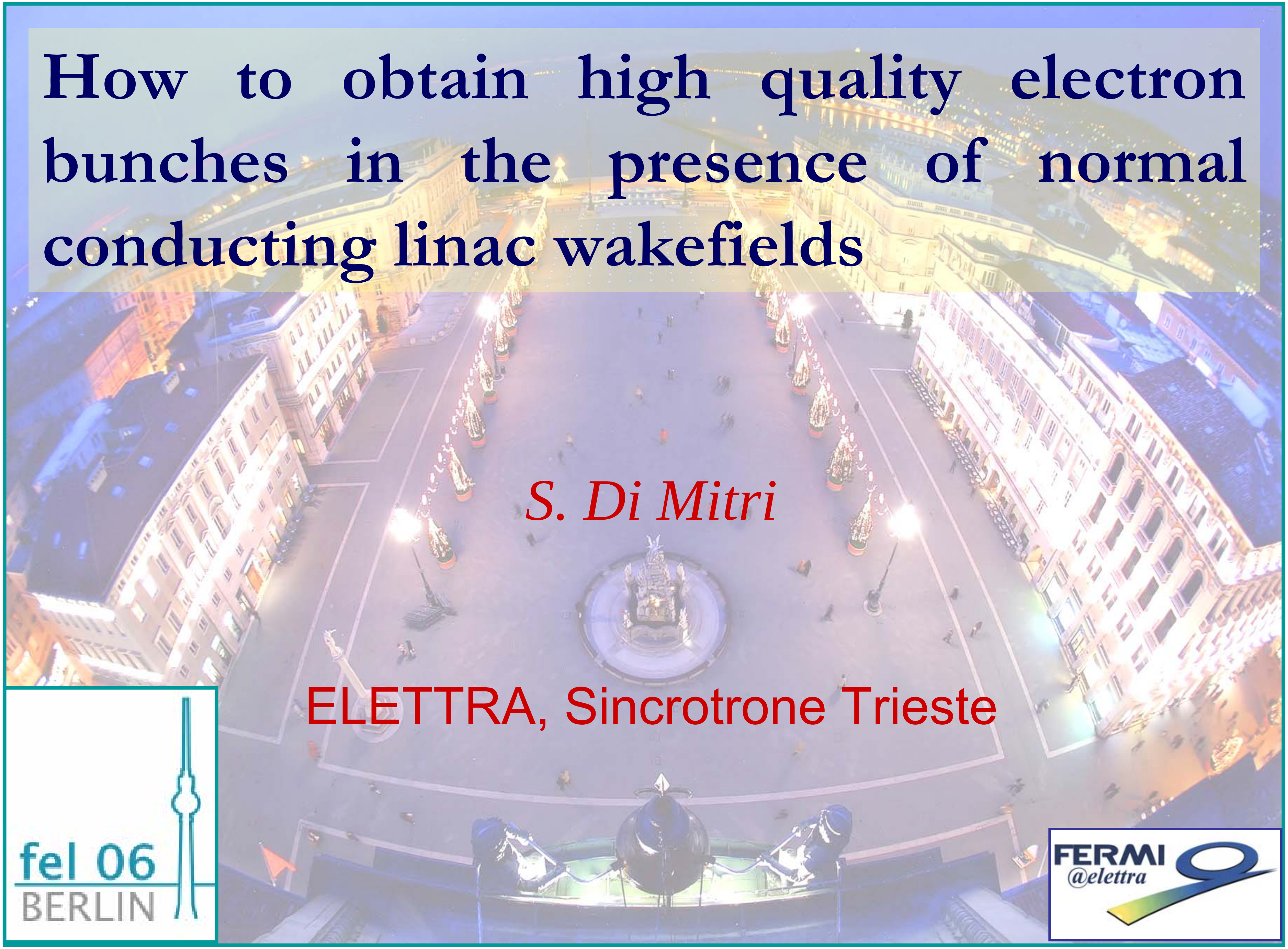

How to obtain high quality electron bunches in the presence of normal conducting linac wakefields

S. Di Mitri

ELETTRA, Sincrotrone Trieste

fel 06 BERLIN

FERMI @elettra

Outline

- Wake fields in normal conducting Linacs for Single Pass FELs:
  - Accelerating Structures
  - CSR
  - LSC
- How such wake fields affect the beam quality for FEL

Problems

- Beam manipulation techniques to compensate wake fields:

  control of higher order energy chirps

- Low charge regime to minimize wake fields
- Cures for μ-bunching instability

Solutions

Beam Quality

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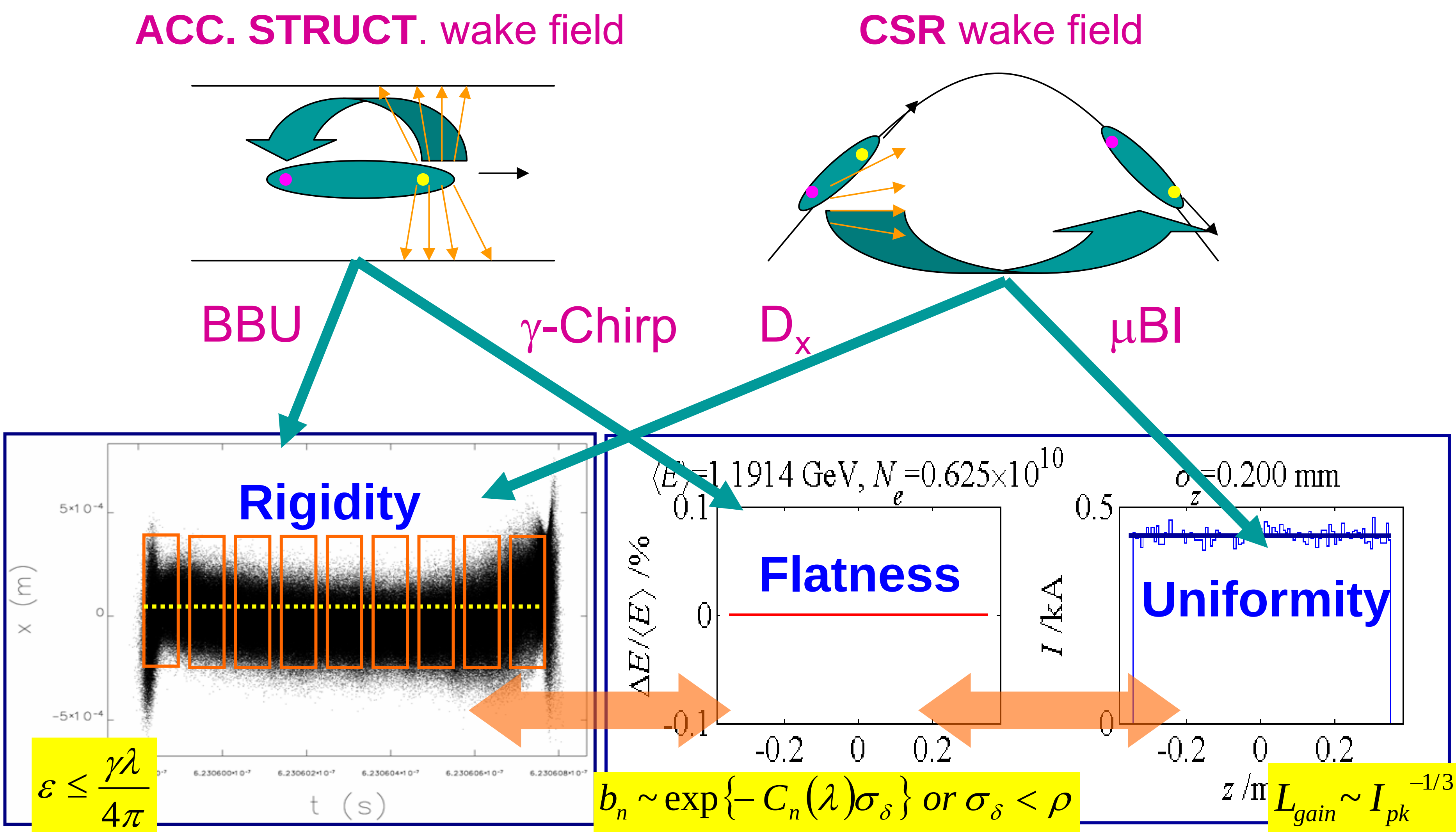

$$\varepsilon \leq \frac{\gamma\lambda}{4\pi}$$

$$b_n \sim \exp\{-C_n(\lambda)\sigma_\delta\} \; or \; \sigma_\delta < \rho$$

$$L_{gain} \sim I_{pk}^{-1/3}$$

Beam Quality (cont'd)

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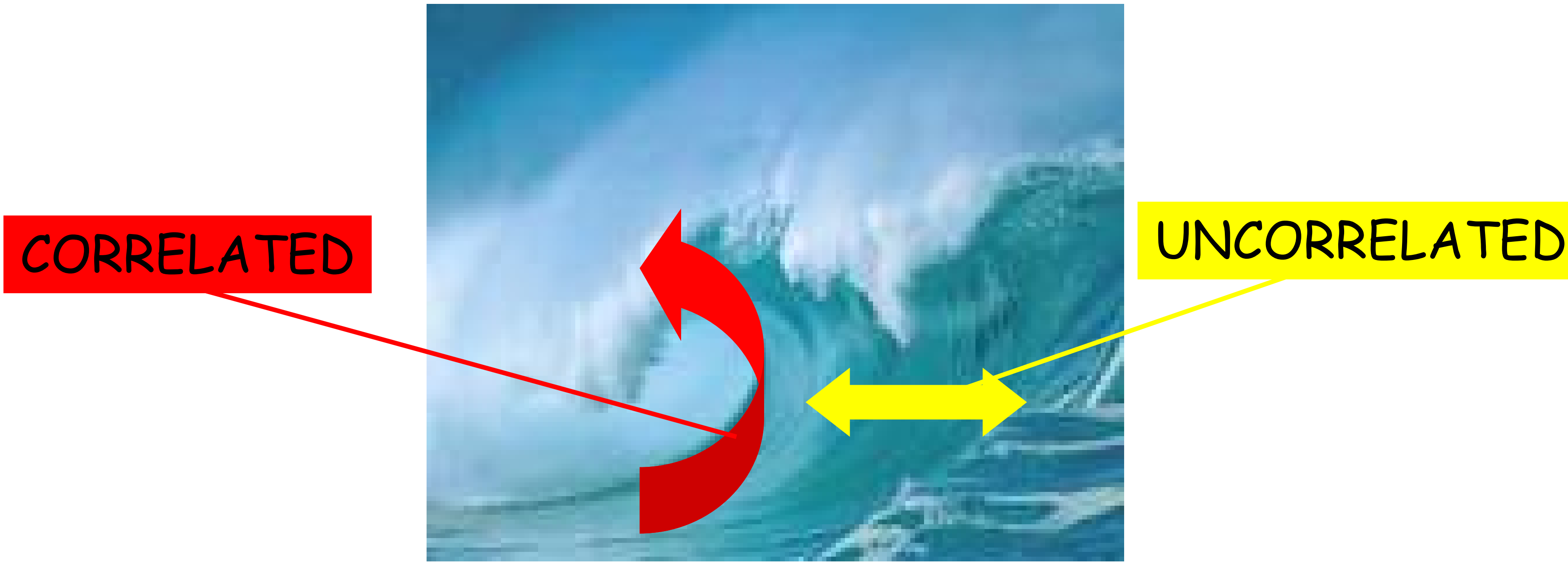
Cooperative process in undulator → e-beam longitudinal *slicing*

Slicing in a Linac? Not physical – arbitrary binning



large λ ← slice → small λ

Correlations make the slice beam quality dependent on the slice length

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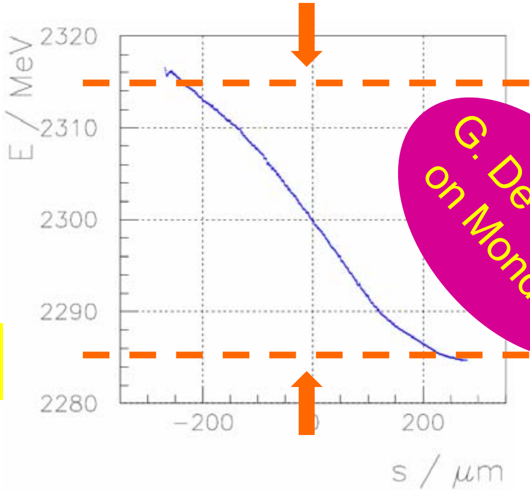
Flatness

