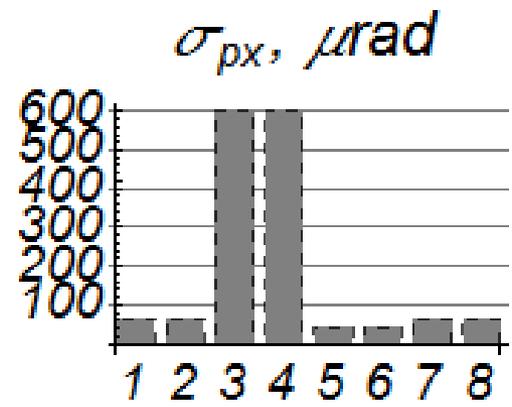
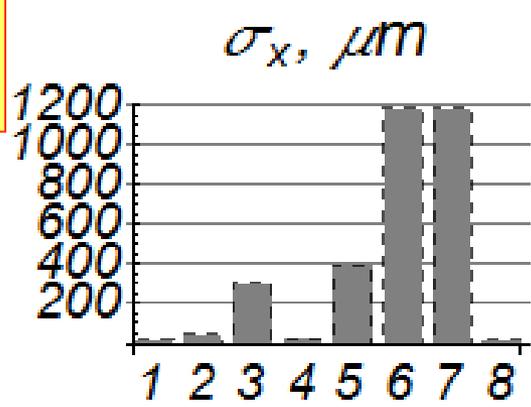


Input parameters

- $E_b = 250 \text{ MeV}$
- $\epsilon_x = 0.5 \text{ } \mu\text{m}$
- $\sigma_{\delta 0} = 10^{-4}$
- $\sigma_{E0} = 25 \text{ keV}$
- $\sigma_{z0} = 160 \text{ } \mu\text{m}$

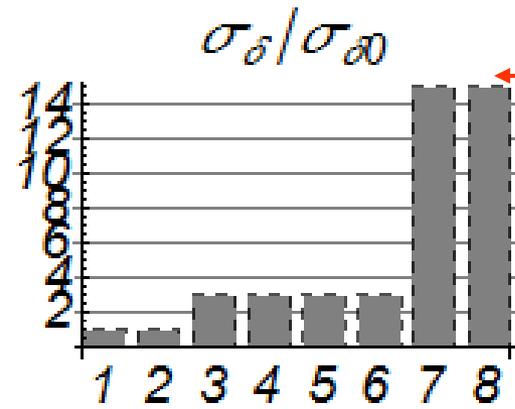
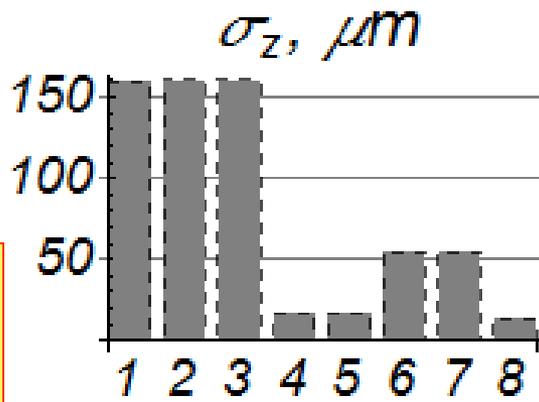


$m=15$

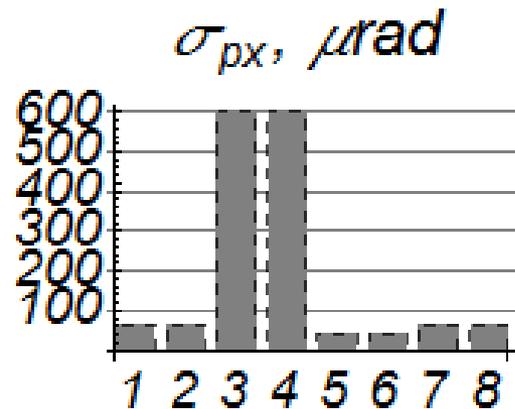
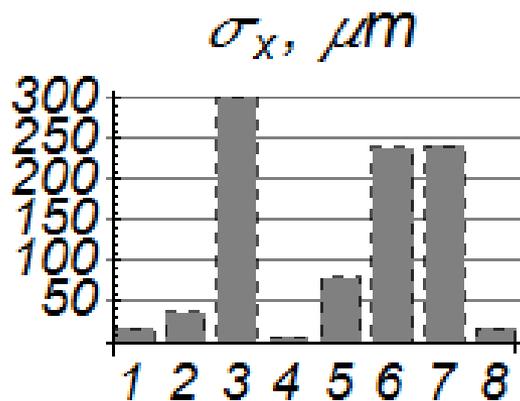


Same as before, but with a reduced energy spread to 5 keV

$E_b = 250 \text{ MeV}$   
 $\varepsilon_x = 0.5 \text{ } \mu\text{m}$   
 $\sigma_{\delta 0} = 2 \times 10^{-5}$   
 $\sigma_{E0} = 5 \text{ keV}$   
 $\sigma_{z0} = 160 \text{ } \mu\text{m}$

