Features and Applications of the Program **elegant**

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Outline

- Overview of features and capabilities
- SDDS and the tool-based approach to accelerator modeling
- Start-to-end simulation and the CSR microbunching instability
- Other interesting or notable examples
  - Top-up safety tracking
  - Direct optimization of storage ring beam dynamics
- Summary

High-level View of elegant[1]

- Code for design and modeling of single- and multi-pass accelerators
- Open source C/C++
  - Runs on Linux, Windows, MAC, Solaris, ...
- Highly-extensible with dictionary-driven lattice parser
- Serial and parallel[2] versions with common code base
- New version released about twice a year
  - Use revision control system and regression testing suite to reduce chance of errors
- Extensive on-line resources

1: M. Borland, APS LS-287, 2000; M. Borland *et al*., ICAP09, 111.
2: Y. Wang *et al*., ICAP09, 355 and refs. therein.

Basic Features of elegant

- Lumped-element, 6D tracking code
  - Over 100 element types, >90% of which are parallelized
  - Various methods, allowing user to customize model to needs, e.g., symplectic integration or matrices
- Calculation of lattice parameters, transfer matrices, orbits, beam moments, etc.
- Serial and parallel dynamic aperture, momentum aperture, frequency map analysis
- Optimization, including both serial and parallel algorithms
- Multi-dimensional scanning of parameters
- Errors and corrections
- Time-dependent ramping and modulation
- Thorough use of self-describing data files (SDDS)

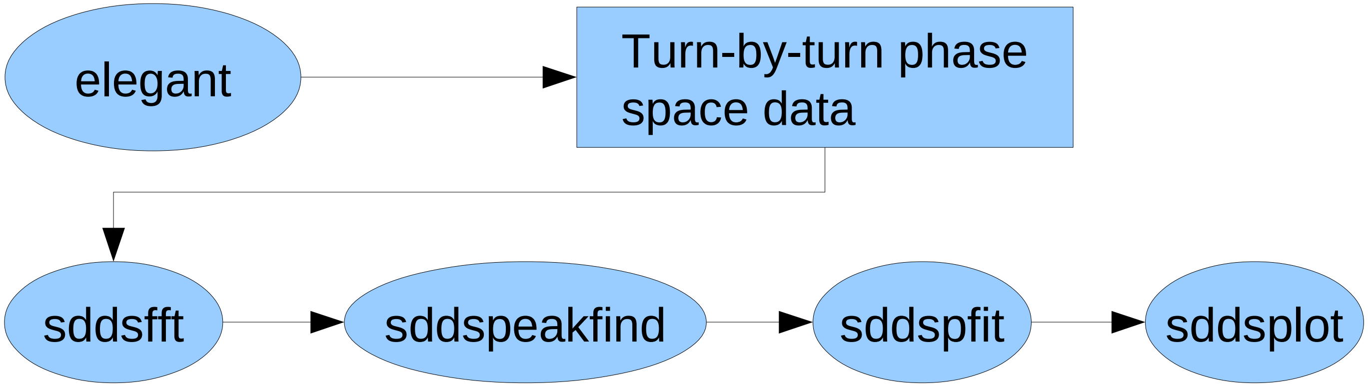
SDDS Files

- SDDS = Self-Describing Data Sets file protocol[1]
  - Originally developed for use in APS control system
  - Allows robust interchange of data among programs
    - Data is accessed by name only
    - Programs can check units and data type instead of doing something inappropriate with invalid data
  - **elegant** uses SDDS files for, e.g.,
    - Input and output of phase space data
    - Input and output of element parameters (e.g., magnet strength)
    - Twiss parameters, beam moments, matrices, orbits, etc., vs s
    - Input of wake functions, impedances, HOM properties
    - Input of ramp/modulation data, kicker waveforms
    - Input and output of errors and corrections
- SDDS I/O libraries are open source
  - Support for C/C++, FORTRAN, Java, MATLAB, Tcl[2]
  - MPI-based parallel I/O for high performance[3]

1: M. Borland, PAC95, 2184.
2: R. Soliday, ICALEPCS01, 545.
3: H. Shang *et al.*, ICAP09, 347.

SDDS Toolkit[1,2,3]

- SDDS Toolkit
  - Open source collection of generic programs that read and/or write SDDS files
  - Functions include graphics, analysis, and manipulation of data, plus control system applications
  - All the SDDS data that **elegant** reads or writes can be pre- or post-processed with SDDS tools
- Due to the relative simplicity of SDDS files, SDDS tools can be used sequentially as operators to transform data
  - E.g., to compute and plot amplitude-dependent tune



1: M. Borland, PAC95, 2184.
2: H. Shang *et al.*, PAC03, 3470.
3: R. Soliday *et al.*, PAC03, 3473.

