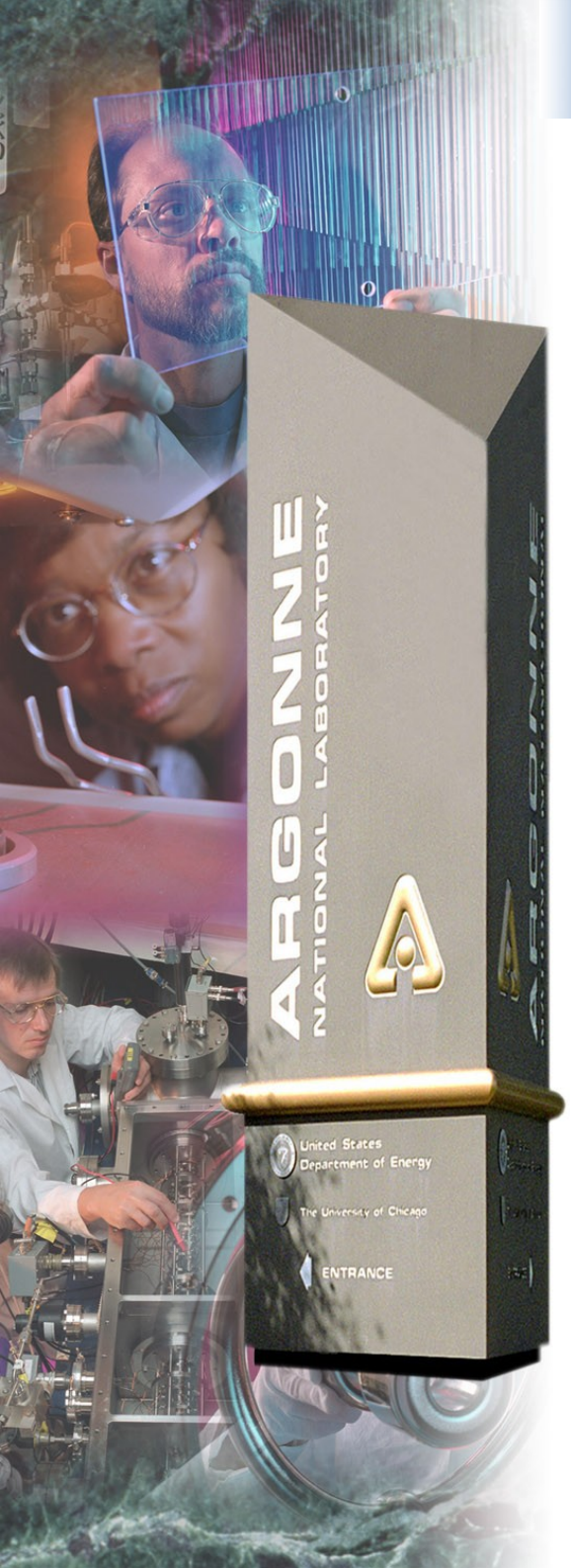

ARGONNE NATIONAL LABORATORY

Introduction to elegant

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August 18, 2006

THE UNIVERSITY OF CHICAGO

Office of Science
U.S. DEPARTMENT OF ENERGY

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Outline

- Notable applications of **elegant**
- Program philosophy
- Details
  - Elements in **elegant**
  - Computations performed by **elegant**
- Related programs
- Examples
- Acknowledgements.

Notable Applications of elegant

- Beam transport lines for the SSRL pre-injector
- All APS accelerators now use **elegant**-designed optics
  - Design of the APS Positron Accumulator Ring and transport lines
  - Low-emittance optics development for the APS and APS booster
  - Design of bunch compressor and new linac optics for LEUTL
- APS top-up safety tracking
  - Ushered in a new mode of storage ring operation
- LCLS start-to-end and S2E jitter simulations
  - Discovered CSR-driven microbunching instability
- Used world-wide for FEL driver linac design, e.g.,
  - SLAC, DESY, BESSY, Sincrotrone Trieste, SPRing-8
- Used world-wide for ERL projects, e.g.,
  - Cornell, JLAB, BNL, Daresbury, JAERI
- Used to design the LTI Compact Light Source (commercial accelerator).

Quality Control

- **elegant** is important to APS operations and to users around the world
- Quality control is taken very seriously
- Source code is in CVS for version control and tracking
- Use extensive regression testing to "guarantee" that program updates don't break anything
  - When a feature is added, it is thoroughly tested
  - Selected test results are saved and used for checking of later versions
  - Program design allows us to largely automate this process.

Computer Science Philosophy

- Adopt a tool approach
  - Graphics and display functions external to program
  - Vastly simplifies the simulation code
  - Allows common pre- and post-processing tools for many codes
- External scripting required and supported
  - Program delivers data to user, not graphs of data
  - Data provided in a form that emphasizes scripting, not manual examination
  - Simplifies the program while empowering the user
  - Allows use of open-source scripting languages
  - Well suited to automated and cluster computing.

SDDS

- SDDS = Self-Describing Data Sets
  - A file protocol for data storage
  - A toolkit of programs that transform such files
  - A set of libraries for working with such files
    - *Support for C/C++, Tcl/Tk, Java, MATLAB, Python, FORTRAN*
  - A central component of the APS control system
- Knowing SDDS is key to using **elegant** effectively
  - Pre- and post-processing
  - Graphical and text output
  - Linking of multiple simulations and codes
  - Cluster computing.

Why Use SDDS Files?

- Programs that use SDDS can be made robust and flexible
  - Check existence, data-type, units of data instead of crashing or doing an incorrect calculation
  - Respond appropriately to the data provided
    - *Exit and warn user if required data is missing, has unknown units, etc.*
    - *Supply defaults for missing data (e.g., old data set)*
- Existing data doesn't become obsolete when the program is upgraded
- Self describing files make generic toolkits possible, which saves effort on writing pre- and post-processors
- SDDS-compliant programs are “operators” that transform data
  - Using pipes allows concatenating operators to make a complex transformation
  - UNIX-like philosophy: everything is a (self-describing) file.

