Start-to-End Simulation of Beam Dynamics in SASE FELs

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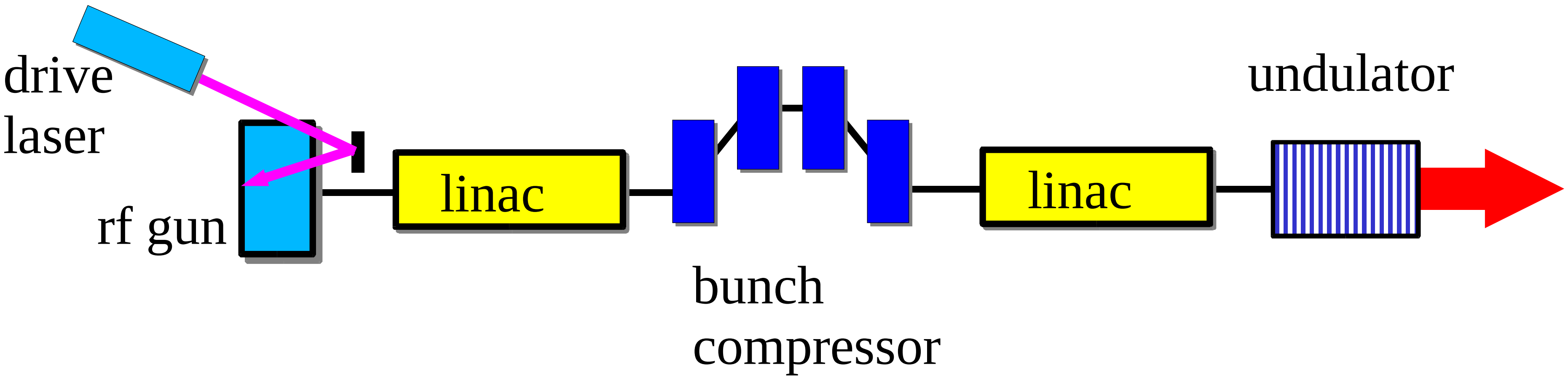
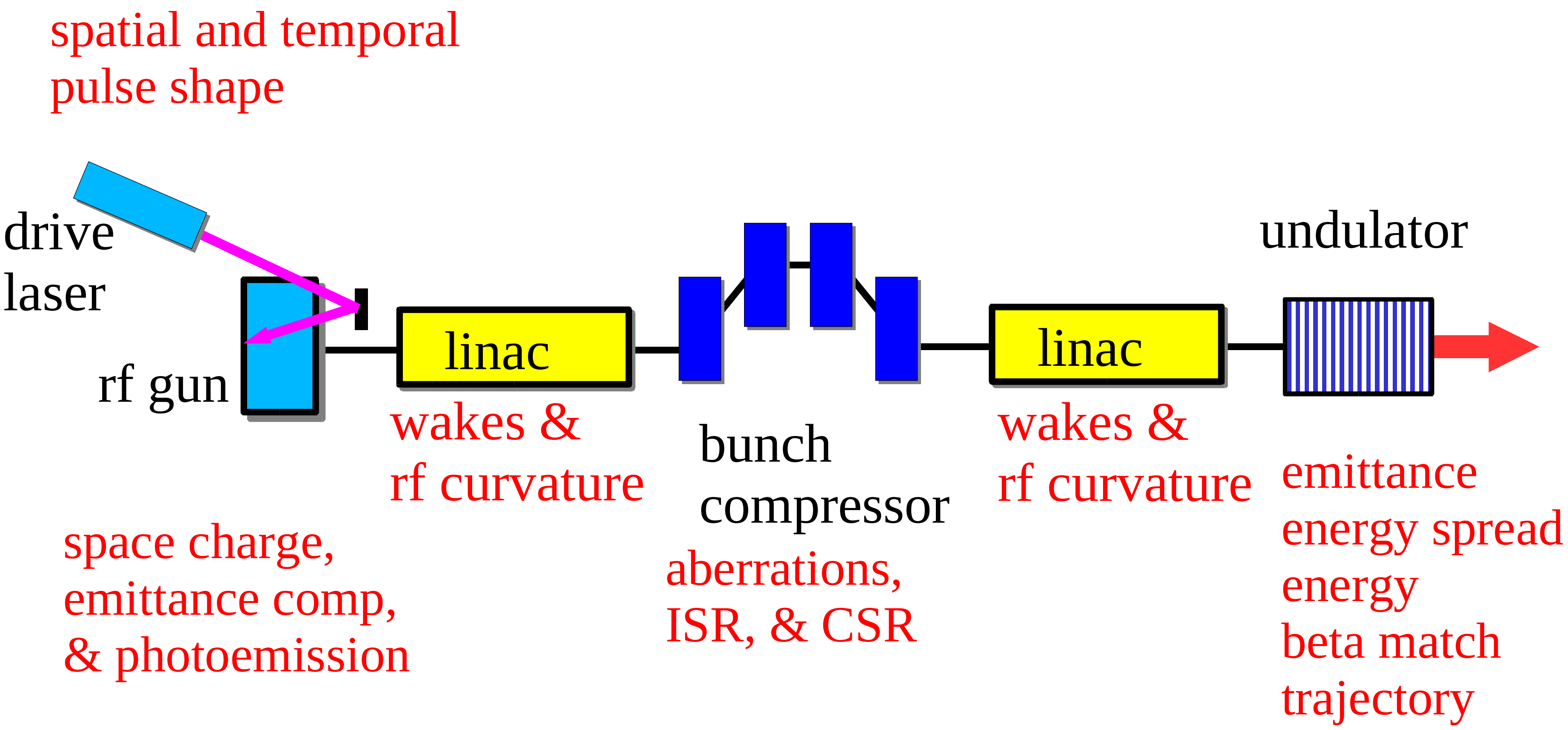
Outline

- Why do start-to-end (S2E) simulations?
- Simulation methods and codes
- LCLS simulations
  - Discovery of the CSR microbunching instability
  - Simulation of pulse-to-pulse X-ray output
- Conclusions and suggestions