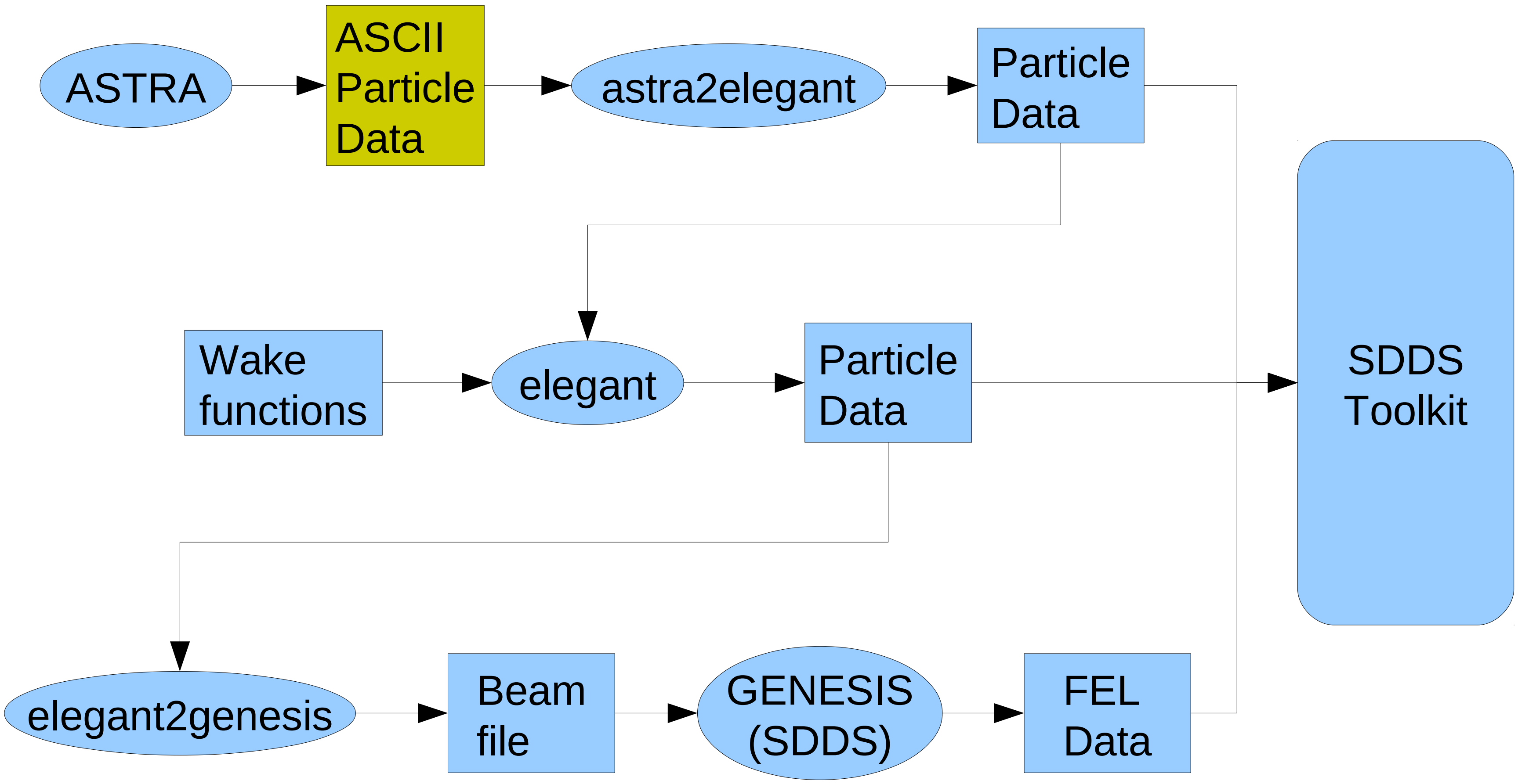
Tool-based Approach to Accelerator Simulation[1]

- SDDS Toolkit provides generic data processing, manipulation, and display
- Elegant Tools, a set of physics programs specifically designed to supplement **elegant**, including
  - Calculations of x-ray brightness, flux, etc.
  - Touschek lifetime and intrabeam scattering
  - Beam analysis, transformation, and modulation
- Other simulation codes, perhaps interfaced via conversion tools, e.g.
  - Injector simulation
  - Radiation shower simulation
  - Wake function or impedance calculation
  - Multibunch instability analysis
- Advantages of this approach
  - Multiple physics codes share pre- and post-processing tools
  - Physics codes are simplified
  - Robust interface between codes
  - Complex simulations are easier and faster

1: M. Borland *et al*., PAC2003, 3461.

Example of Tool-based Approach

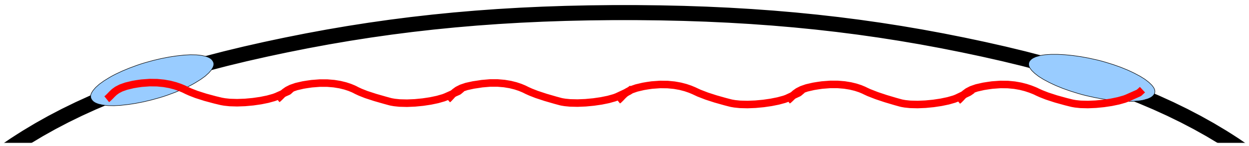
- One possible configuration for start-to-end simulation of FELs



ASTRA: K. Floettman *et al*.
GENESIS: S. Reiche, NIMA 429, 242 (1999)
SDDS GENESIS and elegant2genesis: Y. Chae et al., PAC2001, 2710.