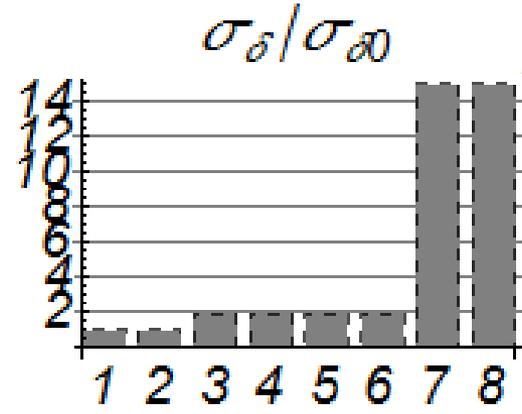
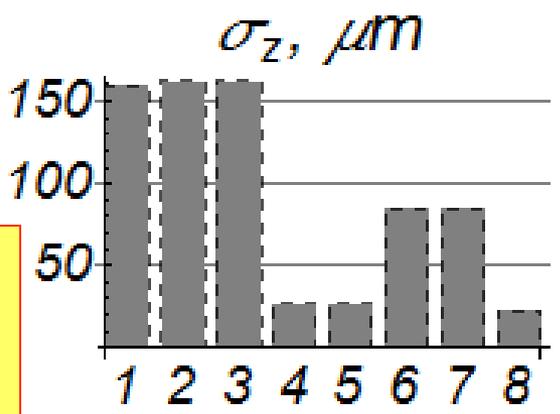


$m=15$

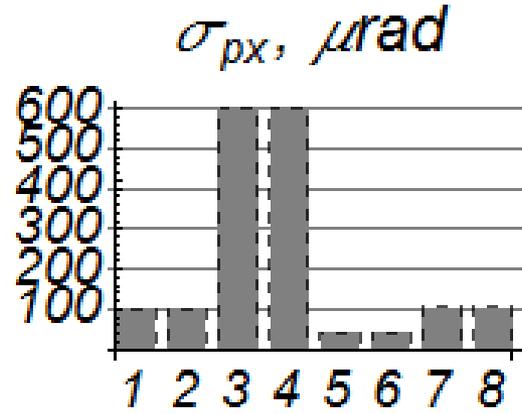
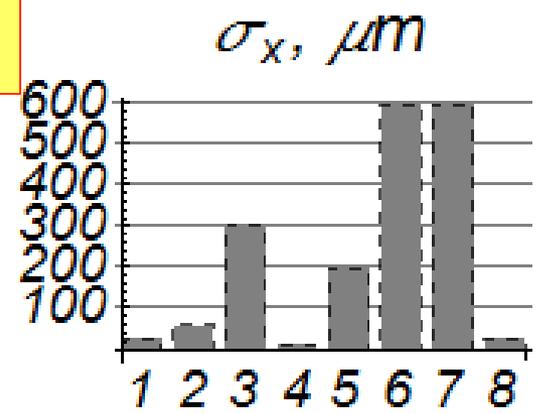


Same as before, but with a reduced beam energy to 100 MeV  
 This may eliminate a need in the laser heater

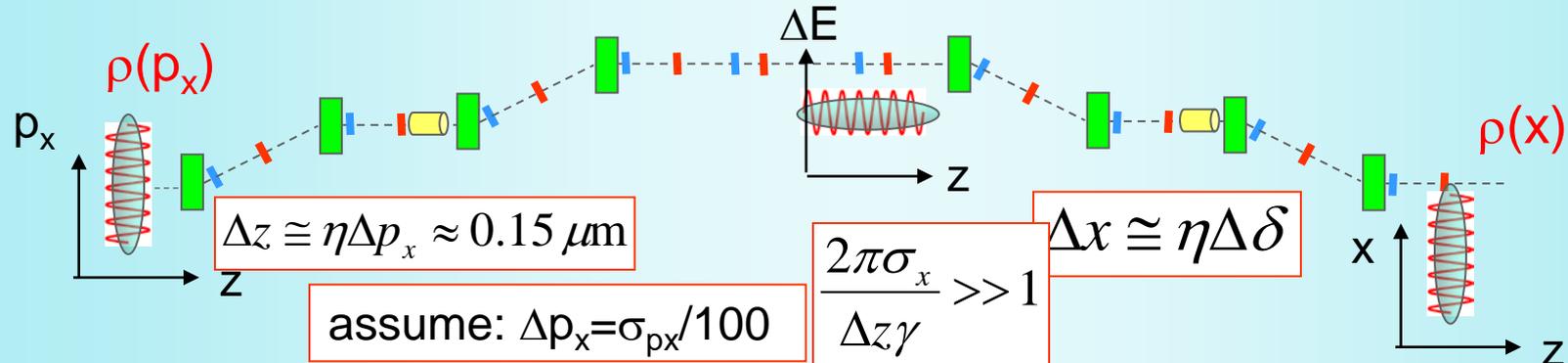
$E_b = 100 \text{ MeV}$   
 $\epsilon_x = 0.5 \text{ } \mu\text{m}$   
 $\sigma_{\delta 0} = 5 \times 10^{-5}$   
 $\sigma_{E0} = 5 \text{ keV}$   
 $\sigma_{z0} = 160 \text{ } \mu\text{m}$