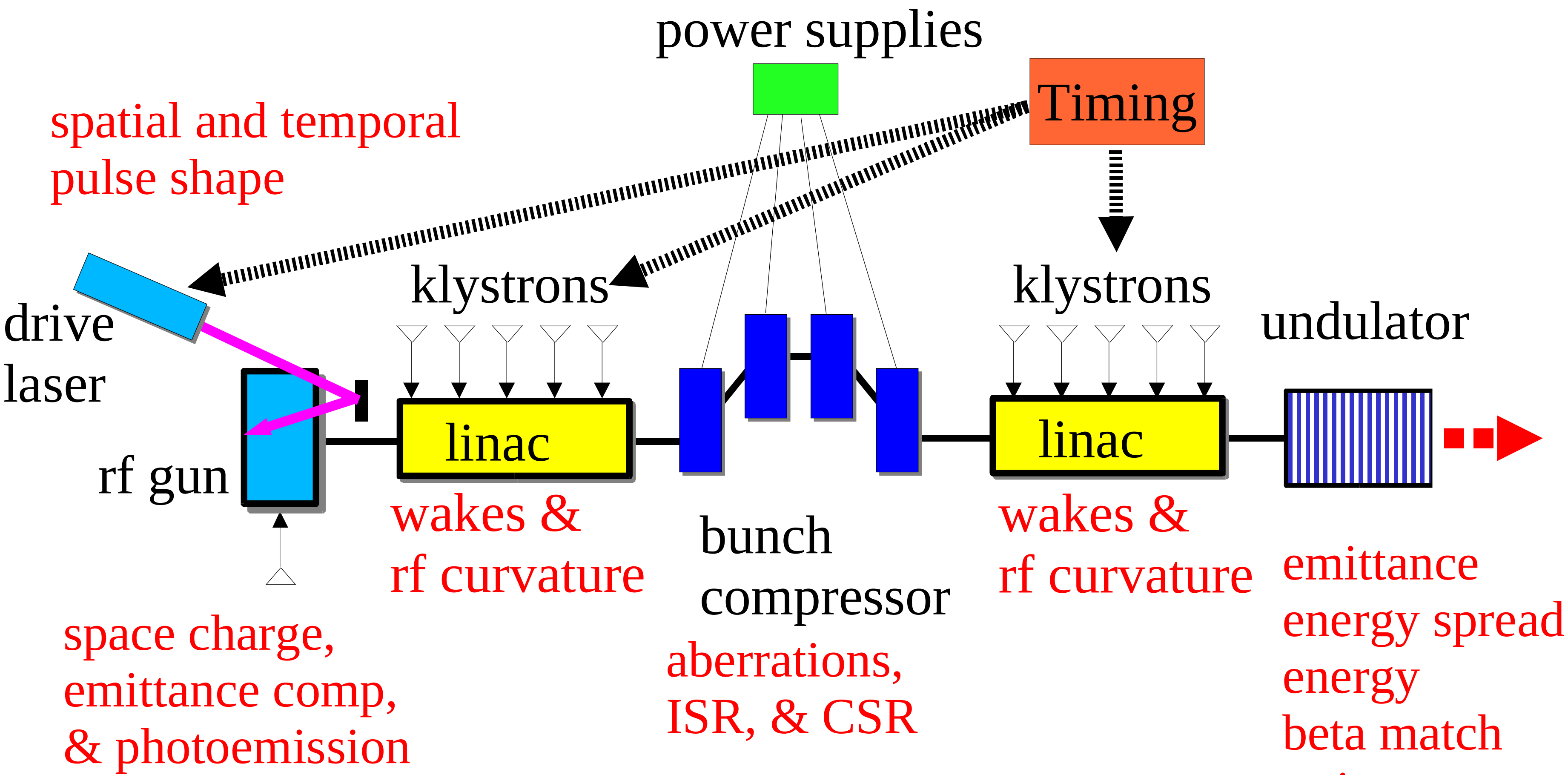
Simplified SASE FEL Schematic



Simplified SASE FEL Schematic



~~Simplified~~ SASE FEL Schematic



FEL is critically affected by interplay of physics details.

Methodology of S2E Simulations

- *Don't* try to write a single code that does everything
- *Do* try to preserve as much information as practical in going from one code to the next
- *Do* develop a way to use existing codes together efficiently
  - Standardized file format ("SDDS") for data exchange
  - Standardized data processing tools (SDDS toolkit)
  - Script-based automation

Codes for S2E

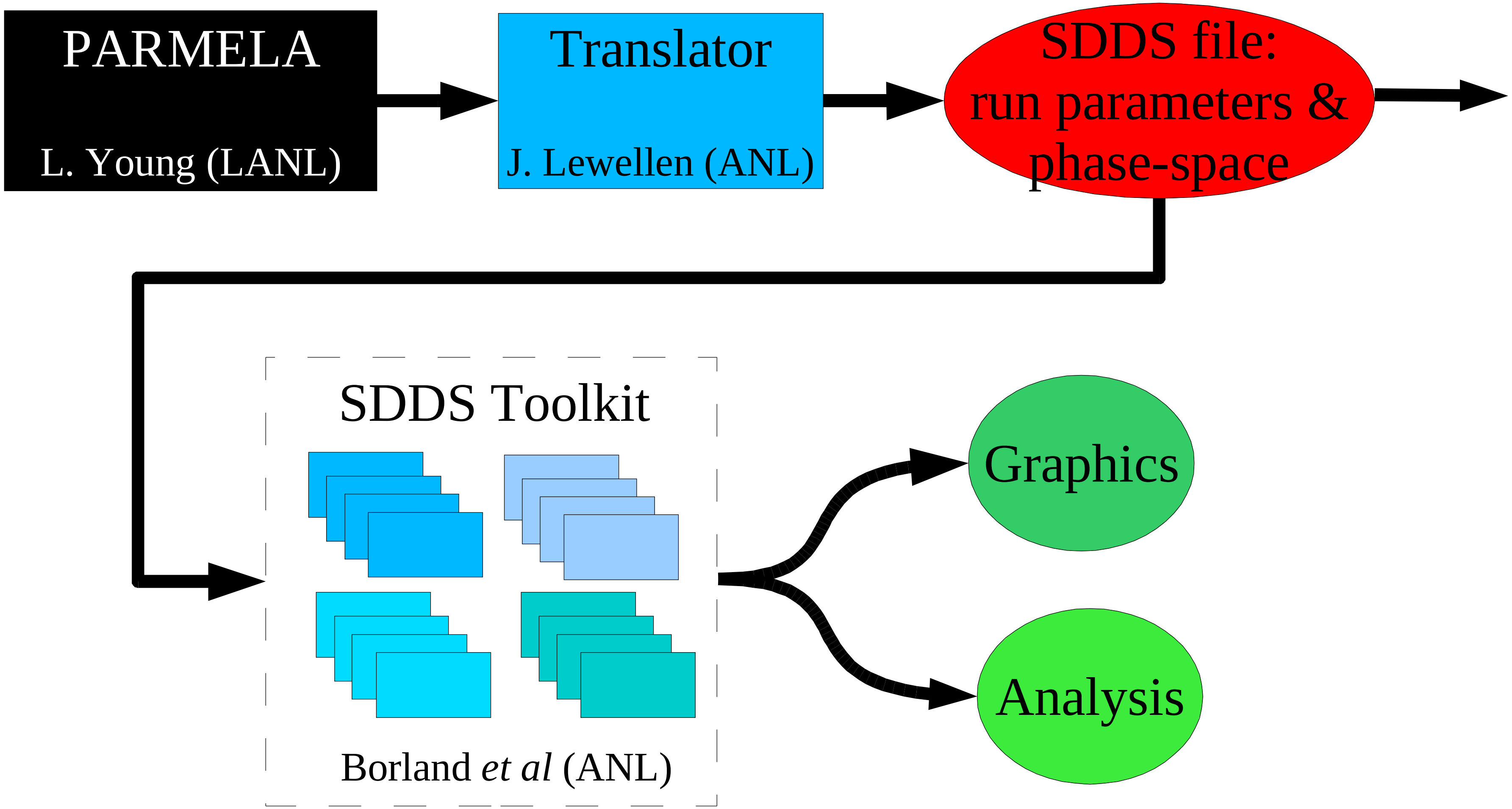
- PARMELA (L. Young, LANL)
  - Photoinjector simulations
  - Space charge, rf curvature, nonlinear transport
- elegant (M. Borland, ANL)
  - Linac and bunch compressor
  - CSR, ISR, wakefields, rf curvature, nonlinear transport
- GENESIS (S. Reiche, UCLA)
  - 3D FEL simulation

GENESIS simulations

- Full time-dependent simulation requires millions of particles and is impractical for jitter simulation
- FEL codes and accelerator codes require very different particle loading
- Our solution
  - Perform slice analysis with 136 slices ($L_{slice} = L_{slippage}$)
  - Simulate each slice independently in steady-state mode

