# Suppression of microbunching instability *with* magnetic bunch length compression in a linac-based free electron laser

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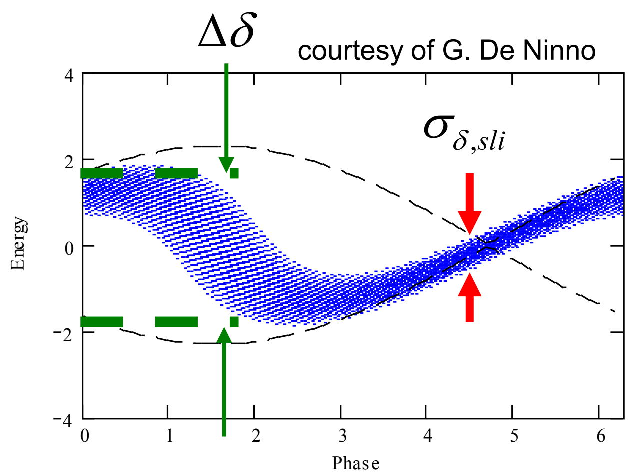
# outline

1. motivations
2. *enhanced longitudinal phase mixing*
    3. single compression
    4. phase mixing
    5. collective effects
6. comments
7. summary

# motivations

- The gain length of multi-stage HGHG FEL is very sensitive to the **slice energy spread**. Microbunching instability must be suppressed to avoid unacceptable growth of the slice energy spread.
  [see E. Allaria, G De Ninno, PRL **99**, 014801 (2007); M.Venturini, PRST-AB **10**, 104401 (2007)].




$$\sigma_{\delta,tot} = \sqrt{\sigma^2_{\delta,chirp} + \sigma^2_{\delta,sli} + (\Delta\delta_{seed}/2)^2}$$

$$\sigma_{\delta,tot} \le \rho \qquad \Delta\delta_{seed} \ge N\sigma_{\delta,sli}$$

$$\sigma_{\delta,chirp} \le 1 \cdot 10^{-3}$$

$$\sigma_{E,sli} \le 150 \div 200 keV$$

- The optimization of the bunch length **compression scheme** (linac + chicanes) is a priority for preserving the injector beam quality, manipulating the bunching and improving the FEL gain.
  [see S. Di Mitri et al., NIM A **608** (2009) 19 – 27].

# enhanced longitudinal phase mixing

*What*

- We propose a machine configuration that is more efficient in suppressing the microbunching instability than the double and even the single compression scheme.

- The proposed scheme can be tuned to arbitrarily redshift the residual instability gain before entering into the undulator.

- The feasibility of this scheme and its capability to preserve the beam quality is demonstrated with 1-D analytical and 3-D particle tracking model.

*How*

I. Adopt the single compression (BC1).

II. Add a second chicane (BC2) at higher energy.

III. Remove the energy chirp between BC1 and BC2 with a proper RF phase.

IV. Use BC2 to dilute the energy and density modulation induced by the microbunching instability - *not* to compress the beam (already done in BC1).

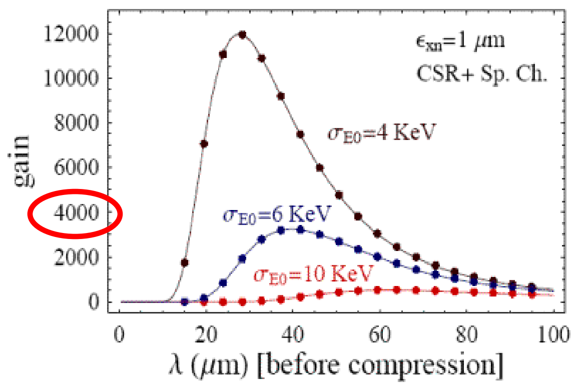
# single compression (1)

- *pros:* suppression of the *ubi* is more efficient than in the two-stage compression because…

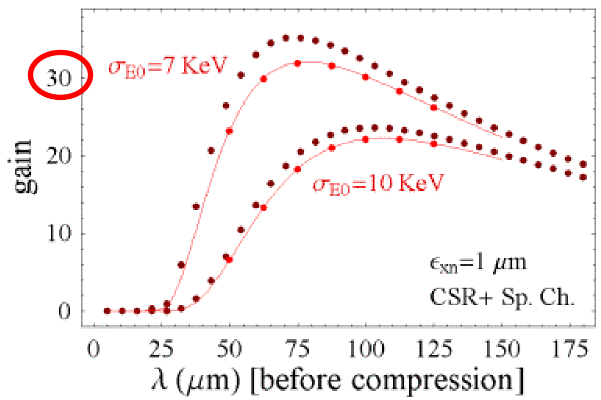
1) …Landau damping is made stronger by a larger $R_{56}$ applied to a bigger relative energy spread;

2) …there is not a second chicane to transform the LSC-induced energy modulation into current modulation.

