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Measurements and Simulations of CSR Effects in the APS Bunch Compressor

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May 31, 2001

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Contributors

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- Experiments and support: M. Borland, P. Emma, J. Lewellen, Y. Li, S. Milton
- Software: N. Arnold, M. Borland, Y. Chae, R. Soliday, J. Stein
- Management: S. Milton

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Outline

- APS linac and bunch compressor overview
- Beam requirements and limitations
- CSR simulation methods
- Design simulation results
- Comparison of experiments and simulation
- Plans

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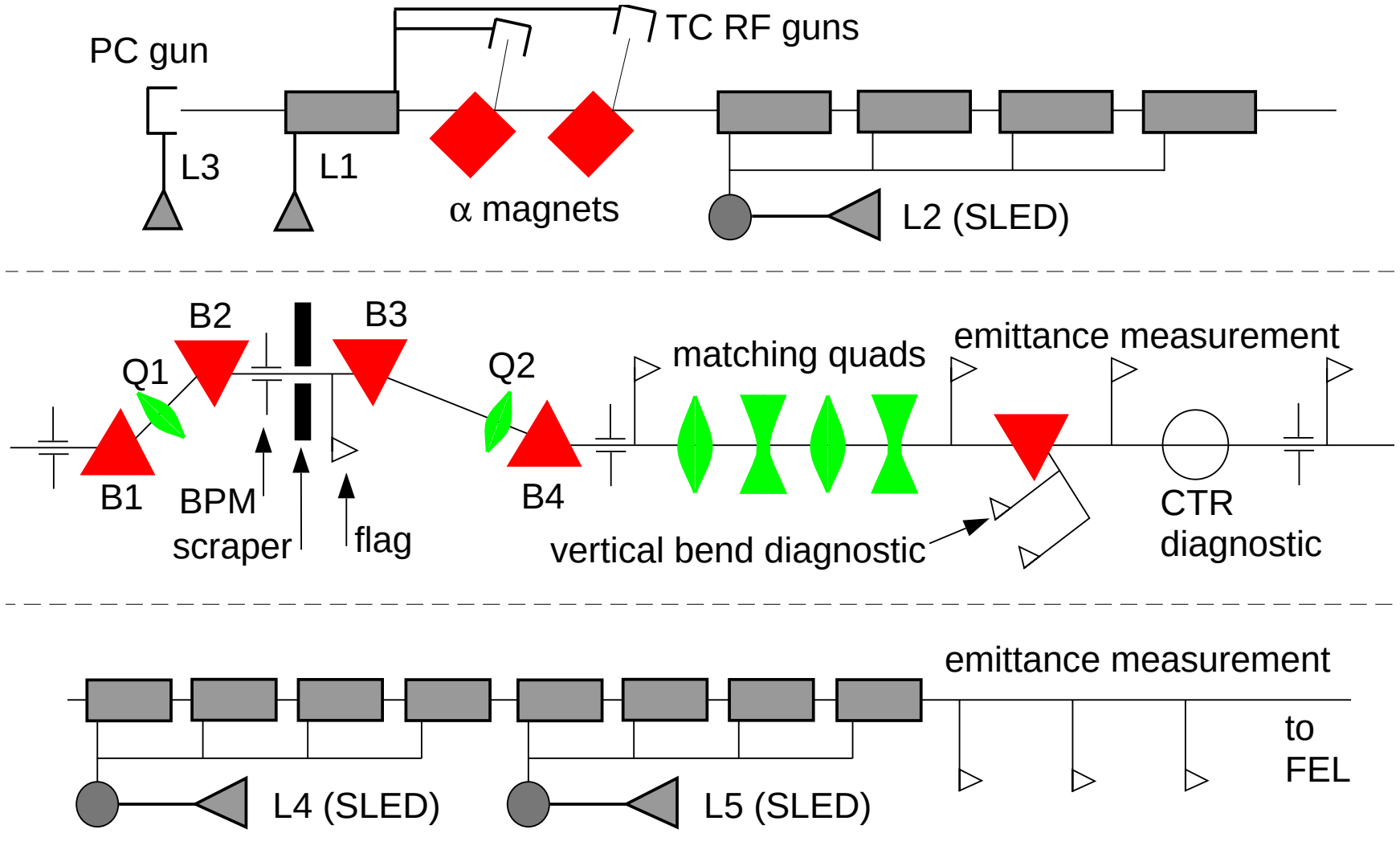
APS Linac Schematic



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Beam Specifications for LEUTL FEL

Energy MeV	Peak Current A	RMS Energy Spread %	Normalized Emittance um	Charge nC
217	300	<0.1%	5	>0.5
457	600	<0.15%	5	>0.5

- Prior to bunch compressor installation, ~150A was achieved with ~0.7nC. Modest FEL gain was seen.
- With the bunch compressor, up to 600A was achieved with ~0.2nC. Saturation at 530nm and 385nm followed shortly.

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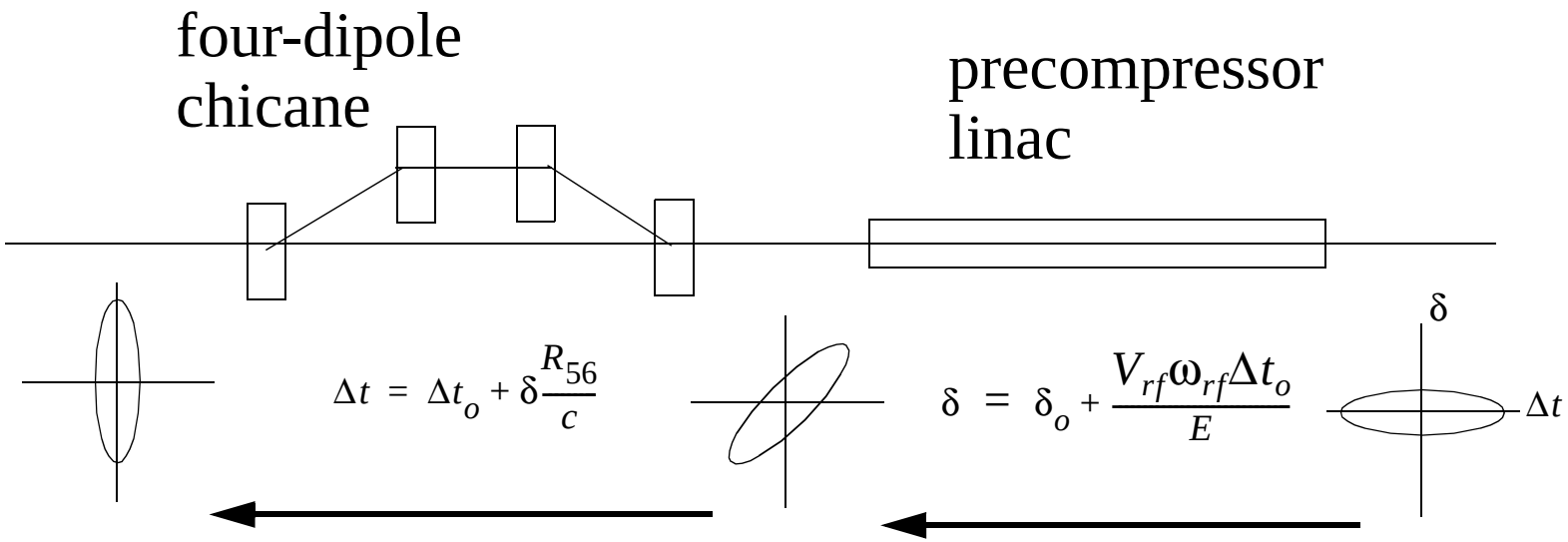
Bunch Compression in a Nutshell



$$\Delta t = \Delta t_o + \frac{R_{56}}{c}\left(\delta_o + \frac{V\omega\Delta t_o}{E}\right) \longrightarrow \langle \Delta t^2 \rangle \approx \langle \Delta t_o^2 \rangle \left(1 + \frac{R_{56}V\omega}{cE}\right)^2$$

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Limits on Injector Performance

- Space charge and rf focusing in the gun.
- Wakefields in accelerating tanks.
- Jitter of rf systems and laser.
- Rf curvature and other nonlinear transport effects.
- Coherent synchrotron radiation (CSR) in chicane.

With the exception of CSR, these are “easy” to model.

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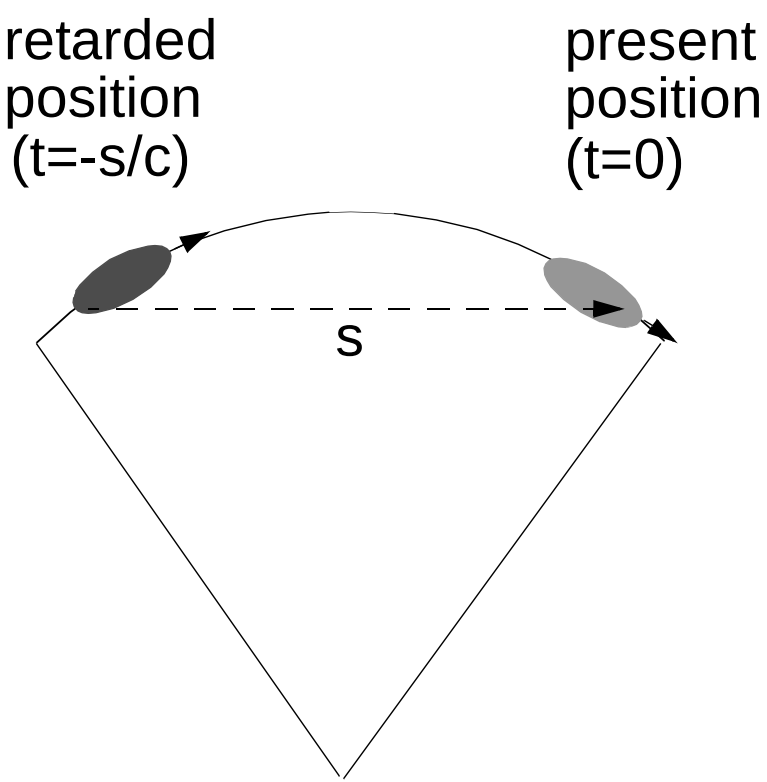
Qualitative Explanation of CSR



Curved trajectory allows radiation from tail to catch up with the head.

Particles in bunch radiate coherently at wavelengths much less than the bunch length.

This radiation produces a position-dependent energy modulation along the bunch.

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How CSR Affects the Bunch

- CSR imposes a longitudinal-position-dependent energy modulation on the bunch. This will show up in the *energy spectrum*.
- This modulation is imparted inside a dipole and inside the chicane, producing a modulation of the slopes of particle trajectories.
- This results in a growth of the *projected emittance* in the bending plane.
- CSR also introduces *x-p correlations*. These can be seen on a vertical bend ("Dowell diagnostic") after the chicane.

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Simulation of CSR Effects

- Inside dipoles, use free-space, 1-D formalism of Saldin, *et al.,* in NIM A 398 (1997):

$$\frac{dE(s,R,\phi)}{cdt} = T_1(s,R,\phi) + T_2(s,R,\phi)$$

where R is the bend radius, ϕ is the angle into the bend, and $s = ct$. The two terms are

$$T_1(s,R,\phi) = K \int_{s-s_l}^{s} \lambda'(z)\left(s-z\right)^{\frac{-1}{3}} dz$$

and

$$T_2(s,R,\phi) = K\frac{\lambda(s-s_l)-\lambda(s-4s_l)}{s_l^{1/3}}$$

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where $K = \frac{-2e^2}{(3R^2)^{1/3}}$, $s_l = \frac{R\phi^3}{24}$ is the slippage length, and $\lambda(s)$ is the longitudinal density of the bunch.

- Dipoles are cut into ~100 slices and the CSR wake is computed from the longitudinal density at the end of each slice. This is used to modify the energy of each simulation particle.

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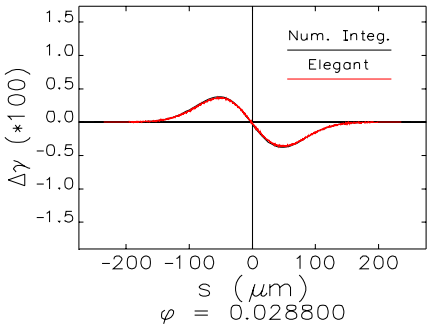
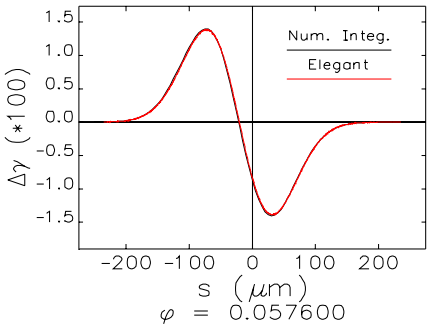
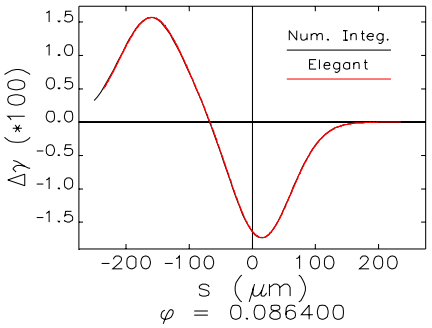
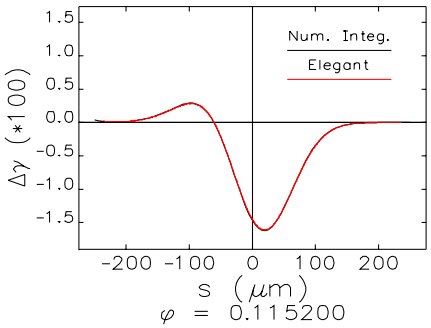
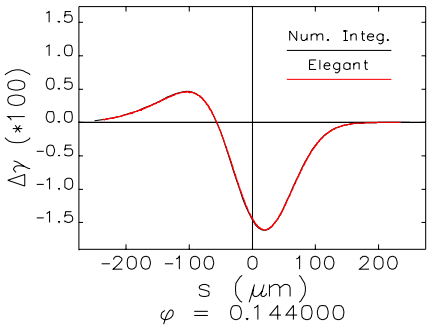
Examples of CSR Wakes in a Dipole

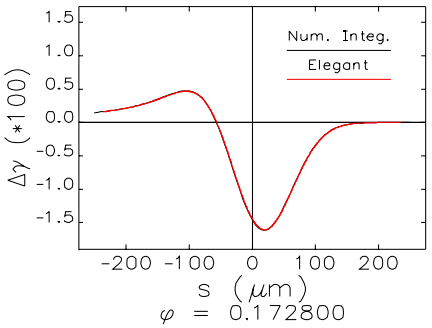


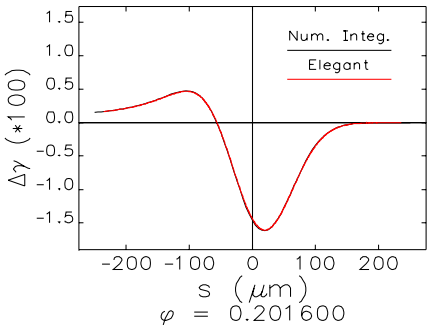


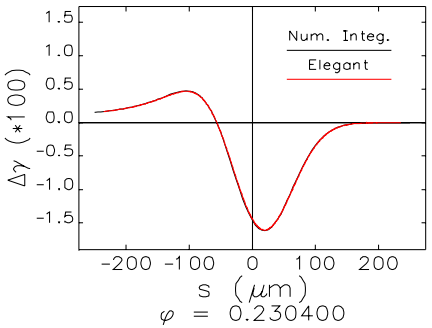












Gaussian beam

R = 1.5m

$\sigma_z = 50\mu m$

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Simulation of CSR in Drift Spaces

- CSR effects are not confined to dipoles, as the radiation continues to propagate with the beam.
- After dipoles, assume the terminal CSR wake propagates with gradual attenuation but fixed shape. This is confirmed by detailed simulations (Dohlus *et al.*).
- Attenuation length is roughly given by the "overtaking length," $(24\sigma_z R^2)^{1/3}$.
- Saldin *et al.* give equations for this radiation for an idealized rectangular beam distribution. In **elegant**, these are used to determine how quickly the radiation attenuates.