Toolkit Approach to Physics

- **elegant** is a very complex SDDS "operator."
  E.g., it
  - Transforms phase space from beginning to end of a system
  - Transforms magnet parameters into, e.g., Twiss parameters, tunes
- All input to and output from **elegant** is in SDDS files *except*
  - Lattice structure
  - Command stream
- **elegant**'s capabilities are augmented by other operators
  - SDDS toolkit: a large collection of inter-operative data analysis, manipulation, and display programs
  - SDDS-compliant physics programs.

Capabilities of elegant: elements

- **elegant** has no assumed "best" approach to modeling
  - User can often select from expedient methods
- Matrix methods
  - Second-order matrices for drifts, solenoids, bends, and correctors
  - Third-order matrices for quads, sextupoles, and alpha magnets
  - User-supplied second-order matrix
- Symplectic methods:
  - Fourth-order Ruth integrator for bends, quads, sextupoles, higher multipoles.
  - Hamiltonian has exact energy dependence
  - Can invoke classical synchrotron radiation and quantum excitation for tracking.

Capabilities of elegant: elements

- Time-dependent elements
  - Kicker with user-specified waveform
  - Rf cavities with exact phase dependence
    - *Simple cavity with perfect source*
    - *Phase-, frequency-, and amplitude-modulated*
    - *Phase-, frequency-, and amplitude-ramped*
    - *User-specified on-axis field profile*
    - *Deflecting cavity with noise and modulation*
  - Momentum ramp
  - Traveling-wave accelerator.

Capabilities of elegant: elements

- Numerically-integrated elements
  - Planar undulator with co-propagating laser beam
  - Solenoid from user-supplied field map
  - Dipole with extended fringe fields
- Apertures/material
  - One- and two-sided rectangular, elliptical, and super-elliptical collimators
  - Scrapers with optional elastic scattering
  - Foil elastic scattering.

Capabilities of elegant: elements

- Collective effects
  - Intra-beam scattering in rings (L. Emery)
  - Short-range longitudinal and transverse wakes
  - Longitudinal- and transverse rf modes
  - Coherent synchrotron radiation in dipoles and drifts
  - Longitudinal space charge in drifts and cavities
  - Linear transverse space charge (A. Xiao)
- Diagnostics
  - Beam position monitors
  - Particle coordinate/property analysis points (to SDDS file)
  - Histogram analysis points (to SDDS file).

Capabilities of elegant: elements

- Miscellaneous
  - SCRIPT element will incorporate an external program as an element in an elegant lattice
  - User-specified scattering distribution
  - Lumped-element synchrotron radiation
  - Pick-up/driver elements for simulating transverse single-bunch digital feedback in rings.

Capabilities of elegant: Calculations

- Twiss parameter computation
  - Optionally-computed on-orbit and with errors
  - Includes radiation integrals
  - Includes chromaticity to third order and first-order tune shift with amplitude
  - Optional computation of coupled Twiss parameters (V. Sajaev)
  - SDDS output
- Transport matrix
  - Optionally computed on-orbit and with errors
  - SDDS and text output vs s (first- and second-order)
- Floor coordinates
  - Fully three-dimensional computation
  - SDDS output.

Capabilities of elegant: Calculations

- Variation
  - Nested sweeps of “any” parameters of any elements
  - Sweep using values supplied in an external SDDS file
- Errors
  - Errors for “any” parameter of any element
  - User-selectable distributions, amplitudes, cutoff, ...
  - Linking of errors between elements
  - Multiple error sets in one run
  - Loading of error sets from SDDS files
  - Saving of error values to SDDS files.

Capabilities of elegant: Calculations

- Saving and loading
  - Optimized lattice can be saved
    - *To a new (text) lattice file*
    - *To an SDDS lattice parameter file*
  - SDDS file can be manipulated with Toolkit, reloaded
  - SDDS file can be generated by another program to provide loadable custom error sets.

Capabilities of elegant: Calculations

- Closed orbit
  - Variable or fixed path length
  - On- and off-momentum
  - SDDS output
- Correction
  - Will correct tunes, chromaticities, and trajectory/orbit
  - Does these sequentially with optional iteration
  - SDDS output
    - *trajectory/orbit correction matrix*
    - *corrector strengths*
    - *correction statistics*
    - *quadrupole strengths*
    - *sextupole strengths.*

Capabilities of elegant: Calculations

- Optimization
  - Optimizes user-supplied penalty function depending on almost any calculated quantity
    - *Final or interior beam parameters from tracking*
    - *Final or interior Twiss parameters*
    - *Global values like equilibrium emittance, tunes, chromaticities*
    - *Final or interior matrix elements*
    - *Final or interior floor coordinates*
  - Uses Simplex by default, but has other methods.

Capabilities of elegant: Calculations

- Beam generation
  - Gaussian, hard-edge, and other distributions
  - Optional quiet-start sequences
  - Bunch train generation
  - Initial distribution can be saved to SDDS file
- Beam importation
  - Load beam from SDDS file
    - *Previously-generated and saved*
    - *Previously tracked*
  - Sequences of beams in one SDDS file.

Capabilities of elegant: Calculations

- Aperture finding (dynamic and physical)
  - Searches for aperture boundary with optional subdivision of search interval
  - Various search modes
    - *Single- and multi-particle search starting from large amplitudes*
    - *Search along one or more lines starting at zero amplitude*
- Particle losses
  - Optional output of locations and coordinates of lost particles
  - Optional output of initial coordinates of transmitted particles.

Capabilities of elegant: Calculations

- Miscellaneous
  - Frequency map analysis
  - Position-dependent momentum aperture
  - Orbit/trajectory amplification factors, with correction
  - Slice analysis along a beamline
  - Approximate SASE FEL evaluation
  - Subdivision of elements
  - Subprocess execution for pre-, intermediate-, or post-processing
  - Set up semaphore files for flagging run status.

