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Integrated Modeling of Damping Rings and Beyond

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September 26, 2006

U.S. Department of Energy

THE UNIVERSITY OF CHICAGO

Office of Science
U.S. DEPARTMENT OF ENERGY

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Outline

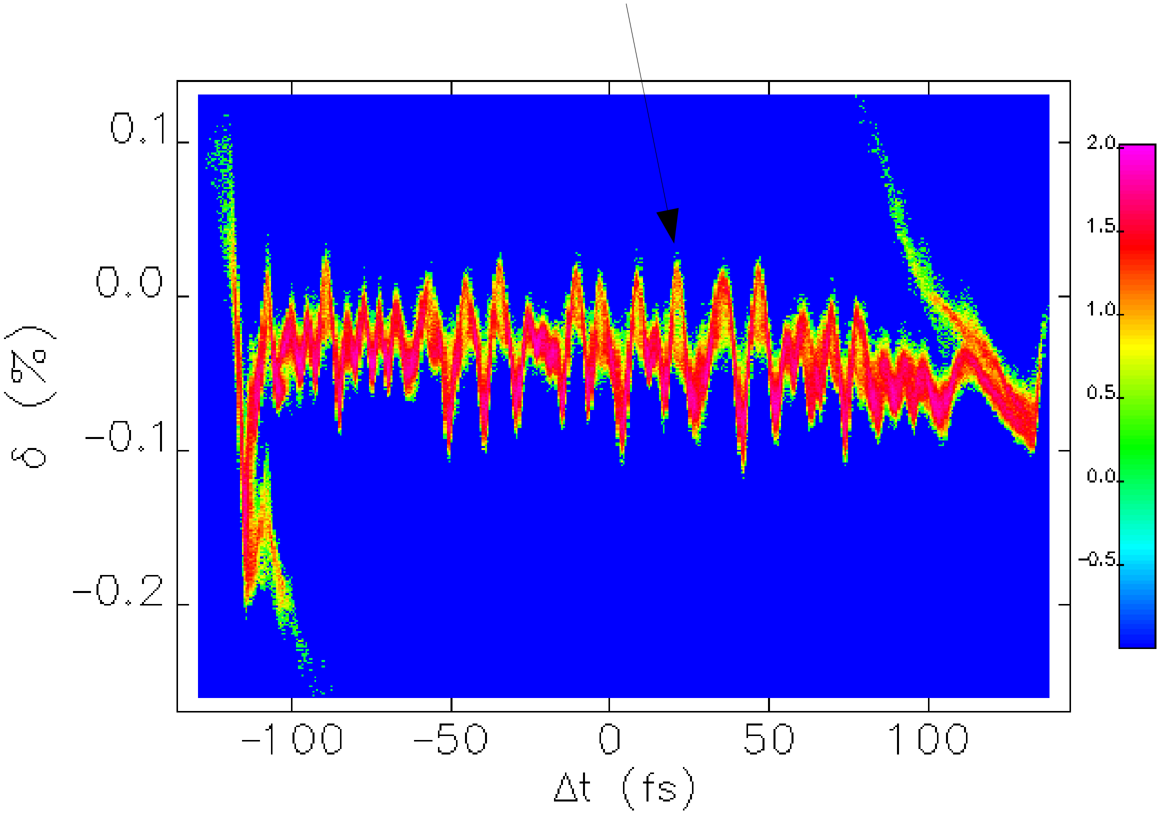
- Integrated modeling:
  - Cautionary tale from LCLS
  - Lessons for ILC
- Capabilities of **elegant** for damping ring work
  - Single-particle dynamics
  - Collective effects
- Planned improvements for DR work
- Beyond DR modeling

A Fragmented Approach is Very Natural...

- 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, which are compartmentalized
  - Gun/injector
  - Linac
  - Damping ring
  - Transport lines
  - Final focus
- Communication between subsystem experts is often still in terms of basic statistics
- The details may hide an unpleasant surprise
- However, integrated modeling isn’t necessarily easy.

Is Integrated Modeling Worthwhile? Ask LCLS!

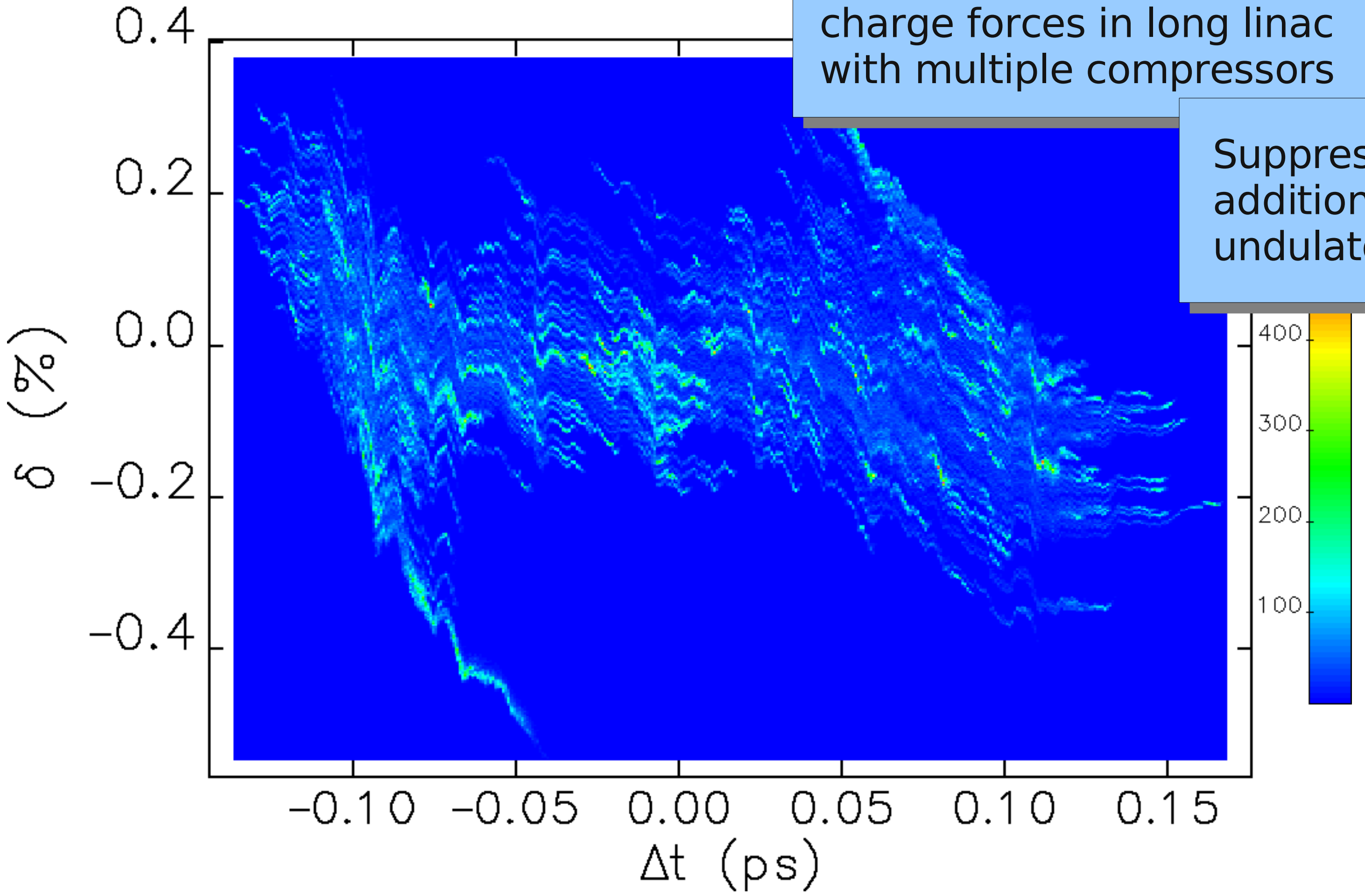
Micro-bunching instability in bunch compressors driven by CSR, discovered with **elegant**