$W_{//}$ cancels the final energy chirp allowing larger chirps for compression and reduced CSR by smaller R_{56} in BC2…

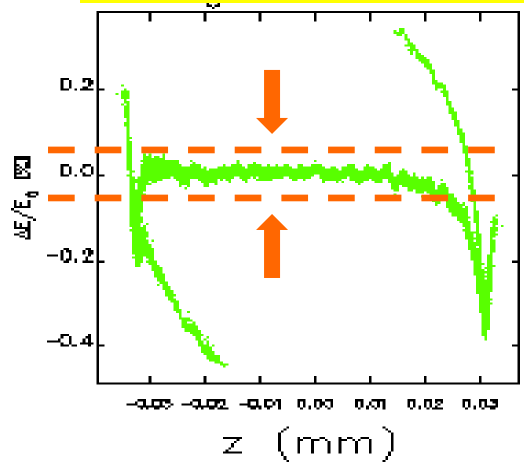
courtesy M.ABO-BAKR

$\sigma_\delta \approx$ 8 MeV



G. De Ninno, on Monday

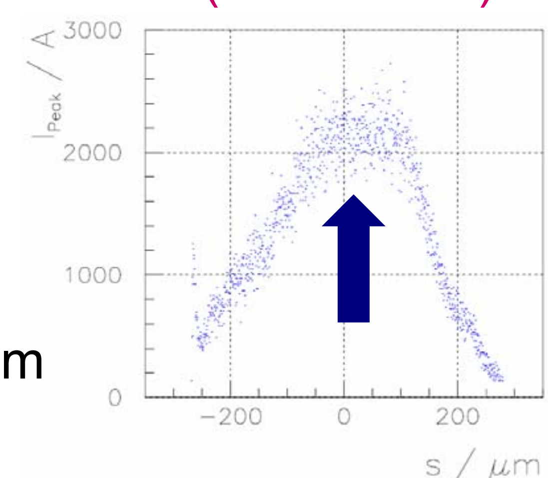
$\sigma_\delta \approx$ 2 MeV $\rightarrow$ $\sigma_\delta \approx$ 14 MeV

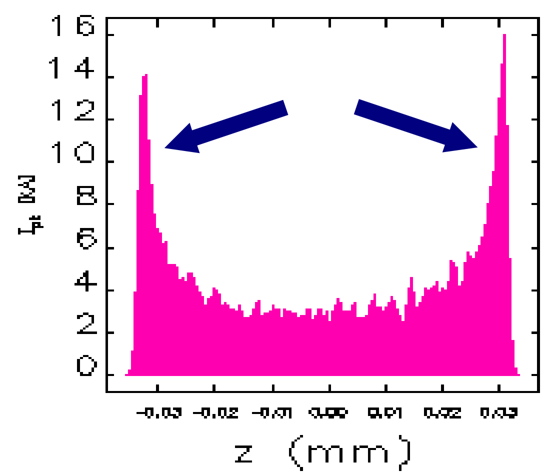


courtesy P. EMMA

…but introduces nonlinearities which degrade the current profile of the compressed beam (see later…)

2.5 nC
$\sigma_z \cong 70\mu m$





1.0 nC
$\sigma_z = 23\mu m$

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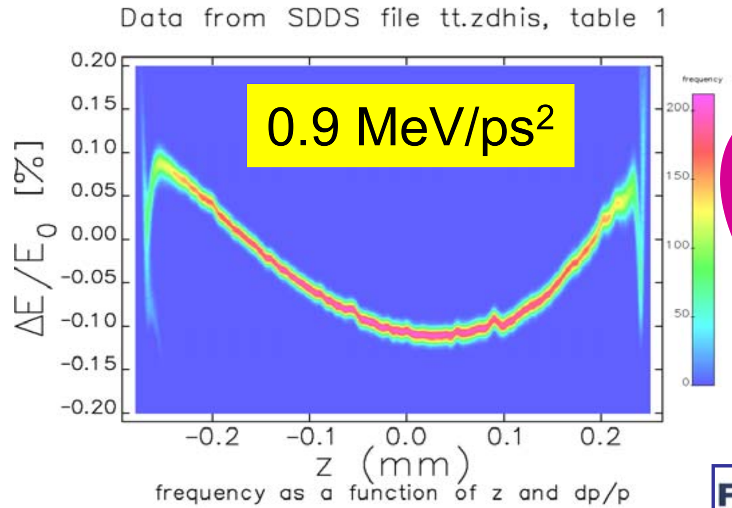
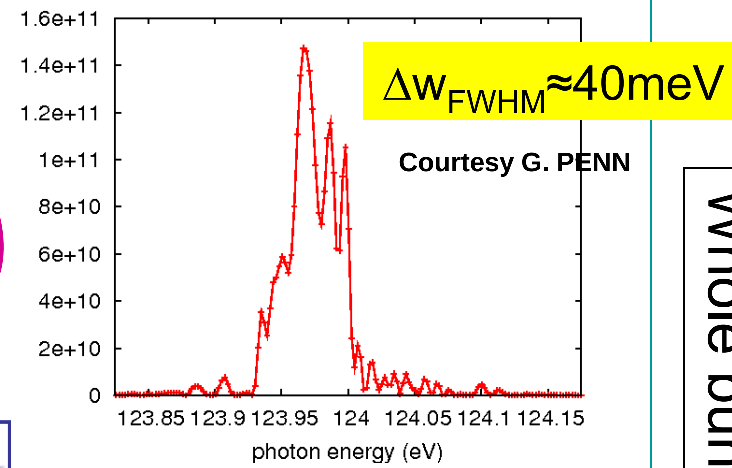
Flatness (cont'd)

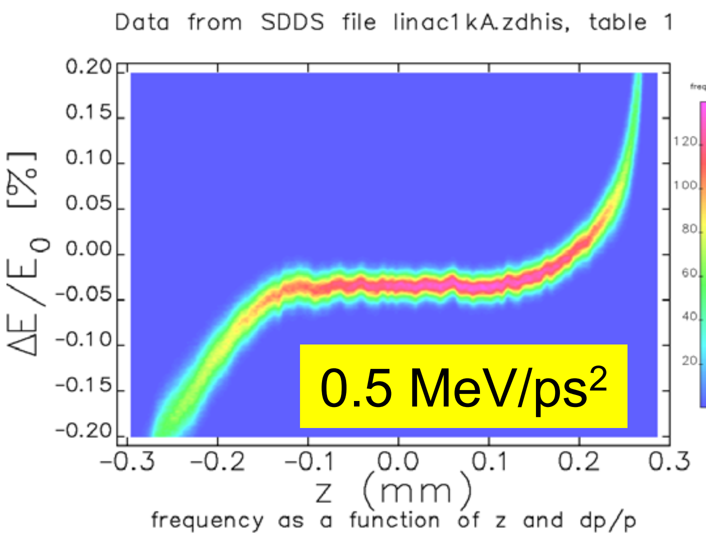
One of the goals for HGHG FELs is FT limit signal with a narrow BW

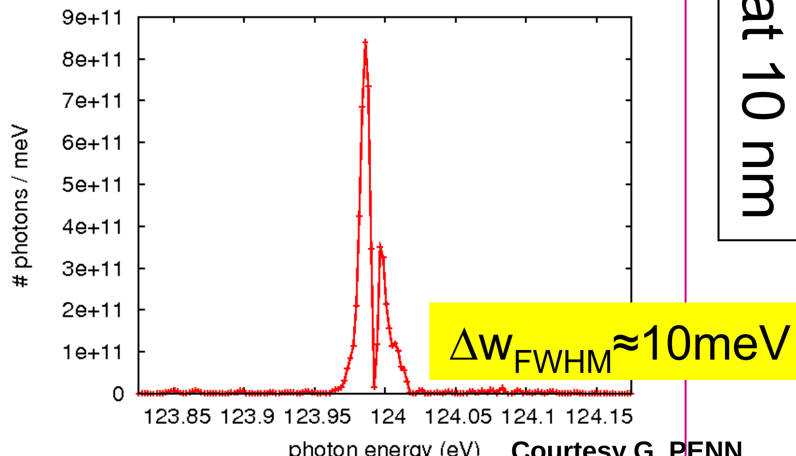
B. Fawley, G. Penn

Fermi Linac









Courtesy G. PENN

Whole bunch at 10 nm

Uniformity

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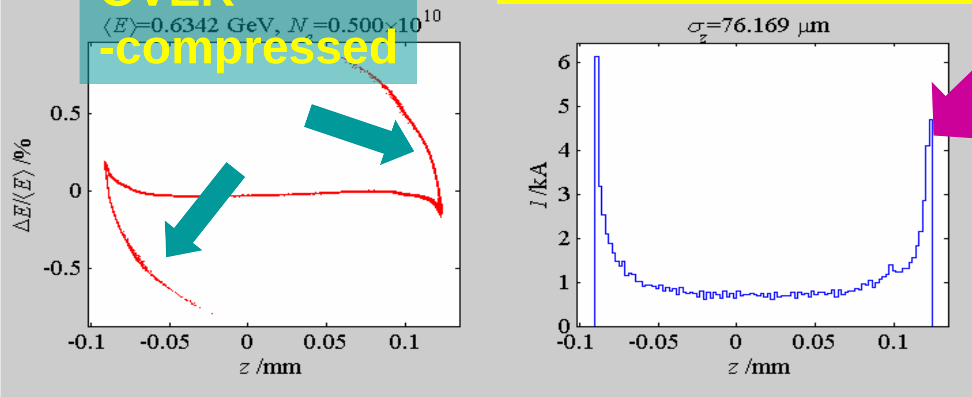
FEL06, Berlin

bifurcations and spikes due to longitudinal wakes, T_{566} and cubic chirp

$$\delta(z) \cong \delta_0 + D(1)\Delta z + D(2)\Delta z^2 + D(3)\Delta z^3$$

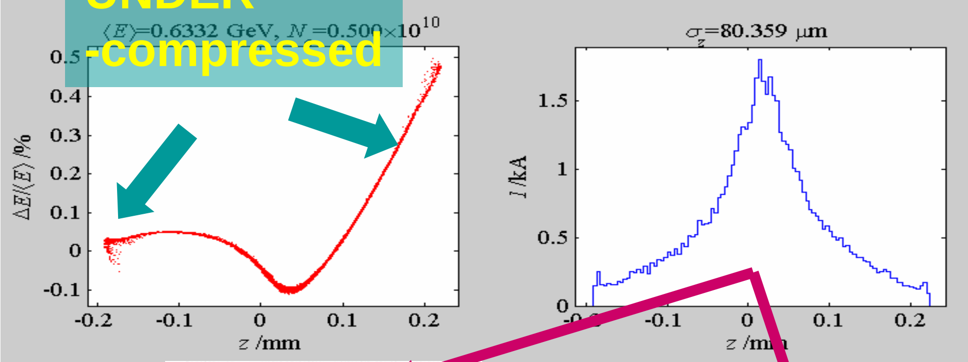
OVER -compressed

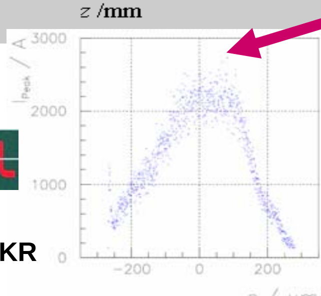
D(3)=-0.039mm^{-3} at PI



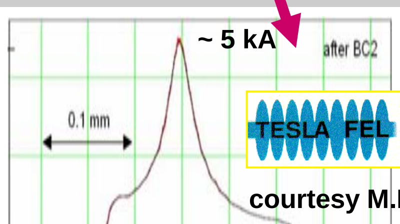
UNDER -compressed

D(3)=+0.081 mm^{-3} at PI





courtesy M.ABO-BAKR

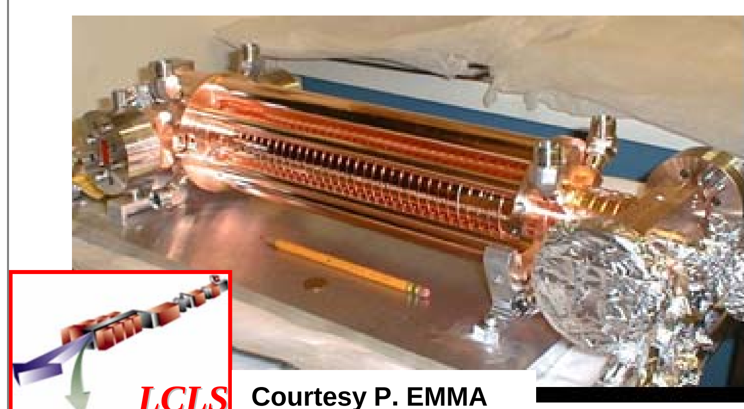


courtesy M.DOHLUS

Cubic chirp manipulation:

- PI → No! D(3) always < 0
- X-band phase → OK!

