Longitudinal Space Charge Instability Simulations with **elegant**

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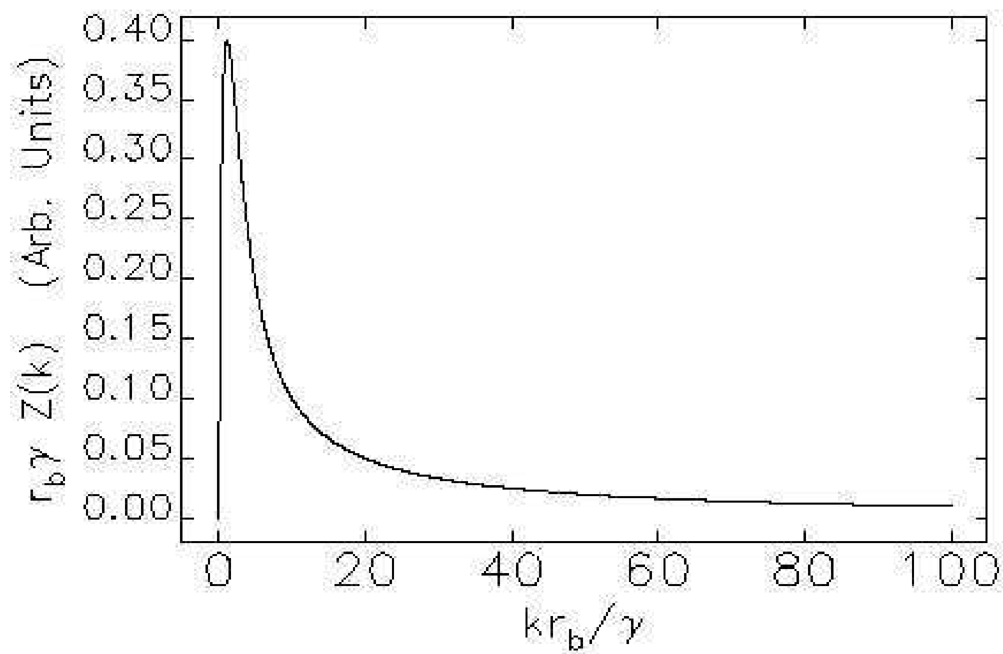
Outline

- Review of relevant theory
- Simulation method
- Test problems
  - Spreading gaussian beam
  - Density oscillations
- LCLS simulations
  - Preparing the beam
  - S2E results

Review of Theory (Z. Huang)

- Space charge impedance for r=0

$$Z(k) = \frac{Z_0 i}{k \pi r_b^2}\left[1 - \frac{k r_b}{\gamma} K_1(k r_b/\gamma)\right]$$



Review of Theory (Z. Huang)

- Wavenumber for space charge oscillations:

$$k_{SC} = \left[\frac{I_b}{\gamma^3 I_A} k \left| \frac{4\pi Z(k)}{Z_0} \right| \right]^{\frac{1}{2}} \leqslant \frac{2}{r_b} \left[\frac{I_b}{\gamma^3 I_A} \right]^{\frac{1}{2}}$$

- Step-size should be:

$$\Delta z \ll Min \left[\frac{1}{k_{SC}}, \gamma / \left(\frac{d\gamma}{ds} \right) \right]$$

Simulation Method

- **elegant** provides simulation of LSC in drifts and accelerating structures
- Both use a simple drift-kick-drift method
- New LSCDRIFT element
  - Automatically chooses step size
- Upgraded RFCW (RF Cavity + Wakes) element
  - Kick includes LSC, structure wakes, acceleration
  - User-specified number of kicks, checked for validity by program

Simulation Method

- Use FFT to compute the wake

$$W(t) = IFFT\left[FFT\left[I(t)\right] f(\omega) Z(\omega)\right]$$

- *I(t)* is a histogram of current with a user-specified number of bins
  - Typically use a constant number of bins so time resolution is a constant fraction of bunch length
  - Peak current used for I_b in computing k_{SC} to determine step size

Simulation Method

- $f(\omega)$ is an optional low-pass filter to control noise
  - Essential in getting stable behavior
  - Smoothing algorithms (e.g., Savitzky-Golay) not helpful
- Typically choose number of bins so frequencies of interest are about 0.2 Nyquist or less
- Typically place the filter at 0.4 Nyquist
- Simply using fewer bins would force us to worry about details of interpolation within bins