$m=15$

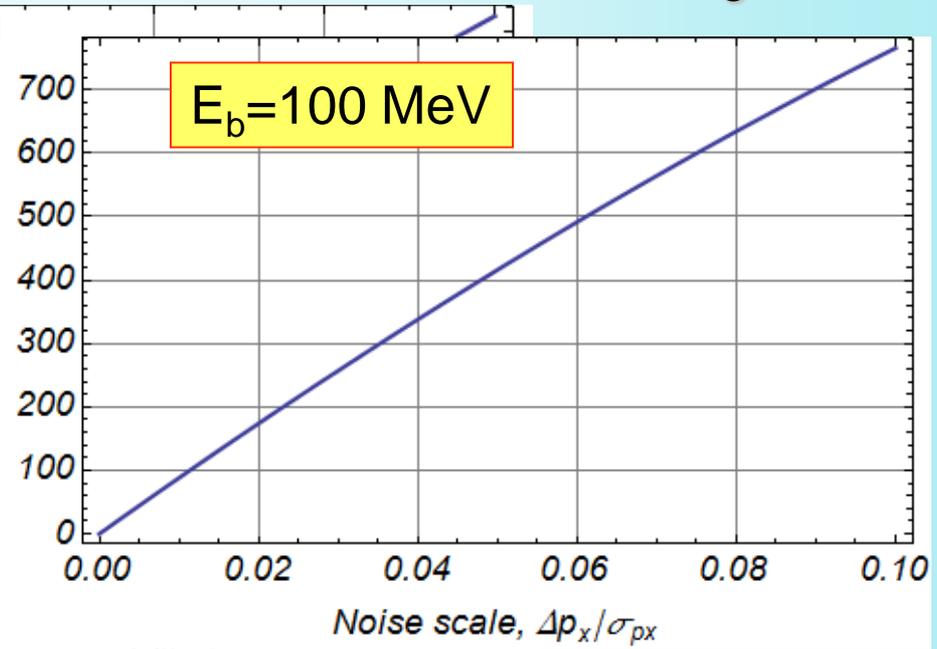
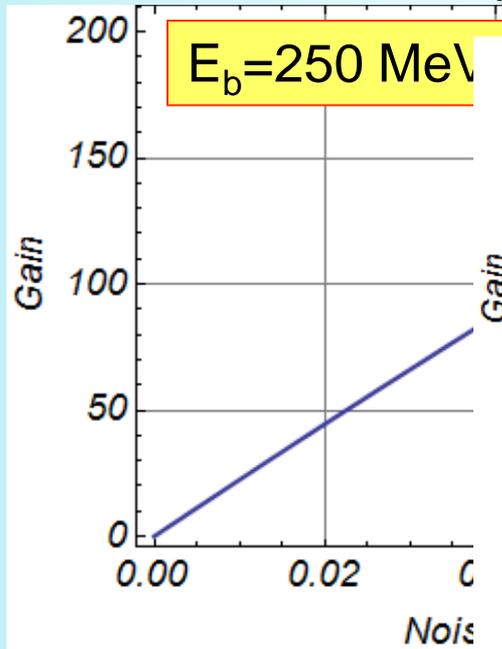


# Emittance degradation



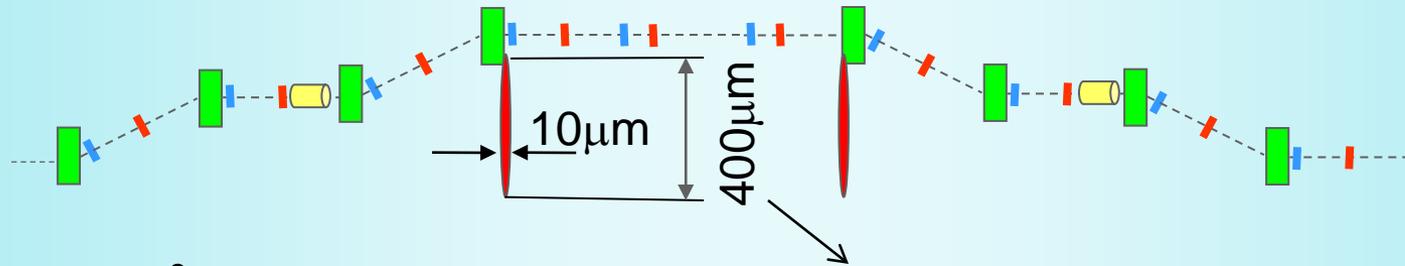
Concern: space charge induced energy modulation in the telescope section can transfer into the coordinate space and be seen as emittance degradation

$\epsilon_x = 0.5 \mu\text{m}$   
 $\sigma_{E0} = 5 \text{ keV}$   
 $\sigma_{z0} = 160 \mu\text{m}$   
 $\eta = 0.25 \text{ m}$   
 $\beta_0 = 0.25 \text{ m}$   
 $\beta_1 = 10 \text{ m}$   
 Inside telescope  
 $I_{\text{peak}} = 3 \text{ kA}$



No emittance degradation is expected

# Coherent synchrotron radiation



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

at  $\sigma_E = 25\text{ keV}$  and  $80\mu\text{m}$  at  $\sigma_E = 5\text{ keV}$

$k$  is the wave number

$$f(k) = (2\pi\sigma_x\sigma_z)^{-1} \left| \iint dx dz \rho(x, z) e^{-ikx \sin\theta + ikz \cos\theta} \right|^2 = e^{-(k\sigma_x \sin\theta)^2 - (k\sigma_z \cos\theta)^2}$$

When  $k\sigma_z \cong 1$ ,  $k\theta\sigma_x \cong 500$  at  $\sigma_E = 25\text{ keV}$

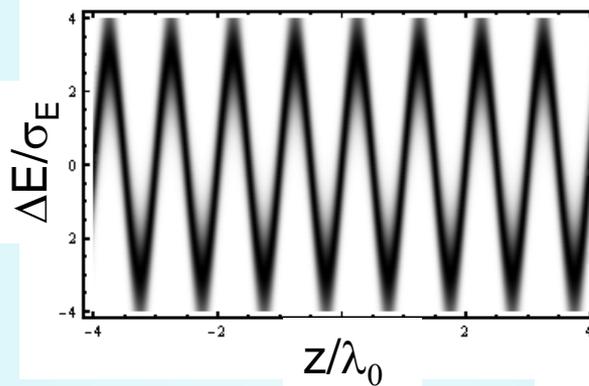
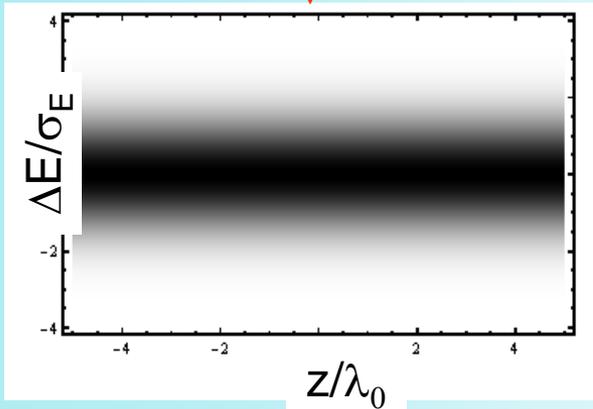
$$\text{Here } \theta \approx \frac{0.8}{\gamma} \left( \frac{\sigma_z}{\lambda_{crit}} \right)^{1/3}; \quad \lambda_{crit} \approx 20\text{ nm}$$

