Start–to–End Simulation of SASE FELs from the Gun through the Undulator

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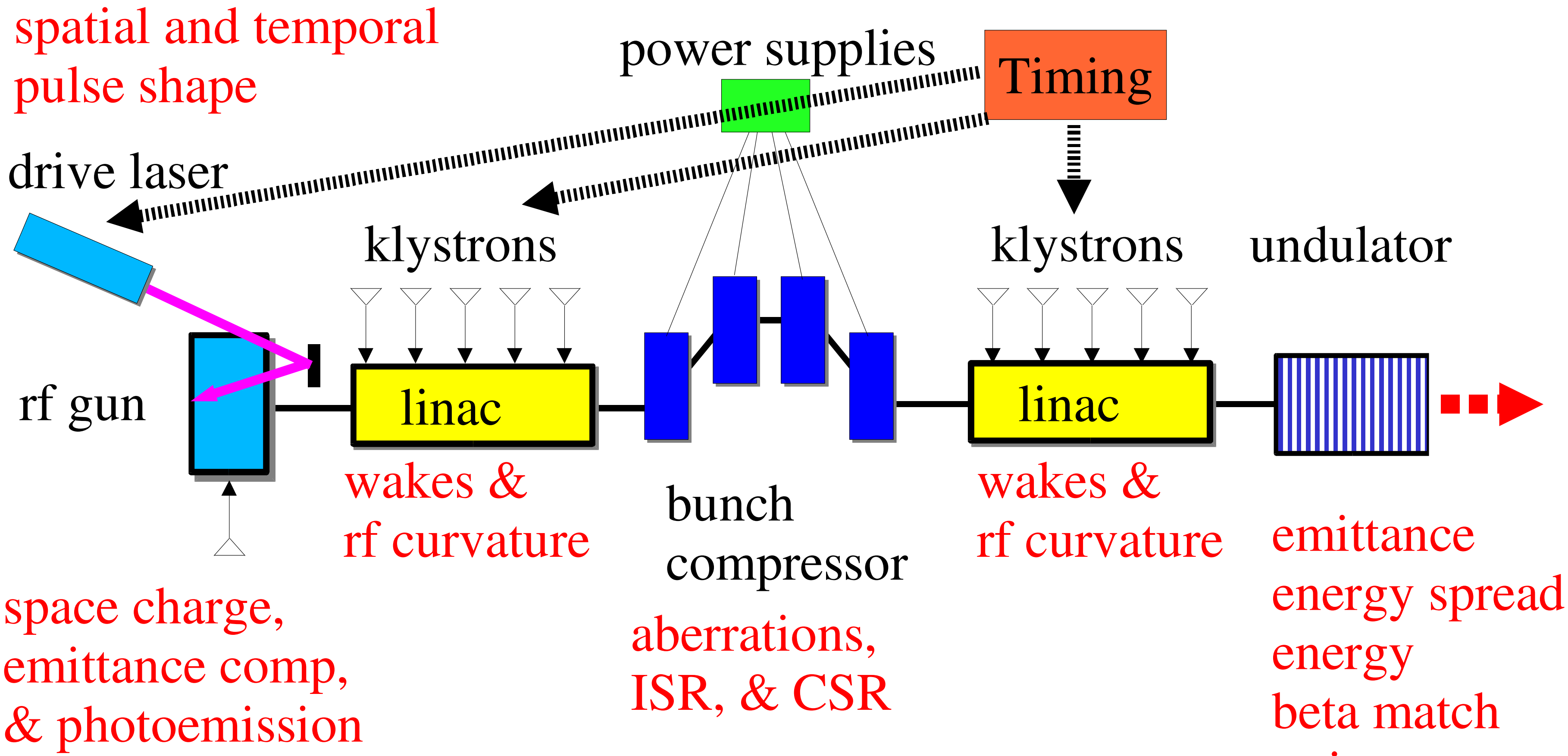
Outline

- Why do start–to–end (S2E) simulations?
- Simulation methods and codes
- Example: S2E simulation of LCLS
- What's next?
- Conclusions

~~Simplified~~ SASE FEL Schematic



Simulation Methodology

- We *do not* want to write a new, all–encompassing S2E code.
- Need a flexible and robust method of using existing codes together
- Automate the preparation, execution, sequencing, and analysis of simulations.
  - Reduce impact of human error
  - Investigate more cases with less work
  - Model effects of errors and jitter

Photoinjector Simulation

- We used LANL's PARMELA (V3)
  - Space charge
  - Beam file input
- Well–accepted code, but has limitations
  - No built–in jitter capability
  - Doesn't simulate wakefields or CSR
  - Unavailable for UNIX (Windows only)
- For jitter runs, scripts were used to perturb selected values in the input file

Linac Simulation

- We end the photoinjector simulations at 30 MeV for LEUTL and 150 MeV for LCLS.
- ANL's **elegant,** a 6–D tracking code, is then used
  - Fast 1–D transient CSR simulation
  - Longitudinal and transverse wakes
  - Optical aberrations
  - Flexible, built–in jitter simulation and correction algorithms

FEL Simulation

- Used 3–D, time–dependent code GENESIS (S. Reiche) for FEL simulations
- How to transform accelerator code output into FEL code input?
  - projected or whole–beam analysis is misleading
  - "typical" analysis slice is better
  - multislice analysis is best
- GENESIS' BEAMFILE capability supports multislice analysis

