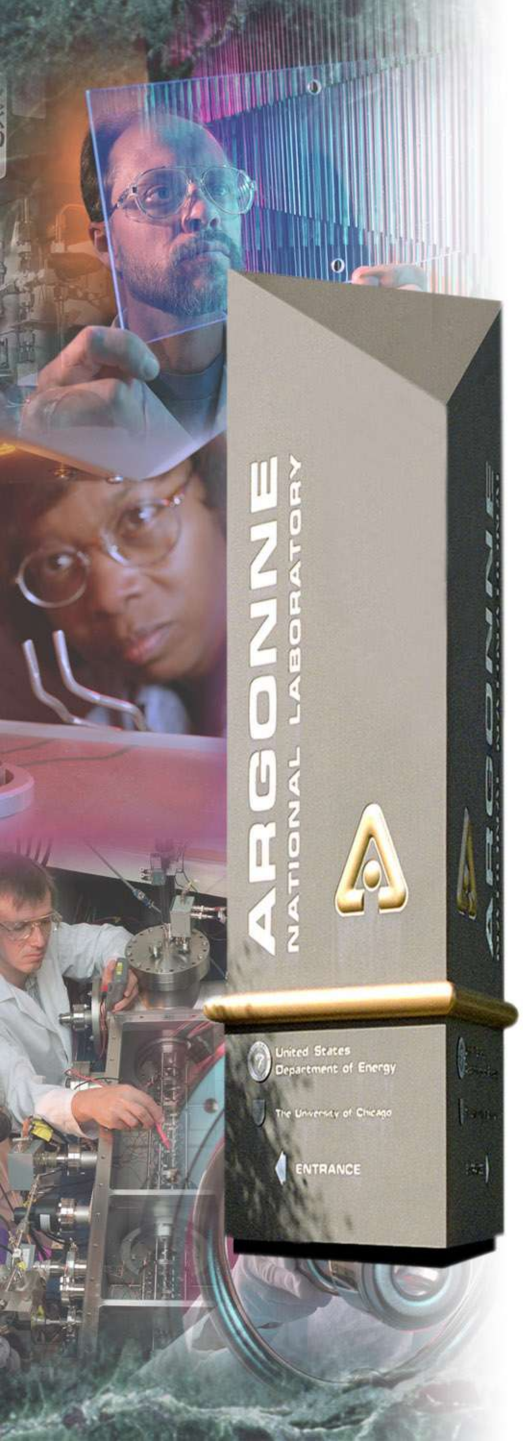


Start-to-End Simulations

Motivation, Methods, and Examples

Michael Borland
Operations Analysis Group
APS Operations Division
March 20, 2005

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Motivation

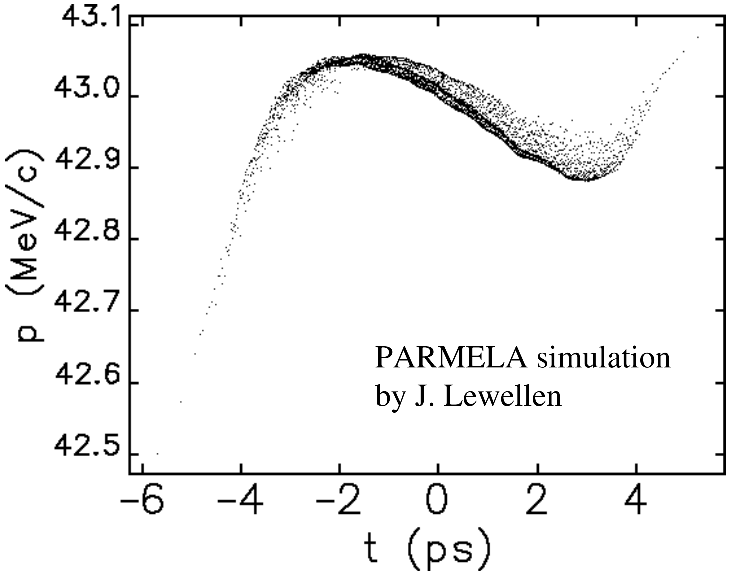
- In the early stages of an idea, we do estimates
  - Use approximate expressions
  - Use rms or FWHM parameters for beam
- Later we move on to simulations
- Complex work gets compartmentalized, e.g.,
  - Drive laser
  - Gun/injector
  - Linac and bunch compressor
  - FEL
- This approach holds the potential for disaster