Even for  $E = 100\text{ MeV}$  and  $\sigma_E = 5\text{ keV}$ ,  $k\theta\sigma_z \cong 15$

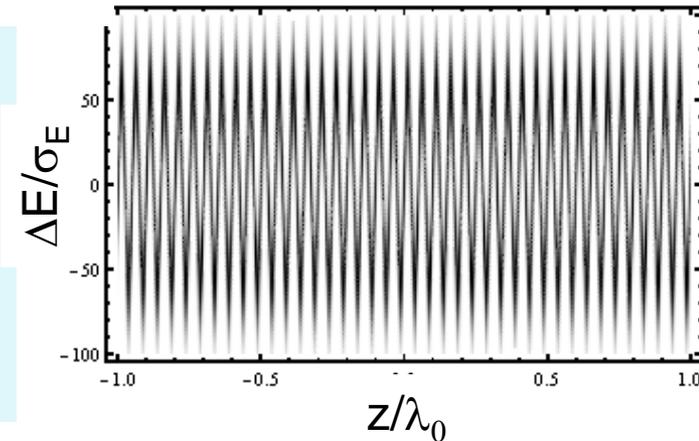
Conclusion: CSR is largely suppressed



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



Compressed modulation



Bunching efficiency at  $m$ -th harmonic of modulating frequency:

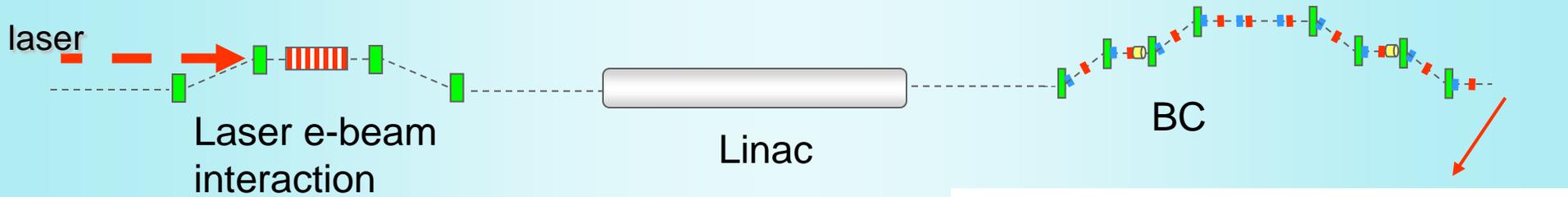
HGHG:  $|b_m| \propto e^{-\frac{1}{2} \left( \frac{m\sigma_E}{\Delta E} \right)^2}$

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

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

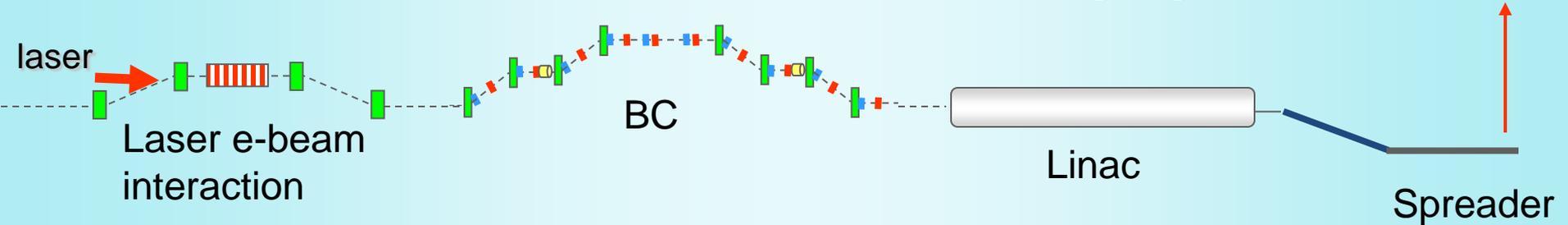
Plots of longitudinal phase space at various locations