Simulation Method

- Must compute beam radius, r_b, to compute step size and impedance
- Present results used a guess

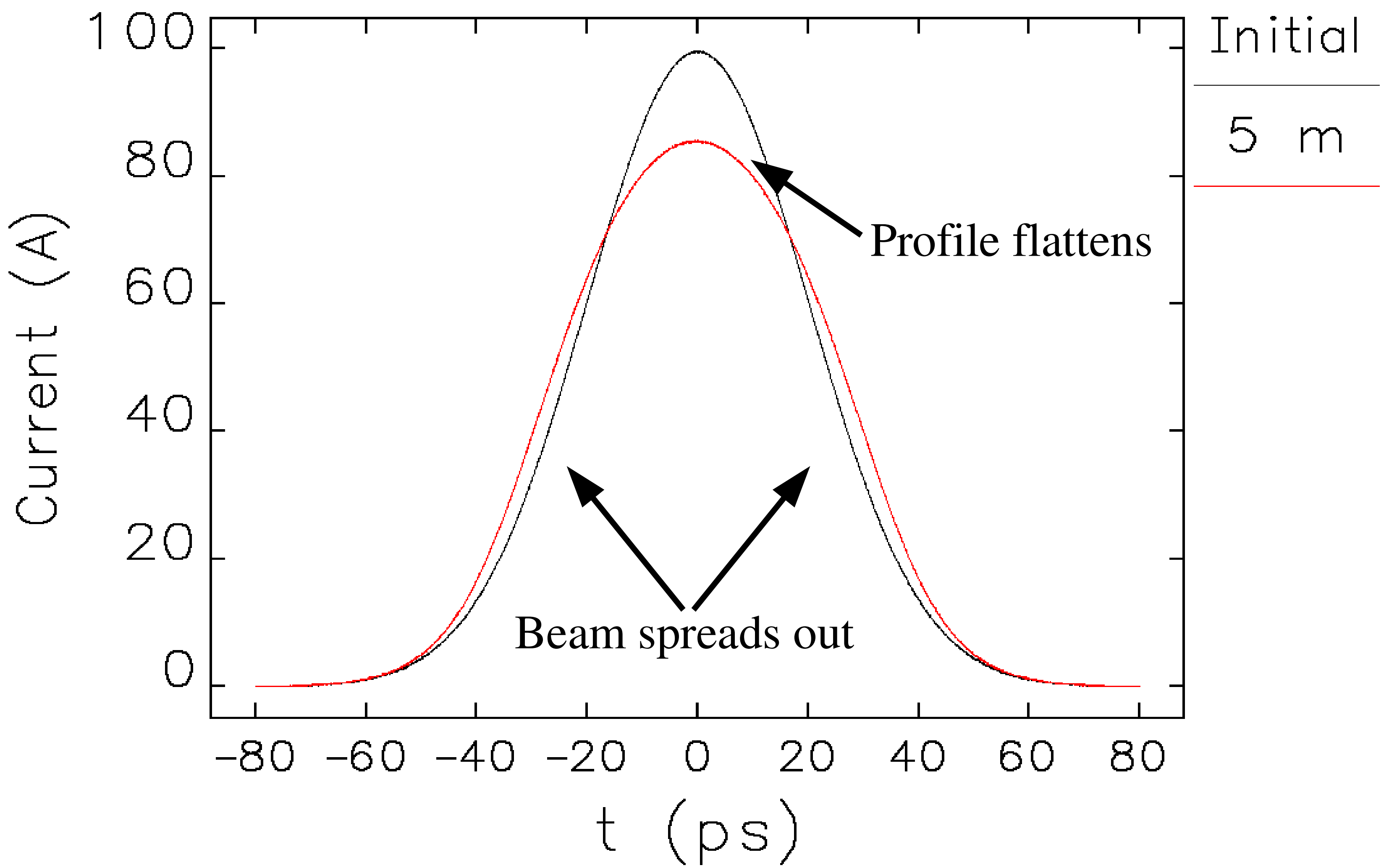