Combining Simulations

- Using files for data transfer is an obvious choice, but rarely a robust one
- Use ANL's Self Describing Data Sets (SDDS) file protocol for uniform, robust data transfer
  - very stable and well supported
  - used for many complex projects already
- **elegant** and GENESIS are SDDS−compliant
- PARMELA requires a (fragile) translator

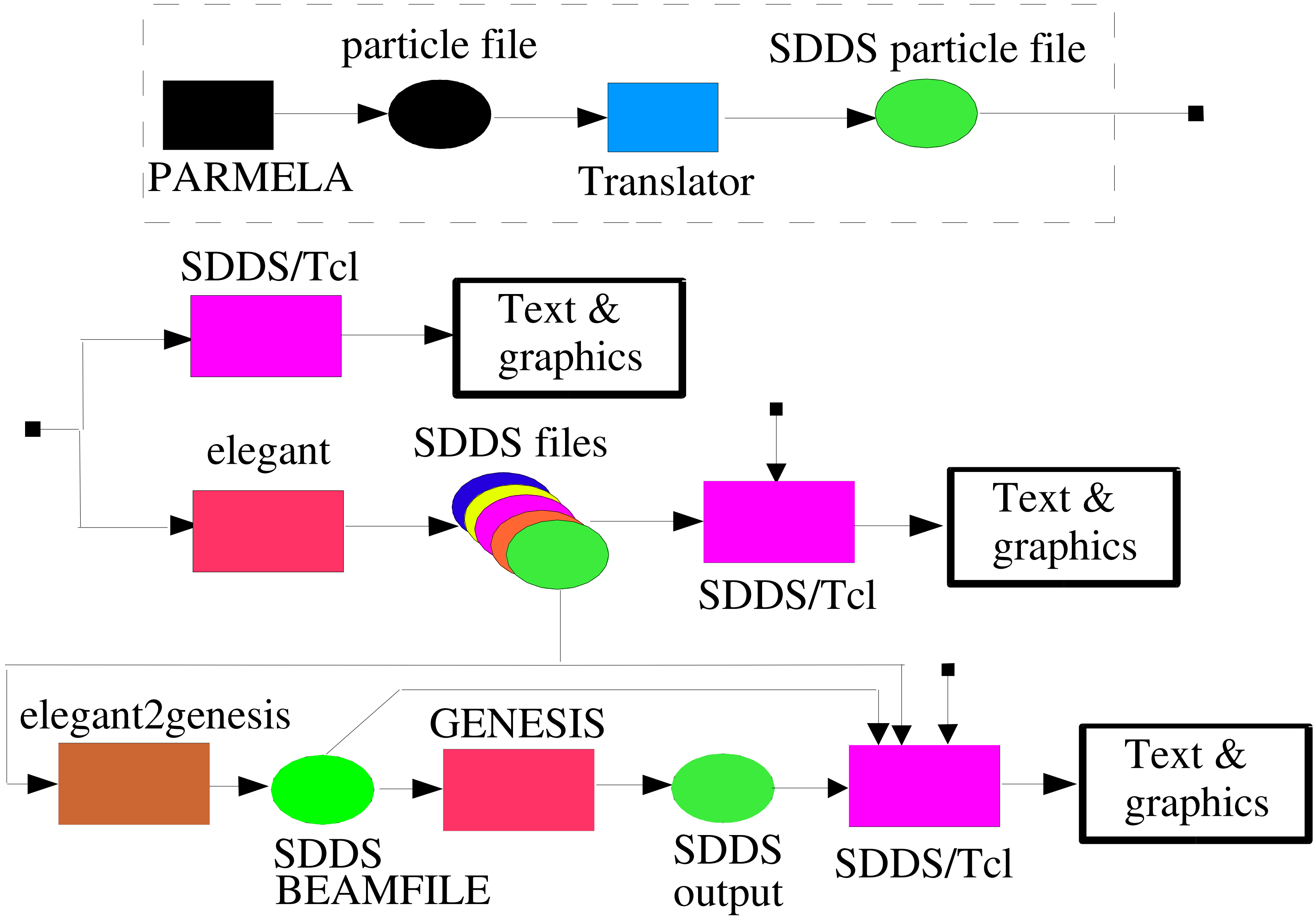
SDDS Advantages

- SDDS files are flexible and can be easily augmented.
- Users of files are unaffected by augmentation.
- SDDS files are self−documenting
- SDDS Toolkit programs provide generic, flexible pre− and post−processing.