0.5 m X-band section for LCLS (22 MV, 11.4 GHz)



Courtesy P. EMMA

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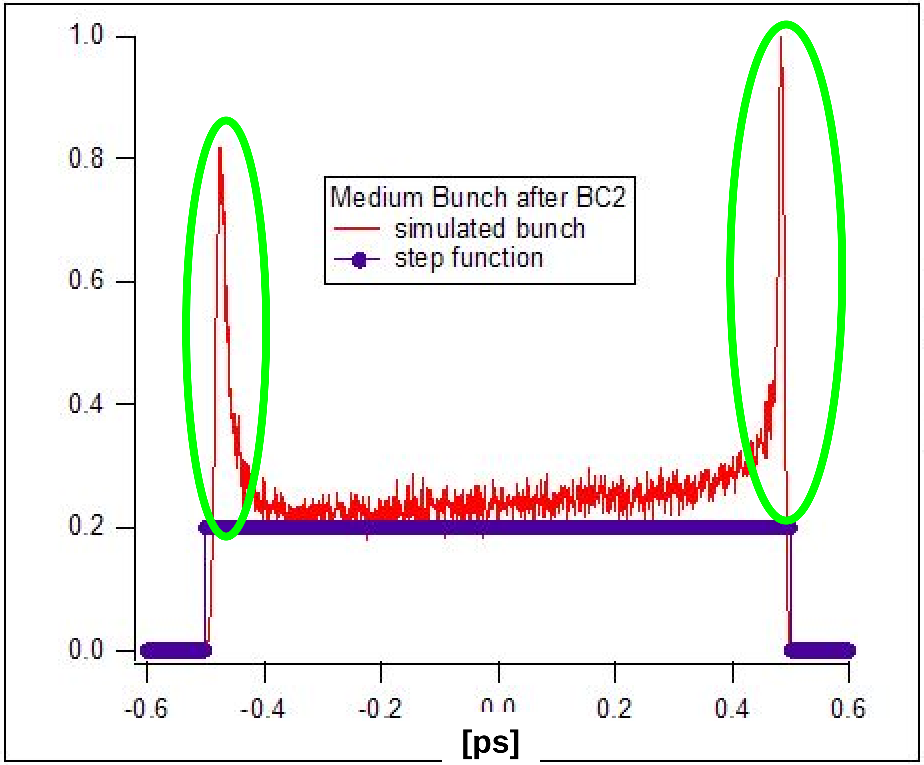
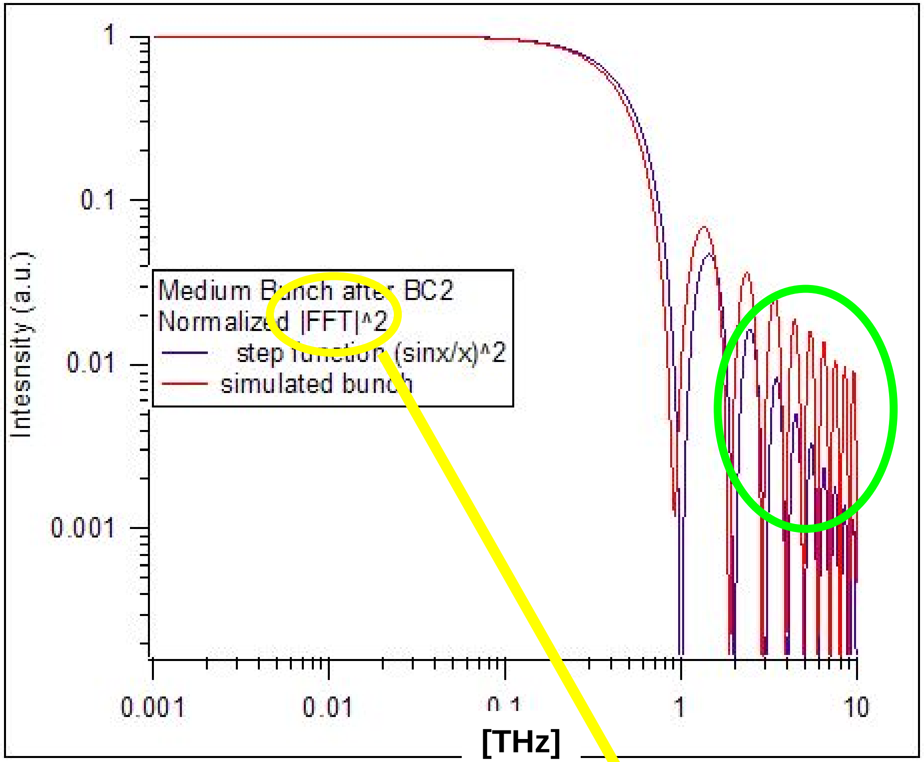
Uniformity (cont'd)

Current spikes should be avoided because:

- compression efficiency reduced
- wake field in undulators
- Current spikes enhance higher frequencies





$$\left(\frac{dI}{d\omega}\right)_{CSR} = \left[N + N(N-1)\left|F(\omega)\right|^2\right]\left(\frac{dI}{d\omega}\right)_{ISR(e)}$$

Courtesy
M. VERONESE

Flatness + Uniformity

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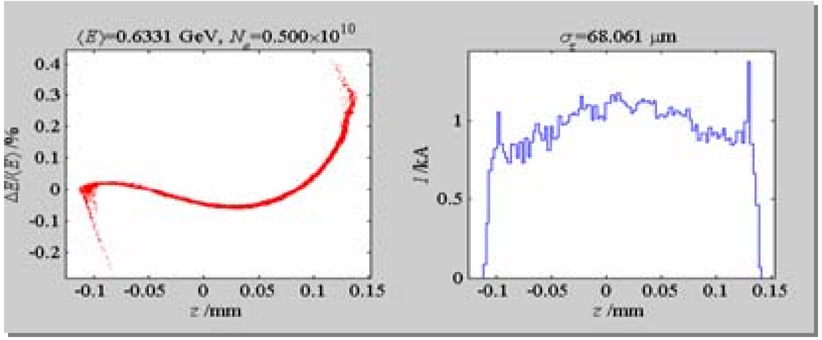
FEL06, Berlin

- X-band phase can control the cubic chirp but affects the flatness



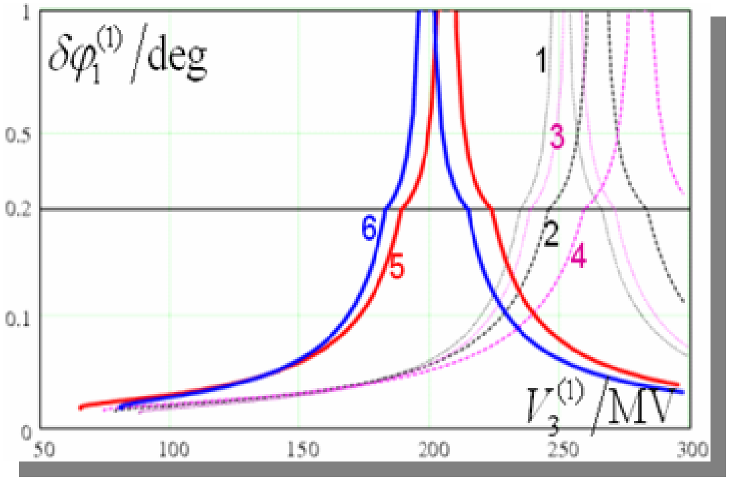
$$U_4 = -\frac{U_0 + U_1\cos(\phi_1)}{16\cos(\phi_4)}$$

$$U''' = -k^2 U'(U_4, \phi_4) + \frac{15}{4} k^3 [U_0 + U_1 \cos(\phi_1)] \tan(\phi_4)$$

- X-band can relax the linac sensitivities but affects the cubic chirp

TESLA FEL

courtesy M.DOHLUS



A global solution is not always guaranteed…

…another knob for bunch shape manipulation is required

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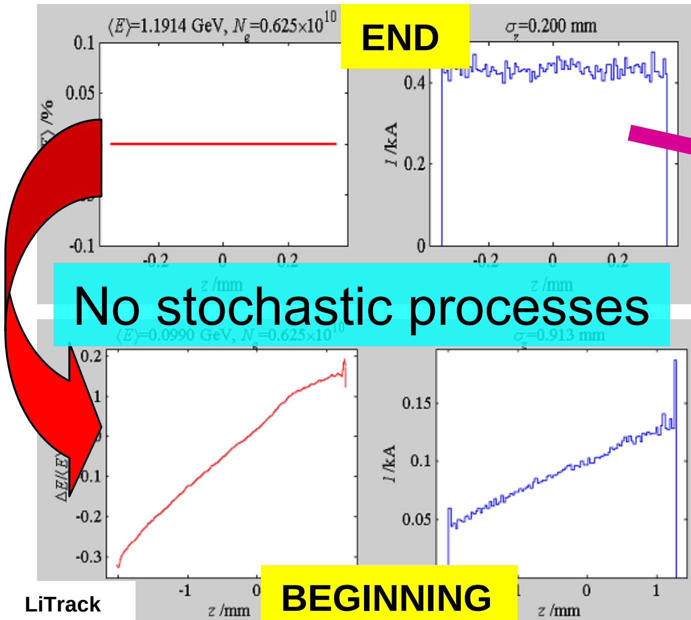
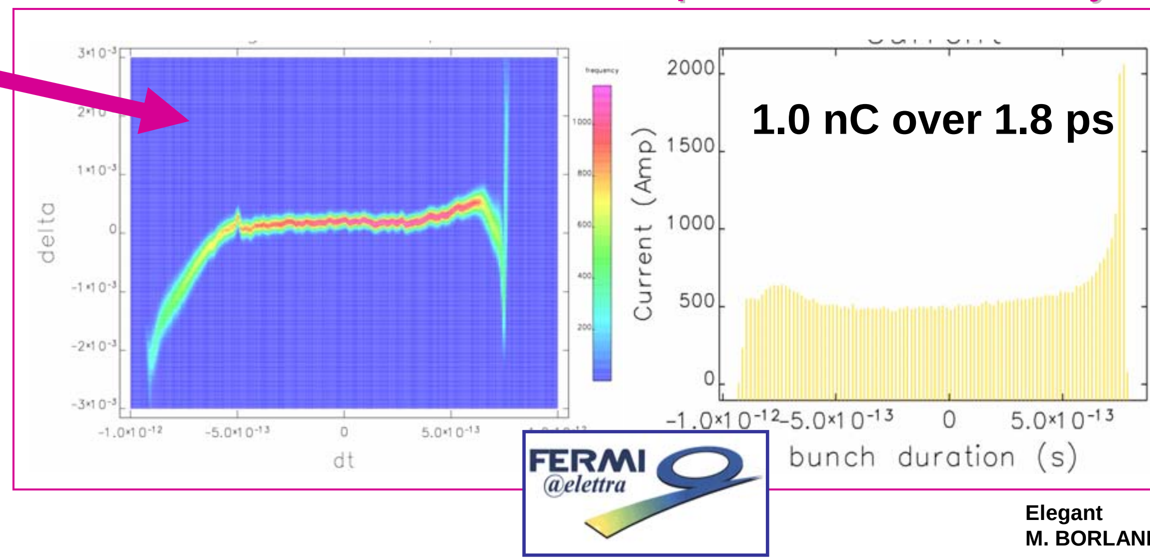
Reverse Tracking