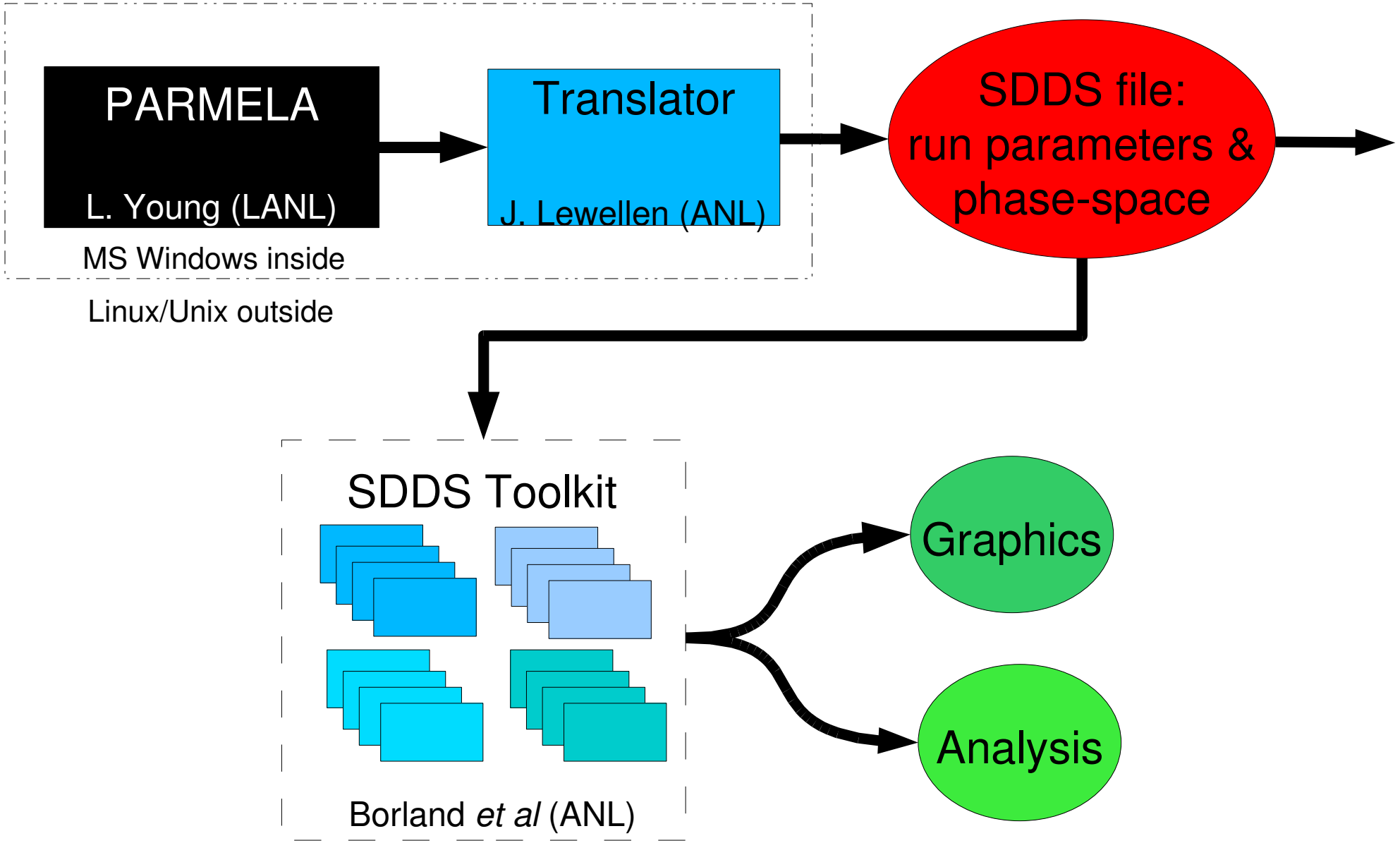
Related Programs

- SDDS files increase productivity by letting programs interface smoothly
- Programs that work with **elegant** include
  - **shower**, an interface to the EGS4 electron-gamma shower code (L. Emery)
  - **spiffe**, a PIC code for gun simulations (M. Borland)
  - **clinchor** computes single- and coupled-bunch growth rates due to HOMs (L. Emery)
  - URMEL/APS provides mode data in a form that **clinchor** and **elegant** accept (L. Emery)
  - ABCI/APS provides wake data that **elegant** accepts for tracking (L. Emery)
  - MAFIA/APS provides data that can be used in tracking with **elegant** (after a transformation) (L. Emery).