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

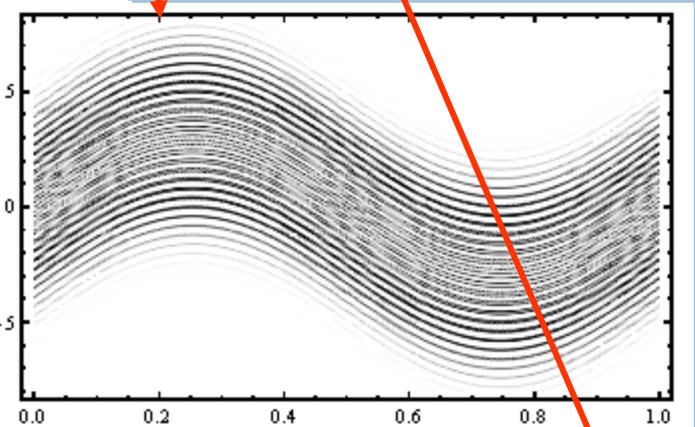
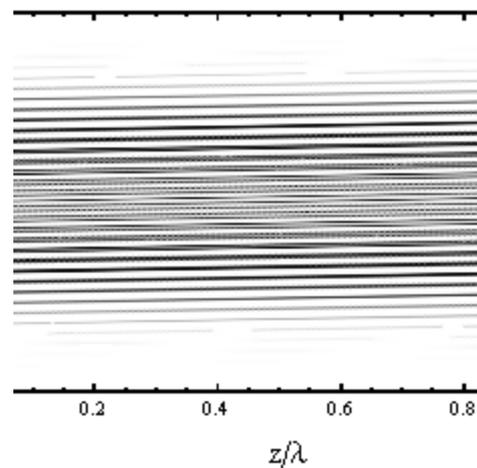
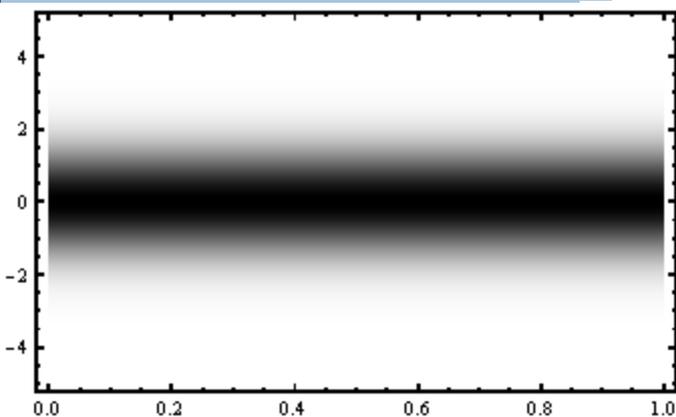
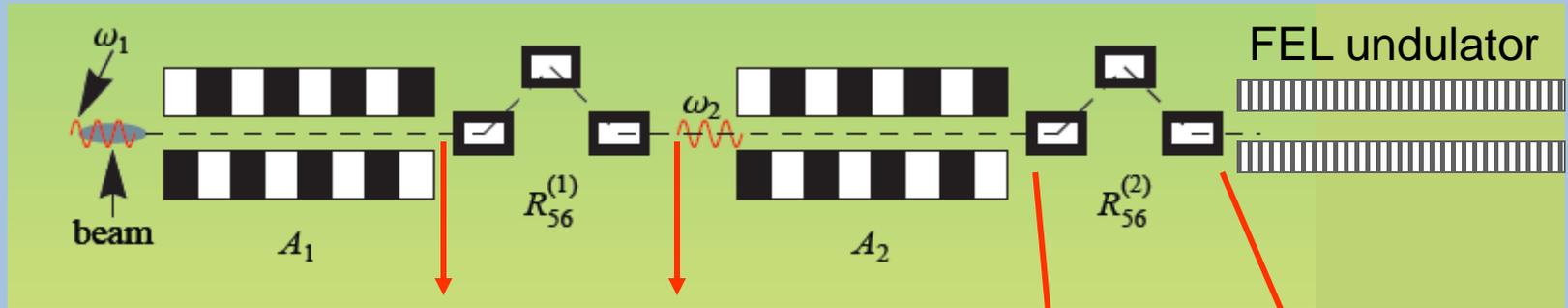


... or be deferred to a "spreader" / "dogleg"

$z/\lambda_0$



# Echo effect for harmonic generation of x-rays<sup>\*)</sup>



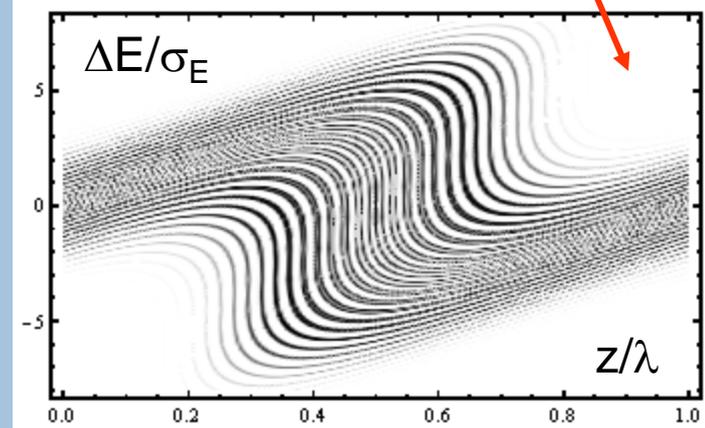
Mitigates the problem of a low bunching at high harmonic and eliminates need for multiple cascades

$$b_n \sim e^{-\frac{1}{2}(n\frac{\sigma_E}{\Delta E})^2}$$

traditional

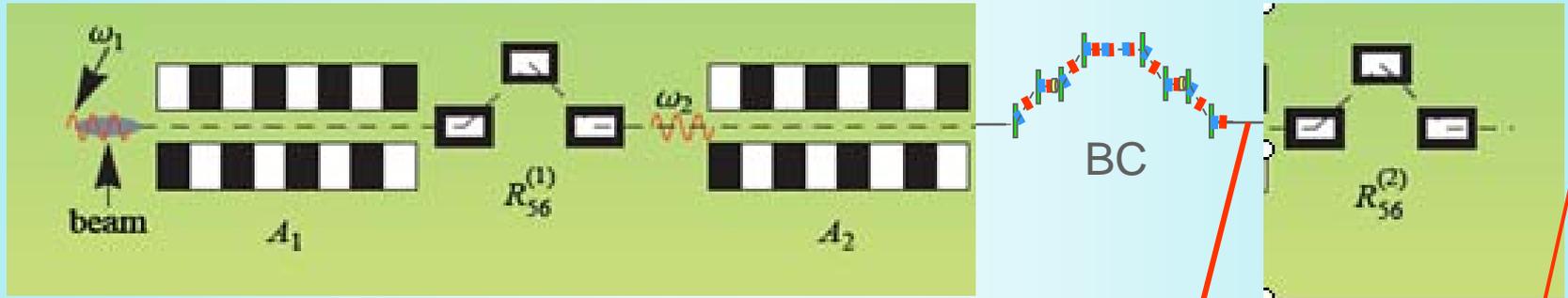
$$b_n \sim 0.4 n^{-1/3} \frac{\Delta E}{\sigma_E}$$

