State-of-art
Electron Bunch Compression

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Outline

- *Introduction*
- *Magnetic-based compression*
- *Ballistic/Velocity compression schemes*
- *Some closing remarks*

Short Bunch Production

Light sources (single-pass FEL), linear colliders and advanced accelerator physics require high peak current

compression

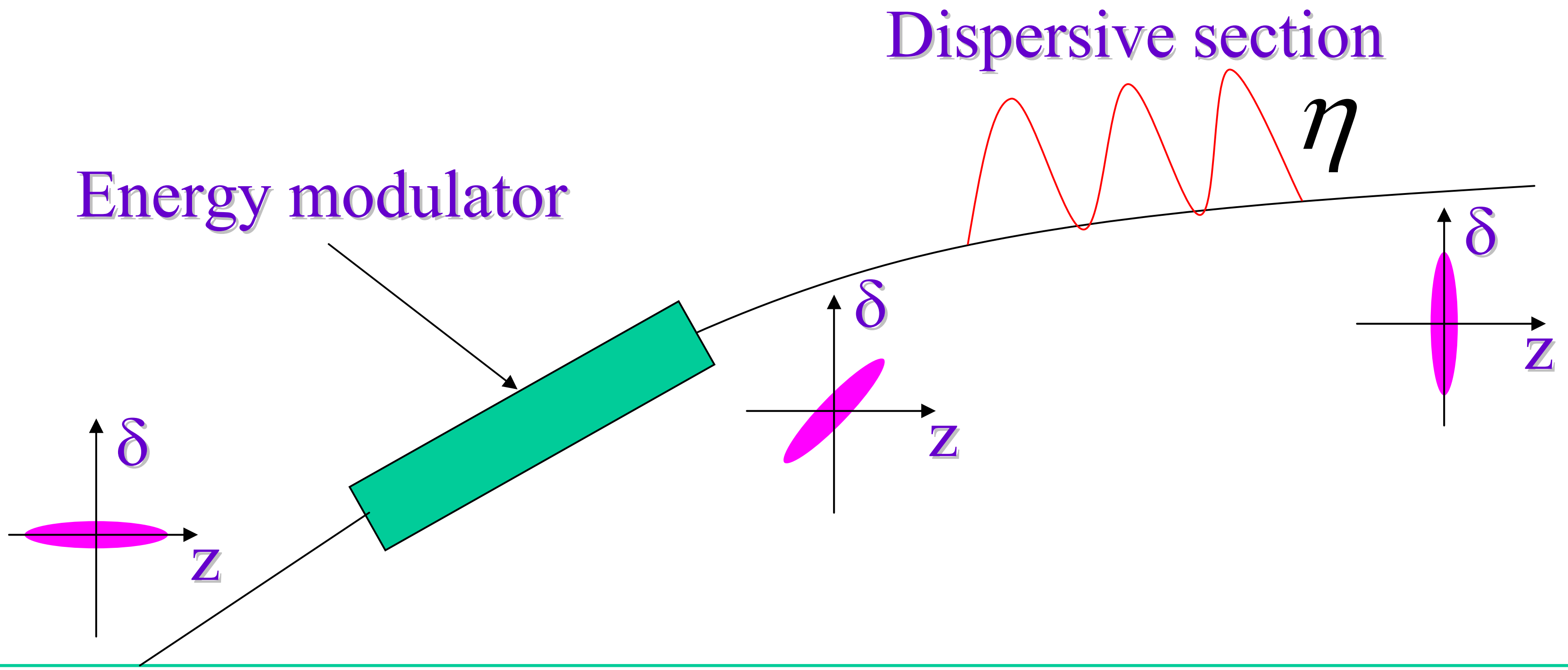
Manipulate the bunch at a later stage during transport

Generate short bunch directly at the e- source:
- *pulse DC e- source,*
- *X-band rf-gun,*
- *laser/plasma e- sources*

Select part of the bunch during the transport:
- *collimator, beam spoiling,*
- *Laser slicing, etc…*

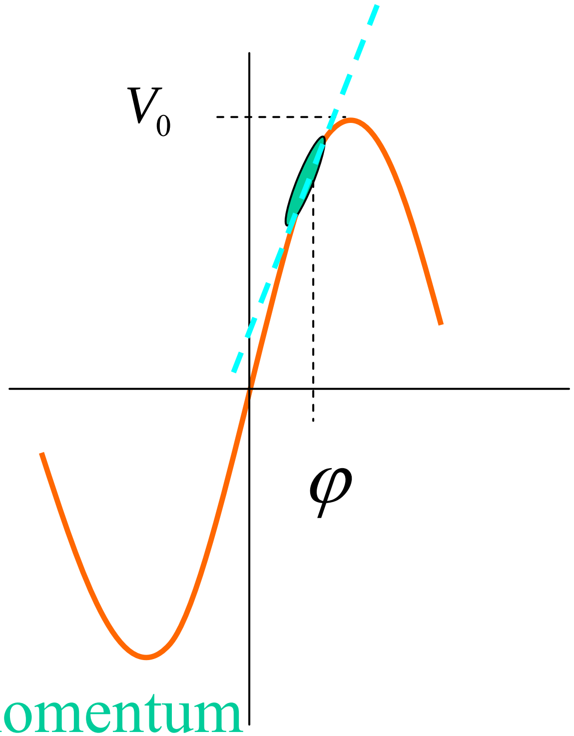
Magnetic bunch compression

- Energy modulator: rf-structure, laser, wake-field
- Non-isochronous section
- In practice: multi-stage compression



Single stage compression (linear theory)

- Energy time correlation:



$$E(z) = E_0 + eV_0 \cos(kz + \varphi)$$

$$\delta = \frac{eV_0}{E_0 + eV_0 \cos\varphi}\left[\cos(kz+\varphi) - \cos\varphi\right] = \kappa z + O(z^2)$$

chirp: $$\kappa \equiv \frac{d\delta}{dz} = \frac{-keV_0}{E_0 + eV_0 \cos\varphi}\sin\varphi$$

- Bunch compressor

1st order momentum compaction

$$z_f = z_i + R_{56}\delta_i$$

- Final bunch length and energy spread (1st order):

$$\sigma_{z,f} = \sqrt{(1+\kappa R_{56})^2 \sigma_{z,i}^2 + R_{56}^2 \sigma_{\delta,i}^2 E_0^2 / E^2}, \sigma_{\delta,f} = \sqrt{\kappa^2 \sigma_{z,i}^2 + \sigma_{\delta,i}^2 E_0^2 / E^2}$$

Min bunch length

Single stage compression (nonlinear effects)

- Energy time correlation:

$$\delta = \kappa z + \mu z^2 + O(z^3)$$

- Bunch compressor

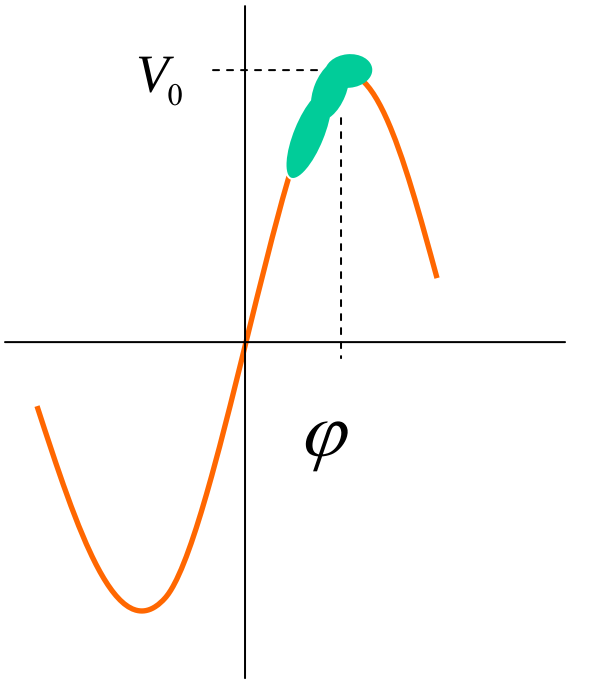
$$z_f = z_i + R_{56}\delta_i + T_{566}\delta_i^2$$