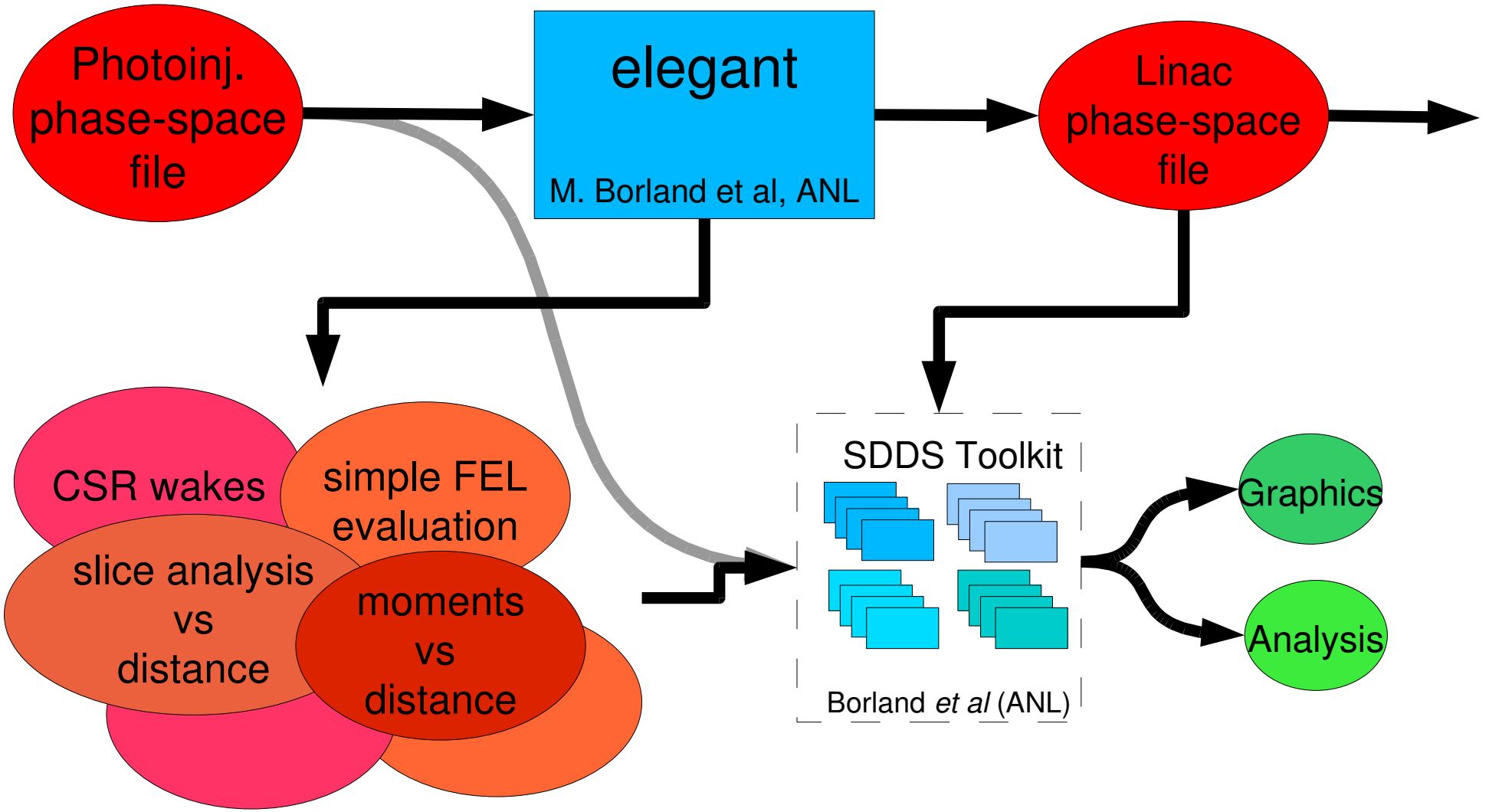
Related Programs

- **sddsrandmult** simulates random construction errors for multipoles and provides data for **elegant** tracking (M. Borland)
- **sddsfindresonances** finds resonances in frequency map data (H. Shang)
- **sddsemitproc** uses **elegant** output and experimental data to analyze emittance measurements (M. Borland)
- **sddsbrightness** uses **elegant** output to compute undulator brightness curves (H. Shang, R. Dejus)
- **sddsurgent** is an SDDS-compliant version the URGENT and US programs for calculation of undulator spectra and radiation patterns (H. Shang, X. Jiao)
- **sddsanalyzebeam** performs analysis of particle distributions (M. Borland)
- **sddsmatchtwiss** performs linear transformations of 6D phase space (M. Borland)
- **ibsEmittance** uses **elegant** output to compute intrabeam scattering effects (L. Emery, M. Borland)
- **haissinski** uses **elegant** output to compute bunch lengthening due to potential well distortion (L. Emery, M. Borland)
- etc. (See M. Borland et al., PAC 2001)