$$r_b = \frac{\sigma_x + \sigma_y}{2}$$

- Based on analysis for parabolic distributions, J. Wu recommends

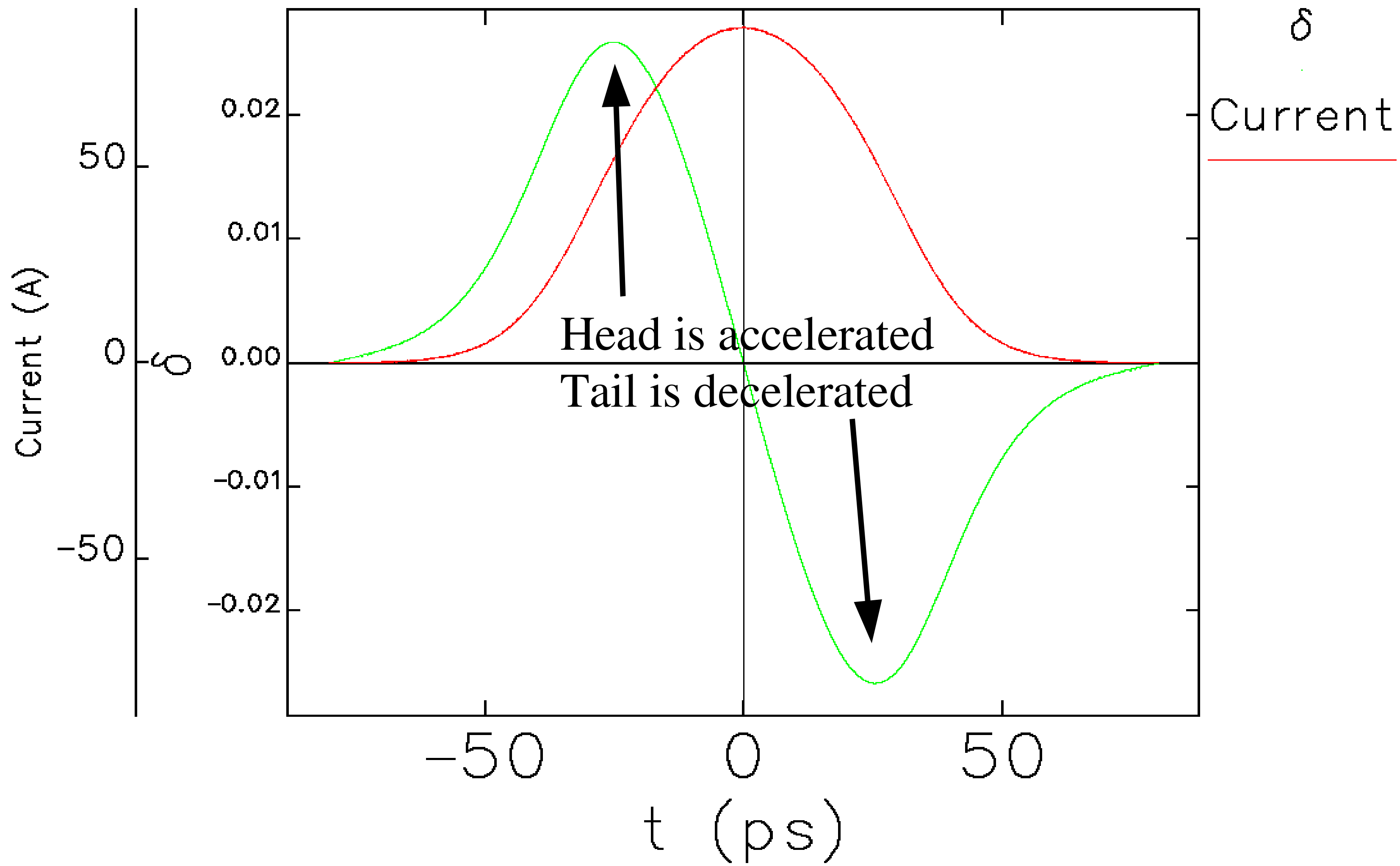
$$r_b = 1.7\,\frac{\sigma_x + \sigma_y}{2}$$