What is CSR and How Does it Affect the Beam?[1]

- Electrons traversing a dipole magnet emit synchrotron radiation
- Electron bunch will radiate coherently and intensely at wavelengths comparable to scale of its longitudinal structure
- Electrons travel in a curved path, while emitted photons travel in a straight path



- Radiation emitted by the tail will catch up with the head, changing its energy
- Since this happens inside dipoles, it leads to emittance growth
- CSR propagating into drift spaces between or downstream of dipoles can have very significant impact[2,3]

1: B. E. Carlsten et al, Phys. Rev E 51, 1453 (1995).
2: M. Borland, PRSTAB 070701 (2001).
3: G. Stupakov *et al*., SLAC LCLS-TN-01-12, 2001.

Modeling the Linac Coherent Light Source

- Early simulations of LCLS were not "start-to-end" simulations but used gaussian beams
- Indicated that using double-chicane bunch compressors with 180 deg betatron phase advance would result in calculation of CSR effects

December 2000 Design (P. Emma)

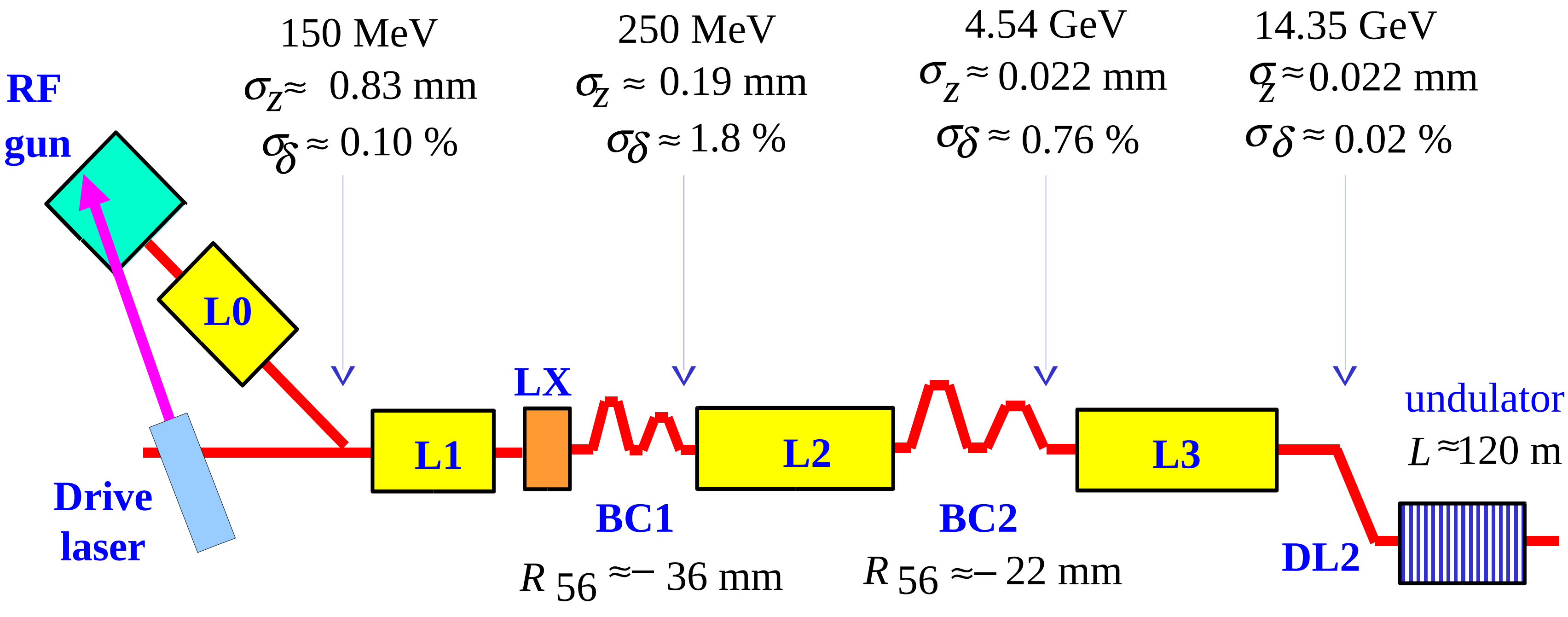
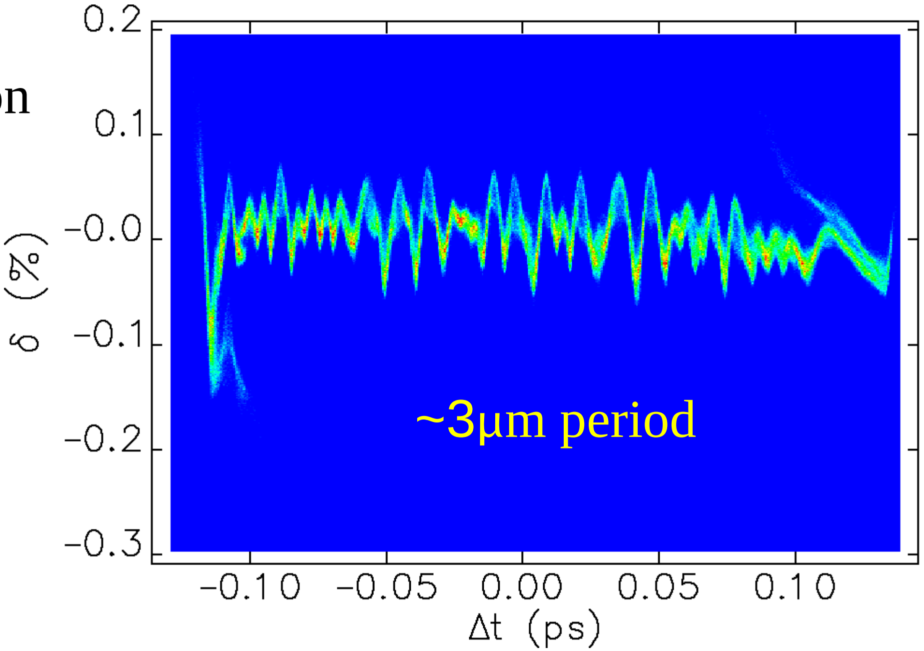