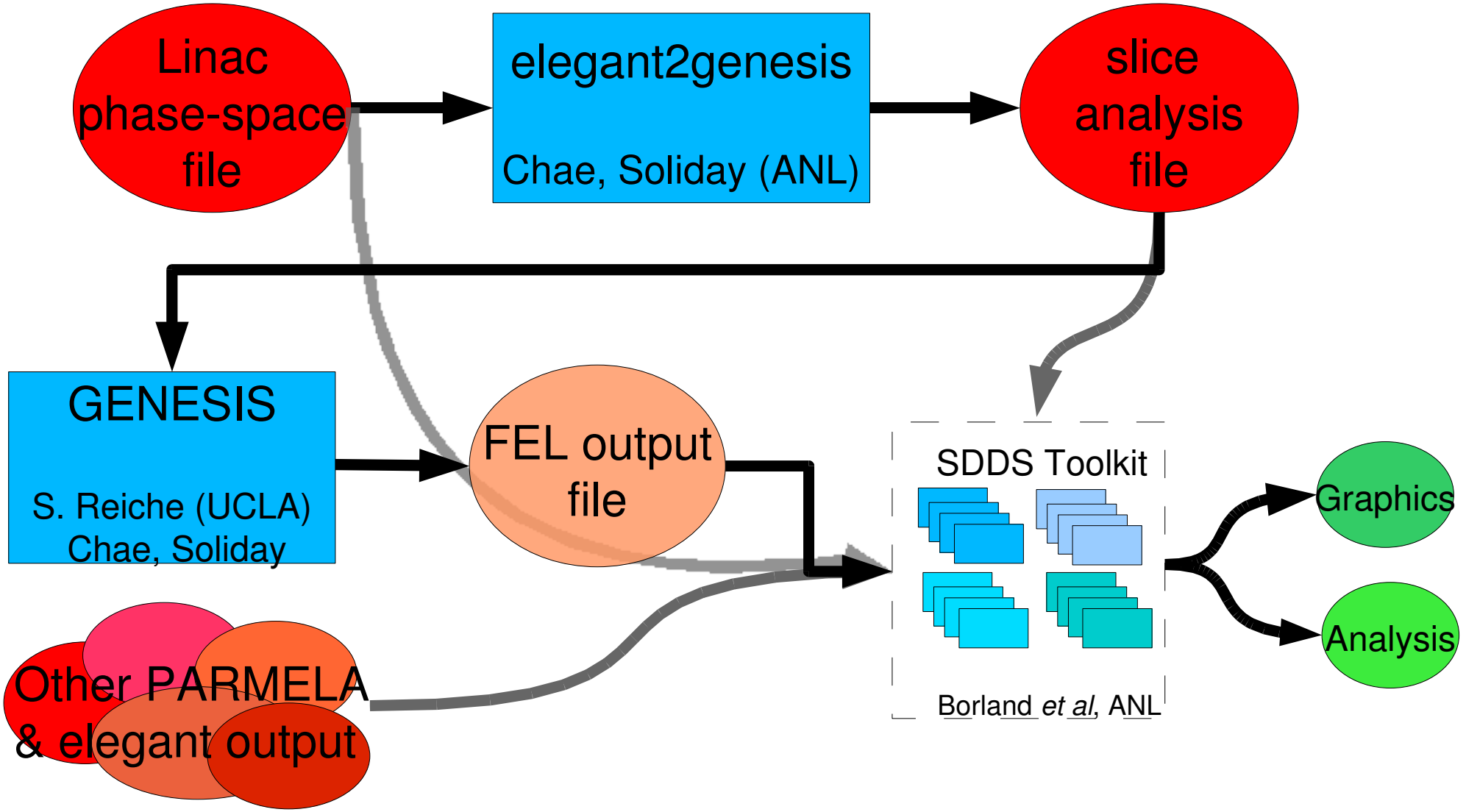
LCLS S2E Simulation Components



LCLS S2E Simulation Components

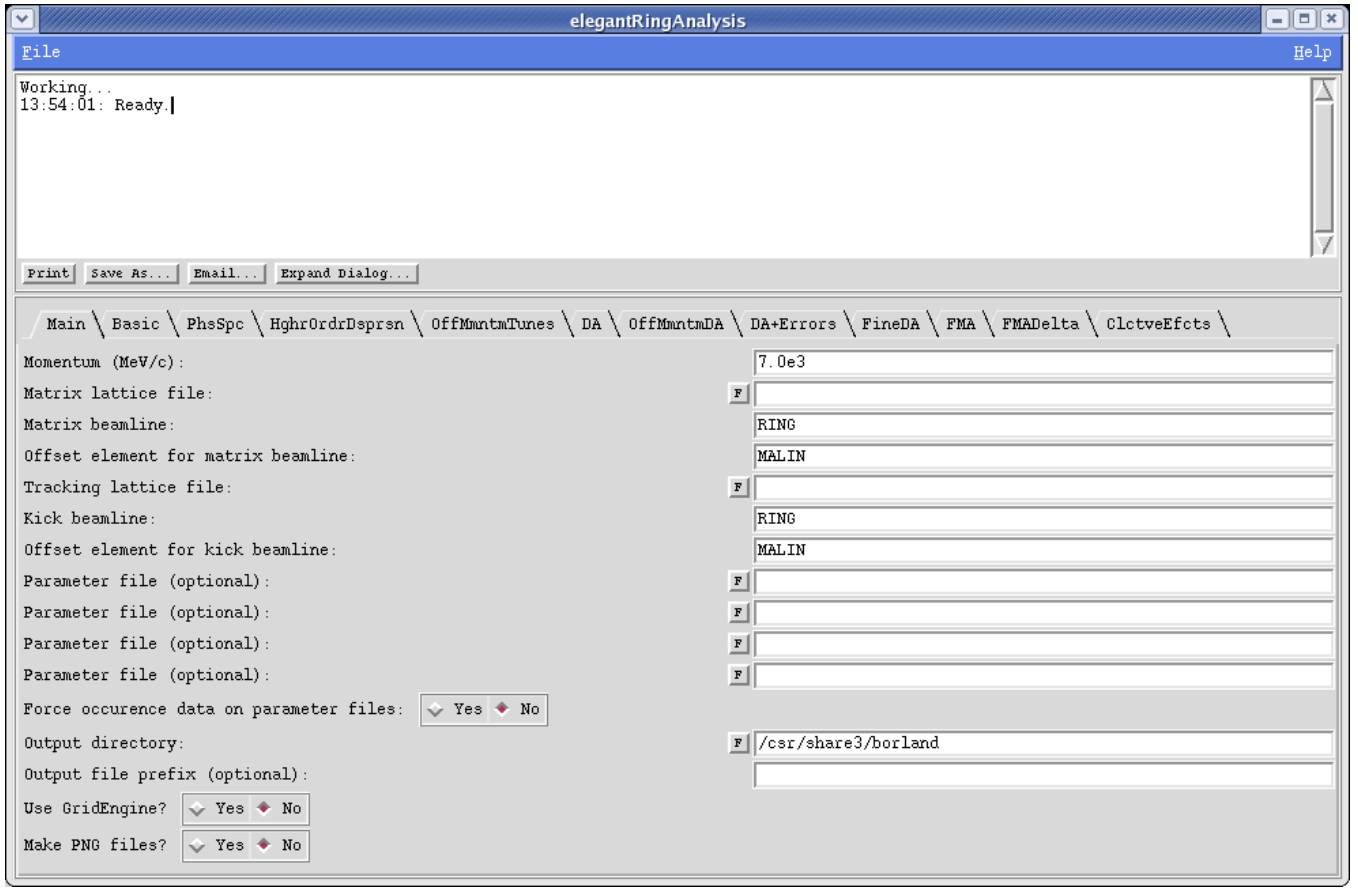


LCLS S2E Simulation Components



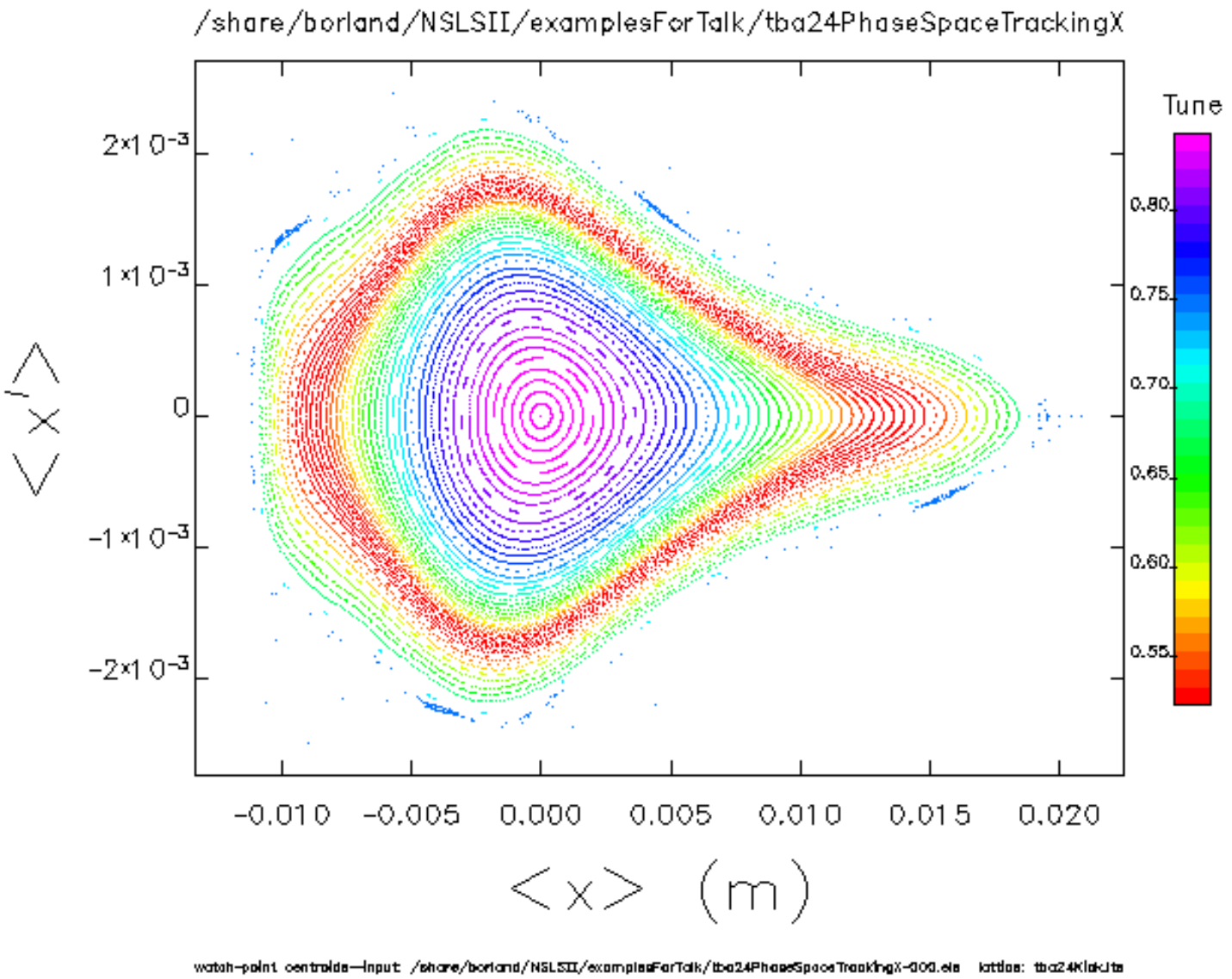
elegantRingAnalysis Application