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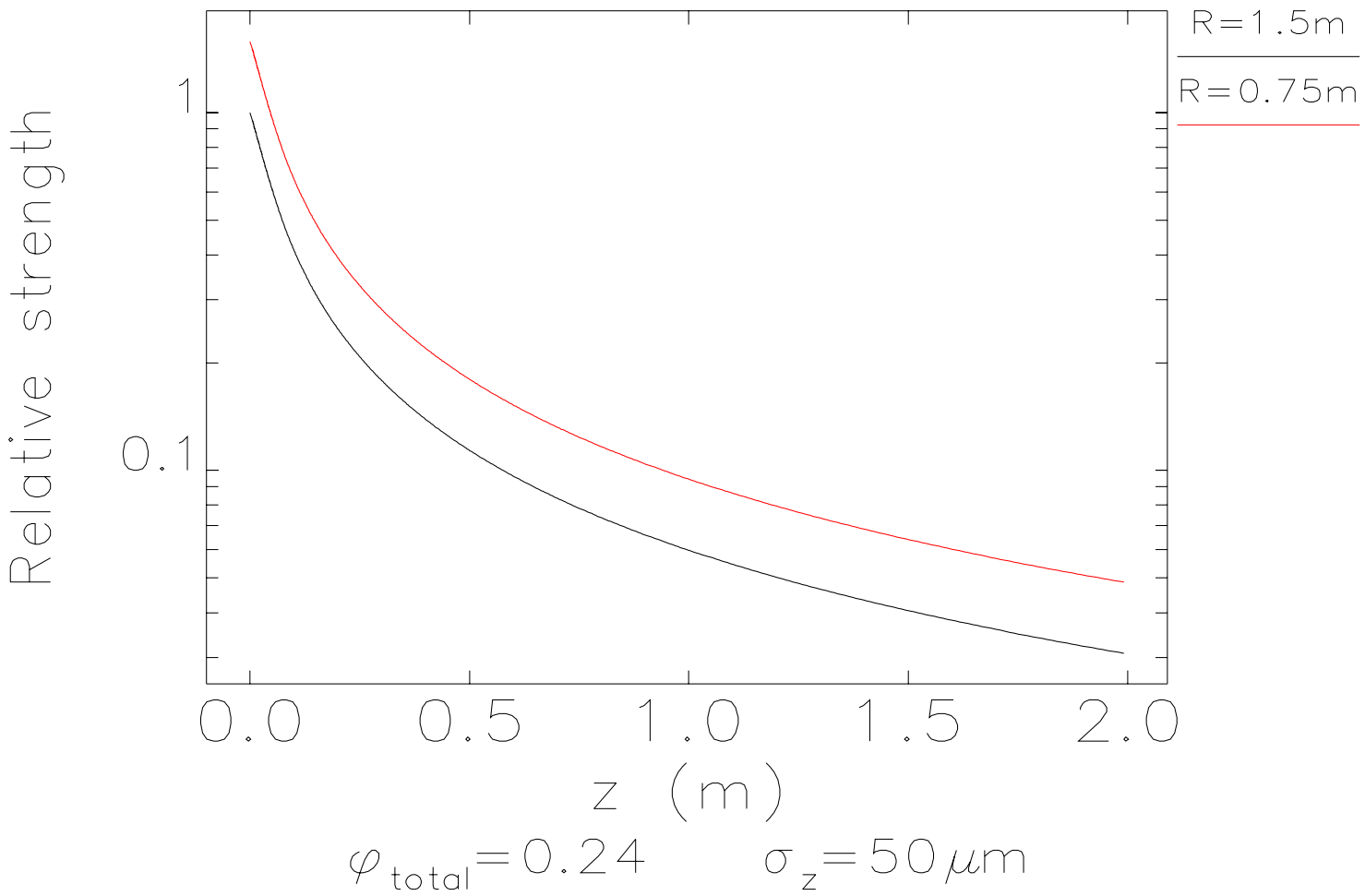
Attenuation of CSR in Drift



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Simulation Method for APS Compressor

- Photoinjector (J. Lewellen) uses PARMELA
  - Simulate a nominal 1nC bunch.
  - Scale the charge and emittance of this distribution to match what we actually run.
- Linac-to-FEL uses **elegant**, including
  - longitudinal and transverse matching
  - longitudinal wakes
  - exact rf curvature effects
  - second-order matrix for quadrupoles
  - symplectic integrator for chicane dipoles
  - CSR in dipoles and drifts

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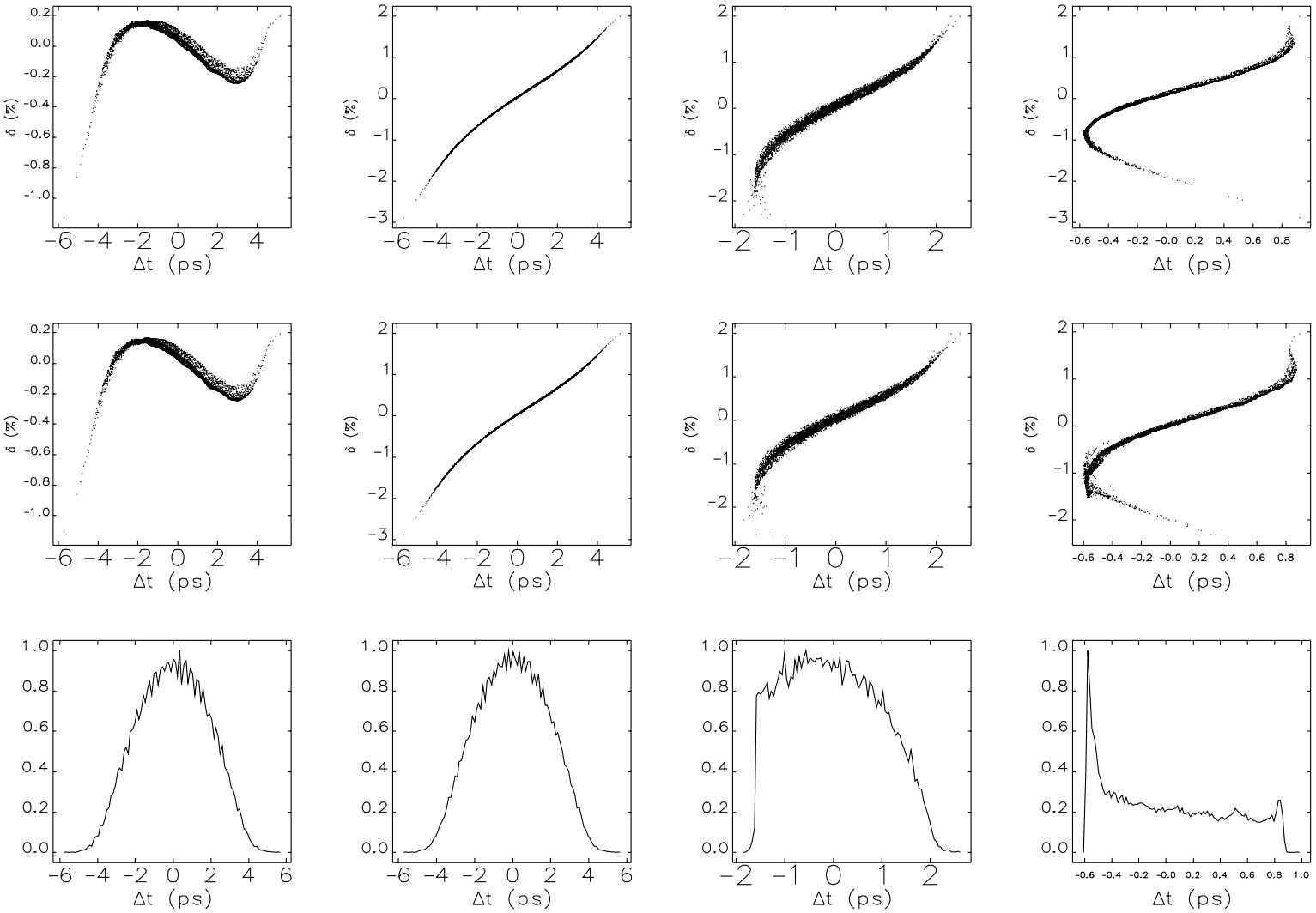
Example of Bunch Compression and CSR Effect



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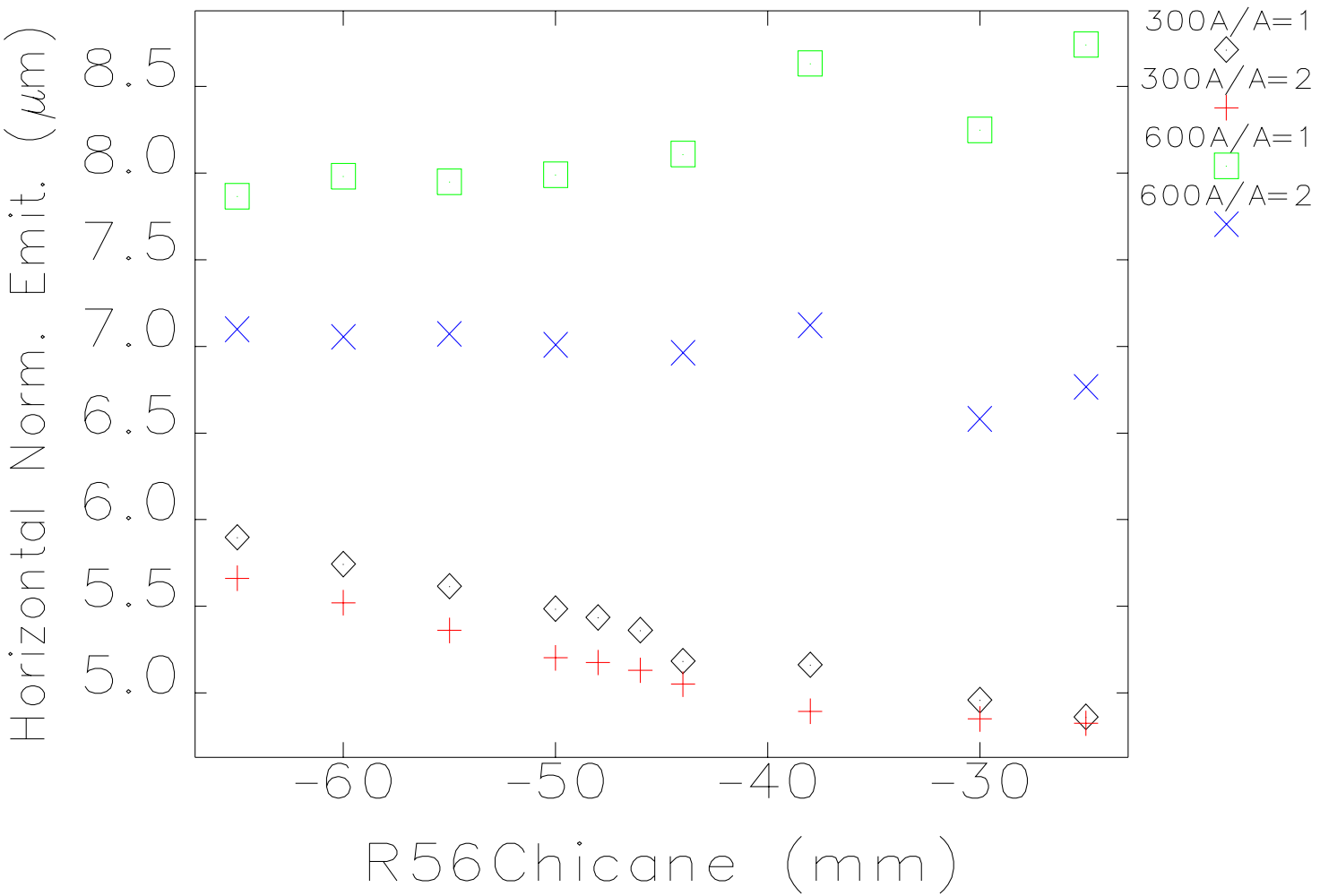
Predictions for Design Operation Conditions



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Bunch Compressor Experiments

- Bunch compressor is fixed in position (chamber problem), so we basically have two knobs: charge and rf phase.
- Rf phase scans allow varying the energy chirp and thus the bunch length.
- We vary the rf voltage to keep the beam energy fixed.
- Measurements include:
  - “incoming” energy spectrum (at center of chicane)
  - energy spectrum after chicane (vertical bend line)
  - emittance after chicane (three screen system)
  - bunch length after chicane (rf zero-phasing)