echo enhanced

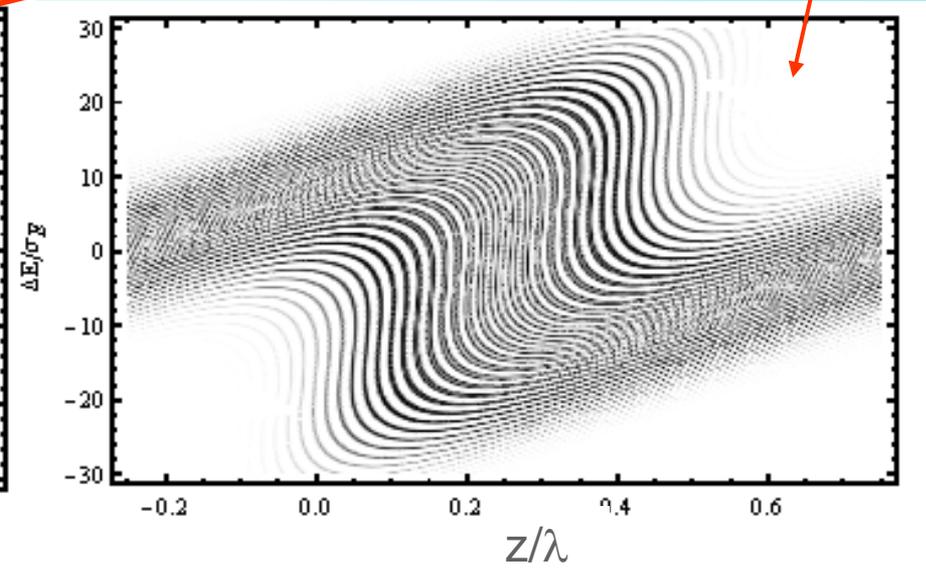
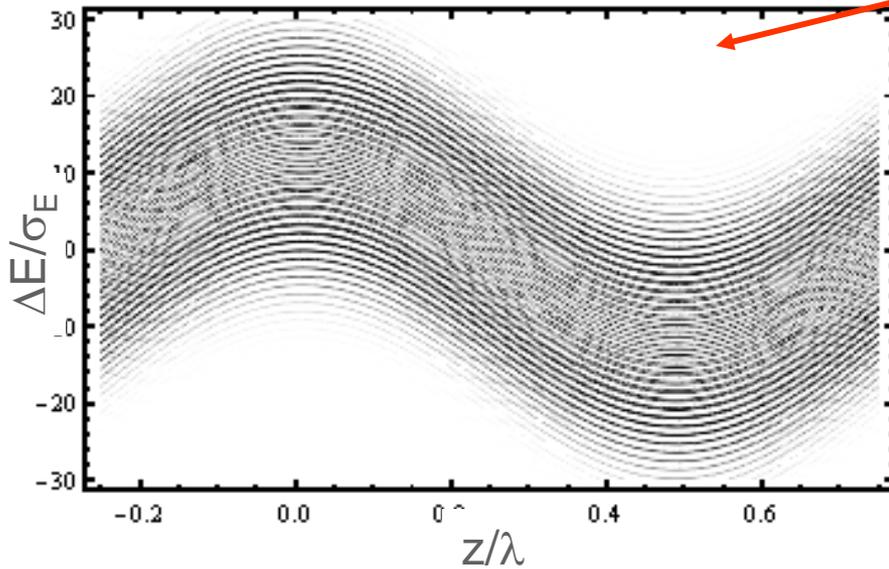


<sup>\*)</sup> G. Stupakov, PRL, 102, 074801(2009).