Risks of Compartmentalized Approach

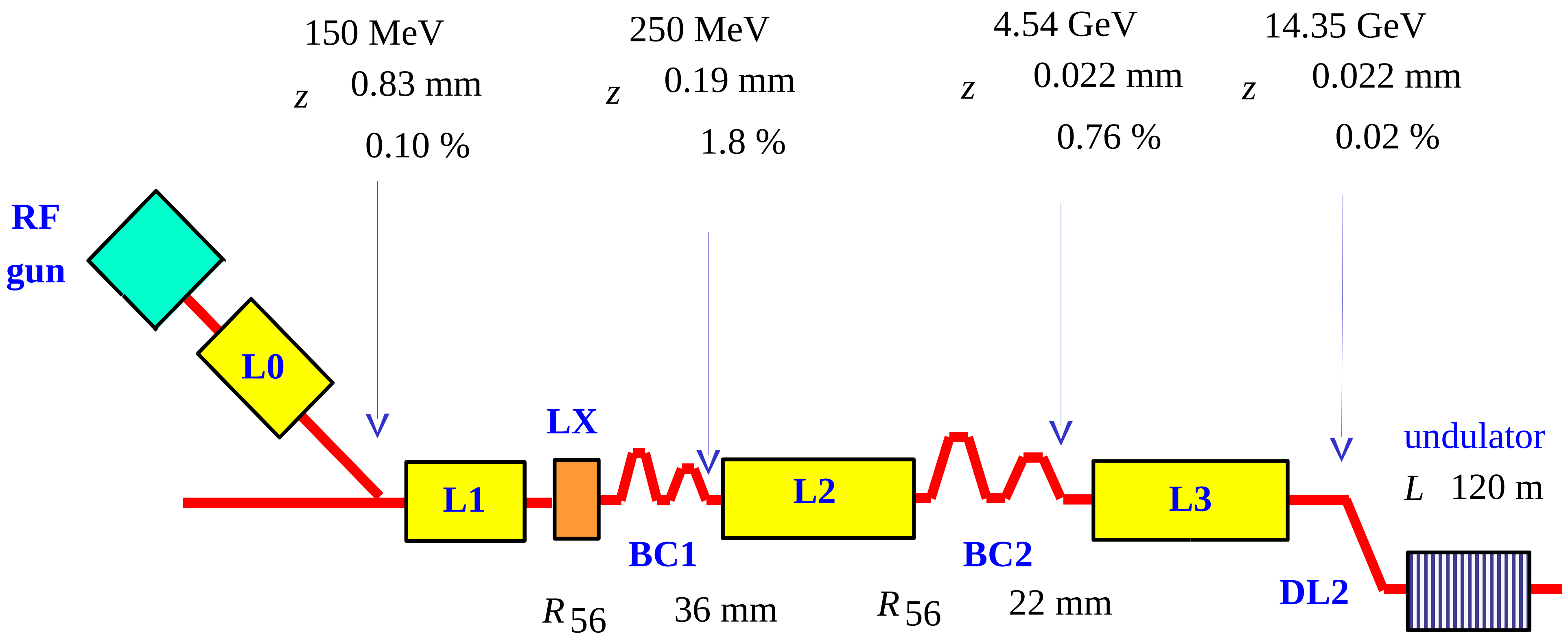
- Tendancy to give upstream performance in simplified terms
  - Rms beam properties
  - Ideal performance instead of realistic performance
- Use of simplified beam properties can hide vital details
  - Complex correlations in phase space
  - Spikes or modulations in distributions
  - Correlations that show up when errors are added
- S2E simulation preserves physics details of upstream systems
  - Can result in major design changes
  - S2E now common in FEL community

Some Specific Risks

- Beams from rf linacs are rarely smooth or gaussian
  - Rf photoinjectors particularly bad
- Many processes make matters worse
  - Wakefields
  - Rf curvature
  - Nonlinear terms in beam transport
  - Coherent synchrotron radiation
  - Longitudinal space charge
- Linac-driven light sources are uniquely sensitive to spoiling of initial beam brightness