- Final bunch length is minimized if

$$0 = z_i(1+\kappa R_{56}) + z_i^2(\mu R_{56} + \kappa^2 T_{566})$$

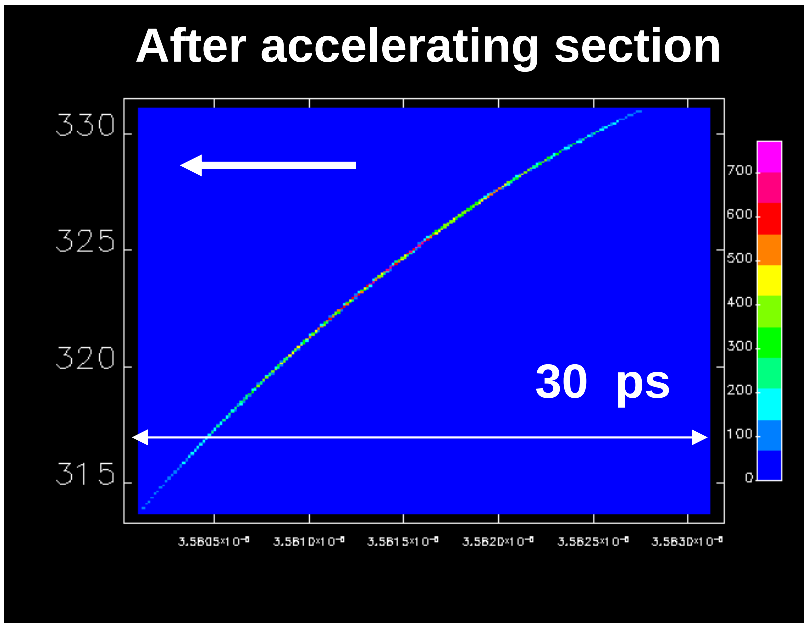
Limit achievable minimum Bunch length

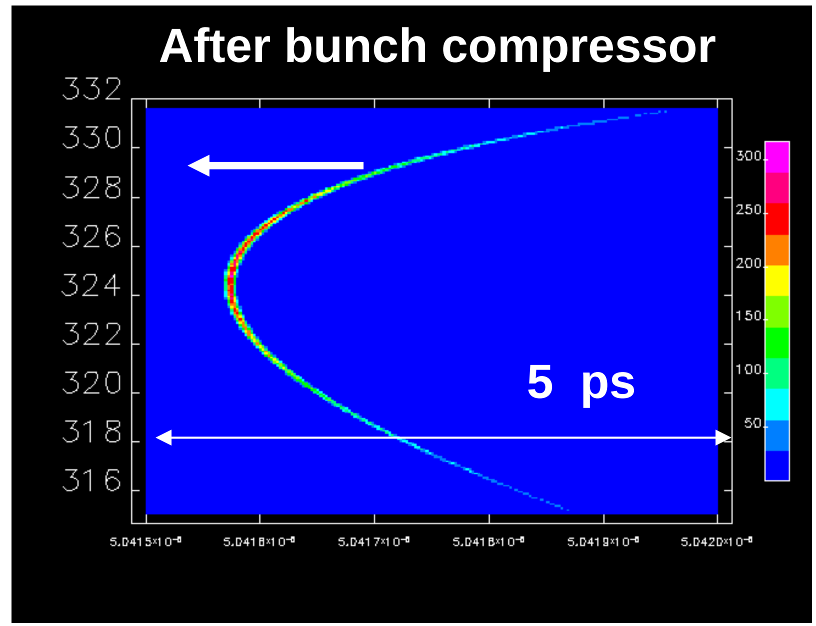
2nd order momentum compaction



Higher order effects: pulse control

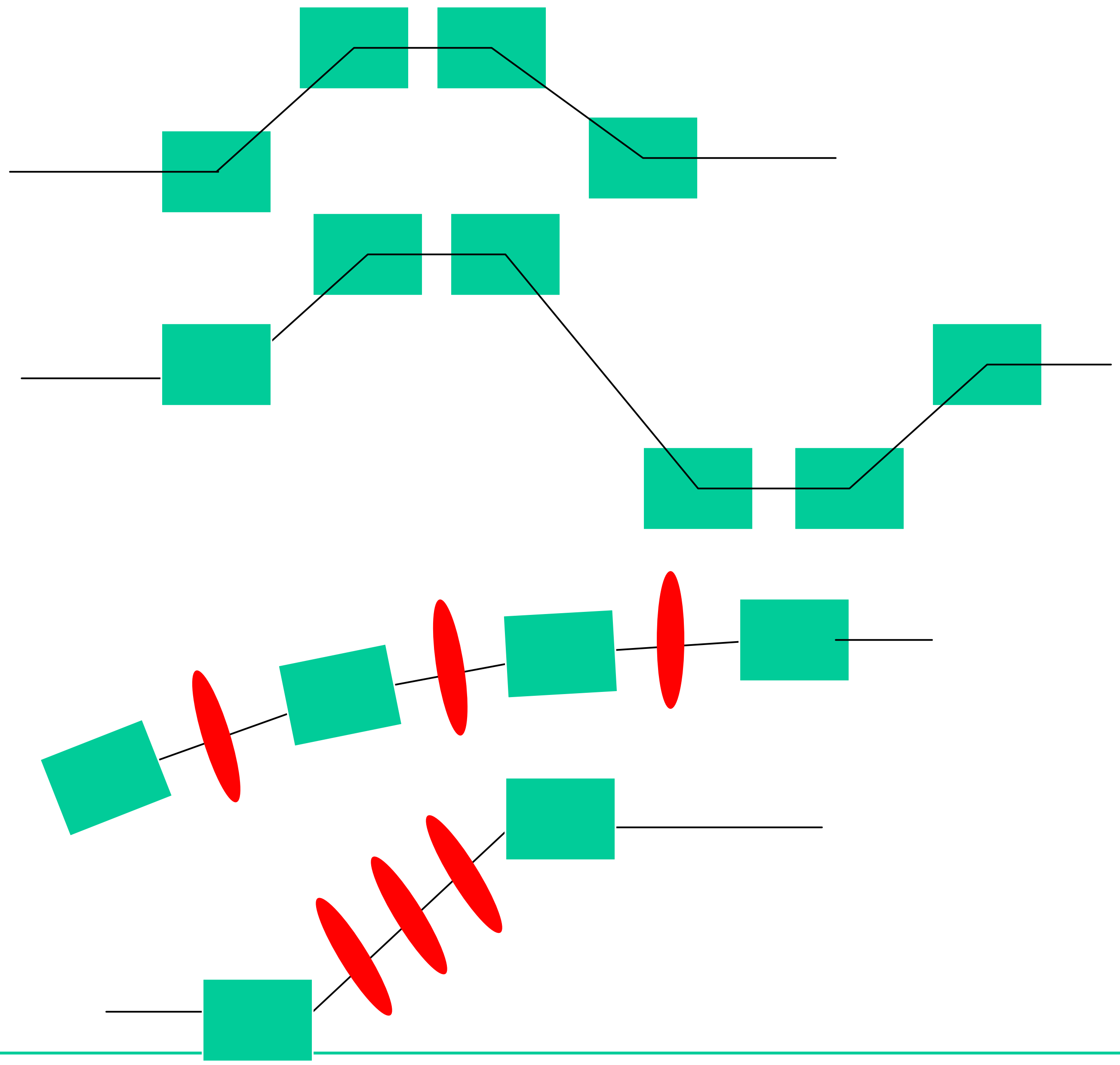
- e- source produces electron bunch that does not *a fortiori* satisfies $k\sigma_{z,i} << 1$ (due to other consideration -- transverse ε)





- "Banana shape" longitudinal phase space results in spike on longitudinal density

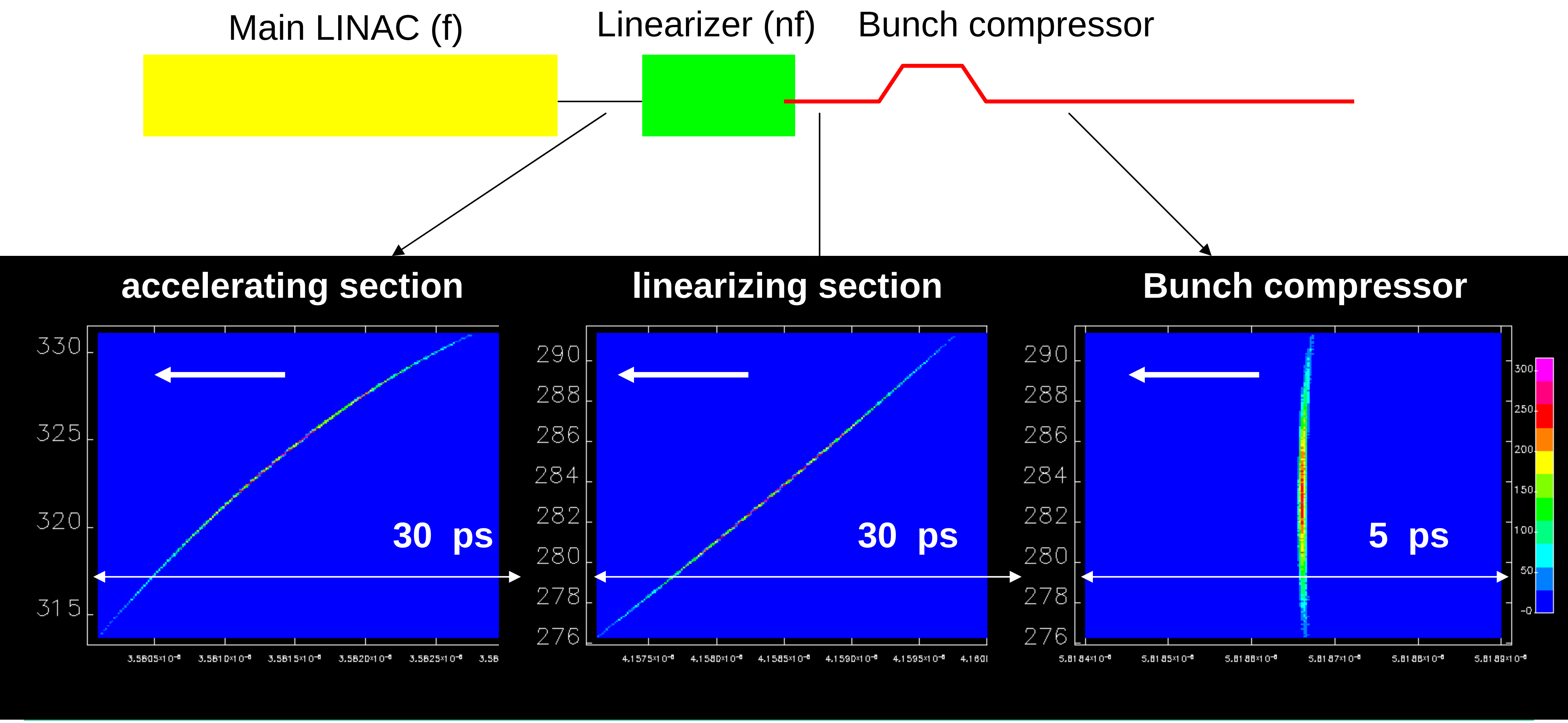
Type of magnetic bunch compressors



- Chicane
  $R_{56}<0$, $T_{566}>0$
- S-chicane
  $R_{56}<0$, $T_{566}>0$
- F0D0 arc
  $R_{56}>0$, $T_{566}>0$
- Dog-leg
  $R_{56}>0$, $T_{566}>0$

Higher order effects: pulse control

- Correction with higher harmonic rf-field provide two independent knobs (κ and μ parameters to minimize σ_z given R_{56} and T_{566})



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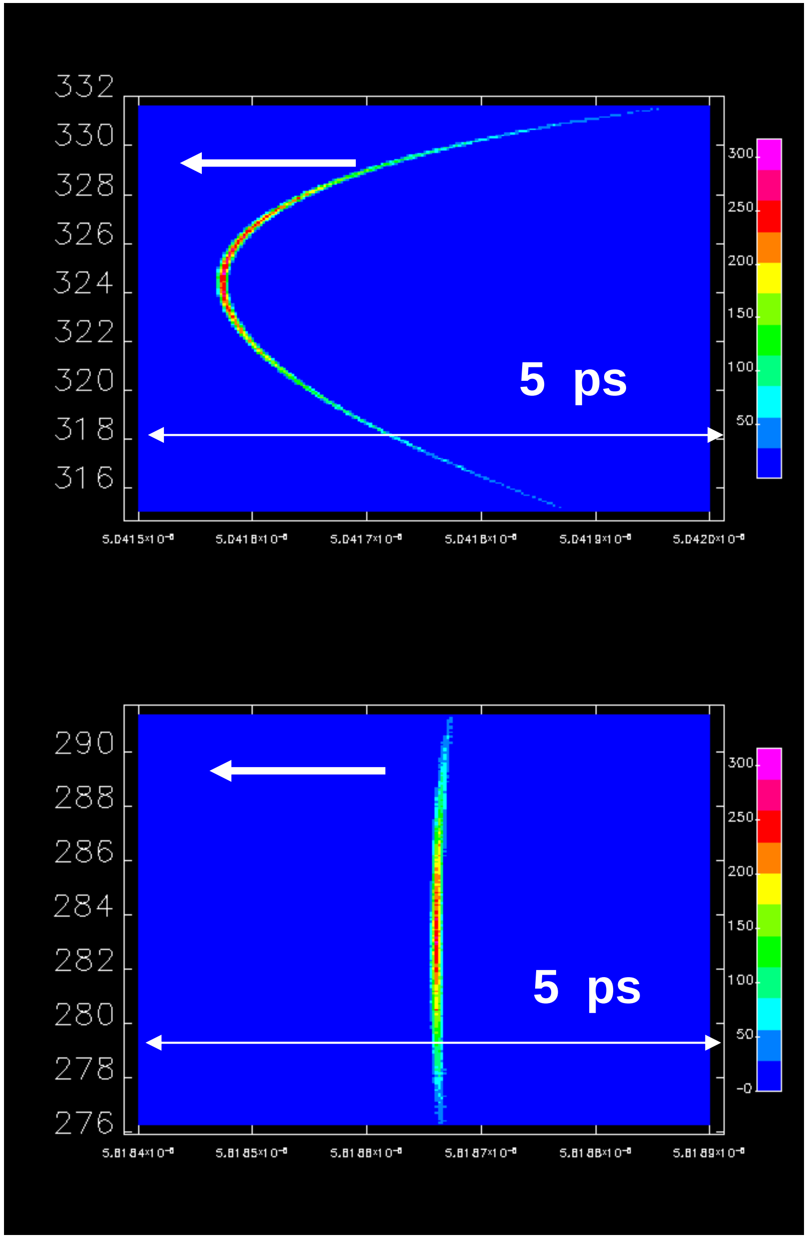
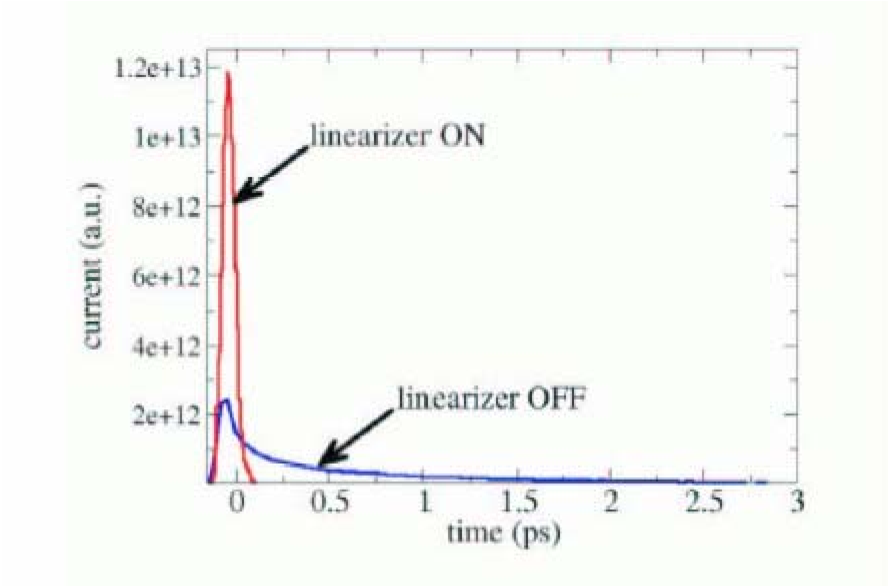
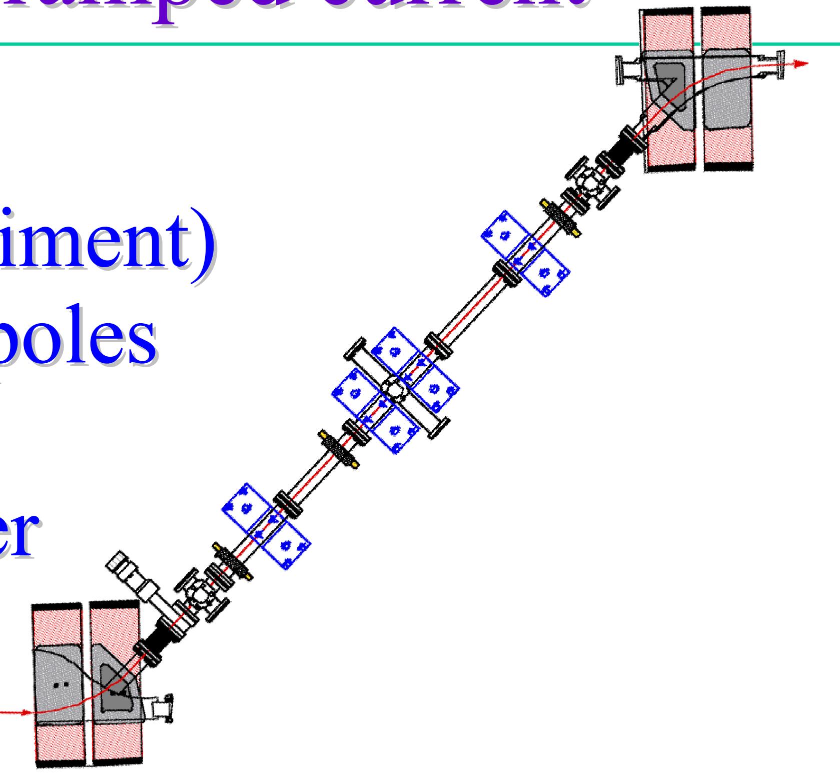
Higher order effects: pulse control