- Longitudinal phase space self-adjusted by e-density distribution which alters the wake fields

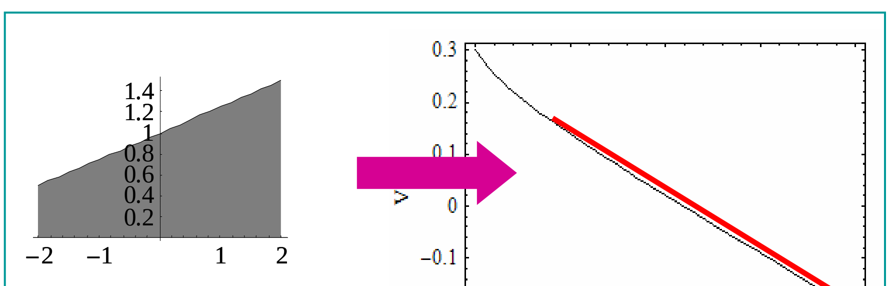


LiTrack
P. EMMA

Forward S2E: 90% compression efficiency

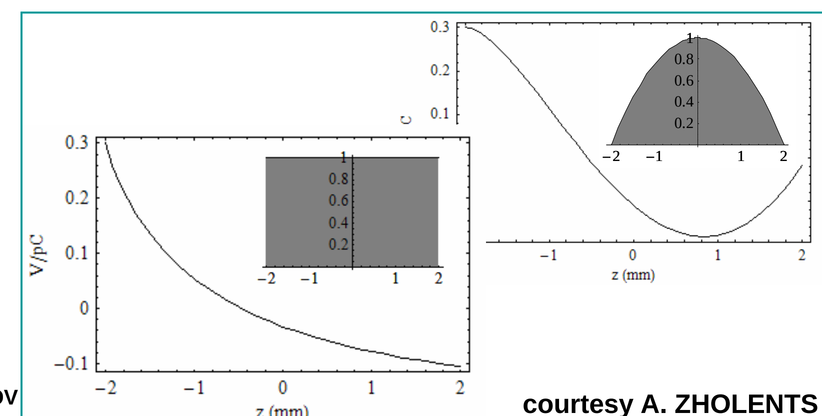


Elegant
M. BORLAND



$$w(s)_{//} \cong 1345 \cdot e^{-\sqrt{s(mm)/0.3}} \left[\frac{V}{pC \cdot m} \right]$$

Wakefields from
CRAIEVICH, WEILAND, ZAGORODNOV
NIM A 2006



courtesy A. ZHOLENTS

Reverse Tracking (cont'd)

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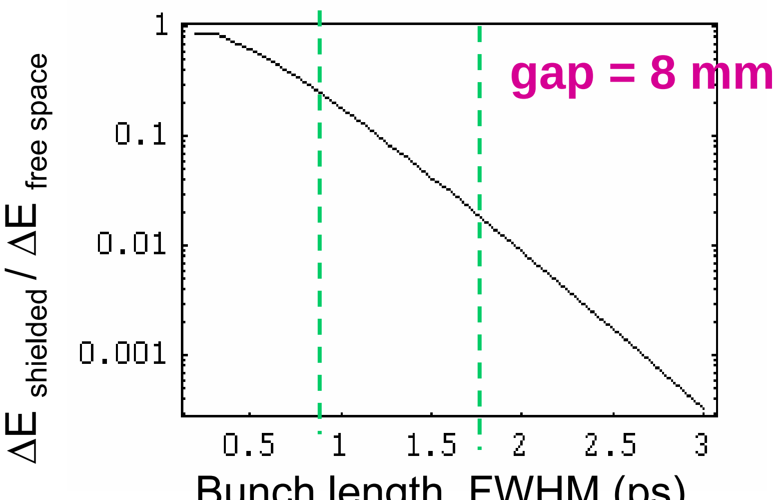
FEL06, Berlin

Frozen beam

$$\delta_f\left(z_f = z_i\right) = \delta_i(z_i) + eU\cos\left(k_{rf} z_i + \phi\right) + e\int^{z_i} \rho(s) W\left(s - z_i\right) ds$$

$$z_f\left(\delta_f = \delta_i\right) = z_i + R_{56}\delta_i + T_{566}\delta_i^2 + \ldots + f_{CSR}(z_i, \delta_i)$$

A) Shielding of CSR by the vacuum chamber*

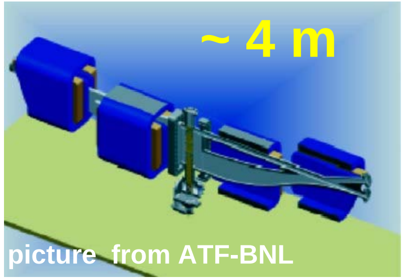


*R.Li, C.L. Bohn, J.J. Bisognano, PAC 1997

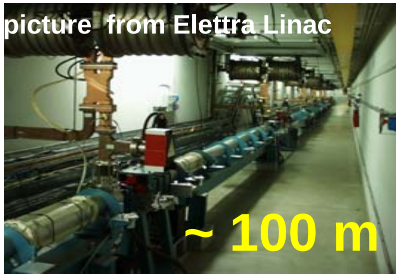
courtesy A. ZHOLENTS

B) "long" bunches: CSR energy losses are weak at $\omega \sim 1/\tau_b$

$$\left|Z_{CSR}\right| \sim \left(\frac{k}{R^2}\right)^{\frac{1}{3}} \approx 8\ m^{-1} \text{ over}$$



$$\left|Z_L\right| \sim \frac{4}{ka^2} \approx 0.5\ m^{-1} \text{ over}$$



$\Delta E_{tot}(CSR) \leq 150$ keV << $\Delta E_{tot}(W_{//}) \approx 15$ MeV

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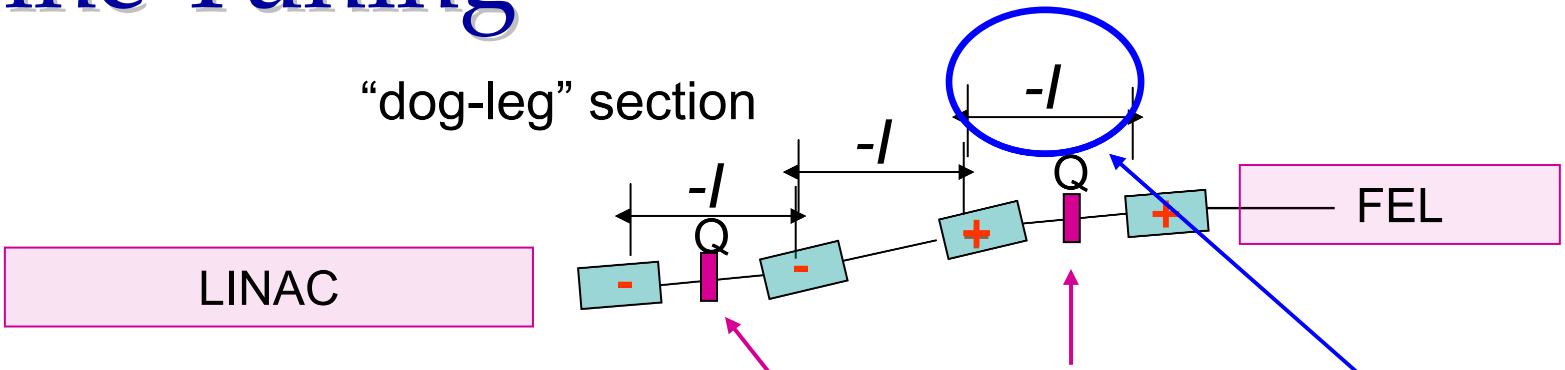
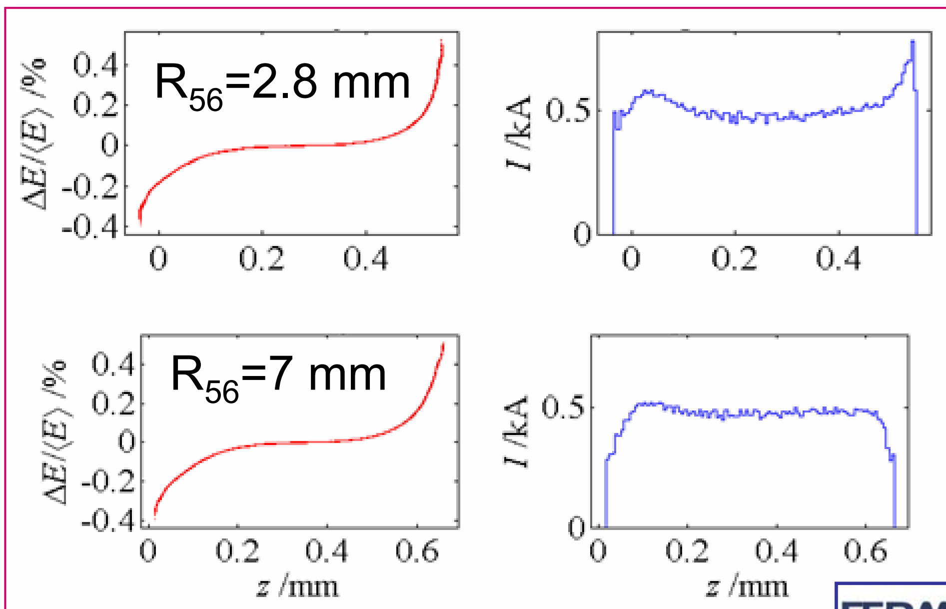
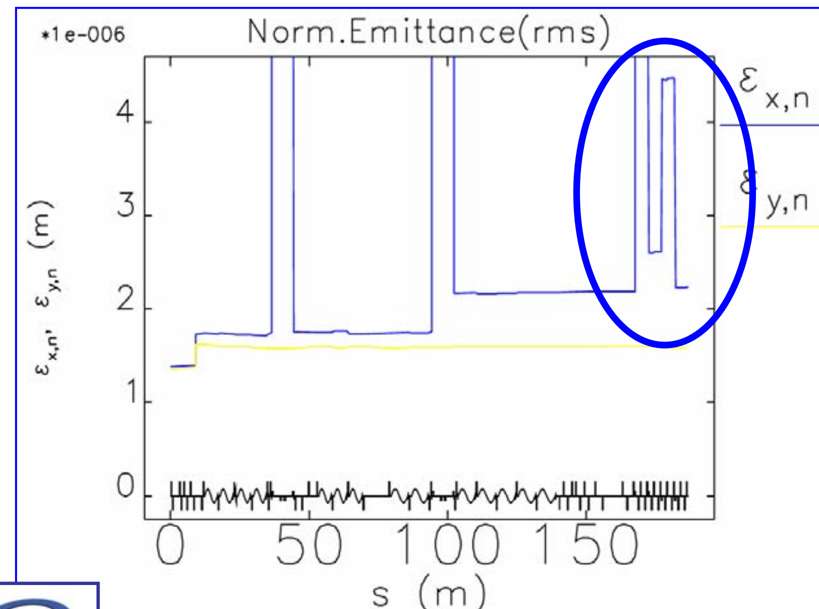
Fine Tuning



