# Generation of Short Wavelength Modulation through Compression

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# Acknowledgements

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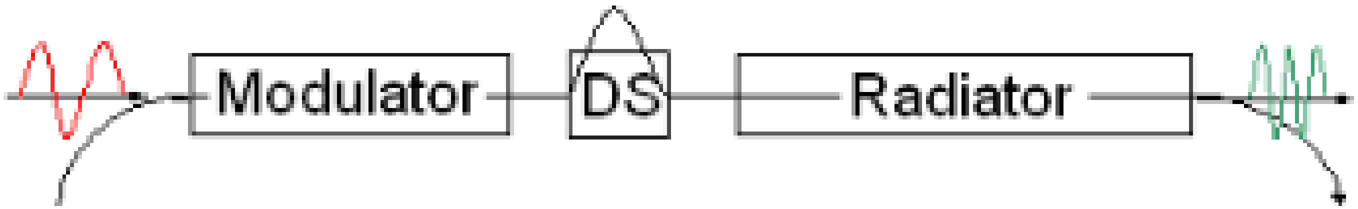



High Gain Harmonic Generation(HGHG) scheme

- Both temporal and transverse coherent
- Pulse to pulse stablablity
- Shorter saturation distance

$$b_n \equiv \langle e^{i\psi} \rangle = e^{-1/2((\partial\psi/\partial\gamma)\sigma_\gamma)^2} J_n\left(\frac{\partial\psi}{\partial\gamma}\Delta\gamma\right)$$

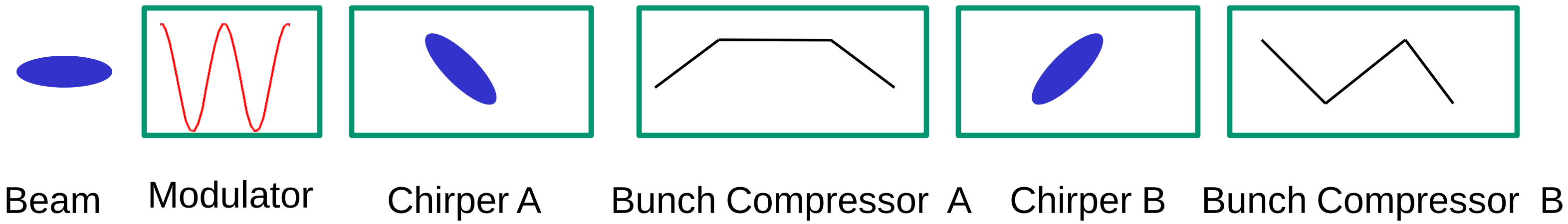
$$\frac{\partial\psi}{\partial\gamma} \propto n\frac{k_{w1}}{\gamma}$$

normally limited to a small harmonic number in a single stage

L. H. Y, Phys. Rev. A 44, 5178 (1991).

# A Schematic Plot of Lattice for Modulation Compression






$$f_1(z_1,\delta_1) \;=\; F(z_1, \frac{\delta_1 - A\sin(kz_1)}{\sigma})$$

$$C = 1/(1+R_{56}^a h)$$

$$\boxed{h^b = -h^a D^b C,} \qquad D^b = E_3/E_4$$

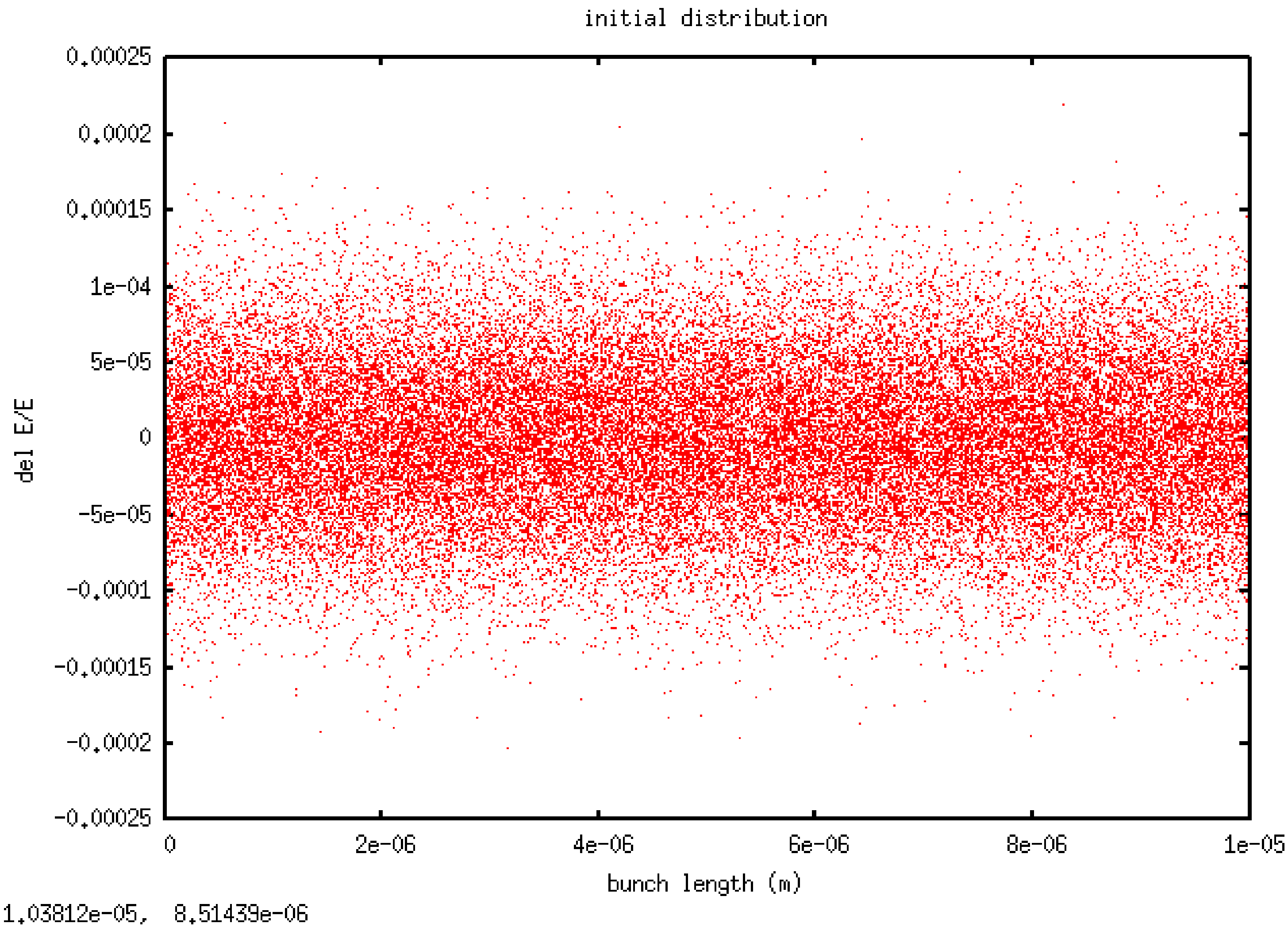
$$\boxed{R_{56}^b = -R_{56}^a/(D^b C),} \qquad D^a = E_1/E_2$$

$$f_5(z_5,\delta_5) \;=\; F(Cz_5, \frac{\delta_5 - CD^bD^aA\sin(kCz_5)}{CD^bD^a\sigma})$$

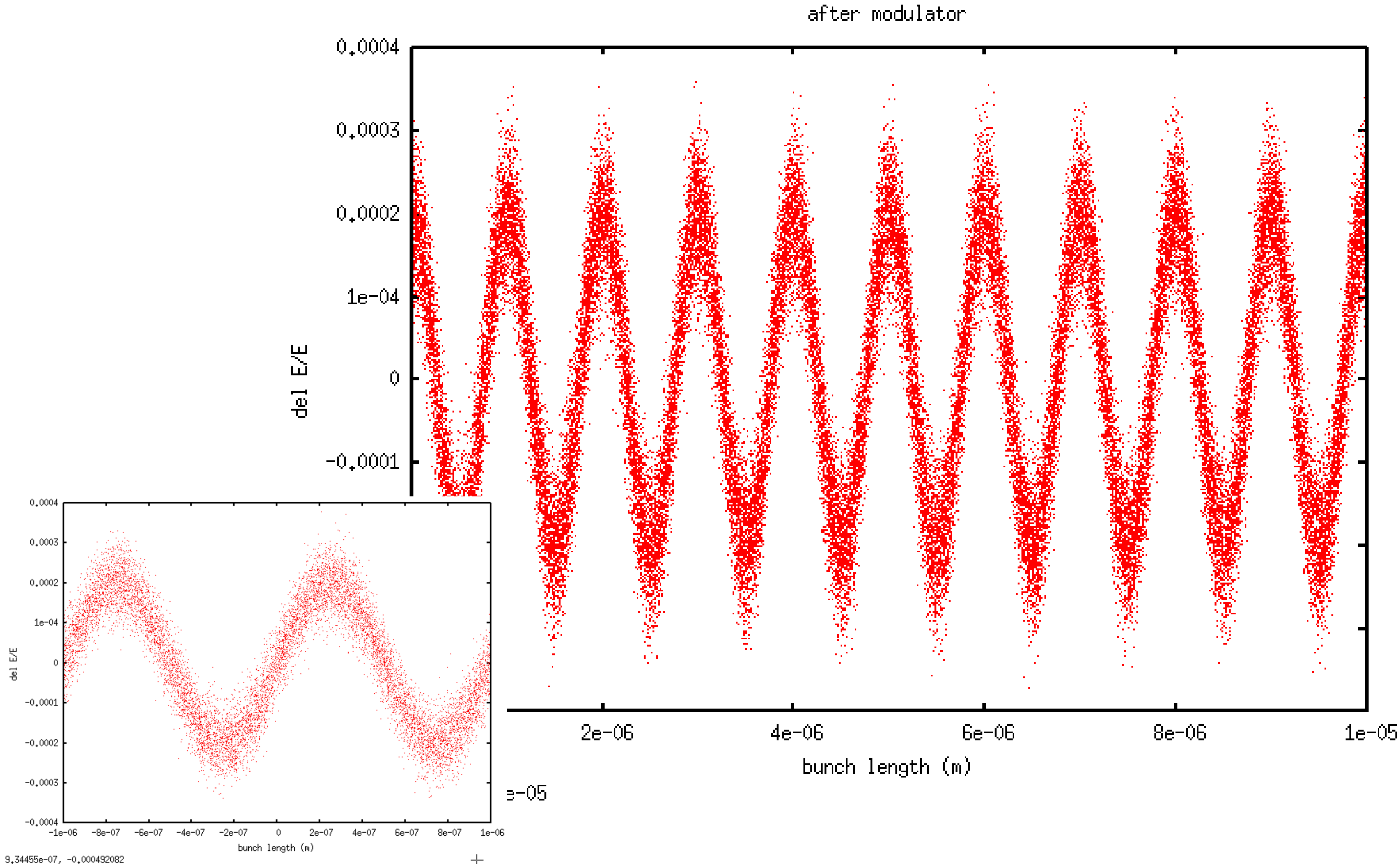
# Numerical Parameters Used for Illustration