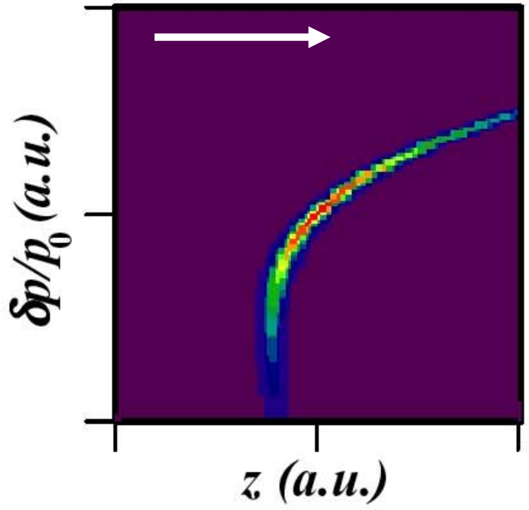


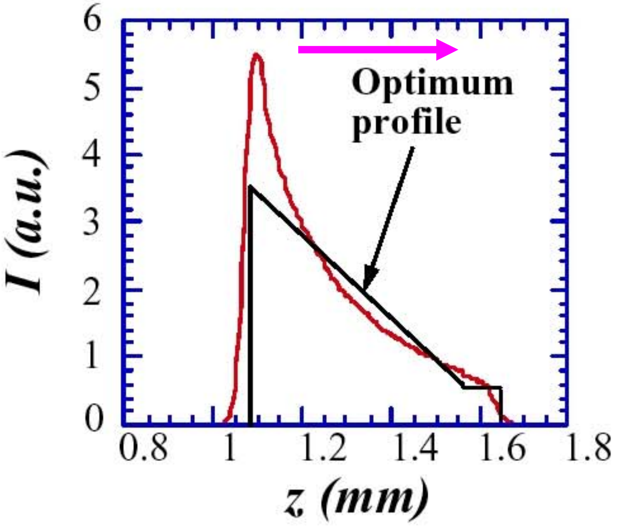
Higher order effects: ramped current

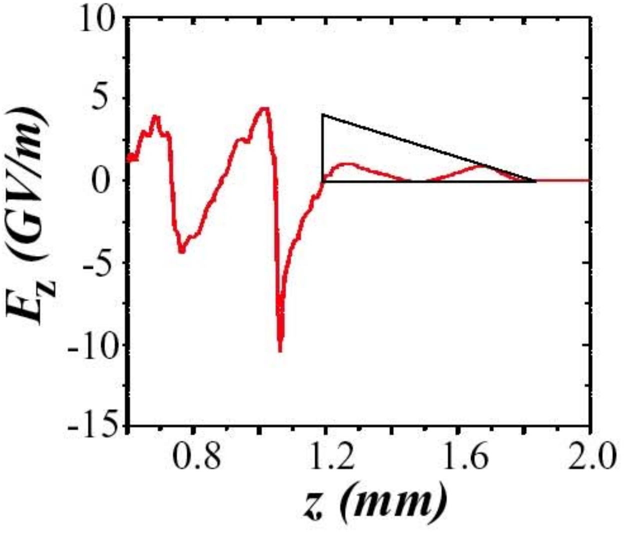


- UCLA (Neptune lab)
- Investigation (theory + experiment) of dog leg with quad + sextupoles for beam current shaping
- Improve so-called transformer ratio in plasma-wakefield accelerator

(R. J. England et al., PAC'03)





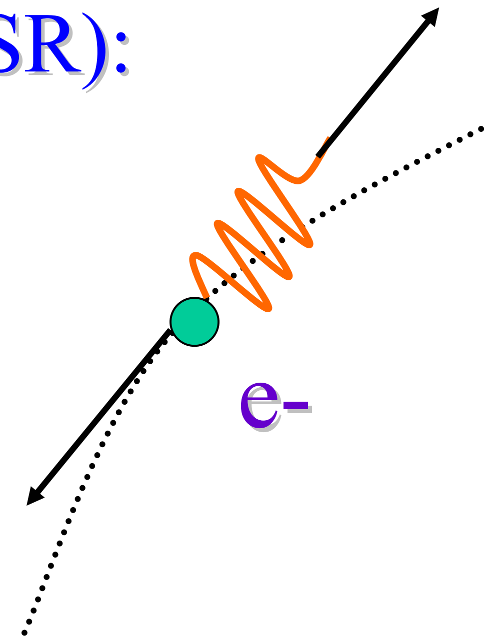


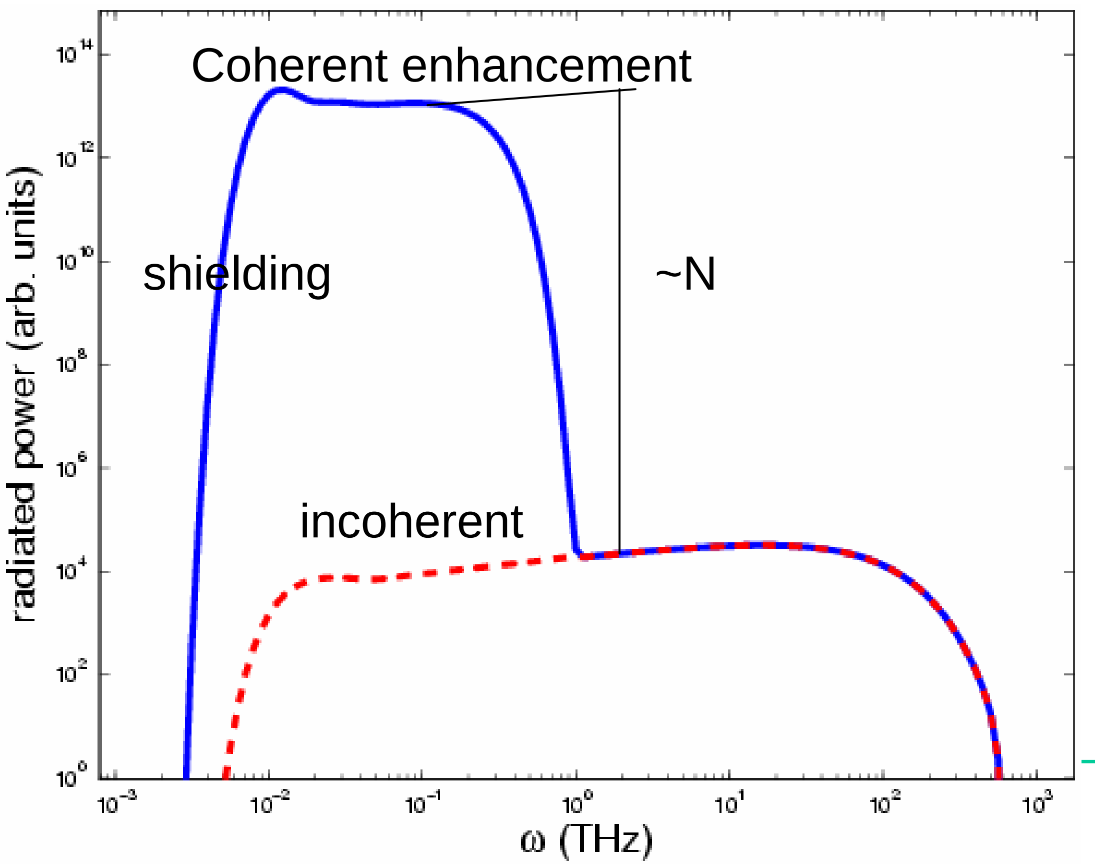
Synchrotron radiation issues

- Incoherent synchrotron radiation (ISR):
  - energy spread dilution
  - bend-plane emittance growth

$$\Delta\varepsilon \approx 0.04 E^6 I_5$$

[mm-mrad] [GeV] [m]





- Coherent synchrotron radiation (CSR):
  - self-interaction process

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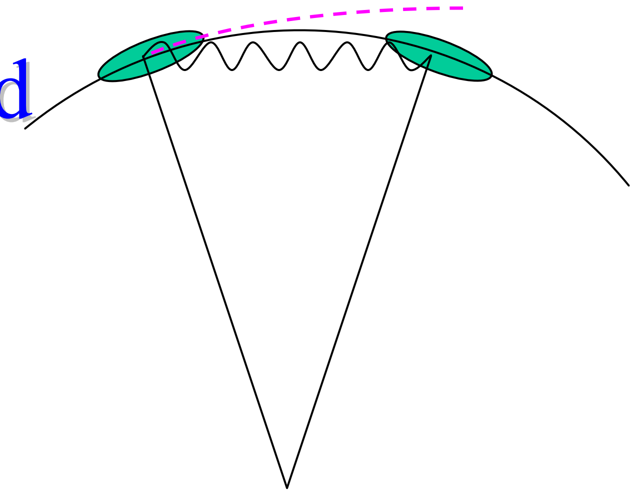
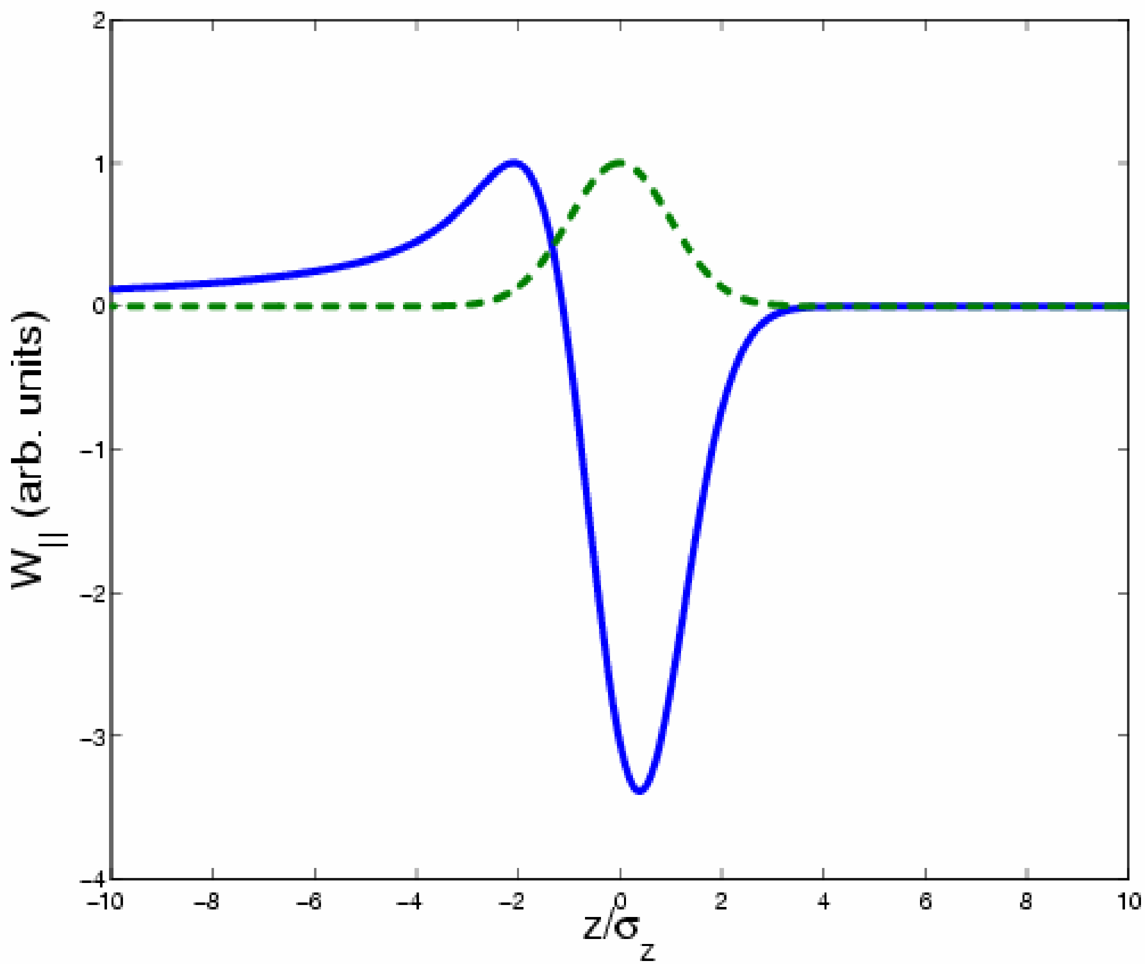
Coherent Synchrotron Radiation