Figure courtesy P. Emma (SLAC).

1: J. Arthur *et al.*, SLAC-R-521 (1998)

CSR Microbunching Instability

- Team from APS and SLAC created tools to allow start-to-end modeling of LCLS and LEUTL
- As part of this effort, added to **elegant** modeling of CSR in dipoles and drift spaces[1]
- Used a line-charge model with several advantages over previous efforts
  - Fast, permitting use of large numbers of particles
  - High longitudinal resolution
  - Arbitrary longitudinal distribution instead of gaussians
- These simulations[2,3] predicted a micro-bunching instability driven by CSR
- CSR-driven instability in rings was described theoretically at the same time[4] and suggested by experimental evidence[5]

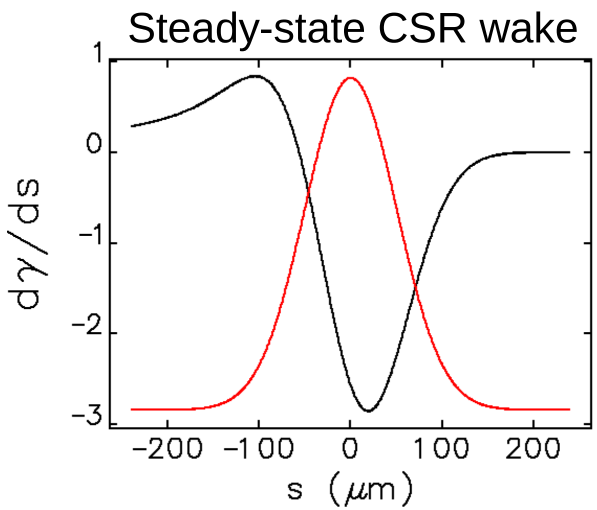


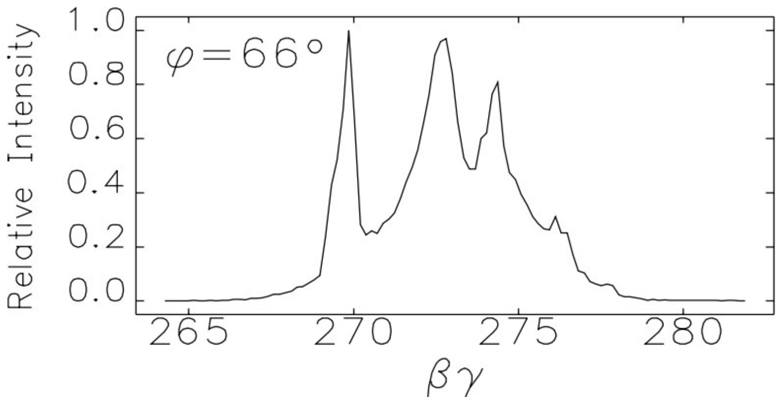
1: M. Borland, PRSTAB 070701 (2001).
2: M. Borland *et al.*, PAC2001, 2707.
3: M. Borland *et al.*, NIM A 483 (2002) 268.
4: Heiffets *et al*, PAC2001, 1856 (2001).
5: J. Byrd *et al.*, PRL 224801 (2002) and refs. therein.

Qualitative Explanation of the Instability

- If a density clump exists in a beam, CSR will be emitted
- Head of clump is accelerated, while tail is decelerated
- A particle that gains (looses) energy in a dipole falls back (moves ahead)
- Thus, the clump is amplified, which amplifies the CSR wake, ...
- Related to longer-scale "phase-space fragmentation" seen experimentally at JLAB and TESLA[2,3,4] and in simulations of APS LEUTL[5]