Double compression




Single compression



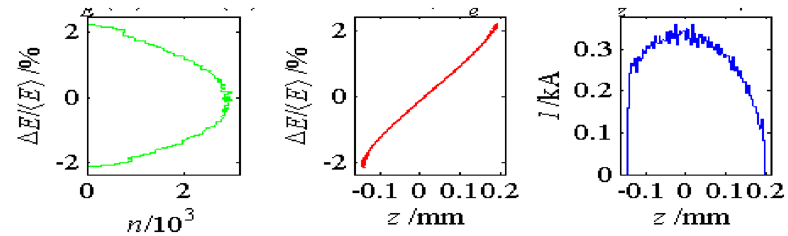

M.Venturini, PRST-AB **10**, 104401 (2007).

# single compression (2)

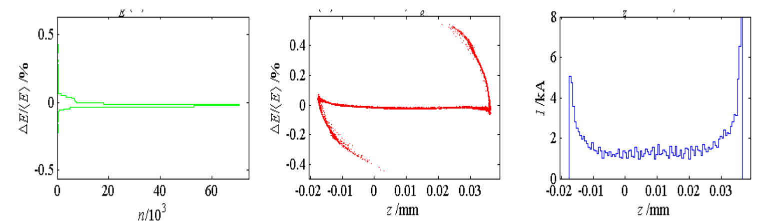
- cons: a shorter bunch is affected by stronger longitudinal wakefield along a longer path than in the two-stage compression

  → use this wakefield to remove the energy chirp required by the compression

at BC1




at linac end

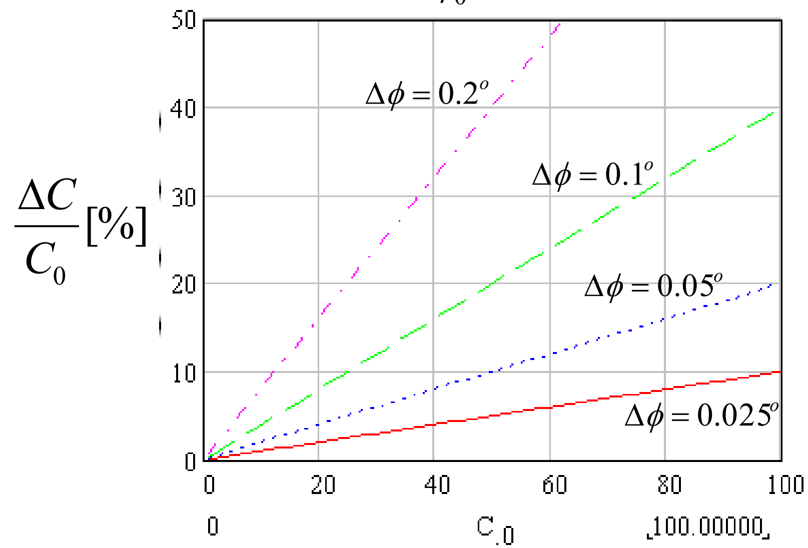



- cons: shot-to-shot variations of the bunch length due to initial timing jitter are no more compensated by the second chicane

  → limit the compression factor to meet the specification for the final current jitter,

$$\frac{\Delta C}{C_0} = -C_0 \frac{\Delta\phi}{\phi_0}$$

$\phi_0 = -25^o$



# single compression (3)

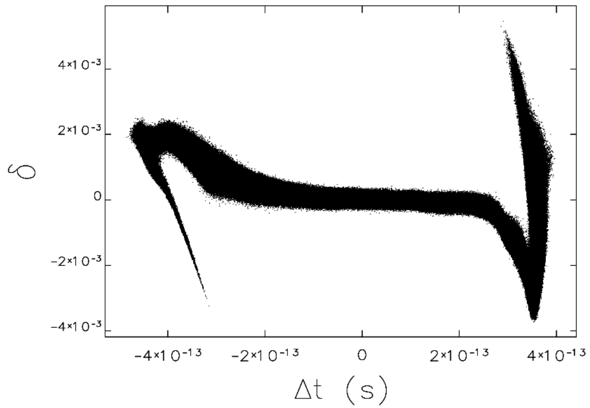
- *prescriptions:*

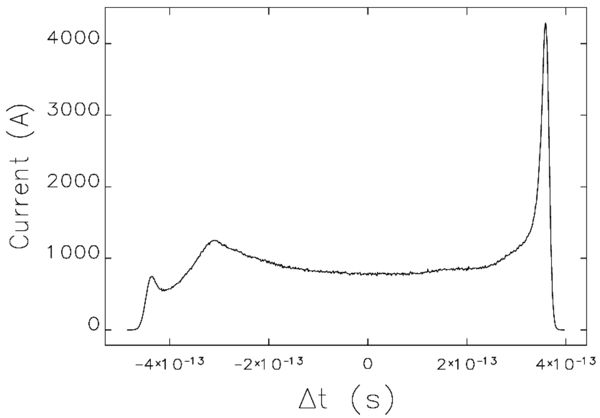
  1) compress at E ≥200MeV  to avoid emittance blow-up by space charge forces