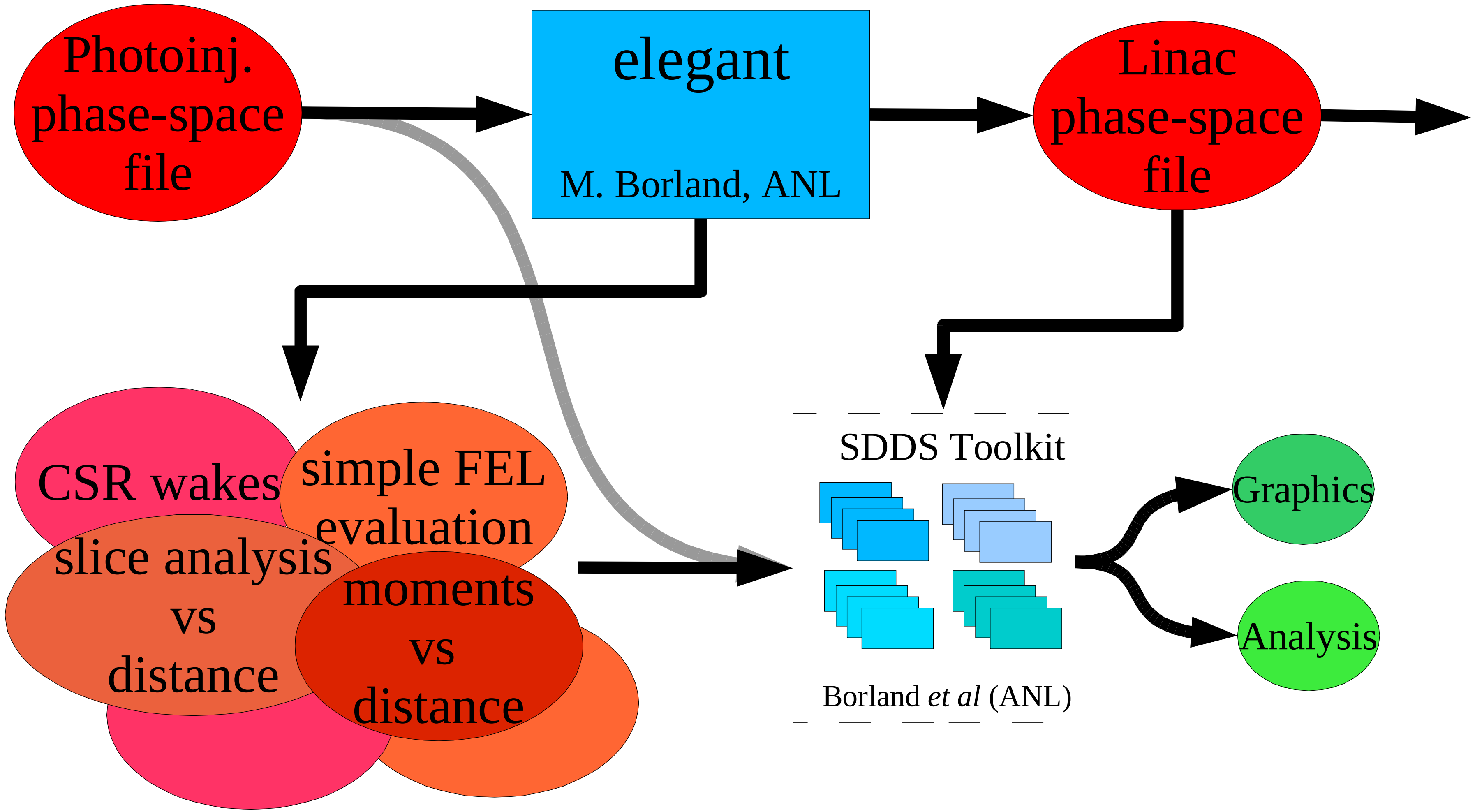
Components of S2E Simulations

— Photoinjector —



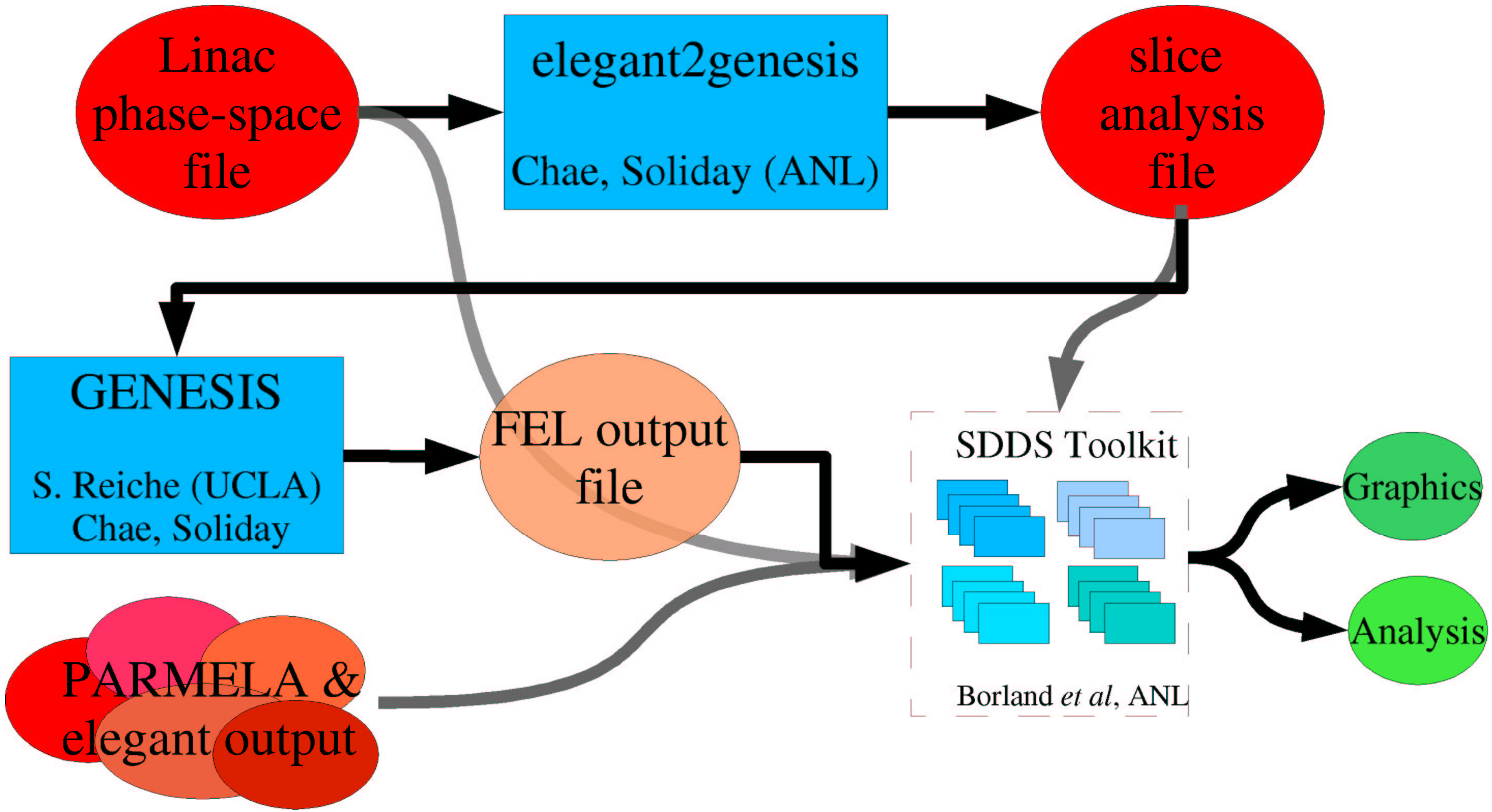
Components of S2E Simulations

— Linac/Bunch Compressors —