- CSR emission generates energy spread
- achromaticity is broken
- bend-plane emittance dilutions



Overtaking length

$$L_0 = (24\sigma_z \rho^2)^{1/3}$$



- CSR "wake":

$$W(s) \propto \int_{-\infty}^{s} \frac{ds'}{(s-s')^{1/3}} \frac{d\Lambda(s')}{ds'}$$

Micro-bunching instability in compressors

- Initial density modulation

$$b(k;s) = \frac{1}{N}\int d\mathbf{X}e^{-ikz} f\left(\mathbf{X};s\right)$$

- Impedance (geometric wakes, longitudinal space charge, CSR)

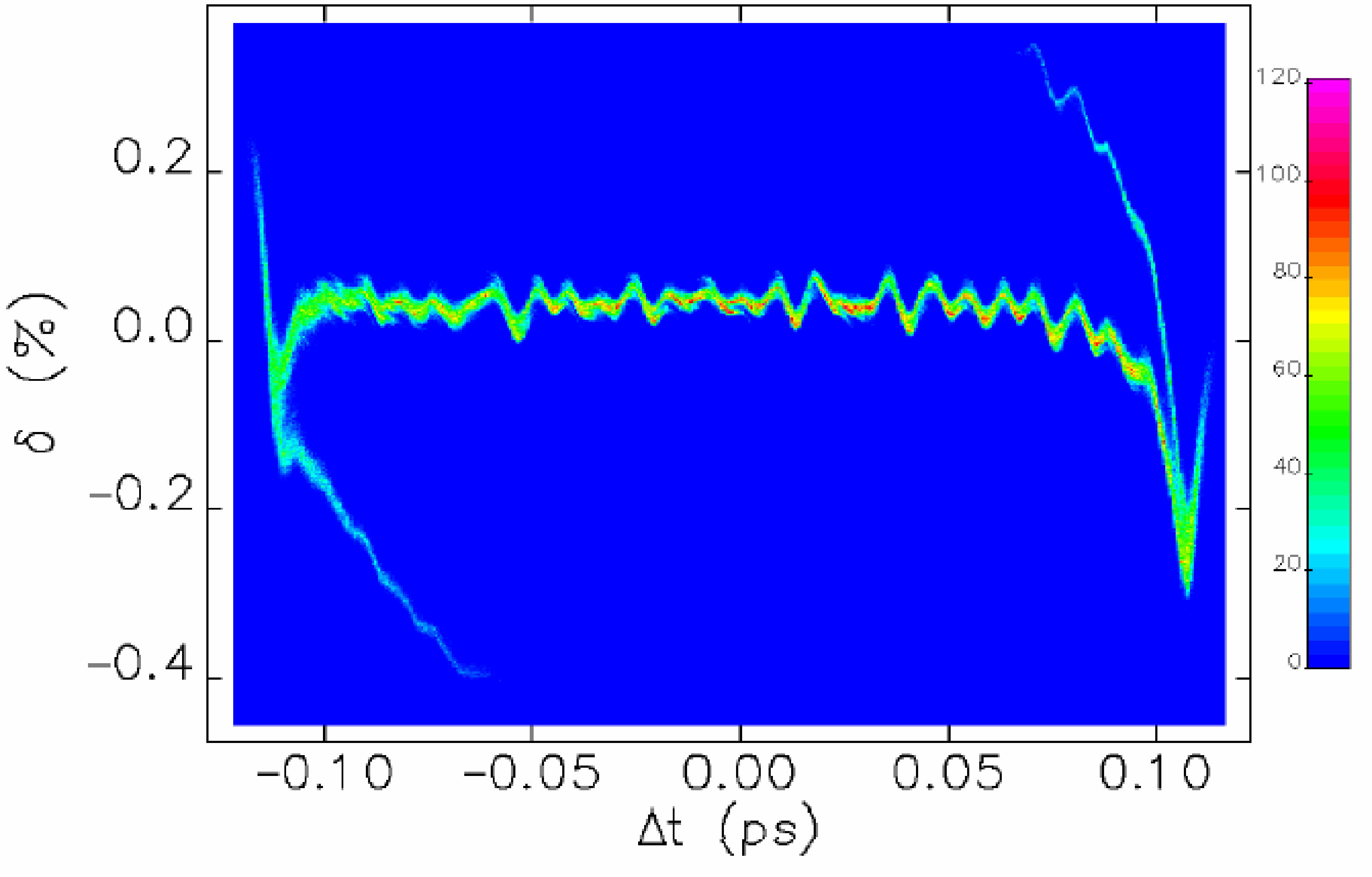
$$\Delta\gamma(s) = -\int_0^s d\tau \frac{I_0 Z[k(\tau);\tau]b[k(\tau);\tau]}{I_A}$$

- Magnetic bunch compressor couple energy modulation into density modulation via R_{56}

Feedback loop with potential high gain!

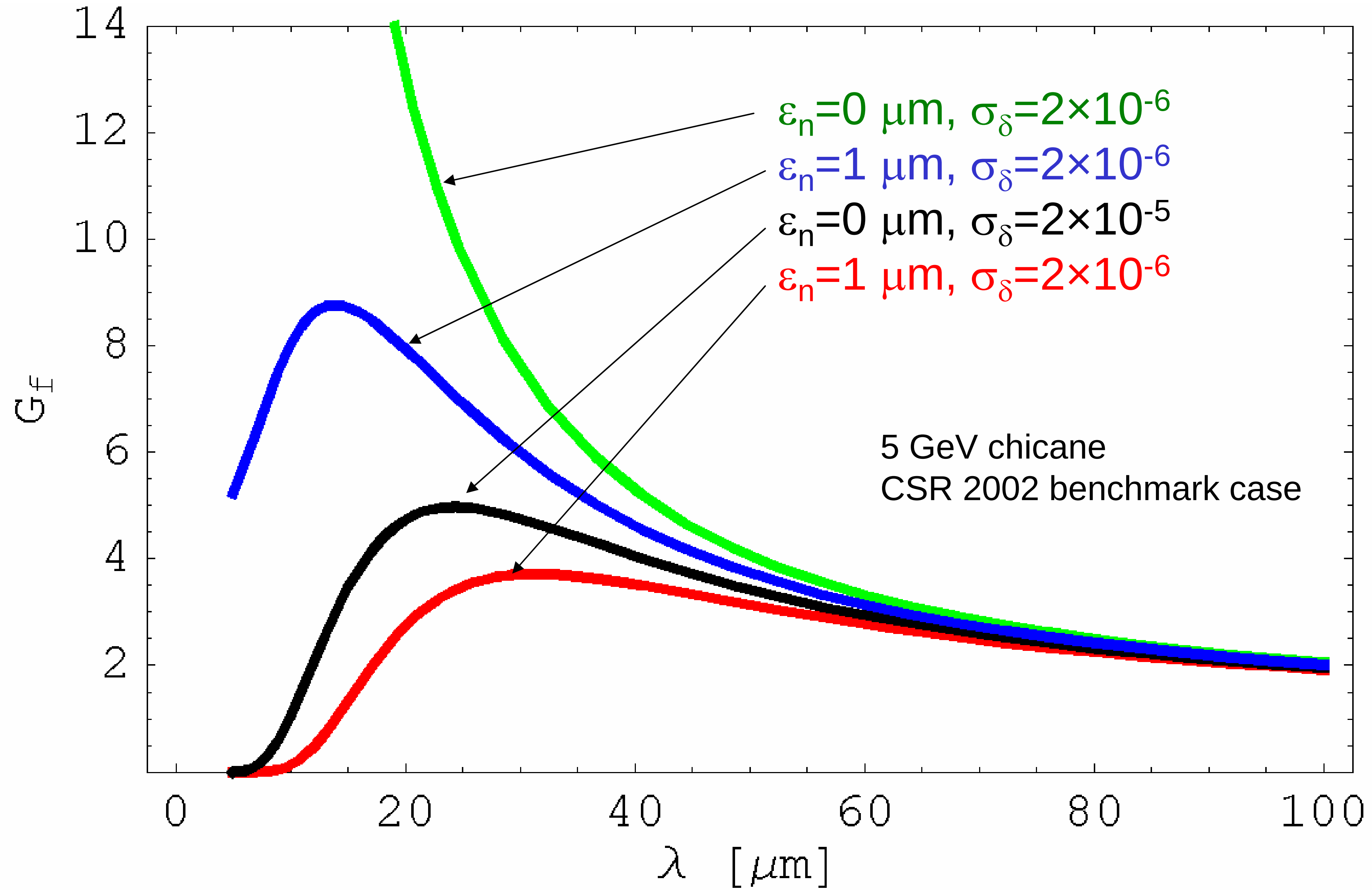
(Saldin et al. TESLA-2002-02, Huang/Kim PRSTAB 5:074402 (2002), Saldin et al TESLA 2003-02)

Micro-bunching instability in compressors



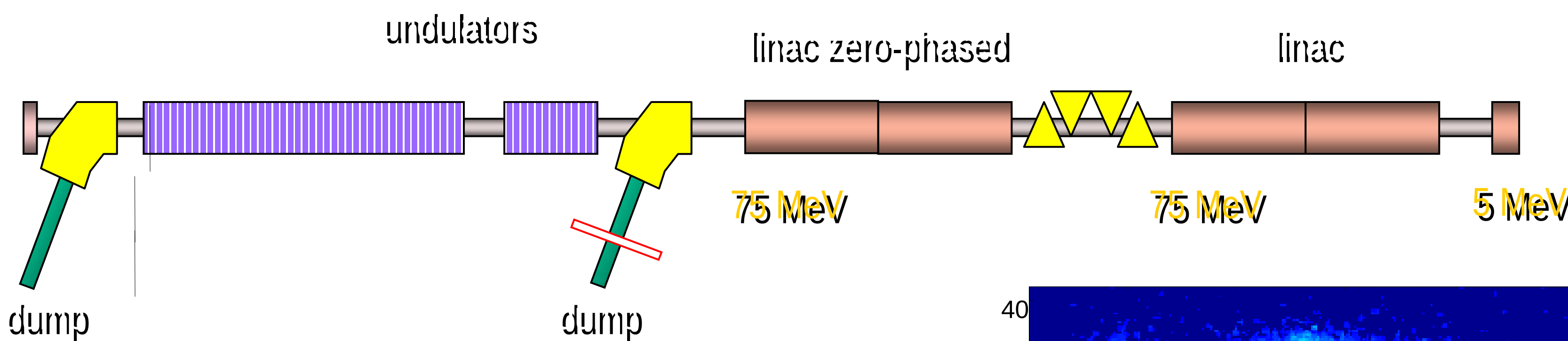
(ELEGANT simulation of LCLS by M. Borland, CSR2002 workshop Zeuthen)