Initial sigma_del/E = 0.5 e-4
Modulation amplitude = 2e-4
Modulation wavelength = 1 um
Linac 1 chirp = -19 /m
Chicane 1 R56 = 5 cm
Chicane 1 compressing factor = 20
Linac 2 chirp = 380
Chicane 2 R56 = -2.5 mm

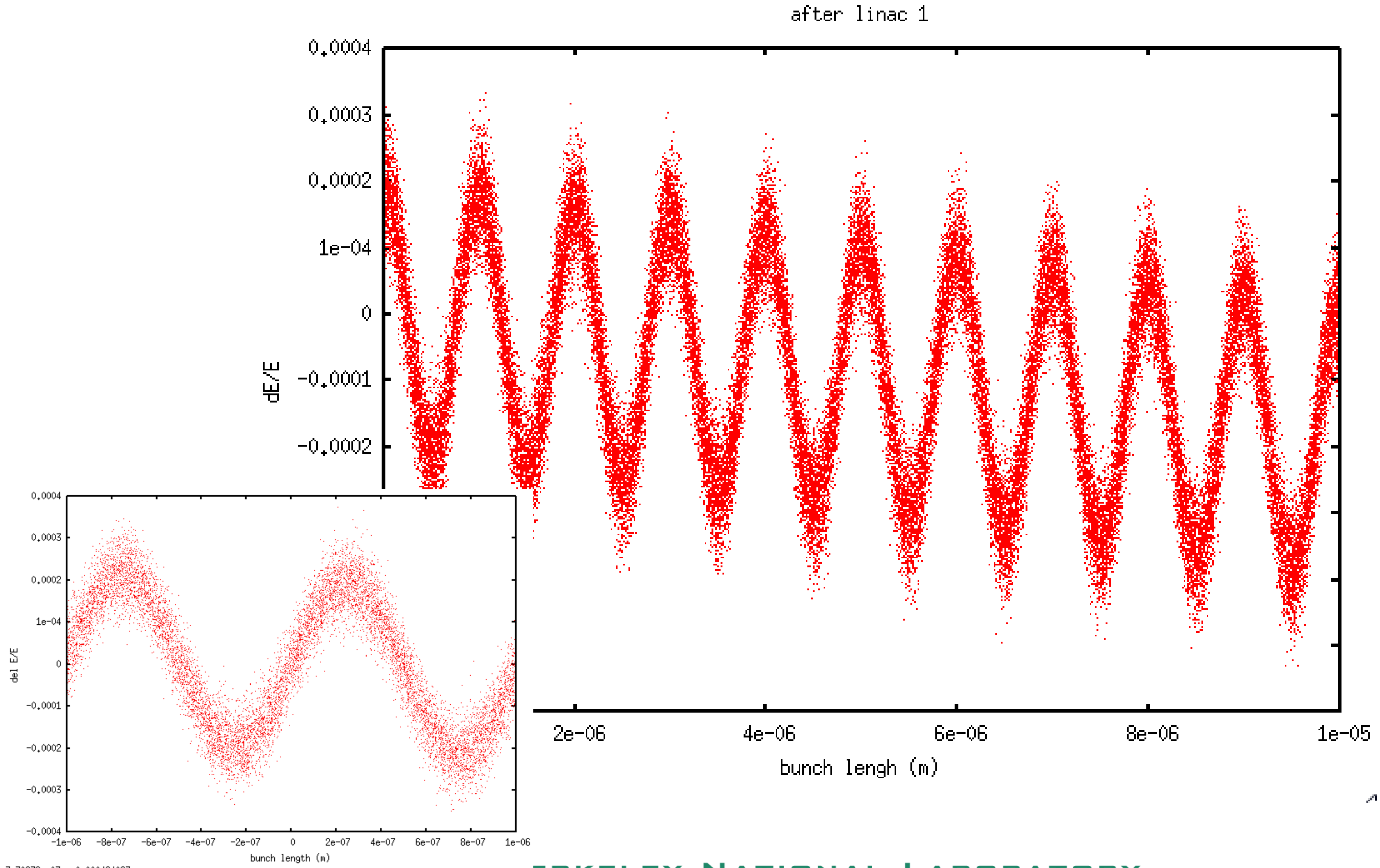
# Initial Longitudinal Phase Space



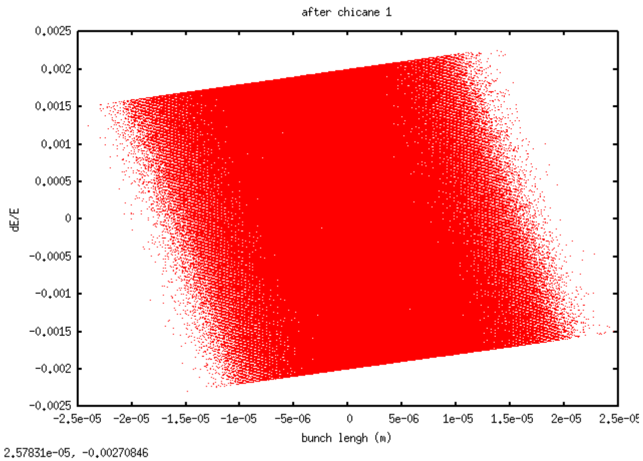
# Longitudinal Phase Space After Modulator

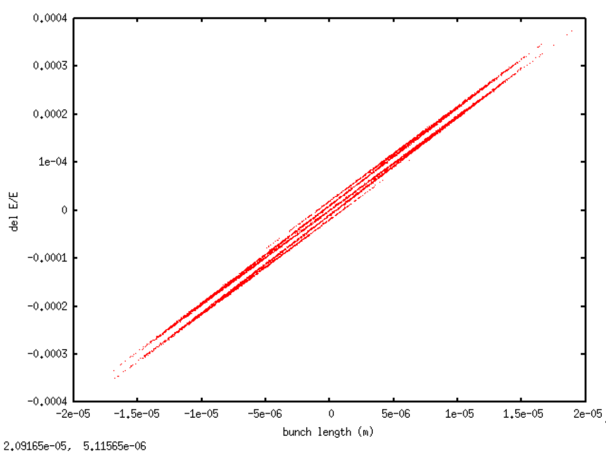


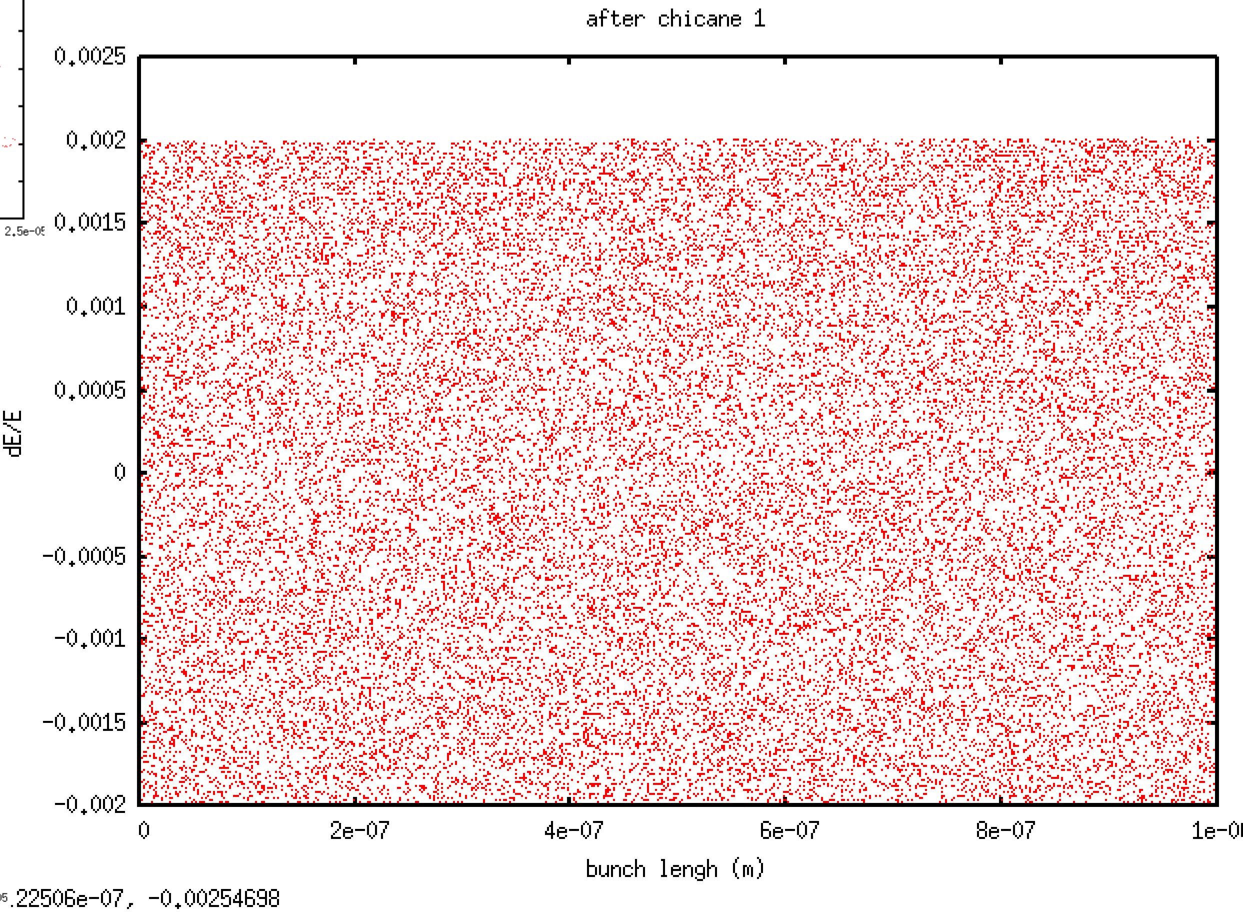
# Longitudinal Phase Space After Chirper A