- Instability not seen until photoinjector and linac simulations were joined
- Impact on LCLS operation would be very serious
- Resulted in redesign of LCLS bunch compression scheme.

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

LSC Micro-bunching Instability in LCLS

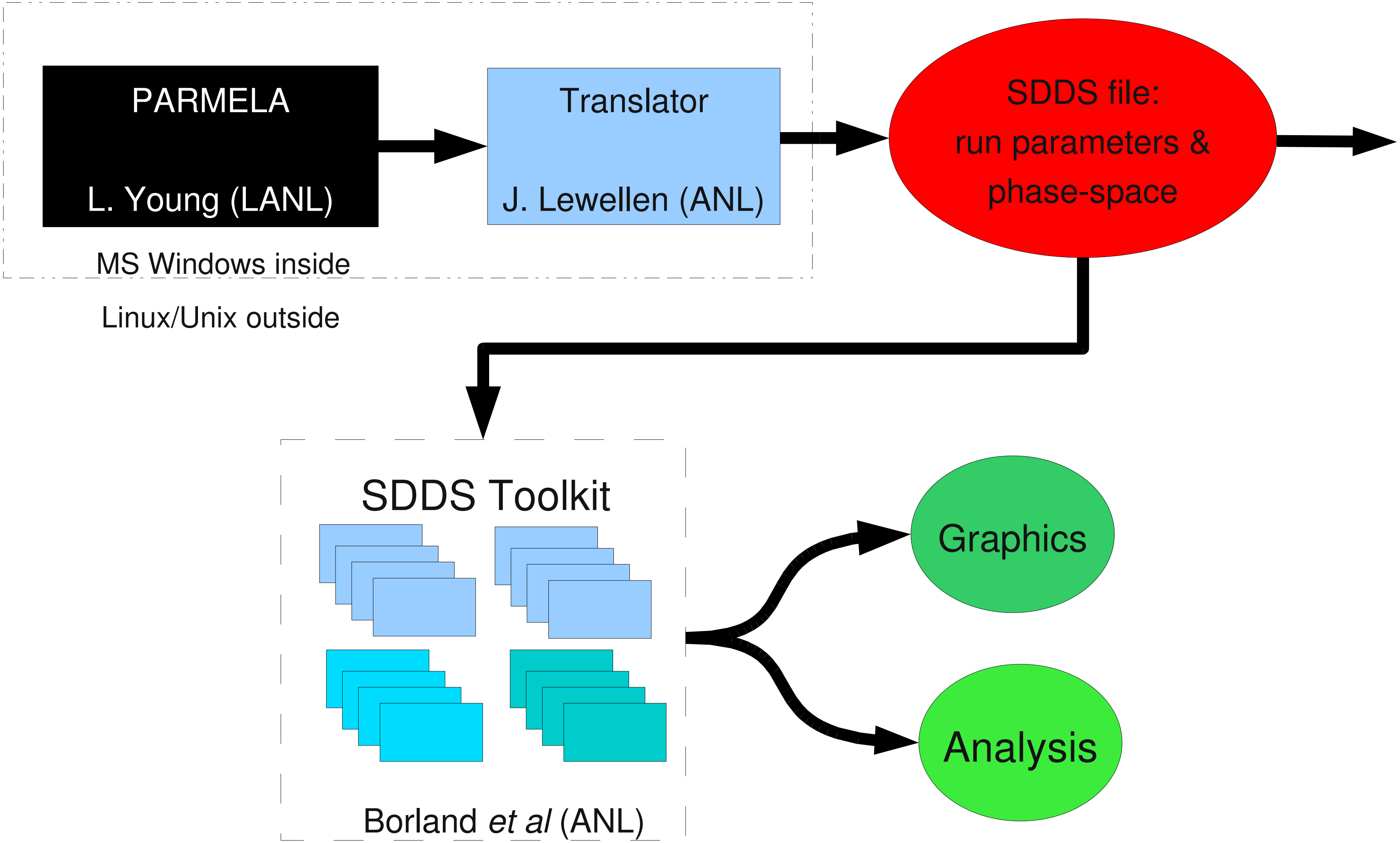


Longitudinal space charge instability due to weak space charge forces in long linac with multiple compressors

Suppression required addition of a laser-undulator beam heater.

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

LCLS S2E Simulation Components: Making One Code from Many



PARMELA

L. Young (LANL)

Translator

J. Lewellen (ANL)

MS Windows inside

Linux/Unix outside

SDDS file:

run parameters &

phase-space

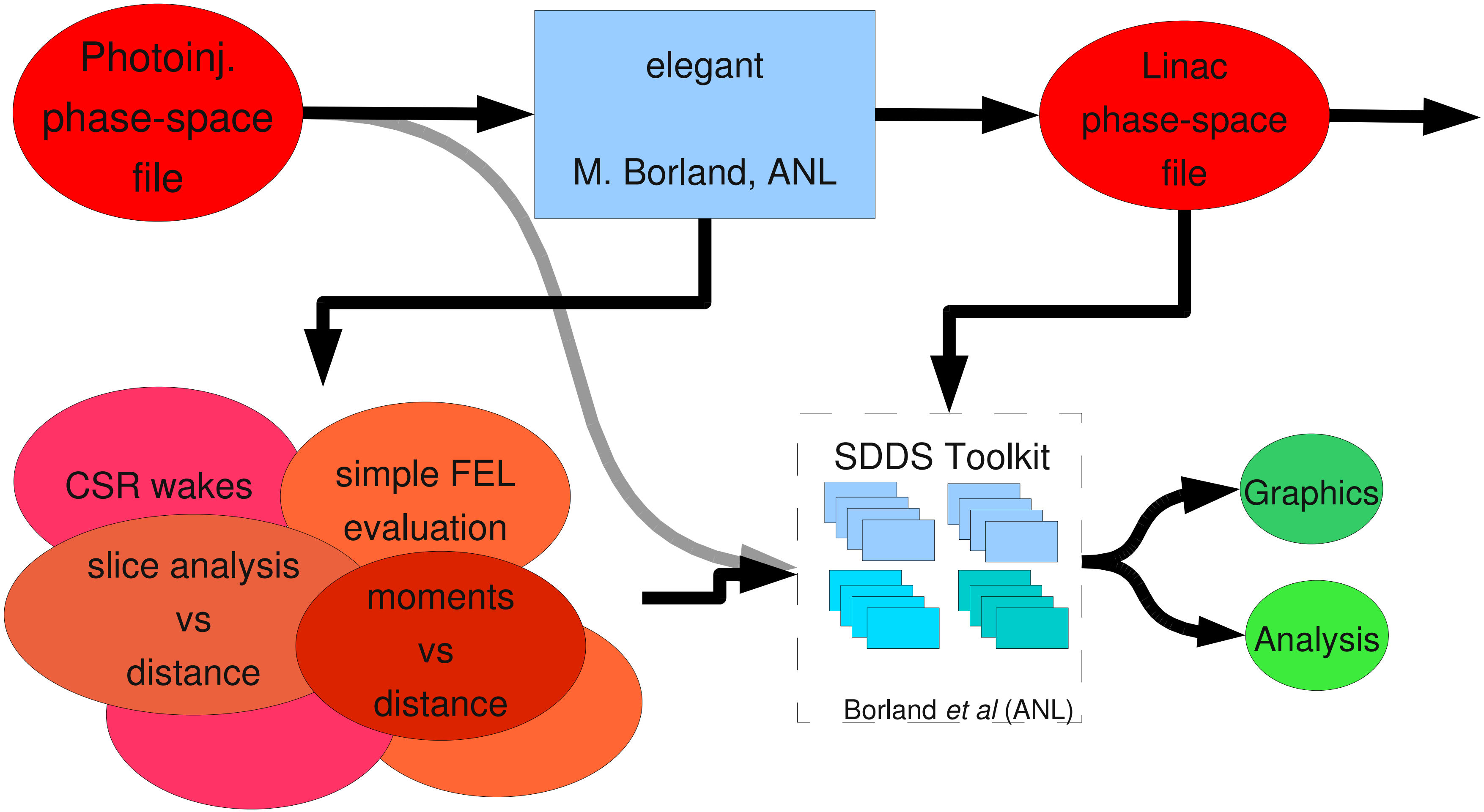
SDDS Toolkit

Borland *et al* (ANL)

Graphics

Analysis

LCLS S2E Simulation Components



Photoinj. phase-space file

elegant

M. Borland, ANL

Linac phase-space file

CSR wakes

simple FEL evaluation

slice analysis vs distance

moments vs distance

SDDS Toolkit

Borland *et al* (ANL)

Graphics

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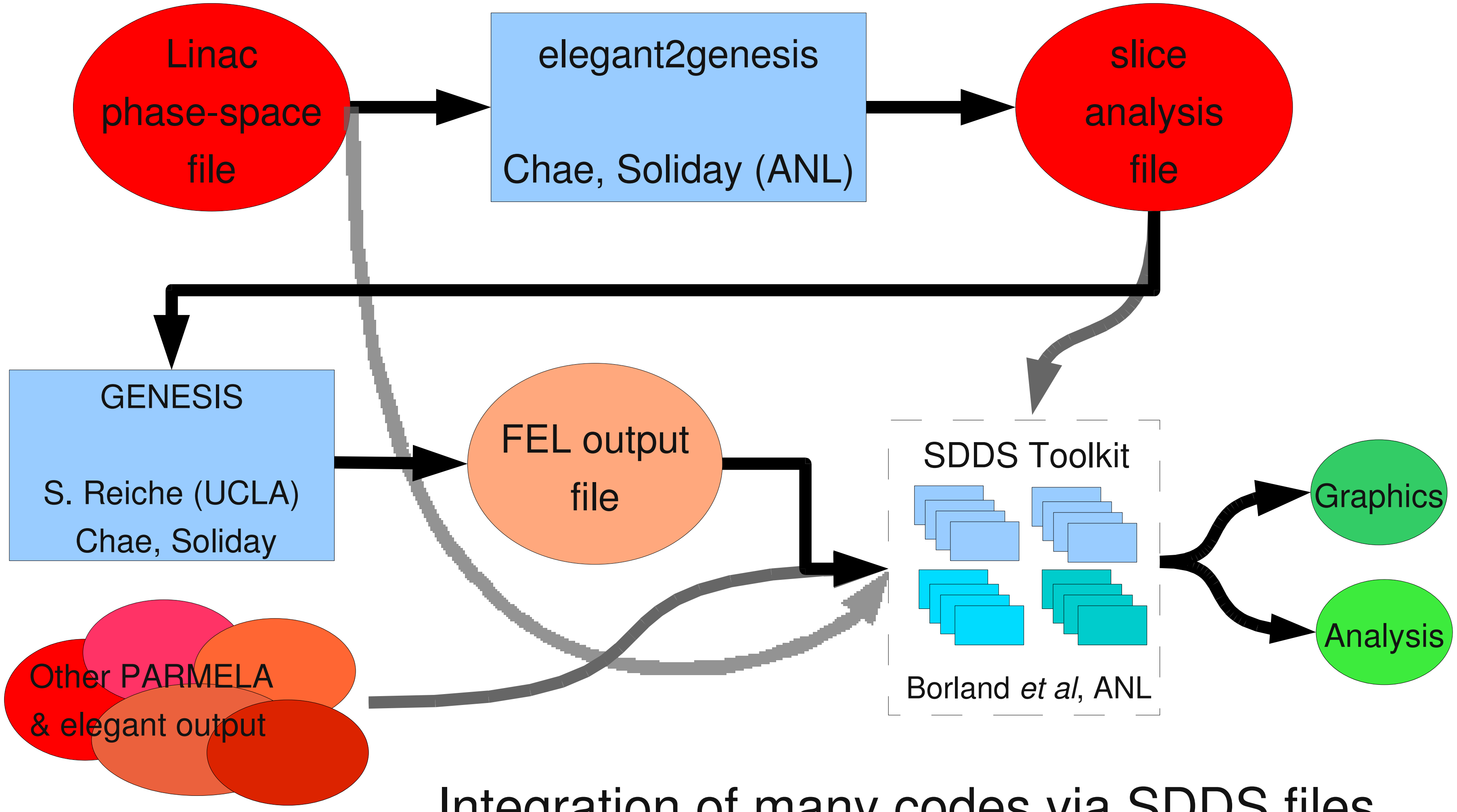
LCLS S2E Simulation Components



Integration of many codes via SDDS files permits integrated analysis (e.g., of jitter)

Possible Parallels for ILC

- Variations from injector will impact the ring
  - Emittance and transverse distribution variation may impact injection efficiency
  - Charge variation may impact final bunch length, energy spread, and emittance
- Variations in ring will impact emittance preservation and bunch compression downstream
  - Quasi-stable bunches in the ring may have structure that gets amplified in bunch compression
- One can’t put firm tolerances on the inputs without knowing how they translate into final performance
- We can start to build an integrated ILC model by building an integrated DR model.