- This is now the default in the code

Spreading of Gaussian Beam



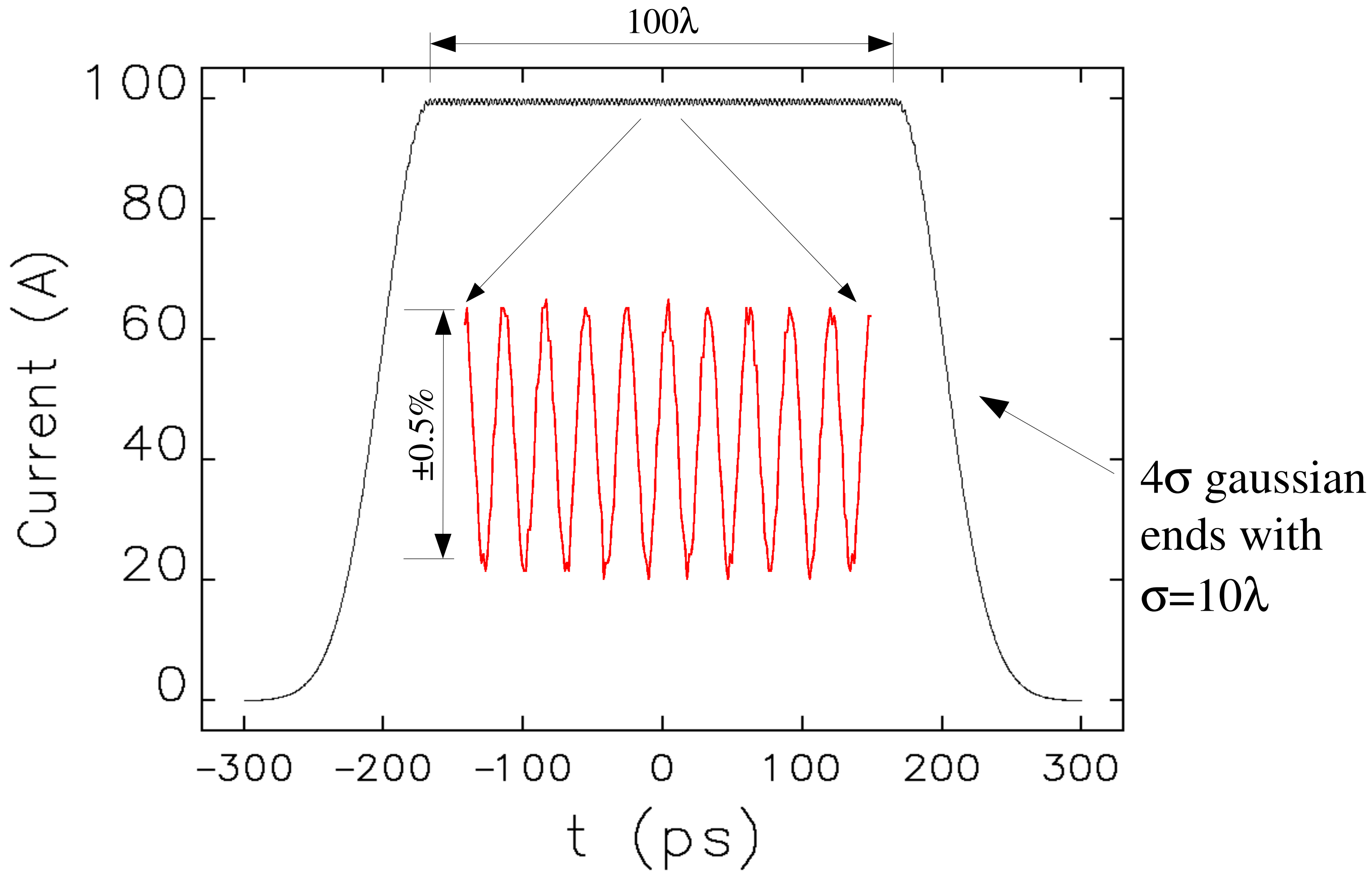
Spreading of Gaussian Beam



LSC Oscillation Tests

- Start with an initially flat-top distribution
  - Gaussian ends to avoid strong end fields
- Impose a 0.5% sinusoidal density modulation
- Noise control
  - Track with LSC using 20 bins per wavelength: modulation is at 0.1 Nyquist
  - Low pass filter at 0.2 Nyquist
  - 8 million particles (~2200 per bin)
  - Halton sequence (quiet start) particle generator
- 4MP and 1% modulation gives same results