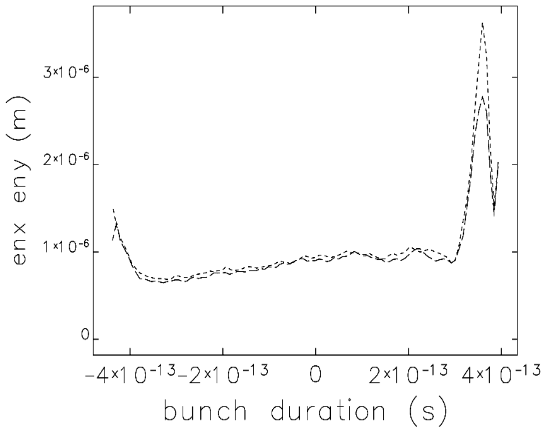
  2) limit $\sigma_\delta \leq$ 2% in BC1 to avoid emittance blow-up by chromatic aberrations

  3) compress by a factor ≤30 to avoid nonlinearities in the longitudinal phase space

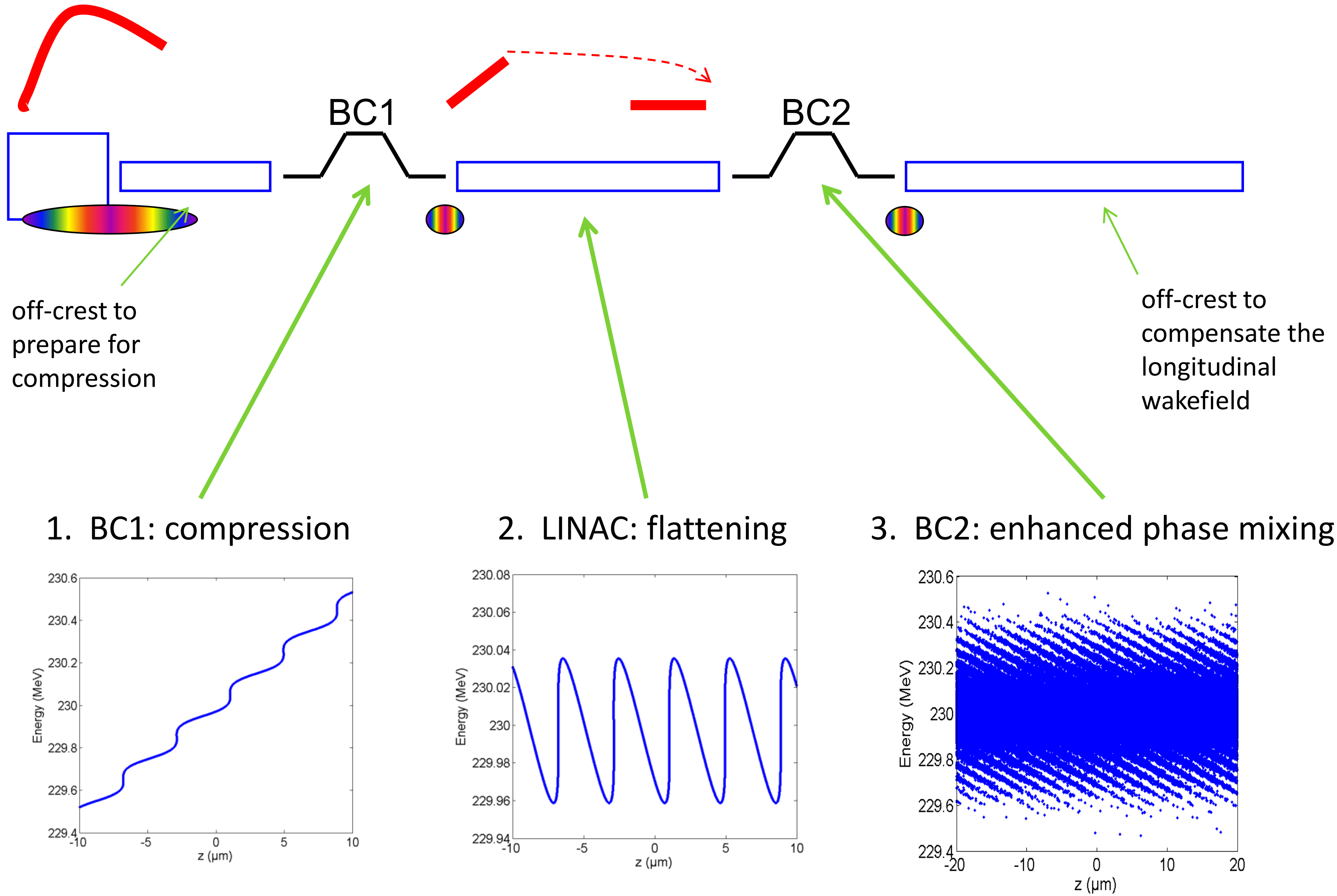
*example: 800pC compressed at 250MeV by a factor 10 ($\rho_{LAM} \cong 3$), final energy is 1.2GeV*



# enhanced longitudinal phase mixing



# model

[see Z. Huang et al., PRST-AB, **7**, 074401 (2004), M. Borland, APS LS-287, 2000].