Fragmented vs Integrated Modeling

- Fragmented modeling is frequently chosen for speed, convenience, or simplicity of understanding
  - This often motivates creation of single-purpose codes
  - These are valuable for developing modeling techniques, but limited
- Integrated modeling ideally makes “all” the physics available in one simulation
  - E.g., impedance, space charge, single particle dynamics, lattice errors, correction schemes, feedback, ...
  - <u>Details</u> of the input beam (reflecting upstream physics)
- Our approach with **elegant** is to provide capabilities that span the spectrum so user can
  - Start with a simple model
  - Add effects one at a time.

Relevant Capabilities of elegant (Latest Release , V16.1)

- Lattice simulation (serial or parallel)
  - ILMATRIX element:
    - *Individual Linear MATRIX*
    - *Simulate periodic systems by giving end-point lattice functions, tunes, chromaticities, tune-shifts with amplitude*
    - *Linear matrix for each particle computed for next turn based on present energy offset and betatron amplitude*
  - Symplectic tracking:
    - *Element-by-element tracking with 4th order Ruth integrator*
- Radiation effects (serial or parallel)
  - Lumped element synchrotron radiation (classical plus quantum)
  - Element-by-element synchrotron radiation
    - *Option for using real photon number, energy, and opening angle distributions (V16.2)*

Other Relevant Single-Particle Dynamics

- RF cavity simulation with exact time dependence
  - Phase and voltage modulation
  - Optional linearization of time dependence
- Kicker simulation with arbitrary-length user-specified waveforms
- Symplectically-integrated wiggler (Y. Wu)
- Flexible apertures
  - Localized collimators or beam tube declaration
    - *Rectangular, elliptical, super-elliptical*
    - *One- or two-sided*
  - Aperture specified in external file.

Impedance Effect Modeling

- Short range impedances/wakes (serial now, parallel soon)
  - Each pass is independent
  - Longitudinal and transverse
  - Time- and frequency-domain implementations
  - Input options
    - *Broad-band impedance (R, Q, f)*
    - *Input Z(f) from SDDS file*
    - *Input W(t) from SDDS file*
  - Smoothing options
    - *Savitzky-Golay*
    - *Low-pass filter*
  - Ramp-on option to prevent transients[1].

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[1] Suggestion of M. Blaskiewicz

Short-Range Wakefields

- Each pass is independent
- Longitudinal and transverse
- Time- and frequency-domain implementations

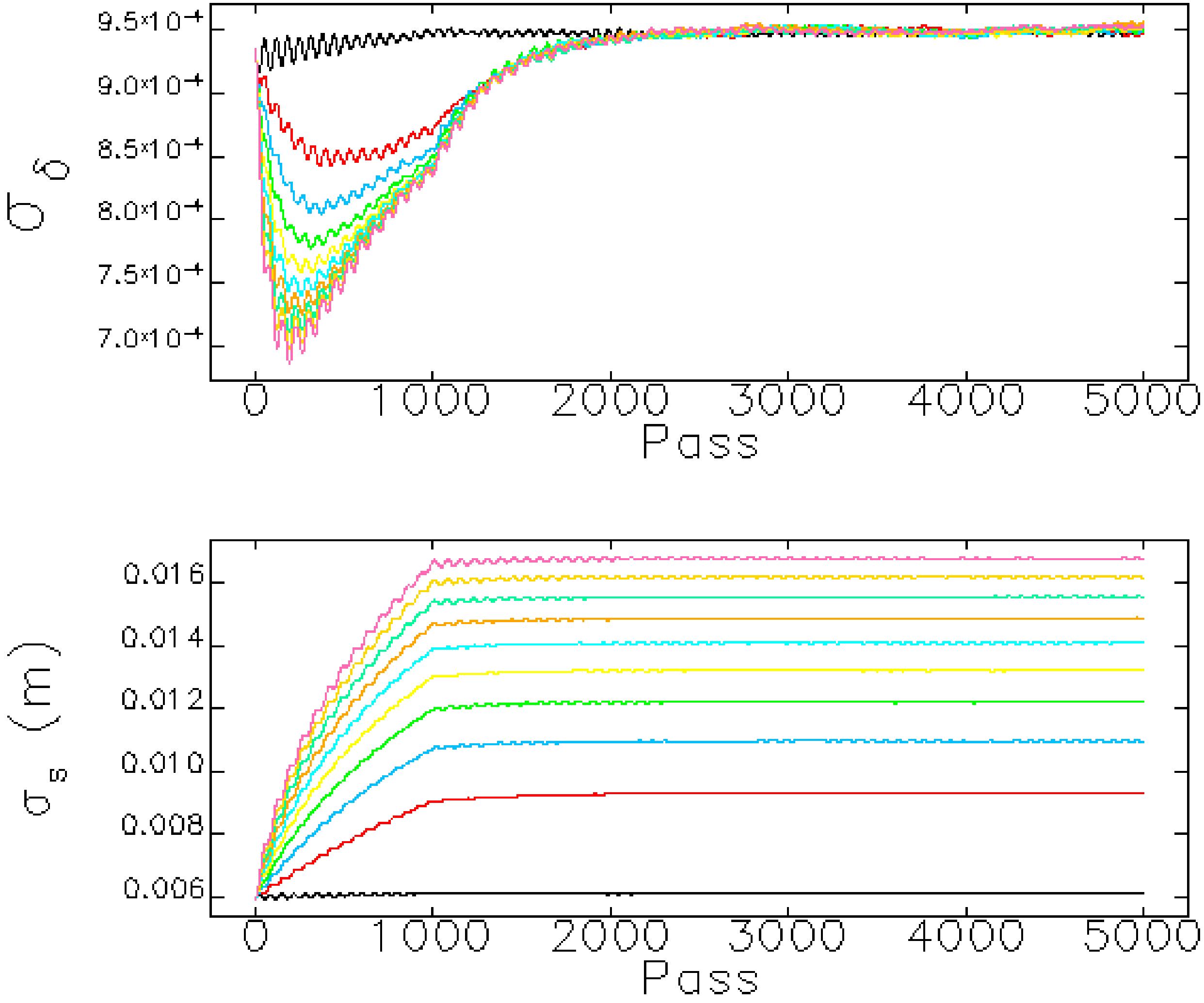
- Time-domain:
  - Make arrival-time histogram weighted by charge*position^n
  - Optionally smooth
  - Convolve in time domain with W(t) to get V(t)
  - Apply V(t) to particles with optional intra-bin interpolation