$$W(s) = K \int_{-\infty}^{s} \frac{dz}{(s-z)^{1/3}} \frac{d\lambda}{dz}$$



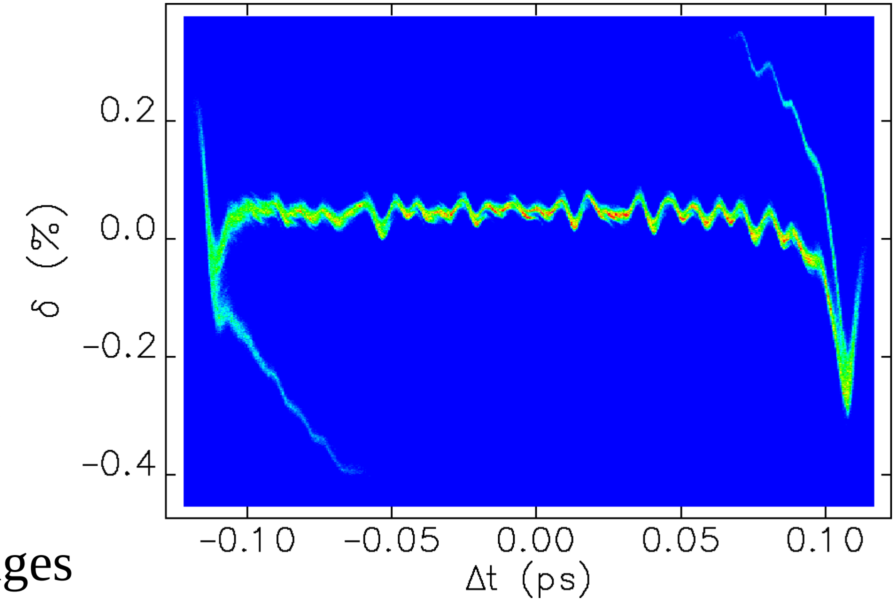


Energy distribution fragmentation from LEUTL simulations of full compression[5]

1: E. L. Saldin *et al*., NIMA 398 (1997), 373.
2: T. Limberg *et al*., NIMA 475 (2001) 353.
3: R.Li, EPAC2000, 1312.
4: P. Piot *et al*., EPAC 2000, 1546.
5: M. Borland, PRSTAB 070701 (2001).

Improved LCLS Design

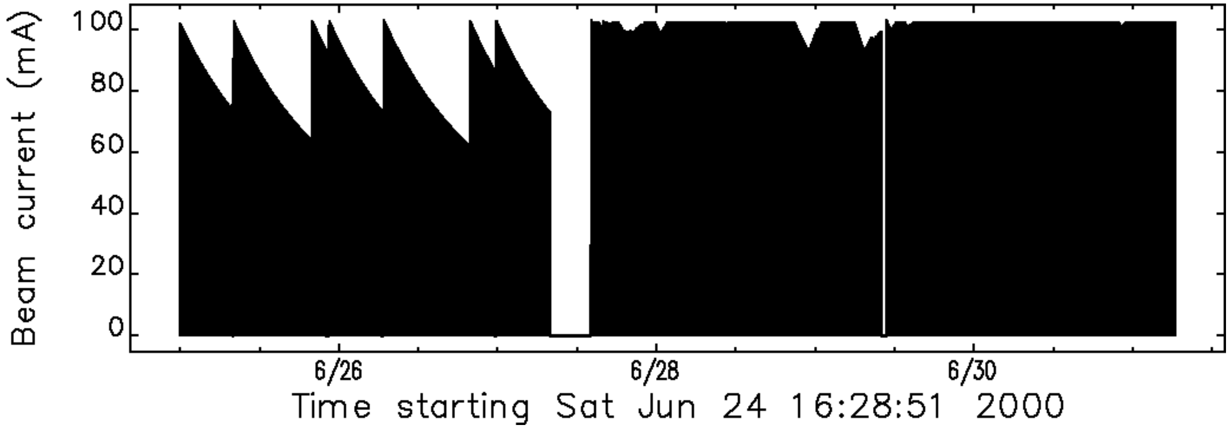
- P. Emma revised LCLS design to reduce CSR problem
  - Single instead of double chicanes
  - Long chicanes with weak dipoles
  - Superconducting wiggler before BC2 to increase incoherent energy spread and suppress instability
- Later discoveries[1] added to the challenges surrounding magnetic bunch compression
  - Magnification of instability due to longitudinal space charge in linac
  - Use of laser/undulator beam heater to suppress instability
  - These discoveries were subsequently verified[2] with **elegant**
- The microbunching instability remains an active topic of research with periodic workshops



1: E. L. Saldin *et al*., DESY TESLA-FEL-2003-02.
2: Z. Huang *et al*., PRSTAB 074401 (2004).

Top-up Operation

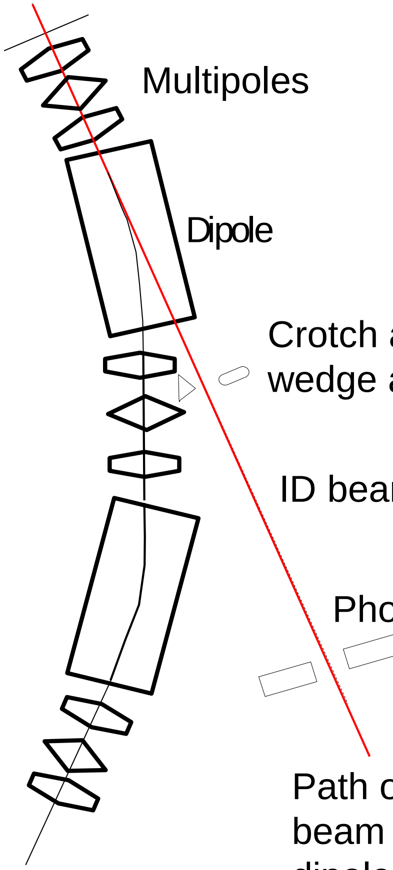
- Traditionally, light source rings operated in “decay mode,” where the beam current decays for many hours before being refilled
- This has several drawbacks
  - Users see variation in x-ray intensity
  - X-ray optics see variation in heat load, impacting stability
  - Emittance, coupling, and bunch intensity limited by need for long lifetime
  - Intensity-dependence of diagnostics and chamber temperatures results in beam position drift
- Top-up operation entails fairly rapid addition of small amounts of beam current, keeping the intensity nearly constant