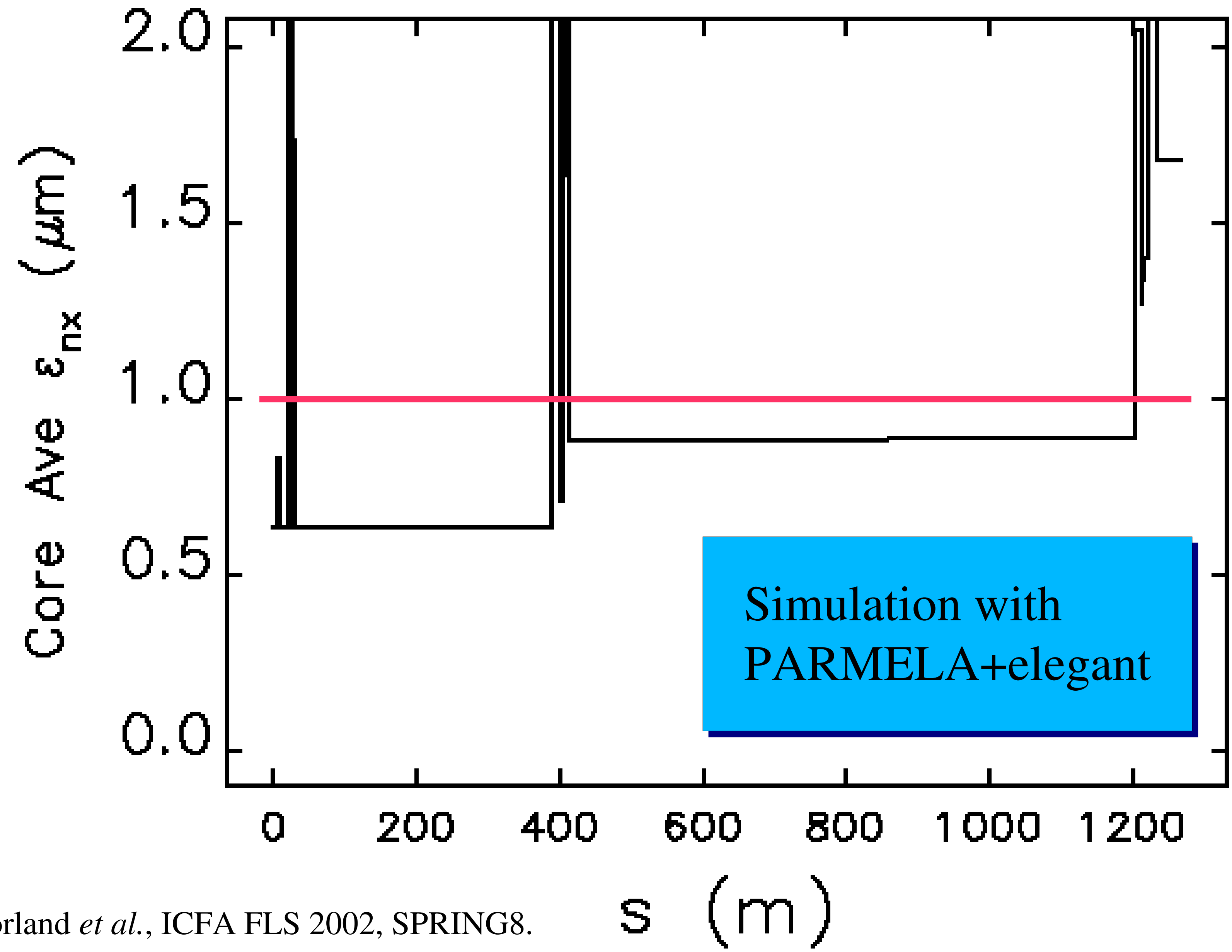
LCLS Configuration (06Dec00)



CSR simulations with gaussian beams and low longitudinal resolution predicted 5% projected emittance growth due to cancellation in double-chicanes, but ...