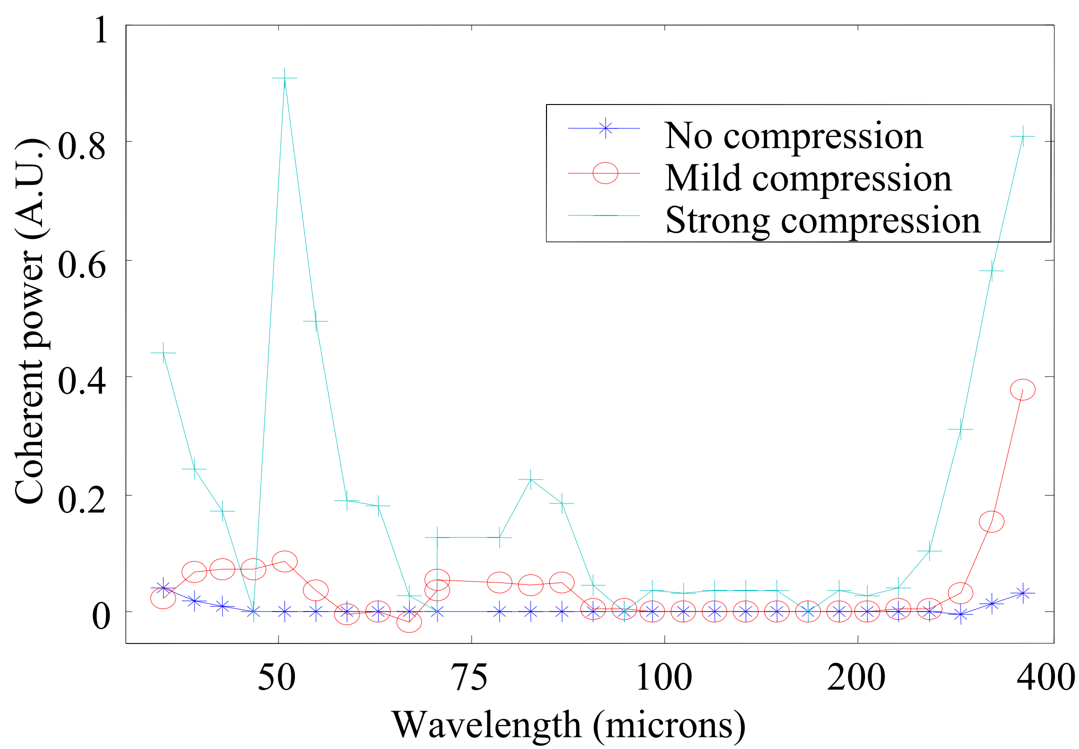
Micro-bunching instability in compressors



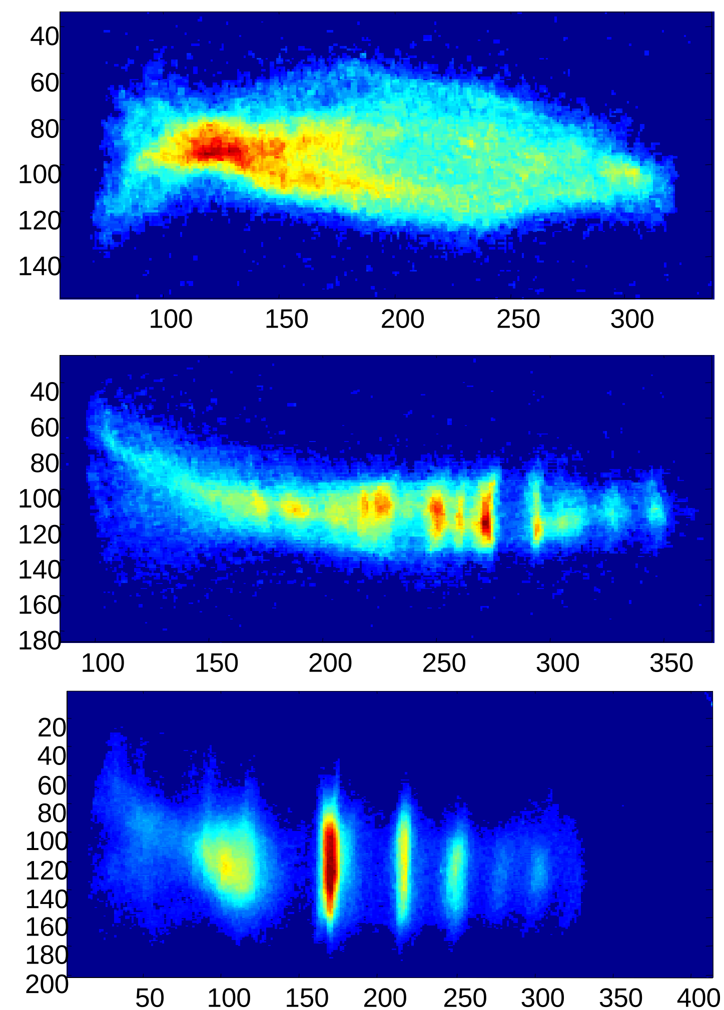
(Z. Huang, CSR workshop 2002, Zeuthen)

Magnetic bunch compression



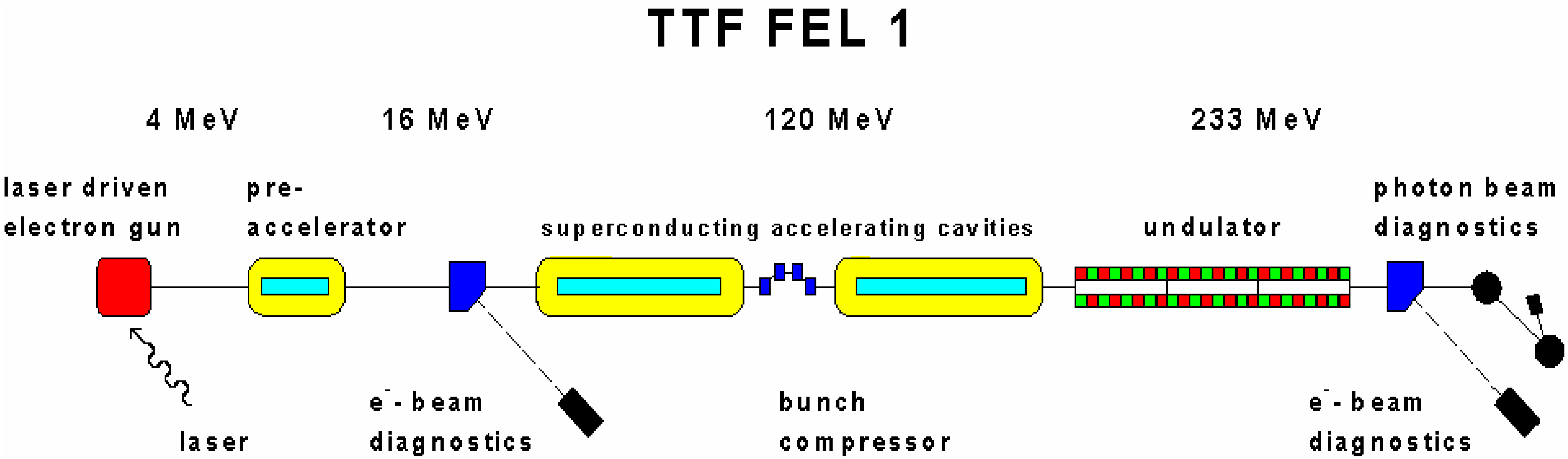


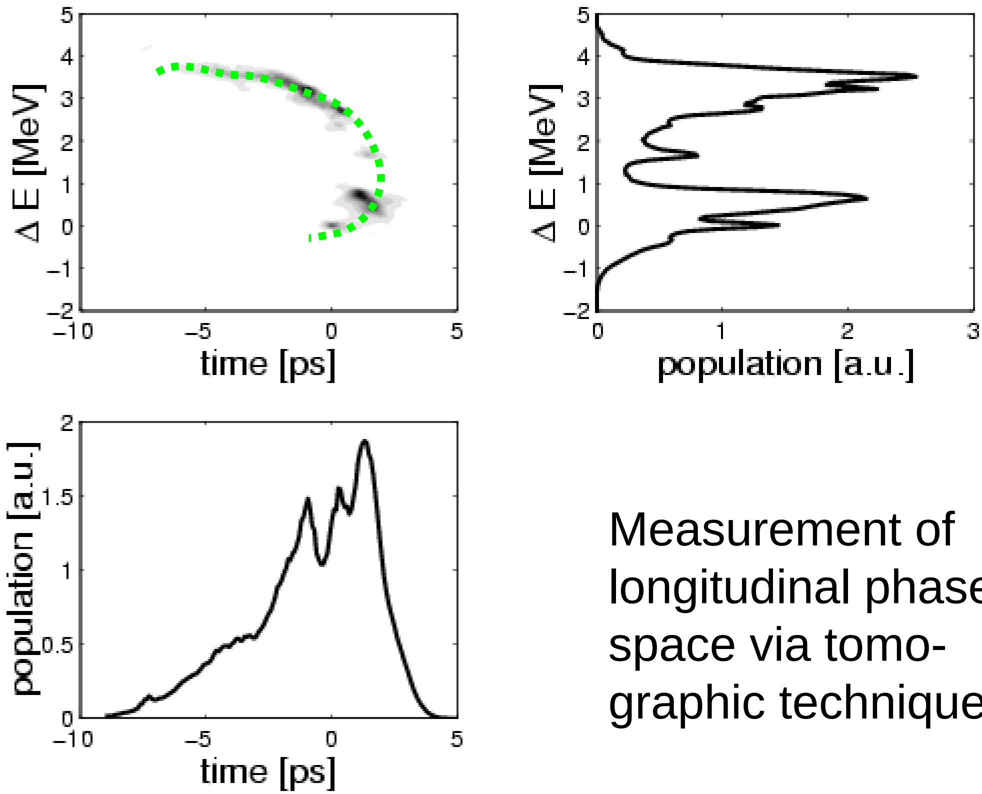
Stronger compression



(W. Graves, et al PAC’01, T. Shaftan et al PAC’03)