- Frequency-domain:
  - Make arrival-time histogram
  - Optionally smooth
  - Take FFT to get I(f)
  - Multiply with Z(f), optionally low-pass filtered to control noise
  - Invert FFT to get V(t)
  - Apply V(t) to particles with optional intra-bin interpolation

Short-Range Wakefields

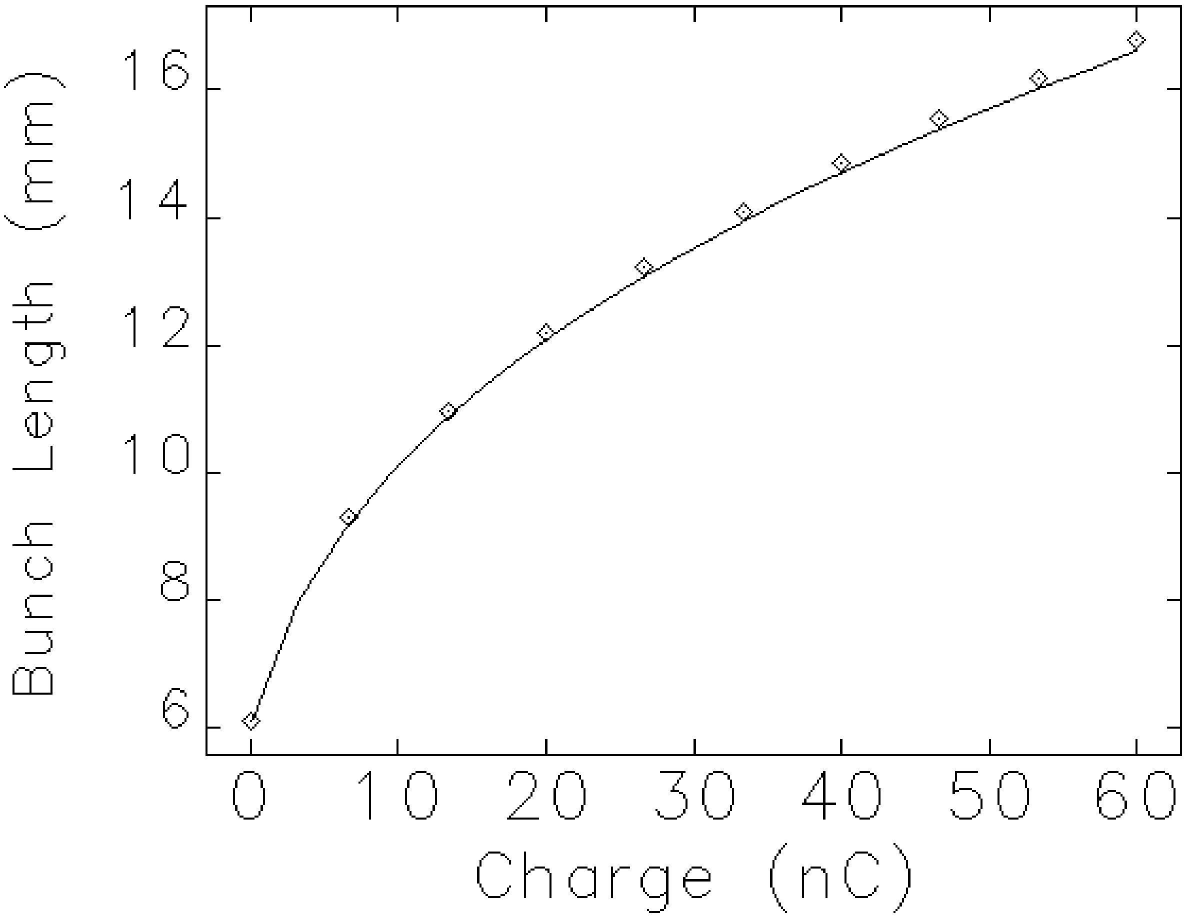
- Input options
  - Broad-band impedance (R, Q, f)
  - Input Z(f) from SDDS file
  - Input W(t) from SDDS file
- Smoothing options
  - Savitzky-Golay (time- or frequency-domain approach)
  - Low-pass filter (frequency-domain approach only)
- Ramp-on option to prevent transients (V16.2)
- Parallel version working now (V16.2)
  - Depending on required time and frequency resolution, time-domain approach may be much faster
  - Still needs some optimization before release.

Example: Potential Well Distortion from Inductive Impedance



- Simulated APS with ILMATRIX
- Used frequency-domain approach for impedance
- Varied charge from 0 to 60 nC
- Set low-pass filter to cut off noise outside bunch spectrum
- 1000-turn ramp to prevent transients