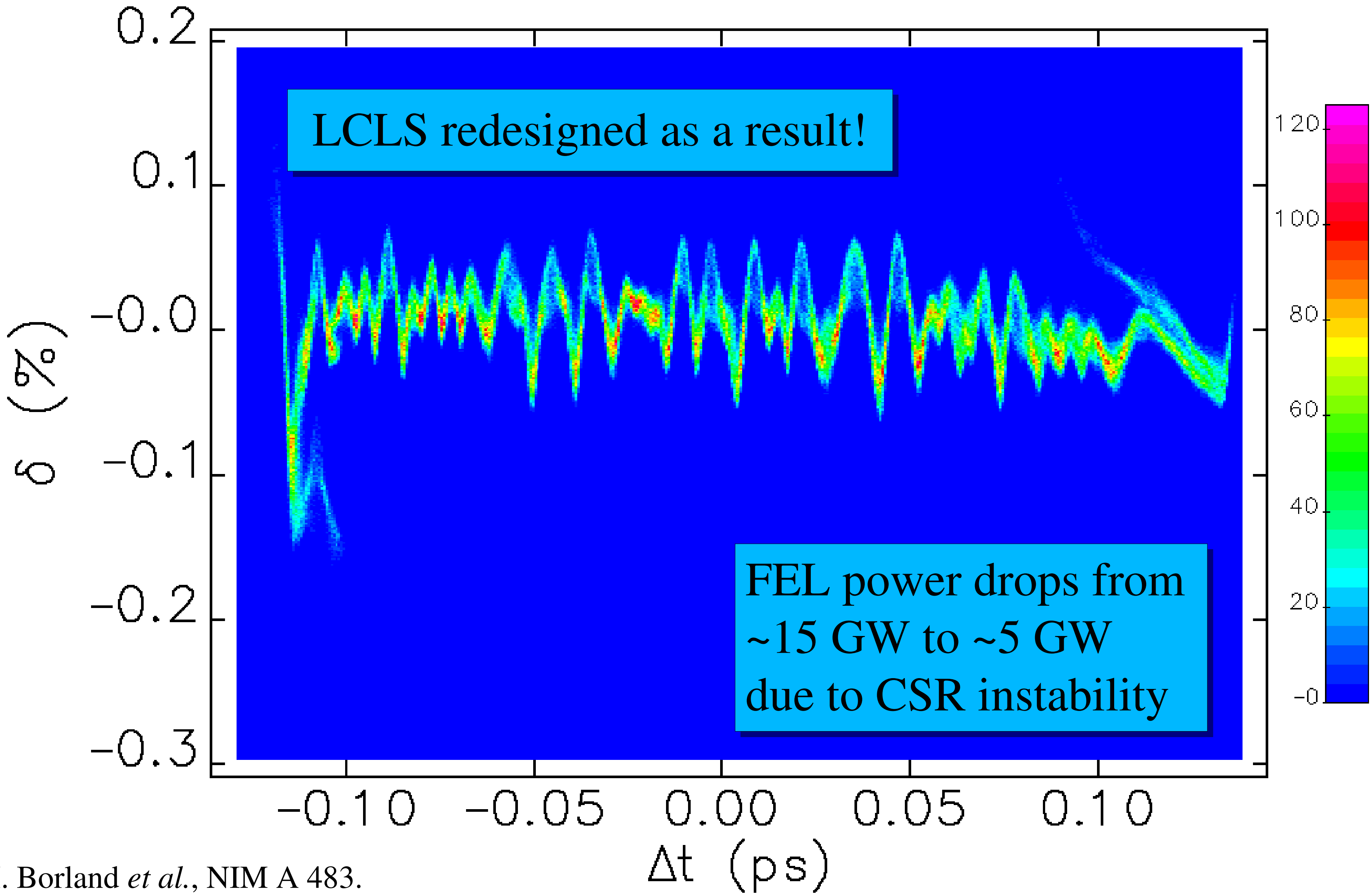
Graphic courtesy P. Emma (SLAC)

Emittance Growth from S2E Simulation



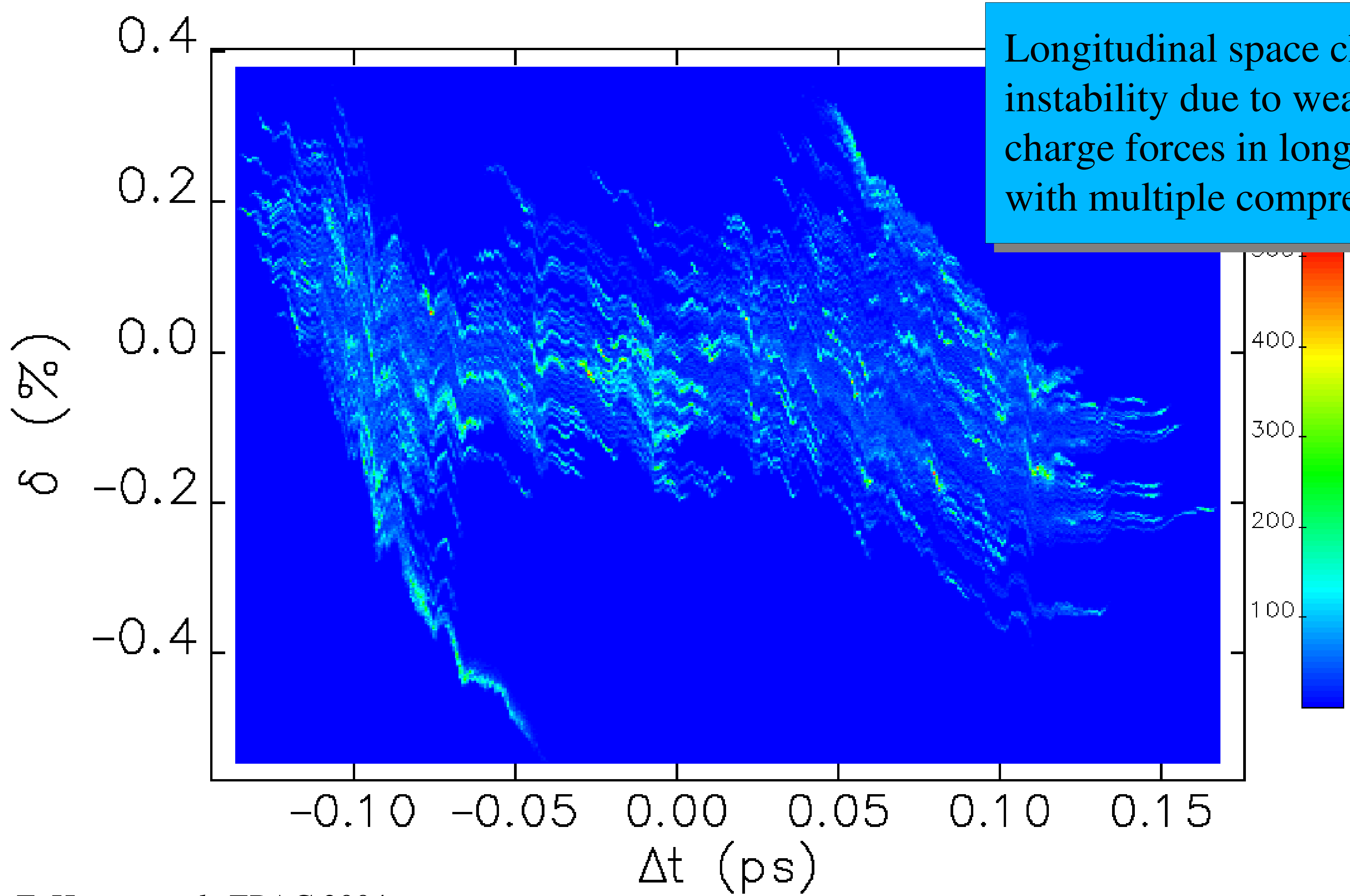
M. Borland *et al.*, ICFA FLS 2002, SPRING8.

