Design Considerations
for
Linac FEL Drivers

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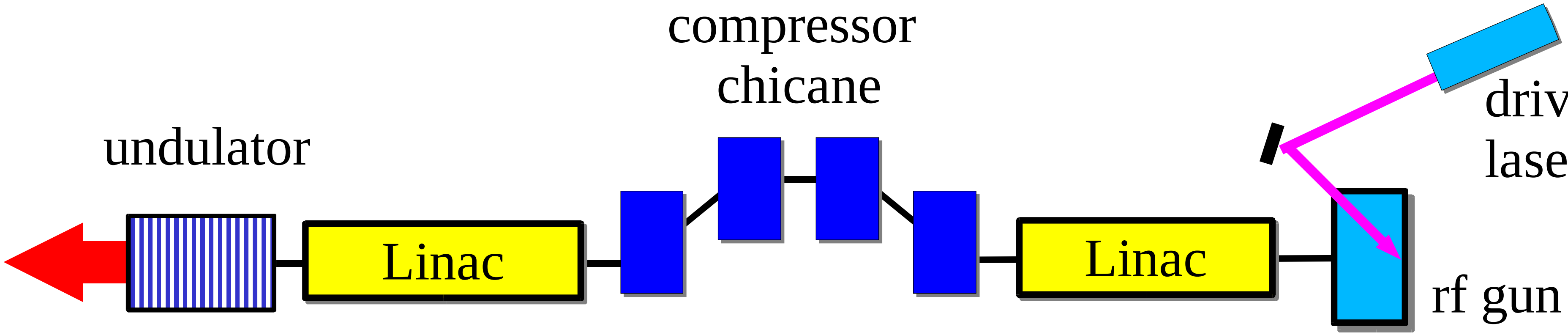
June 3, 2002

Outline

- Basic concept
- Some details
  - Injector
  - Bunch compression
  - Coherent synchrotron radiation
  - Wakefields and other nonlinearities
- LCLS results
  - CSR instability
  - Jitter sensitivity
- A quick look at Bates parameters

Basic FEL System



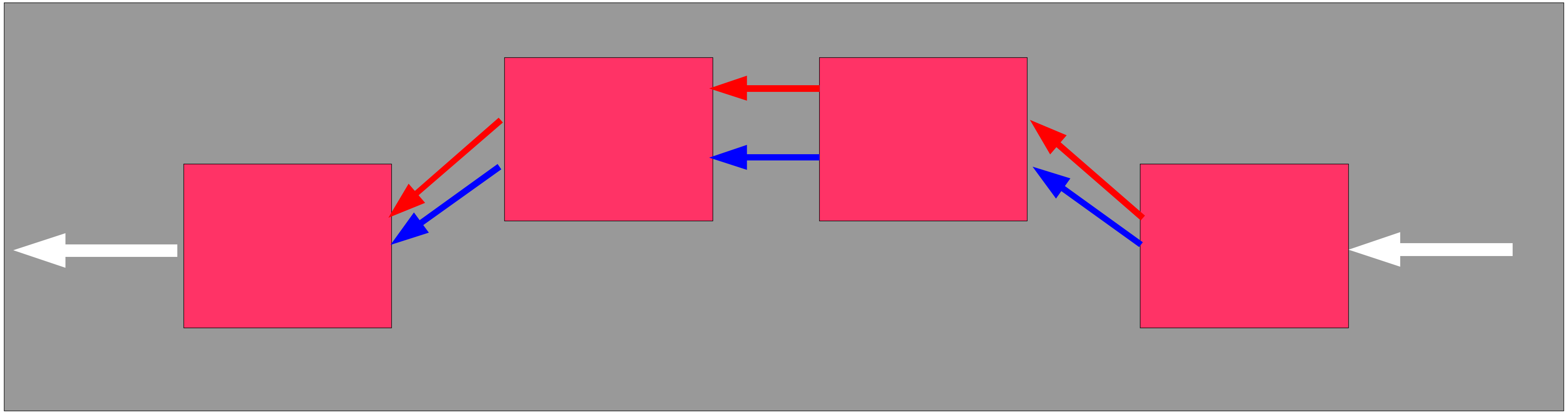
Typical FEL Requirements

- Normalized rms emittance of 1 to 2 μm

$$\epsilon_n = \gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x' x \rangle^2}$$

- Rms energy spread of 0.02 to 0.1 %
- Current of 1 to 4 kA
  - ➔0.5 to 1.0 nC/pulse
  - ➔FWHM bunch length of 200 to 500fs
- Properties to be evaluated over a longitudinal beam slice of length ~$L_{\text{slippage}} = N_{\text{poles}}\ \lambda_{\text{light}}$

Magnetic Bunch Compression

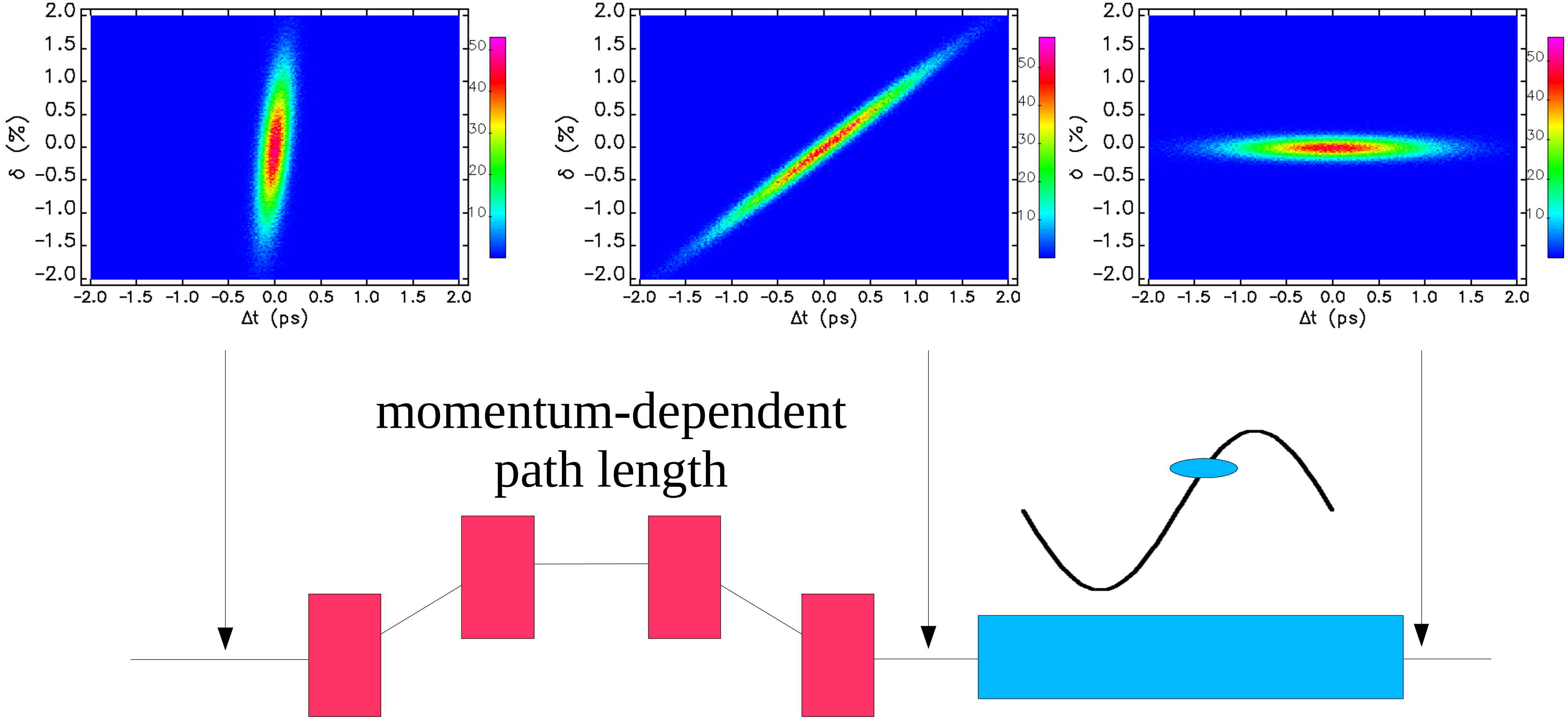


- Magnetic "chicane" introduces a momentum-dependent path-length

$$\Delta s = R_{56}\,\delta + T_{566}\,\delta^2 + \ldots \qquad \delta = (p-p_0)/p_0$$

- If position in bunch and energy are correlated, we can perform compression

Magnetic Bunch Compression

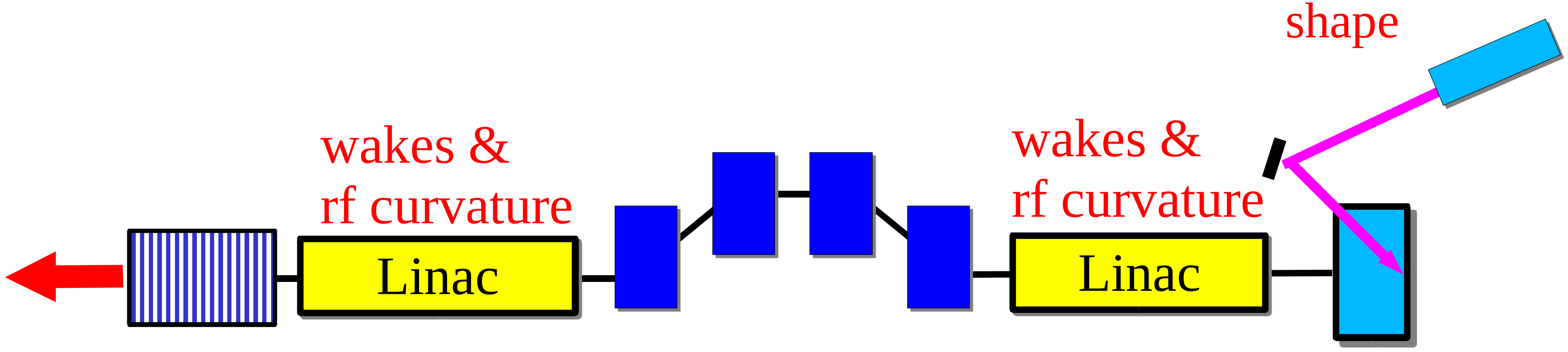


momentum-dependent
path length

4-dipole chicane

Linear accelerator

The Details...



spatial and
temporal pulse
shape

wakes &
rf curvature

wakes &
rf curvature

emittance
energy spread
energy
beta match
trajectory

aberrations,
ISR, & CSR

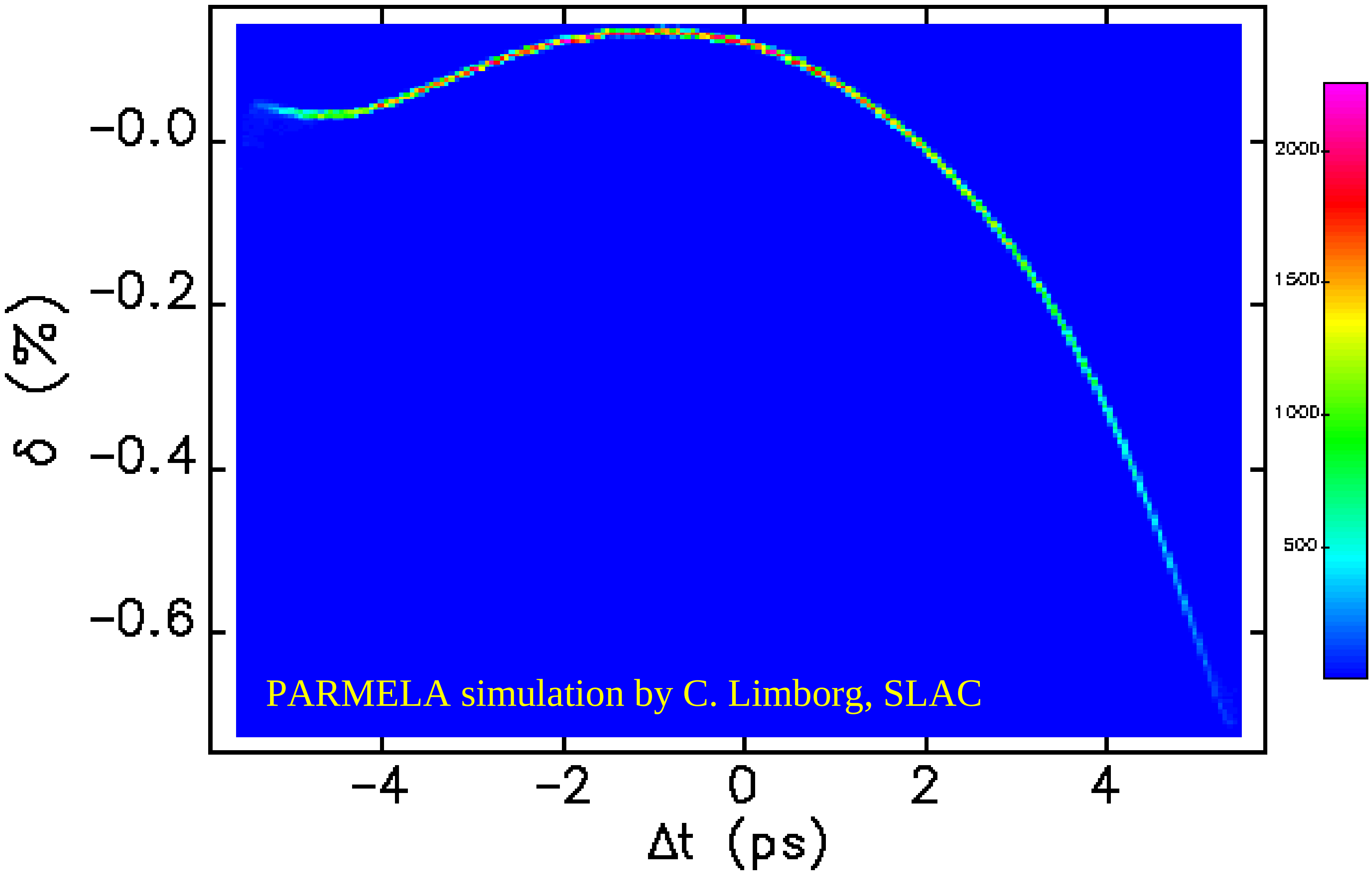
space charge,
rf curvature,
emittance comp,
& photoemission

FEL is critically affected by interplay of physics details.