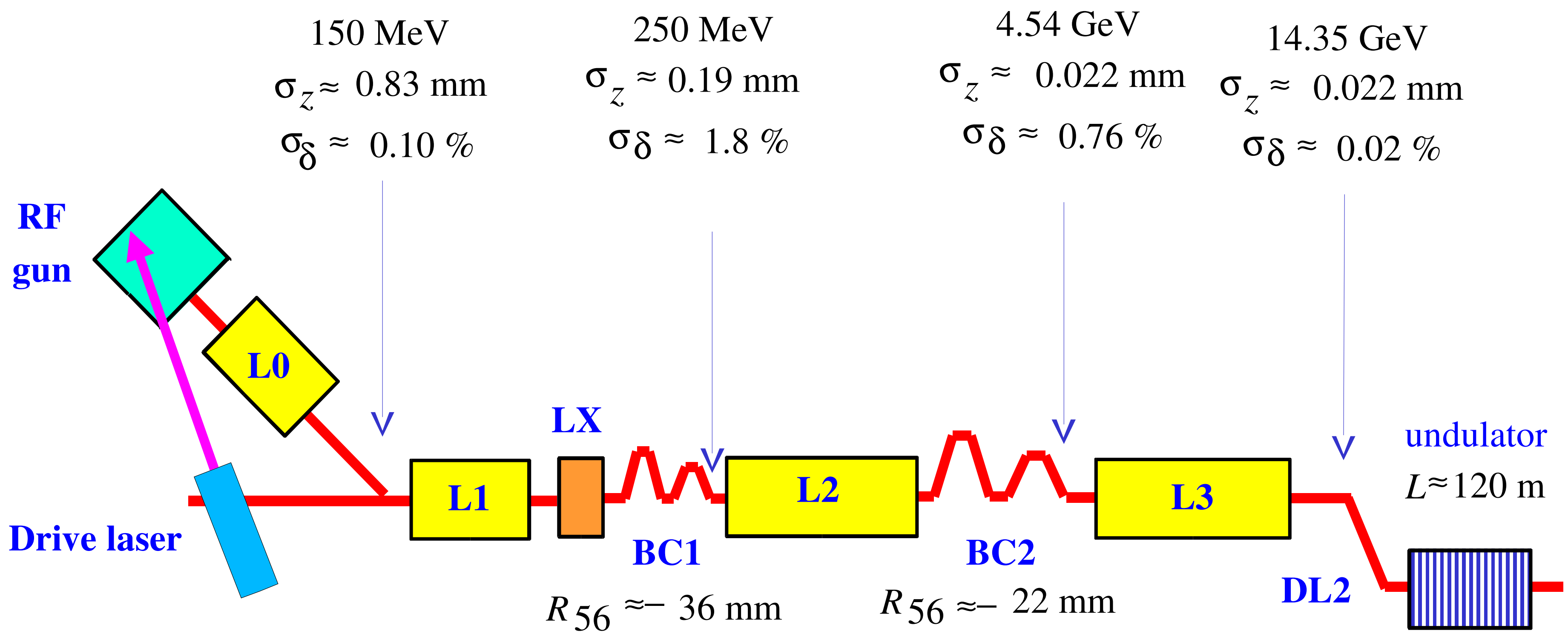
Orchestrating Simulations

- We use scripts to orchestrate all these programs
- Scripts allow
  - automated job setup and execution
  - automated job postprocessing
  - automated transfer of data between simulations
  - easy repetition and variation
- Such orchestration is possible only with commandline−driven programs