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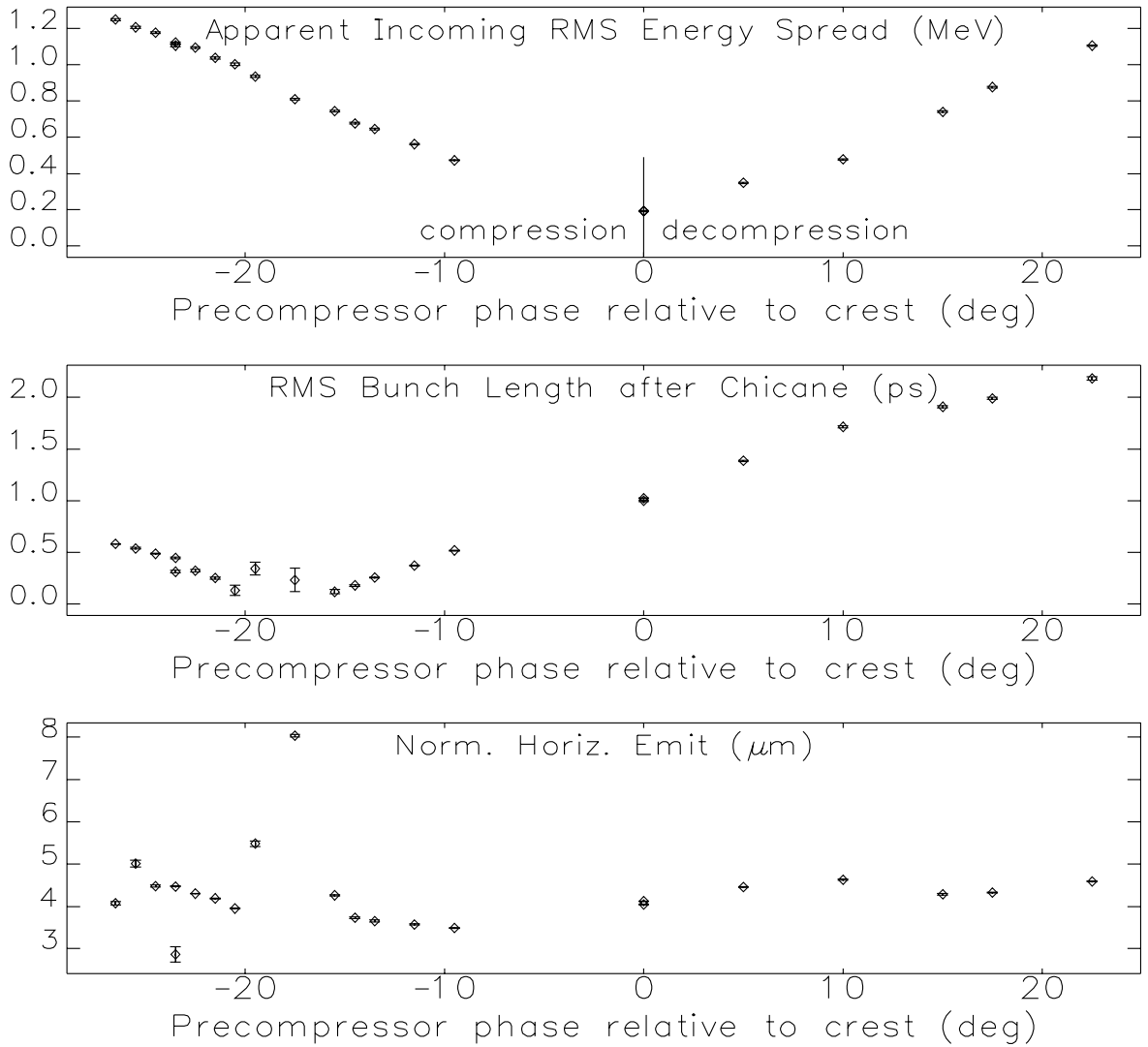
Phase Scan for 200pC Beam (3/31/01)



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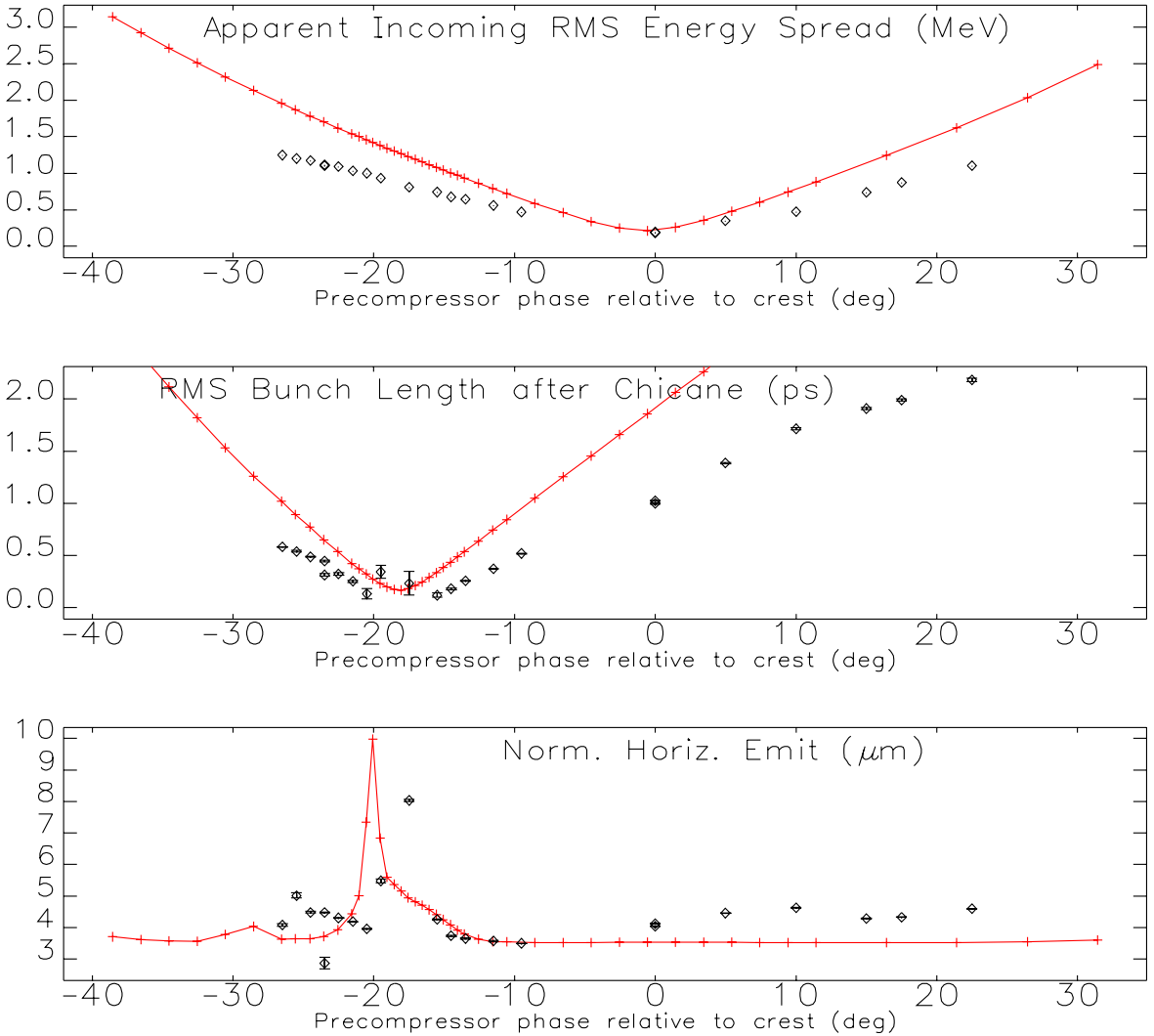
Comparison with "Nominal" Simulation



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Matching Simulation to Experiment

- Knowledge of the initial longitudinal phase space entering L2 is critical to getting the bunch length and emittance correct.
- Used **elegant** without CSR to match the measured bunch length data by adjusting initial RMS longitudinal properties.
- “Morphed” the PARMELA-generated bunch to have the same RMS longitudinal properites and emittance.

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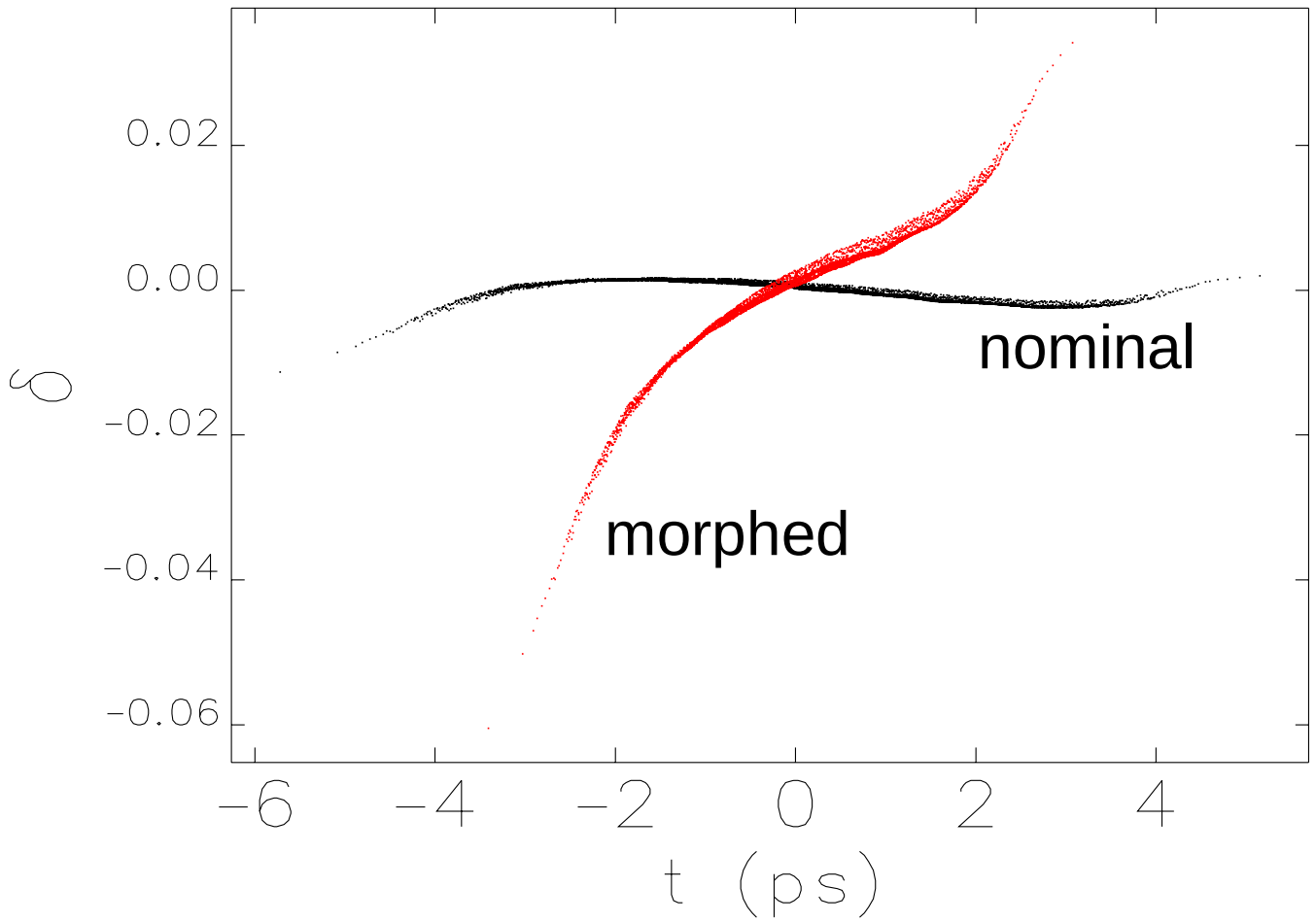
Nominal and Morphed Longitudinal Phase-Space



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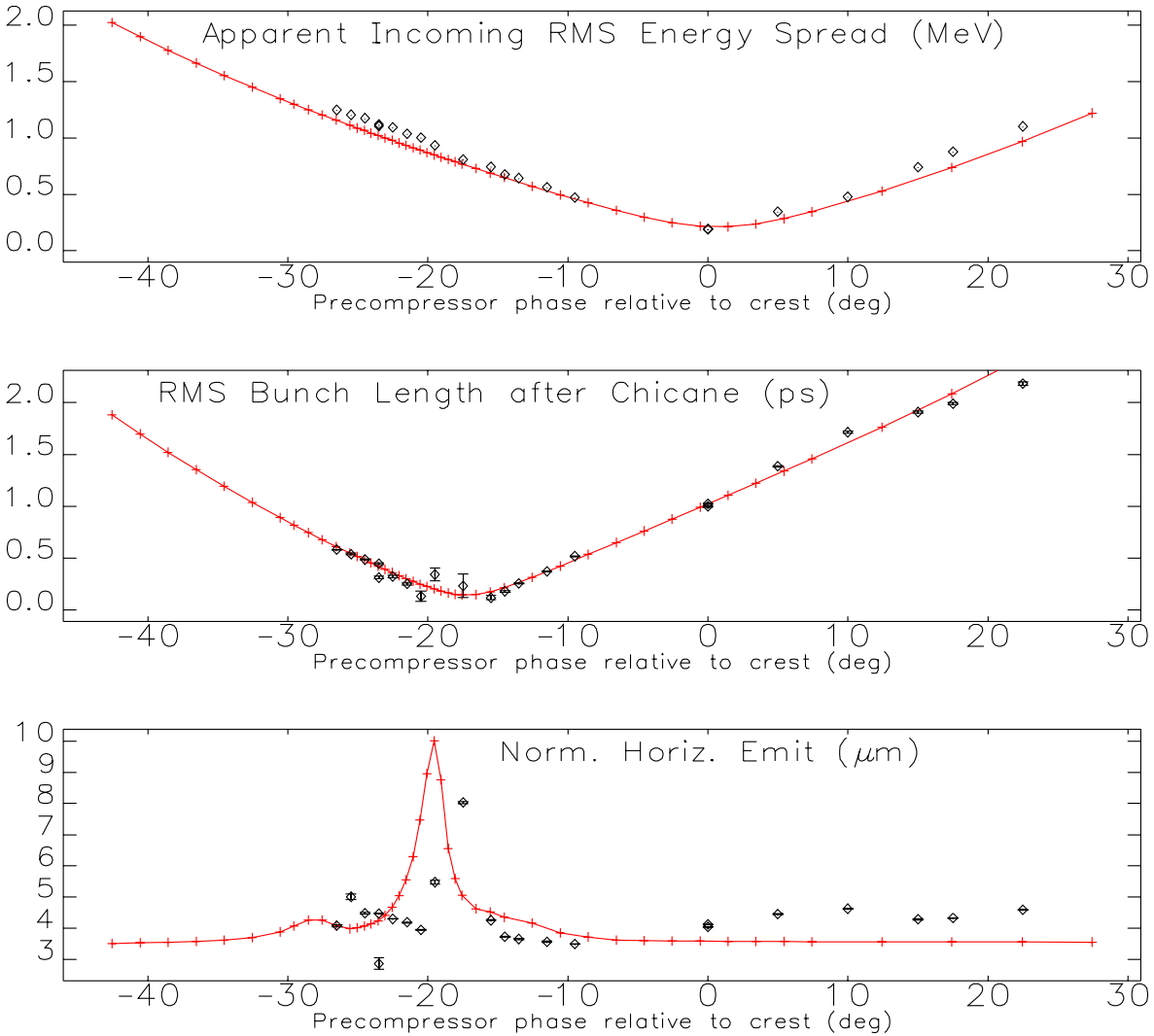
Comparison with Bunch-Length-Matched Simulation