Injector

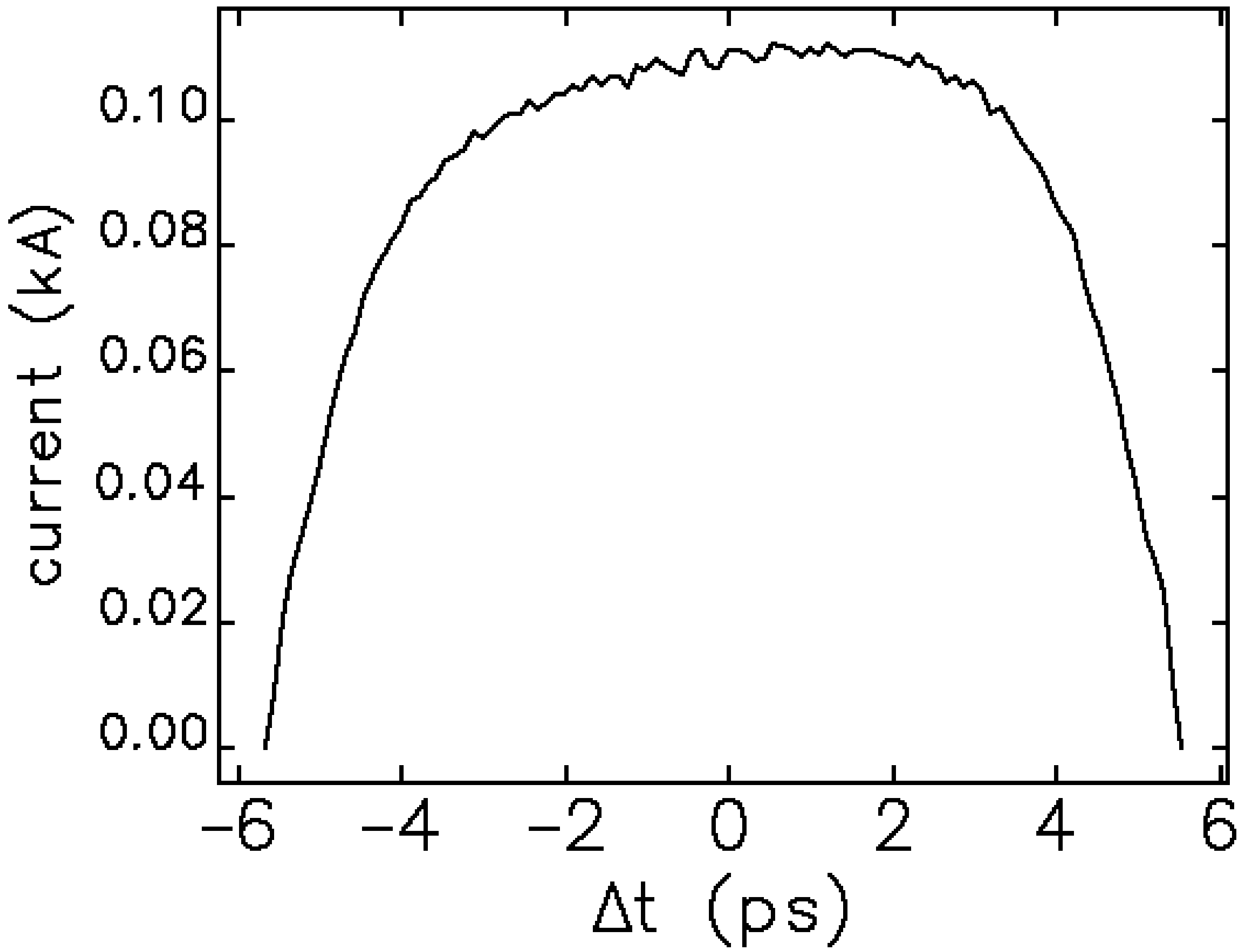
- An rf gun photoinjector is the most common choice
  - Rapid acceleration gives better emittance
  - Avoids bunching at low energy
- Problems particular to this choice
  - Laser spot uniformity
  - Laser reliability and longevity
  - Laser stability
- Reality rarely lives up to simulations!

LCLS Photoinjector Longitudinal Phase Space

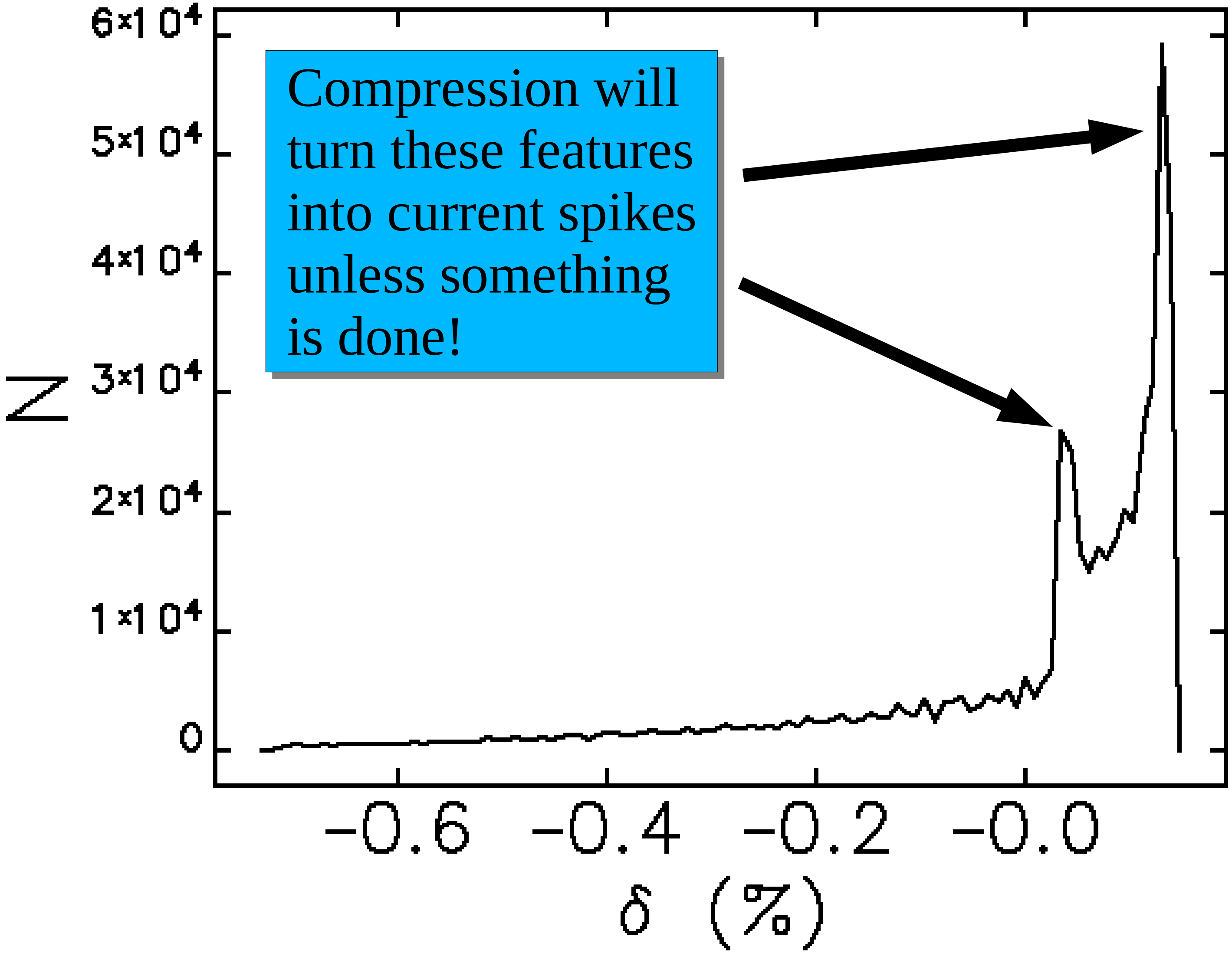


PARMELA simulation by C. Limborg, SLAC

LCLS Photoinjector Longitudinal Phase Space

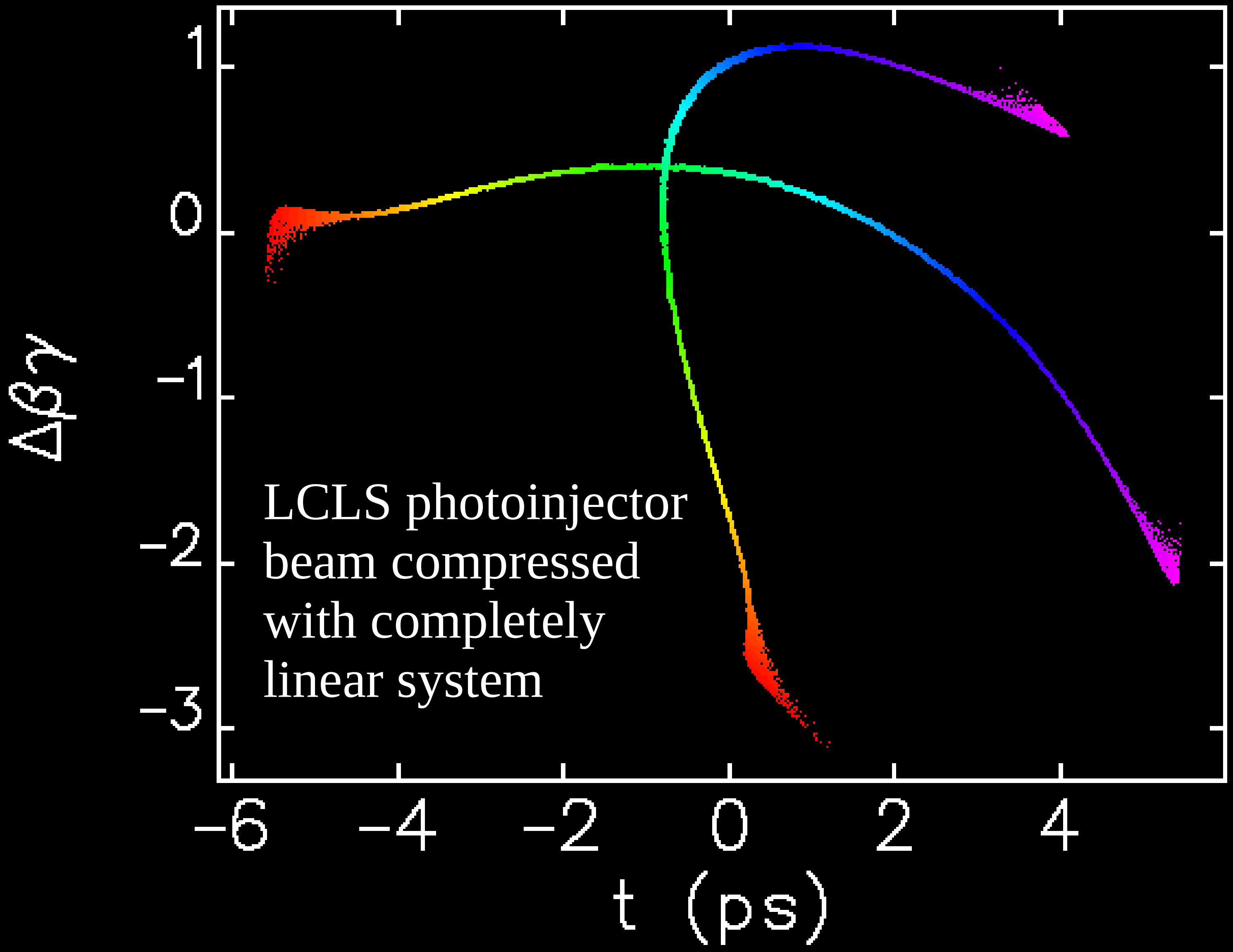


LCLS Photoinjector Longitudinal Phase Space



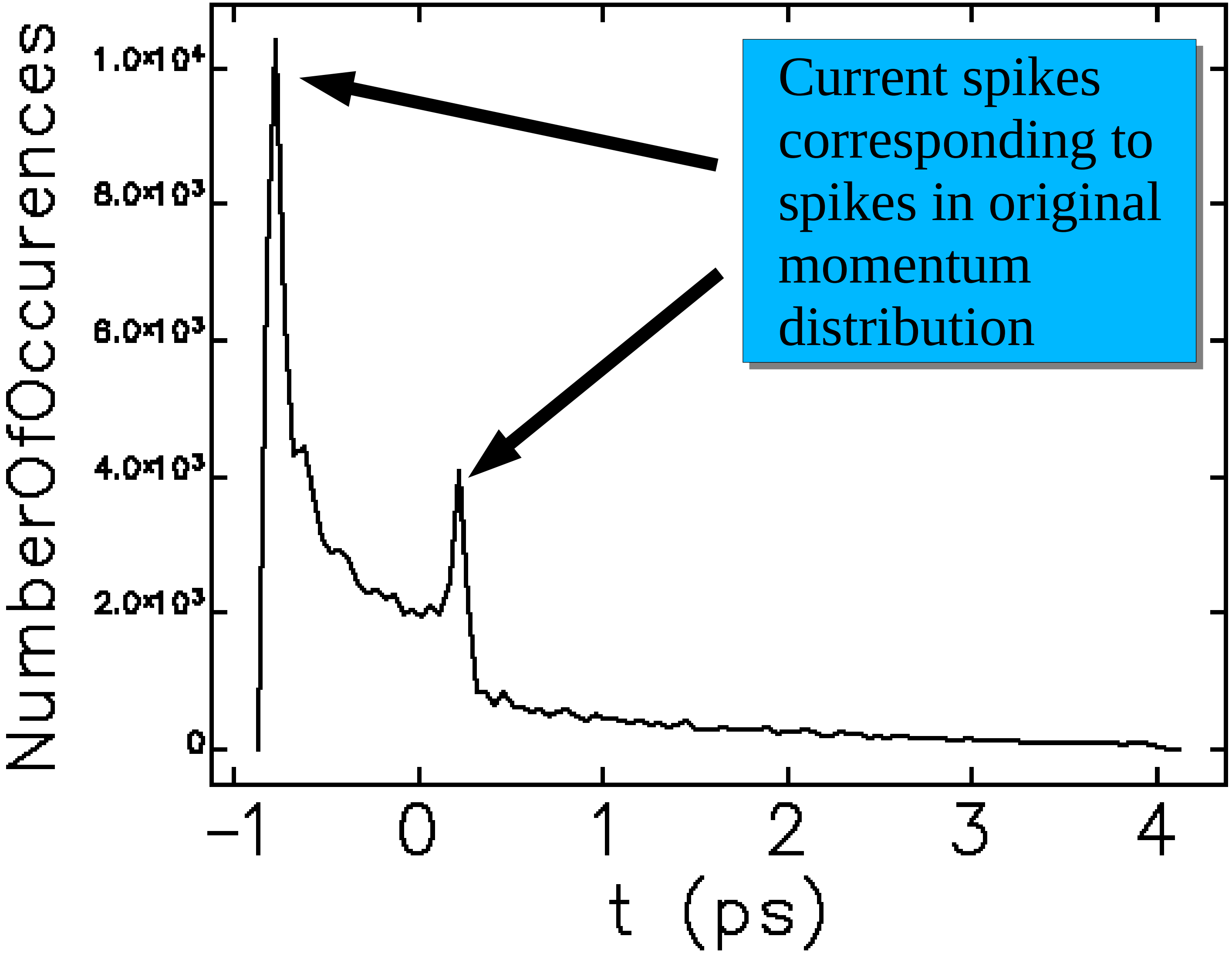
Compression will turn these features into current spikes unless something is done!