Adjustable R_{56} using trim quadrupoles to refine the longitudinal phase space

Preserve emittance





Courtesy M. CORNACCHIA

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Rigidity

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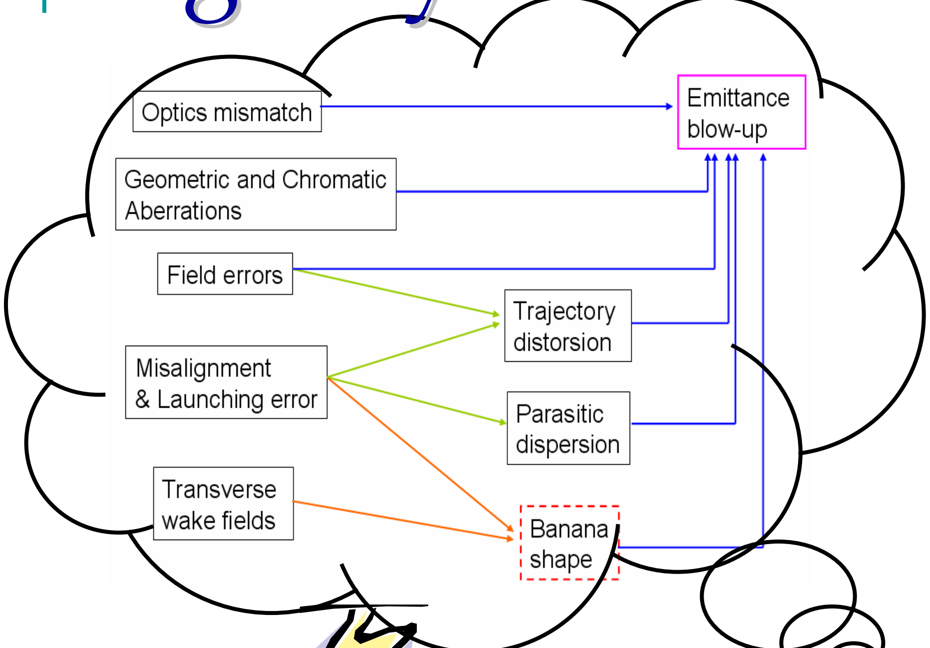

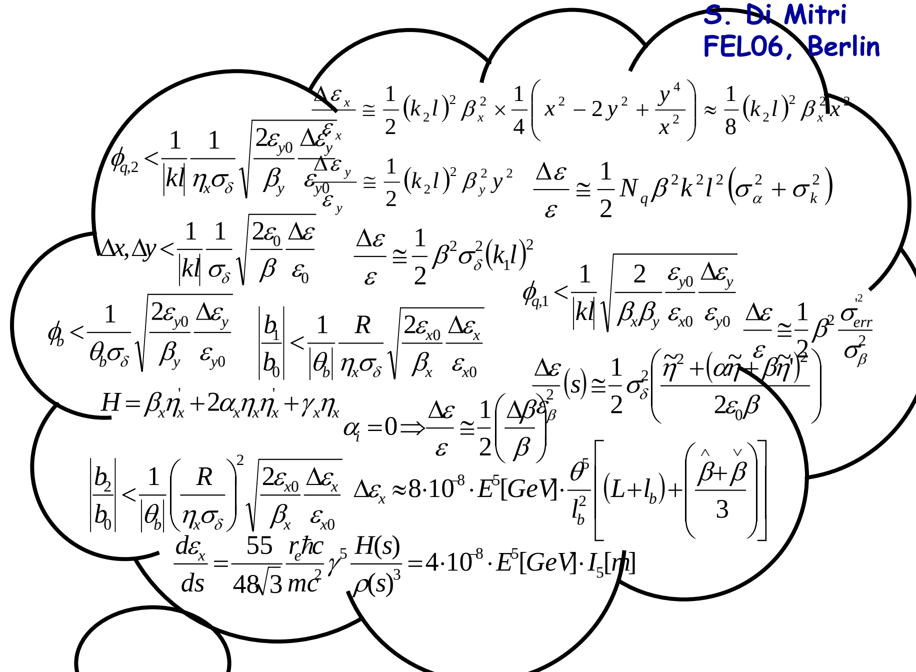

$$\frac{\Delta\varepsilon}{\varepsilon} \cong \frac{1}{2}\beta^2\sigma_\delta^2 (k_1 l)^2 \leq 1\%$$

Chromatic Aberrations

Super-conducting
TESLA-FEL ≤ 2%

$$\varepsilon_r = \frac{4\pi\varepsilon_0 W_0 I_{max} l_b L^2}{\gamma(0) I_A} >> 1$$

BBU

Normal-conducting
LCLS ≤ 10%

BBU: "Banana" shape

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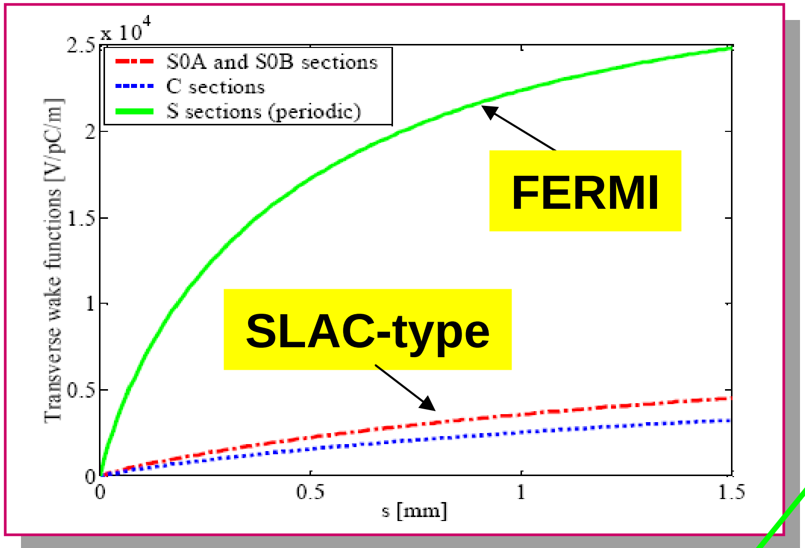
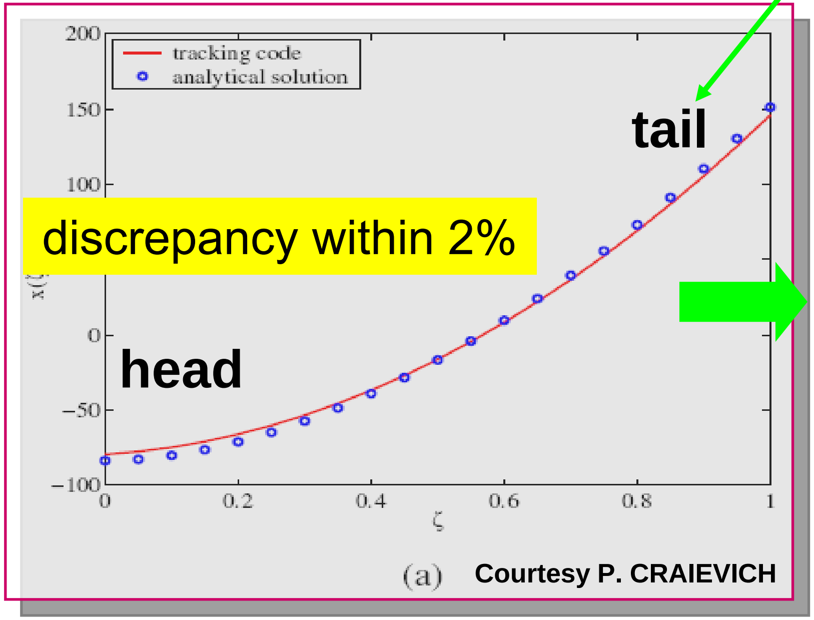
Wake Functions



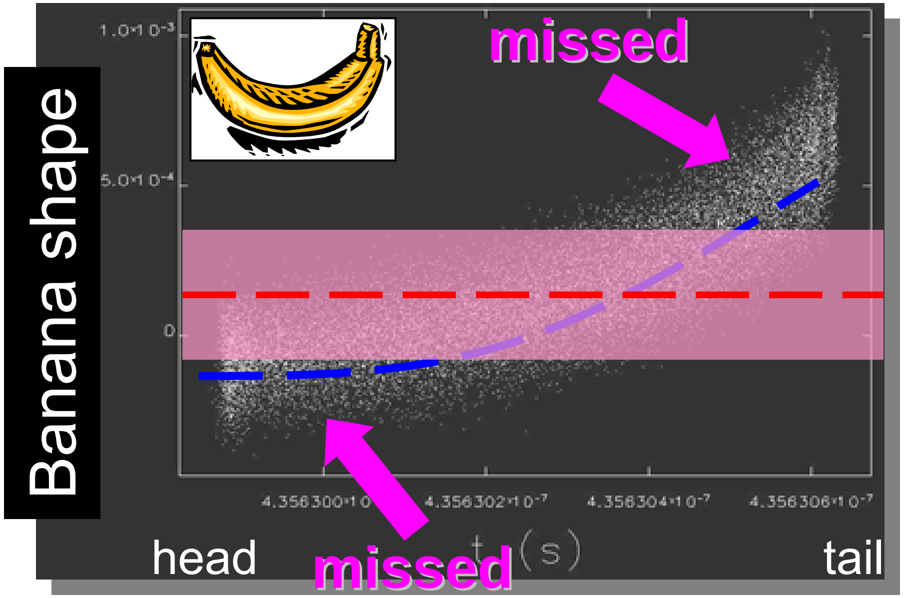
DYNAMICS of BANANA SHAPE

$$\frac{1}{\gamma(\sigma)}\frac{\partial}{\partial\sigma}\left[\gamma(\sigma)\frac{\partial}{\partial\sigma}x(\sigma,\zeta)\right]+\kappa(\sigma)^2 x(\sigma,\zeta)=$$
$$\varepsilon(\sigma)\int_{-\infty}^{\zeta} w_n(\zeta-\zeta_1)F(\zeta_1)\left[x(\sigma,\zeta_1)-d_c(\sigma)\right]d\zeta_1$$

Elegant vs. Analytical



Seeded FEL



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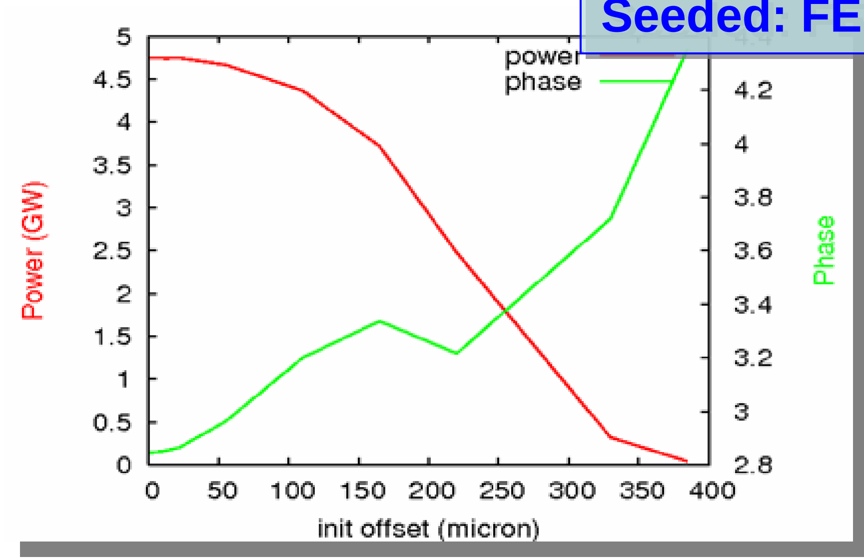
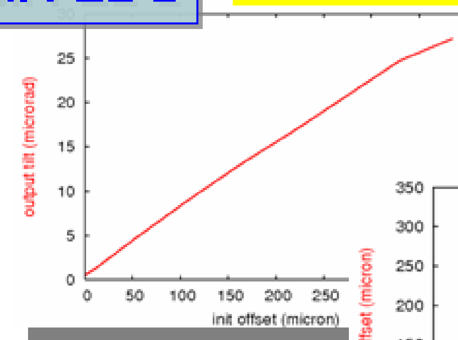
BBU: Impact on FEL