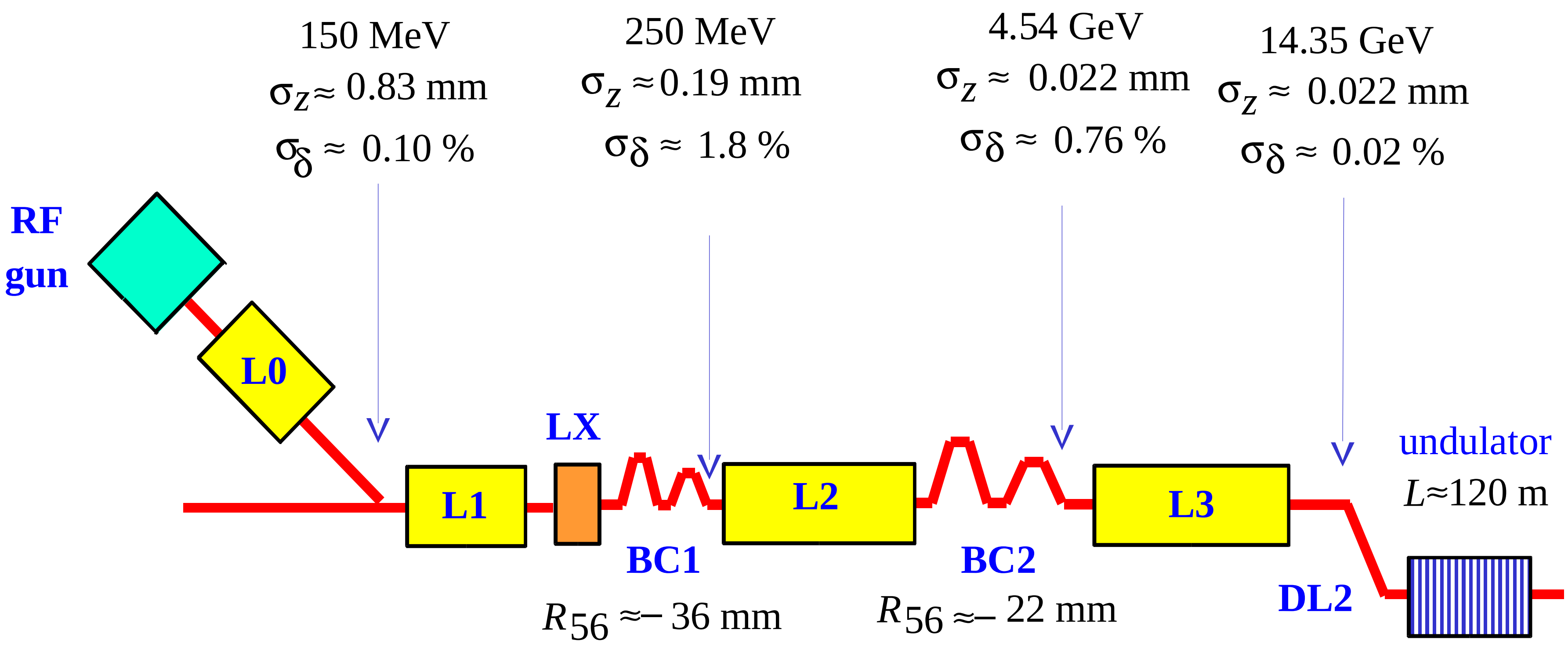
Components of S2E Simulations

— FEL Simulation —



LCLS Schematic

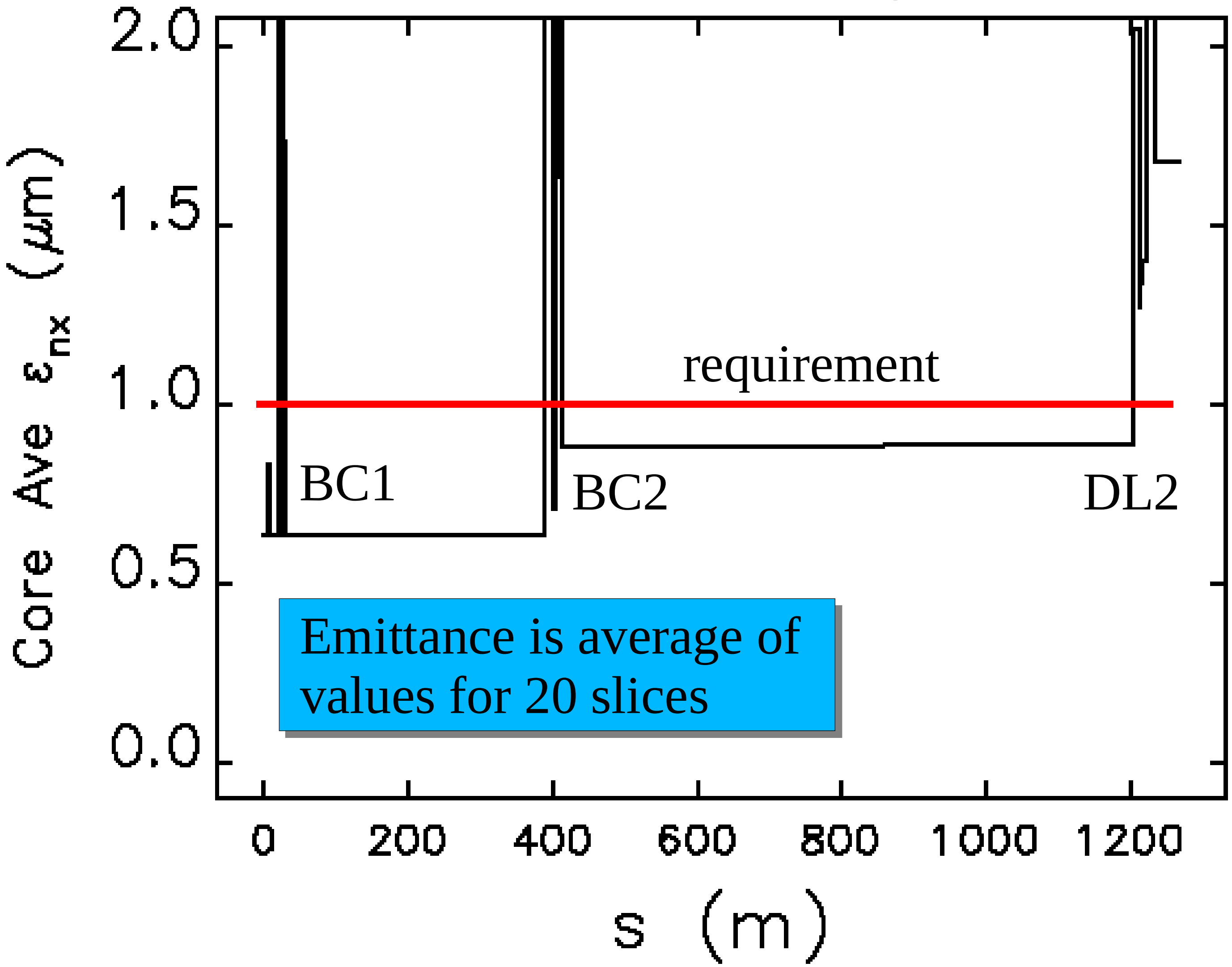
06Dec00 Design (P. Emma)