Simulation Diagram



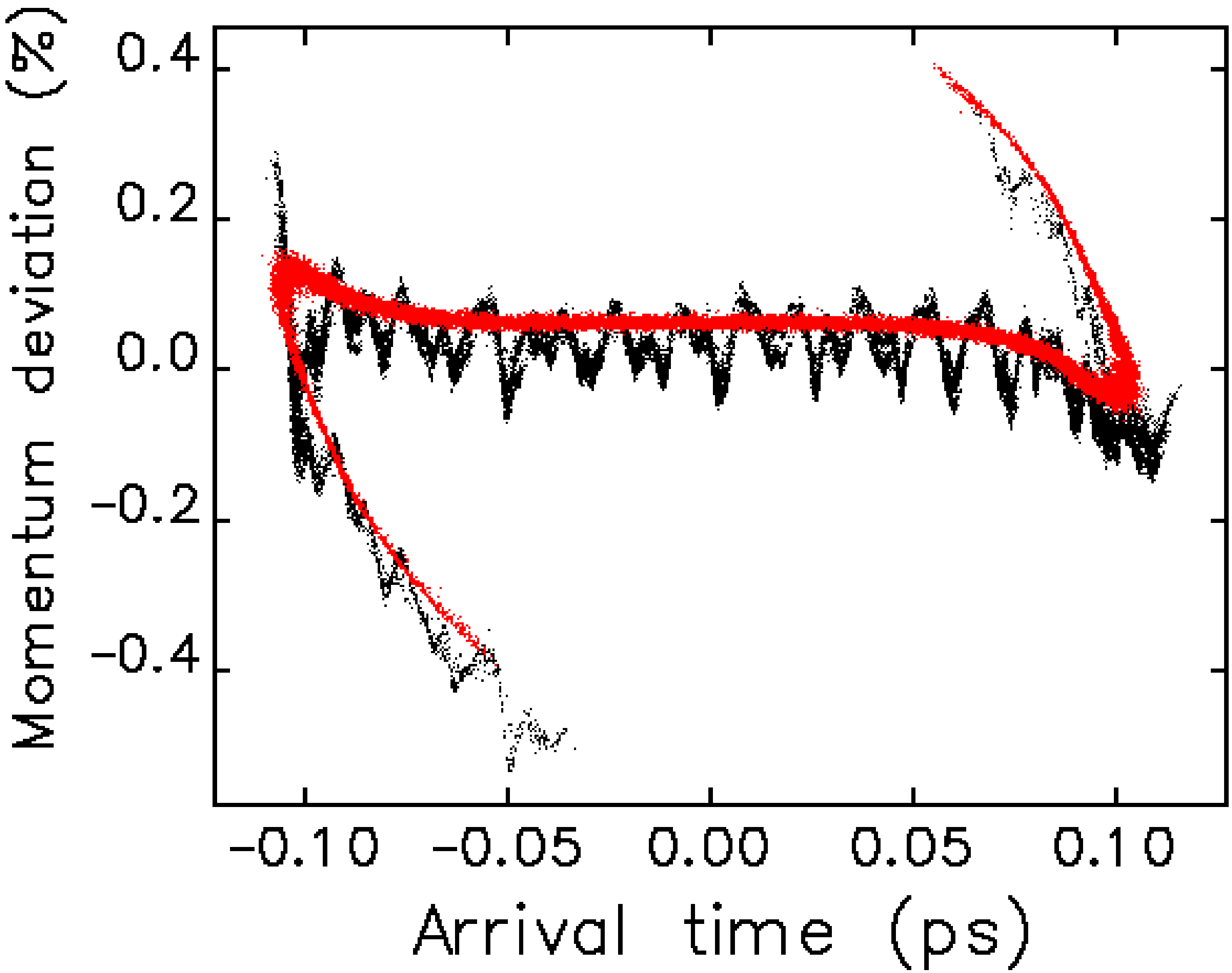
LCLS Schematic



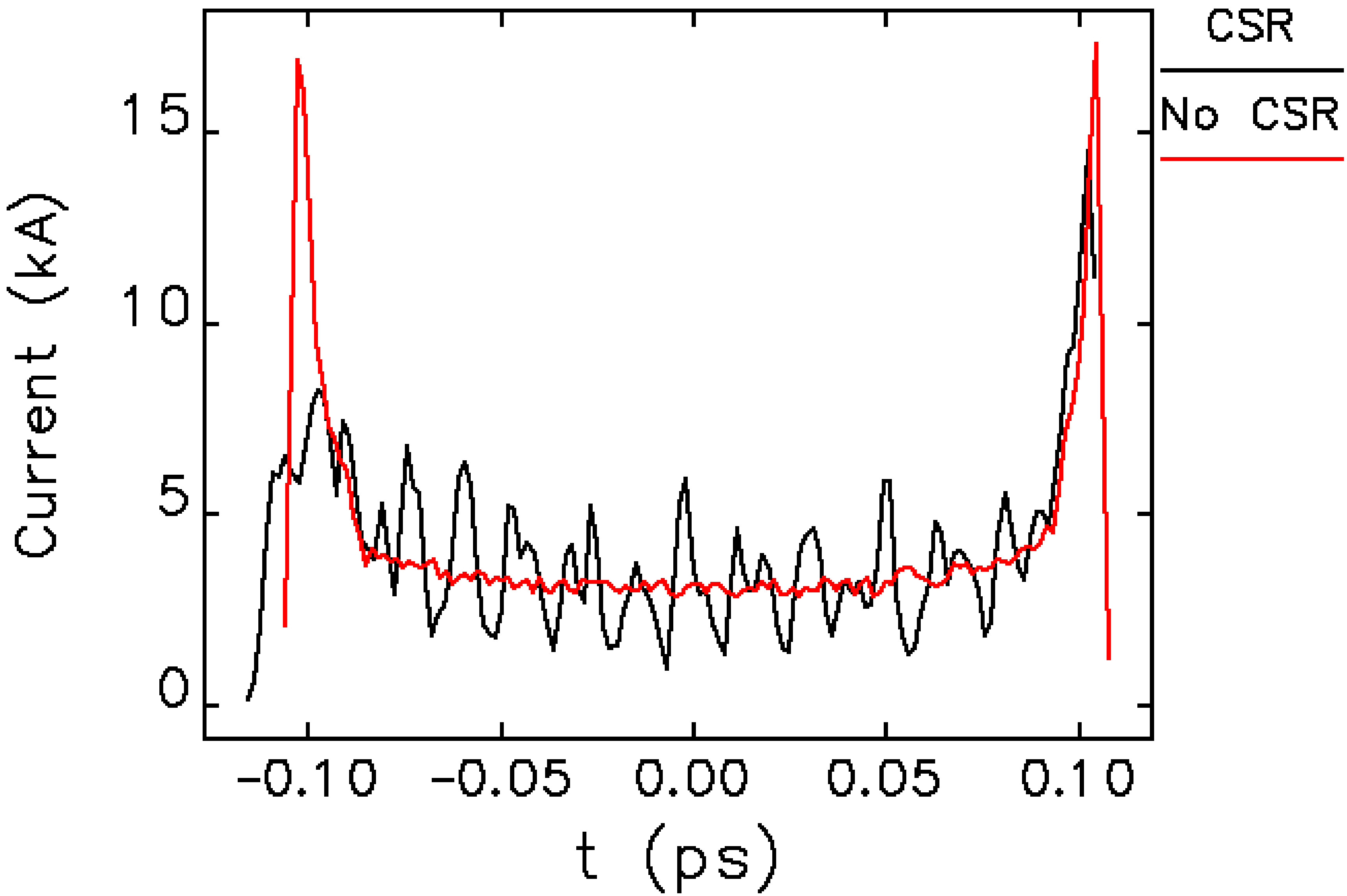
S2E Simulations of LCLS

- 100K particles tracked through PARMELA and **elegant**
- Bunch occupies ~136 slippage lengths
- Use "steady−state" mode in GENESIS with 136 slices
- Slice results combined to give averages and totals for FEL performance