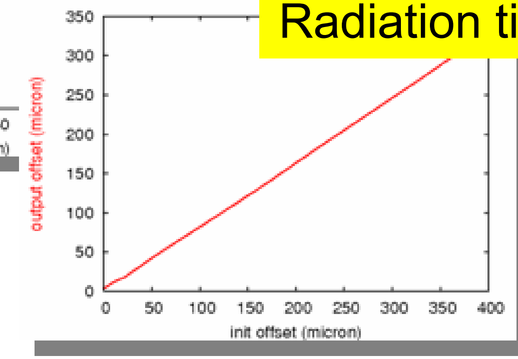
Seeded: FERMI FEL-1



Radiation offset



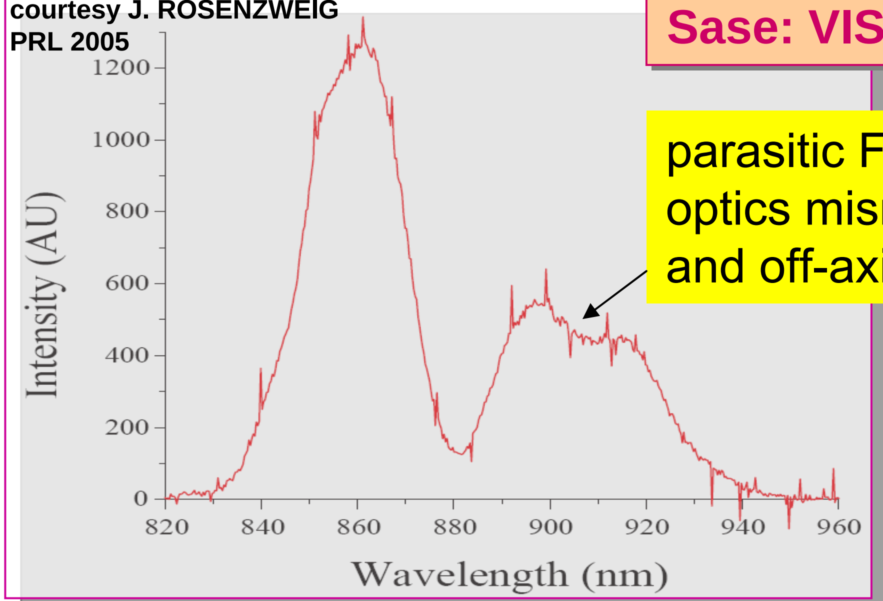
Radiation tilt



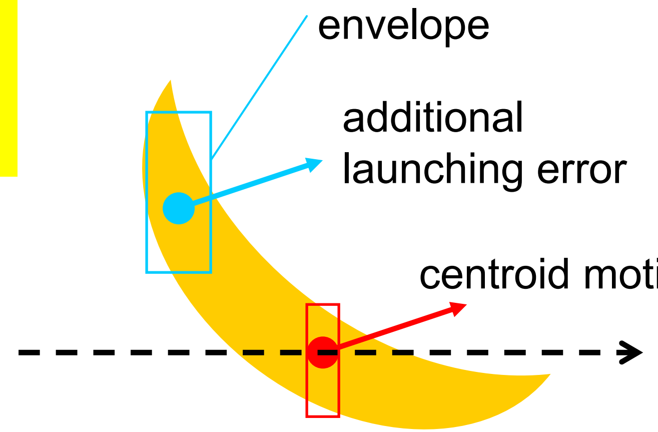
courtesy W. FAWLEY

Sase: VISA IB

courtesy J. ROSENZWEIG
PRL 2005



parasitic FEL from optics mismatch and off-axis motion



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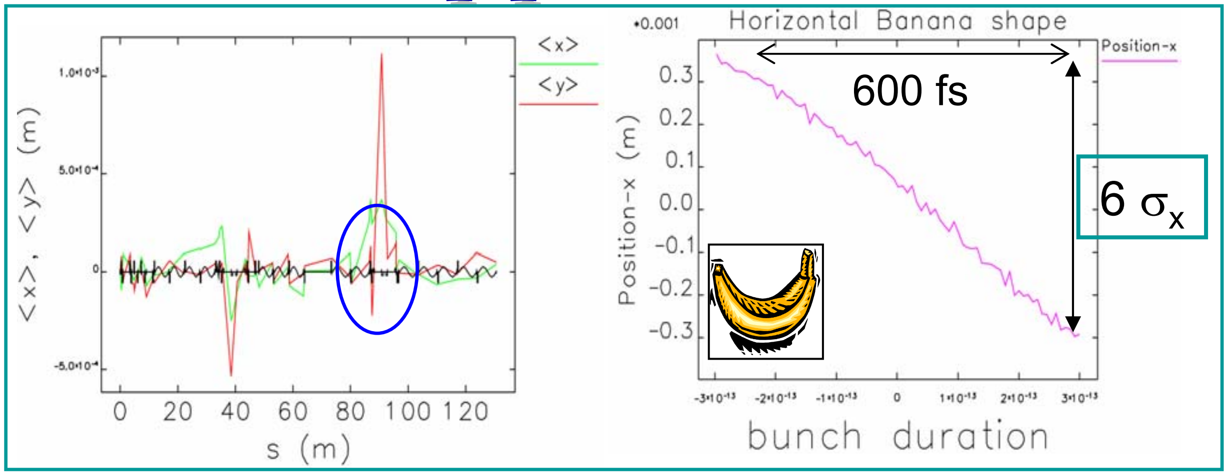
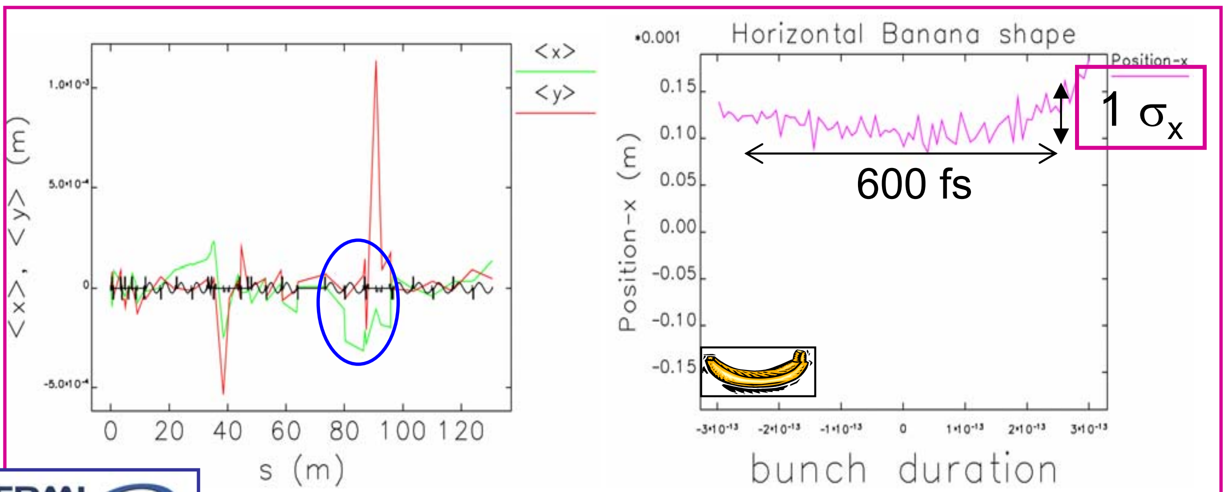
BBU: Suppression



Conventional correction can be NOT sufficient



Trajectory **bumps** cancel "banana" shape

$$\begin{cases} \frac{\Delta\varepsilon}{\varepsilon} \sim \sqrt{\beta} \quad \textbf{(A. Chao)} \\ x_{err} \sim k\sqrt{\beta} \sim 1/\sqrt{\beta} \end{cases}$$

Strong focusing reduces the emittance dilution but increases the sensitivity to trajectory errors

Low Charge Option

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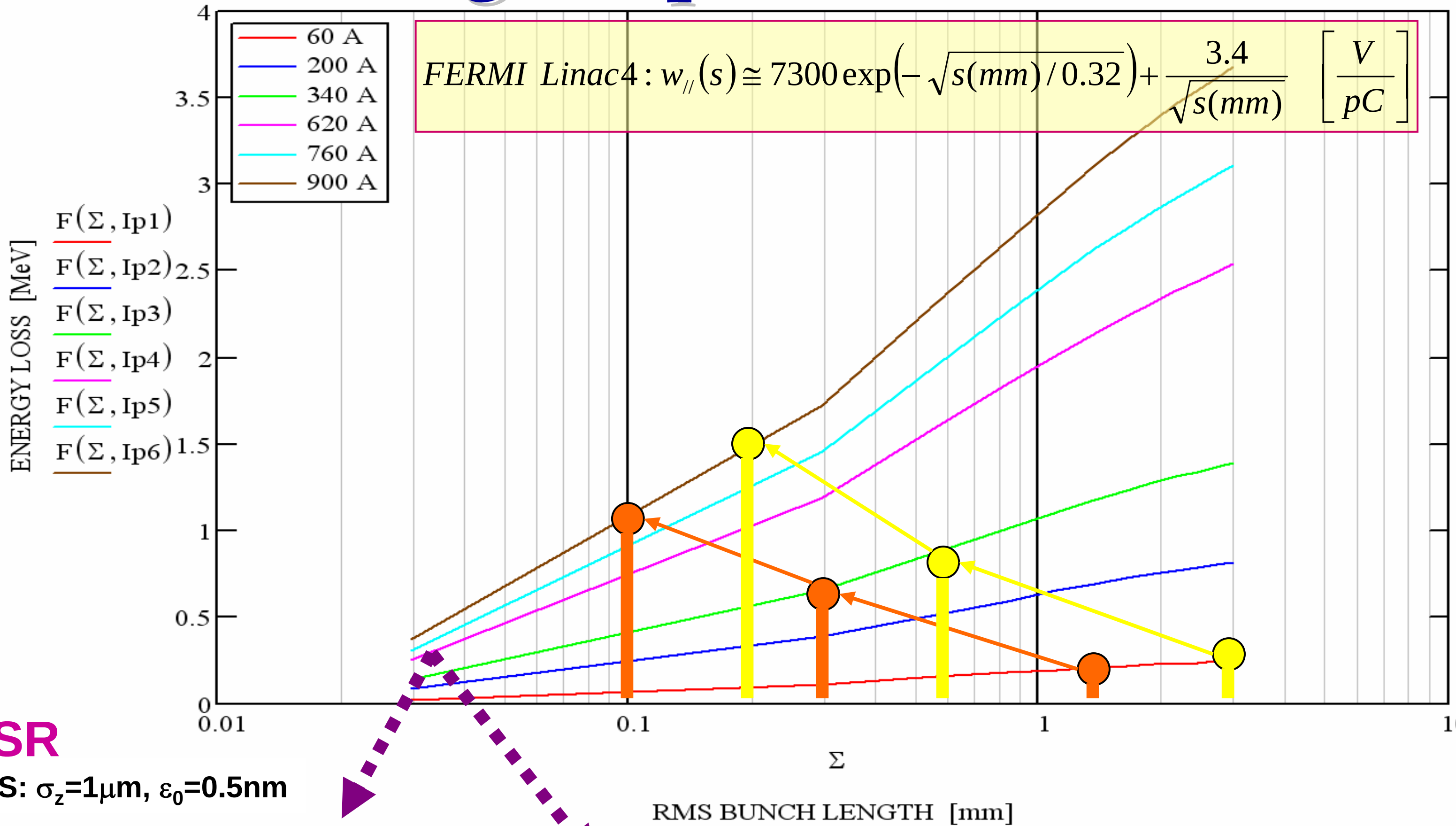
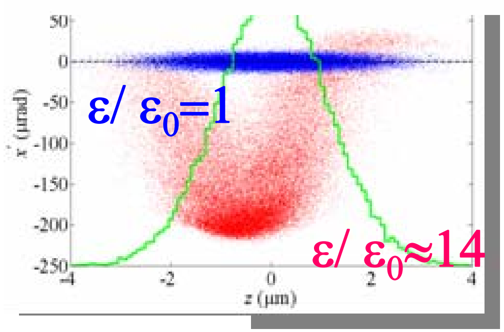