First user top-up operation at APS in June 2000.

Top-up Safety[1]

- One concern with top-up is injection while user shutters are open
  - Electron beam from injector might be delivered down user beamline, with potentially catastrophic consequences
- One scenario
  - Dipole magnet (partially) shorted
  - Downstream magnets adjusted to compensate perturbation to stored beam
  - Injected beam energy higher-than-normal
- APS performed the first tracking studies[2] of this question using **elegant**
- Demonstrated that it was essentially impossible to simultaneously store beam and extract injected beam down a beamline
  - Hence, top-up safety could be ensured by interlocking injector to stored beam



1: L. Emery, PAC99, 2939.
2: M. Borland *et al.*, PAC99, 2319.

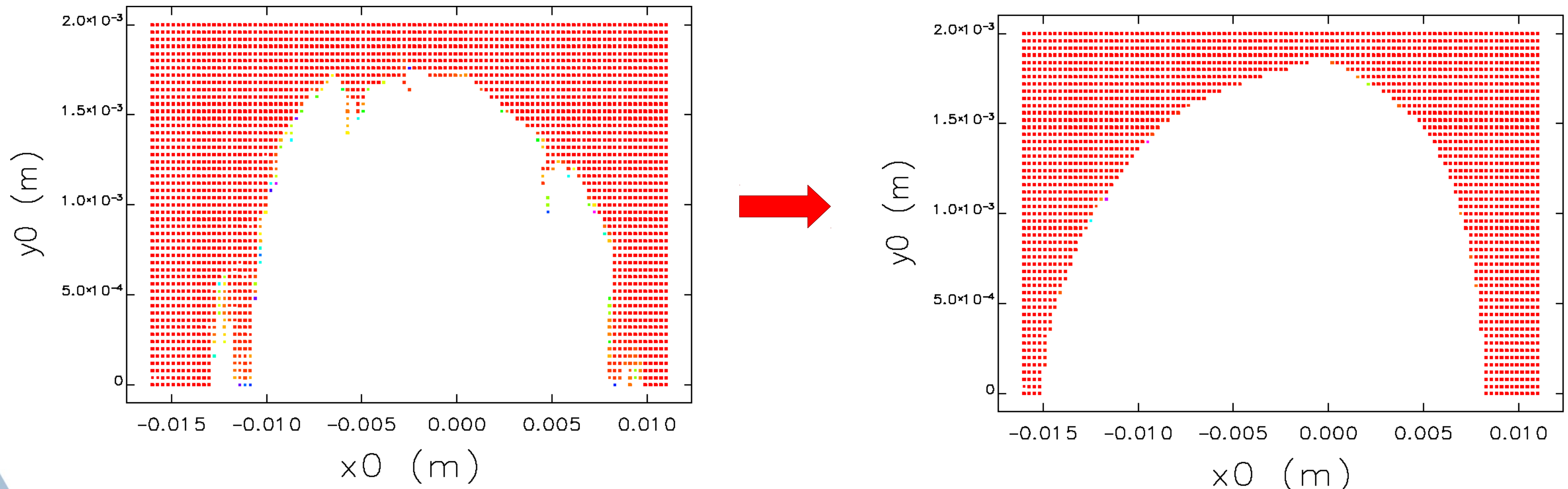
Scope of Tracking Problem

- About 250 runs of **elegant** are required for each of six beamline configurations
- Runs involved 20 to 50 different conditions, such as degree of shorting, size of quadrupole error, etc.
- In total, about 50,000 different physical situations had to be simulated
  - Simulation of whether stored beam was possible, including orbit correction using downstream correctors
  - Simulation of whether backtracked beam could exit the sector
- In 1999, took several days on ~20 Sun workstations
  - Presently, just a few hours on an eight-core PC
- Data was postprocessed automatically using SDDS, taking just a few minutes to provide an answer:
  - The minimum safety gap was 14% of the full dipole strength
- Subsequently, other groups have made similarly thorough studies of top-up safety[1-4]

1: H. Nishimura *et al*., NIM A 608, 2 (2009).
2: A. Terebilo *et al*., SSRL-ACC-007, 2009.
3: I.P.S. Martin *et al*., EPAC08, 2085.
4: Y. Li *et al.*, PRSTAB 14, 033501 (2011).