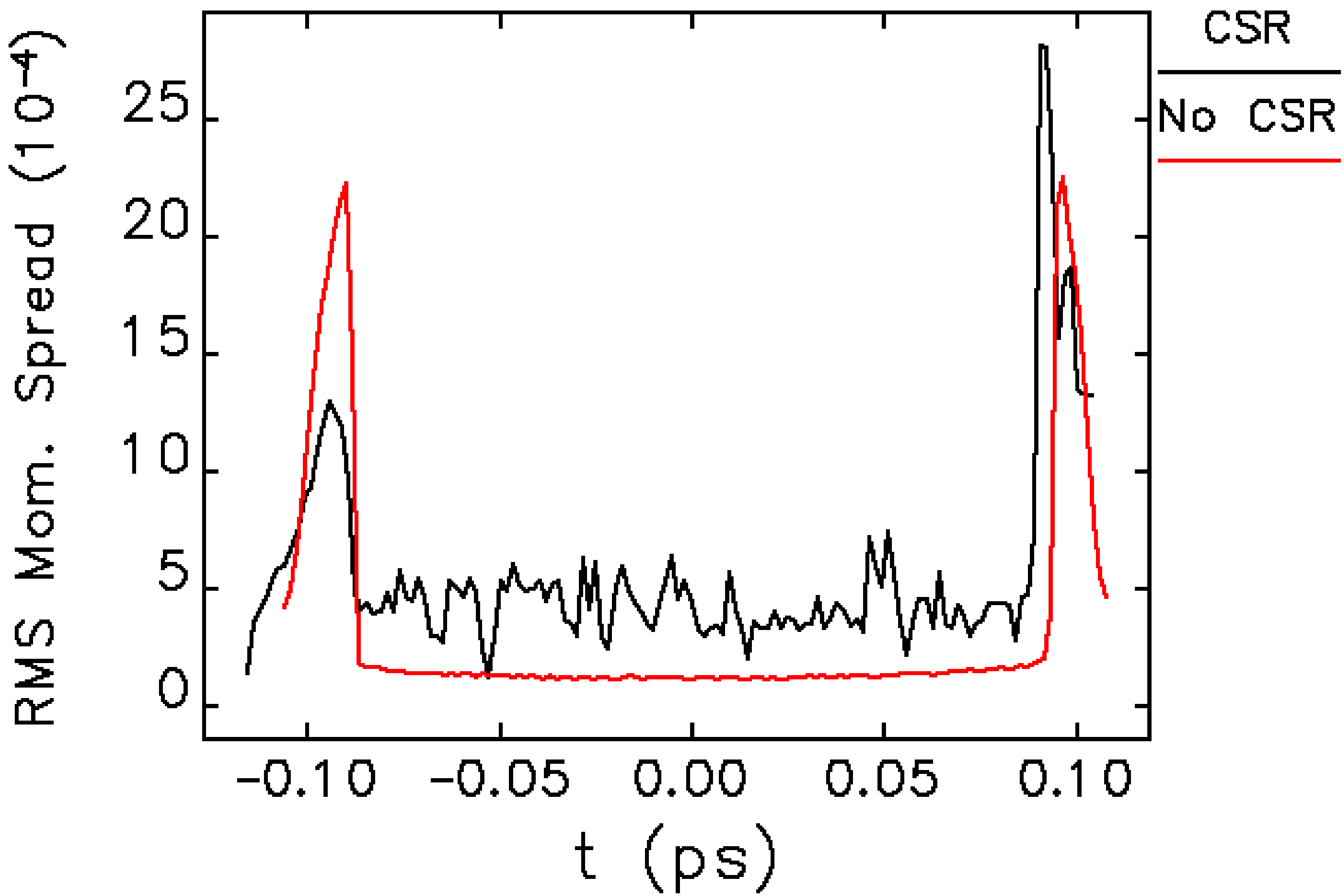
Longitudinal Phase Space at Undulator Entrance