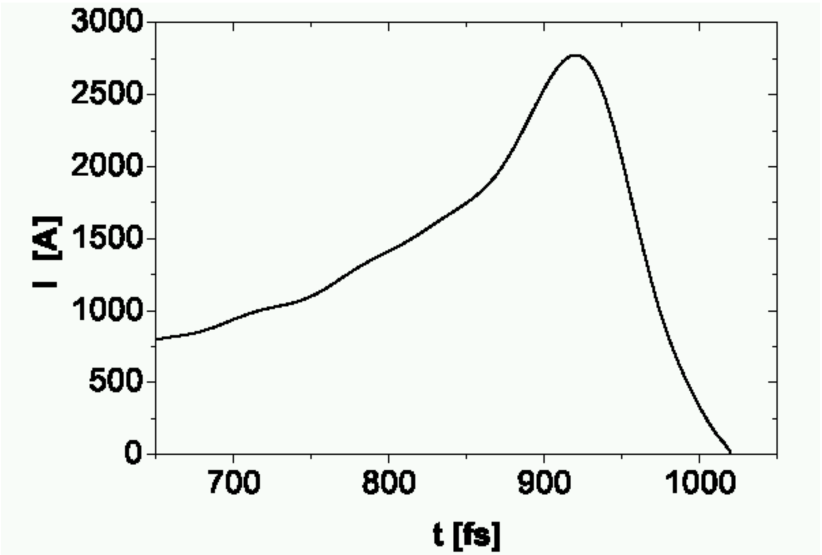
Magnetic bunch compression





Measurement of longitudinal phase-space via tomo-graphic technique

Estimated peak current from SASE-FEL performance



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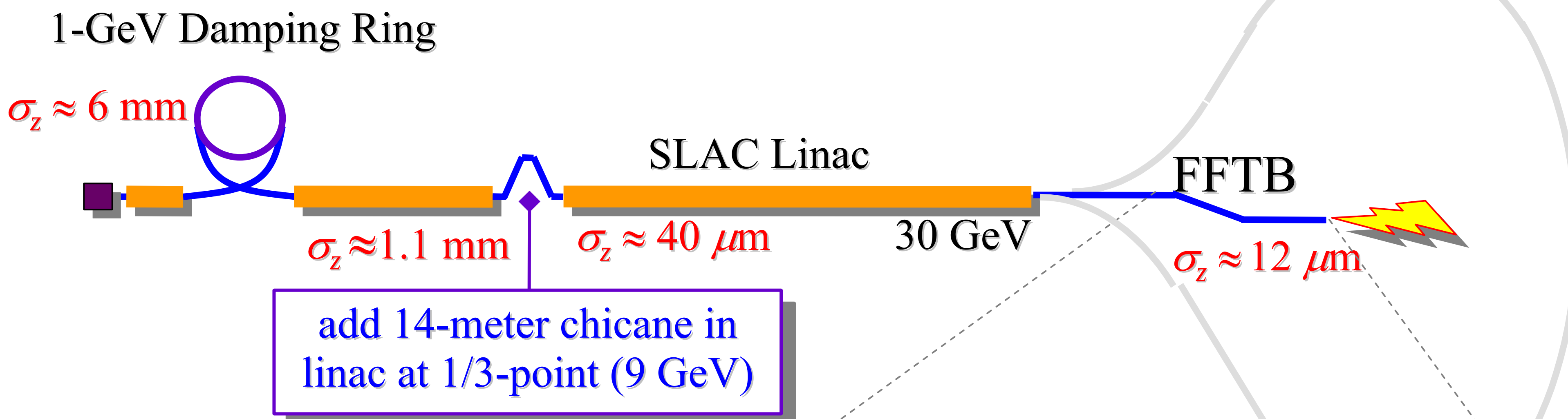
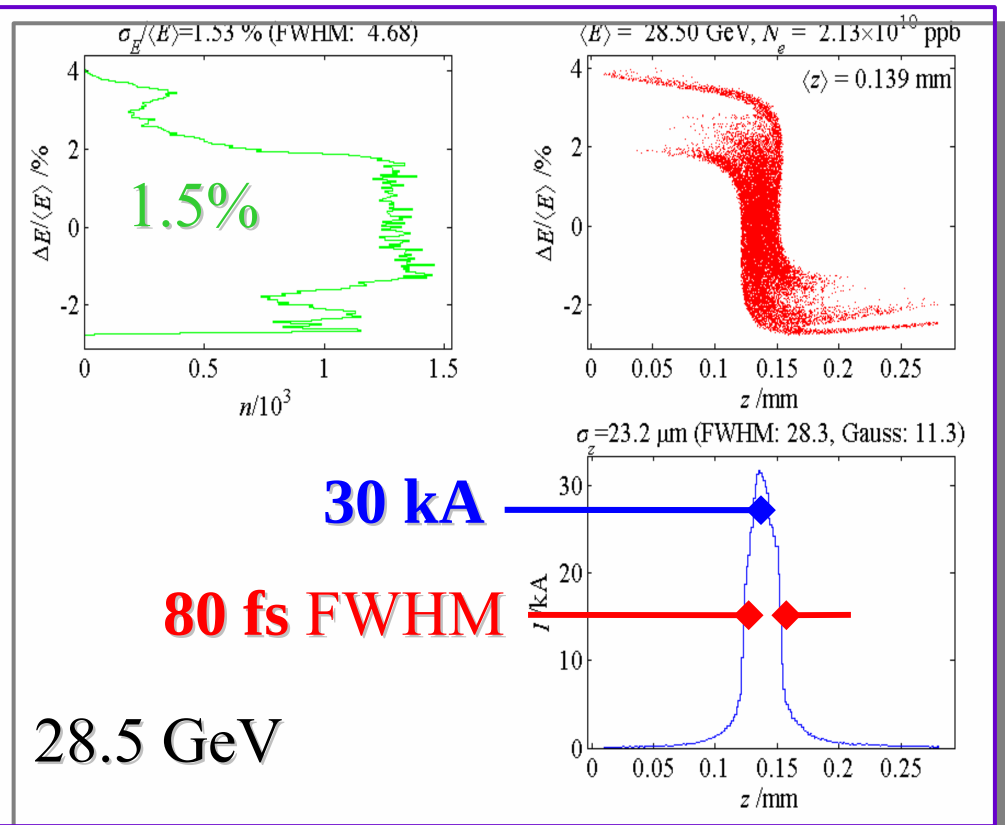
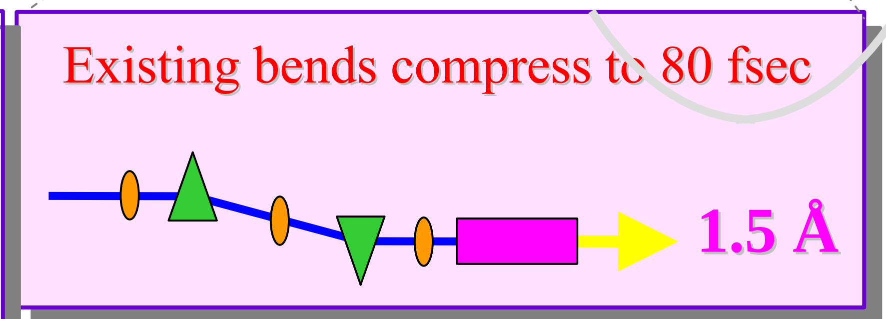
(M. Huening, et al FEL'2000)

Short Bunch Generation in the *SLAC* Linac (SPPS)







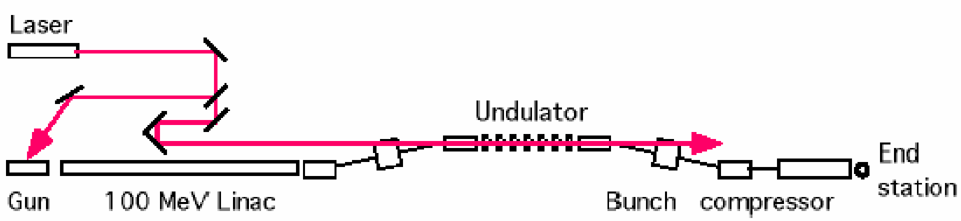
compression by factor of 500

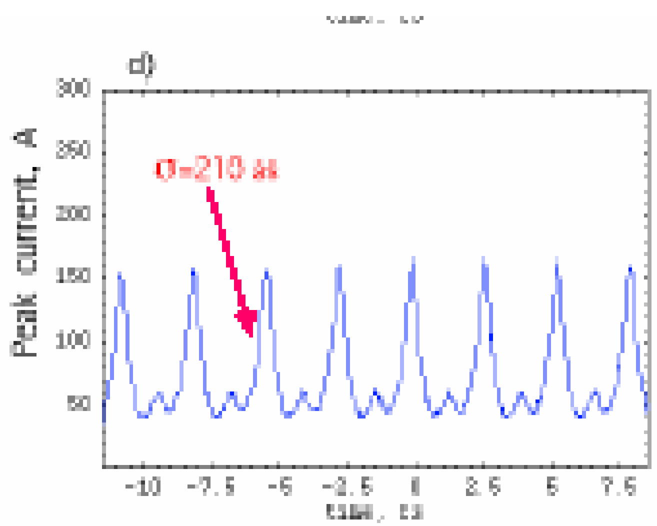
Measured ~9 kA after BC

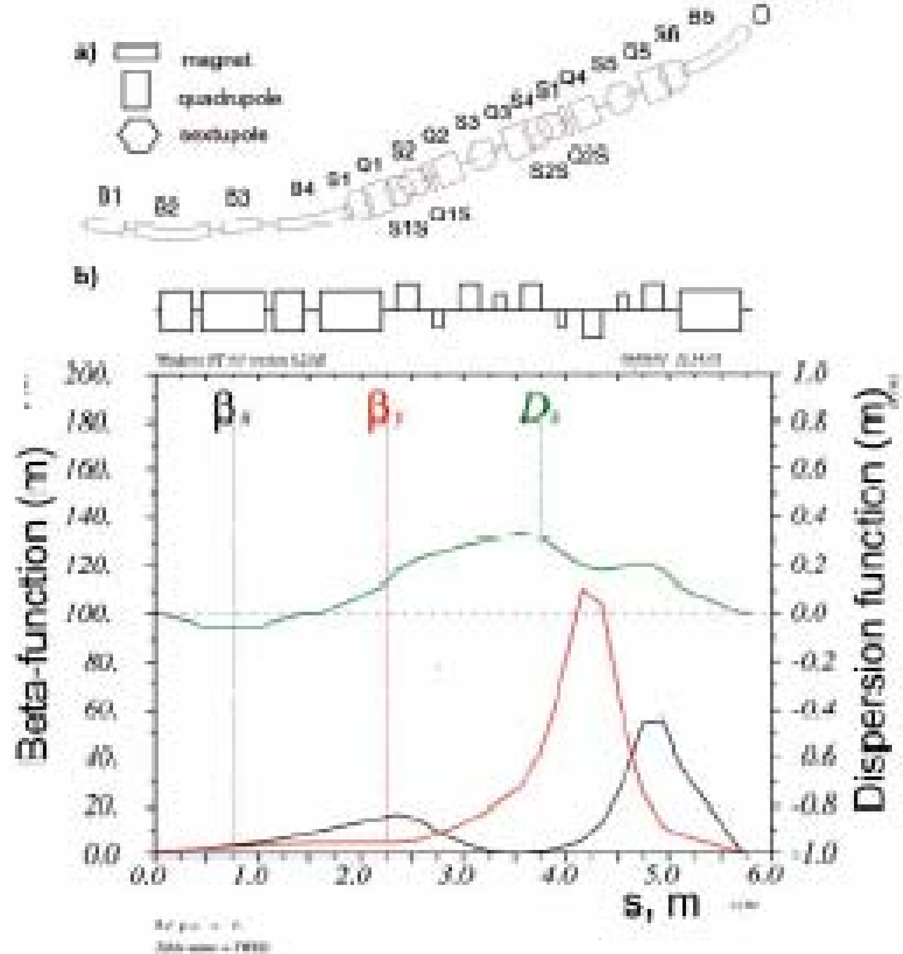
(P. Emma et al, PAC'01)

micro-bunch generation using IFEL

- Possible use of an IFEL + dedicated bunch compressor to produce attosecond bunches



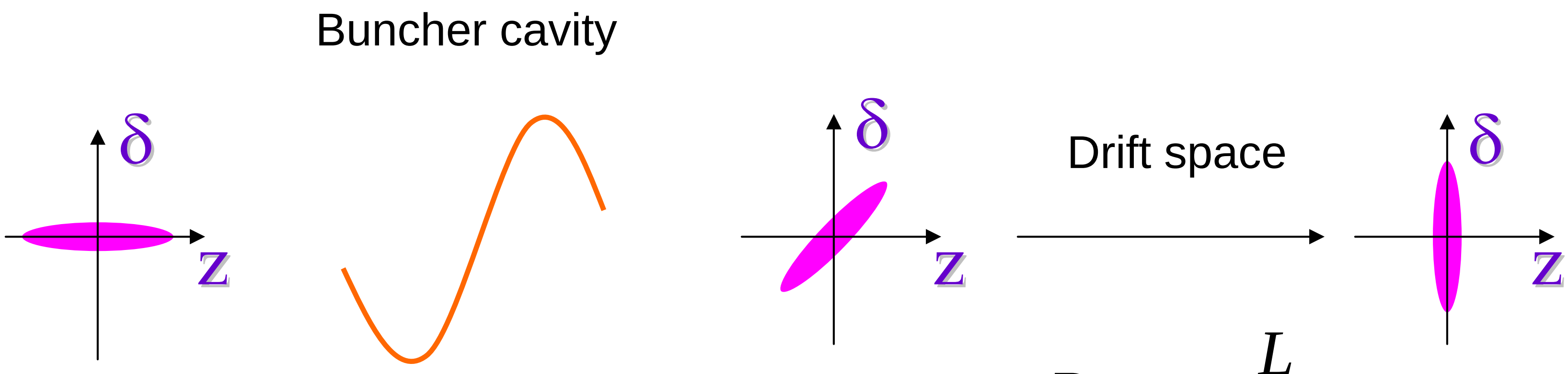




(A. Zholents, et al PAC'01)

Ballistic bunch compression

- Usually used at very low energy, typically downstream of DC-gun
- Can be viewed as thin lens limit of velocity bunching
- Buncher imparts an energy chirp large enough to yield compression in a downstream drift