CSR Microbunching Instability in LCLS



M. Borland *et al.*, NIM A 483.

LSC Microbunching Instability in LCLS



Longitudinal space charge instability due to weak space charge forces in long linac with multiple compressors

Z. Huang *et al.*, EPAC 2004.

Goals for S2E

- Make use of existing codes
  - Different codes are suited to different regimes and problems
  - Different disciplines continue to develop their own codes
- Requirements
  - Preserve maximal information in going from one code to next
  - Rapidly make changes to any input and rerun
  - Do analysis across all stages, e.g., correlate drive laser parameters with FEL output
  - Do full-system error simulations
  - Do full-system optimization
- Everything exists to do this now

A Partial List of S2E Projects and Codes

- Boeing group: PARMELA and FELIX
- LEUTL group: PARMELA, elegant, and GENESIS
- SLAC/APS group: PARMELA, elegant, and GENESIS for LCLS jitter simulations
- SLAC/UCLA group: PARMELA, elegant, and GENESIS for LCLS time-dependent FEL simulations
- TTF group: ASTRA, TraFiC^4, elegant, and FAST
- VISA group: PARMELA, elegant, and GENESIS

Code Issues

- Every code has its own data format(s)
  - Must write a translator between each code pair!
- Data formats may change when either code is upgraded (e.g., PARMELA V2 vs V3)
  - Must rewrite the translator for new data
  - Must keep the old one for use with old data
- If you aren't a programmer, it may be too much trouble
  - Uncooperative codes encourage sloppy simulation
- APS-developed SDDS file protocol is a solution

SDDS Protocol

- SDDS = Self Describing Data Sets
- File protocol
  - A way to describe parameters, columns, and arrays in a file
  - Includes units, data types, description, etc.
- Programs detect what's in the input
  - Inform user if input is incomplete/inappropriate
  - Supply defaults for missing data
  - Detect/convert wrong units
- SDDS makes programs hard to break and easy to upgrade

SDDS Toolkit

- SDDS Toolkit
  - Suite of generic programs that read and write SDDS files
  - Data analysis, manipulation, and display
  - Comparable to MATLAB plus a database
- SDDS programs are like operators
  - Apply sequentially to dataset for arbitrary transformation
  - Use from command-line or in scripts
  - Open architecture: anyone can add a private operator
- Open source
- Well supported (vital part of the APS control system)

SDDS Advantage for Simulations

- Developer
  - Ready-made post-processing suite for any compliant code
  - No code-specific post-processor to maintain
  - Separate graphics from the physics code
  - Upgrade (e.g., add output) without hurting users
- User
  - Supports scripting and automation
  - Ideal for concurrent simulation using a cluster
  - Use to create translators between codes (even non-SDDS codes)
  - Don't have to learn a new post-processor for each code