Linear Compression Example



LCLS photoinjector
beam compressed
with completely
linear system

Linear Compression Example



Current spikes corresponding to spikes in original momentum distribution

Coherent Synchrotron Radiation

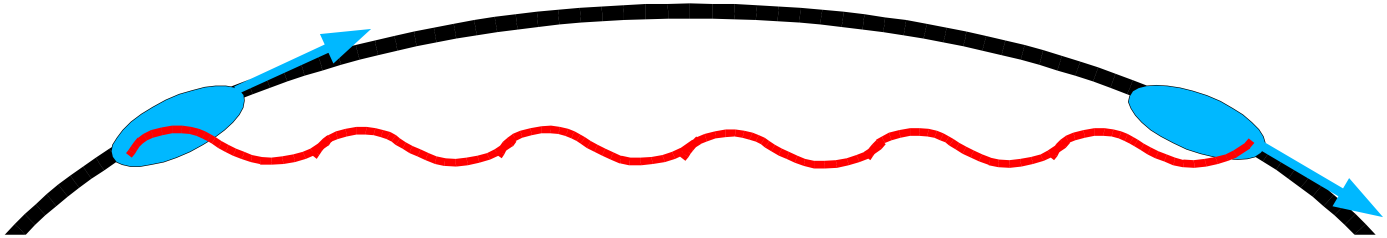
- Synchrotron radiation will be coherent if $\lambda \gg L_b$ and incoherent if $\lambda \ll L_b$.
- Coherent radiation will be suppressed by the vacuum chamber if

$$g \leq 0.6(\rho\sigma^2)^{1/3}$$

- In the APS ring, for example, $\rho \simeq 40$m and $\sigma \simeq 10$mm, so $0.6(\rho\sigma^2)^{1/3} \simeq 100$mm, compared to a dipole chamber gap of 40mm.
- In LCLS, $\rho \simeq 1$m and $\sigma \simeq 22\mu$m, so $0.6(\rho\sigma^2)^{1/3} \simeq 0.8$mm.

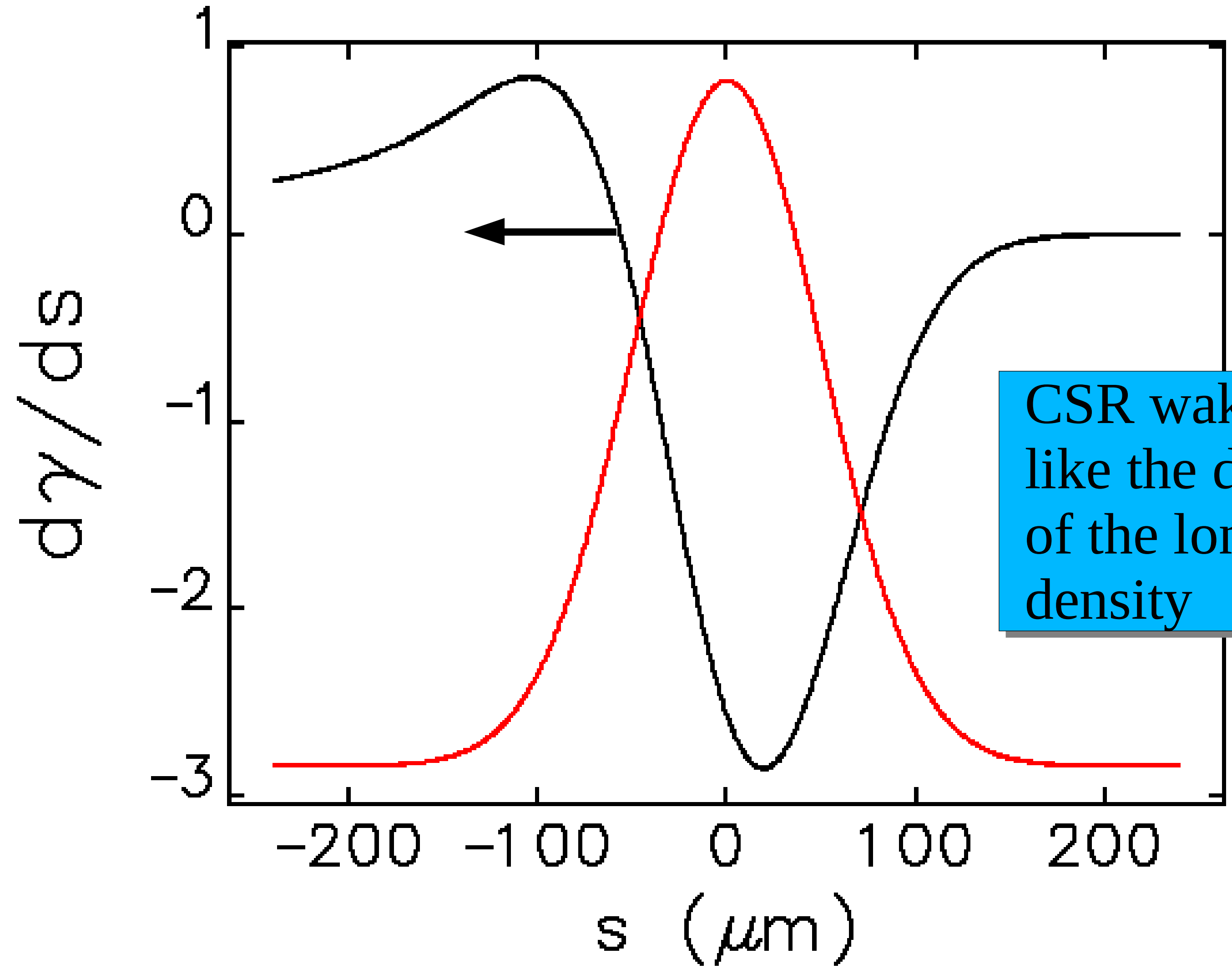
Coherent Synchrotron Radiation

- Electrons travel a curved path while photons travel a straight path.



- Radiation emitted by the tail will catch up with the head
- If the radiation is coherent, it can be intense and significantly modulate the energy of the head

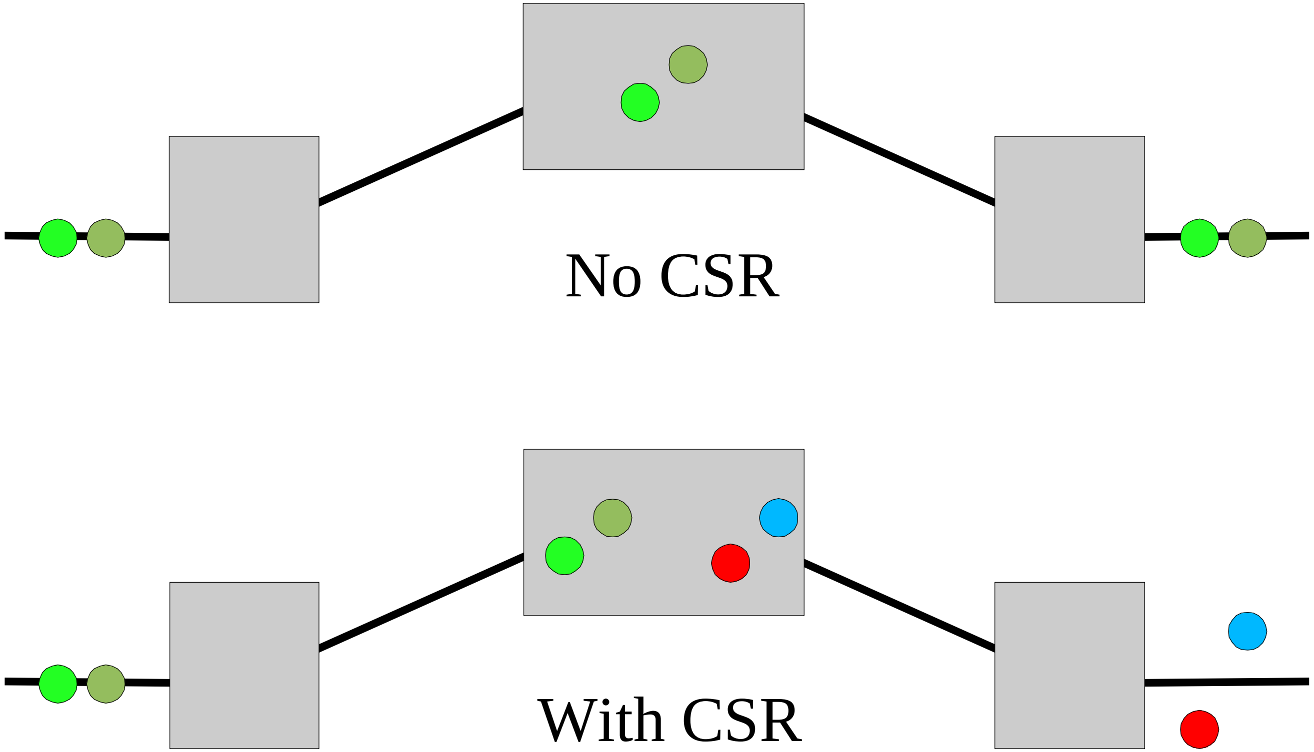
Steady-State CSR "Wake" for Gaussian Beam



CSR wake looks like the derivative of the longitudinal density

Effect of Coherent Synchrotron Radiation on the Beam

- When a bunch gets energy modulation inside a dipole, it leads to emittance growth



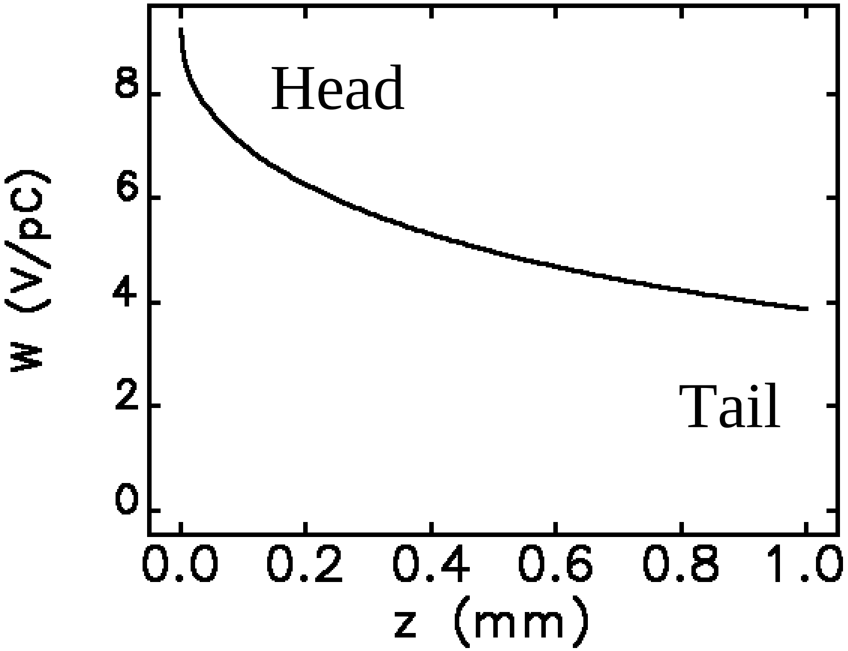
Nonlinearities

- Concerns
  - During and after compression, can result in current spikes that drive CSR
  - Make it difficult to remove energy spread
- Sources*
  - photoinjector (rf)
  - 2nd and higher-order effects in chicane
  - rf curvature in acceleration voltage
  - wakes from accelerating structures

*See P. Emma, 17th ICFA FLS Workshop; LCLS CDR Chapter 7

Wakefields

- Longitudinal wakes of the accelerating structure are *not* entirely bad
  - Help reduce energy spread after compressor
- Nonlinear function of position in bunch



Wake of SLAC structure
(P. Emma)

RF Curvature

- Due to sinusoidal nature of rf voltage

$$V = V_0 \sin(\phi_0) + \Delta\phi\, V_0 \cos(\phi_0) - \frac{1}{2}\Delta\phi^2 V_0 \sin(\phi_0) + \ldots$$

- Can reduce by lowering the rf frequency
- Can correct by using a higher-harmonic cavity

$$V = V_h \sin(\phi_h) + h\,\Delta\phi\, V_h \cos(\phi_h) - \frac{1}{2}(h\,\Delta\phi)^2 V_h \sin(\phi_h) + \ldots$$

  - Cavity is at decelerating phase!
  - Harmonic voltage $V_h = V_0/h^2$
  - 3rd or 4th harmonic is a typical choice

Nonlinearities in Chicane

- The path-length in the chicane depends on all powers of δ
- T_{566} term in bunch compressor
  - In simple chicanes, $T_{566} \simeq -3R_{56}/2$
  - Sextupole correction possible, but alignment tolerances are tight
  - Relatively small in most cases
- T_{566} term and rf curvature (for accelerating phase) *reinforce* each other

Chicane Design Considerations

- Larger $|R_{56}|$ reduces the required energy chirp and allows running closer to rf crest
  - ✔ More efficient acceleration
  - ✔ Reduces chromatic aberrations
  - ✔ Less energy spread to remove after compression
  - ✗ More rf nonlinearity
  - ✗ More CSR effects
  - ✗ More sensitivity to phase jitter
- Optimum decided by simulation, typically 20mm$<|R_{56}|<$ 70mm

Chicane Placement Considerations

- Location of the chicane is not arbitrary
  - One must be able to chirp and unchirp the beam and still achieve the desired final energy
  - Low energy compression wastes the least gradient
  - Low energy compression makes CSR effects worst
  - Shorter bunches are less affected by wakes
- P. Emma has an optimization code that takes some of these factors into account

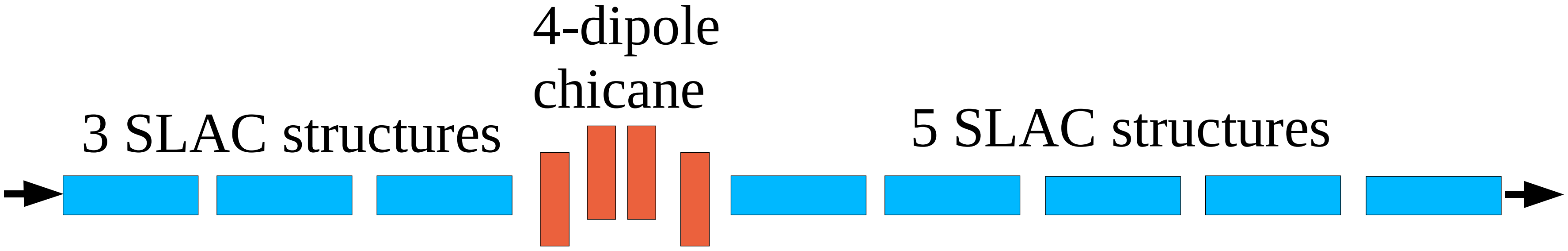
Other Bunch Compression Options

- "Ballastic" compression gun*
  - Uses multiple cavities to produce a beam that compresses itself through velocity differences
- "Rf" compression†
  - Another velocity-based method, taking place inside the post-gun linear accelerator
- These tend to produce complex longitudinal phase space that is difficult to compress further