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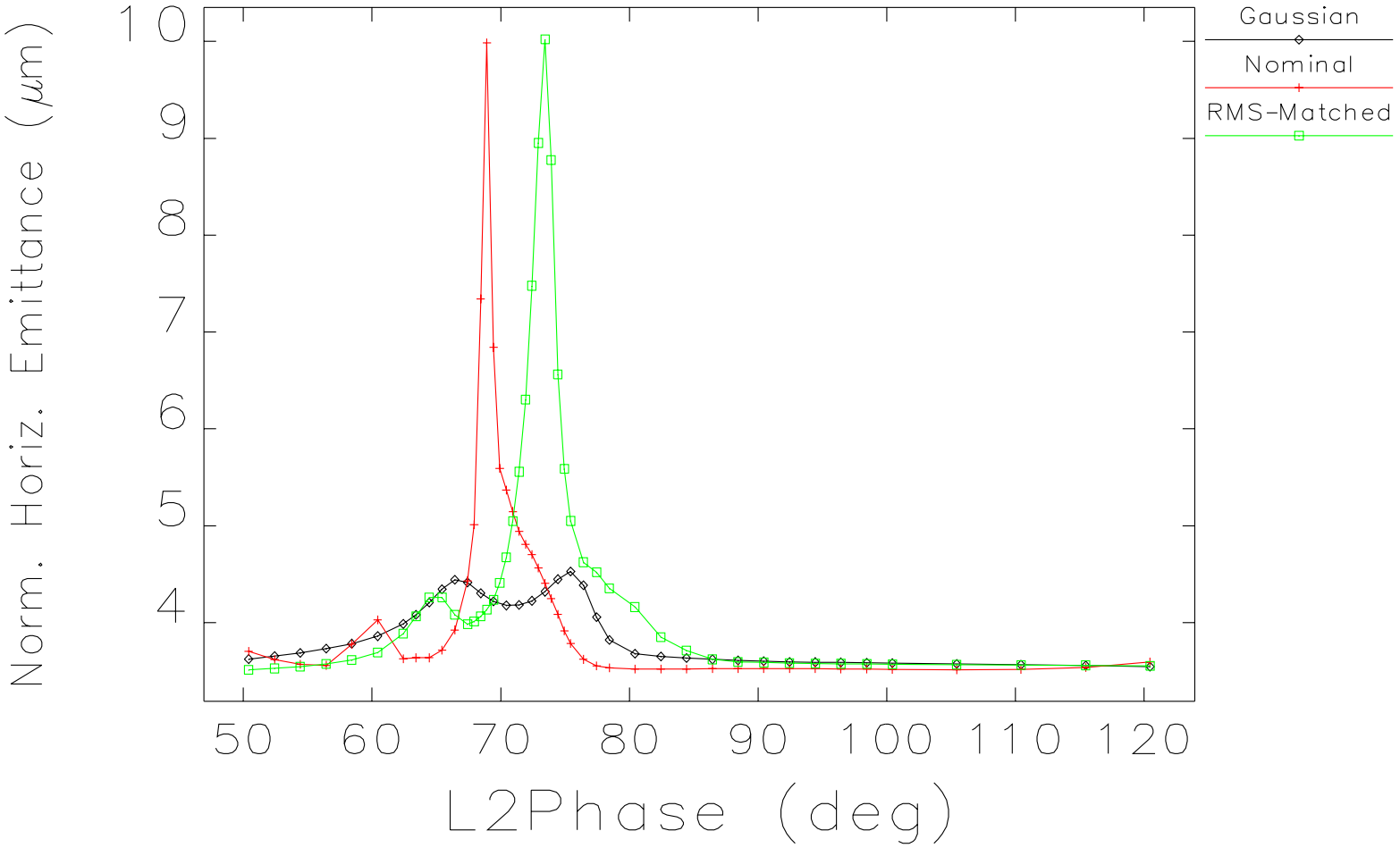
Effect of Using a Gaussian Beam is Dramatic



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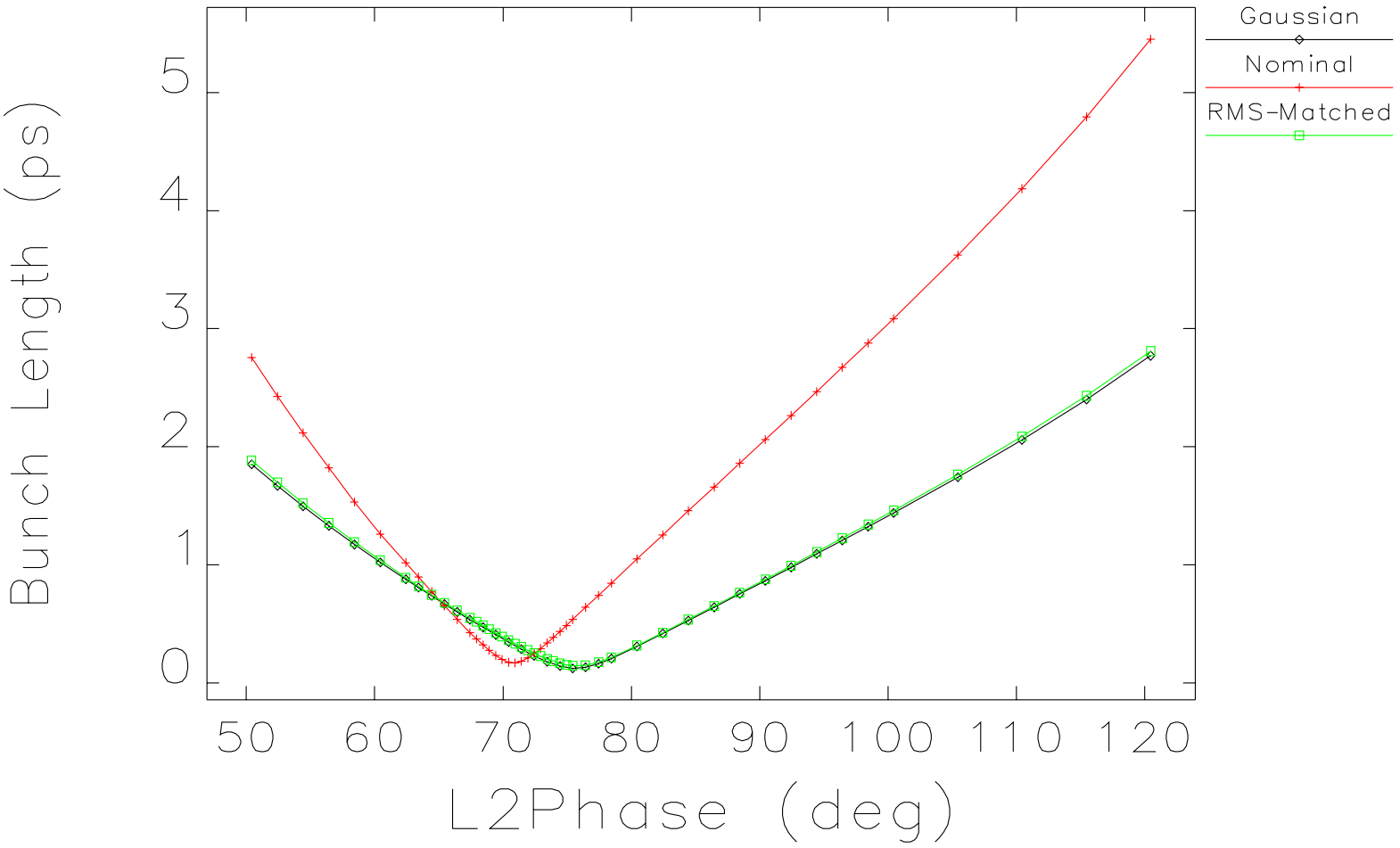
...Even Though the RMS Bunch Lengths Match



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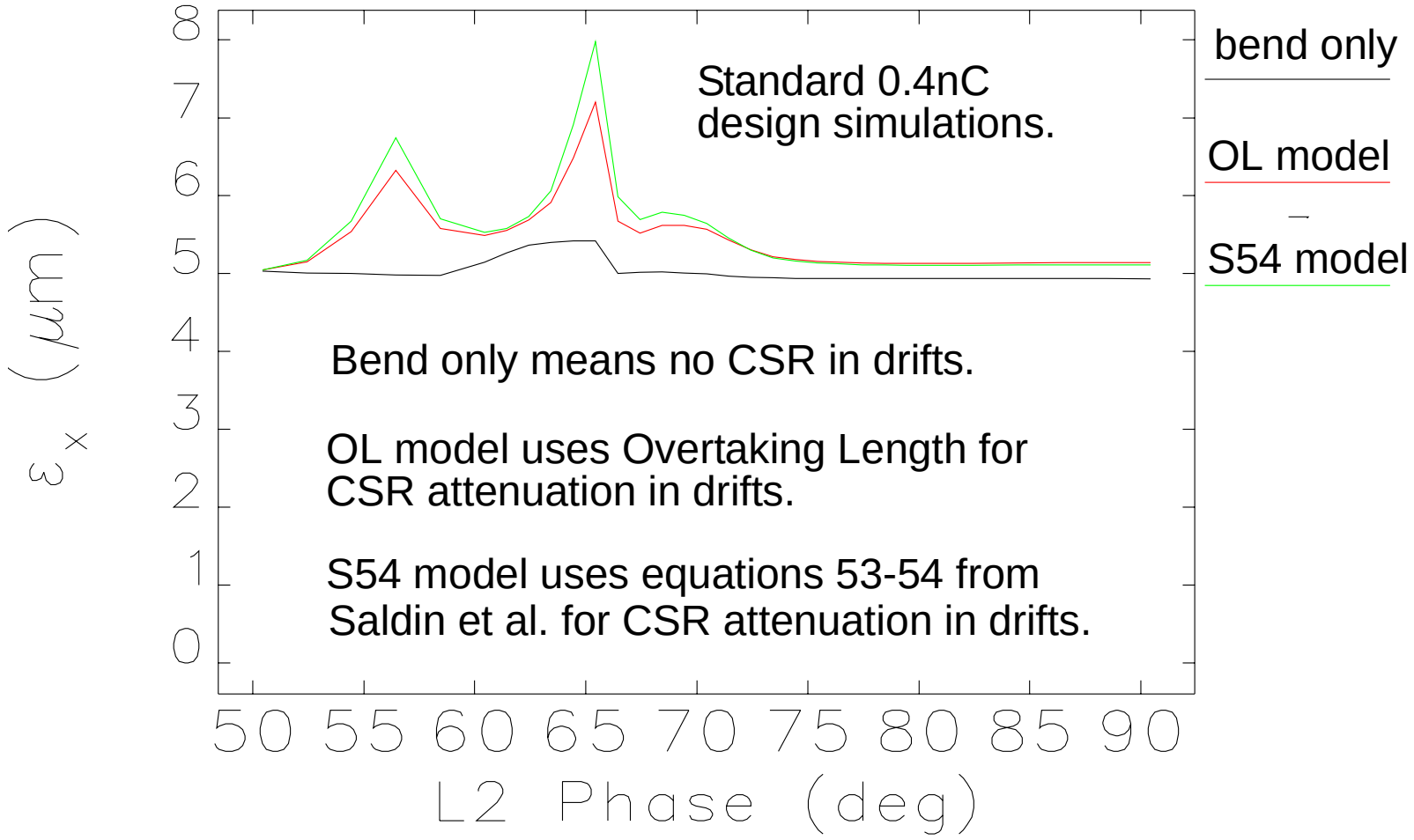
CSR Model for Drifts is All-Important



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Impact of CSR on Energy Spectra (3/30/01)

- In this experiment, we again varied L2 rf phase to vary the bunch length.
- We recorded beam profiles at the center of the bunch compressor (“BCC” flag) and after the vertical bend (“DD” flag).
- Charge was 270pC, normalized emittances 4.3μm and 3.1μm for x and y.

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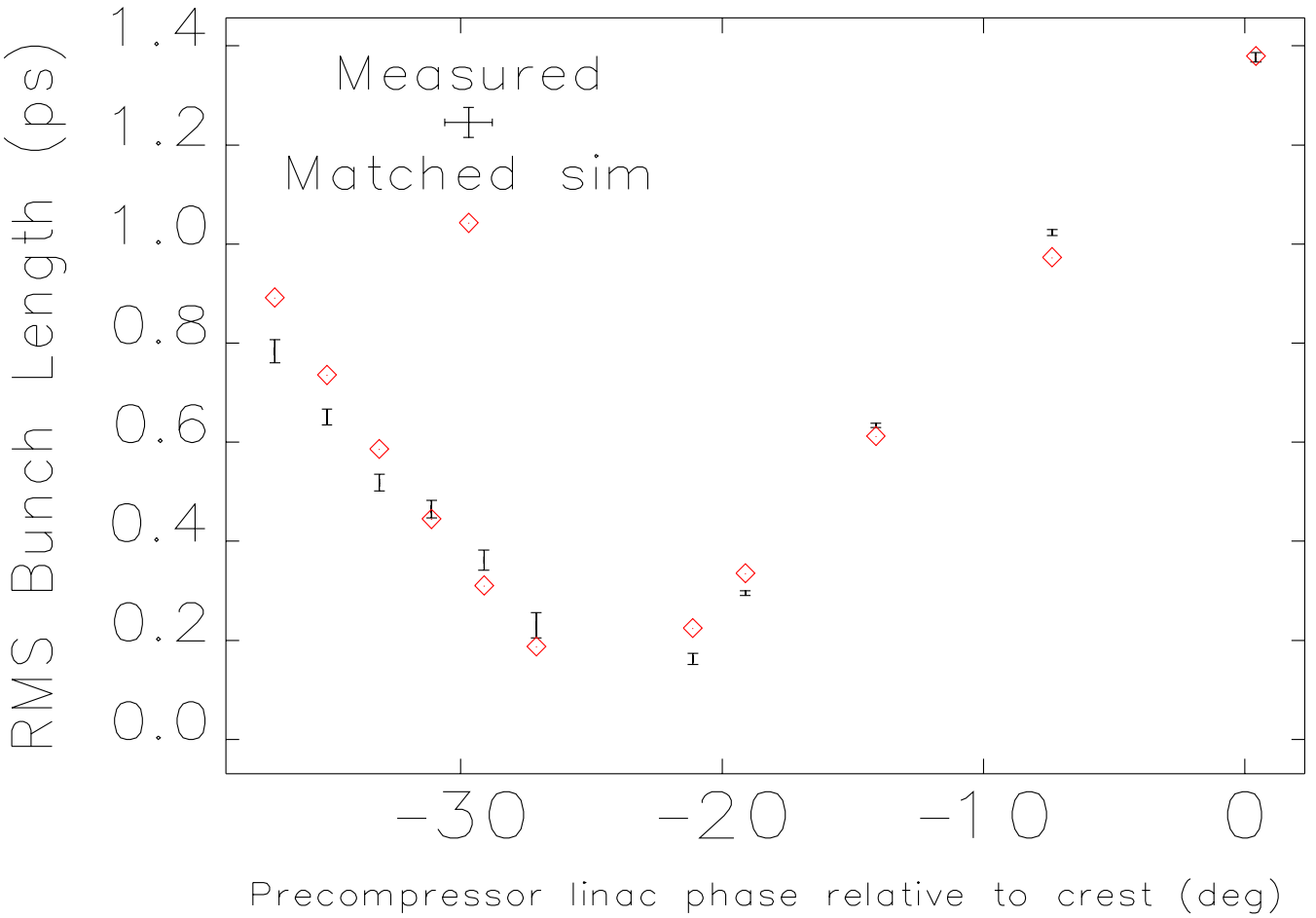
Bunch Length Data