- 1-D LSC impedance $$Z(k)=\frac{iZ_0}{\pi k r_b^2}\left[1-\frac{kr_r}{\gamma}K_1\left(\frac{kr_b}{\gamma}\right)\right]$$

- 1-D bunching factor in the presence of linear transport matrix $$b(k_f)=\left[b_0(k_i)-ik_fR_{56,1}\frac{\Delta\gamma(k_0)}{\gamma}\right]e^{-\frac{\left(k_fR_{56,1}\frac{\sigma_\gamma}{\gamma}\right)^2}{2}}$$

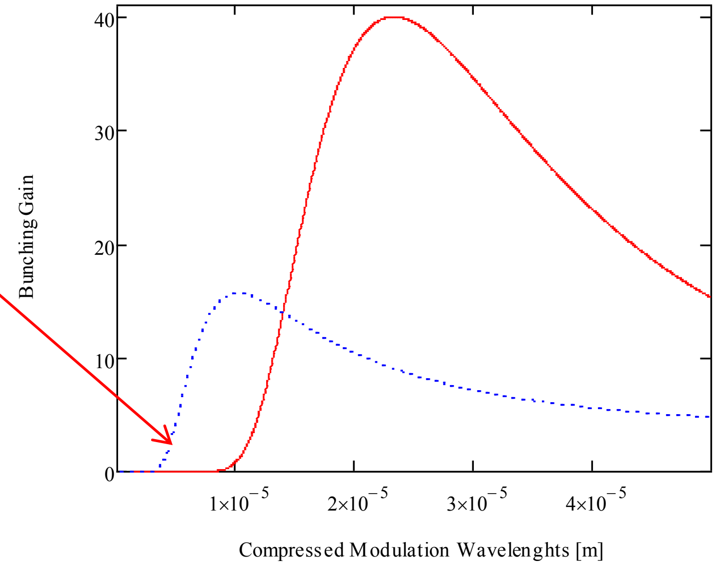
- LSC-induced energy modulation $$\Delta\gamma(k)\approx-\frac{I_0b(k)}{I_A}\int_0^L\frac{4\pi Z(k,s)}{Z_0}ds$$