*J. Lewellen (ANL)
†X. Wang (BNL), L. Serafini (INFN)

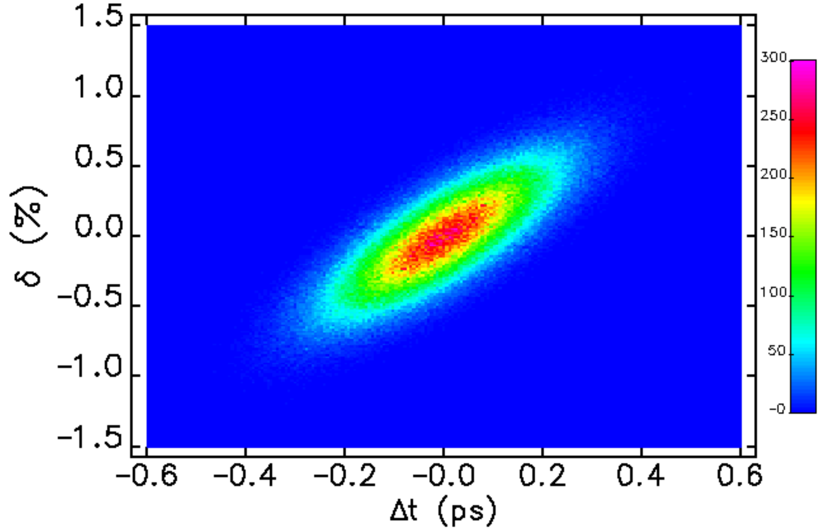
Example of Various Effects

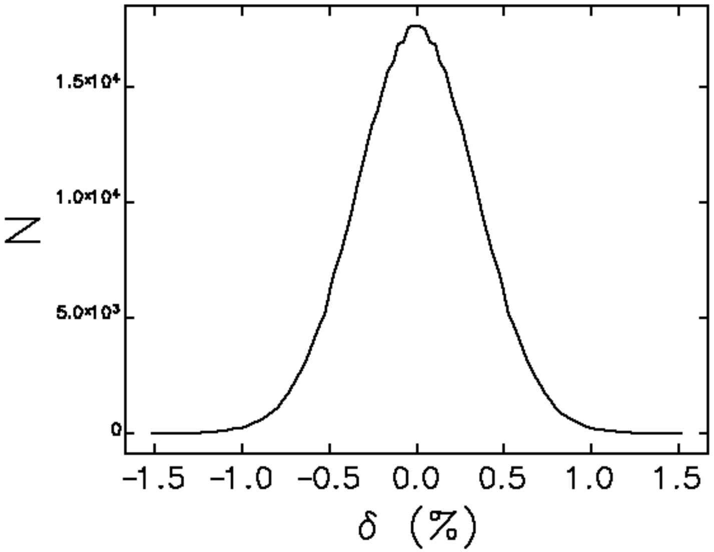
- Start at 50MeV with a gaussian bunch
  - 1 ps rms bunch length
  - 0.05% rms energy spread

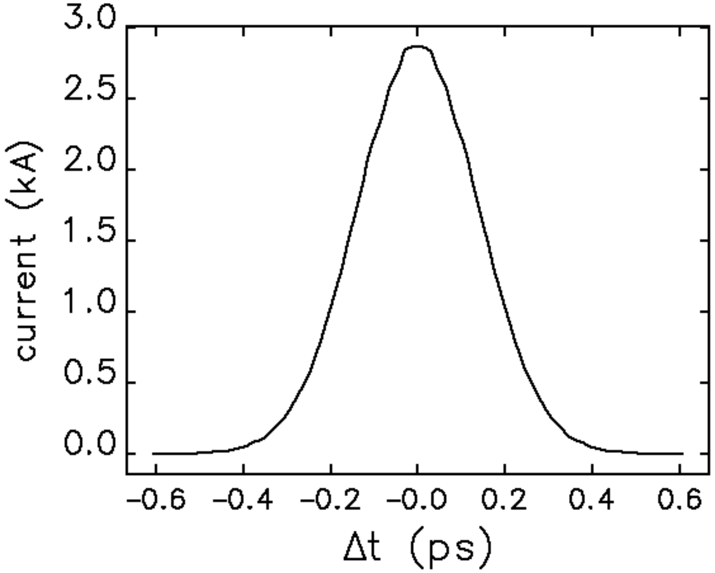


- Optimize phases to get short bunch and low energy spread, including wakes, rf curvature, and aberrations
- Track linear system, add effects one at a time

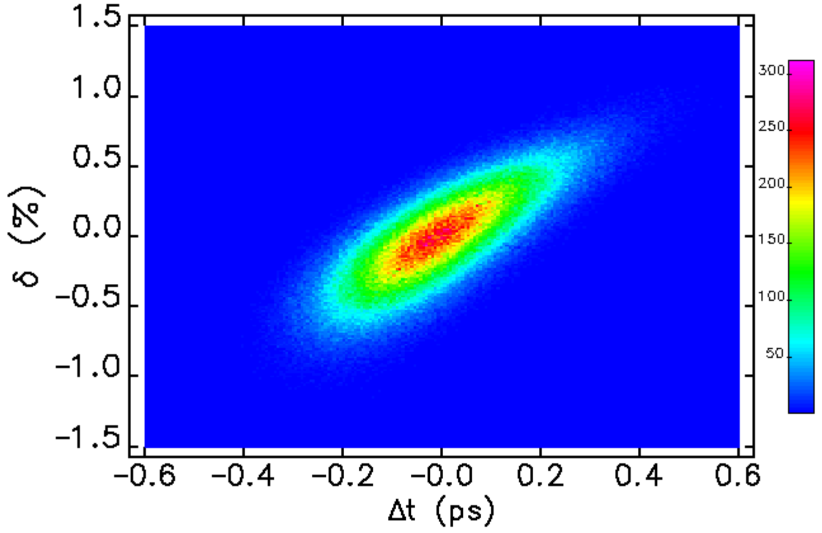
Final Longitudinal Phase Space for Linear System