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

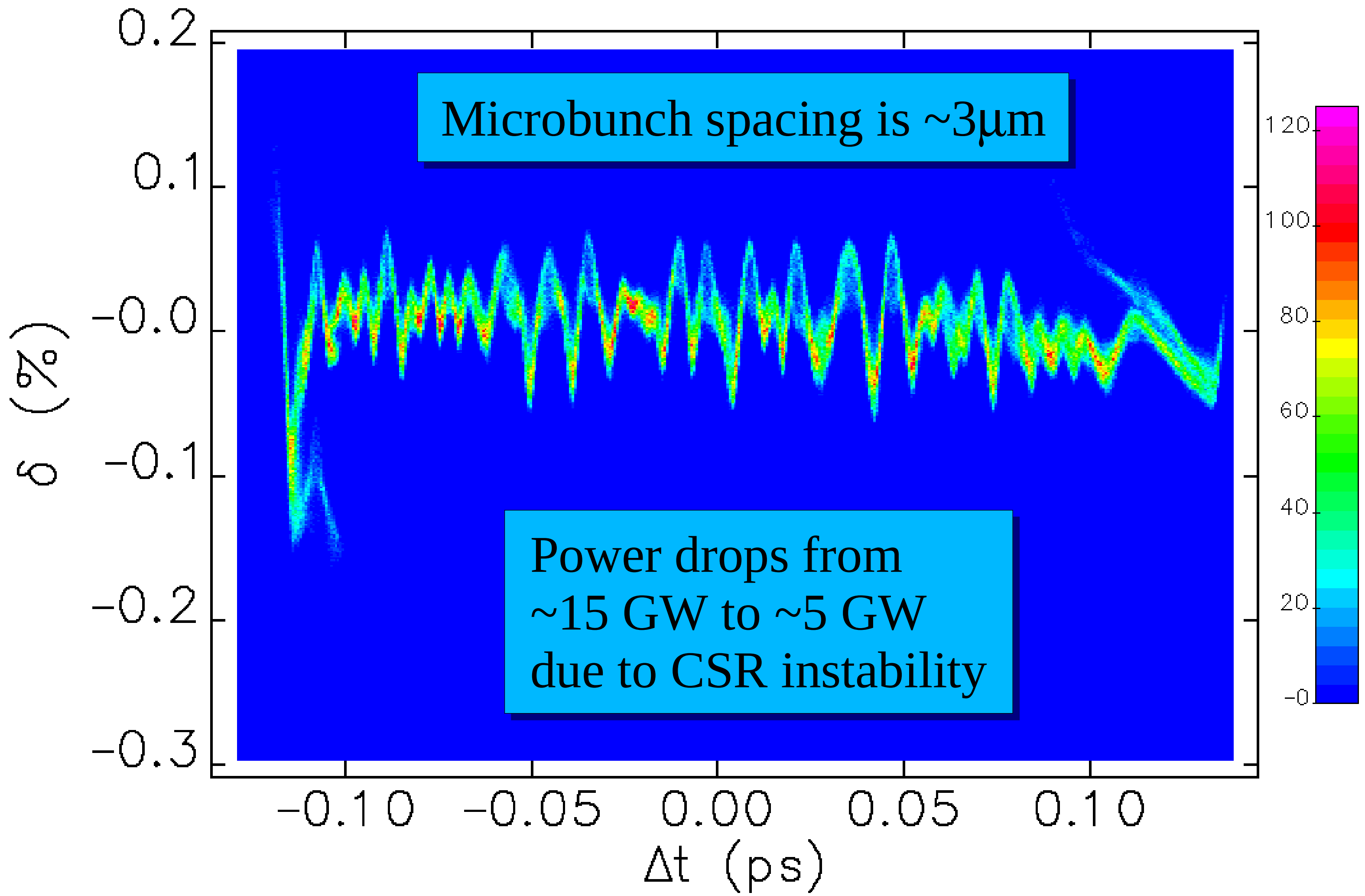
Emittance Growth in LCLS

06Dec00 Design



CSR Microbunching Instability

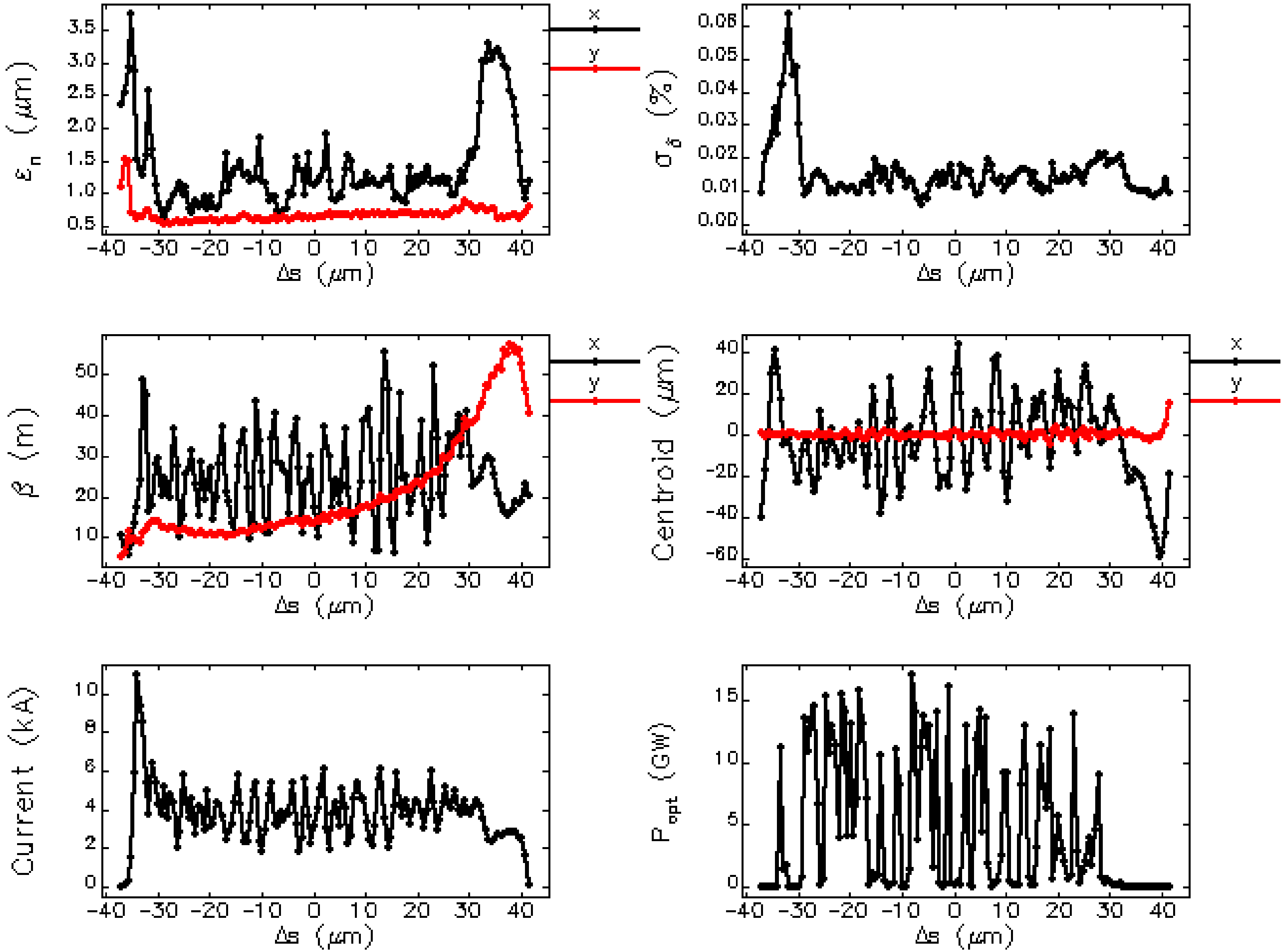
06Dec00 Design



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



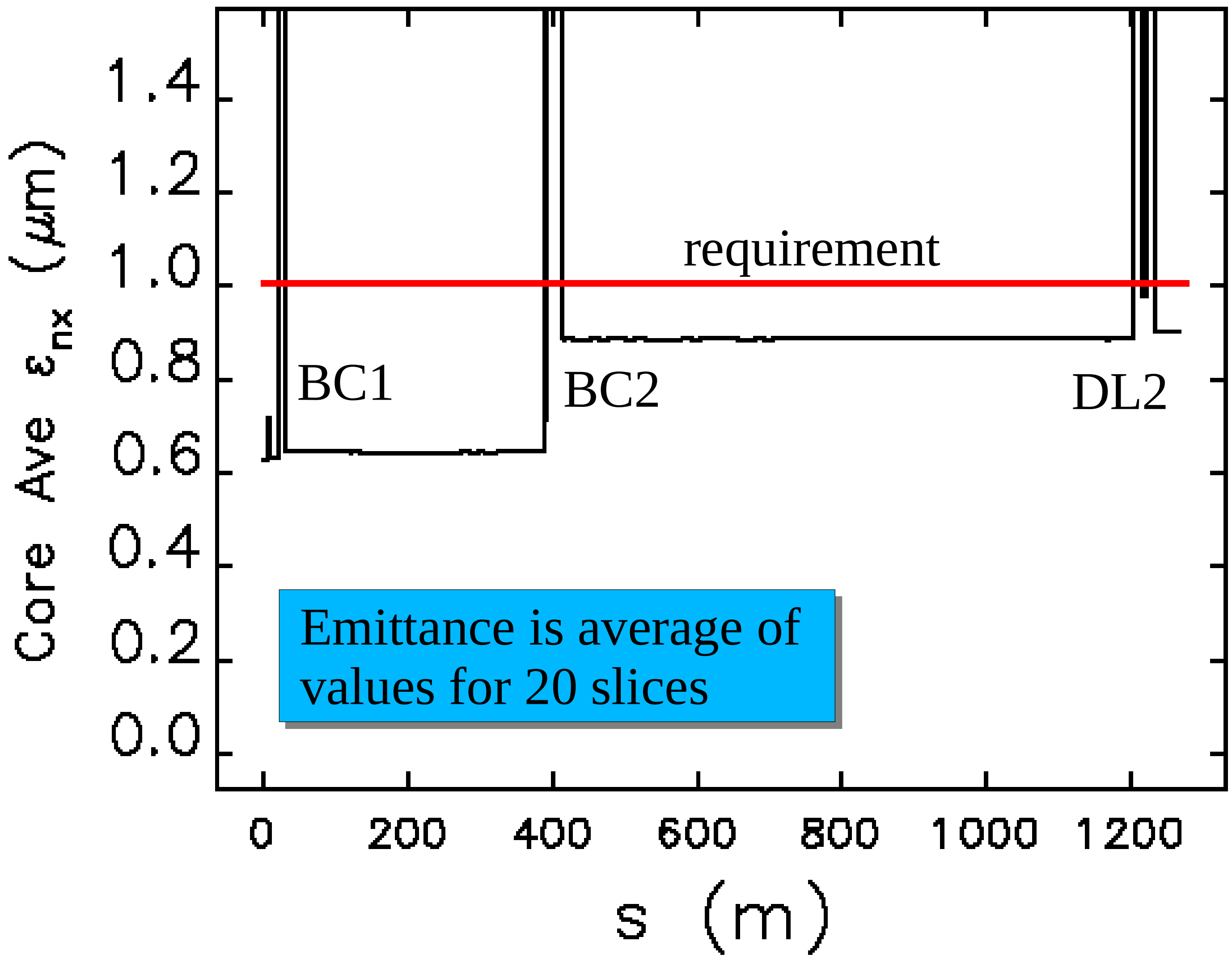
Revised LCLS Design

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%

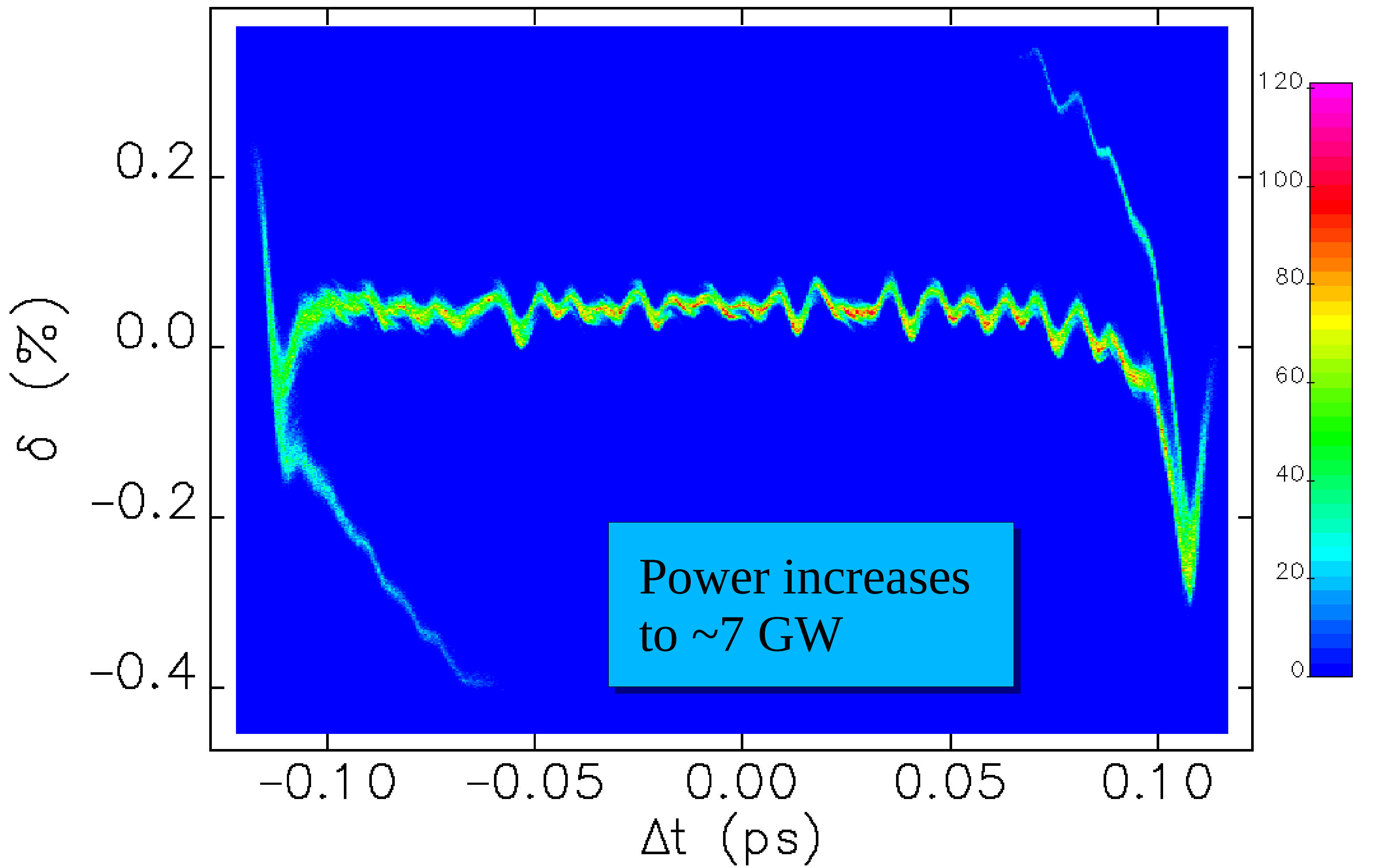