A graphical user interface to many of the capabilities needed for storage ring evaluation.



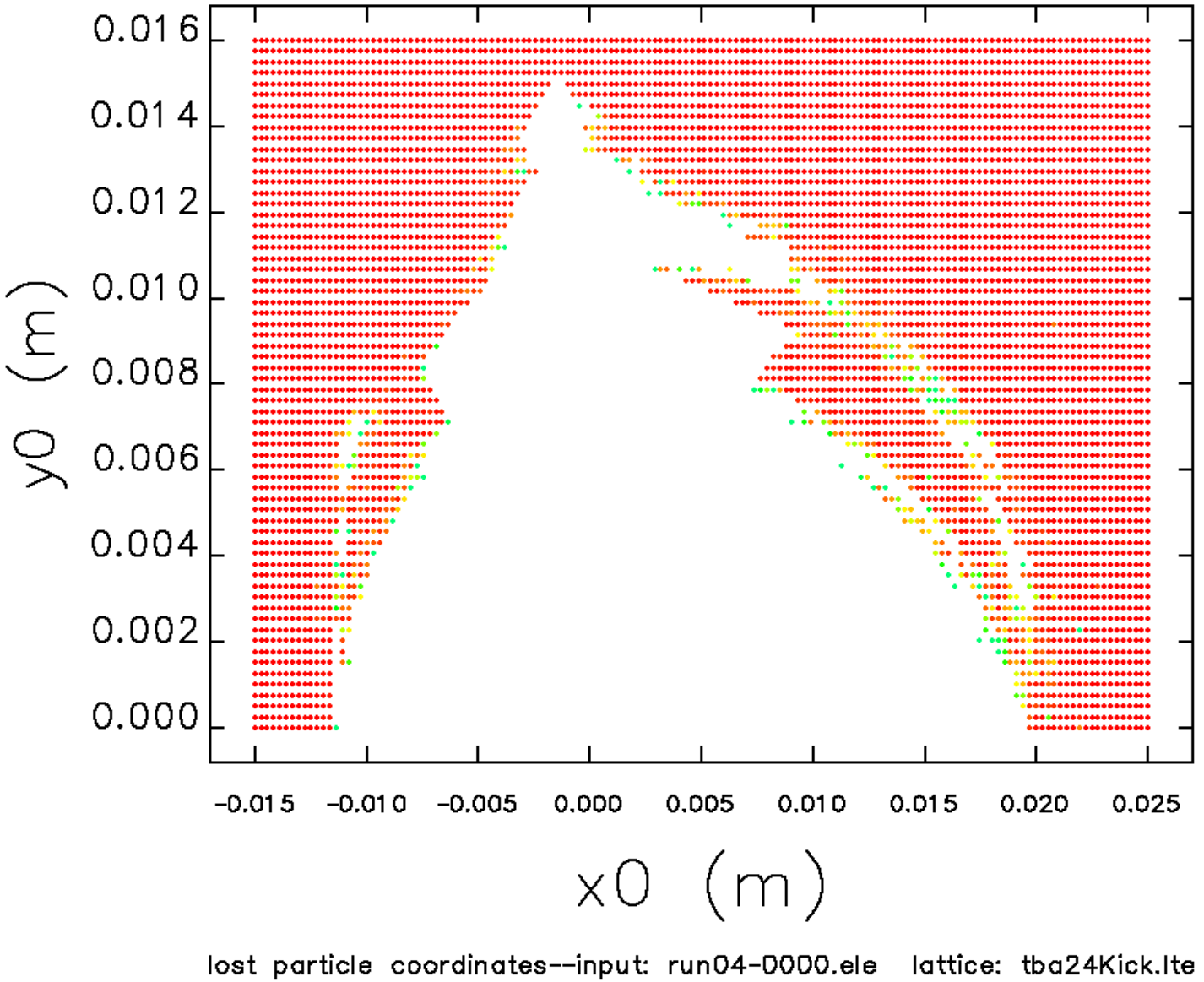
- Written in Tcl/Tk and SDDS
- Designed for use with a linux cluster for high throughput
- Mostly oriented toward tracking and dynamic aperture
- Also some collective effects calculations