Comparison to Haissinski Equation



- Line is solution to Haissinski equation using **haissinski**[1] program

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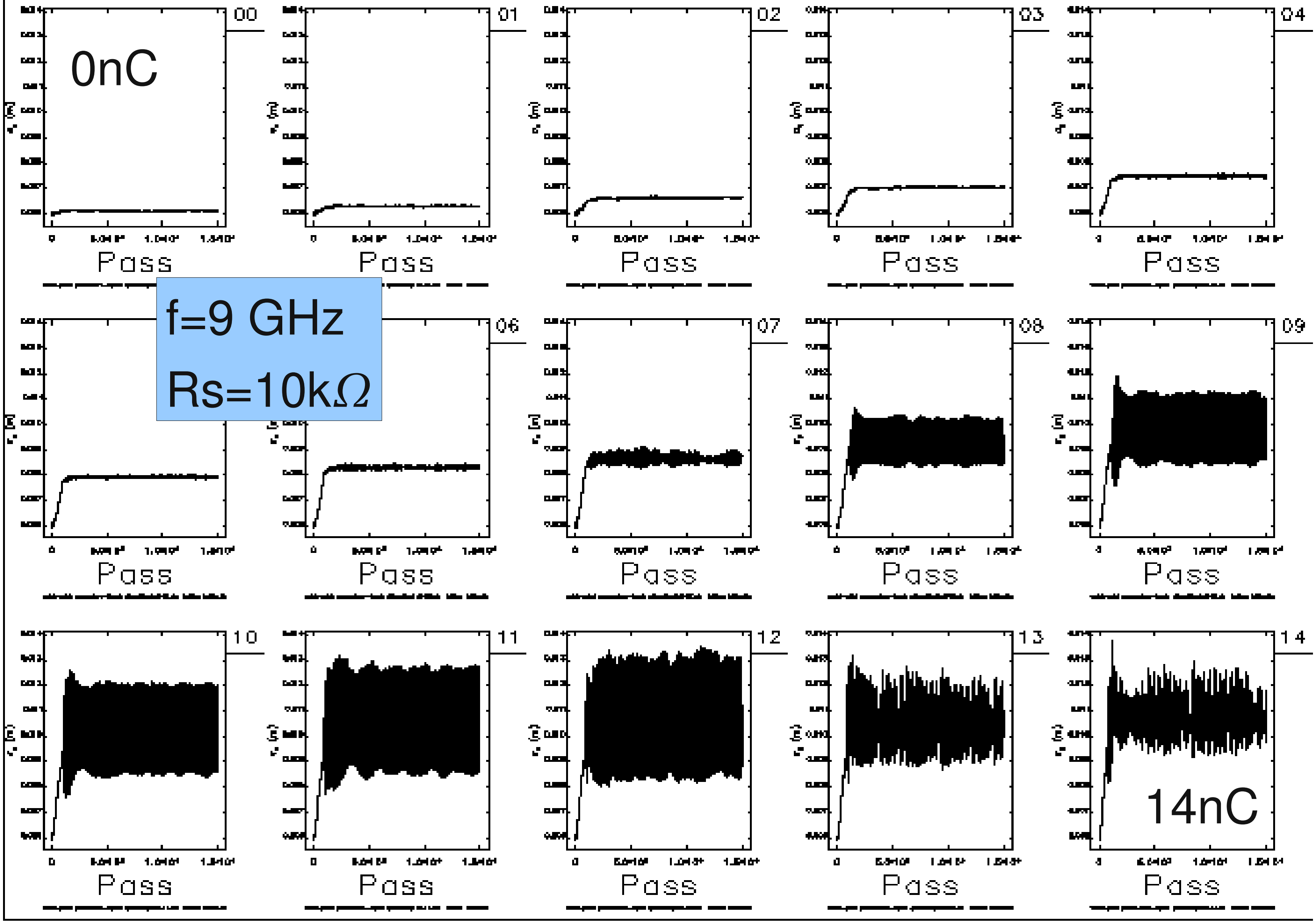
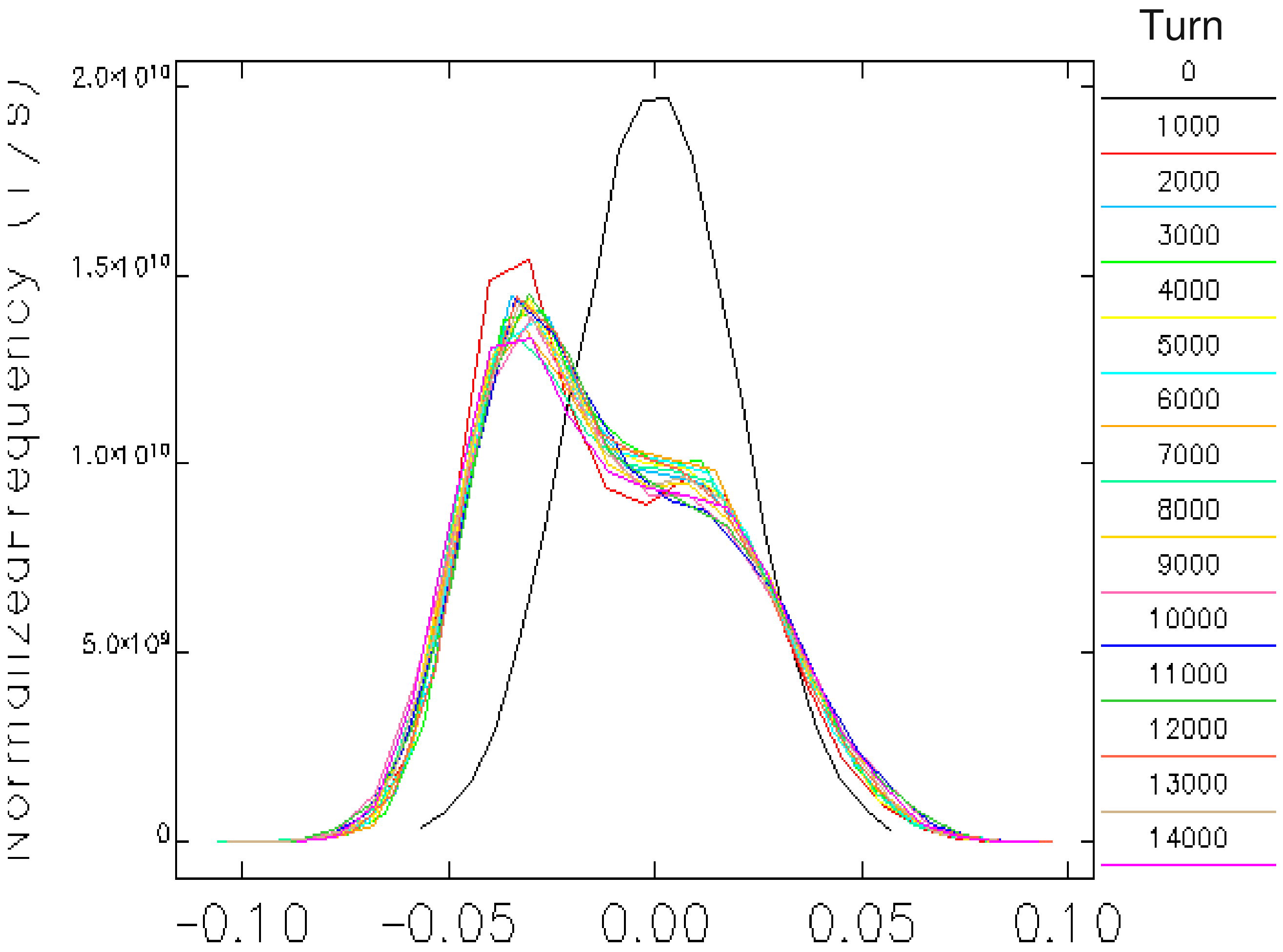
[1] L. Emery, M. Borland

Q=1 Resonator-Driven Instability in APS (C. Yao)