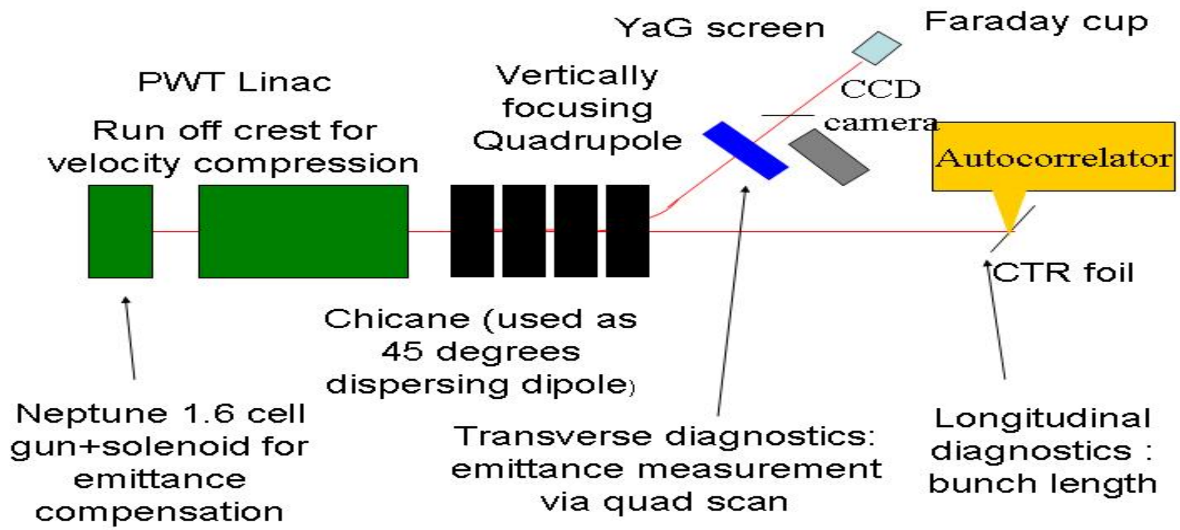


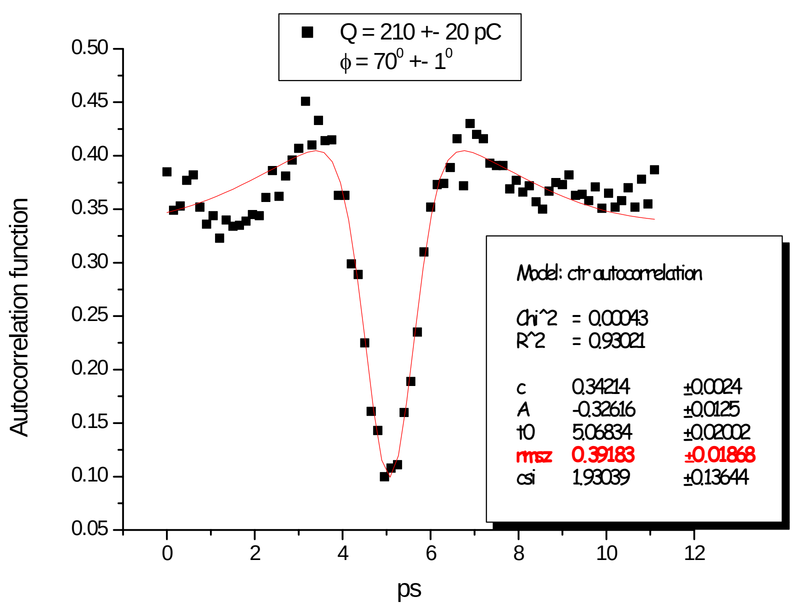
$$R_{56} = -\frac{L}{\gamma^2}$$

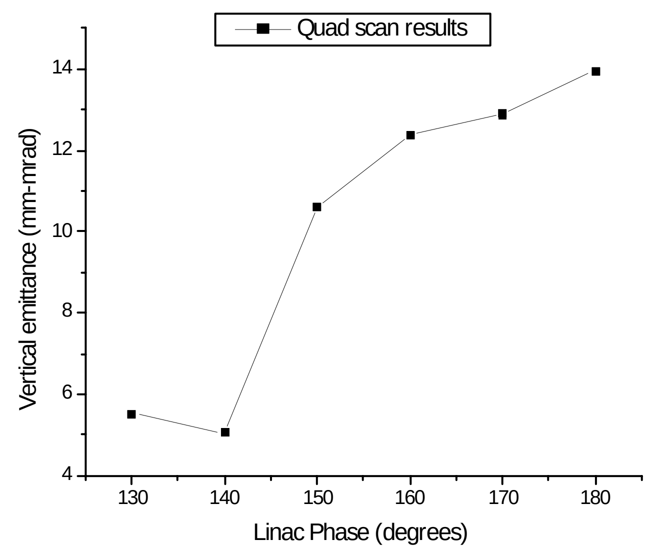
- Example: JLab FELs, polarized beam in LC injectors

Ballistic bunch compression (NEPTUNE, UCLA)

- Compressed beam to 0.4 ps for 200 pC
- Operating 1st linac far off-crest spoils ε compensation process







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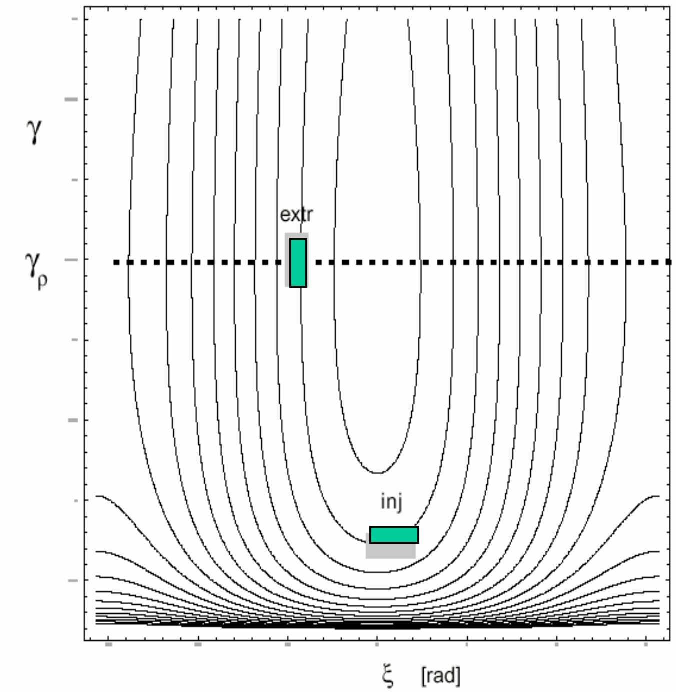
(P. Musimeci, et al PAC'03)

Velocity bunch compression

- Non-rigid bunch: relative longitudinal motions occur within the bunch
- Proposed as 1st stage compression for several projects (SPARC, PLEIADE, …)
- Initial motivation was to avoid the CSR-related problem(s)



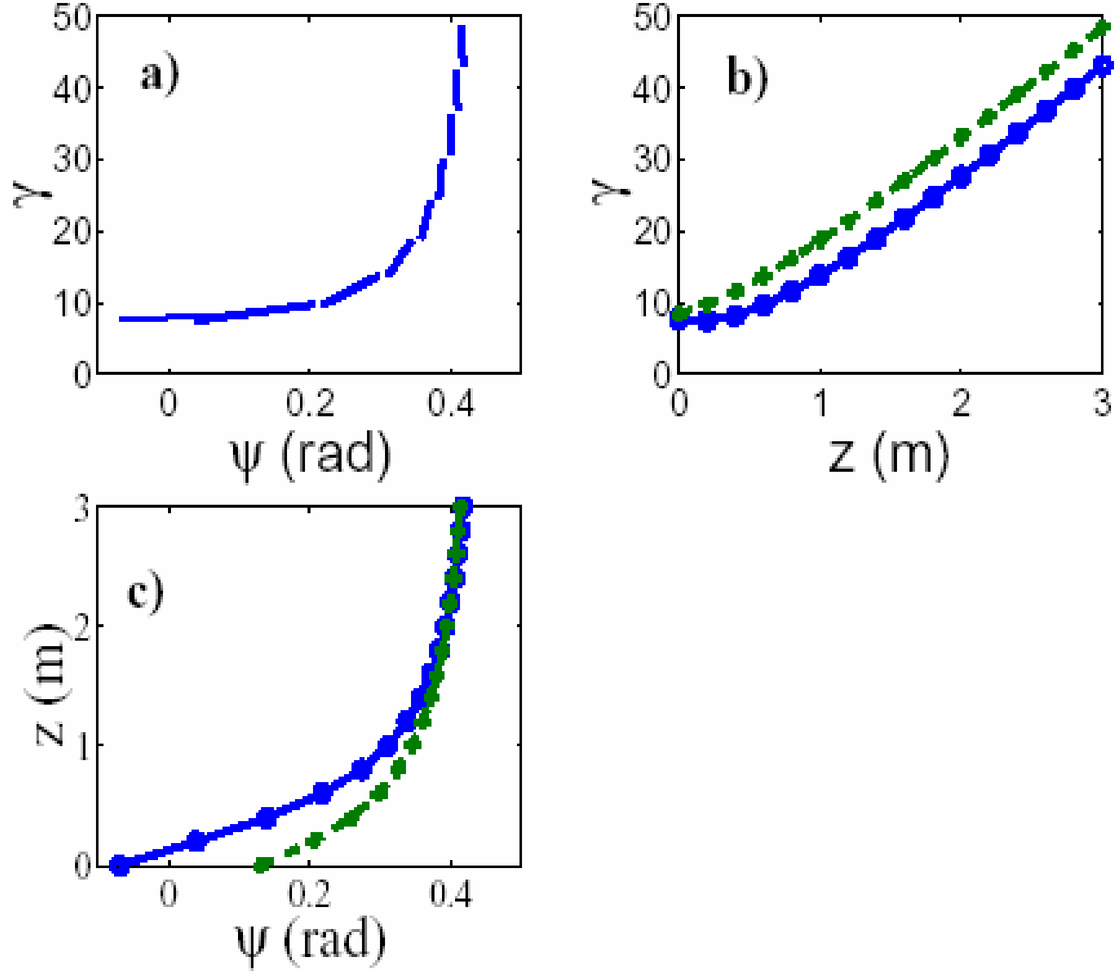
$$\delta\psi_\infty \approx \frac{\sin\psi_0}{\sin\psi_\infty}\delta\psi_0 + \frac{1}{2\alpha\gamma_0^2\sin\psi_\infty}\delta\gamma_0$$

(Serafini/Ferrario, AIP (581):87 (2001))

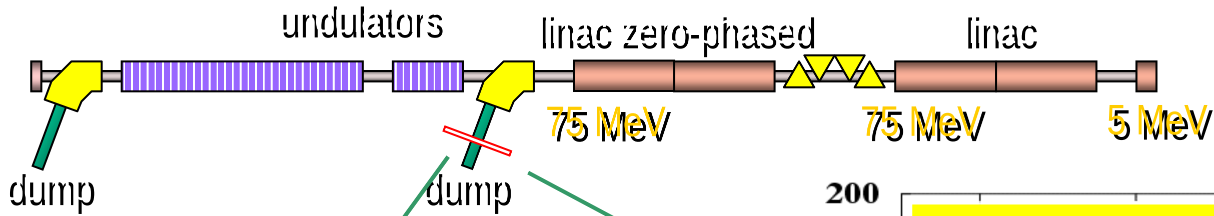
Velocity bunch compression

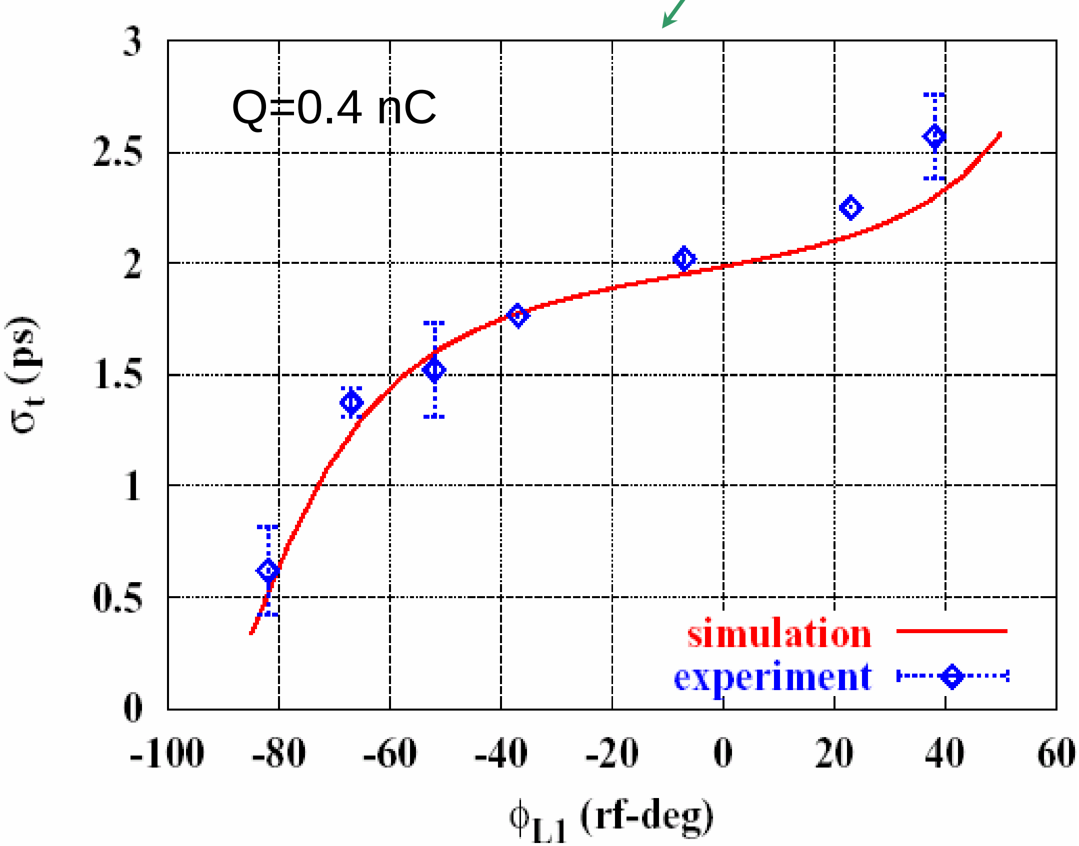
- Numerical example for a 3 m long S-band type structure