# Compression of the Echo induced microbunching

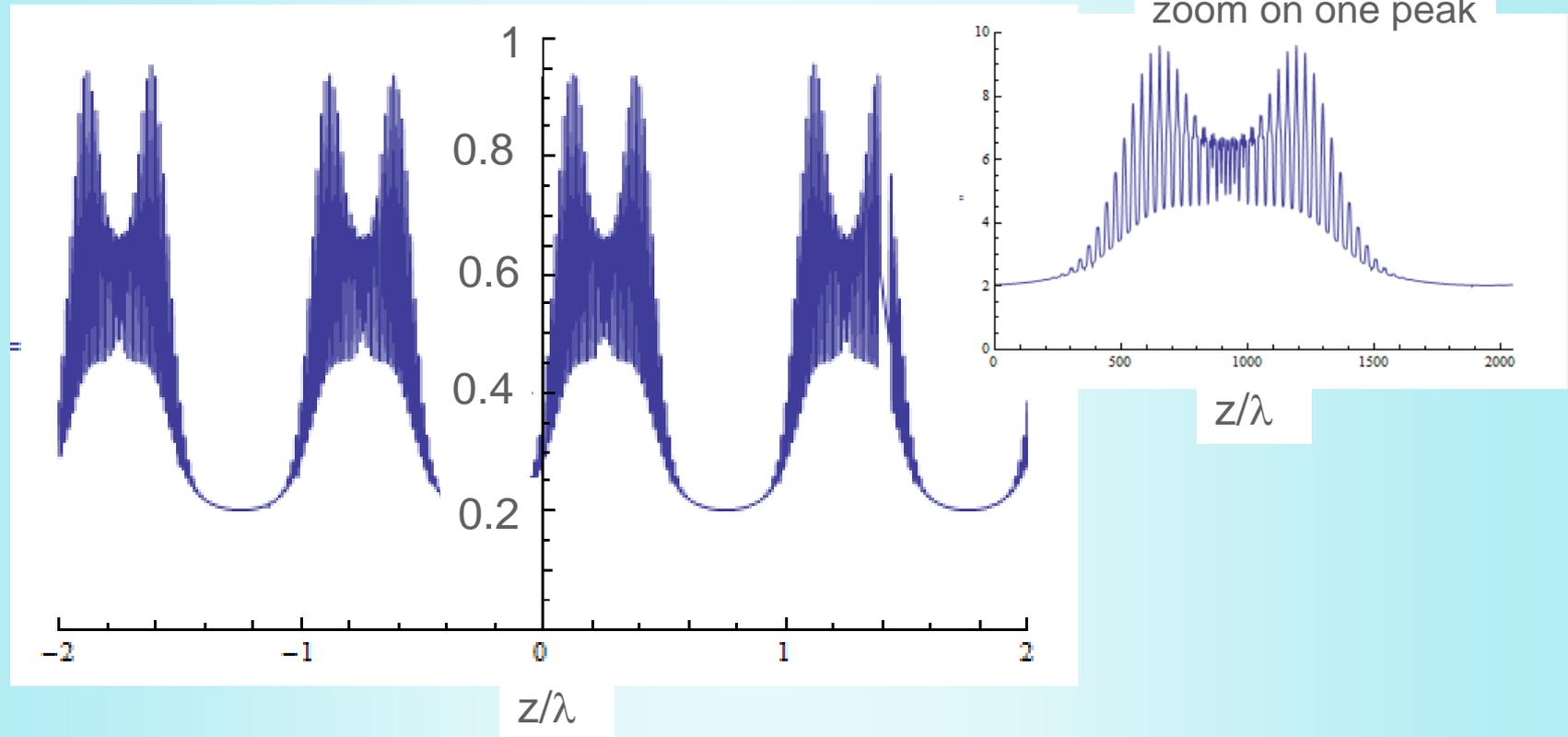


Compression factor,  $m=5$

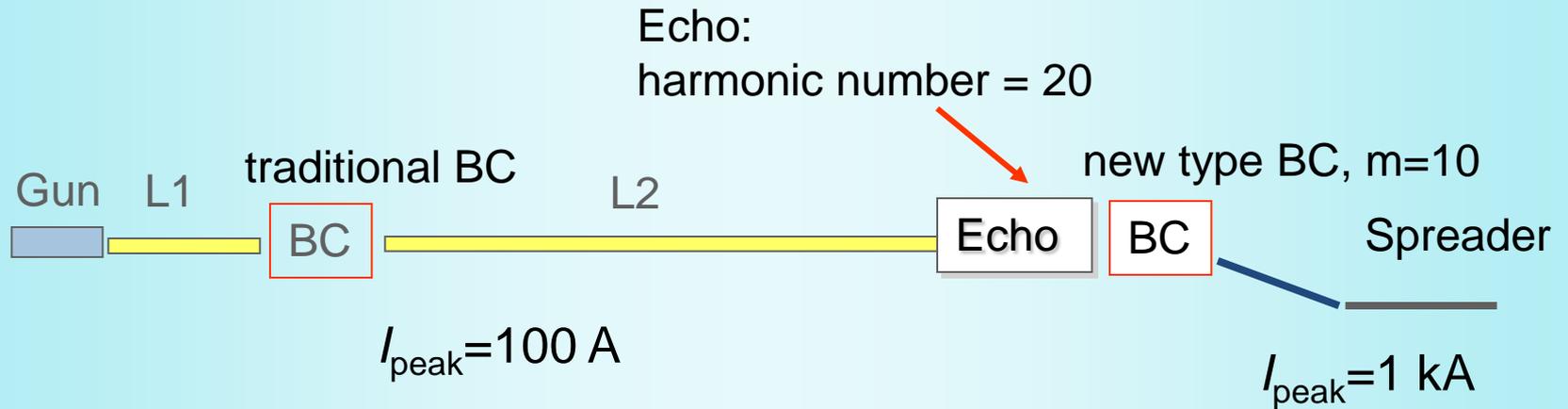


# Compression of the Echo induced microbunching (2)

Peak current after compression, kA



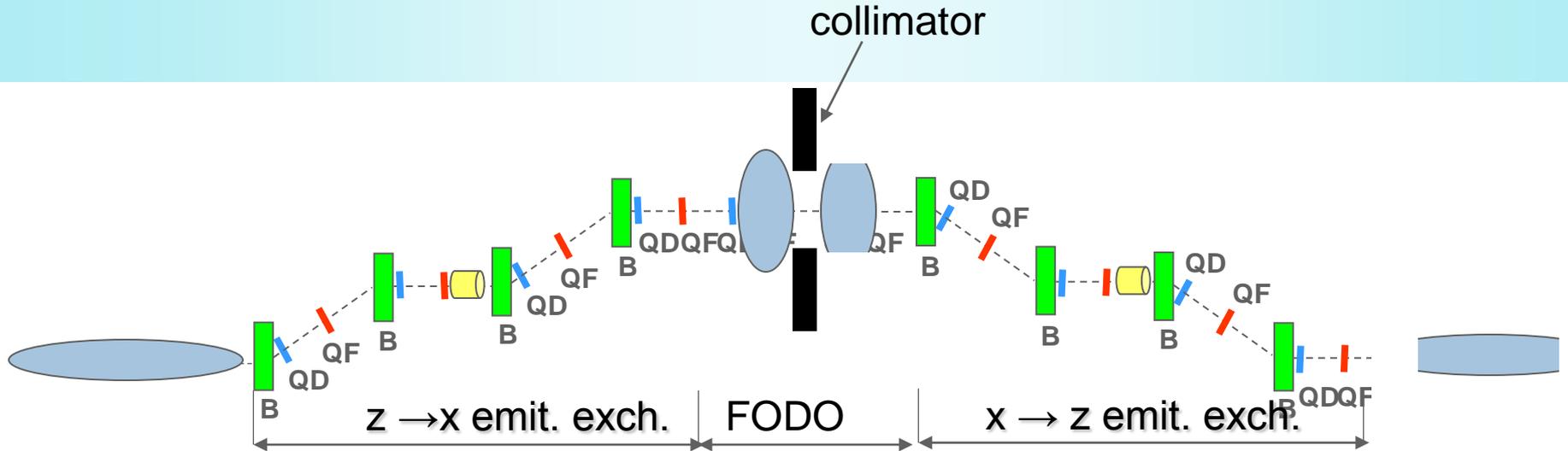
# Producing 1 nm seeding beginning from 200 nm laser modulation



Total harmonic number =  $20 \times 10 = 200$  !