Direct Optimization of Nonlinear Dynamics

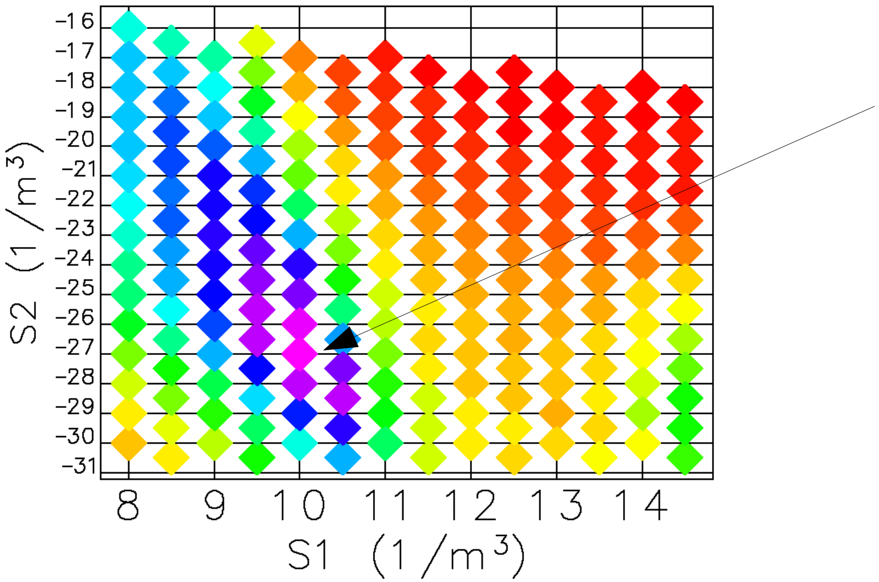
- Designers of low-emittance electron rings must
  - Ensure adequate dynamic aperture for injection
  - Ensure adequate momentum aperture for Touschek lifetime
- Traditionally, several methods have been employed, e.g.,
  - Minimization of amplitude- and energy-dependent tune shifts
  - Minimization of resonance driving terms
  - In the end, tracking is always necessary to verify any solution
- With a modest computing cluster, can directly optimize the results of tracking
- To our knowledge, first published results by APS group using **elegant**[1]
  - Direct maximization of dynamic aperture
  - Direct minimization of tune spread for ensemble of particles



1: H. Shang *et al*., PAC2005, 4232.

Direct Optimization using elegant

- In 2009, we published[1] results of further direct optimization of APS lattice using two algorithms
  - Required high chromaticity (**ξ=**6~10) makes this challenging
- Grid scan algorithm
  - Scan two out of four families of sextupoles
  - Track set of particles filling desired transverse and momentum space
  - Choose settings that result in highest capture rate after 1000 turns
  - Easily implemented with **elegant** thanks to SDDS toolkit
  - Result for ξ=6: 20% higher lifetime, largest DA seen to date

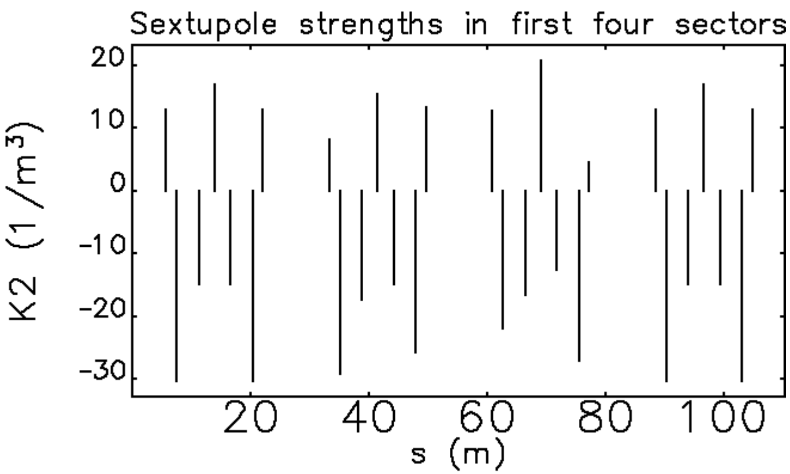


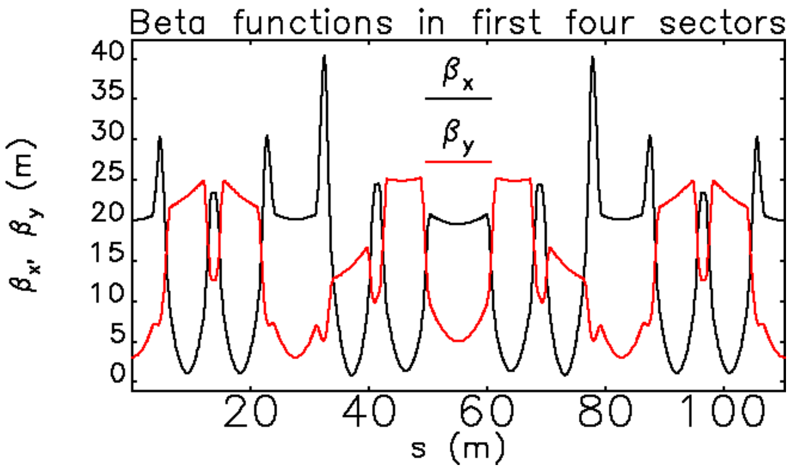
New sextupole settings providing the improved beam lifetime and DA for ξ=6

1: M. Borland *et al.*, PAC09, 3850.