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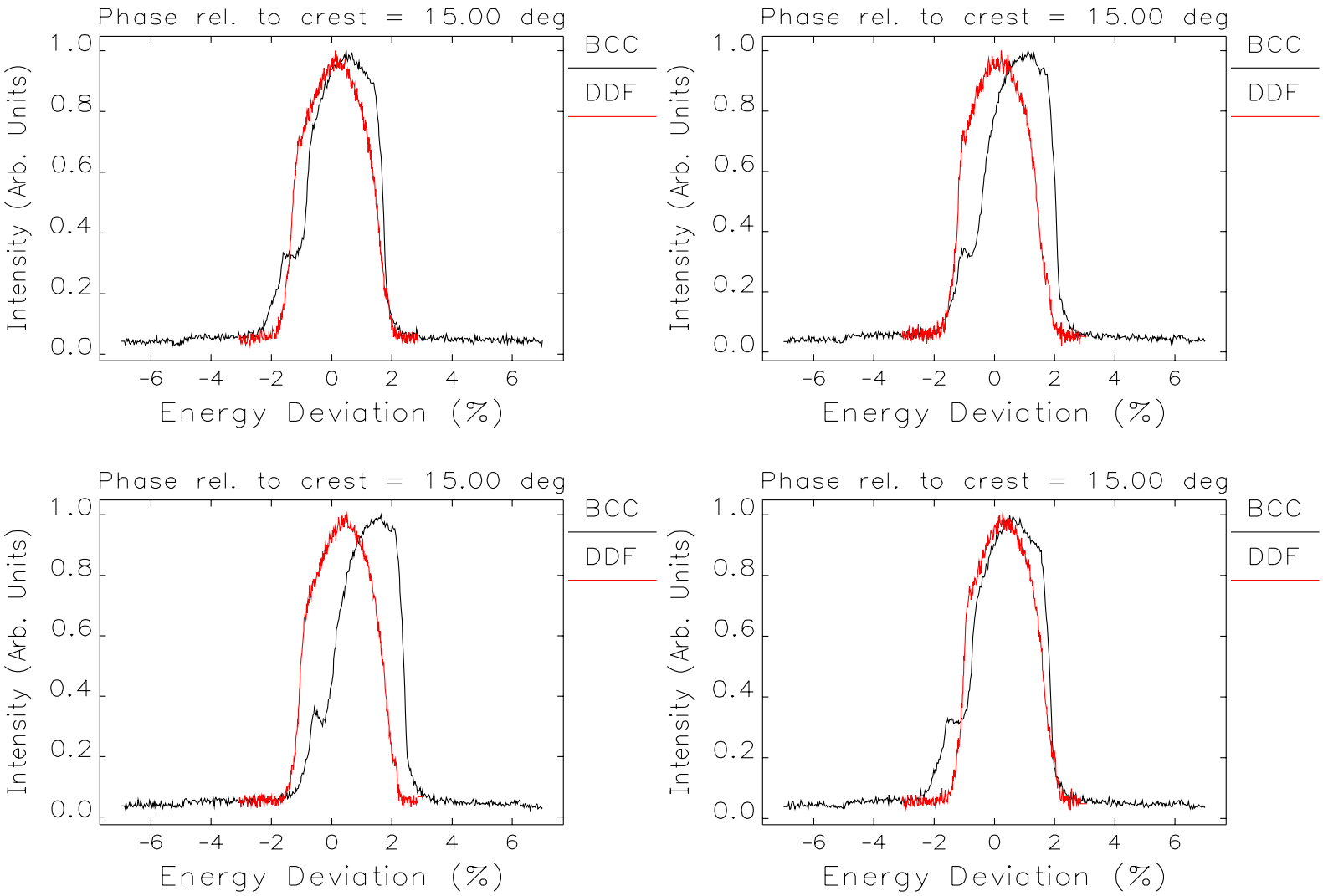
Apparent Energy Spectra in Decompression



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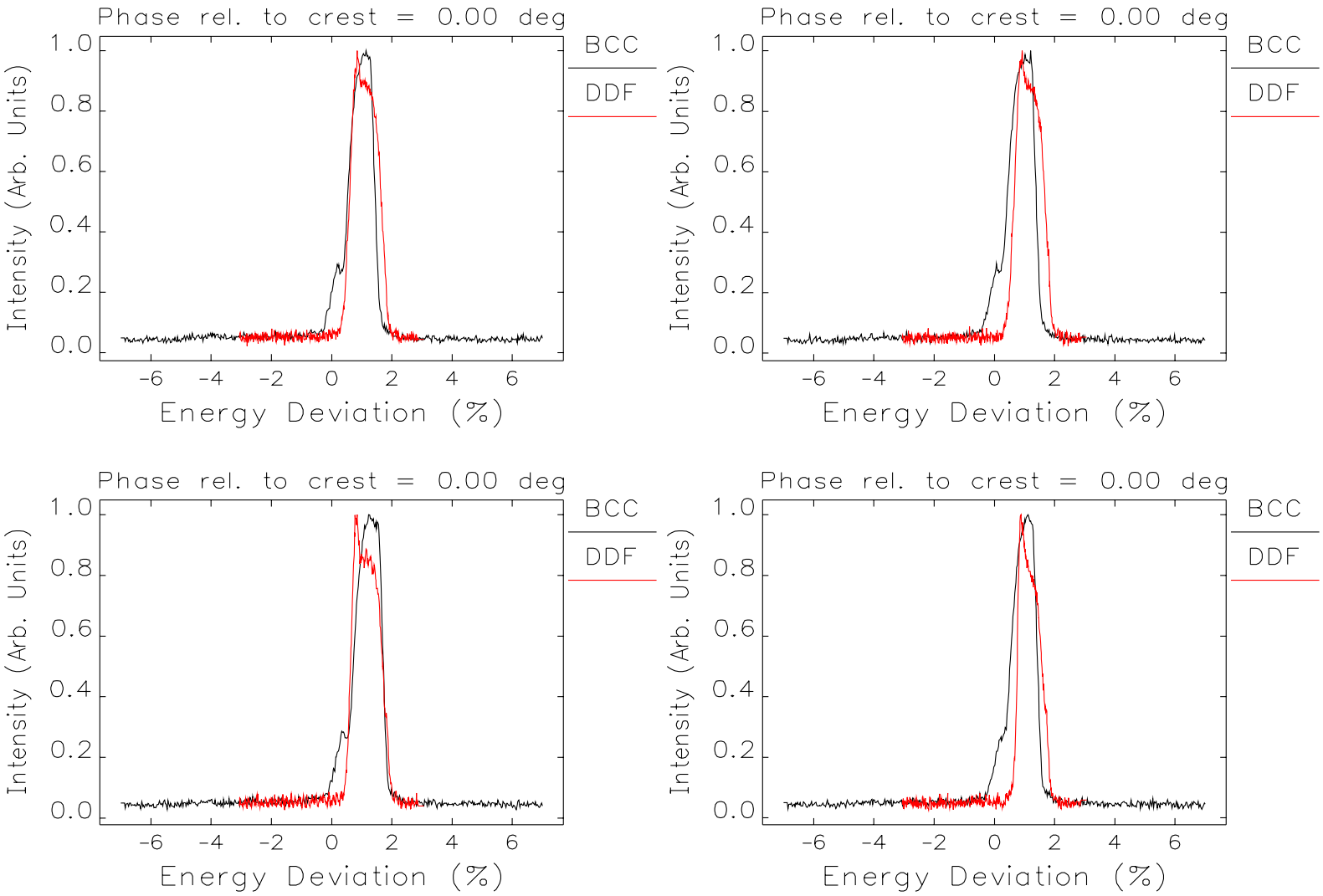
Apparent Energy Spectra Near Crest



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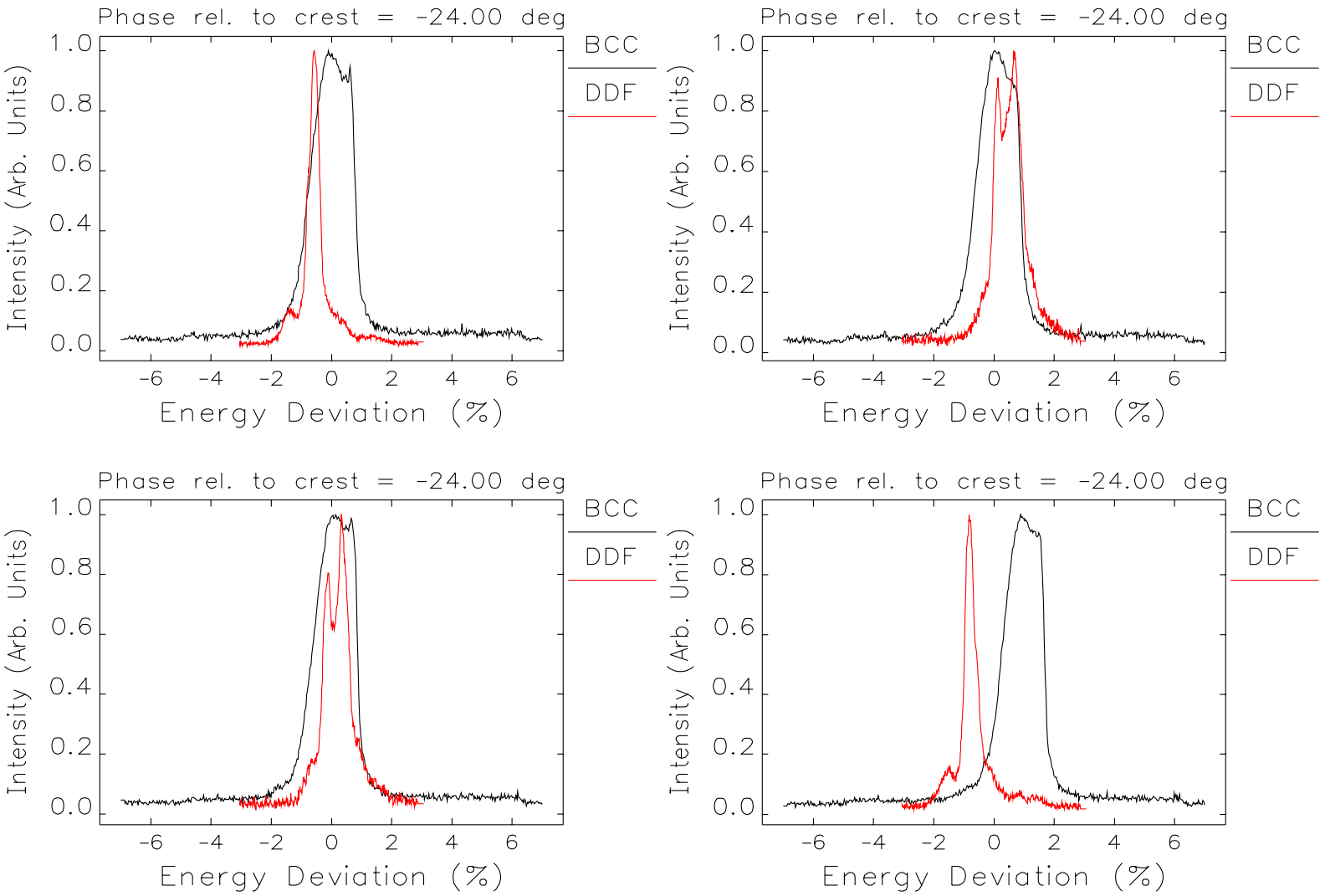
Apparent Energy Spectra Near Maximum Compression



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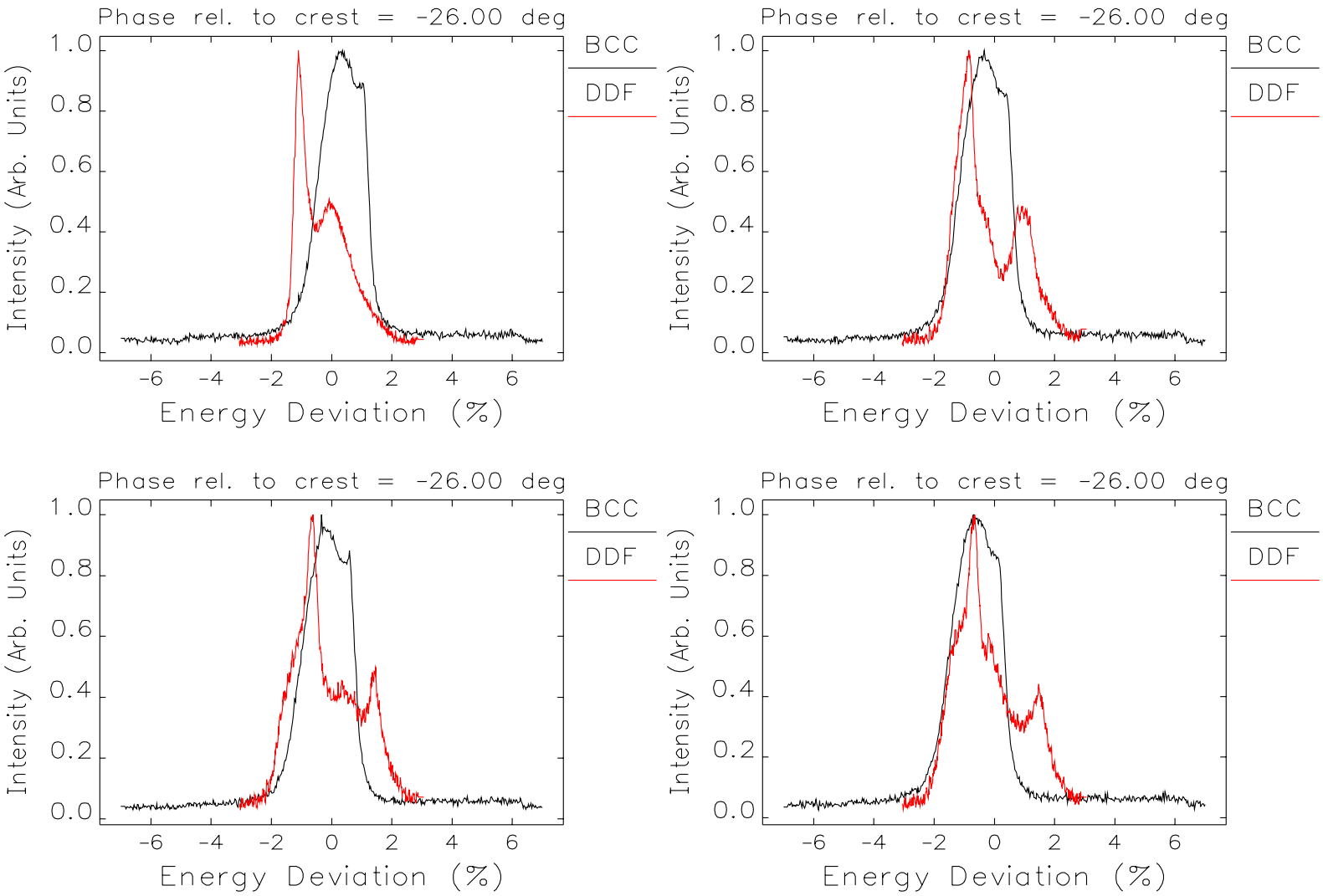
Apparent Energy Spectra Near Maximum Compression



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Why CSR Causes Energy Clumping

- The CSR wake has the shape of the derivative of the longitudinal density.
- CSR accelerates the head and decelerates the tail.
- A temporal clump produces a feature in the wake that looks like the derivative of the local density, accelerating leading particles and decelerating trailing particles.
- In compression, the leading particles are low in energy and the trailing particles are high. Thus, CSR moves them together into an energy clump.
- To reduce the impact of CSR, one needs to linearize (or thermalize) the longitudinal distribution.