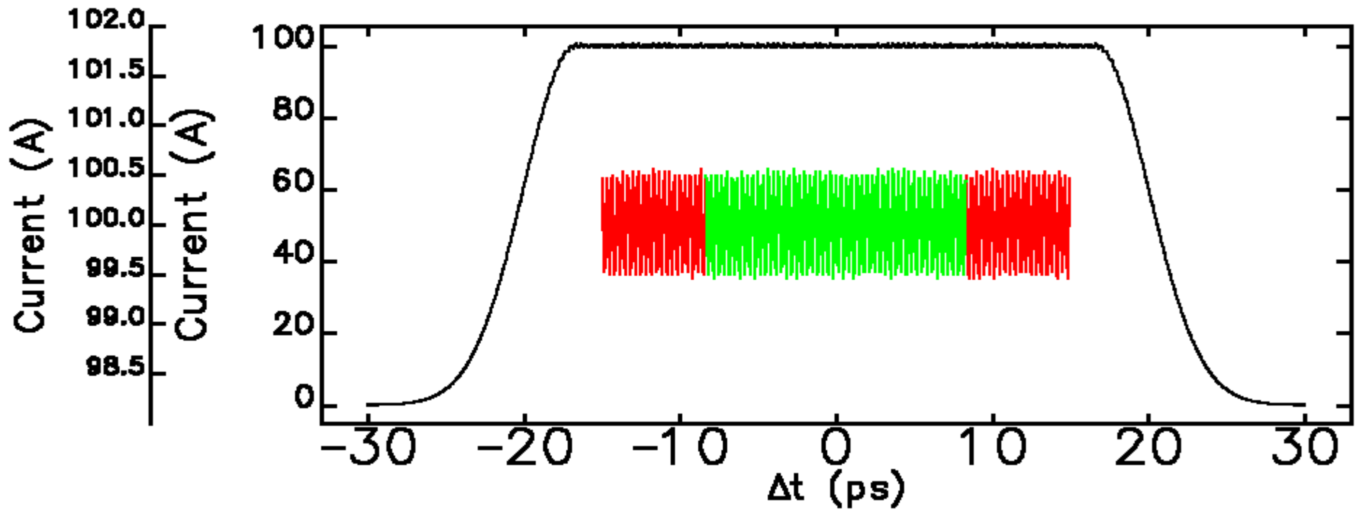
LSC Oscillations: Initial Distribution

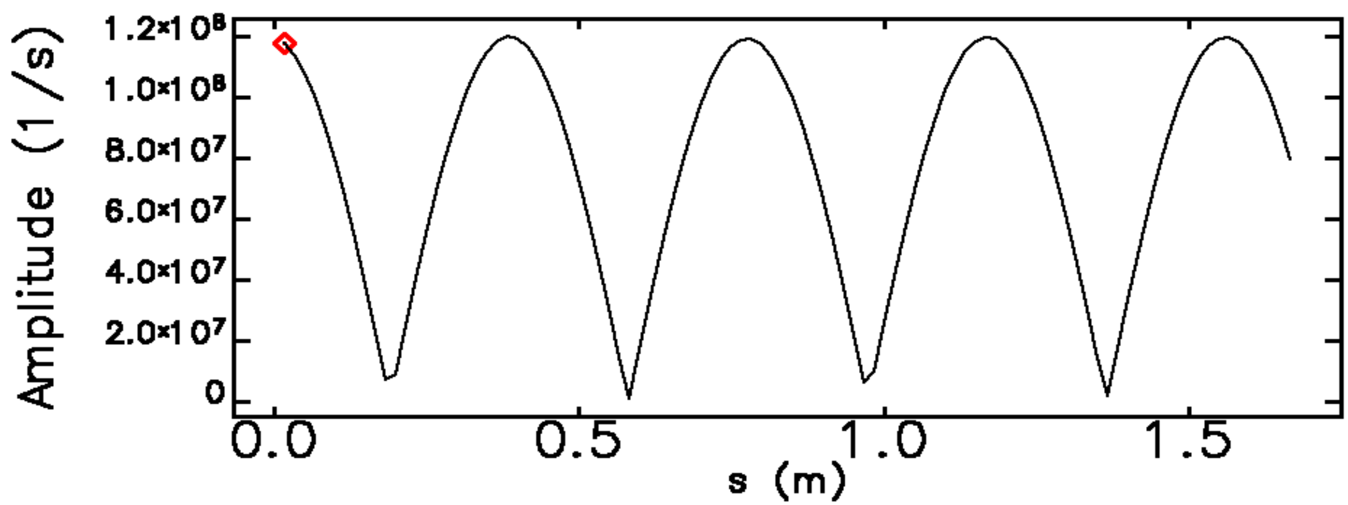


Analysis Method

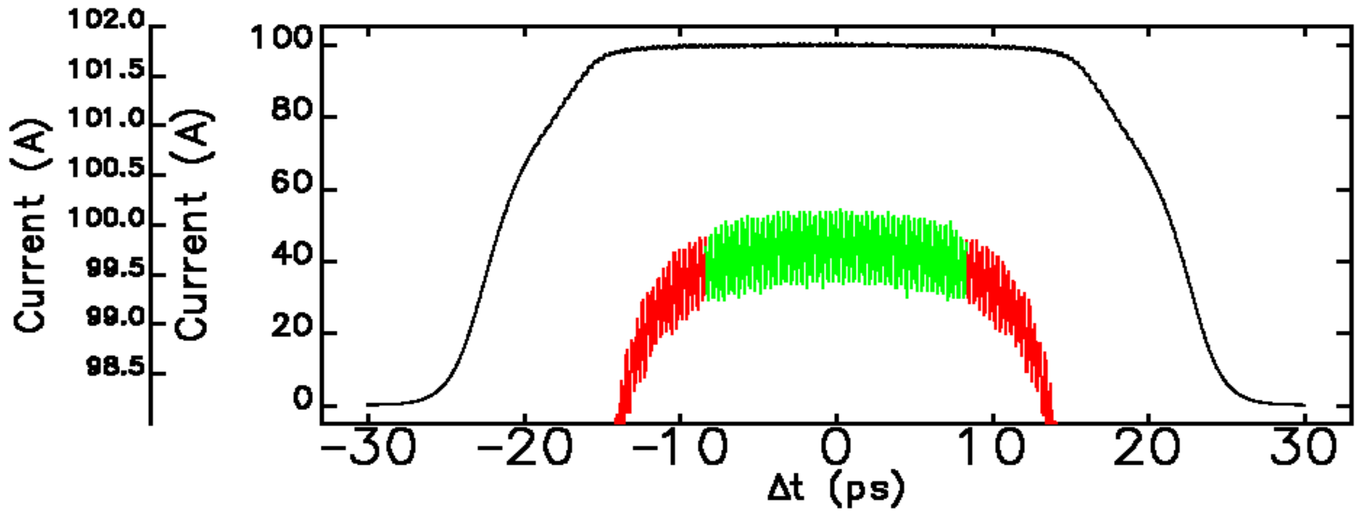
- **elegant** provides current profile at intervals
- To determine modulation amplitude
  - Select central 50λ of the profile
    - Important in eliminating end effects
  - Use polynomial fit to remove any gross variation
  - Apply digital filter to pass only [0.9, 1.1]λ
  - Use NAFF method to determine the amplitude