Direct Genetic Optimization using elegant

- Inspired by Bazarov[1] and Emery[2], we also employed[3] a genetic algorithm
- Method
  - Use dynamic aperture search and robust measure of DA area
  - Use s-dependent momentum aperture search as indicator of Touschek lifetime
  - Also added tune knobs
- Each “function evaluation” uses several runs of **elegant**, plus SDDS for postprocessing
- Developed potential APS upgrade lattices with 2, 4, and 8 symmetric long straights (LSSs)
  - Discovered that breaking the reflection symmetry of the sextupole distribution was very helpful
  - Mock-ups of these lattices showed normal lifetime and injection efficiency

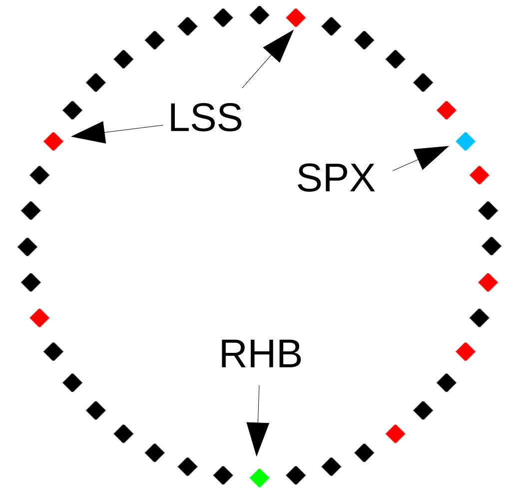


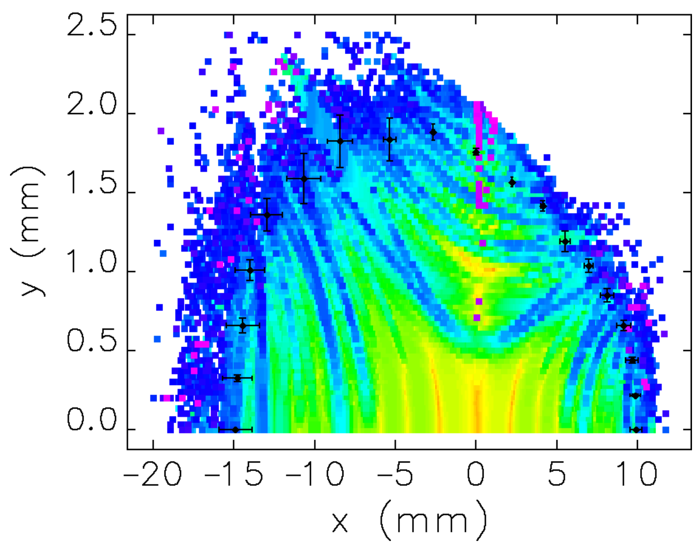


1: I. Bazarov *et al.*, PRSTAB 034202 (2005).
2: L. Emery, PAC05, 2962.
3: M. Borland *et al.*, PAC09, 3850.

Direct Genetic Optimization using elegant

- Methods subsequently refined[1,2]
  - Direct optimization of Touschek lifetime computed from momentum aperture
  - Parallelization of DA and MA scans to permit using massively parallel resources
    - E.g., used >40,000 cores on BlueGene/P
- Addressed increasingly difficulty APS upgrade lattices
  - Non-symmetrical placement of LSSs
  - >2x reduced horizontal beamsize (RHB) needed in one sector
  - Special optics and sextupole tuning needed for short-pulse x-ray system (SPX)
- To address this, gave optimizer
  - Detailed linear optics knobs
  - Over 50 independent sextupole knobs
  - Tracking-based measure of SPX emittance dilution
- Independent work on tracking-based optimization at LBNL[3] and BNL[4]





1: M. Borland *et al.*, FLS2010.
2: M. Borland *et al.*, APS LS-319 (2010).
3: C. Steier *et al.*, IPAC10, 4748.
4: L. Yang *et al.*, FLS 2010.

Summary

- Thanks to input from many users and contributors, **elegant** is a capable and flexible code with some noteworthy contributions
  - Discovery of microbunching instability in bunch compressors
  - Top-up safety tracking
  - Direct optimization of storage ring nonlinear dynamics
  - Many interesting applications from outside APS
- Coupling **elegant** with SDDS is a key feature
  - Flexible and robust interface with other codes
  - Powerful pre- and postprocessing
- Google “elegant download Argonne” to get started
  - Code, executables, and examples for **elegant** and SDDS
  - Manual and forum

Acknowledgements

- Contributors to **elegant**
  - M. Borland, W. Guo, V. Sajaev, H. Shang, C.-X. Wang, Y. Wang, Y. Wu, A. Xiao
- Contributors to **elegant** toolkit
  - M. Borland, Y.-C. Chae, R. Dejus, X. Dong, L. Emery, H. Shang, R. Soliday, A. Xiao
- Contributors to SDDS
  - M. Borland, L. Emery, H. Shang, R. Soliday
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  - R. Soliday
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