- *elegant* tracking code: includes 1-D CSR and LSC impedances

# analysis & particle tracking

μbi gain

**gain goes to zero for $\lambda_i \leq 100\mu m$**

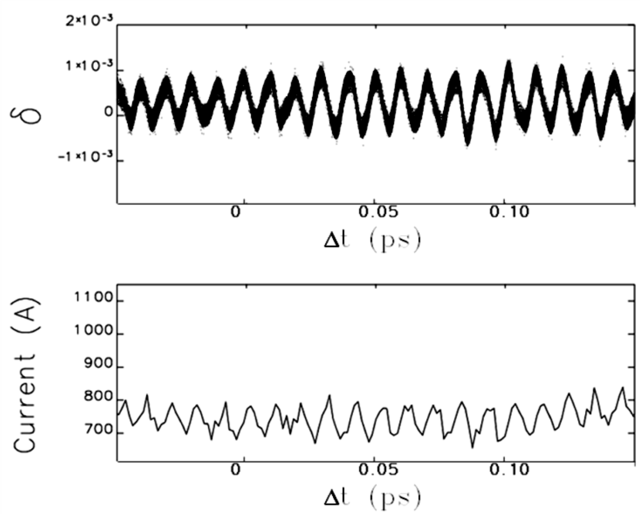



single compression

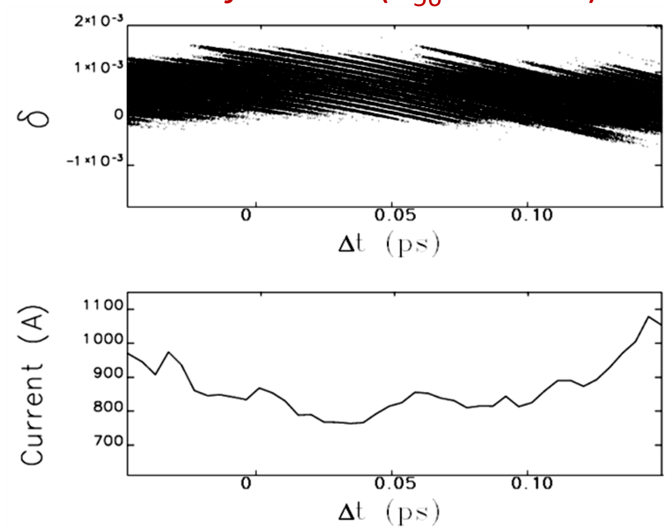
enhanced phase mixing

*elegant* tracking.
$\lambda_i = 30\mu m$,
$\Delta I/I=1\%$

*Before* BC2

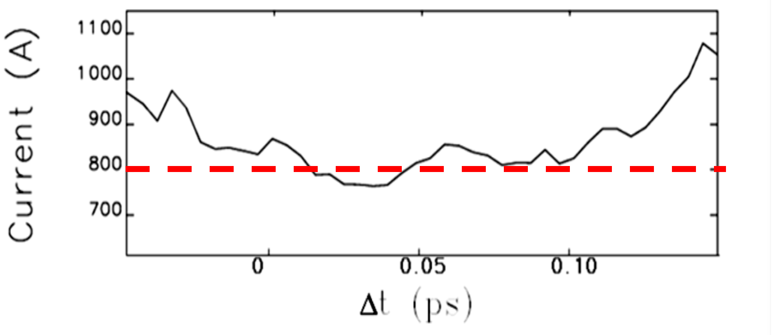



*After* BC2 ($R_{56}$=-30mm)

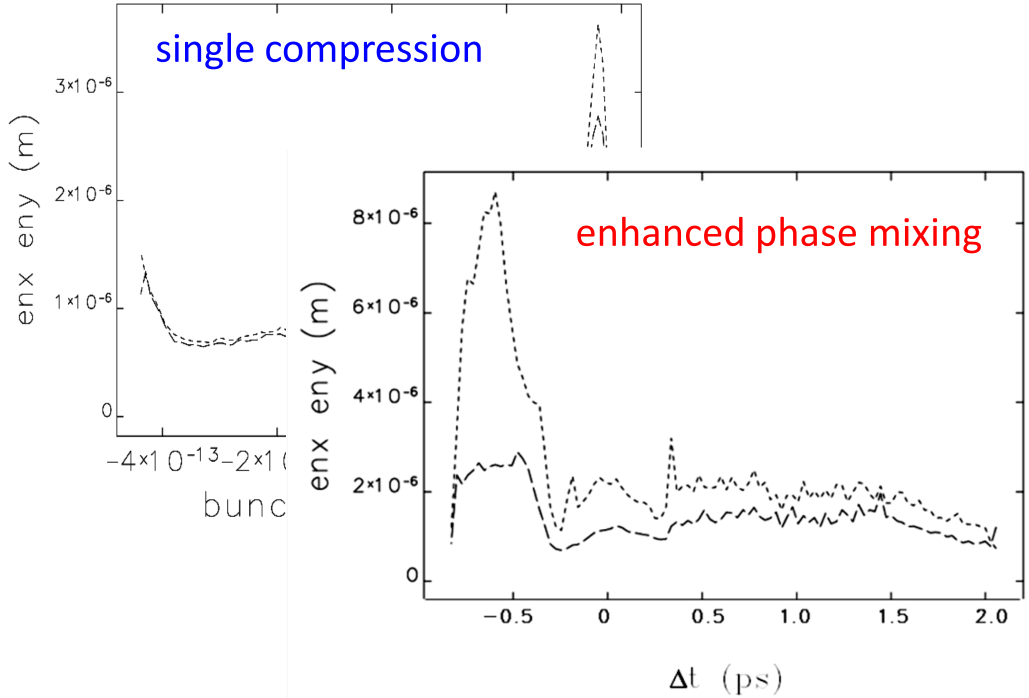


# collective effects

1. longitudinal wakefield *upstream* of BC2 corrupt the current flatness *downstream* of BC2 → correct with harmonic cavity.




2. CSR in BC2 induces emittance growth → possible limitation for high charge, very short bunches



# comments (1)

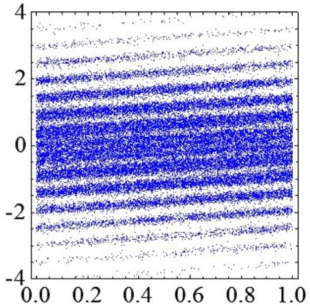
- The "EPM" minimizes the density modulation downstream of BC2.

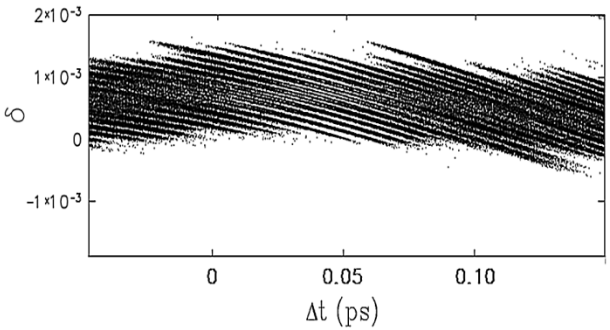
→ *We expect an even smaller energy modulation induced by LSC in the linac downstream of BC2, w.r.t. the double and the single compression.*

- The "EPM" still seems to preserve the E-z correlation of the beamlets after BC2. In fact, this structure is used in the ECHO scheme.

→ *Achromaticity and isochronicity of downstream dispersive lines have to be carefully designed to avoid a revival of microbunching and emittance blow up.*
[preliminary comments in M. Venturini, PRST-AB **10**, 104401 (2007)].