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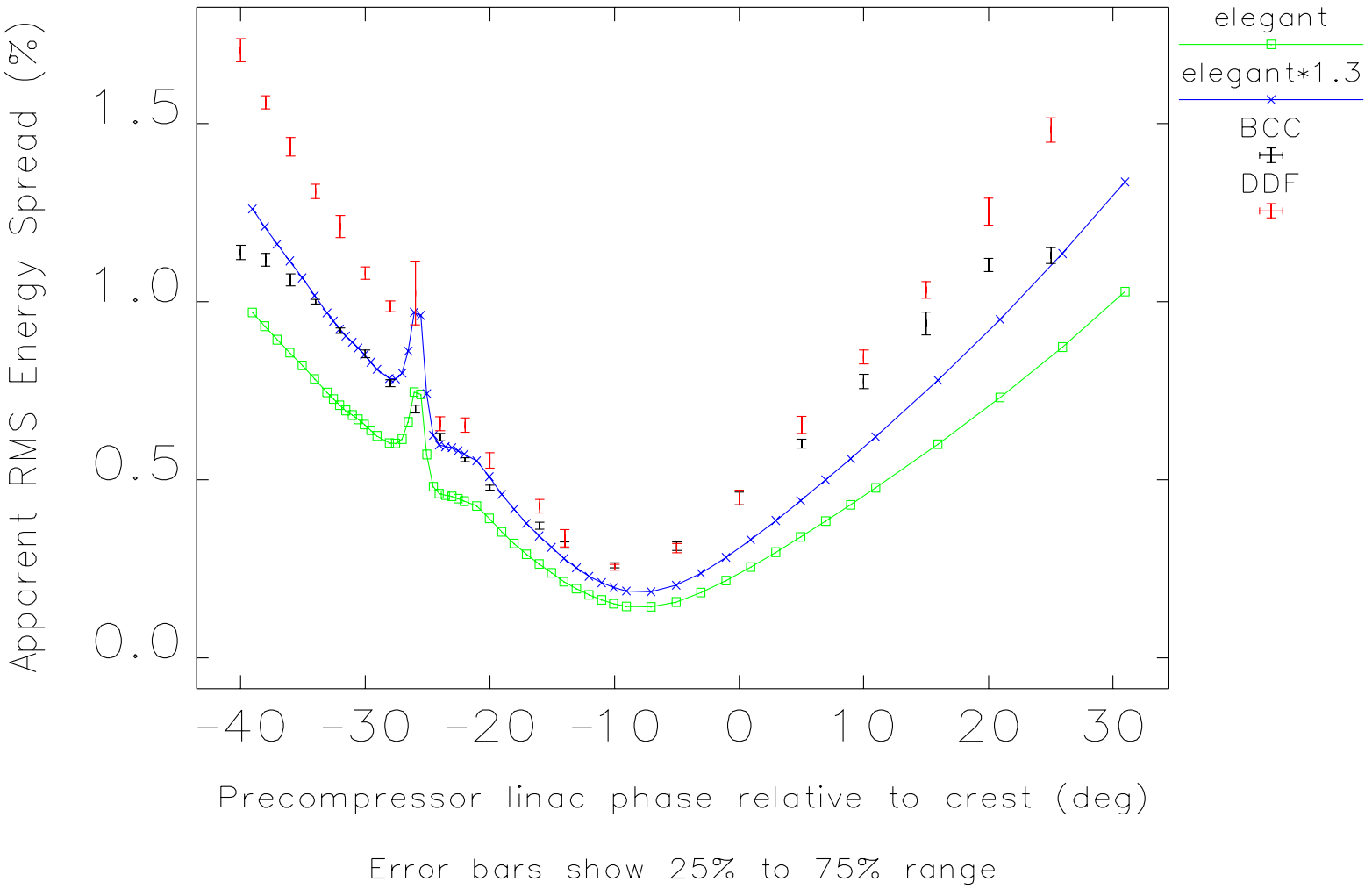
Measured and Simulated Apparent Energy Spreads



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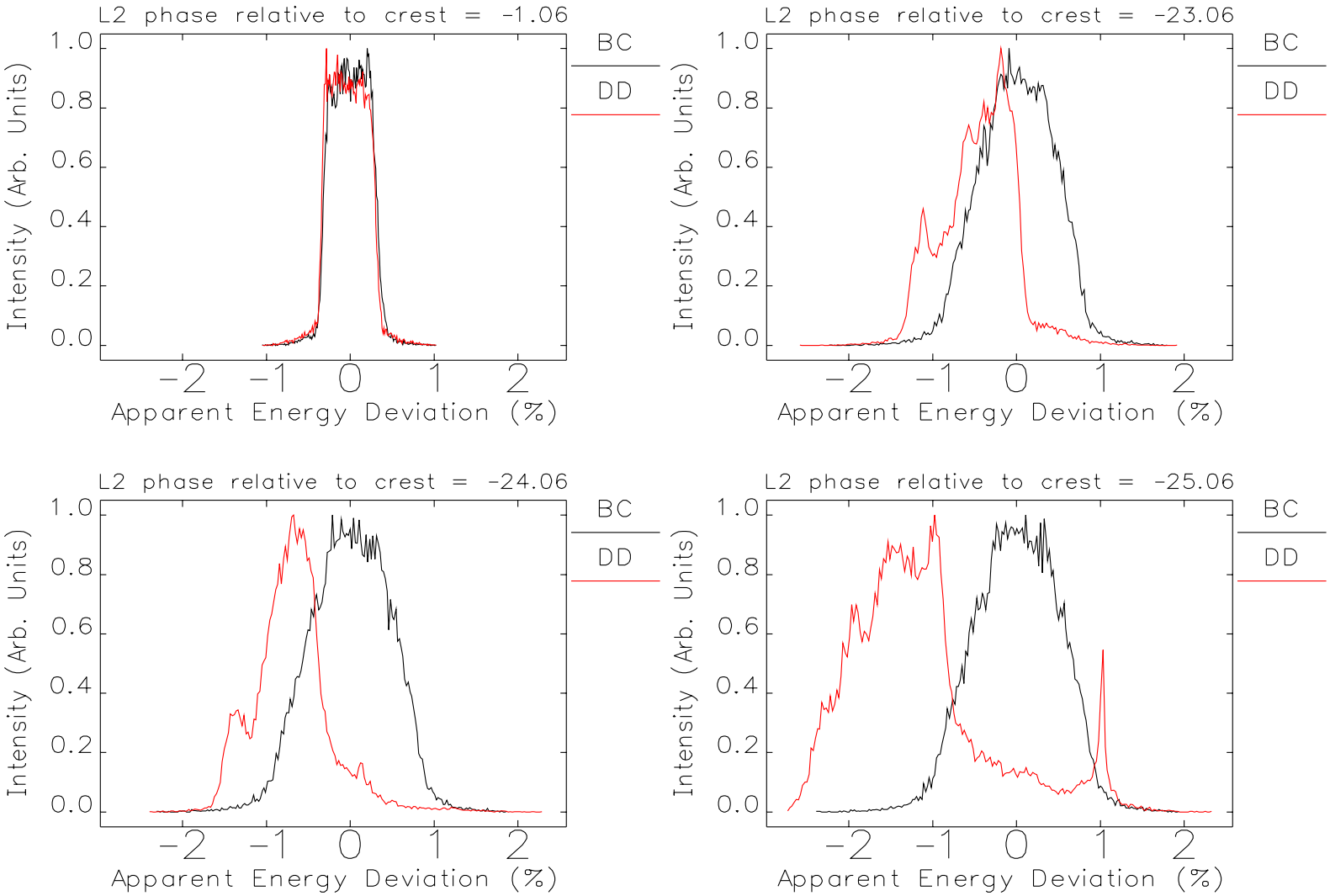
Simulated Apparent Energy Spectra



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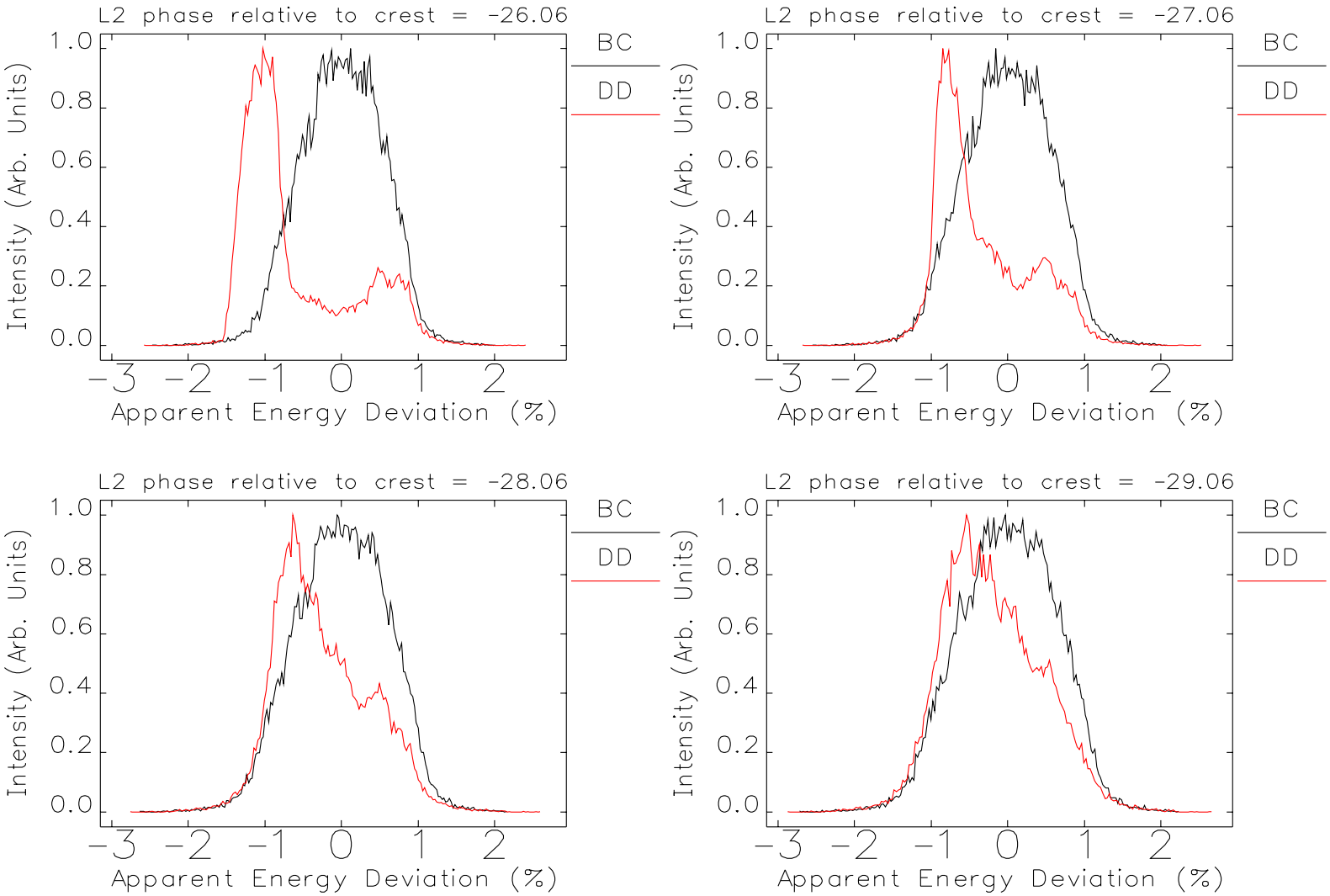
Simulated Apparent Energy Spectra



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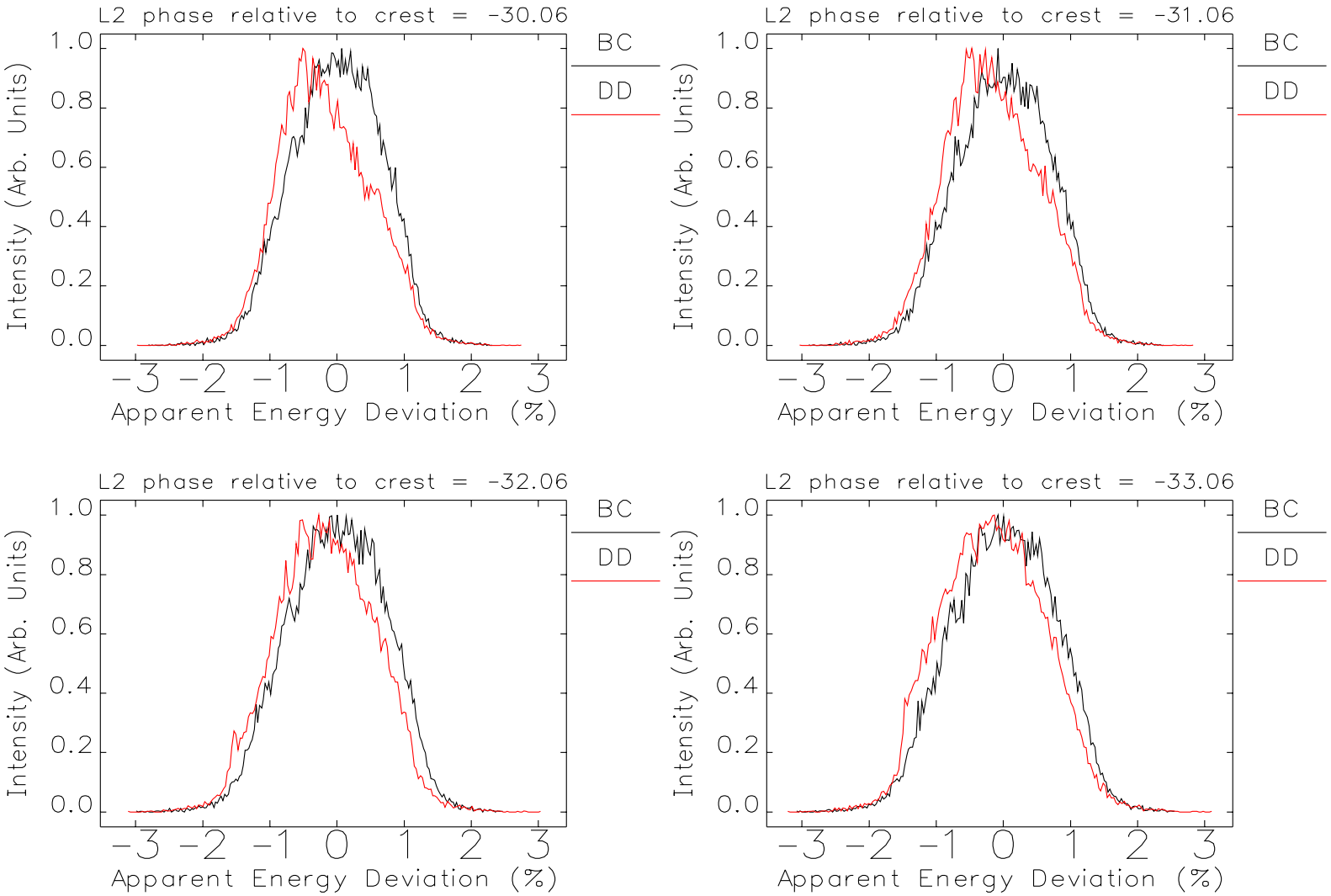
Simulated Apparent Energy Spectra