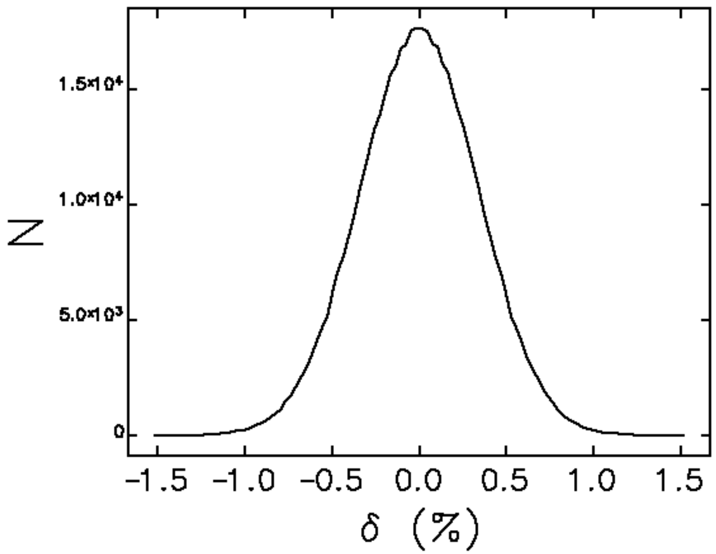


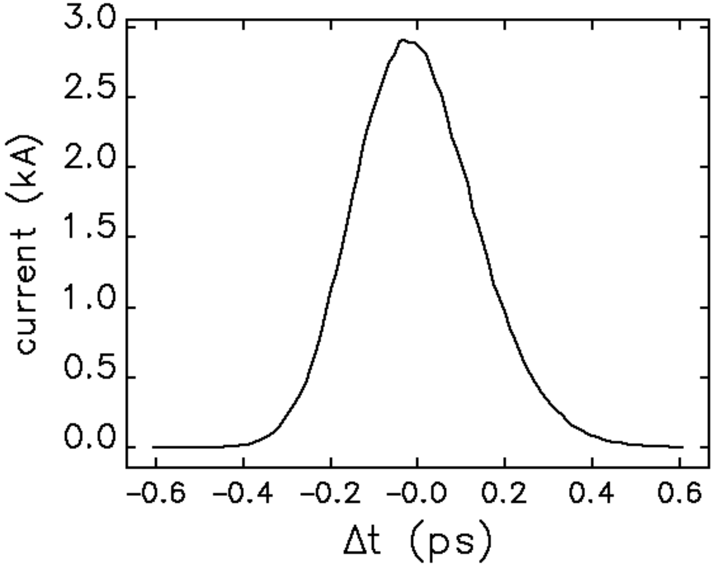




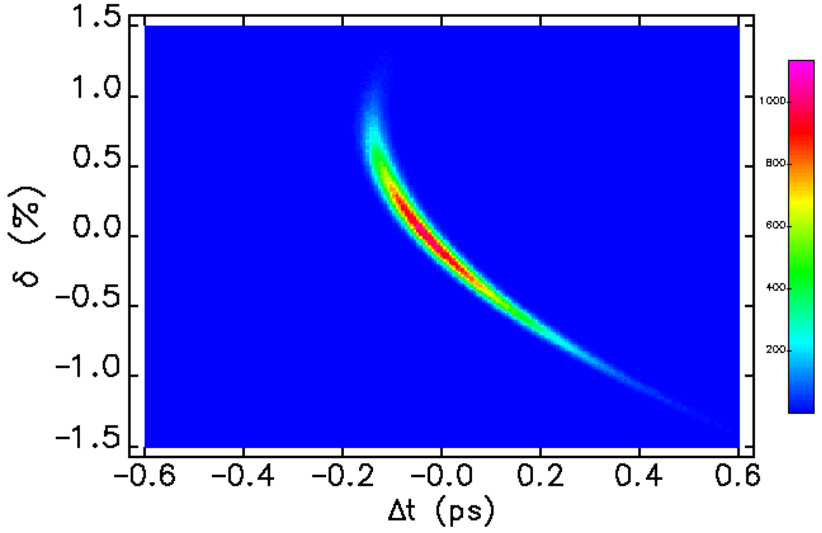
... for Second-Order Chicane

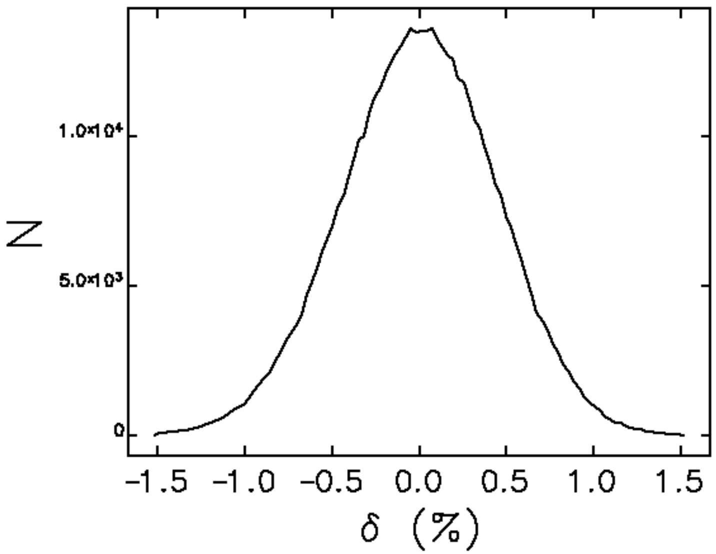


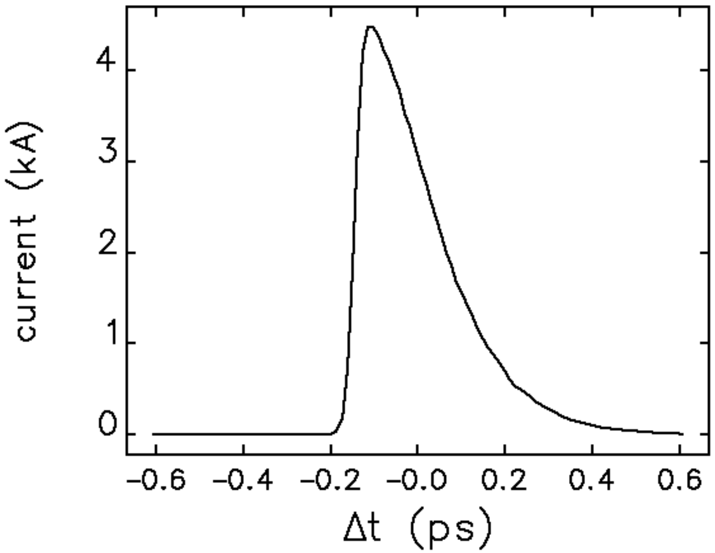




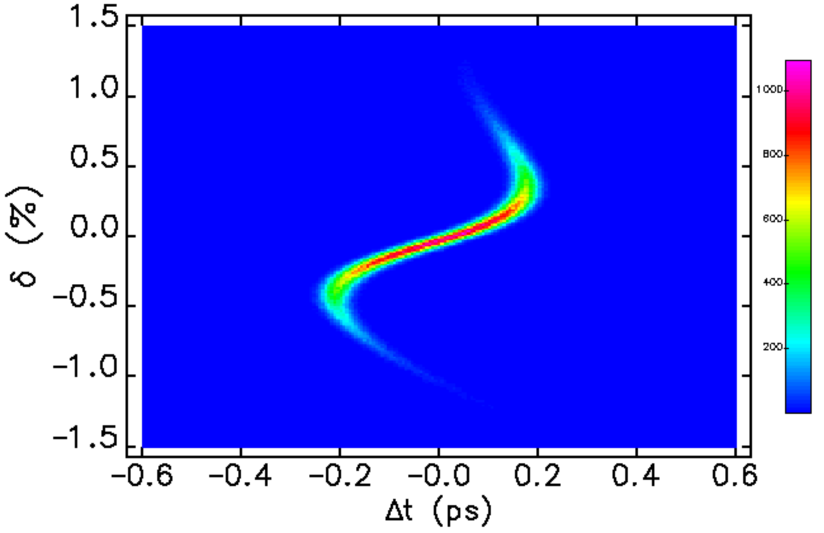
..with RF Curvature

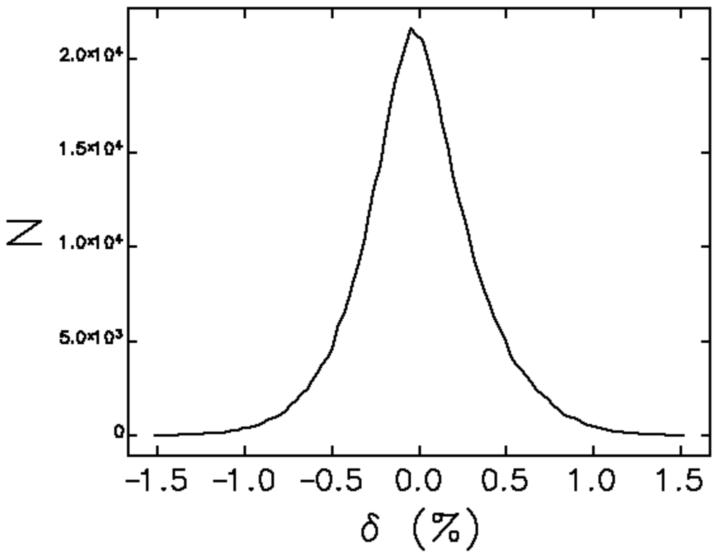


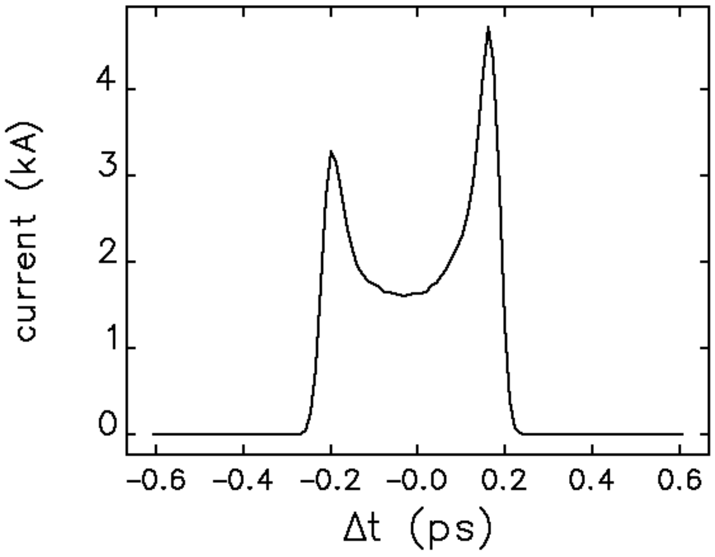




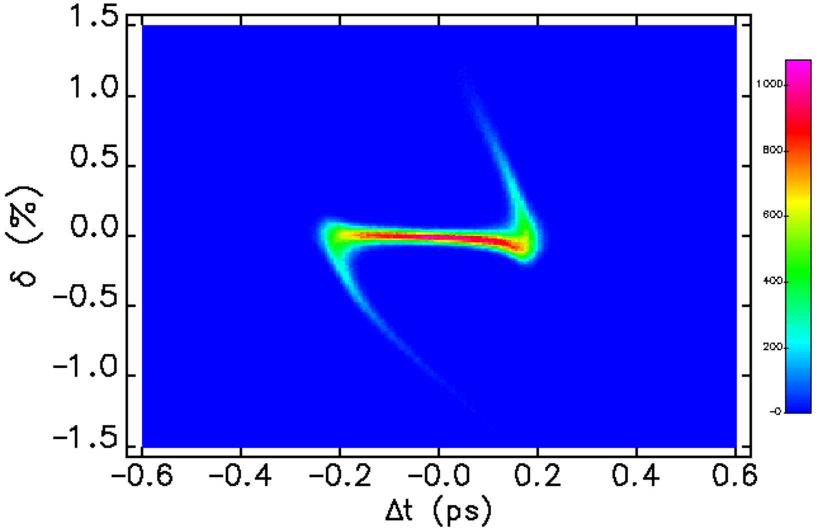
...and Upstream Wakes

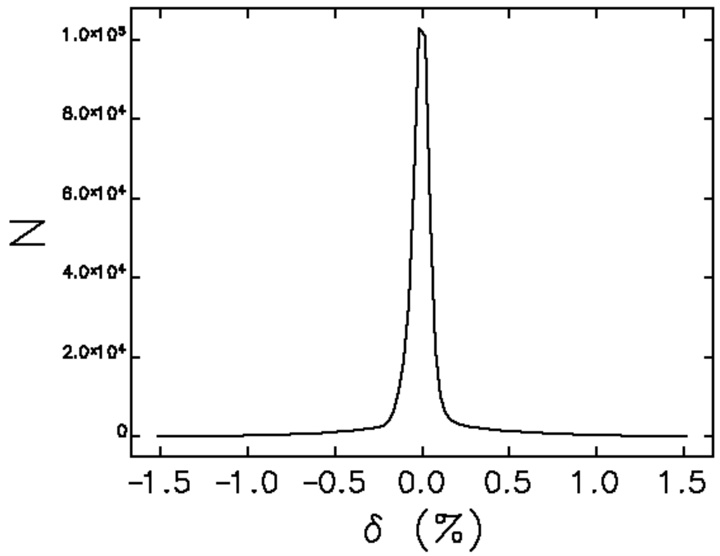


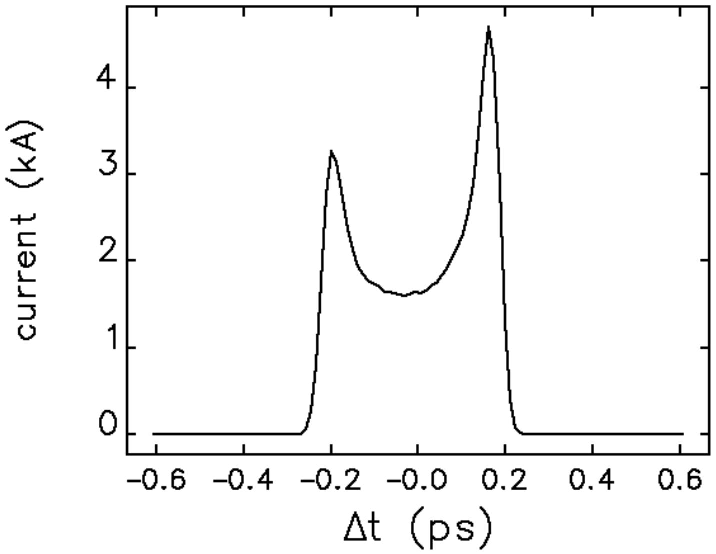




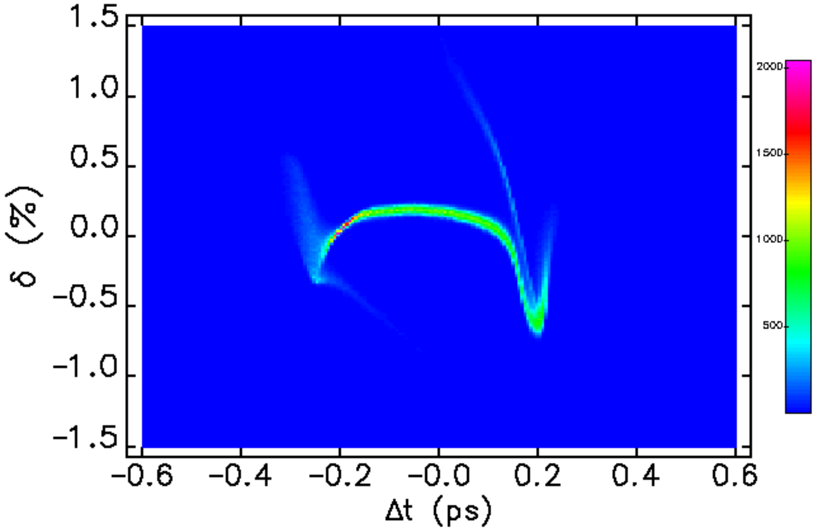
...and Downstream Wakes

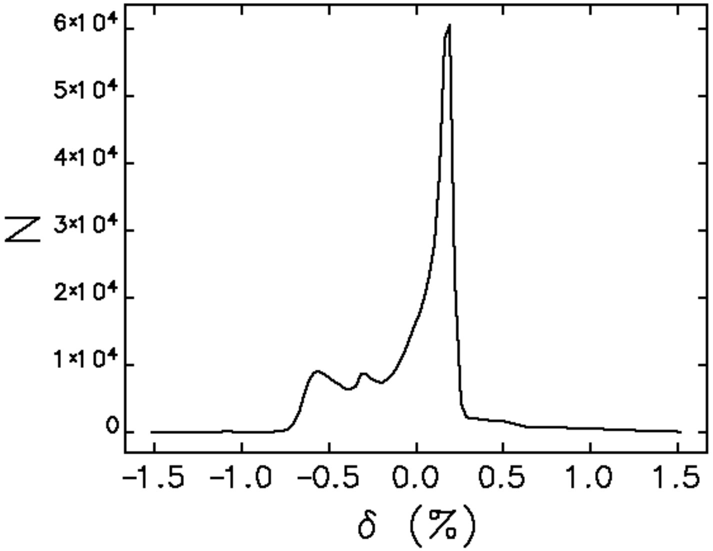


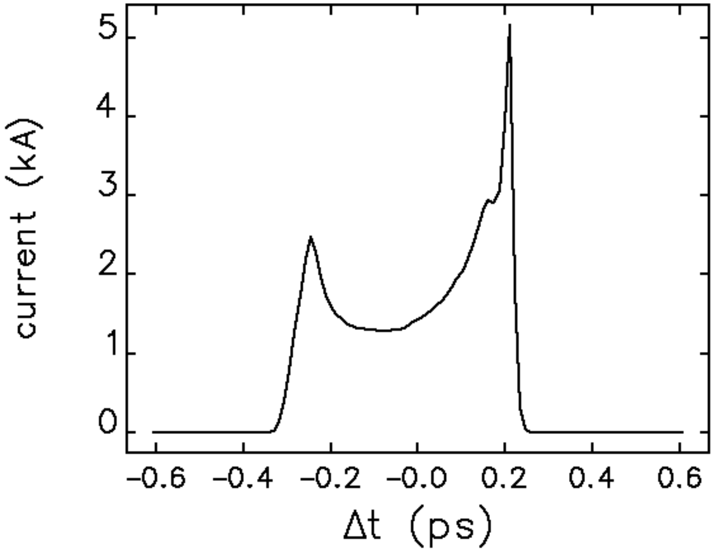




...and CSR


δ (%)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−0.6
−0.4
−0.2
−0.0
0.2
0.4
0.6
Δt (ps)
2000
1500
1000
500


N
6×10⁴
5×10⁴
4×10⁴
3×10⁴
2×10⁴
1×10⁴
0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
δ (%)

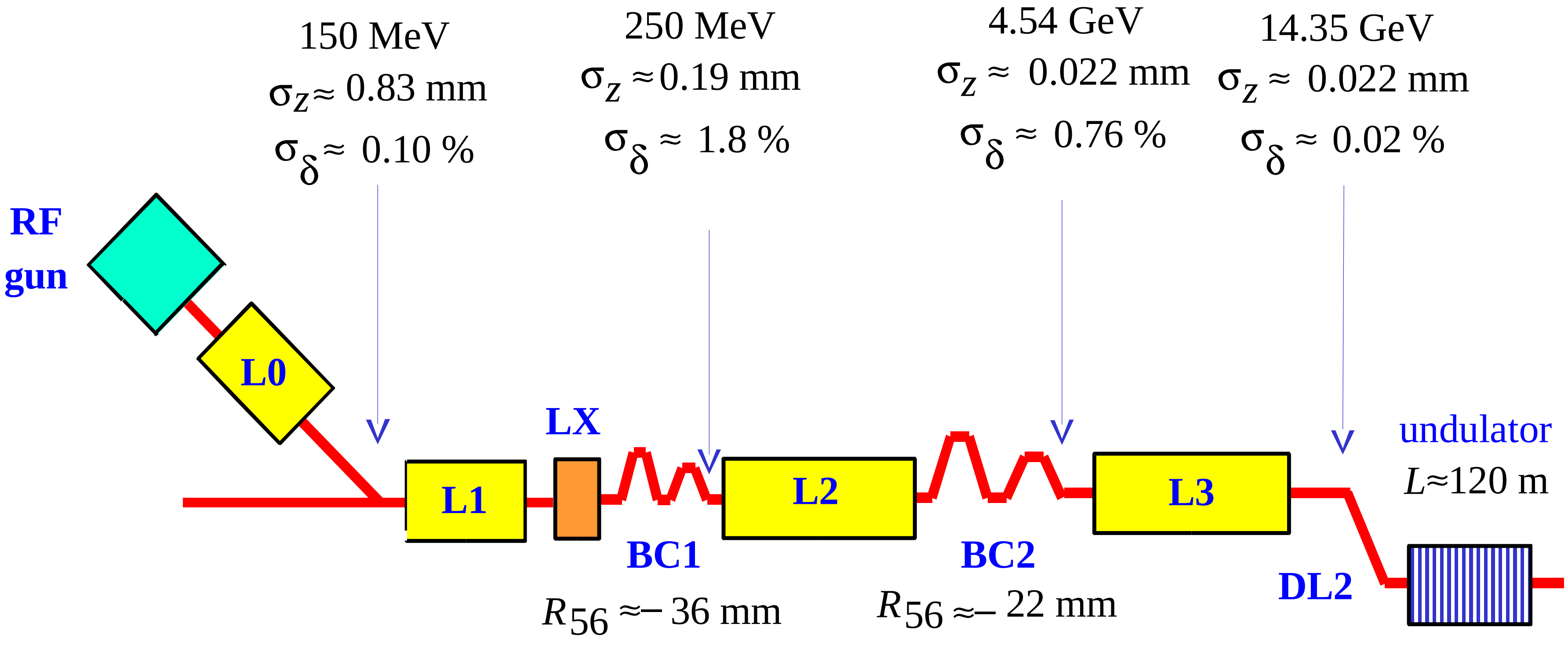

current (kA)
5
4
3
2
1
0
−0.6
−0.4
−0.2
−0.0
0.2
0.4
0.6
Δt (ps)

Start-to-End Simulation

- S2E simulation attempts to keep as much detail as possible from gun to FEL
- We use three codes for S2E
    - PARMELA (LANL) for the photoinjector
    - elegant (ANL) for the linac and compressors
    - GENESIS (DESY) for the FEL
- Integrate these codes with common, self-describing file format and processing tools ("SDDS")

LCLS Schematic

06Dec00 Design (P. Emma)