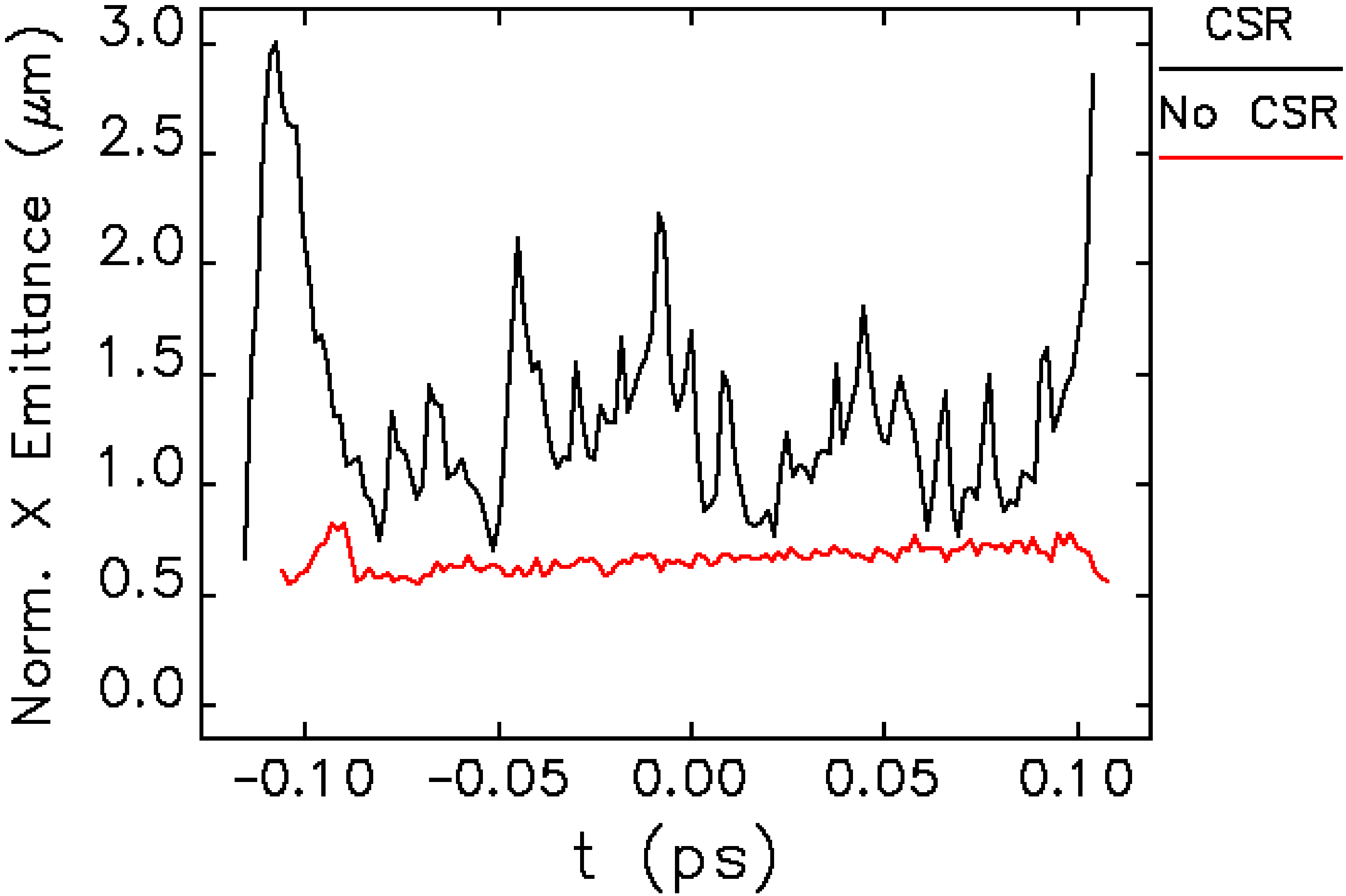
Slice Analysis



Slice Analysis



Slice Analysis



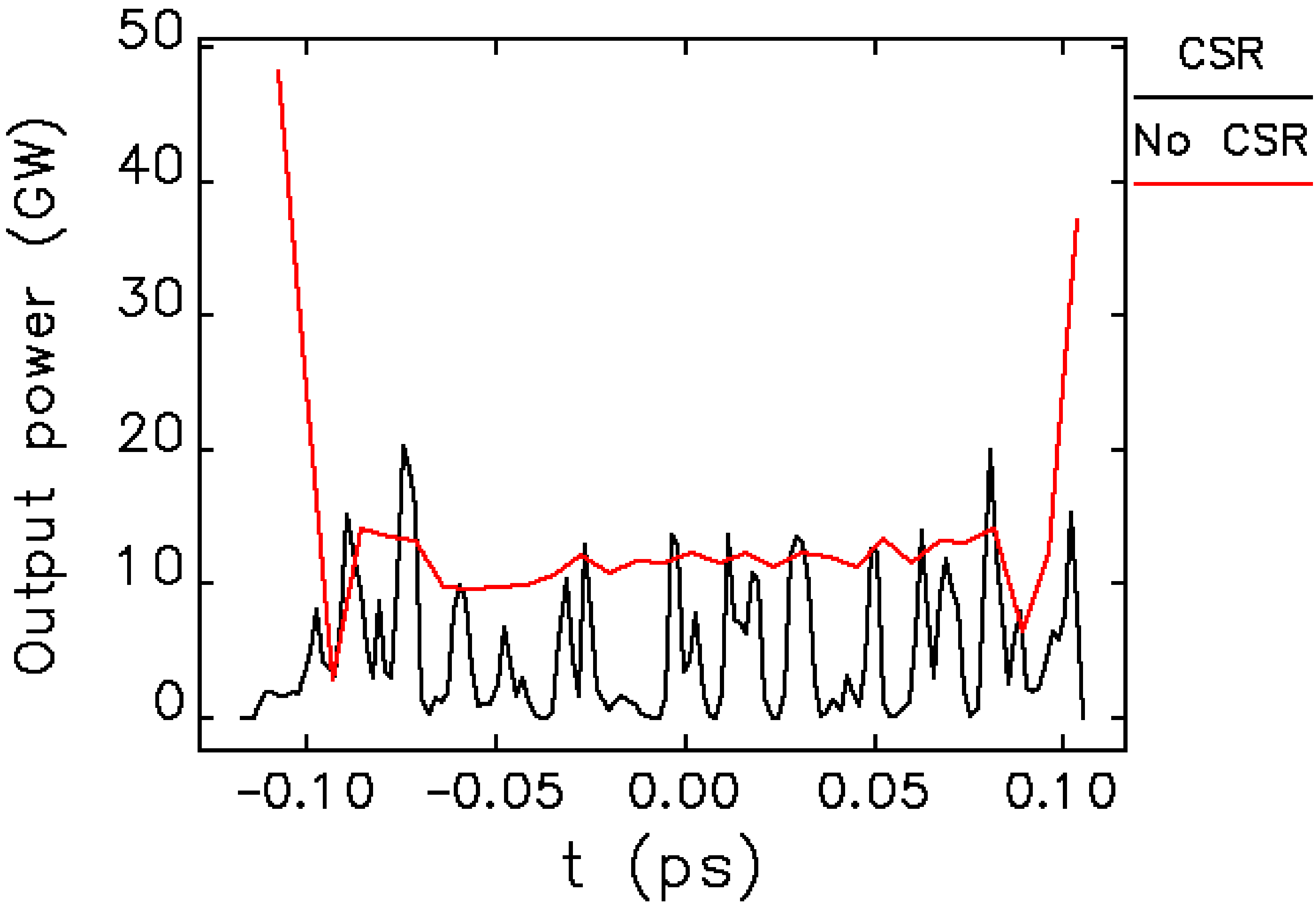
Predicted FEL Performance

- Results are averaged/summed the central 80% "core slices"

CSR ?	*Current (kA)*	*Bunch length (ps)*	*Frac. mom. spread (10^{-4})*	*Norm. x emit. (μm)*	*Gain length (m)*	*Output power (GW)*
no	3.3	0.17	0.49	0.66	3.2	10.7
yes	3.5	0.18	1.6	1.2	5	3.5

- Only a fraction of the slices saturate when CSR is included
- Bunch compressor design being revisited to reduce CSR problems.