SDDS Compliant Codes

- elegant (M. Borland)
  - 6 D tracking code
  - Canonical integration or matrices
  - Rf cavities, deflectors, time-dependent kickers, etc.
  - Wakefields (short and long-range)
  - Incoherent and coherent synchrotron radiation
  - Longitudinal space charge
  - Can run other programs as modules in a beamline (Linux only)
  - Open source
  - Core of APS-developed simulation suite

SDDS Compliant Codes

- spiffe (M. Borland)
  - 2.5 D particle-in-cell code for rf gun simulation
  - Particle output read directly by elegant
- shower (L. Emery)
  - EGS4 wrapper code for electron-gamma showers
  - shower2elegant and elegant2shower scripts provide coordinate transformations
- Brightness curves: sddsbrightness (H. Shang, R. Dejus)
- Intrabeam scattering: ibsEmittance (L. Emery, M. Borland)
- Potential well distortion: haissinski (L. Emery, M. Borland)
- Beam lifetime: beamLifetimeCalc (M. Borland)

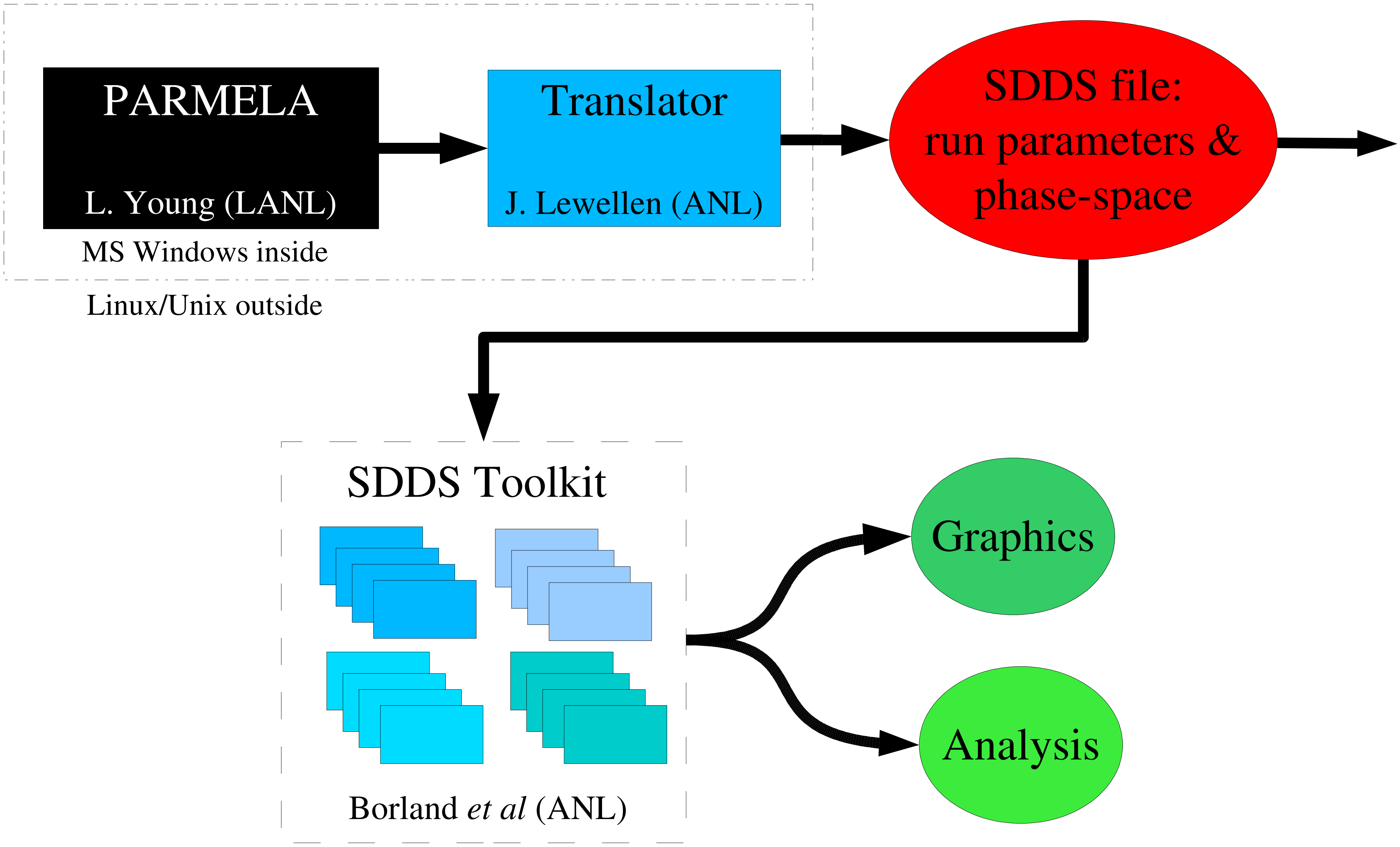
SDDS Compliant Codes

- ABCI/APS and MAFIA/APS
  - Provide wakefield data in form used by elegant
- URMEL/APS
  - Provides rf mode data in form used by elegant
- Our goal is a complete suite of accelerator-related codes with minimal barriers to cooperative use
  - We welcome collaborators on this!
  - Tell your favorite code author to get with it!