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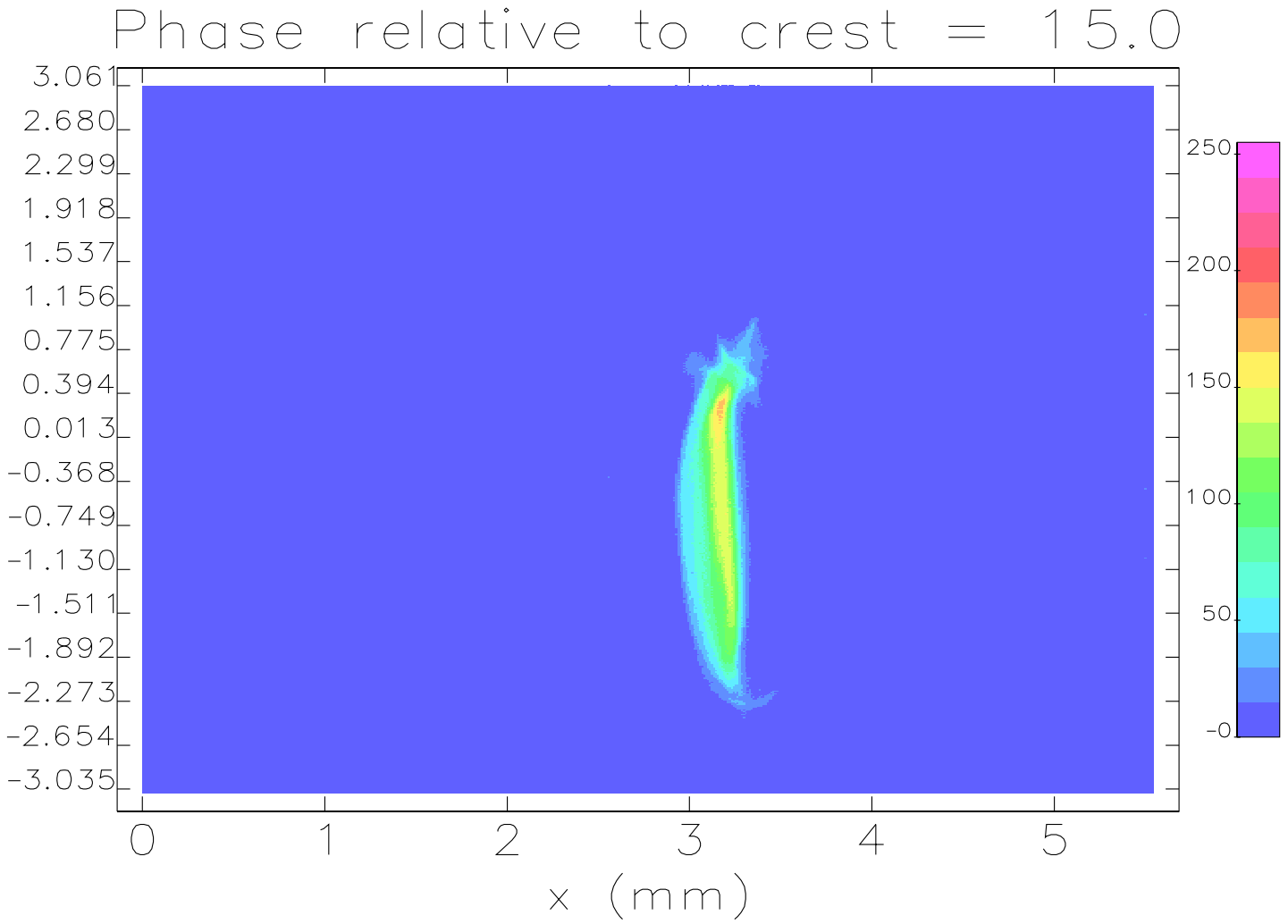
Vertical Bend Diagnostic (Dowell Diagnostic) Images



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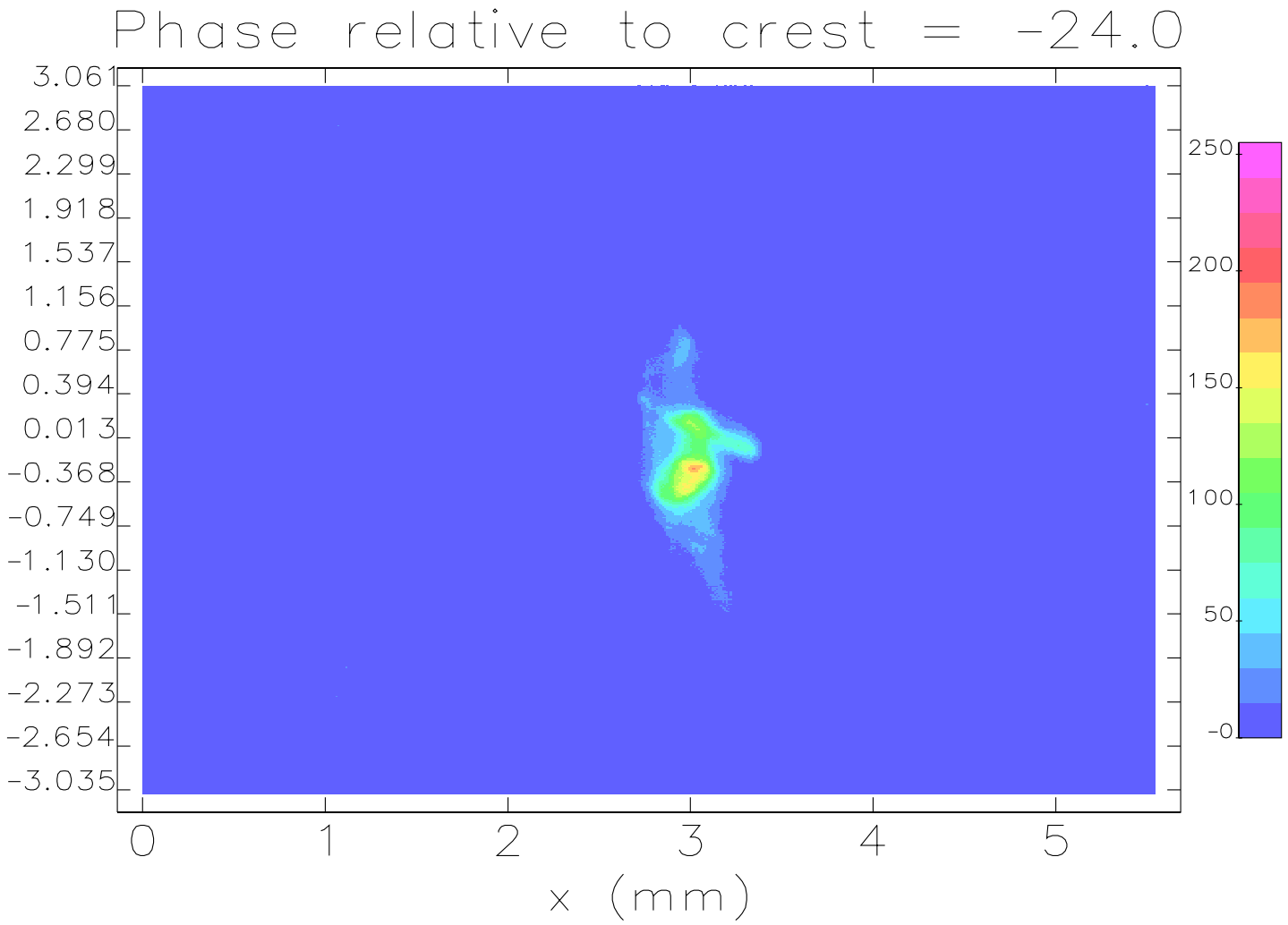

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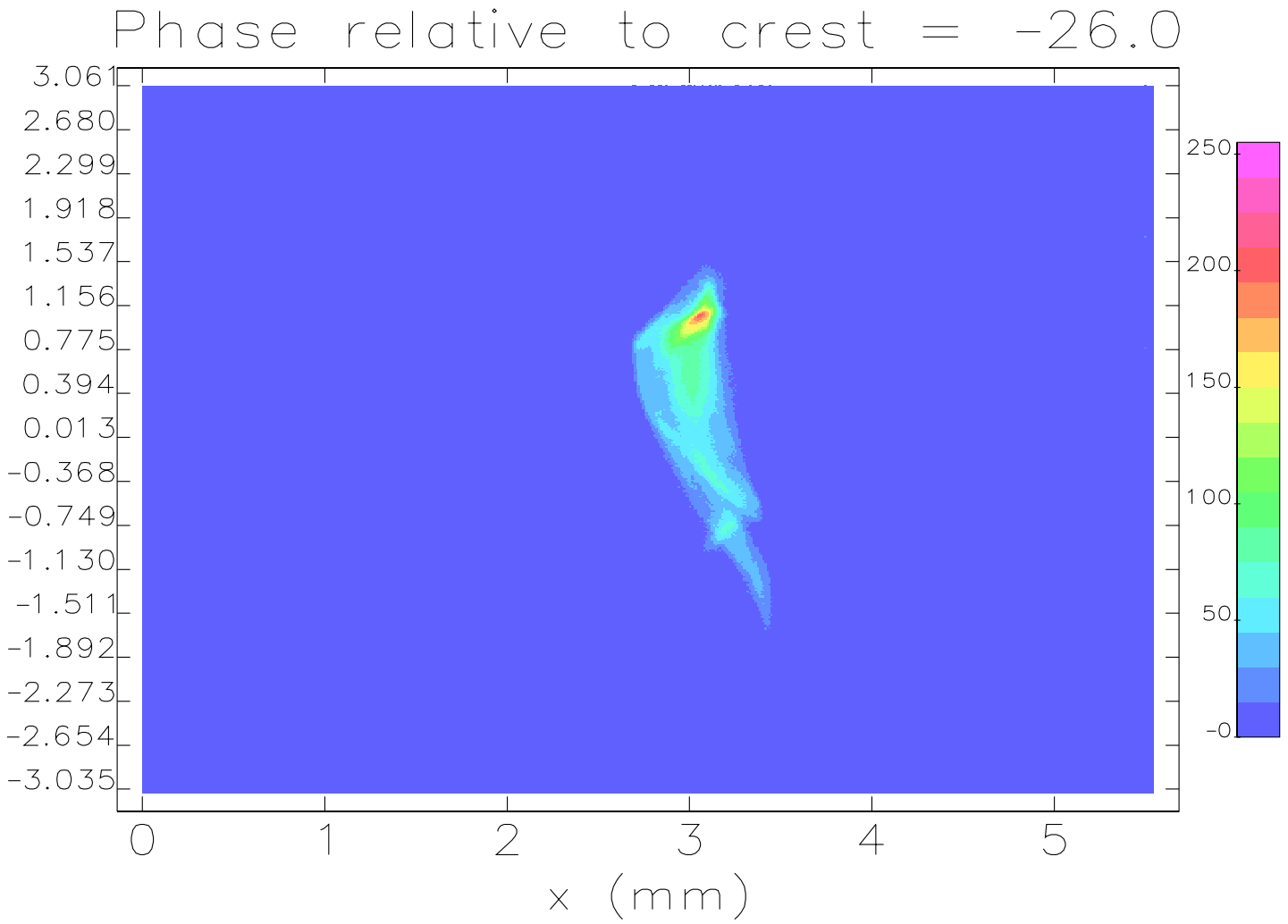

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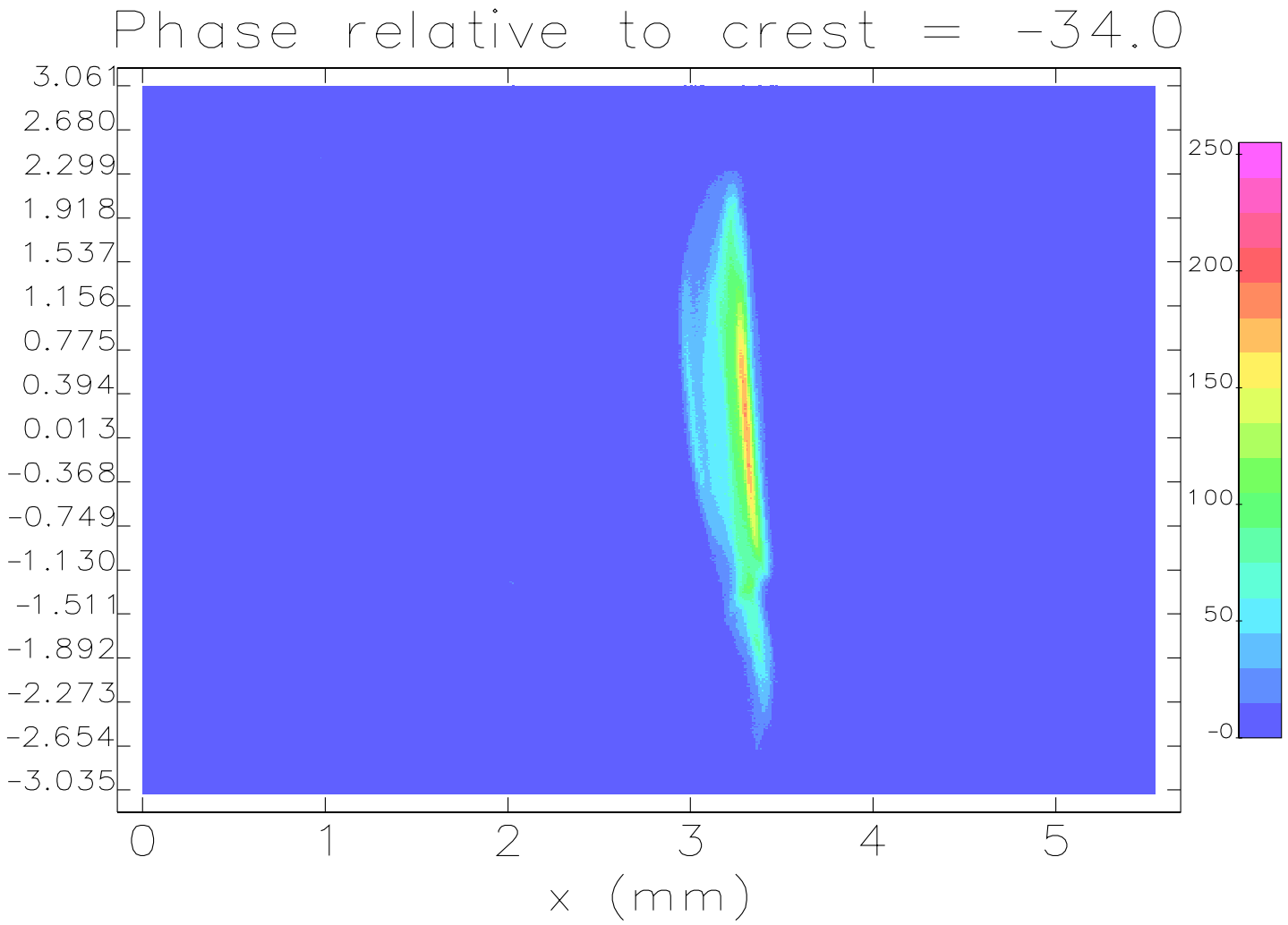