[G. Stupakov, PRL **102**, 074801 (2009)]




[S. Di Mitri et al., PRST-AB, **13**, 010702 (2010)]

# comments (2)

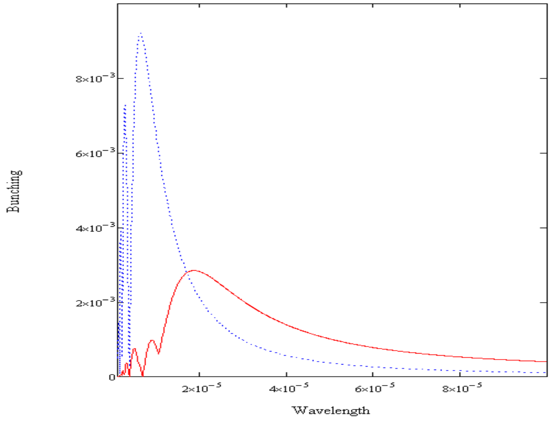
- The "EPM" suppresses the microbunching instability gain function over the wavelength range of interest.

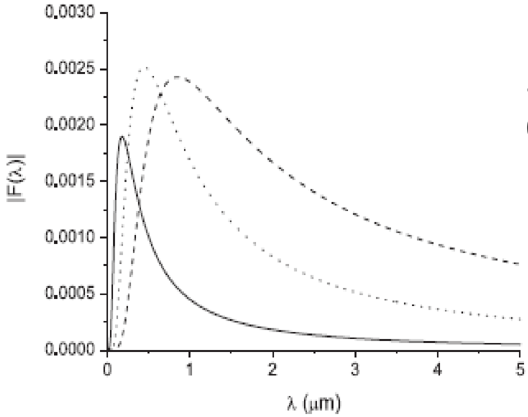
→ *We expect much less heating required to suppress the microbunching instability at these wavelenghts.*

- The "EPM" naturally implies the redshift of the microbunching instability gain function.

→ *The same principle has been adopted in the undulator for the generation of long wavelength output radiation.*

[M. Cornacchia et al., Proc. of EPAC 2008, TUPP03 (2008)]




[E. L. Saldin et al., PRST-AB, **13**, 030701 (2010)]

# summary

- Physics, cost and schedule suggest that the one-stage compression is a valid scheme to achieve a high e-beam quality for moderate compression factors.

- The "enhanced phase mixing" is even more efficient for suppressing the microbunching instability that is to improve the final e-beam energy and current distribution.

- During the machine design, have special care of the current flatness, slice emittance and transport matrix of dispersive lines downstream of BC2.

- The "enhanced phase mixing" can be used, in principle, to properly tune the bunching at the entrance of the undulators without any additional seeding laser.

# acknowledgment

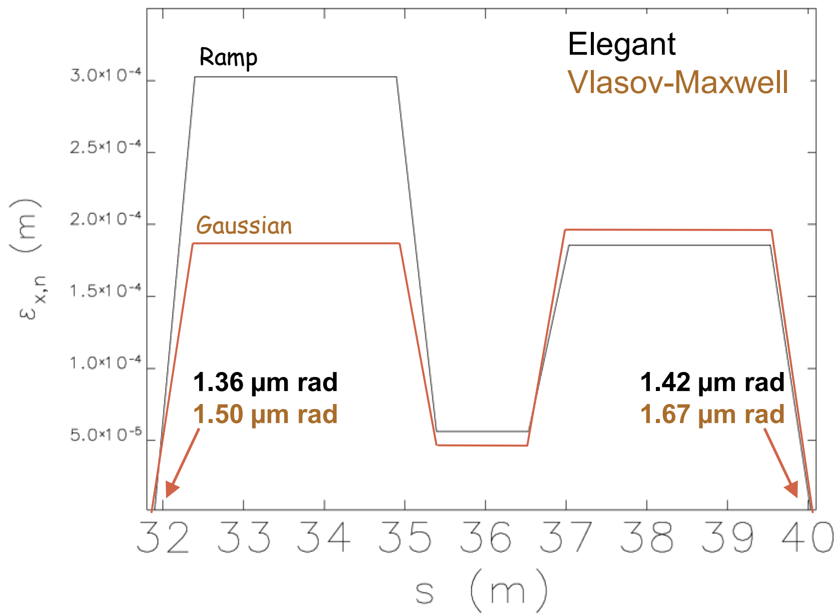
To carry out this work we have started from some works and ideas by Paul Emma (comparison one- vs. two-stage compression), Zhirong Huang (compression at lower energy), Torsten Limberg (stability of the compression factor) and A. Zholents (microbunching in isochronous transfer line).

Thank you for your attention.