0.6 nC
0.3 nC

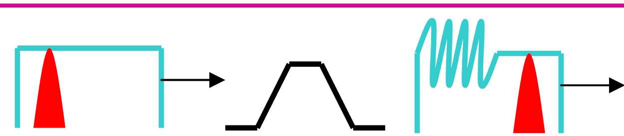
1st CF = 5
2nd CF = 3

CSR

LCLS: σ_z=1μm, ε_0=0.5nm



courtesy P.EMMA



$$\sigma_{z,f} \geq c\sqrt{\tau_{seed}^2 + \tau_{e\gamma-jitter}^2 + \tau_{buffer}^2}$$

Fresh Bunch

Low Charge: Acc. Structures

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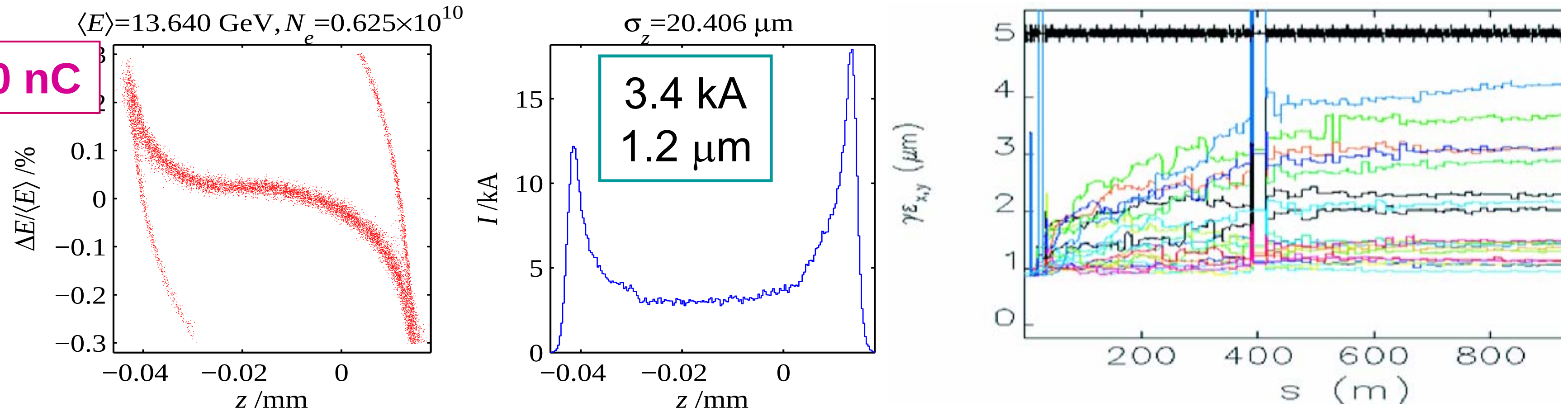
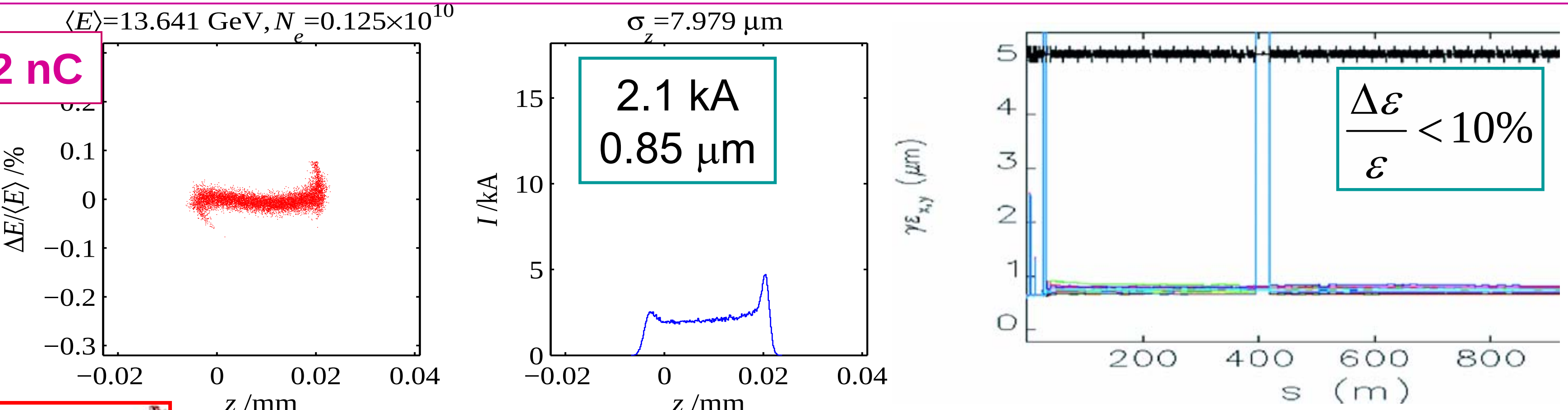
1.0 nC



0.2 nC



courtesy P.EMMA

linearity — no spikes — BBU suppressed

Low Charge: CSR (proj. ε)

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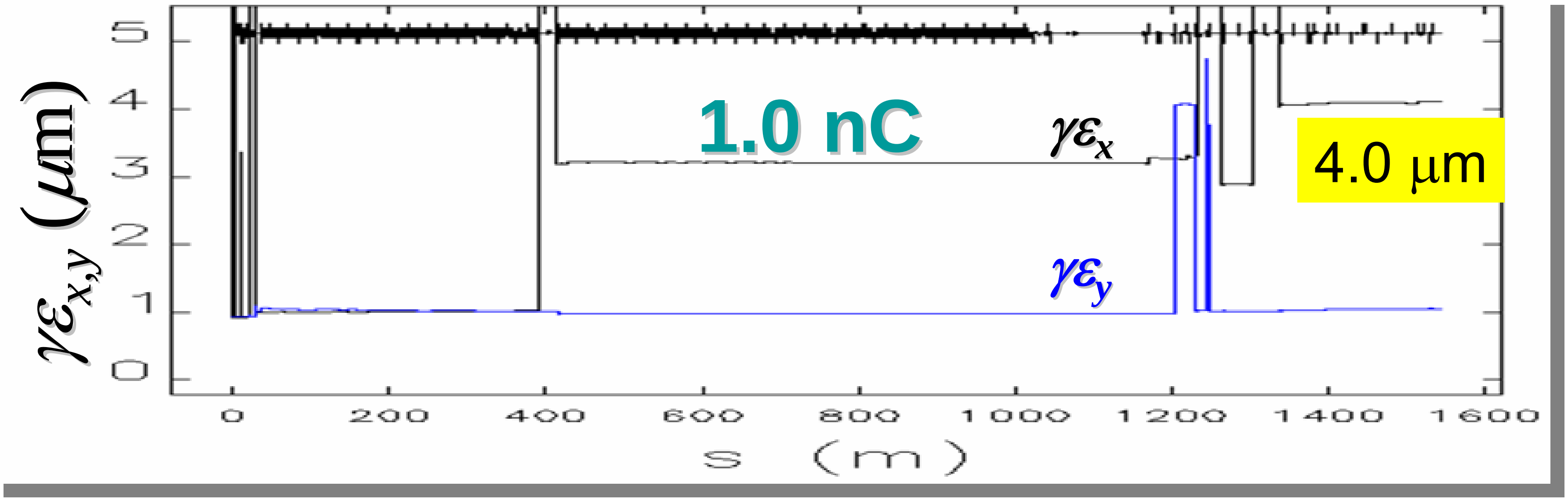

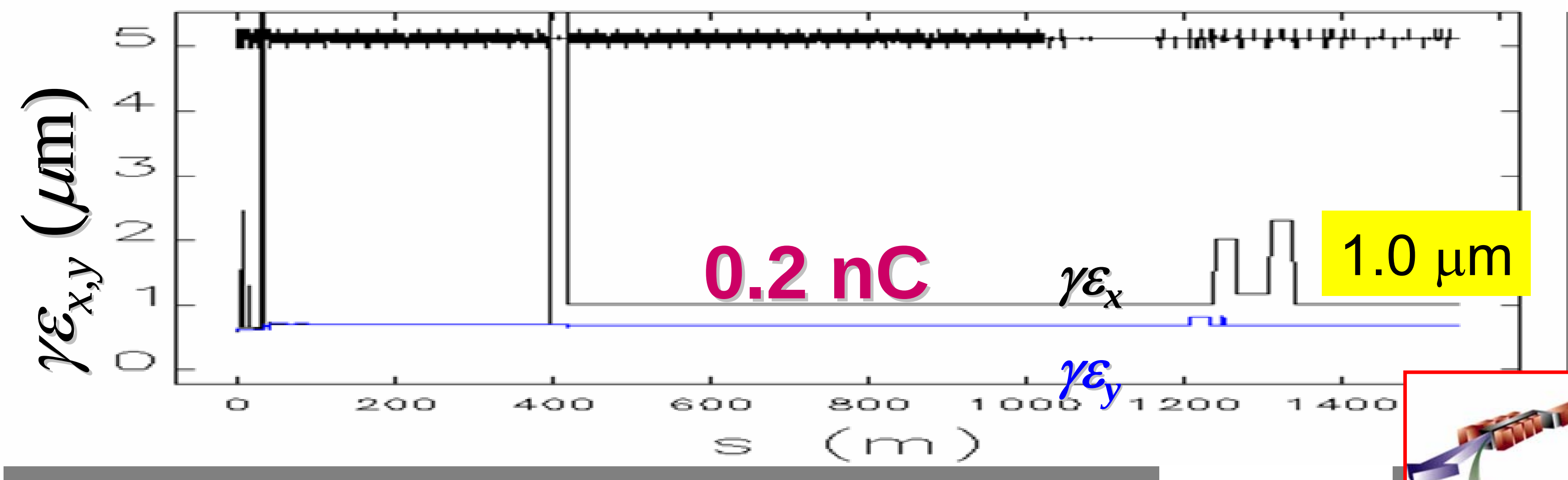

courtesy P.EMMA

LCLS

Low Charge: CSR (slice ε)

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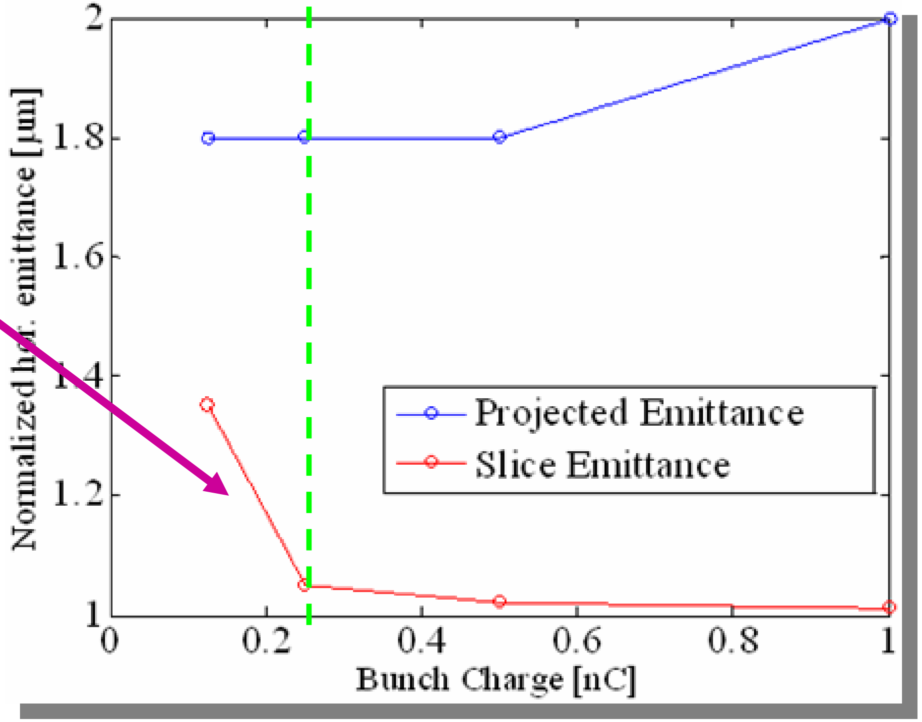
FEL06, Berlin

R_{56}

Low charge:
shorter bunch
⇓
Particles longitudinal crossover provides larger $\Delta\varepsilon_{slice}$



courtesy M.DOHLUS

Q

⇓

working point at low charge Q = 0.25 nC (σ_z=5 μm)