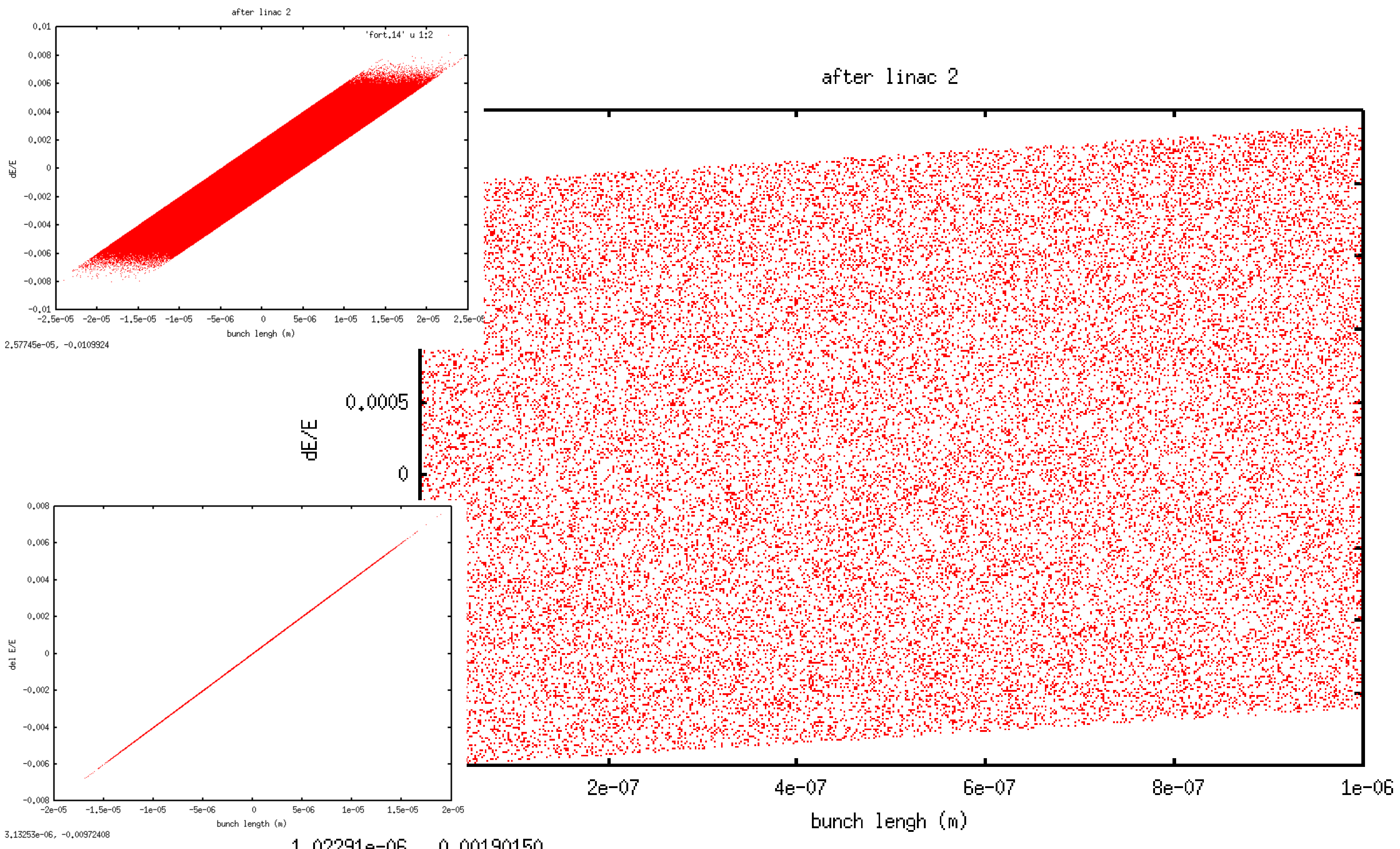
# Longitudinal Phase Space After Bunch Compressor A



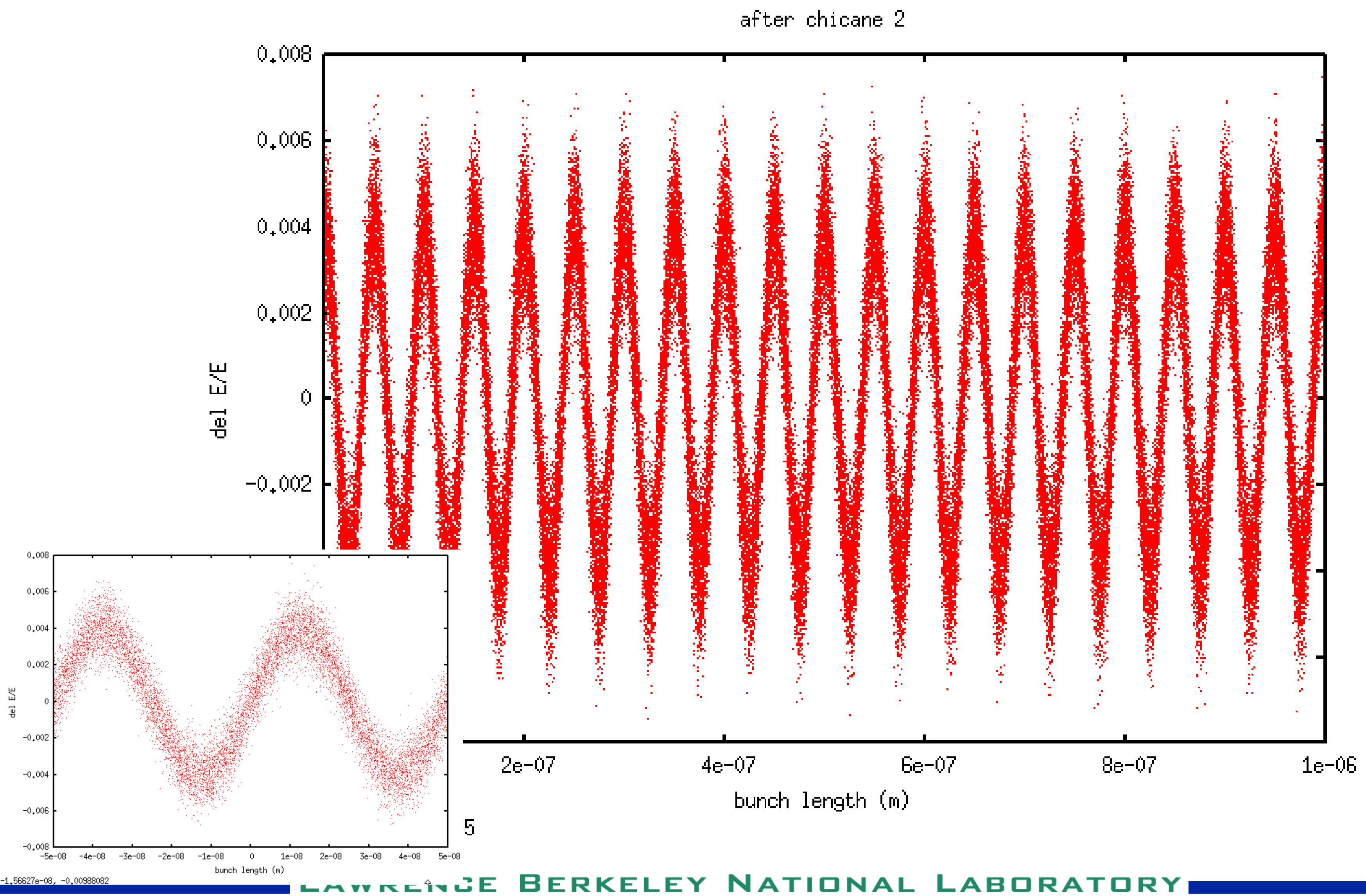



# Longitudinal Phase Space After Chirper B



# Longitudinal Phase Space After Bunch Compressor B



$$R_{56}^b = -R_{56}^a/(D^b C) + \Delta r^b,$$

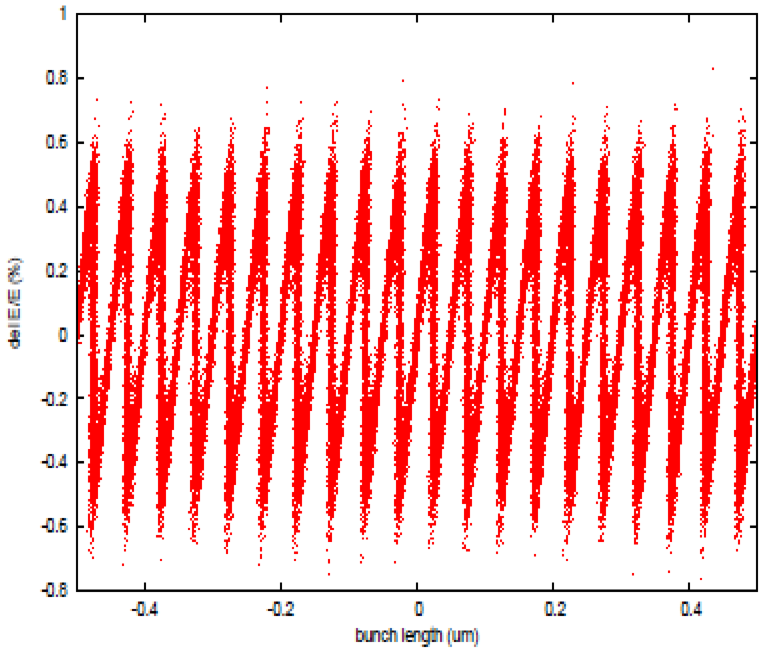
$$f_5(z_5, \delta_5) = \exp(-\frac{1}{2}(\frac{\delta_5 - CD^b D^a A \sin(kCz_5 - kC\Delta r^b \delta_5)}{CD^b D^a \sigma})^2)$$

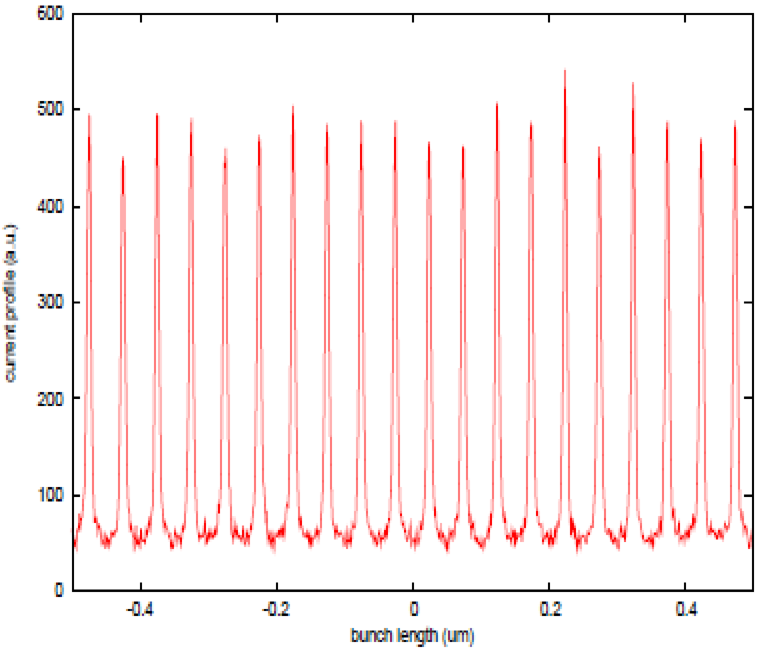
$$I(z) = \int_{-\infty}^{\infty} d\delta \ \exp(-\frac{1}{2}(\frac{\delta - CD^b D^a A \sin(kCz - kC\Delta r^b \delta)}{CD^b D^a \sigma})^2)$$