# magnetic compression

data from G. Bassi, K. Sonnad, J. Qiang

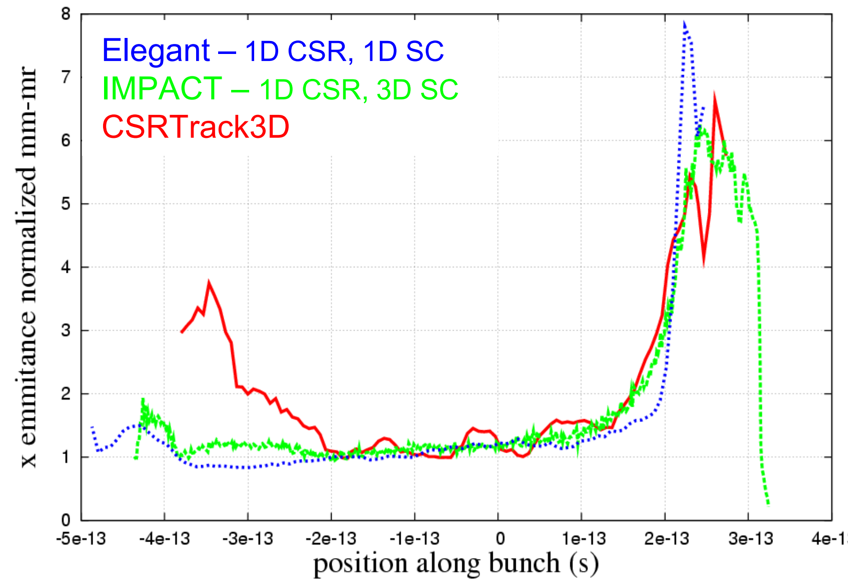
## projected emittance




compression factor = 3.5

*projected* ε-growth minimised by optics matching

## slice emittance




compression factor = 10

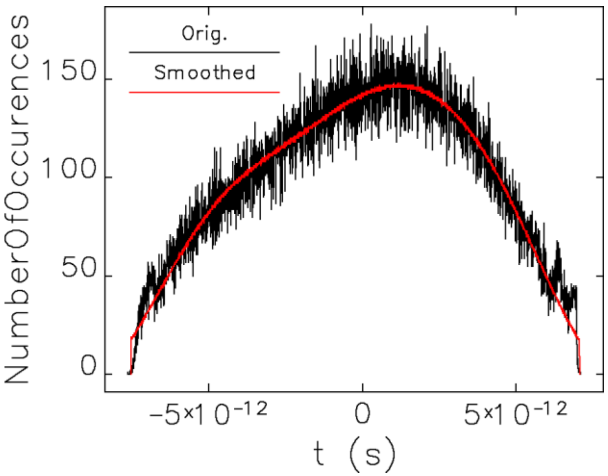
*slice* ε-growth due to:

? 3D CSR forces $\left(\sigma_r \approx \sigma_z^{2/3} R^{1/3}\right)$

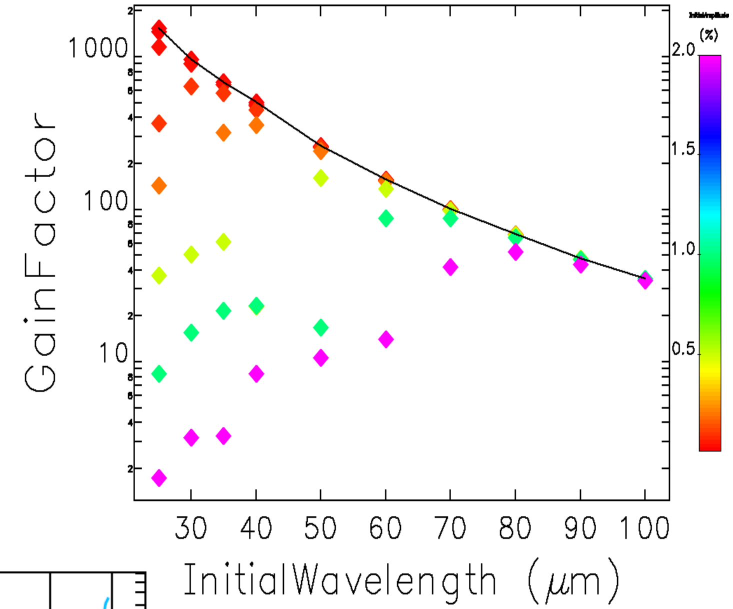
? particle cross-over through adjacent slices