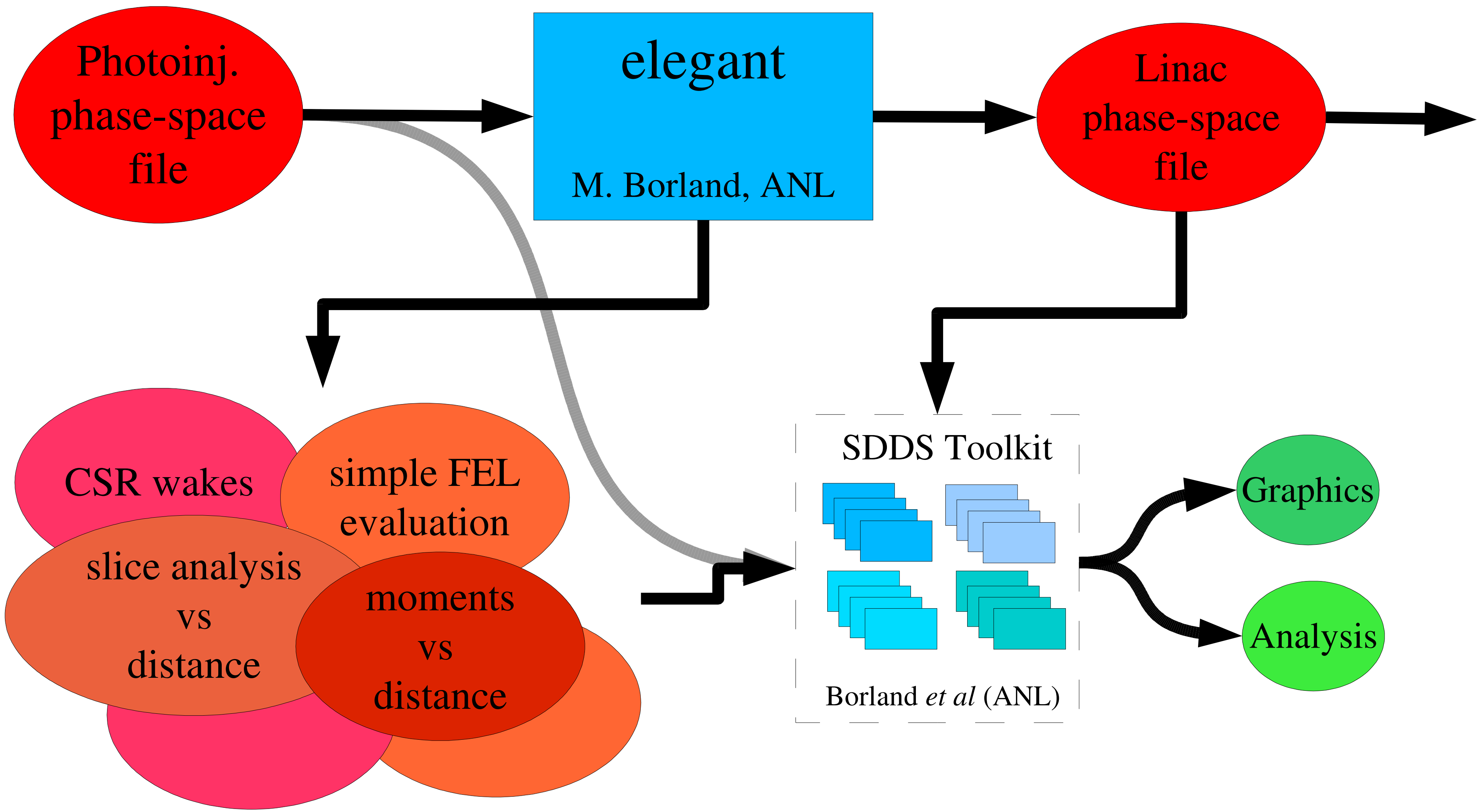
Full-System Optimization

- SDDS-based optimization (H. Shang, APS)
  - Generic SDDS-configured sequential optimizer
  - Parallel genetic optimizer for Linux cluster
  - Parallel Simplex optimizer for Linux cluster
- Can optimize the results of running any program or sequence of programs
- User supplies two scripts
  - Script that accepts input parameters and runs simulation program(s)
  - Script that processes output and returns penalty function
- Linux only