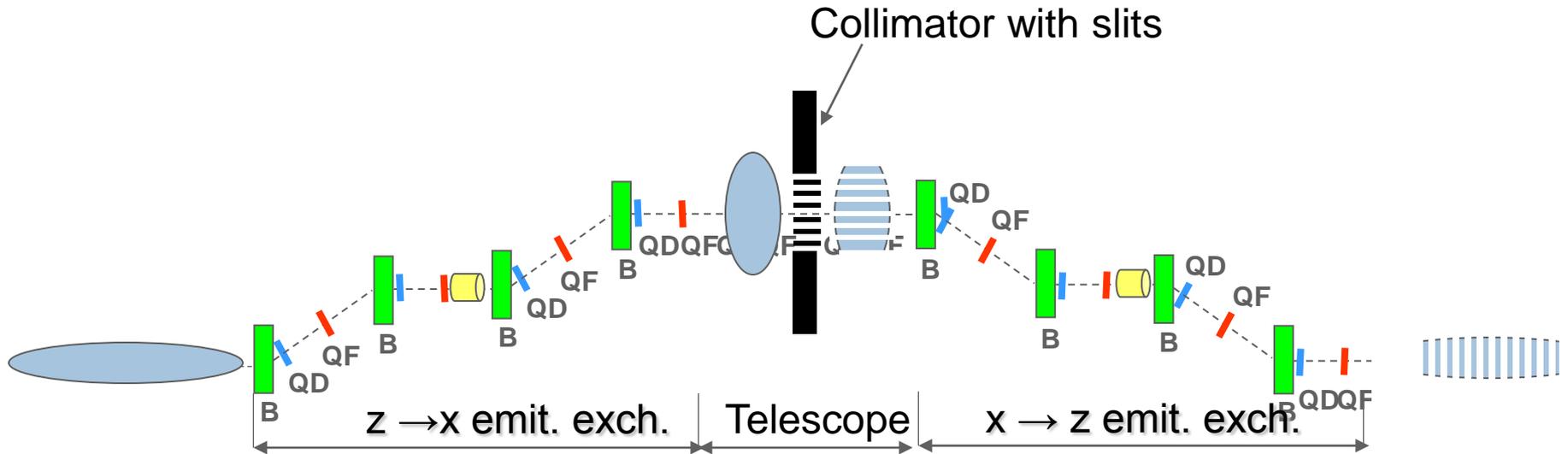
# Other uses

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)

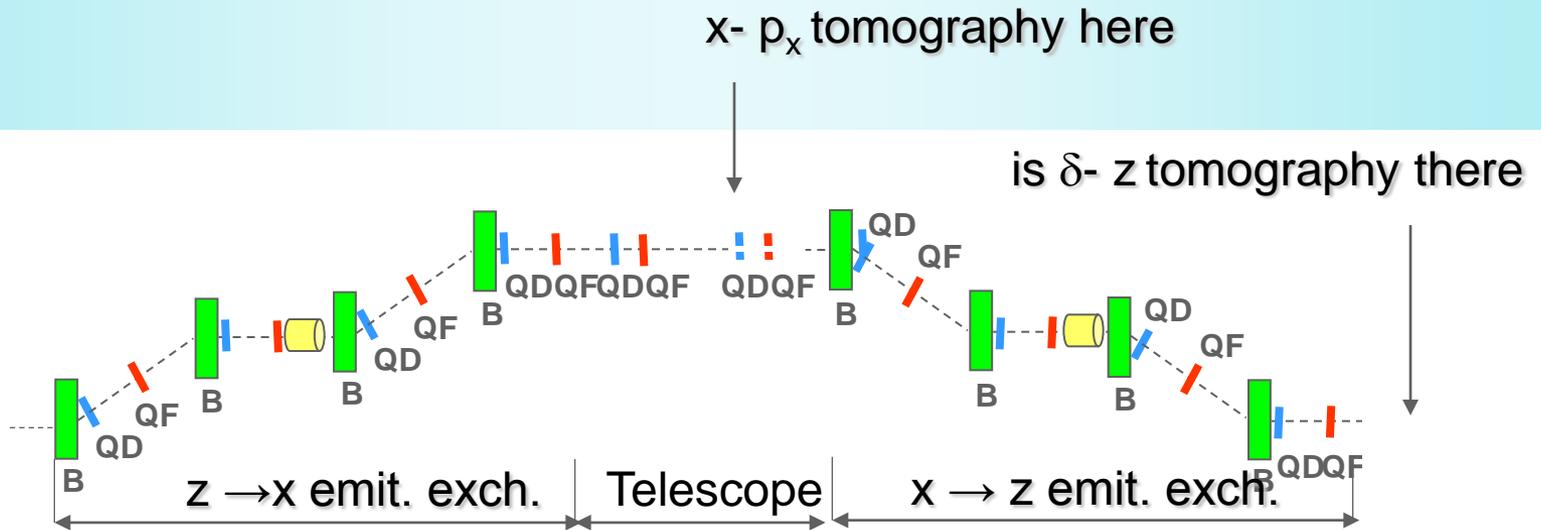
It is possible to create a sequence of a tightly spaced microbunches using a sequence of slits



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.