Emittance Growth in LCLS

07Nov01 Design

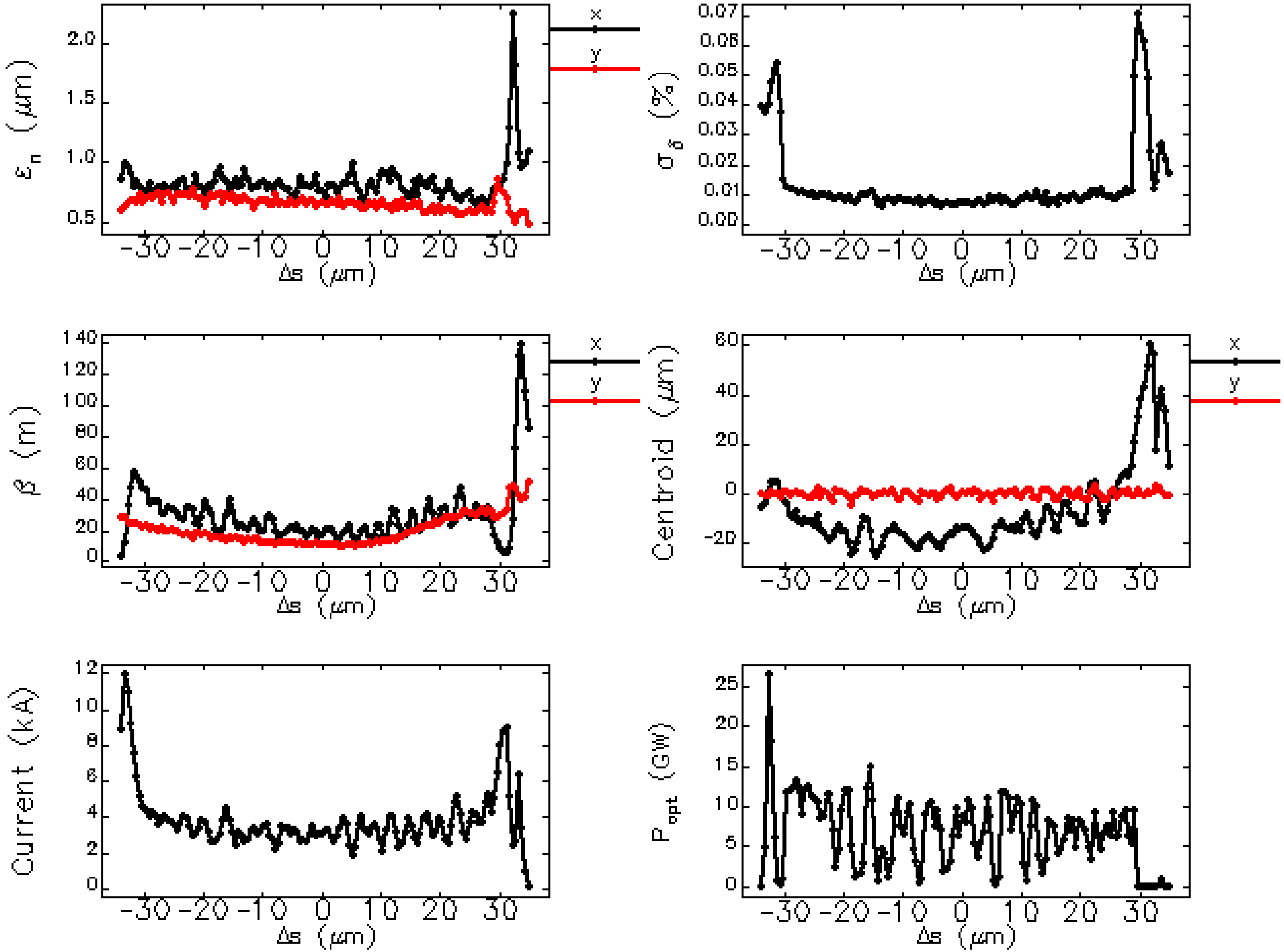


CSR Microbunching Instability

07Nov01 Design



Slice Analysis



S2E Jitter Simulations of LCLS

- "Jitter" refers to any error that we can't correct with alignment, tuning, feedback, etc.
- We assume that the machine is tuned to ideal performance on average
- We simulated jitter, including
  - drive laser timing and energy