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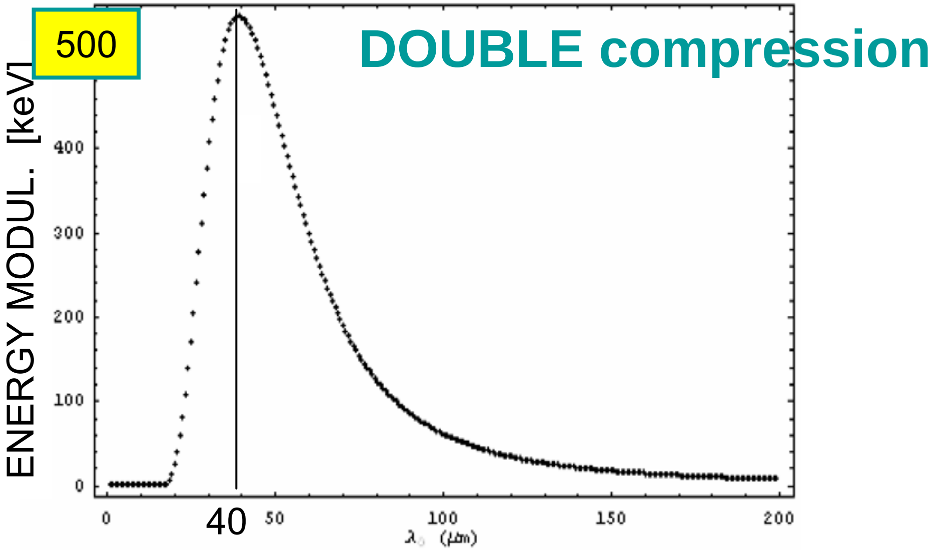
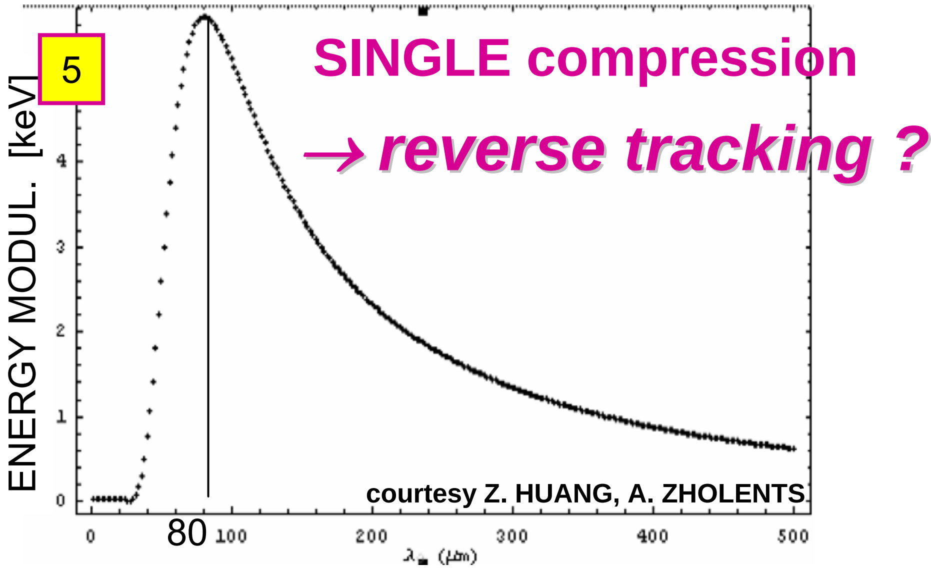
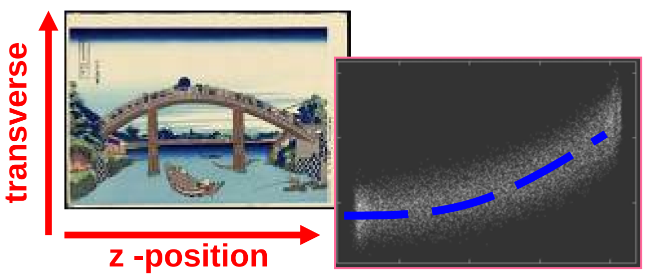
μBI

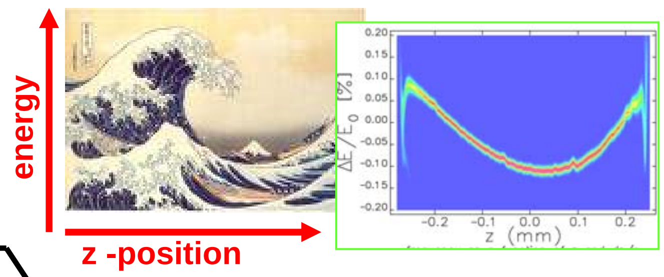
Few keVs energy spread is too small to suppress high–frequency μBI

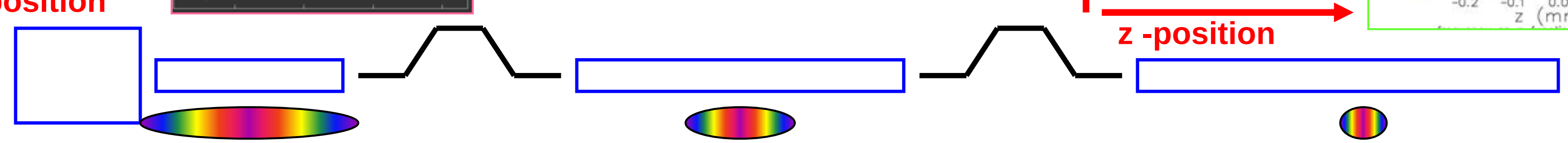
$$\lambda < \lambda_{//} \equiv 2\pi R_{56} C\sigma_{\delta,i}$$







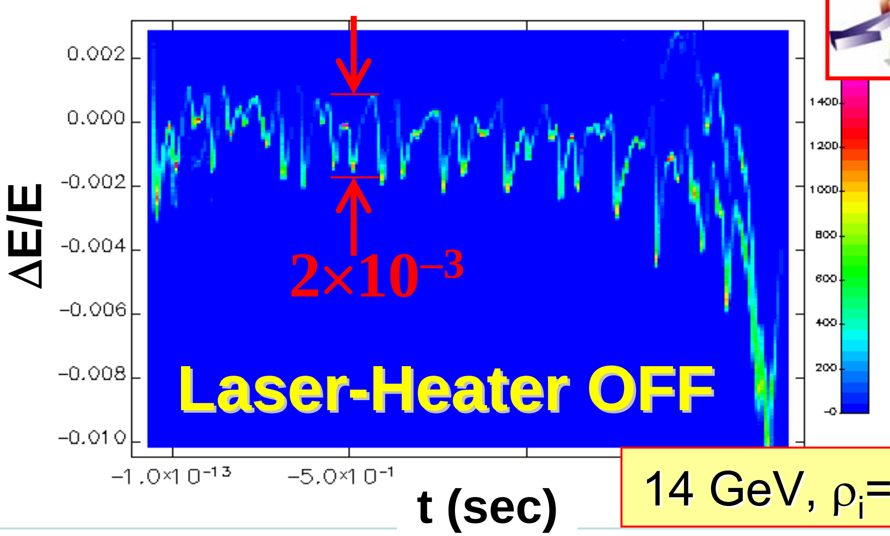


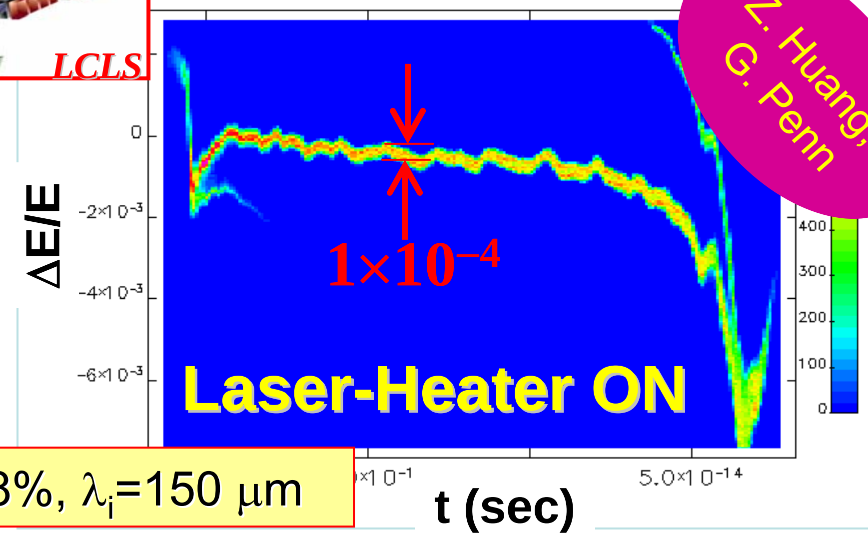


μBI (cont'd)

S. Di Mitri
FEL06, Berlin

courtesy Z. HUANG

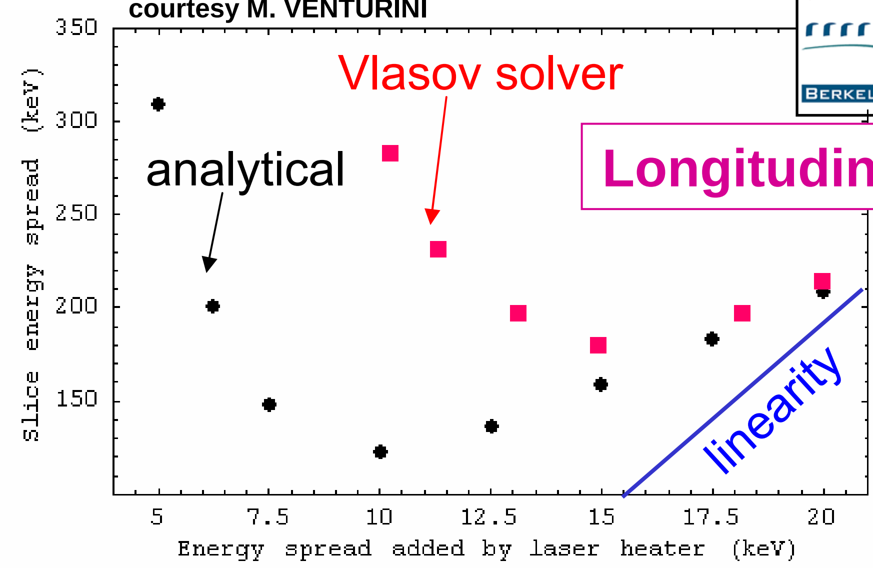




Z. Huang, G. Penn

14 GeV, ρ_i=8%, λ_i=150 μm

courtesy M. VENTURINI



Longitudinal

courtesy A. ZHOLENTS

$$H(s) = \gamma_x D_x^2 + 2\alpha_x D_x^{'} D_x + \beta_x D_x^{'2}$$

Transverse

ε_x excitation:

$$\delta\varepsilon_x \approx \left(H \cdot \sigma_{\delta,CSR}\right)^2 \Rightarrow \downarrow \mathbf{H}$$

Landau damping:

$$\delta l_{rms} \approx \sqrt{H\varepsilon_x} \Rightarrow \uparrow \mathbf{H}$$

Conclusions

COUPLING between 3 DEGREES of FREEDOM

- Split compression allows balance of $W_{//}$ and $W_{\perp}$ induced instabilities
- CSR couples longitudinal to transverse emittance
- μBI force to 4-D Landau damping

e-BEAM MANIPULATION

- Low charge option minimizes growth of projected emittances
- Single compression + reverse tracking to suppress μBI

$\varepsilon_{x,sl} \sim 1$ mm mrad	$(\Delta\varepsilon/\varepsilon)_{pr} \leq 20\%$
$\sigma_{E,sl} \geq 150$ keV	$\sigma_{E,pr} \sim 1$ MeV

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References: sorry, no space! Exaustive list in THBAU03

Danke schön, Berlin!

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Beam Diagnostics and Instrumentation for Particle Accelerator

May 2007