$$I(z) = I_0(1 + 2\sum_{n=1}^{\infty} b_n \cos(nCkz))$$

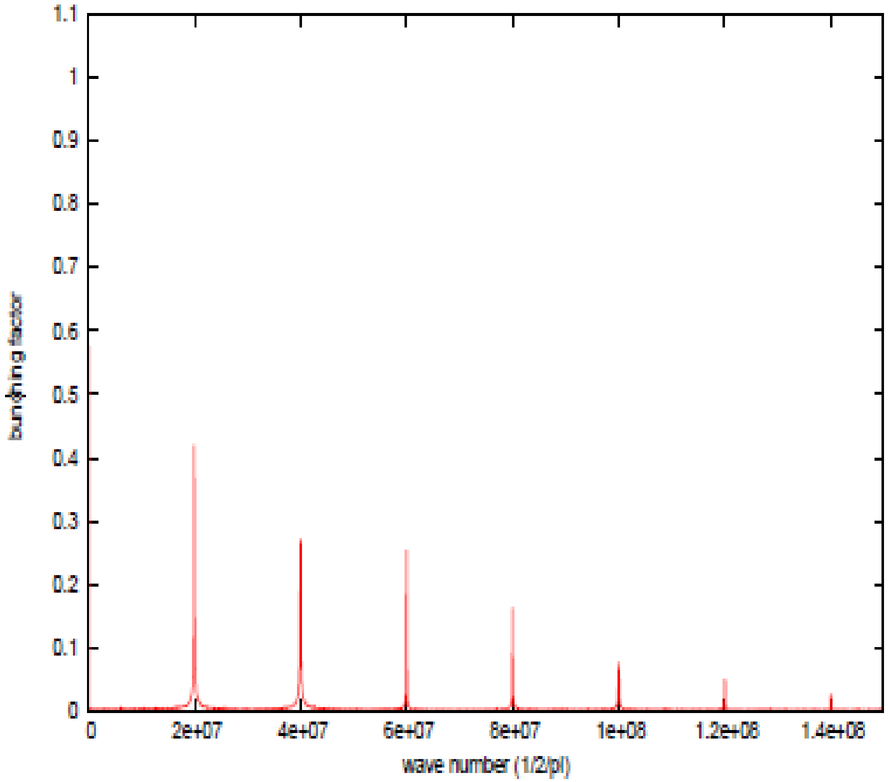
$$b_n = J_n(nC^2 k \boxed{\Delta r^b A} D^b D^a) \exp(-\frac{1}{2} n^2 (C^2 k \boxed{\Delta r^b} D^b D^a \sigma)^2)$$

# Current Density Modulation: Illustration Example



# Current Density Modulation: Bunching Factor



# Previous Study (1): Frequency Upshift

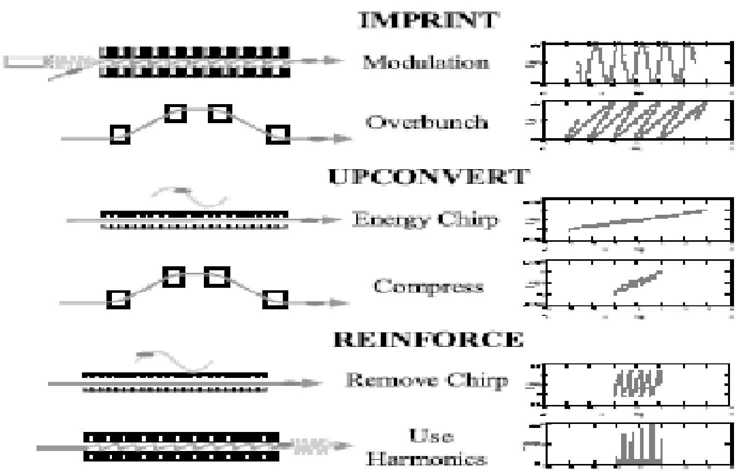



Fig. 2. Example V—wavelength shifting concept.

*) S. G. Biedron, S.V. Milton, and H.P. Freund, NIM A **475** (2001)401.
T.Shaftan *et al.*, Phys. Rev. E, **71**, (2005)046501.

Comparison of Two Different Wavelength Tunging Schemes
In A
Seeded High-Gain FEL

T. Shaftan and L.H. Yu
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, New York 11973

June 2004

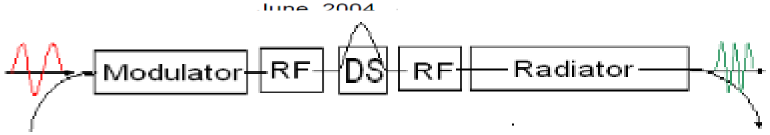



Figure 2: Dedicated scheme for the tuneable HGHG FEL. RF sections are located before and after dispersive section locally providing the energy chirp required for the wavelength compression.

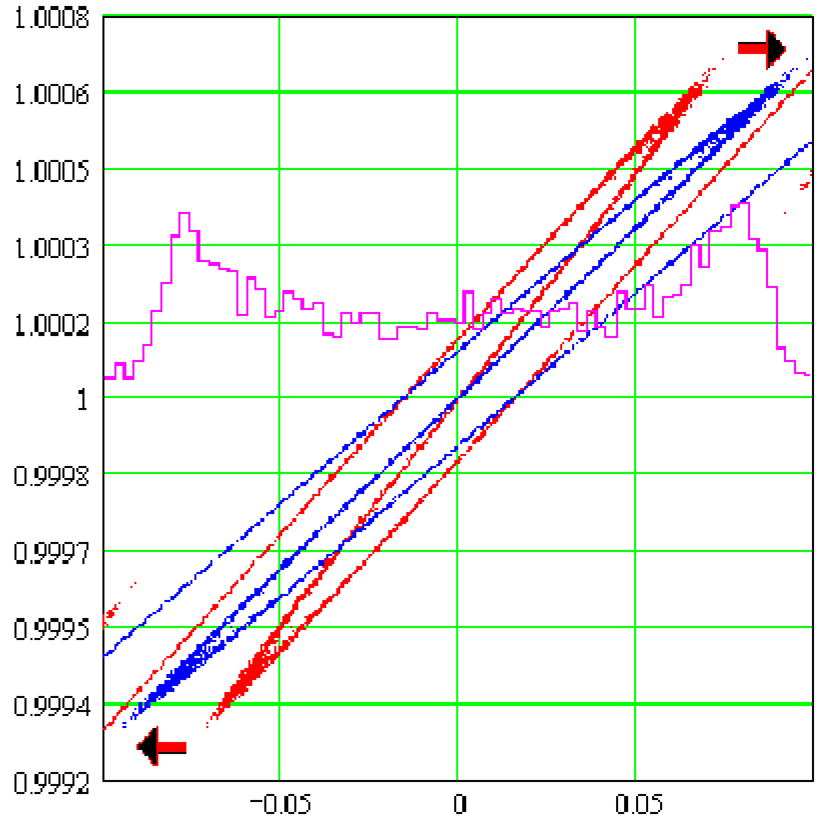
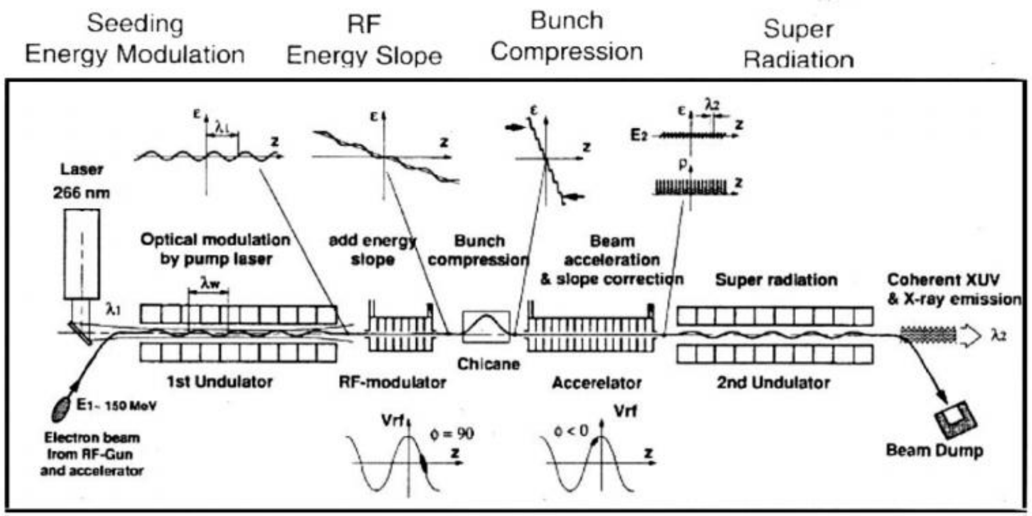
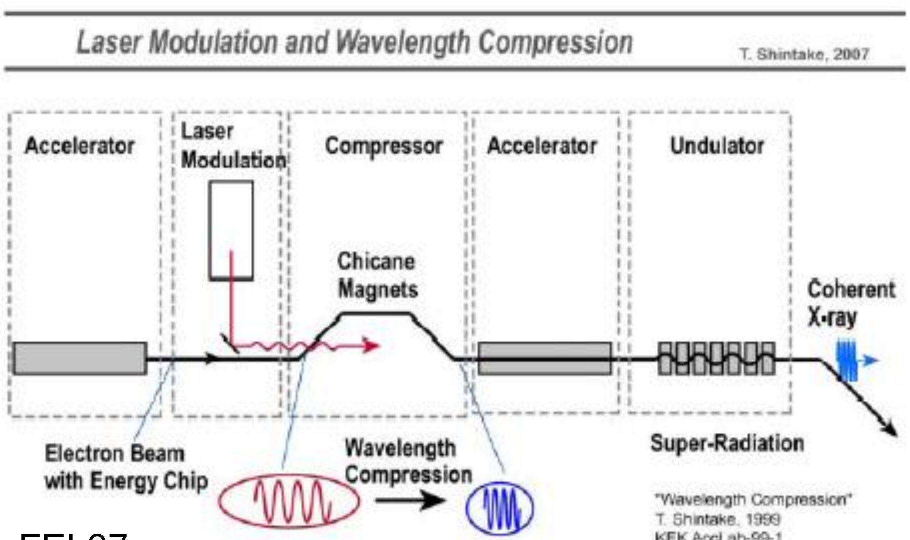



Fig. 7: Phase space of a single modulation period before and after the second chicane (positive chirp). Magenta curve shows the bunching content




$$I(z) = CI_0\left[1 + 2\sum_{n=1}^{\infty} J_n\left(nCkR_{56}\frac{\Delta\gamma}{\gamma_0}\right) \times \exp\left(-\frac{1}{2}n^2C^2k^2R_{56}^2\frac{\sigma_\gamma^2}{\gamma_0^2}\right)\cos(nCkz)\right].$$

Saldin et al., NIM 490, 1 (2002).