150 MeV
$\sigma_z \approx 0.83$ mm
$\sigma_\delta \approx 0.10$ %

250 MeV
$\sigma_z \approx 0.19$ mm
$\sigma_\delta \approx 1.8$ %

4.54 GeV
$\sigma_z \approx 0.022$ mm
$\sigma_\delta \approx 0.76$ %

14.35 GeV
$\sigma_z \approx 0.022$ mm
$\sigma_\delta \approx 0.02$ %

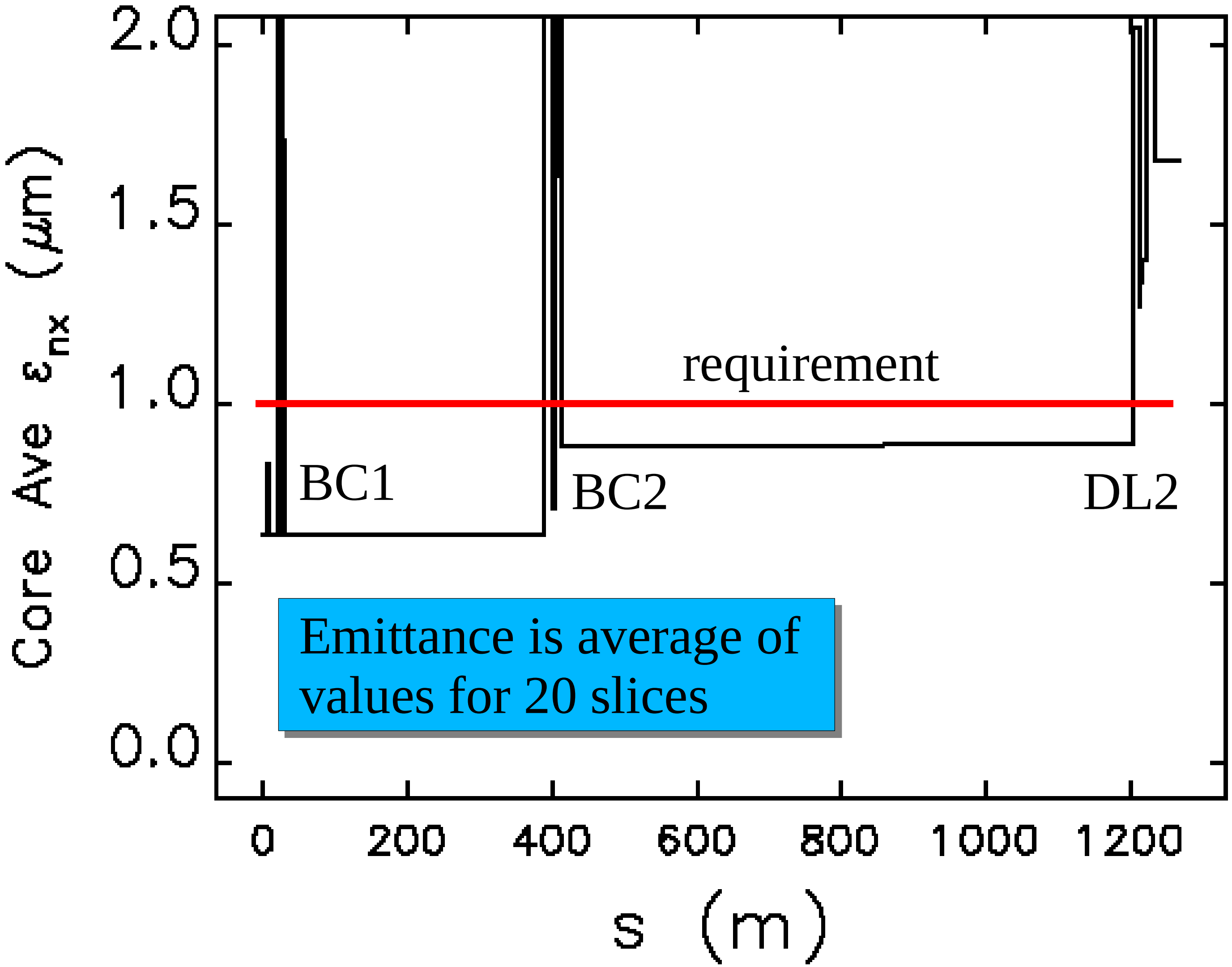
$L \approx 120$ m

$R_{56} \approx -36$ mm

$R_{56} \approx -22$ mm

CSR simulations with gaussian beams and low longitudinal resolution predicted 5% projected emittance growth, but ...

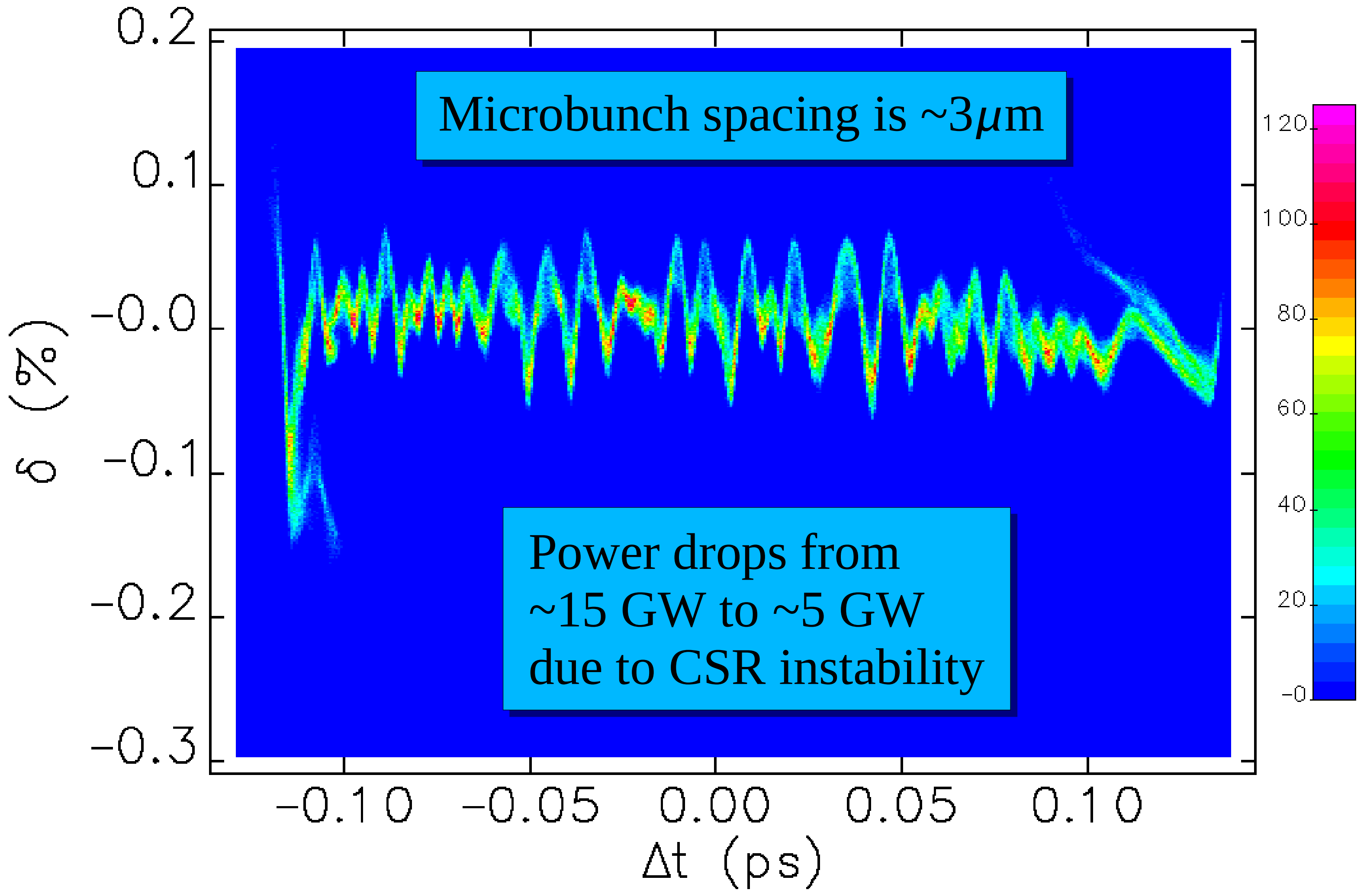
Emittance Growth in LCLS



Emittance is average of values for 20 slices

CSR Microbunching Instability

06Dec00 Design



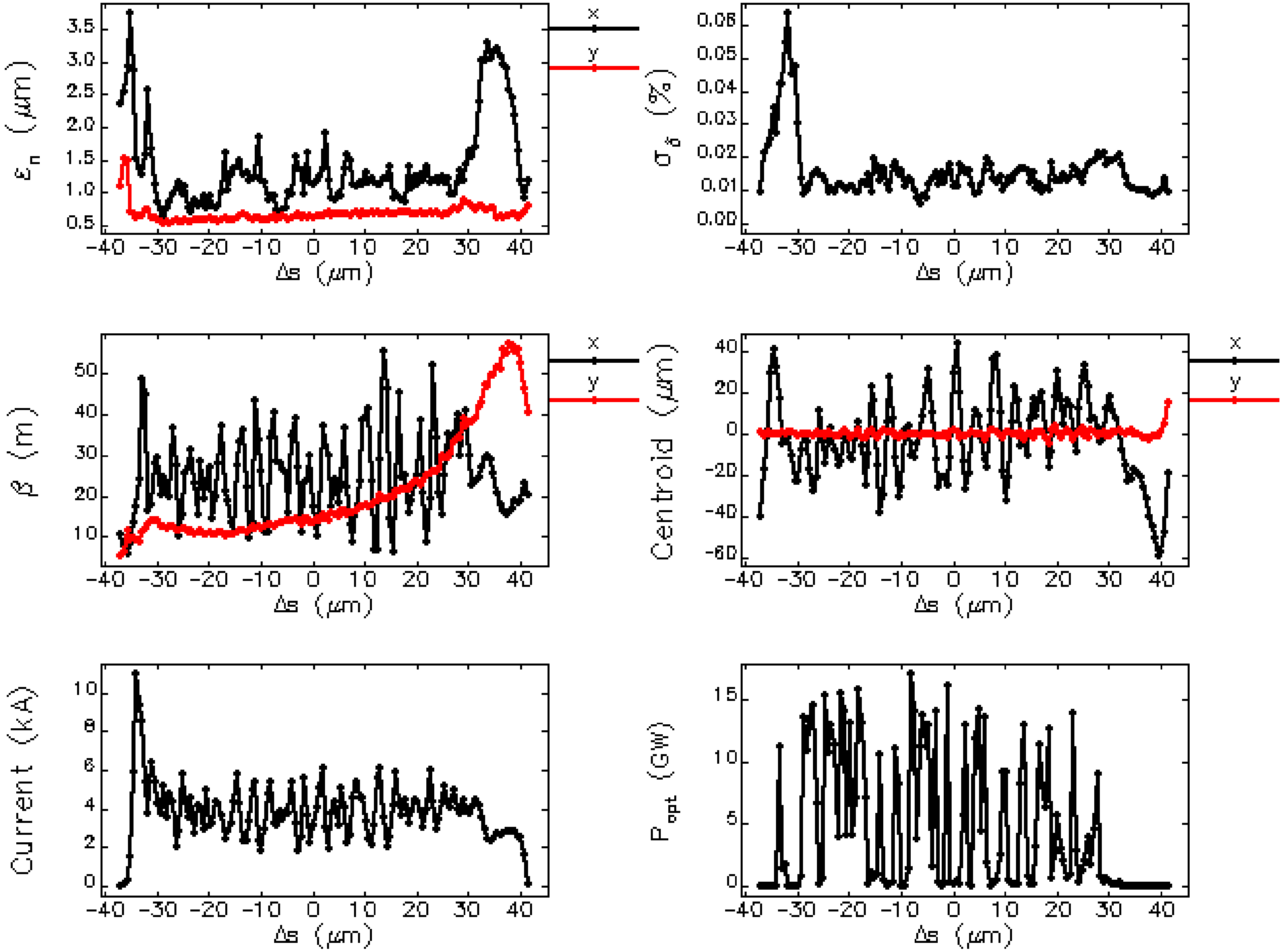
Microbunch spacing is ~3μm

Power drops from
~15 GW to ~5 GW
due to CSR instability

Explanation of the Instability

- CSR wake looks like the derivative of the longitudinal density
- Any density clump causes a local derivative-like feature in the CSR wake
- Head of clump is accelerated, tail is decelerated
- A particle that gains (losses) energy in a dipole falls back (moves ahead)
- Thus, the clump is amplified, which amplifies the CSR wake, ...

Slice Analysis

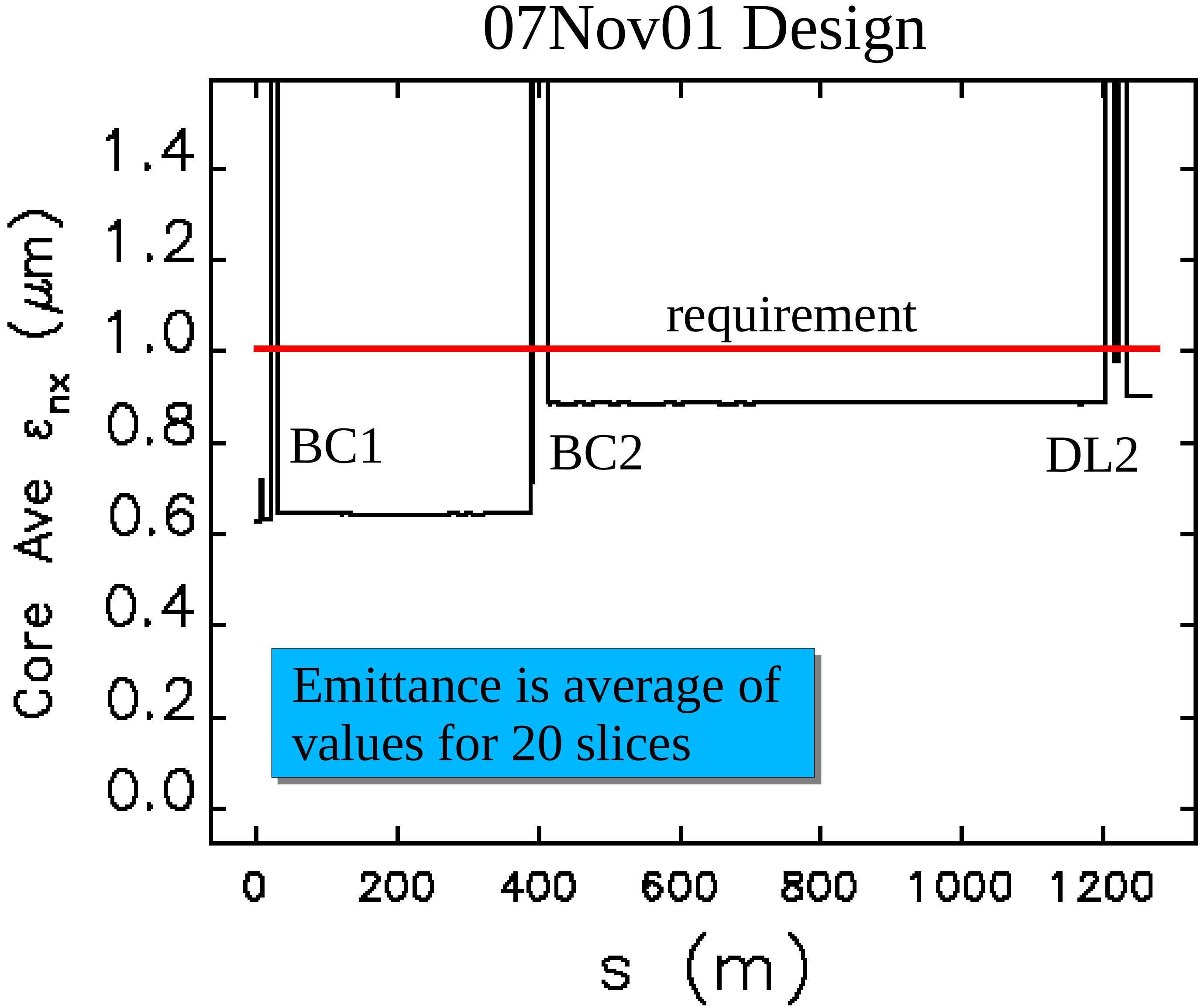


Revised LCLS Design

07Nov01 Design (P. Emma)