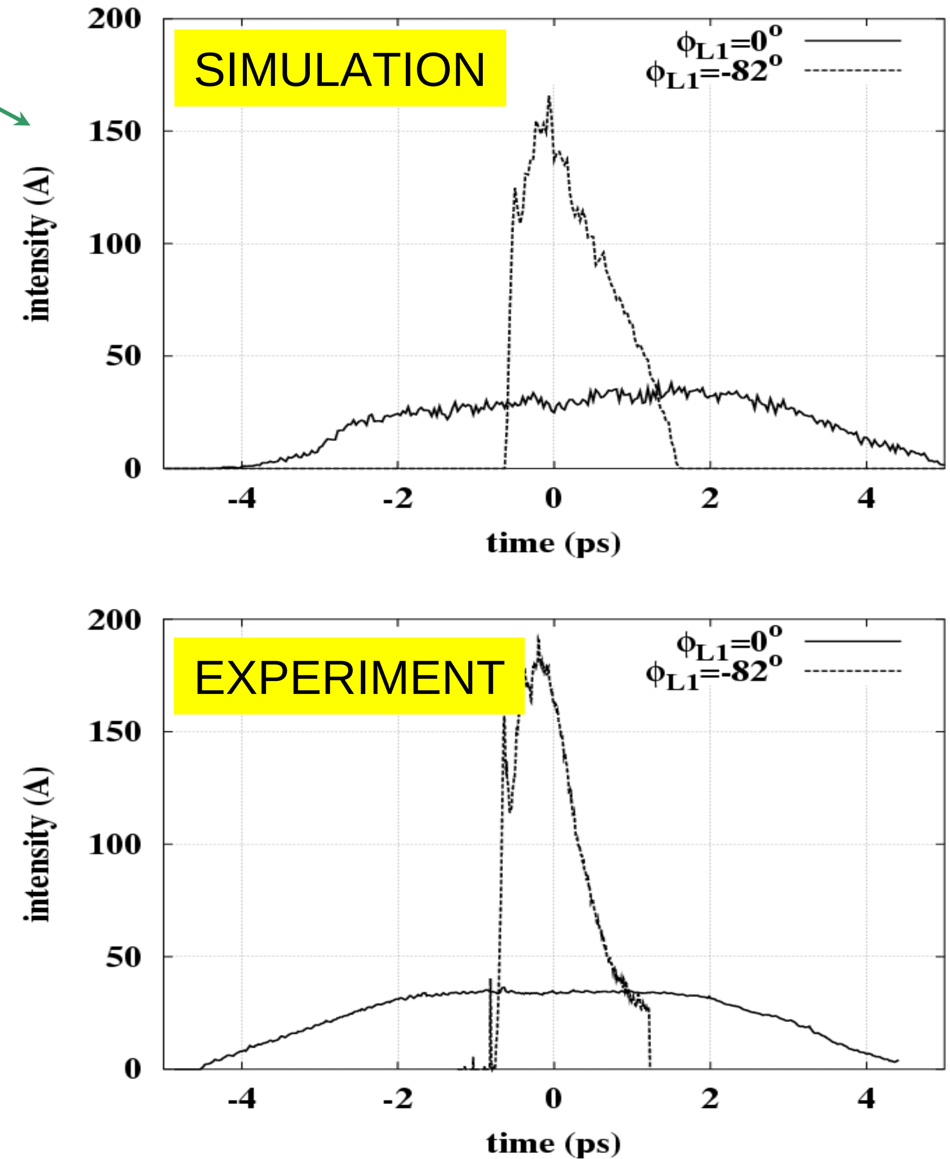
$$\begin{cases} \dfrac{d\psi}{dz} = k\left(\dfrac{\gamma}{\sqrt{\gamma^2-1}} - 1\right) \\ \dfrac{d\gamma}{dz} = \alpha k \sin\psi \end{cases}$$



Velocity bunch compression (DUVFEL, BNL)



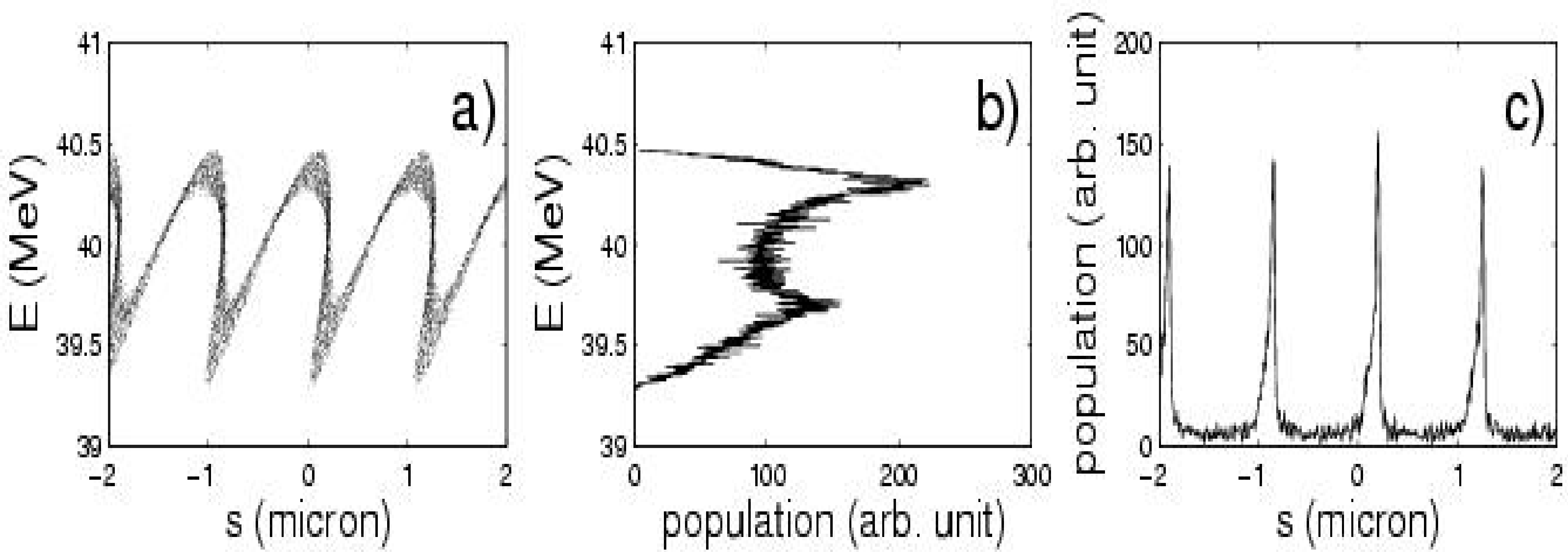




(P. Piot, et al PRSTAB(6) 033503 (2003))

Velocity/ballistic bunch compression

- Modulation can be impressed by a laser resulting in a micro-bunching at laser wavelength,
- Need a “coupling medium” (IFEL, I-Čerenkov, etc…)



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Velocity/ballistic bunch compression

- 1st experiment on microbunching done at ATF, BNL using inverse FEL,
- Latter used inverse Čerenkov radiation

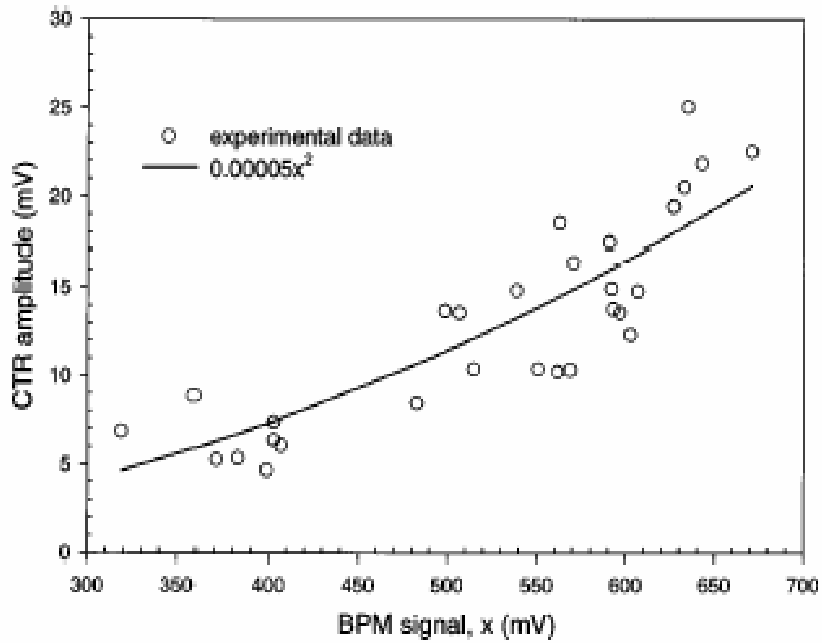
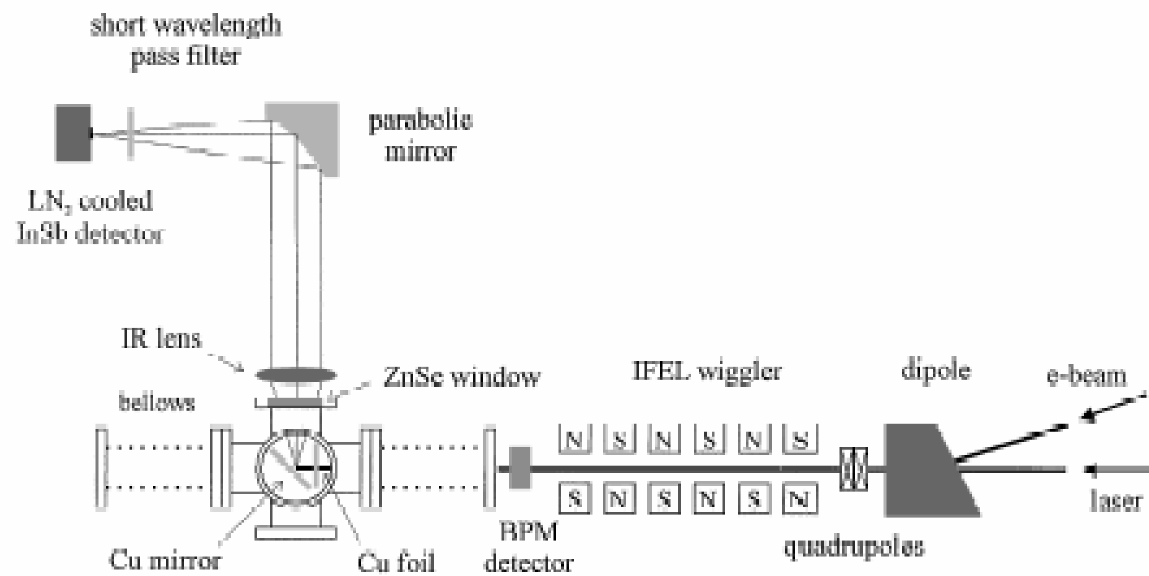


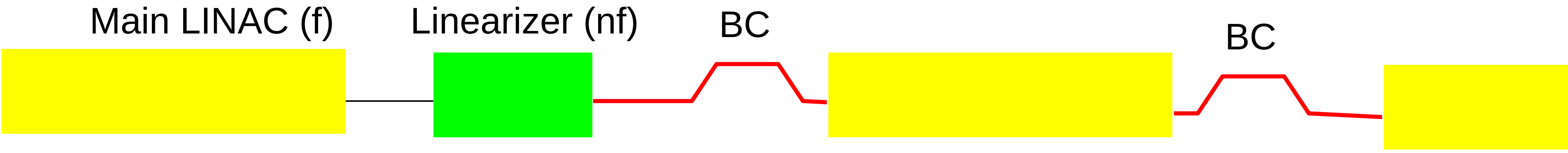
FIG. 4. The transition radiation signal as a function of the total number of electrons. The BPM signal is proportional to the total charge (eN) of the electron beam.



(Y. Liu, et al PRL 80 (20): 4418 (1998))

Concluding remarks (1)

- Reviewed some bunch compression techniques, but did not discuss their full integration,
- Bunch compression is only 2D part of a 6D story: what matters for most applications is 6D brightness,
- Staged compression is generally adopted due to stability, space charge degradations...



- But many BCs can drive micro-bunching instability

Concluding remarks (2)

- In LC's and LS's (SASE-FEL) bunch compression is generally multi-staged (compromise between energy spread, space charge, …)
- Coupling/exchange of emittances + production of flat beam maybe a way to reach brighter beam (eg proposedby Cornacchia & Emma)

Acknowledgements

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