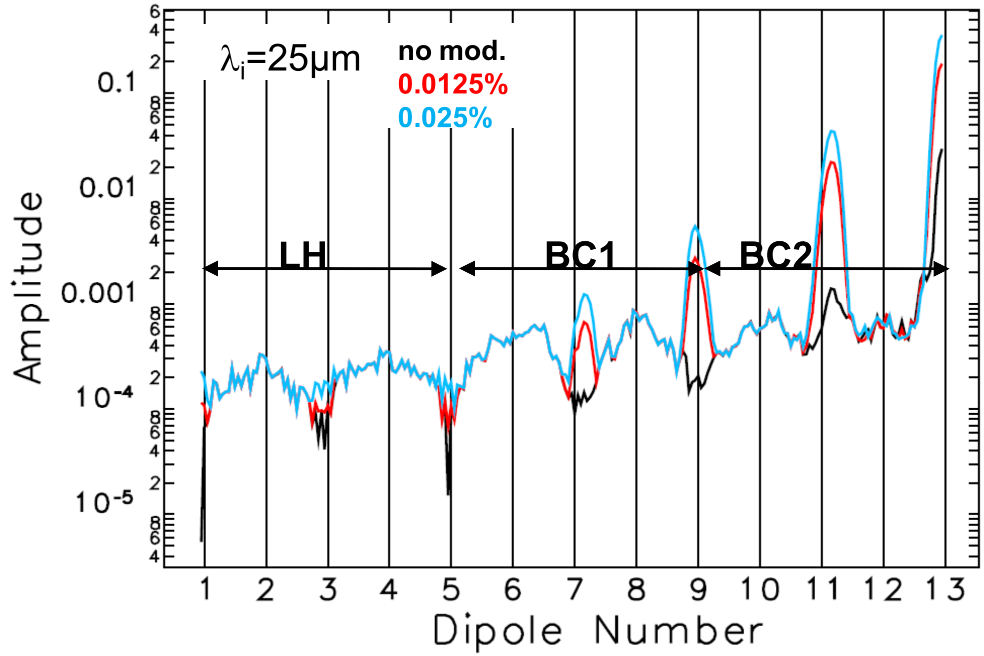
# elegant tracking

M. Borland, PRST-AB 11 030701 (2008)




*elegant*

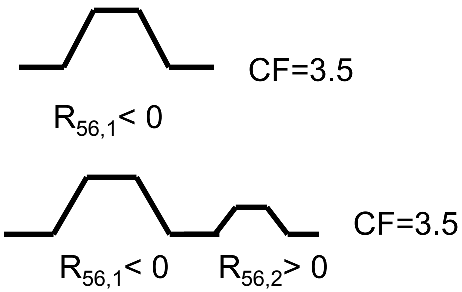


# single compression

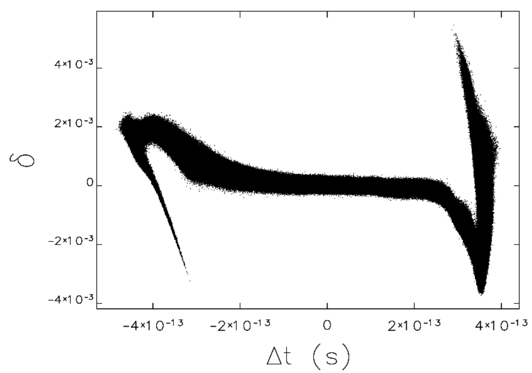
- *pros:* Landau damping

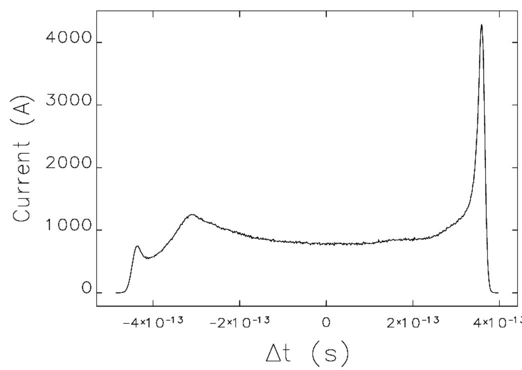
Exercise: calculate the bunching factor for one compressor only and for a compressor + decompressor scheme, but leaving the total compression factor fixed in both cases.




| Initial density modulation | Bunching with BC1-only | Bunching with BC1+DC |
|---|---|---|
| 0.03% at 10 μm | $9 \cdot 10^{-3}$ | $2 \cdot 10^{-3}$ |
| 1% at 100 μm | 0.146 | 0.188 |
| 0.03% at 100 μm | $8 \cdot 10^{-3}$ | $11 \cdot 10^{-3}$ |

- *but:* compression factor limited by beam quality




CF=10, 800pC, 1.2GeV.

Current spikes and nonlinear energy chirp not well controlled for higher compression factors

- cons: bunch length jitter

The bunch length jitter is naturally compensated in the presence of double compression and longitudinal wakefield [see also P. Emma,

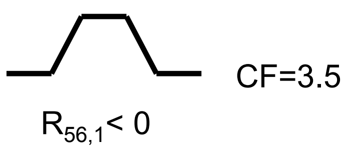
# single compression

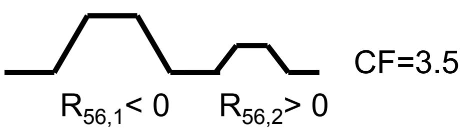
- *pros:* Landau damping is more efficient than in the two-stage compression because:

1) a larger $R_{56}$ is used in the presence of a bigger relative energy spread [Z. Huang]

2) there is not a second chicane to transform the LSC-induced energy modulation into current modulation.

Exercise: calculate the bunching factor for one compressor only and for a compressor + decompressor scheme, but with the *same* total compression factor in the two cases.

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- The limiting case is the single compression.
- The analysis shows that the damping depends more from the wavelength than from the amplitude of the modulation.