  - photoinjector and linac rf voltages and phases
  - bunch compressor power supplies

Assumed Input Jitter 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%

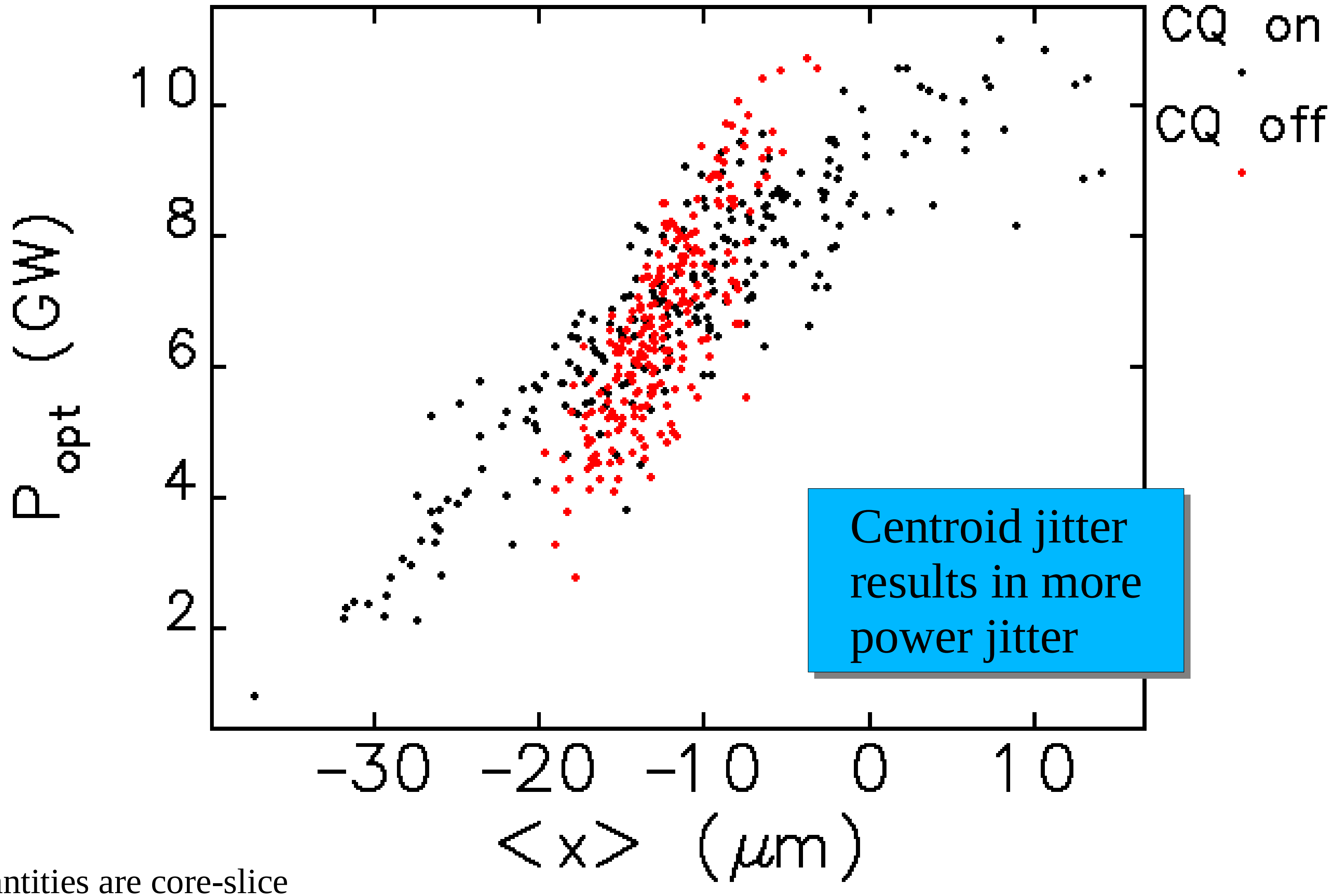
Quantity	*Rms Jitter Level*
L2 phases (28)	0.07 deg-S
L2 voltages (28)	0.07%
L3 phases (48)	0.07 deg-S
L3 voltages (48)	0.05%
BC1 dipoles	0.02%
BC2 dipoles	0.02%
DL dipoles	0.01%
Wiggler dipoles	0.02%
Tweaker quads (4)	0.1%