Phase Space Tracking



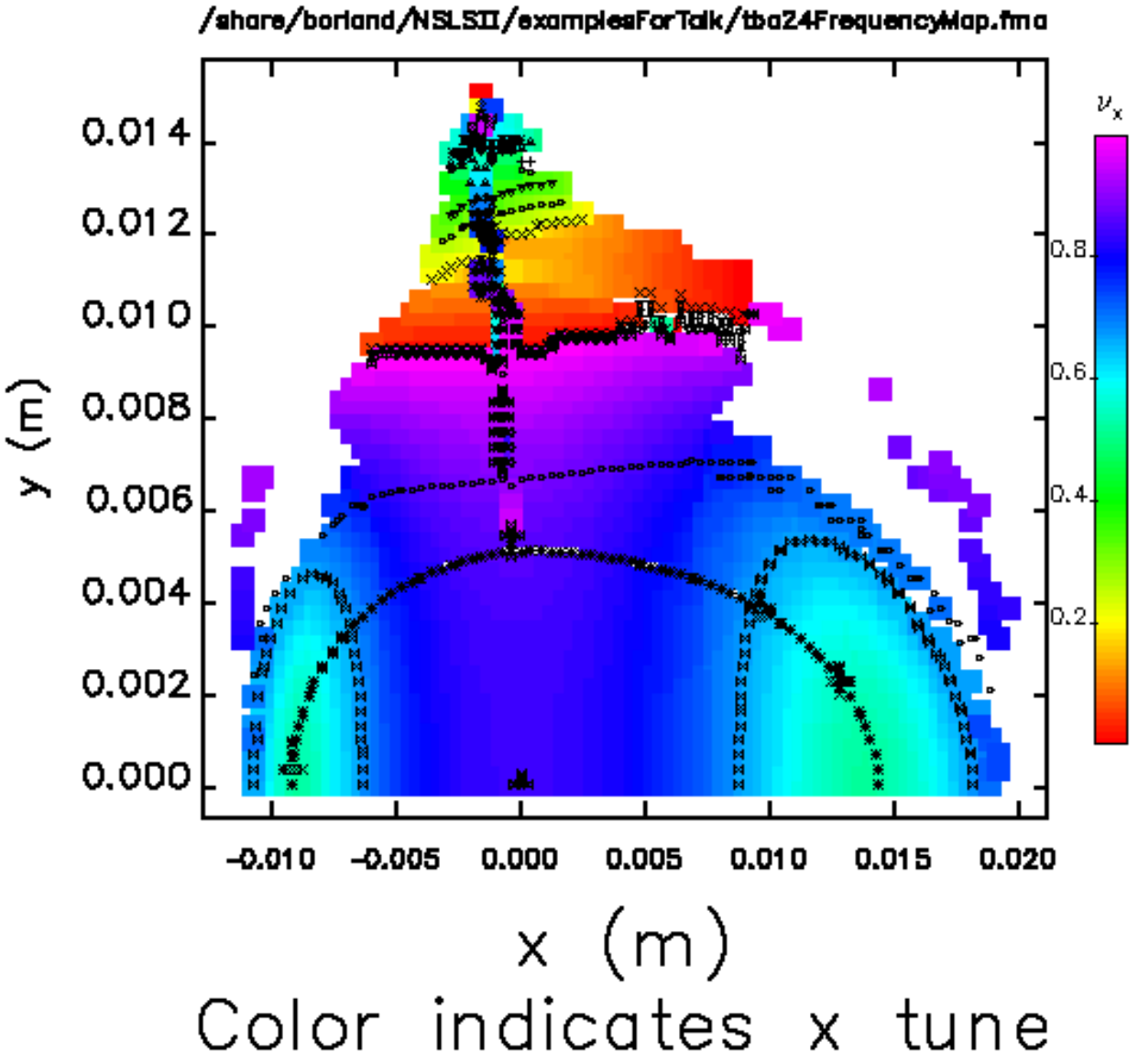
- 500-turn tracking, 15 kicks per element
- Color code shows tune
- 61 independent jobs
- Used ~60, 1.8 GHz CPUs simultaneously
- Took ~2 minutes