Using above numerical parameters
this gives a factor of $10^{-49348}$ reduction of modulation

Shintake, FEL07

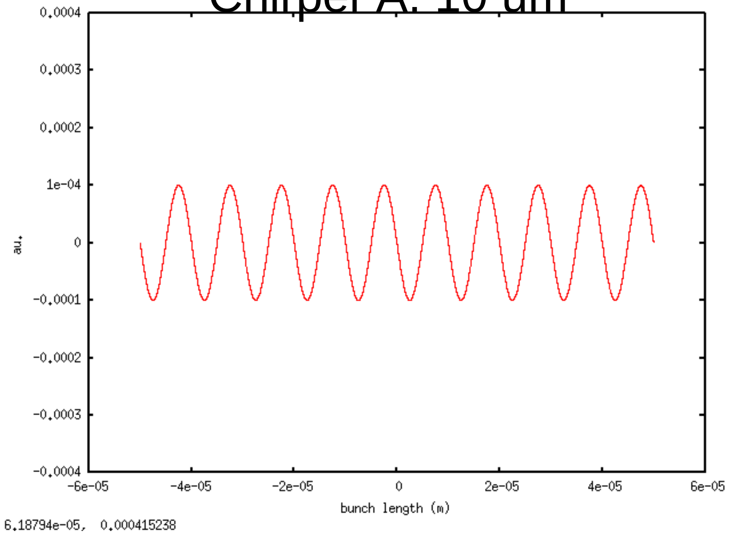
# Chirp Generation

- The chirp generated through an RF wave is given by

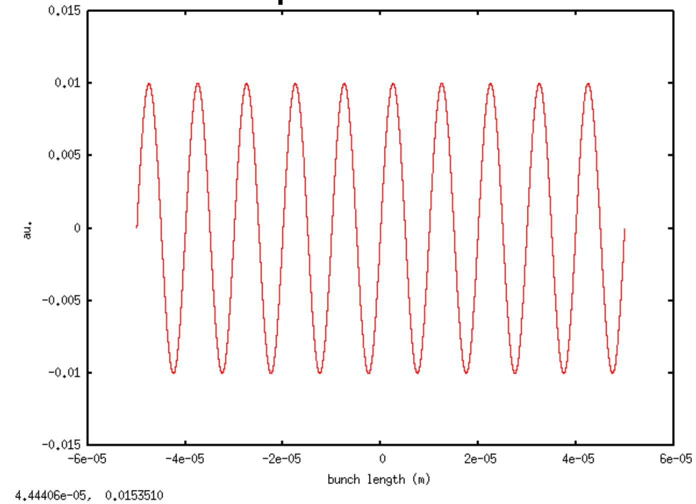
$$h = \frac{eV}{E} k_{rf} \sin(\phi)$$

- This is normally generated by using RF linac
- Chirp may also be generated using laser
- Chirp generation using structure wake field.

Chirper A: 10 um

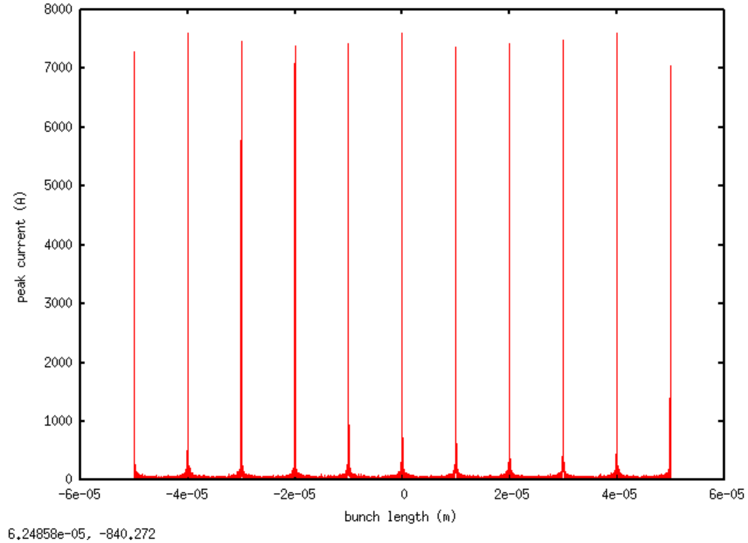



Chirper B: 10 um



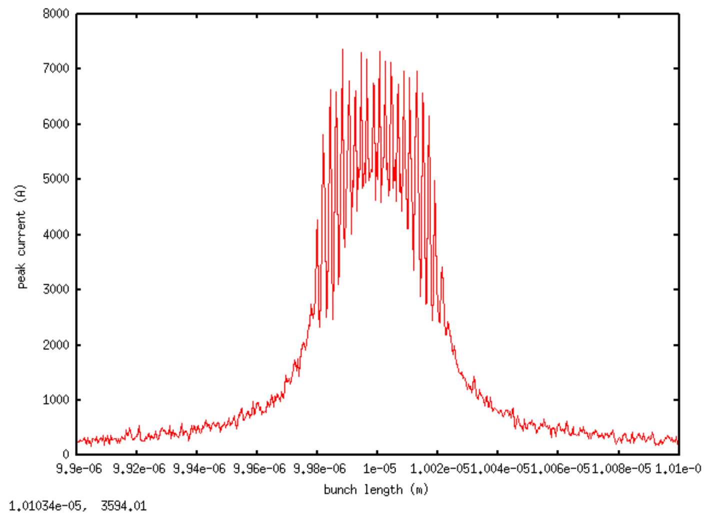

bunch length = 100 um, Q = 20pC, slice energy spread = 1e-5, modulation laser wavelength = 0.2 um, modulation amplitude 2e-5, r56 =1.6cm,, C=100, r56b = -0.16 mm

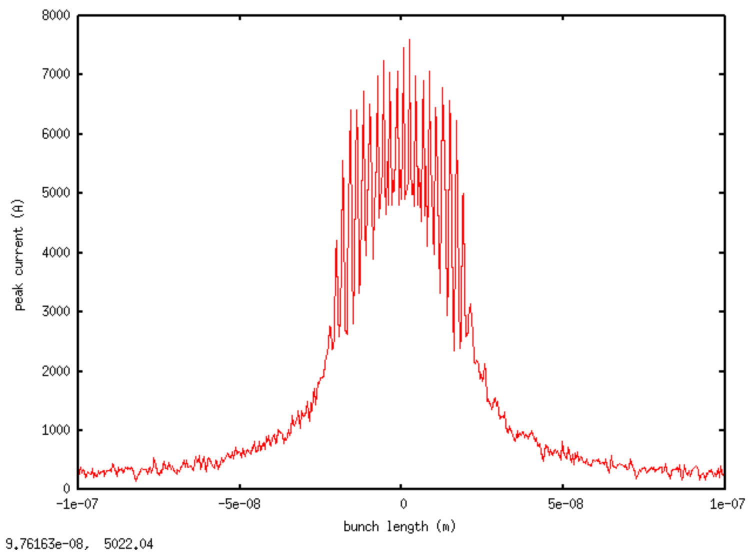
# Current Distribution after Modulation Compression



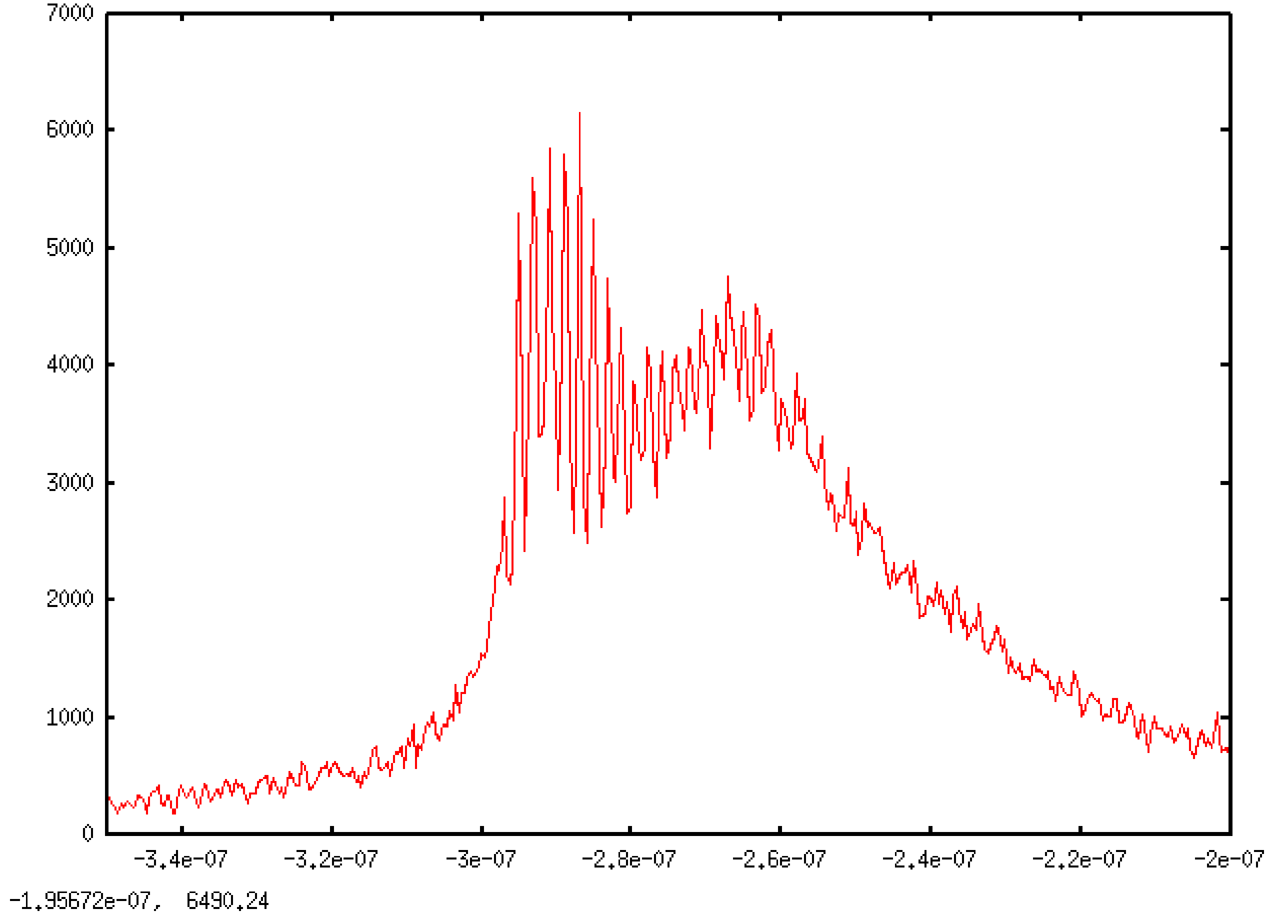

- The width of pulse can be controlled by compression factor and chirp laser wavelength
- The frequency of microbunching can be controlled by compression factor and seed laser wavelength