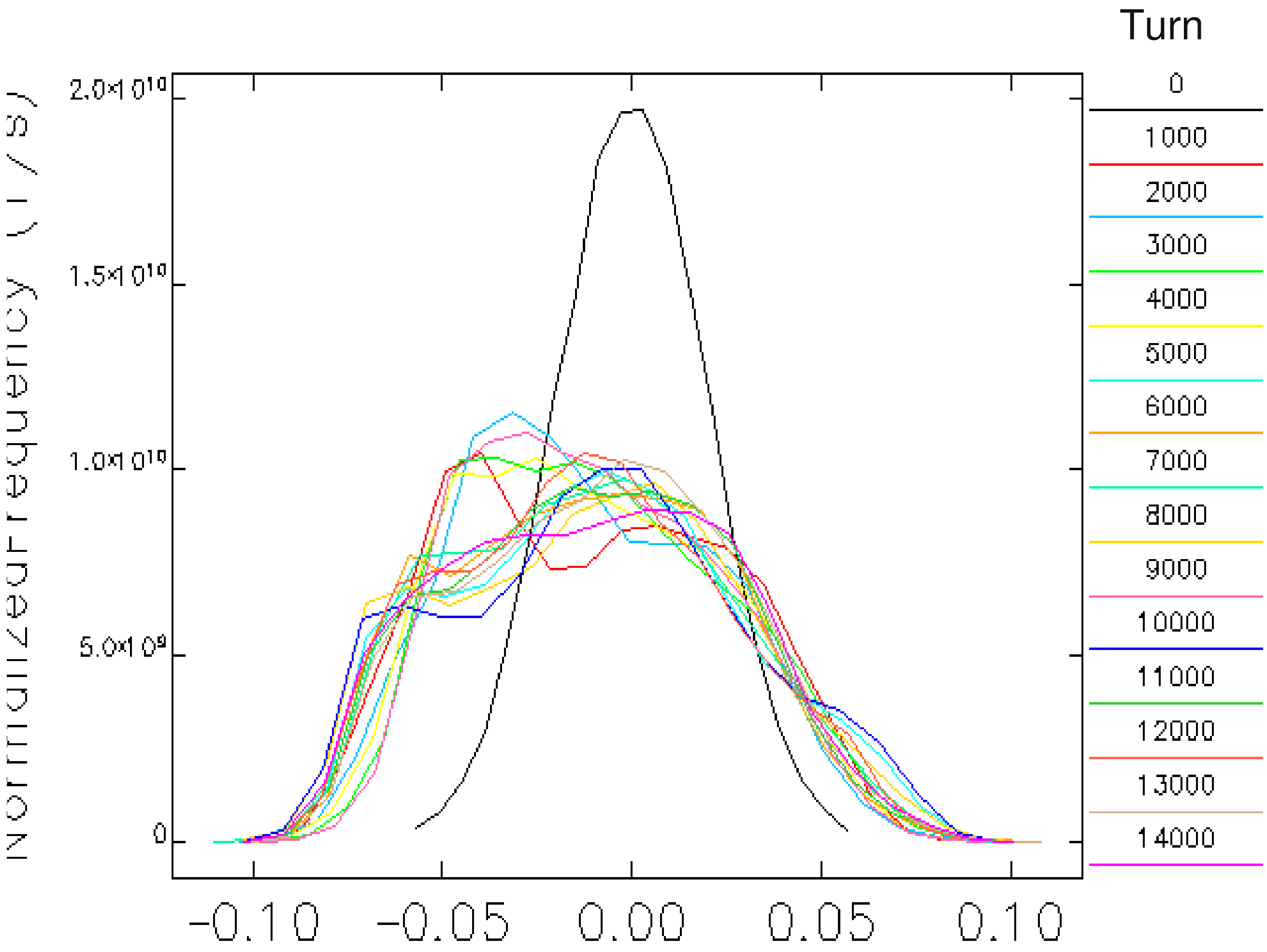


Evolution of Bunch Shape for 6 nC (C. Yao)

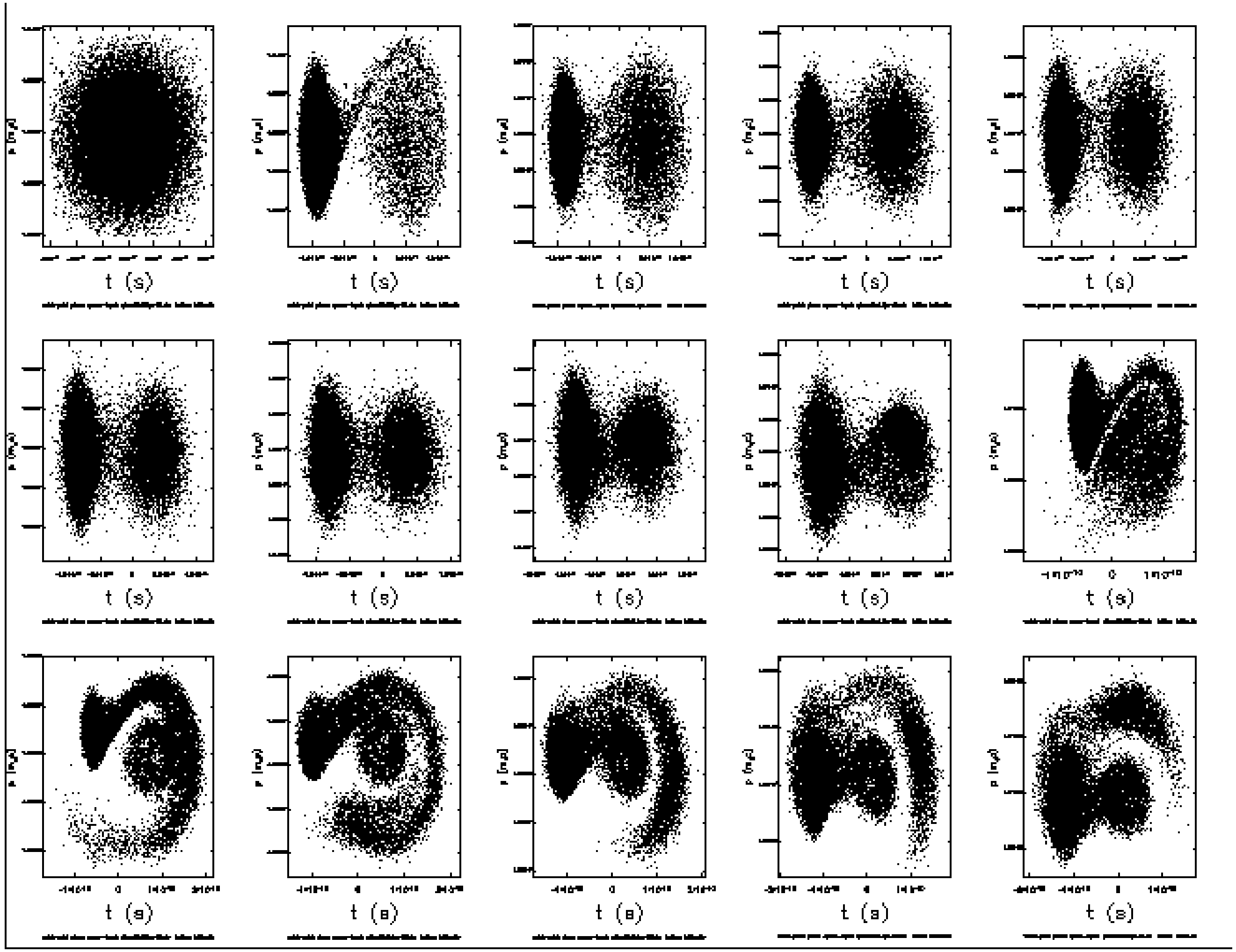


Impedance ramped on over 1000 turns.