- Replace double-chicane compressors with single-chicane compressors
- Add superconducting wiggler upstream of BC2 to increase incoherent energy spread
  - Reduces size of current spikes generated in compression
  - Reduces gain of CSR instability
- Reduced DL2 angles by 50%

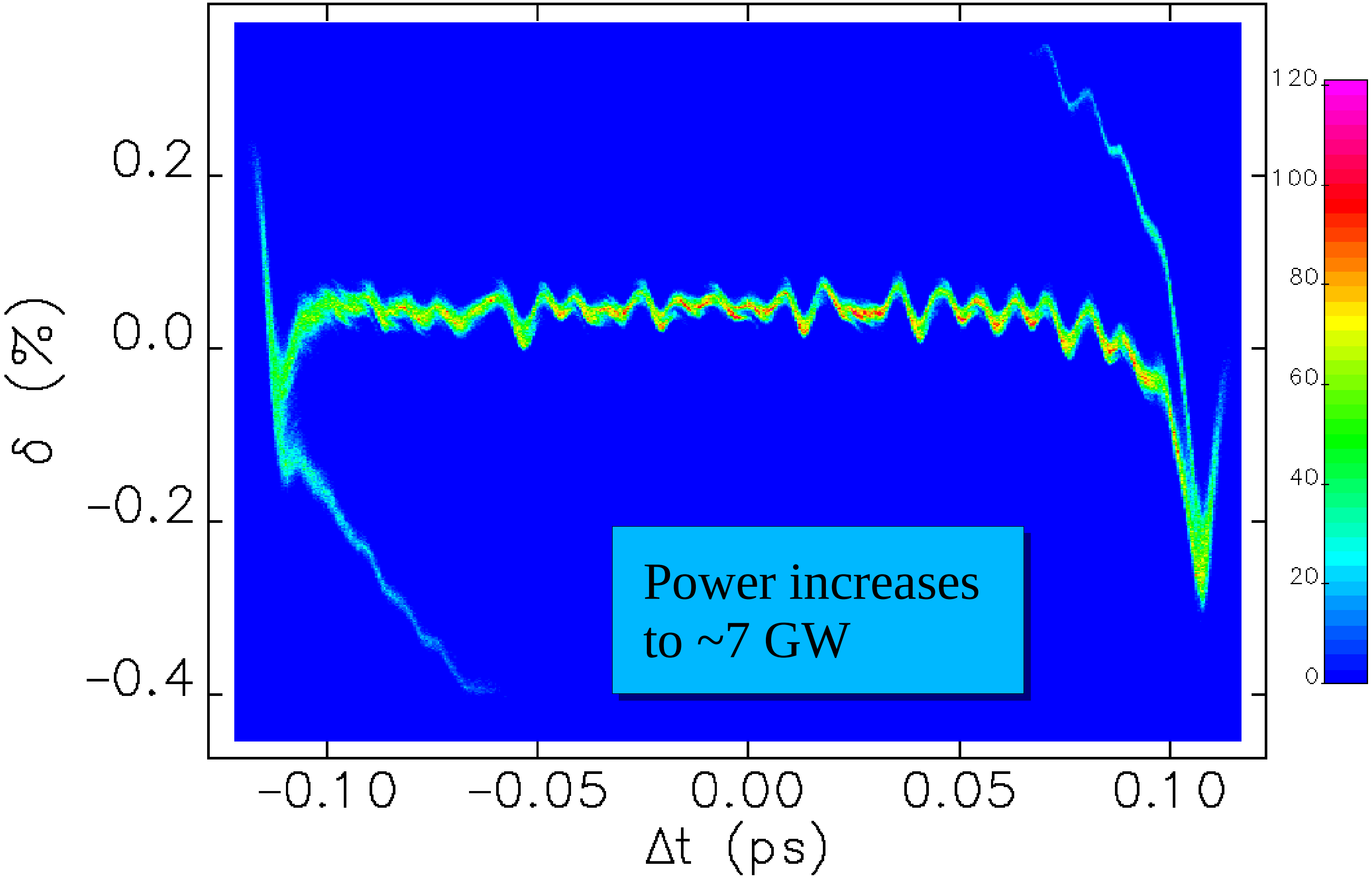
Emittance Growth in LCLS



Emittance is average of values for 20 slices

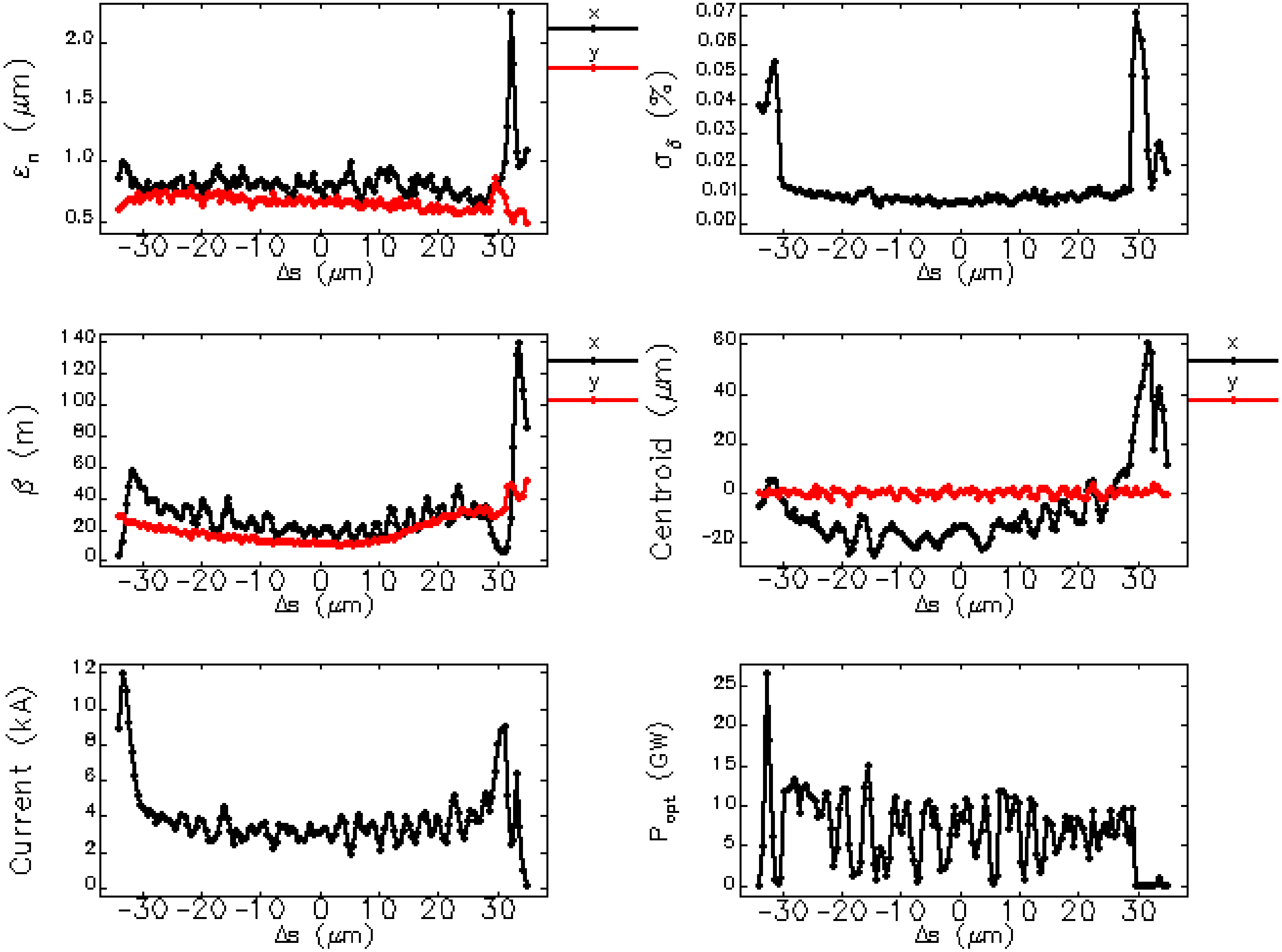
CSR Microbunching Instability

07Nov01 Design



Power increases to ~7 GW

Slice Analysis



Error Simulation

- So far, we've simulated
  - Perfect machine
  - Static conditions
- We need to know how the machine will behave with
  - Static or correctable time-dependent errors (*drift*)
  - Correction schemes
  - Uncorrectable time-dependent errors (*jitter*)

LCLS Jitter Simulation Levels

Quantity	***Rms Jitter Level***
laser phase	0.5 deg-S
laser energy	1.00%
gun phase	reference
gun voltage	0.1%
L0 phase (1)	0.1 deg-S
L0 voltage (1)	0.10%
L1 phase (1)	0.1 deg-S
L1 voltage (1)	0.10%
X-band phase (1)	0.3 deg-X
X-band voltage (1)	0.25%

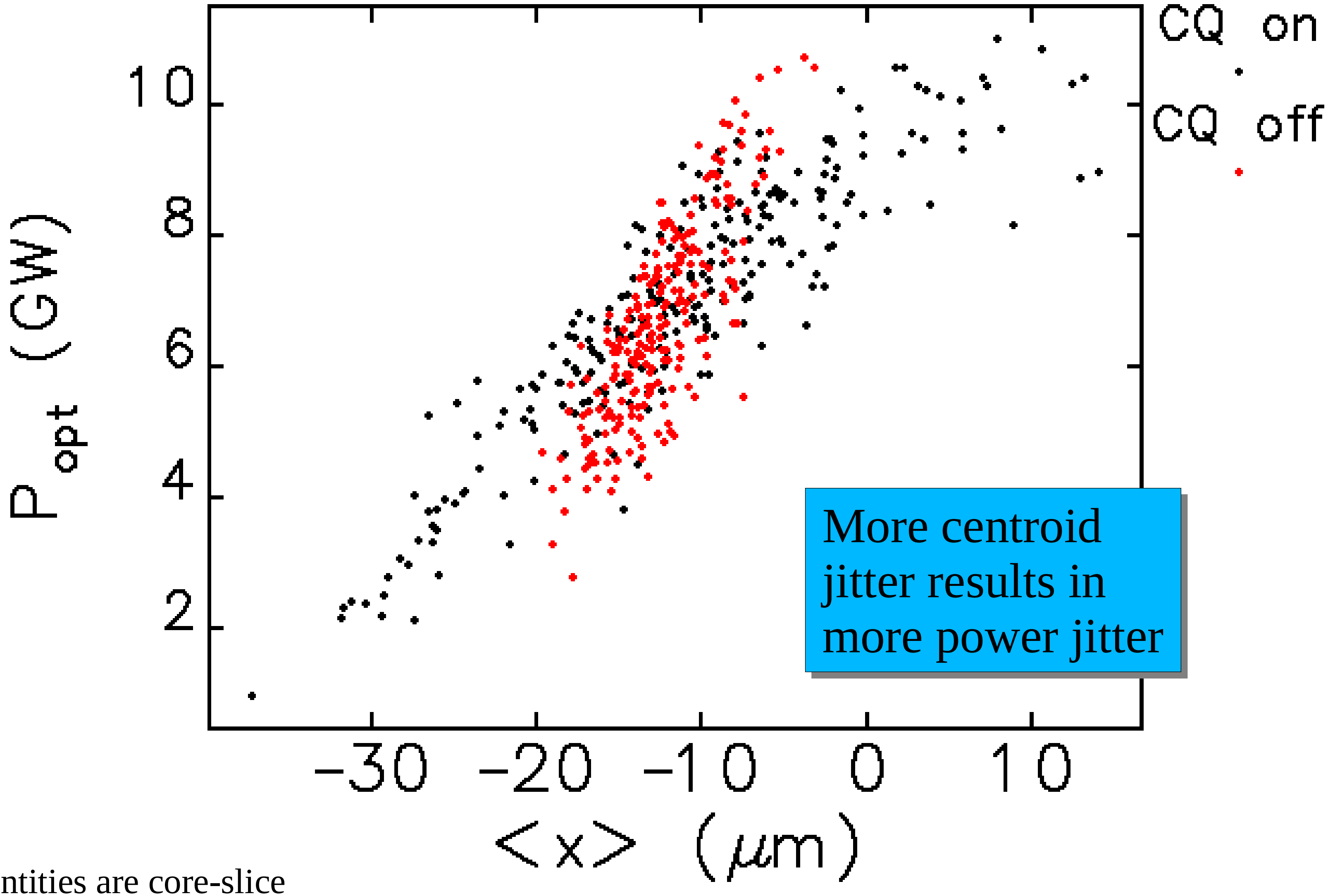
Quantity	***Rms Jitter Level***
L2 phases (28)	0.07 deg-S
L2 voltages (28)	0.07%
L3 phases (48)	0.07 deg-S
L3 voltages (48)	0.05%
BC1 dipoles	0.02%
BC2 dipoles	0.02%
DL dipoles	0.01%
Wiggler dipoles	0.02%
Corr. quads (4)	0.1%

Results of S2E Jitter Simulations

Corr. Quads On	***Current***	***Bunch length***	***Frac. mom. Spread***	***Norm. x emit.***	***Gain Length***	***Wavelength***	***Power***
	kA	ps	10^{-4}	μm	m	A	GW
yes	3.32 ±0.18	0.185 ±0.013	0.817 ±0.043	0.791 ±0.012	3.44 ±0.16	1.4991 ±0.0013	7.1 ±1.4
no	3.27 ±0.17	0.188 ±0.013	0.806 ±0.033	0.789 ±0.011	3.53 ±0.13	1.4987 ±0.0012	6.6 ±1.0

- Correction quads remove dispersion-like correlations due to CSR
- 230 seeds used
- Format: median ± (quartile range)

Results of Jitter Simulations



More centroid jitter results in more power jitter

All quantities are core-slice averages

Correlation Analysis

- Correlation analysis can explain the causes of variation in power

Quantity	*Responsibility (%)*
laser phase	22%
L1 phase	19%

- and wavelength variation

Quantity	*Responsibility (%)*
laser phase	17%
L1 phase	17%
L0 voltage	16%
L1 voltage	15%

- "Responsibility" is the correlation coefficient squared.