Full peak width is ~50 nm(167 as) with 2 nm separation of each spike



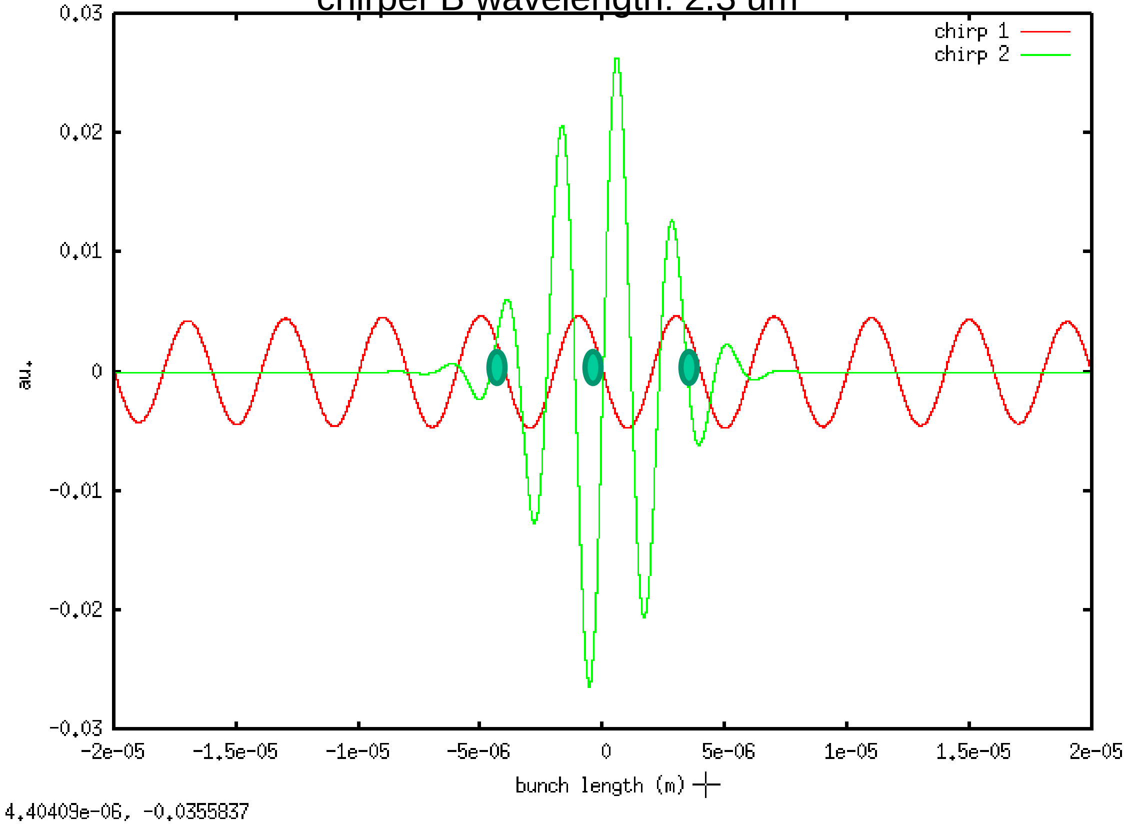



Current Distribution with  20 Degree Phase Errors and 0.2% Amplitude Errors between Laser 1 and Laseer 2



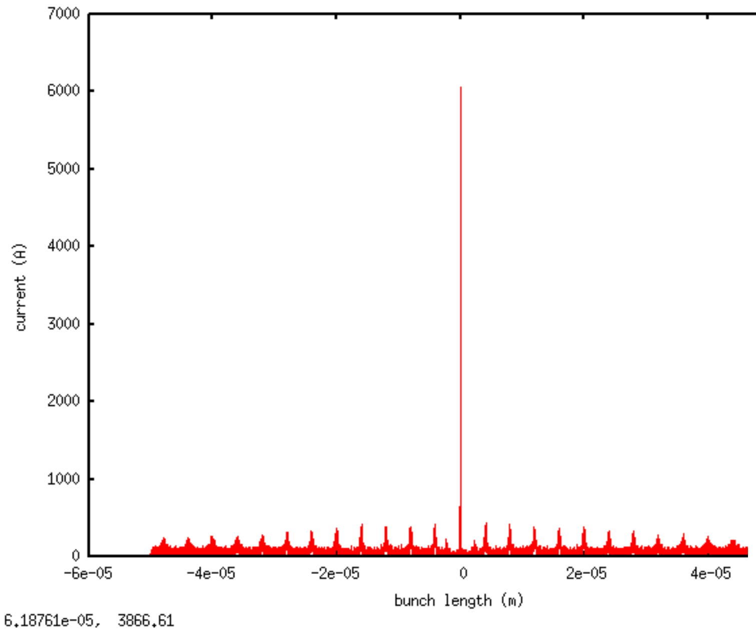
# Generation of a Single Atto-Second Current Modulation

chirper A wavelength: 4 um
chirper B wavelength: 2.3 um

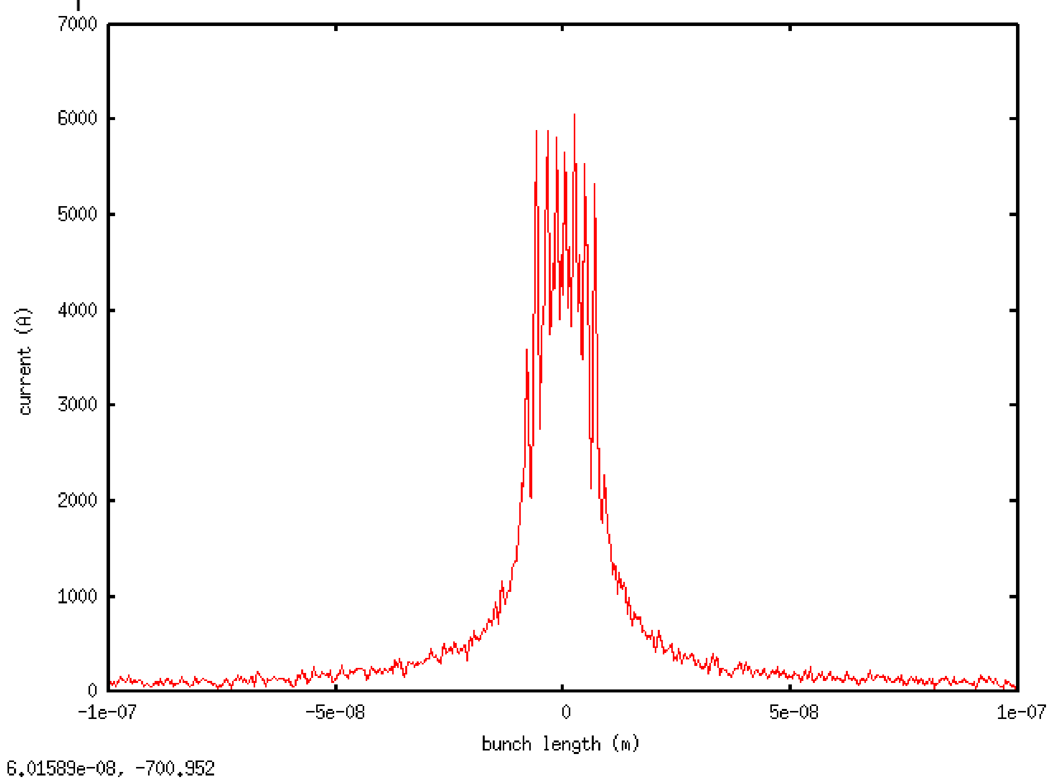



bunch length = 100 um, Q = 20pC, slice energy spread = 1e-5, modulation laser wavelength = 0.2 um, modulation amplitude 2e-5, r56a =6.7mm,, C=100, r56b = -0.067 mm

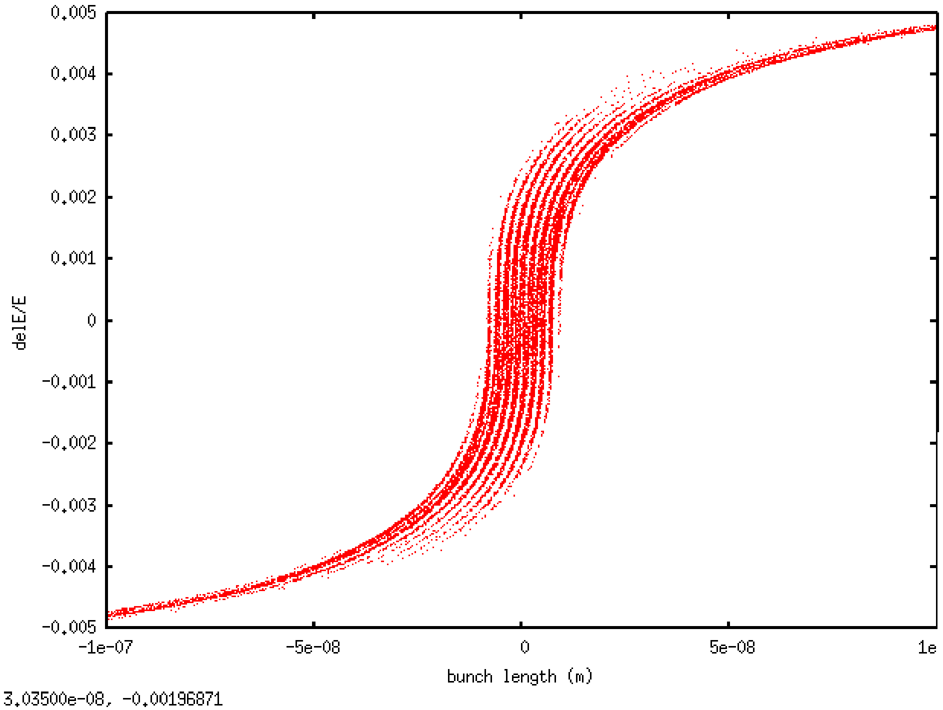
# Current Distribution after Modulation Compression