Output Power Along the Bunch



S2E Jitter Simulations of LCLS

- It isn’t enough to look at the ideal behavior, we must look at the behavior with errors
- "Jitter" refers to any error that we can’t correct with alignment, tuning, feedback, etc.
- We simulated jitter, including
  - drive laser timing and energy
  - photoinjector and linac rf voltages and phases
  - bunch compressor power supplies

Jitter Levels for LCLS

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%

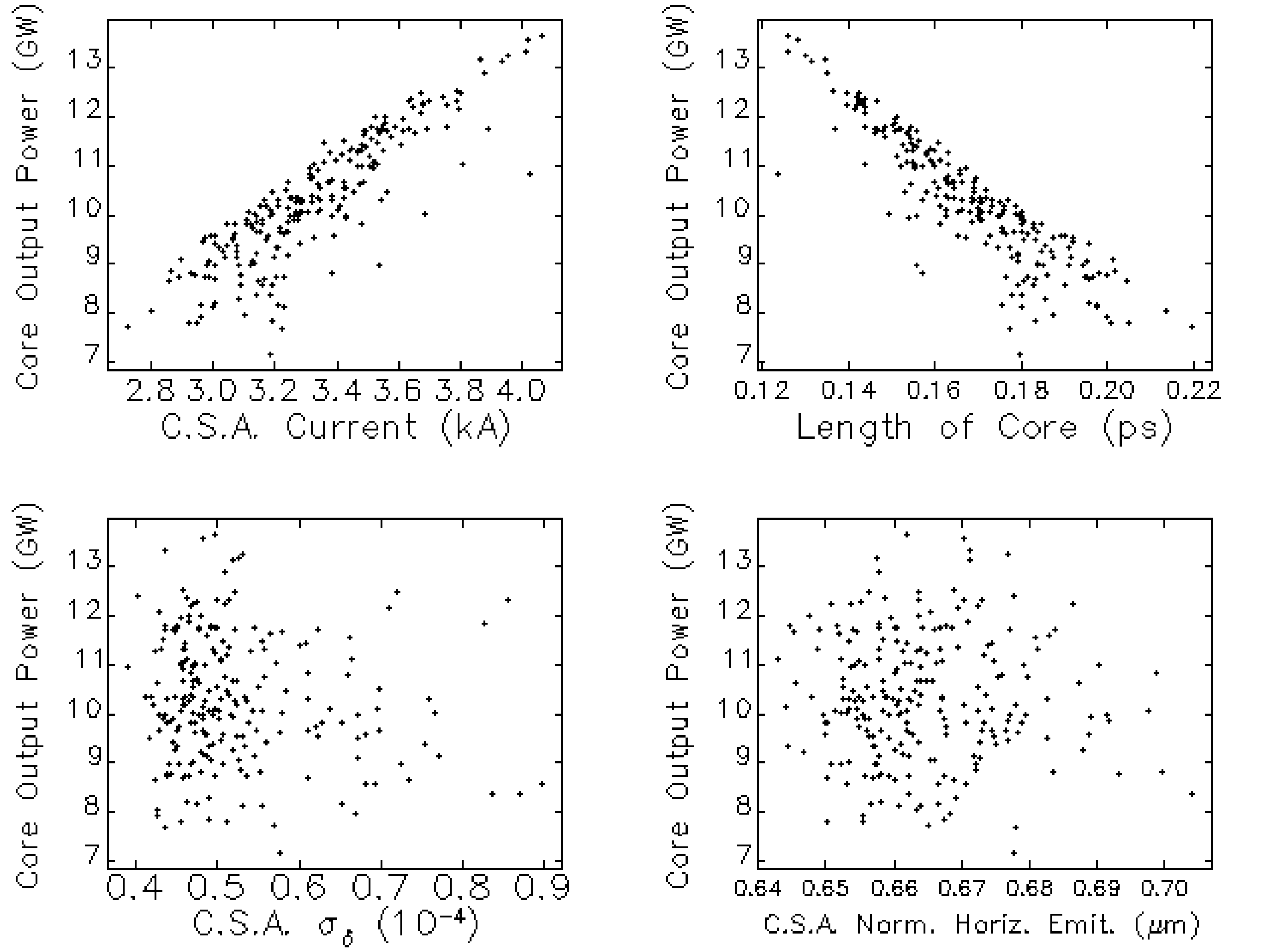
Quantity	***Rms Jitter Level***
X−band phase (1)	0.3 deg−X
X−band voltage (1)	0.25%
L2 phases (28)	0.07 deg−S
L2 voltages (28)	0.07%
L3 phases (48)	0.07 deg−S
L3 voltages (48)	0.05%
BC1 dipoles (2)	0.02%
BC2 dipoles (2)	0.02%
DL dipoles	0.01%