High-Resolution Dynamic Aperture



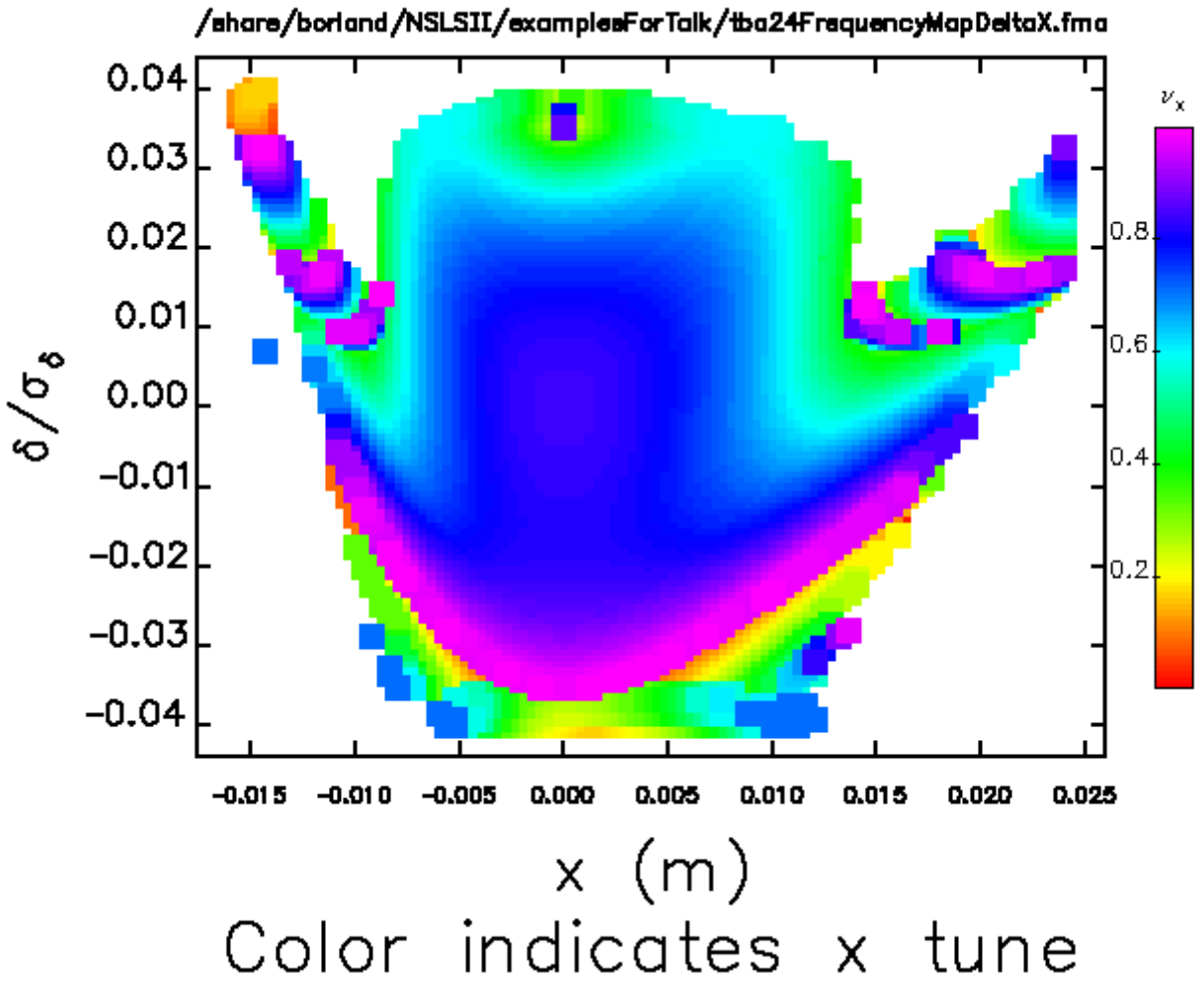
- 500-turn tracking, 15 kicks per element
- Color code shows turns survived
- 144 independent jobs
- Used ~50, 1.8 GHz CPUs simultaneously
- Took ~7 minutes

Frequency Map Analysis



- 512-turn tracking, 15 kicks per element
- Color code shows x tune
- Symbols show resonances
- 100 independent jobs
- Used ~80, 1.8 GHz CPUs simultaneously
- Took ~14 minutes

Frequency Map Analysis



- FMA in (x, δ) space
- 512-turn tracking, 15 kicks per element
- Color code shows x tune
- 100 independent jobs
- Used ~80, 1.8 GHz CPUs simultaneously
- Took ~14 minutes

Parallel elegant

- Have been parallelizing **elegant** for about 1 year
  - Approach allows gradual parallelization
  - Code switches to serial mode as needed
- All single-particle beam dynamics can now be done in parallel
  - Parallel version is in routine use at APS
  - Release expected within a month
  - Parallel efficiency of 95% with 512 processors on BlueGene/L
- Does load balancing to support heterogeneous cluster (e.g., weed)
- Regression tested against serial version.

Conclusions

- **elegant** is a capable, multi-purpose accelerator code
  - design
  - optimization
  - tracking
- **elegant** is at the center of an SDDS-compliant set of accelerator codes
  - Smooths the process of using many codes for complete accelerator design
- **elegant** is SDDS-compliant to allow users to automate simulations
  - LCLS start-to-end simulations
  - elegantRingAnalysis.

Acknowledgements

- Contributors to **elegant**:
  - M. Borland, L. Emery, V. Sajaev, Y. Wang, A. Xiao
  - Parallel version: Y. Wang, M. Borland
- Contributors to related tools:
  - M. Borland, R. Dejus, L. Emery, X. Jiao, H. Shang, R. Soliday
- SDDS Toolkit:
  - M. Borland, L. Emery, X. Jiao, H. Shang, R. Soliday
- Suggestions from users at APS and elsewhere are greatly appreciated.

Linux