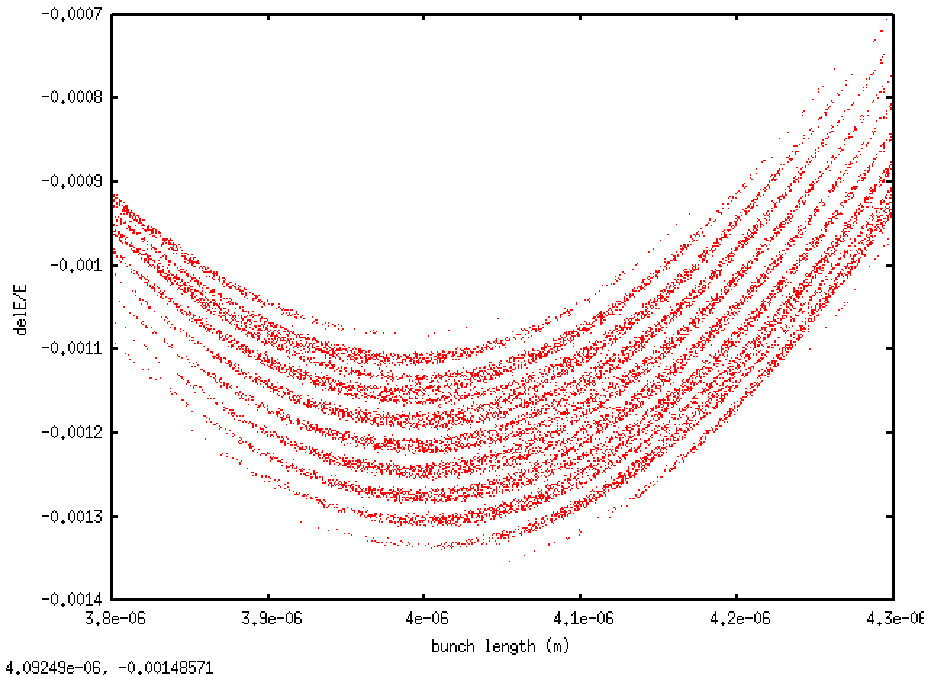



Full peak width is ~20 nm(70 as) with 2 nm separation of each spike

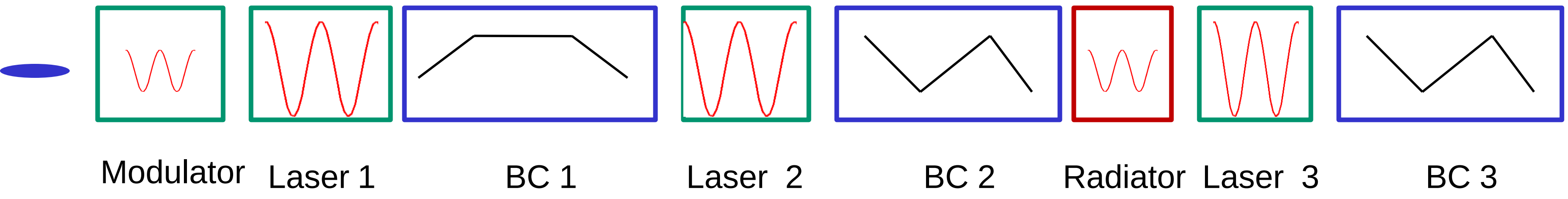


# Longitudinal Phase Distribution after Modulation Compression

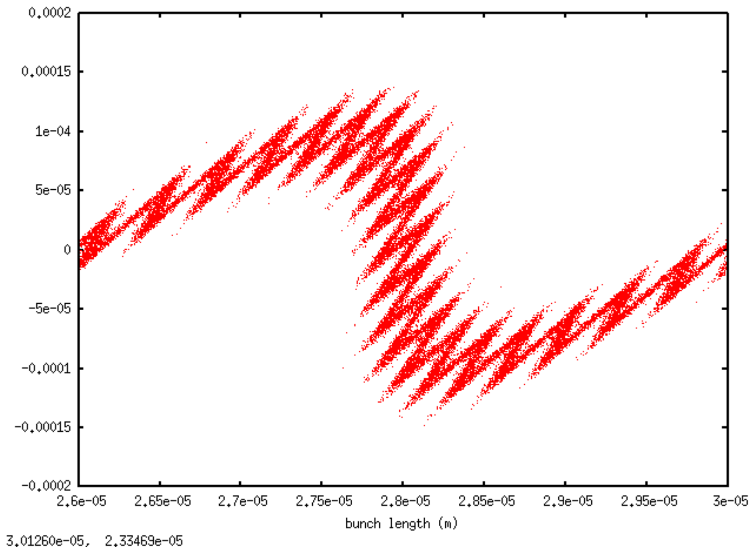


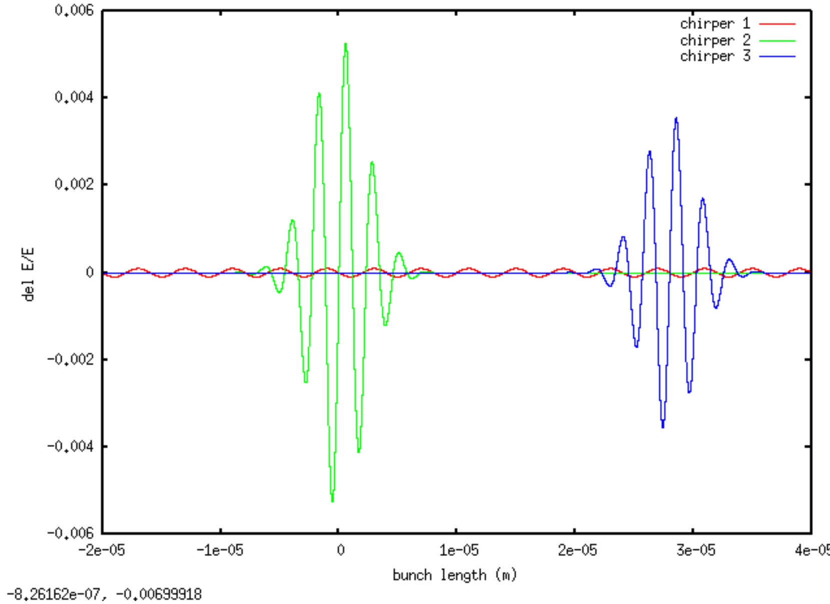
# Generation of Two Color Atto-Second Current Modulation




phase space distribution near 28 um

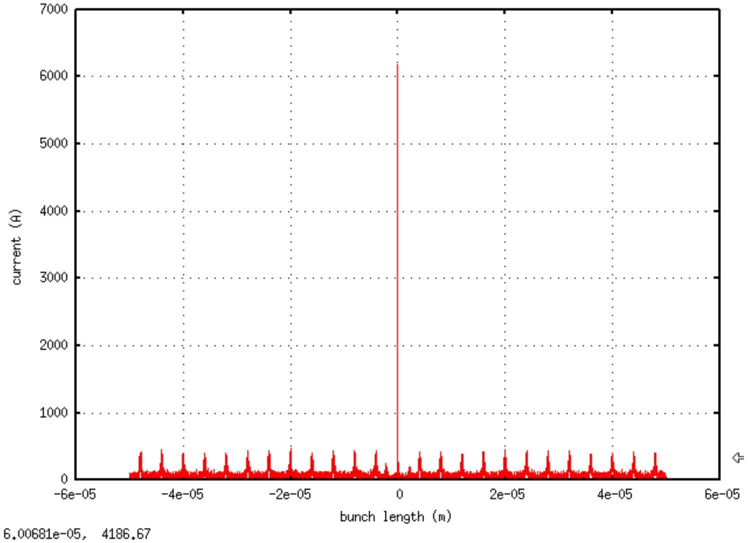


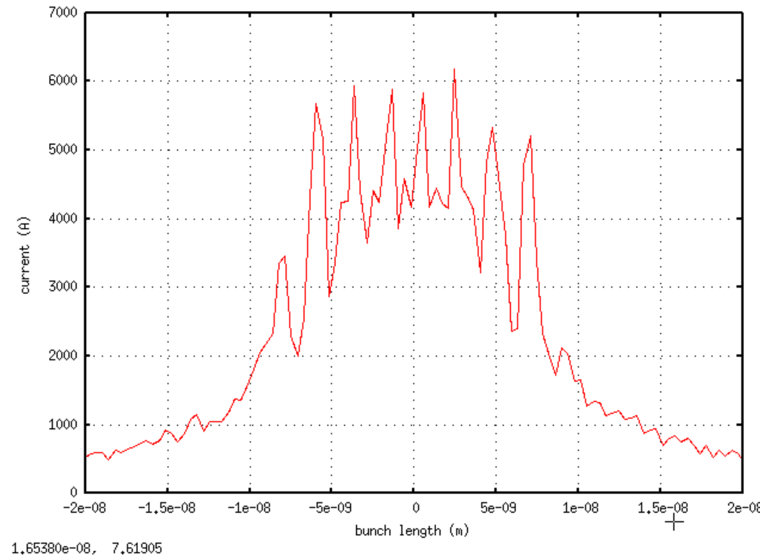

energy chirp from laser 1, 2, and 3

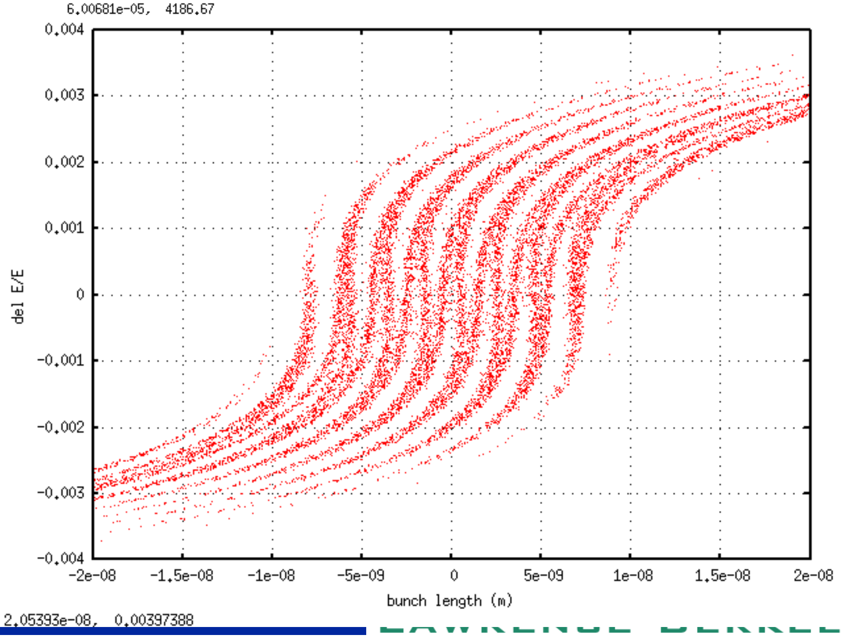



bunch length = 100 um, Q = 20pC, slice energy spread = 1e-5, modulation laser wavelength = 0.2 um, modulation amplitude 2e-5, r56a =6.7mm,, C=100, r56b = -0.067 mm, r56c = -0.099 mm.