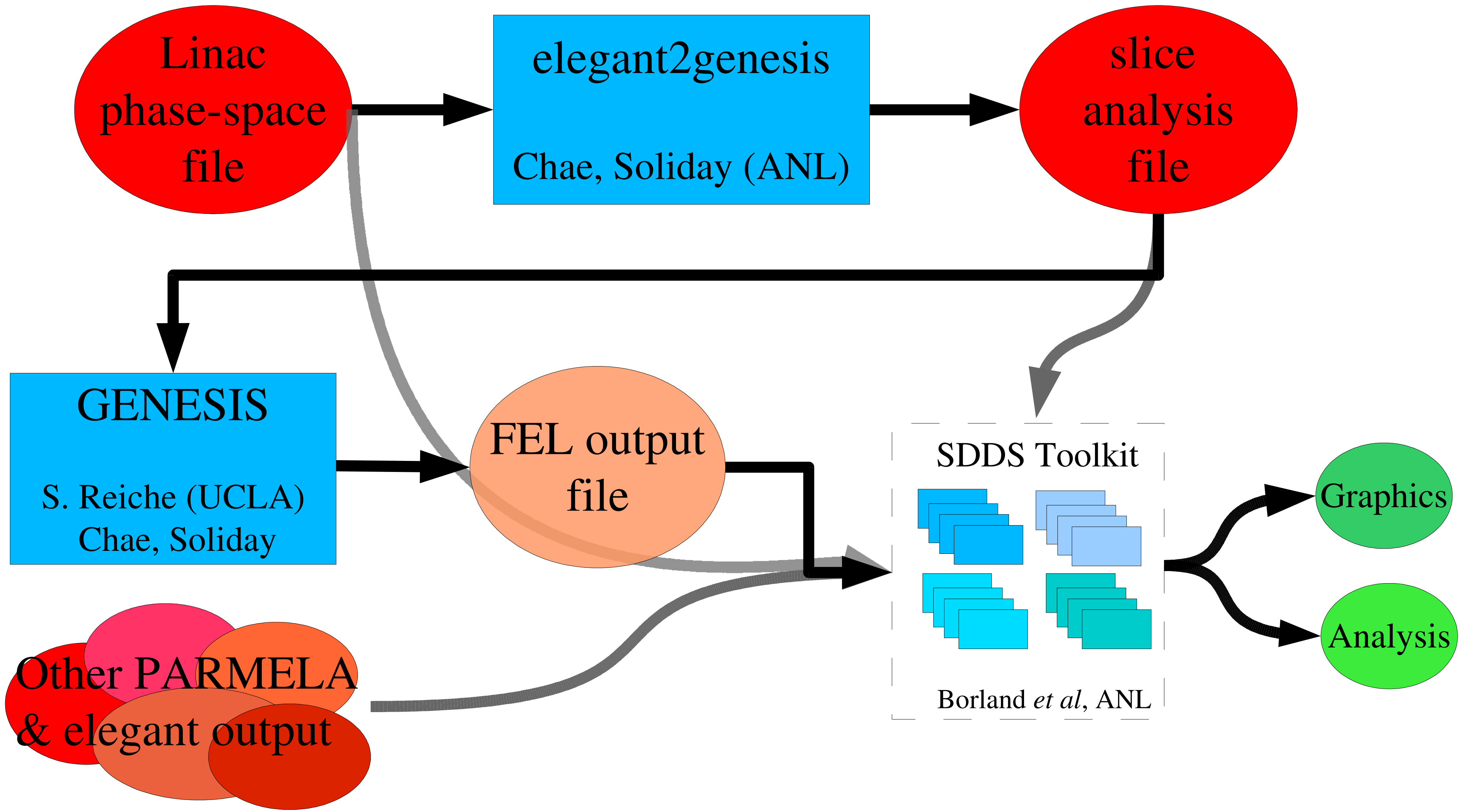
LCLS S2E Simulation Components



LCLS S2E Simulation Components



LCLS S2E Simulation Components



LCLS S2E Jitter Simulations

- "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

LCLS S2E 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 should reduce projected emittance.
  - Surprise: makes power jitter 40% worse
- 230 seeds used.

LCLS S2E Jitter Simulations

- Correlation analysis can explain the causes of variation in FEL 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.

Conclusion

- S2E simulation has made significant contributions to FEL projects, including
  - Discovery of CSR microbunching instability in compressors and validation of cure
  - Verification of LSC instability and cure
  - Refinement of jitter specifications
  - Discovery of unintended consequence of correction quads
- Software tools well-developed, available now
- If you aren't doing S2E simulation for your FEL or ERL proposal, you may get an unpleasant 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
- Created with open source software

Linux