Predicted Jitter of LCLS FEL

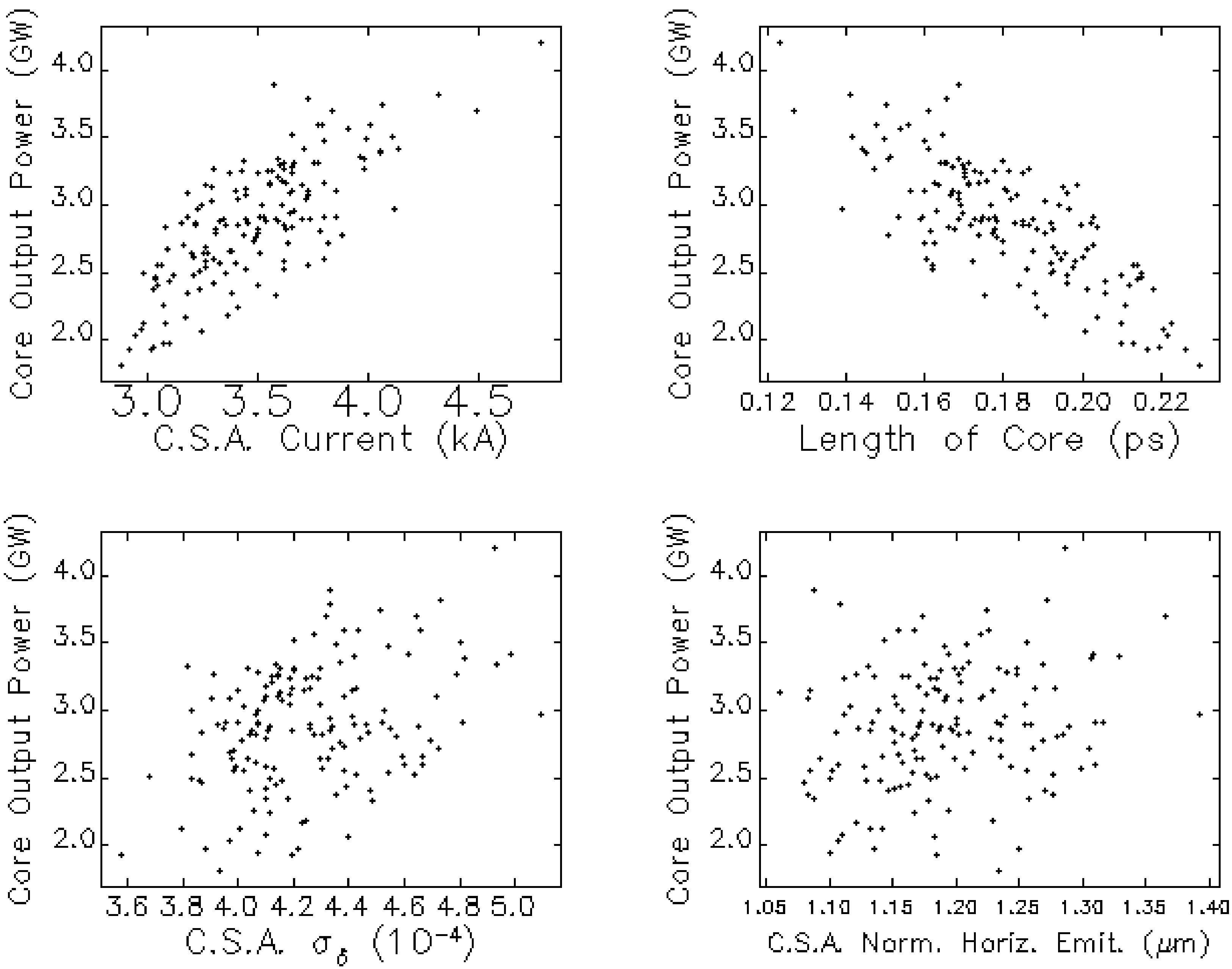
CSR ?	*Current (kA)*	*Frac. mom. spread (10^{-4})*	*Norm. x emit. (μm)*	*Gain length (m)*	*Output power (GW)*
no	3.3±0.2	0.49±0.04	0.66±0.01	3.2±0.1	10.3±0.9
yes	3.5±0.2	1.5±0.1	1.2±0.04	5.0±0.2	2.9±0.3

- 232 seeds without CSR and 149 with CSR
- Jitter in FEL output is roughly 10%

Jitter Correlation Plots (No CSR)



Jitter Correlation Plots (CSR)



Correlation Analysis

- Computing correlation coefficients allows determining causes of power variation

Quantity	*Responsibility (%)*
L1 phase error	25%
Photoinjector beam arrival time	17%
Photoinjector output charge	15%
Laser phase error	13%
X–band phase error	12%

- This type of analysis was used to refine the jitter specifications

Computing Resources

- 64 Sun UNIX workstations, linked by Grid Engine distributed queueing system.
- 6 PCs running Windows, linked by my feet.
- SDDS system well suited to concurrent execution on many computers.

Plans for S2E

- Add a drive laser model
  - realistic spatial/temporal profiles
  - pulse−to−pulse profile jitter
- Include cathode nonuniformity
- Include simulation and correction of static errors
- Adopt a UNIX photoinjector code (ASTRA?)
- Add improved CSR models
- Repeat with improved LCLS designs

Conclusions

- Existing programs can be combined in a robust fashion for large−scale S2E simulations
- Use of SDDS and scripts makes it work smoothly and reliably
- Stability requirements for LCLS are difficult but achievable
- Predictions for LCLS are motivating design changes