Results of Jitter Simulations

Correction 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

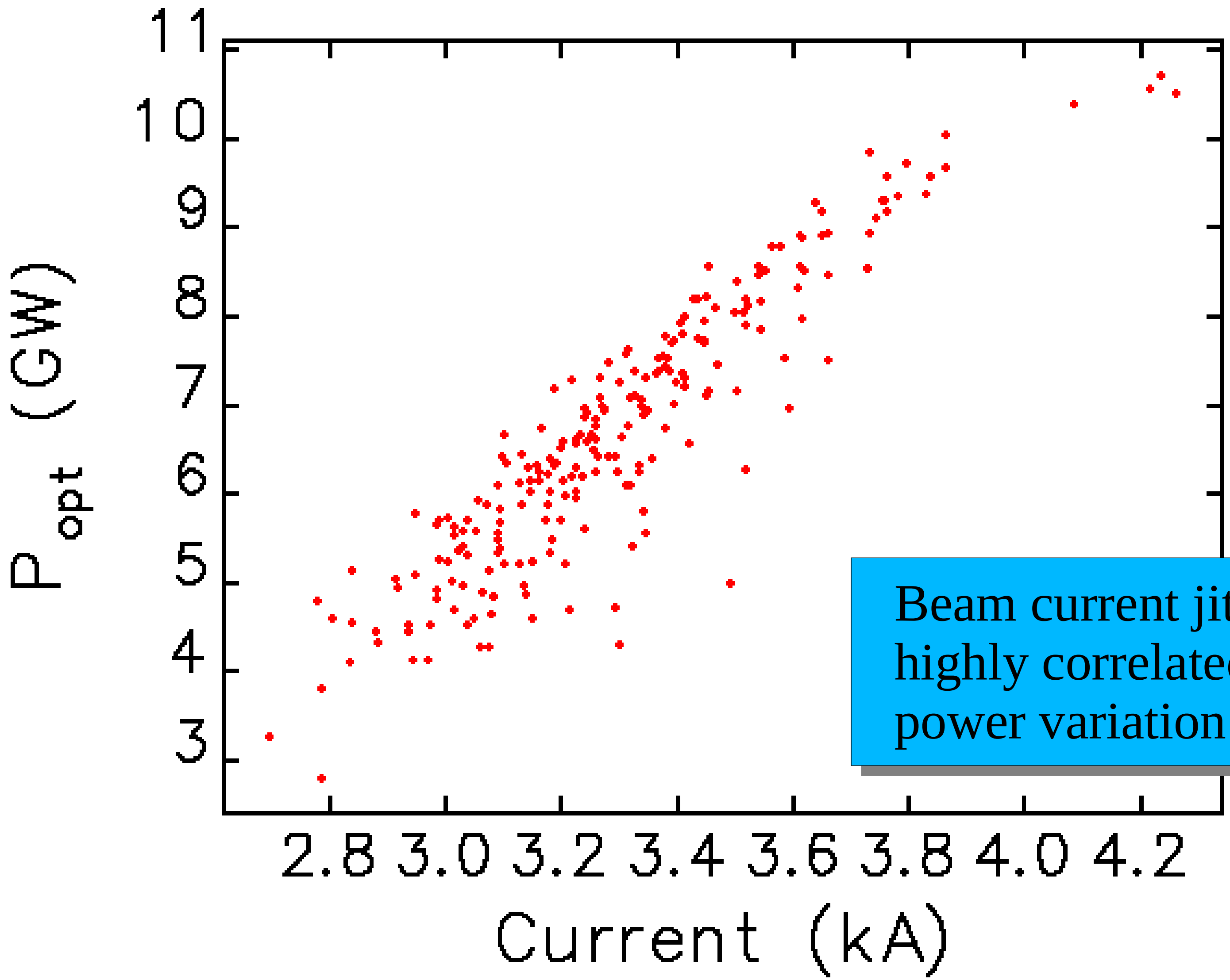
- Correction quads in chicanes remove dispersion-like correlations due to CSR and reduce projected emittance.
- 230 seeds used.
- Values are medians of central-80% core-slice-averages.
- Error bars give half the quartile range.

Results of Jitter Simulations



All quantities are core-slice averages

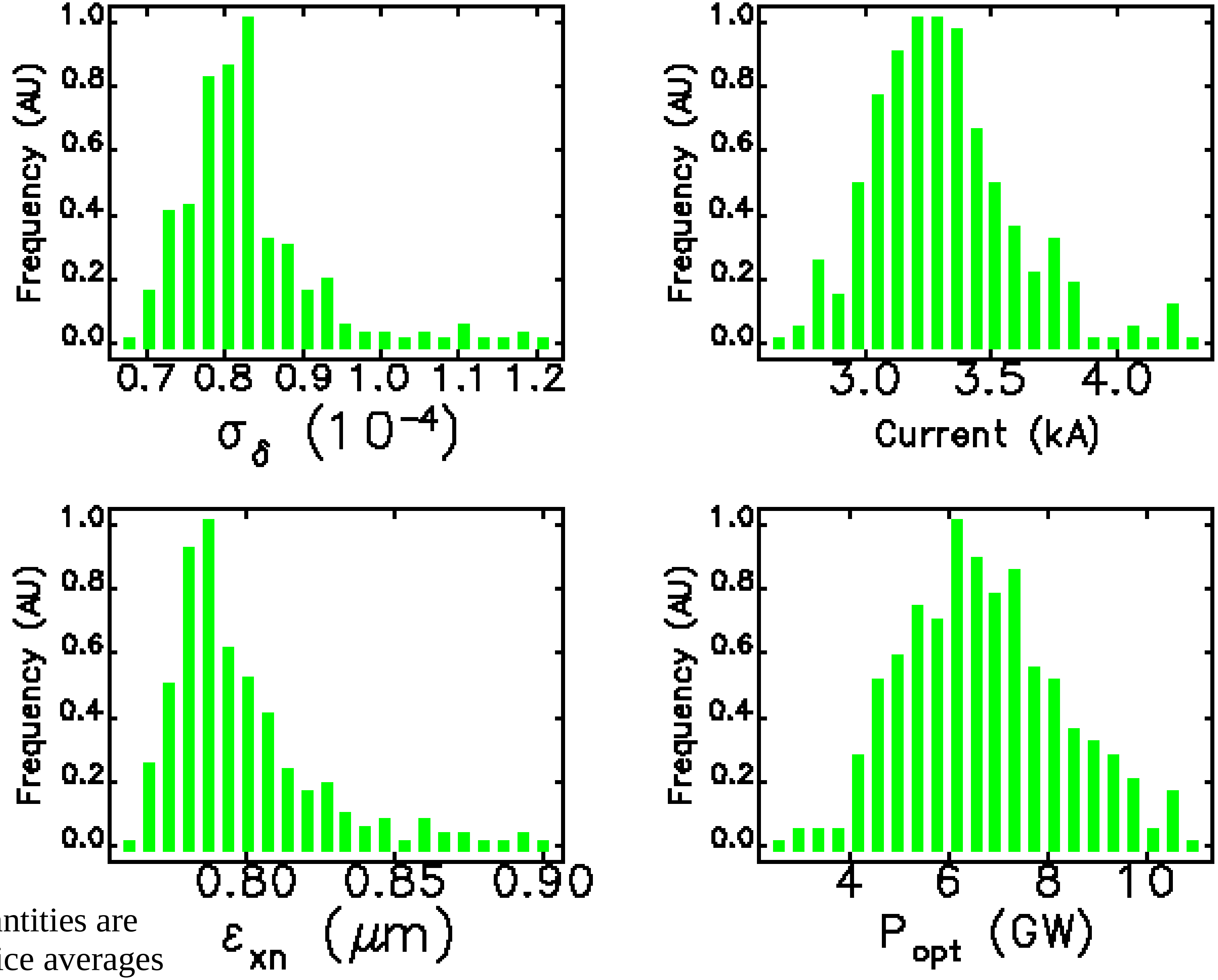
Results of Jitter Simulations



Beam current jitter is highly correlated with power variation

All quantities are core-slice averages

Results of Jitter Simulations



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

Other S2E Efforts

- Boeing group
  - PARMELA→FELEXN
- LEUTL group
  - PARMELA→elegant→GENESIS
- SLAC/UCLA group
  - PARMELA→elegant→GENESIS (time dependent)
- TTF group
  - ASTRA→TraFiC^4→elegant→FAST
- VISA group
  - PARMELA→elegant→GENESIS

Conclusions

- Start-to-end simulations using multiple codes work well due to SDDS files, tools, and scripts
- Results so far include
  - Discovery of CSR microbunching instability
  - Improved jitter specification
  - Photoinjector modeling and stability is critical
  - Unexpected effects of correction quads
- If you aren't doing S2E for your FEL or ERL, you may get a nasty surprise

Contributors

- GENESIS setup: Y.-C. Chae
- LCLS linac design: P. Emma, M. Woodley
- Photoinjector design: P. Krejcik, C. Limborg
- PARMELA setup: J. Lewellen, C. Limborg
- Start-to-end scripts and tools:
  M. Borland, Y.-C. Chae, J. Lewellen, R. Soliday
- Suggestions, motivation, and ideas:
  V. Bharadwaj, W.M. Fawley, H.-D. Nuhn, S.V. Milton
- elegant: M. Borland