Recommendations for Continuation of S2E

- Add a drive laser model
  - realistic spatial/temporal profiles
  - pulse-to-pulse profile jitter
  - pointing jitter
- Include simulation of "static" errors
  - cathode nonuniformity
  - misalignments and drifts, with correction

Summary

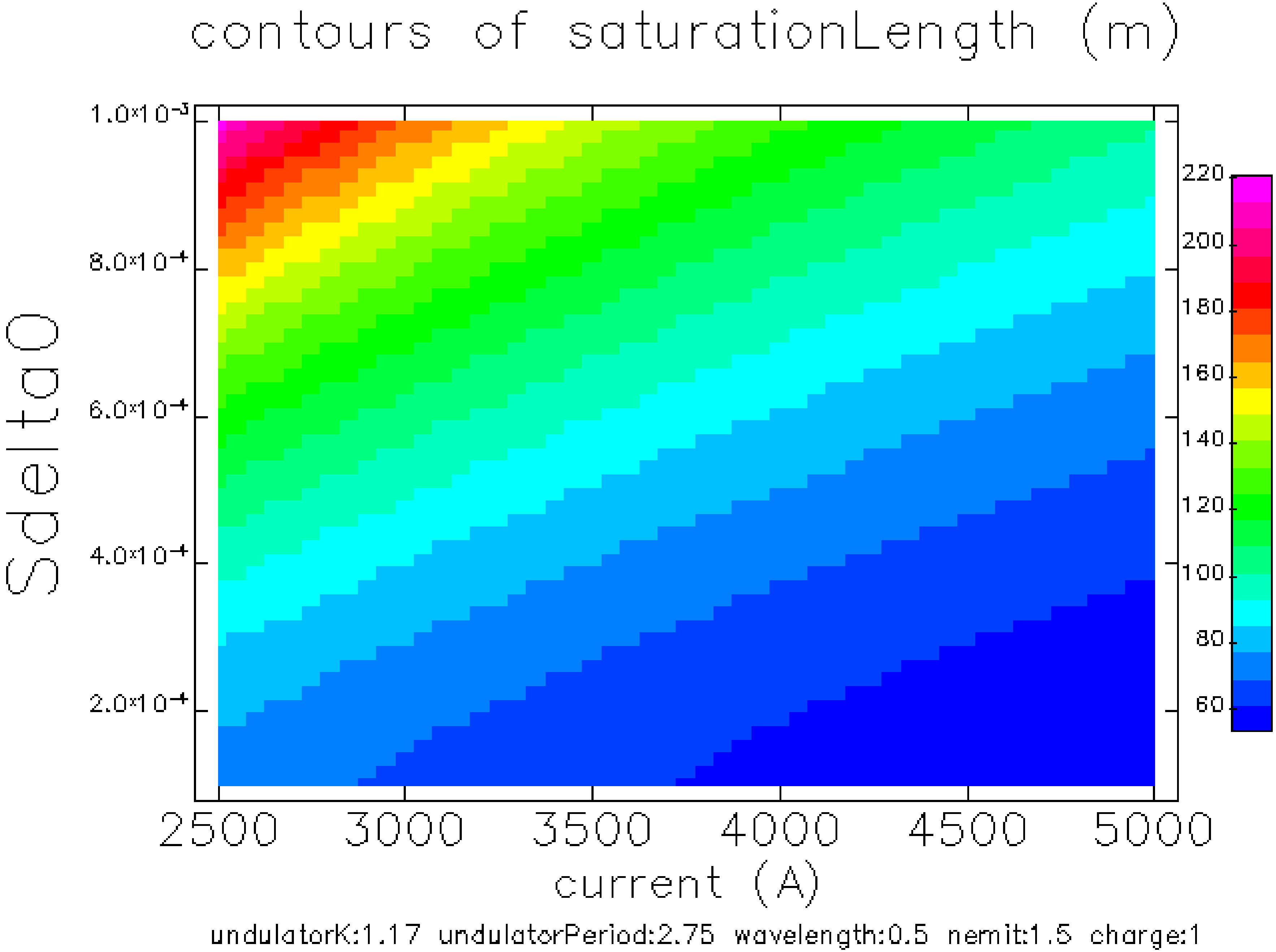
- Simple picture of an FEL-driver linac is misleading
- Physics details from each system need to be included in "start-to-end" simulation
- Simulation codes and tools are available to perform realistic modeling
- Some significant surprises have emerged from this work

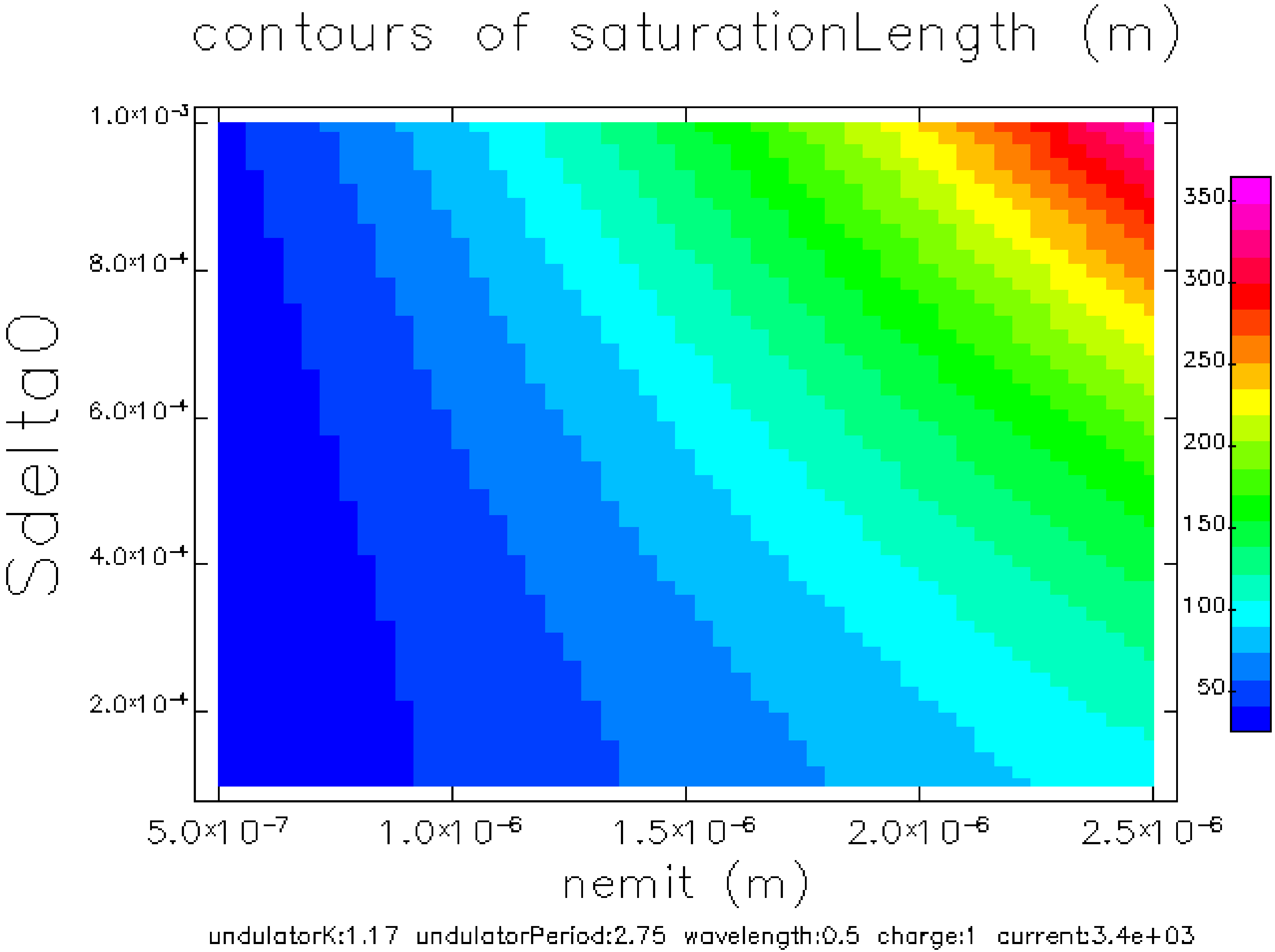
Credits

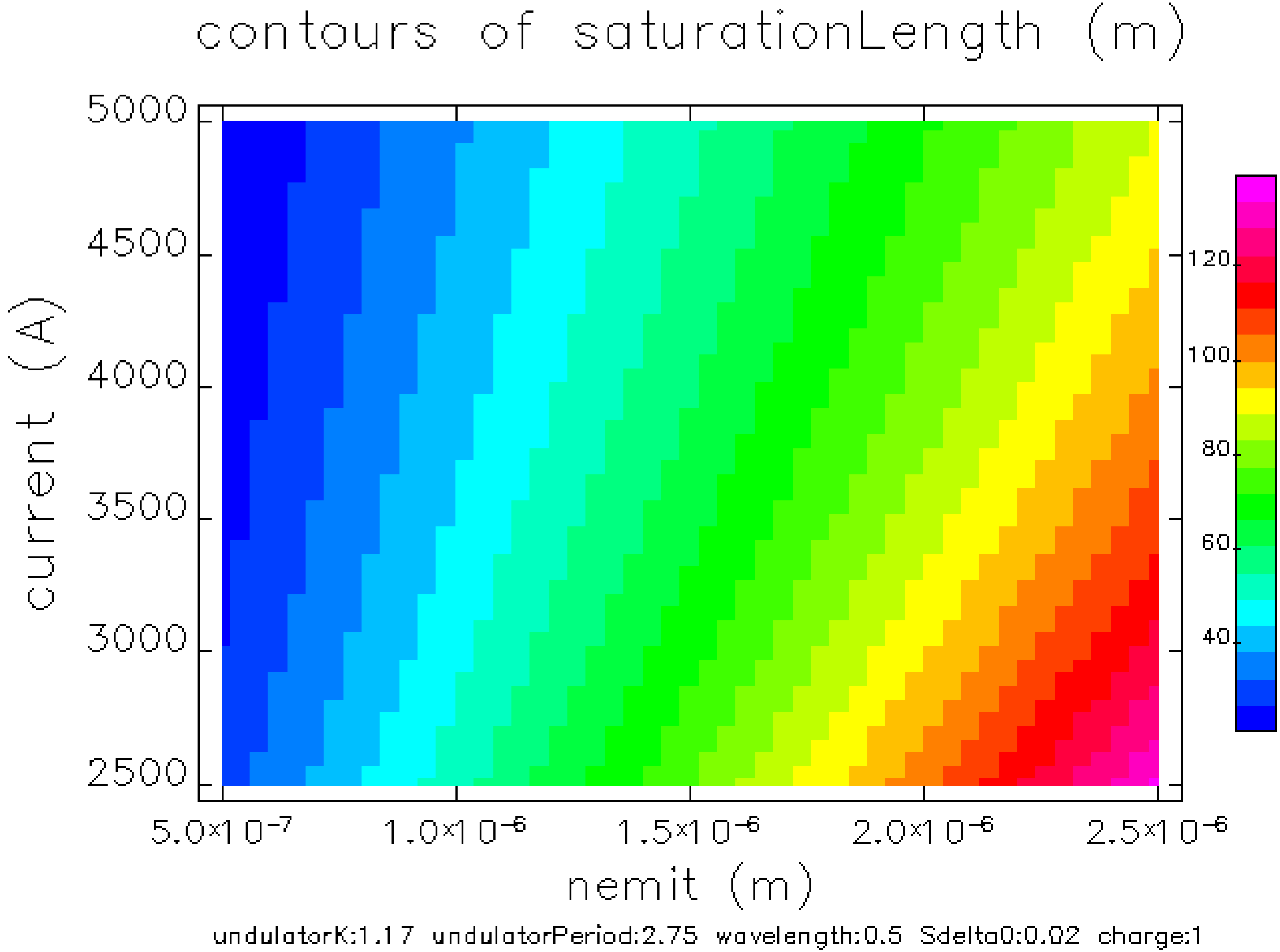
- LCLS S2E simulations: M. Borland, Y.C. Chae, P. Emma, J. Lewellen, C. Limborg, R. Soliday, M. Woodley
- Ideas and references on linac design: P. Emma
- elegant: M. Borland
- PARMELA: L. Young
- GENESIS: S. Reiche

Quick Look at Bates Parameters

- Used M. Xie's FEL formulae for SASE FEL evaluation.
- Goal is saturation at 0.5nm wavelength with a "reasonable" undulator length.
- Assumed undulator: K=1.17, λ_u=2.75cm
- Range of parameters explored:
  - Current from 2 to 5 kA
  - Energy spread from 0.01 to 0.1%
  - Emittance from 0.5 to 2.5 μm


contours of saturationLength (m)
Sdelta0
1.0×10⁻³
8.0×10⁻⁴
6.0×10⁻⁴
4.0×10⁻⁴
2.0×10⁻⁴
2500
3000
3500
4000
4500
5000
current (A)
220
200
180
160
140
120
100
80
60
undulatorK:1.17 undulatorPeriod:2.75 wavelength:0.5 nemit:1.5 charge:1


contours of saturationLength (m)
Sdelta0
1.0×10⁻³
8.0×10⁻⁴
6.0×10⁻⁴
4.0×10⁻⁴
2.0×10⁻⁴
5.0×10⁻⁷
1.0×10⁻⁶
1.5×10⁻⁶
2.0×10⁻⁶
2.5×10⁻⁶
nemit (m)
350
300
250
200
150
100
50
undulatorK:1.17 undulatorPeriod:2.75 wavelength:0.5 charge:1 current:3.4e+03


contours of saturationLength (m)
5000
4500
4000
3500
3000
2500
current (A)
5.0×10^{-7}
1.0×10^{-6}
1.5×10^{-6}
2.0×10^{-6}
2.5×10^{-6}
nemit (m)
120
100
80
60
40
undulatorK:1.17 undulatorPeriod:2.75 wavelength:0.5 Sdelta0:0.02 charge:1