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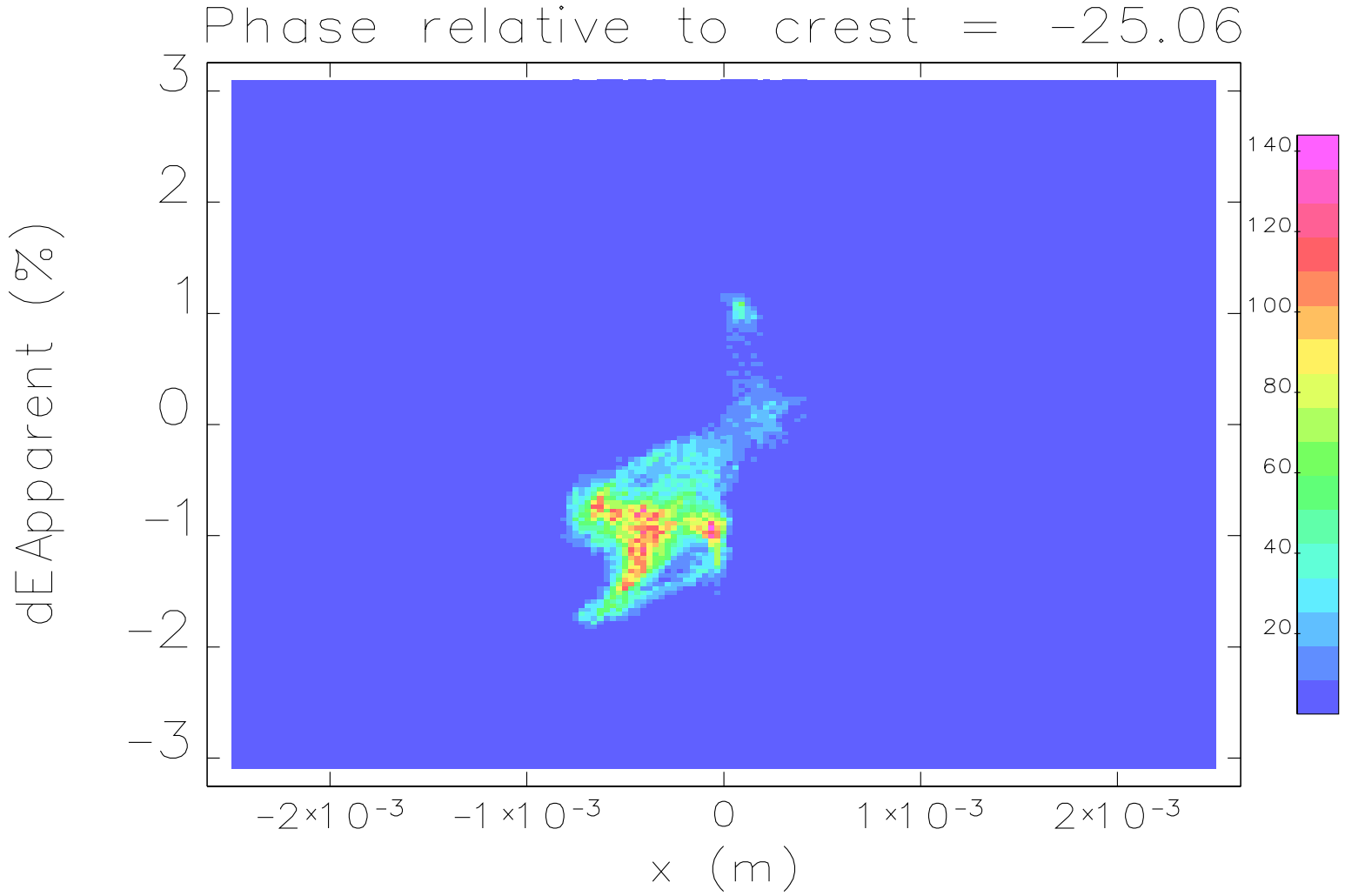
Simulation Produces Similar Images



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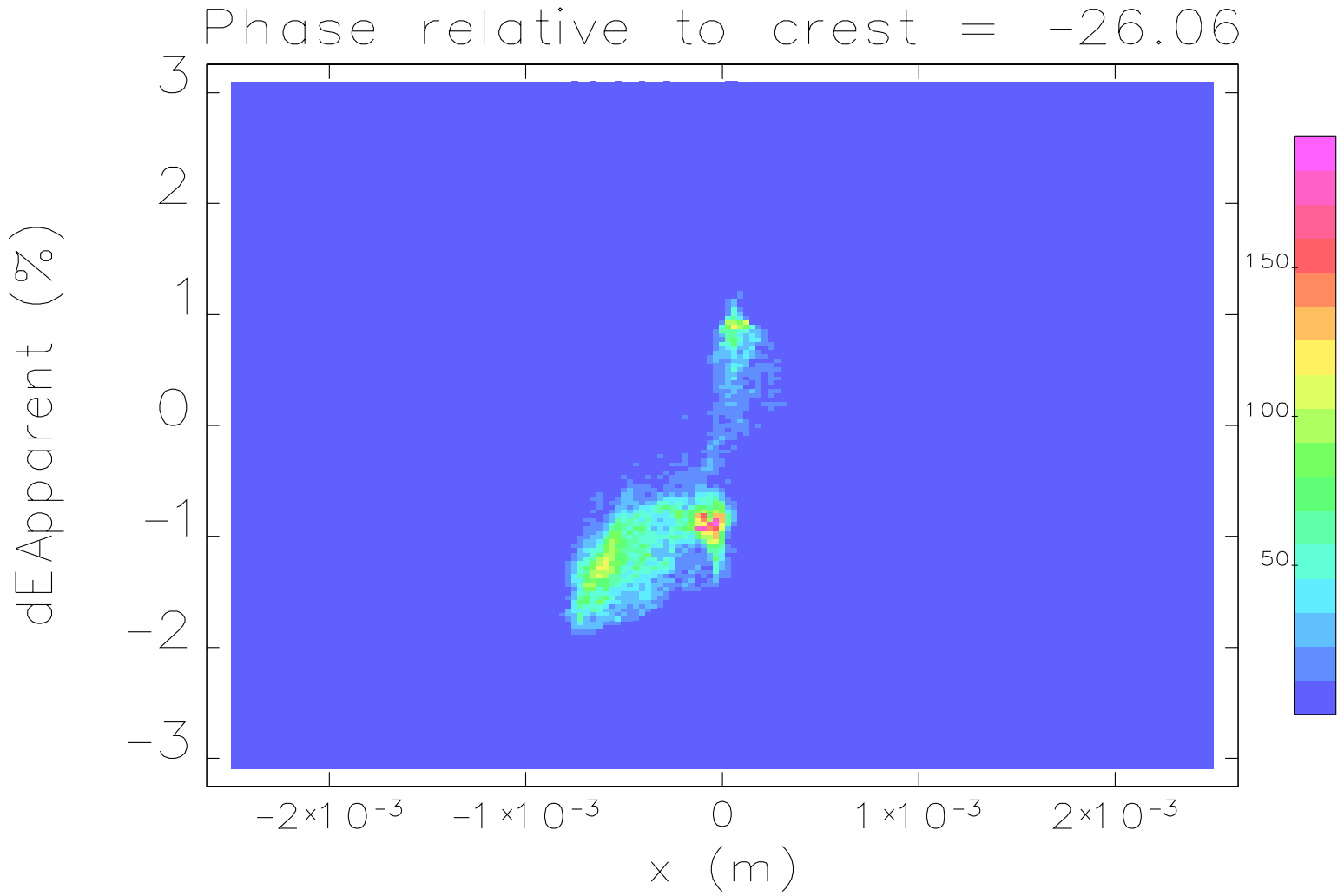

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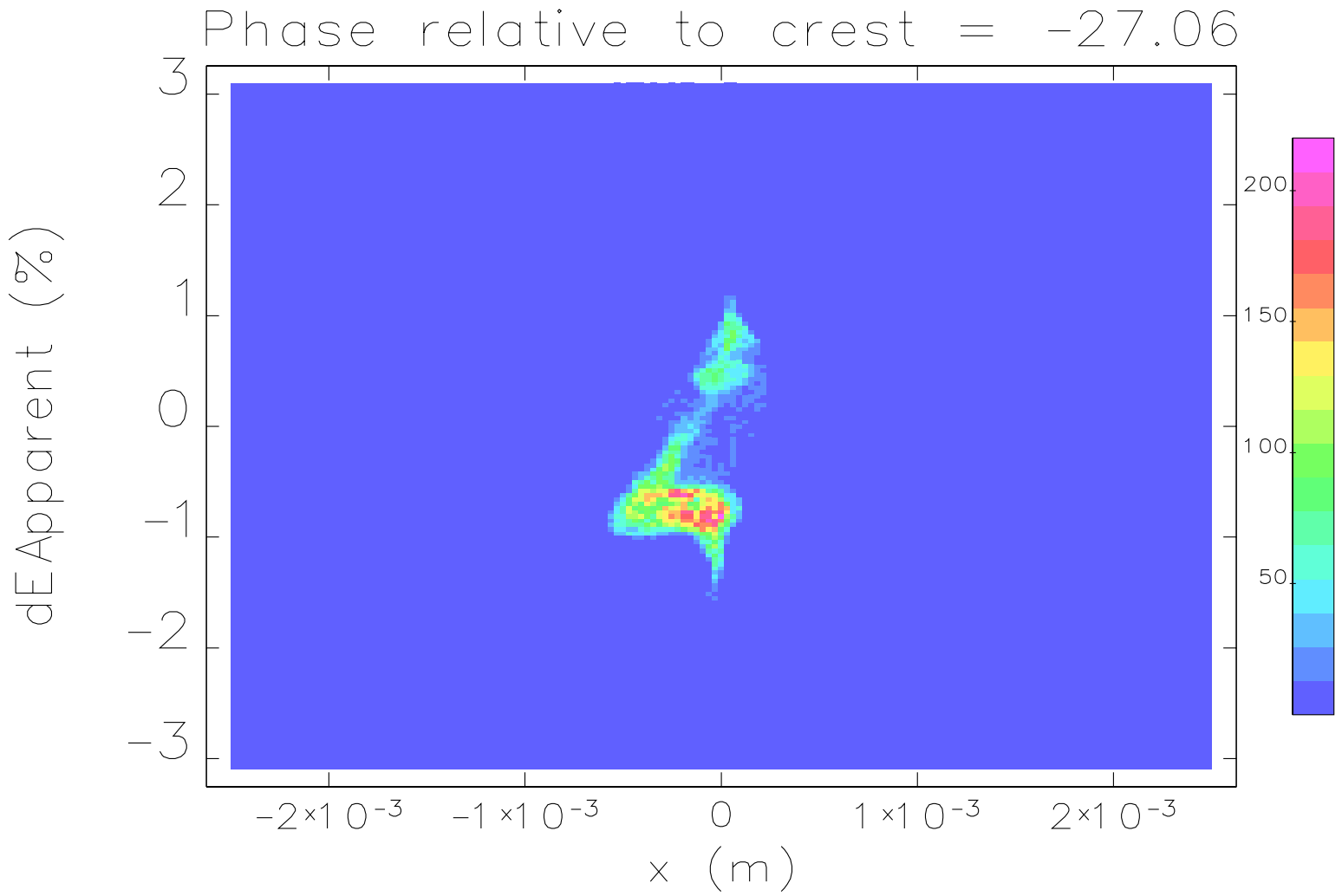

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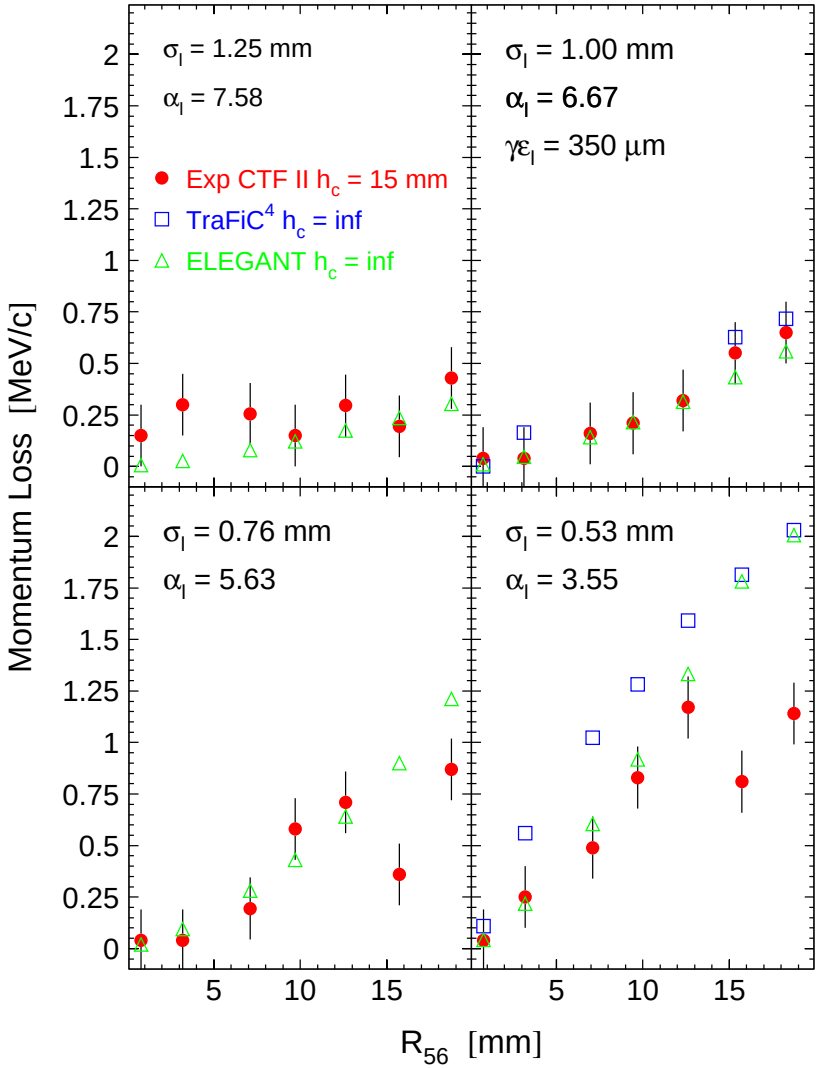
Data from CTF II Experiments (L. Groening et al.)



A four-dipole chicane is used with a 15nC beam from the CLIC Test Facility II.

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Ideas for Future Work on APS Bunch Compressor

- New PARMELA simulations of photoinjector beam to match actual conditions.
- Improve resolution of bunch length measurement.
- Perform tomography to accurately determine incoming longitudinal phase-space.
- Quantify effect of horizontal beamsize in last dipole.
- Verify that effects are due to CSR rather than wakefields. (Requires high charge.)
- Conduct experiments with variable R_{56} and symmetry. (Requires completion of telescoping chamber.)

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