# Current and Phase Space Distribution after BC 2

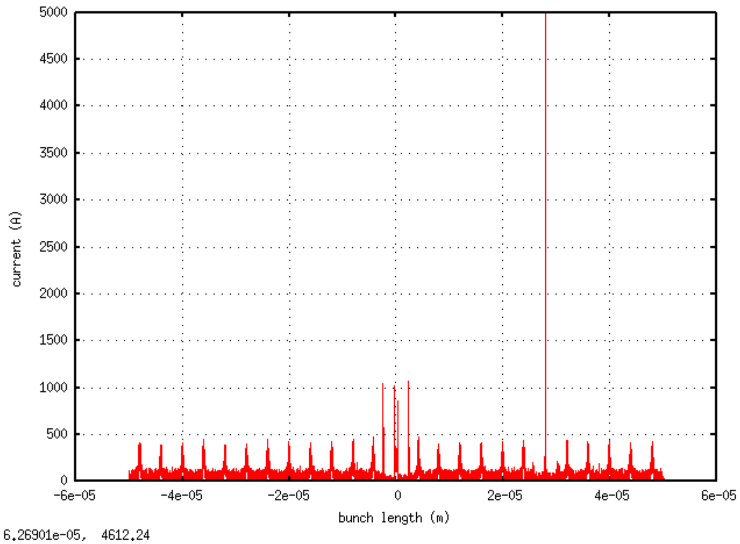


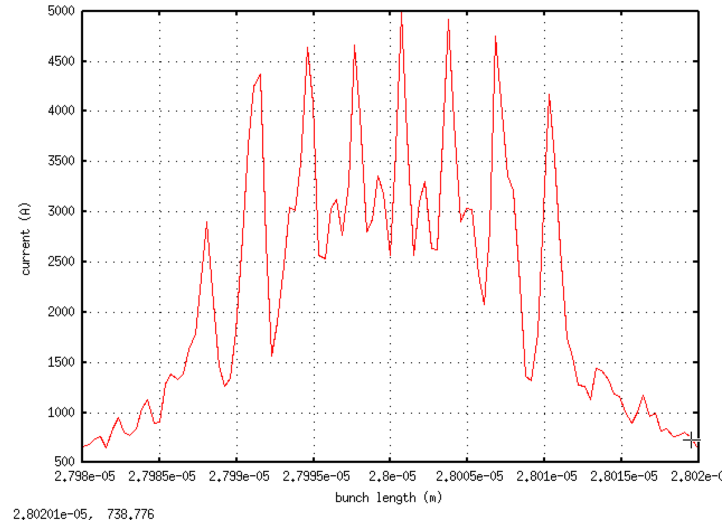



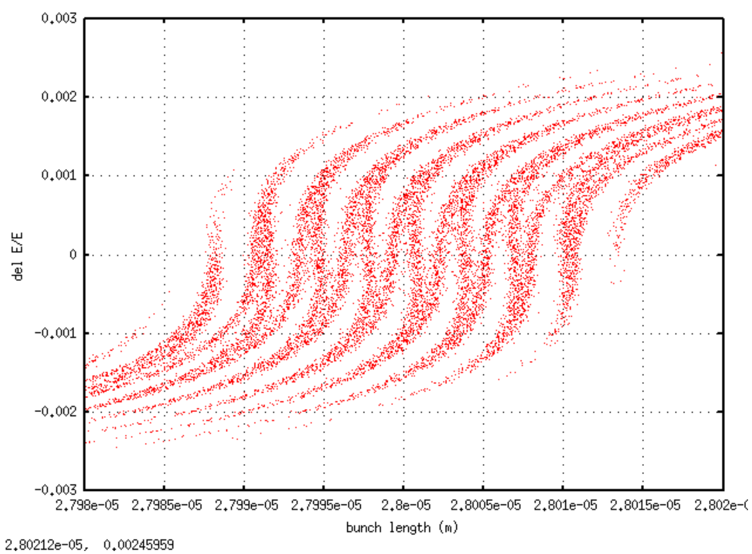




full peak width is ~20 nm(70 as) with
2 nm separation of each spike

# Current and Phase Space Distribution after BC 3



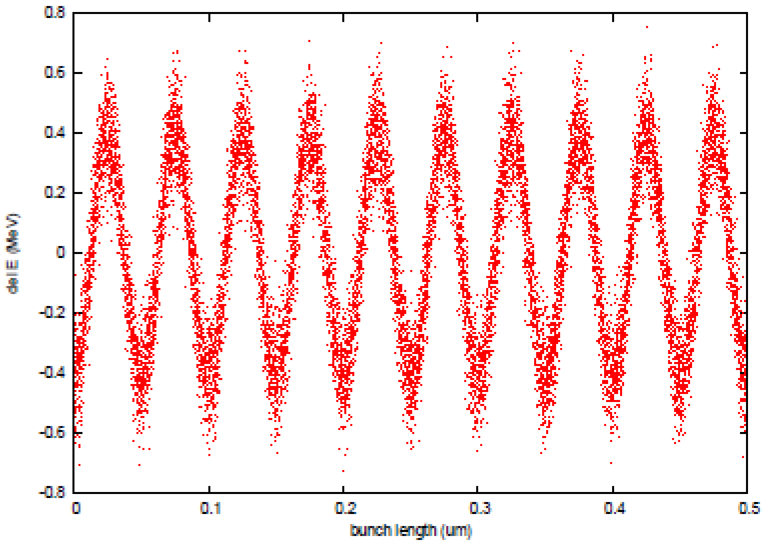

full peak width is ~30 nm(100 as) with 3 nm separation of each spike

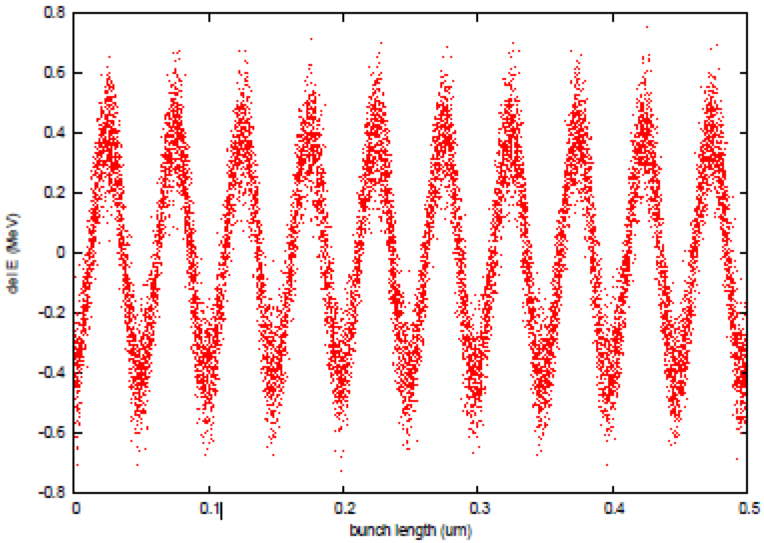
# Some Factors Affecting Compression: Emittance and Energy Spread

$$\Delta \ell = \frac{L}{\gamma^2} \frac{\Delta \gamma}{\gamma}.$$

$$\Delta \ell = \frac{L}{2}(x'^2 + y'^2) \quad \propto \frac{L}{\gamma^2}$$

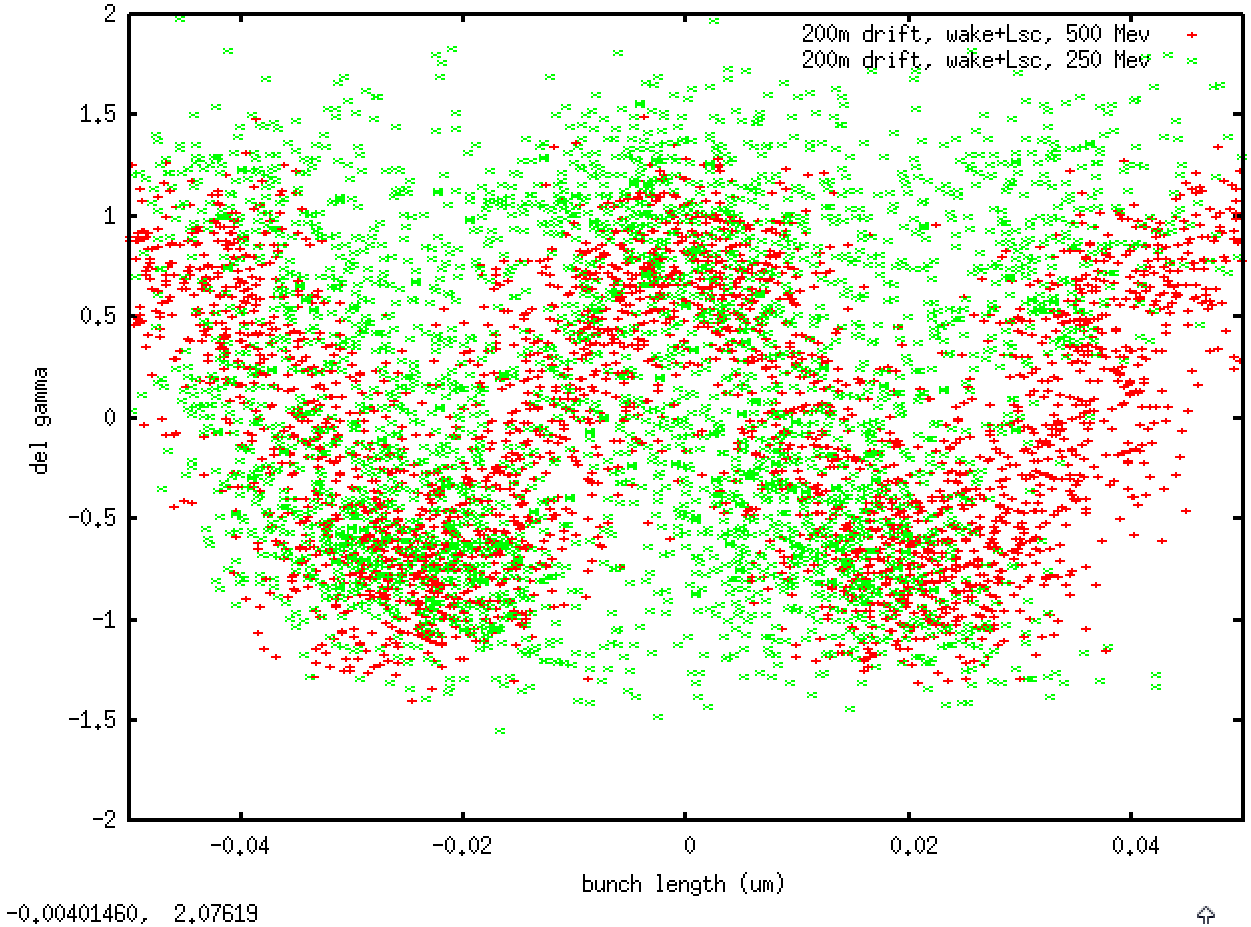
Longitudinal Phase Space without/with 50 m drift between BC1 and BC2
for a uniform cylinder beam with 1 mm-mrad emittance and 0.5 mm rms at 250 MeV energy



# Some Factors Affecting Compression: Wake + Space-Charge Effects

Correlated energy spread as a function bunch length for a 1mm 140 A cylinder beam at 250 MeV drifting 200 meters with only longitudinal space-charge effects.

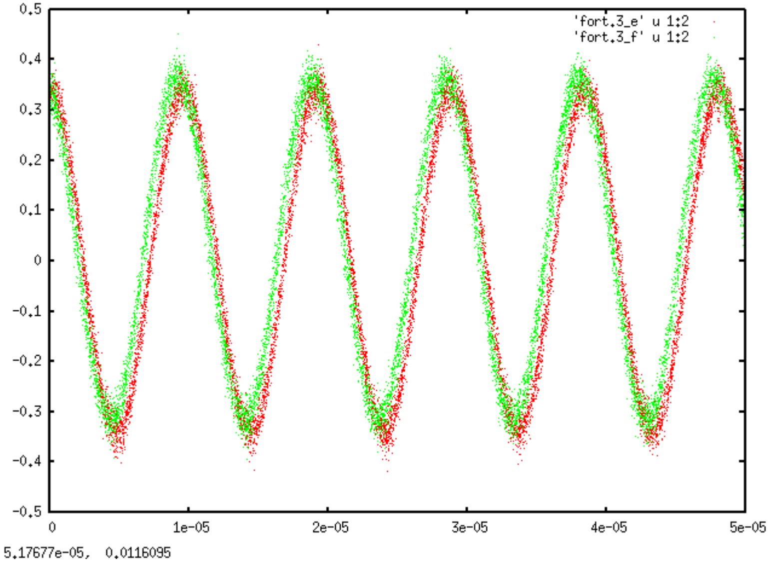


# Some Factors Affecting Compression: CSR

$$\frac{dE}{cdt} = -\frac{2e^2}{4\pi\epsilon_0 3^{1/3} R^{2/3}} \int_{-\infty}^{s} \frac{1}{(s-s')^{1/3}} \frac{d\lambda(s')}{ds'} ds'.$$

CSR wake might contribute mostly to the correlated energy spread.
The effect on the local energy spread might be small.

Final longitudinal phase space with a 160 pC electron beam pass through a chicane with R56=0.136, C = 11.3 without and with only CSR effects.




Red: no CSR
Green: with CSR

# Summary Discussions

Advantages of MCHG:

- tunable short wave length current modulation for FEL radiation
- large bunching factor for short wave length modulation
- potential low global current, high local peak current operation with laser chirpers

To maximize the advantage of MCHG:

- shorter distance between BC1 and BC 2
- higher energy
- higher RF frequency for chirping or unchirping the beam
- smaller R56[b]
- maintain accelerator machine linearity
- minimize jitter effects