Unstable Bunch Shape at 13 nC (C. Yao)



Low-Frequency Cases Show Complex Features (C. Yao)



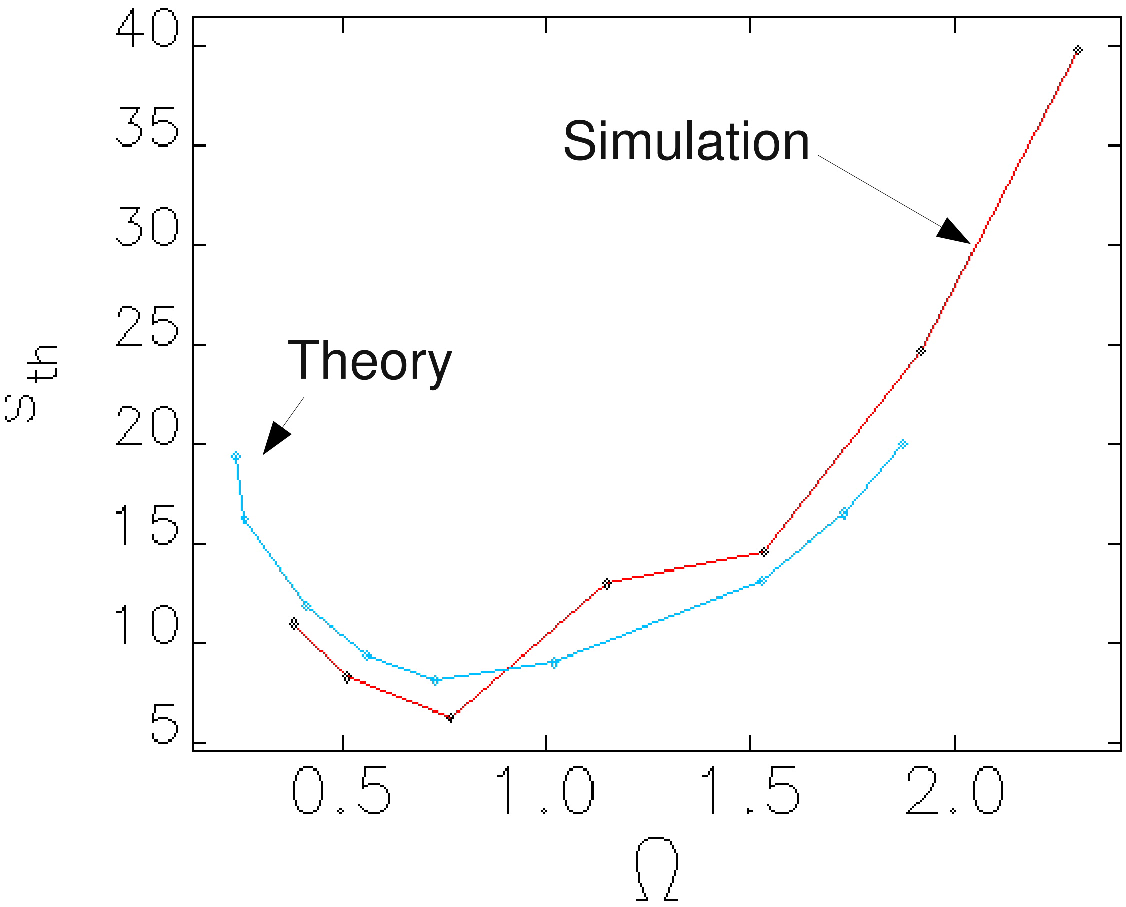
Res. freq: 3GHz, beam charge: 20 nC. Phase space plot at 1000 turns interval.

Comparison to Oide's Theory[1] (C. Yao)

Theory:

$$s_{th} = \frac{2N}{\gamma \nu_{s0} \sigma_\delta} \frac{\omega_0 r_e}{c} \frac{R}{Q Z_0}$$

$$\Omega = \omega_0 \sigma_z / c$$



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[1] K. Oide, KEK Preprint 90-10, April 1990.

Long-Range Impedances

- Implemented using collections of resonators
  - User specifies (R, Q, f) for arbitrary number of resonators
  - Resonator data may be stored in SDDS file
    - *Generated by APS version of URMEL*
- Algorithm:
  - Make arrival-time histogram, weighted by charge*position^n
  - Advance through histogram from early to late arrival time, computing V(t)
    - *Use fundamental theorem of beam-loading to compute voltage induced in each mode by slice of beam*
    - *Advance phasor to next bin position*
- Ramp-on option to prevent transients.

Transverse Space Charge (A. Xiao)

- Implemented linear transverse space charge (SCMULT)
  - Space charge computation assumes gaussian distribution
    - *Computes gaussian parameters from actual beam distribution*
  - Space charge force varies with longitudinal position
    - *Reduces tune shift compared to analytical results*
  - Separate element that user inserts into lattice as needed
    - *E.g., 1 per turn or 10 per turn...*
    - *Automatically gives appropriate strength to each SCMULT element*
    - ***elegant** can automatically insert SCMULT after each element*
- Have added non-linear space charge
  - Formulae from W. Ng
  - Under test now.

Longitudinal Space Charge

- Two elements:
  - LSCDRIFT: longitudinal space charge in a drfit
  - RFCW: rf cavity with wakes and longitudinal space charge
- Uses an impedance-based approach[1]
  - Ignores vacuum chamber walls
    - *Appropriate for looking at short-wavelength modulations*
  - Ignores energy spread due to variation force with radius
  - Function peaks typically at very short wavelength, so careful noise control is vital

$$Z(k)=\frac{iZ_0}{\pi k_0 r_b^2}\left[1-\frac{k_0 r_b}{\gamma}K_1\left(\frac{k_0 r_b}{\gamma}\right)\right]$$

[1] Z. Huang *et al.*, PRSTAB 7, 074401 (2004) and refs. therein.

Feedback System Simulation

- Single-bunch turn-by-turn feedback simulation
- User inserts one or more pick-ups into lattice
  - Measure the beam centroids
  - Apply a 15-turn digital filter with delay
- User inserts on or more drivers into lattice
  - Link any number of drivers to one pick-up
  - Apply a 15-turn digital filter to the selected pick-up output
  - Apply kicks to beam
- Presently assumes the entire beam is one bunch.

Simulation Diagnostics

- Lost-particle file
  - Position of loss
  - Particle transverse and longitudinal coordinates at loss
- Accepted-particle file
  - Initial coordinates of all surviving particles
- “Watch point” elements inserted at any location in lattice
  - Phase space dump at insertion point, every Nth turn
  - Beam moments at insertion point, every Nth turn
- Histogram elements give histograms at insertion point
- All delivered to self-describing SDDS files.

Planned Developments for DR Work

- Finish parallelization of short-range impedance elements
- Parallelize long-range impedance elements
  - Also add smoothing for noise control
- Develop method for long-range non-resonant wakes (e.g., resistive wall)
- Develop longitudinal space-charge kick element
- Generalize ILMATRIX to non-periodic systems
- Incorporate more sophisticated space charge model from *Synergia*.
- Improve support for multi-bunch beams
  - More efficient implementation of short-range impedances
  - Extend feedback simulation from single- to multi-bunch.

Acknowledgments

- Thanks to the following people for help in preparing this talk
  - Louis Emery (ANL)
  - Aimin Xiao (ANL)
  - CY Yao (ANL)