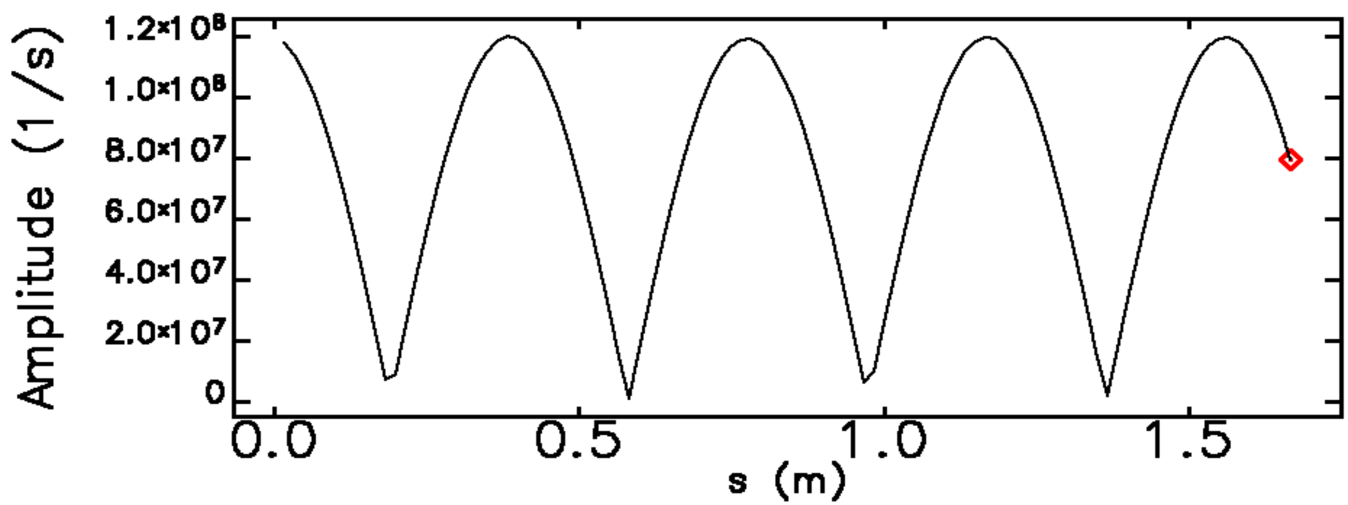
Example for λ=10μm



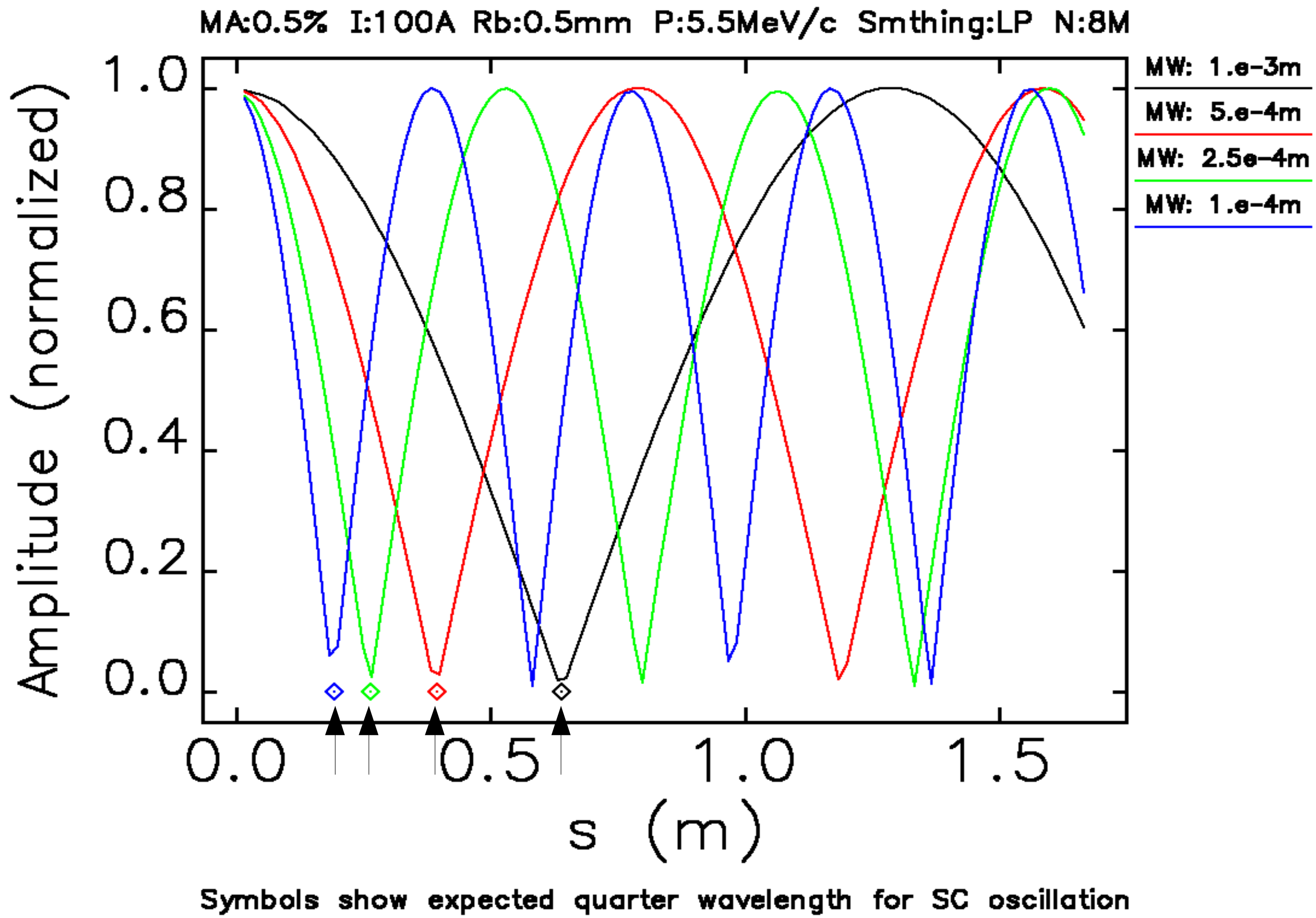


Example for λ=10μm

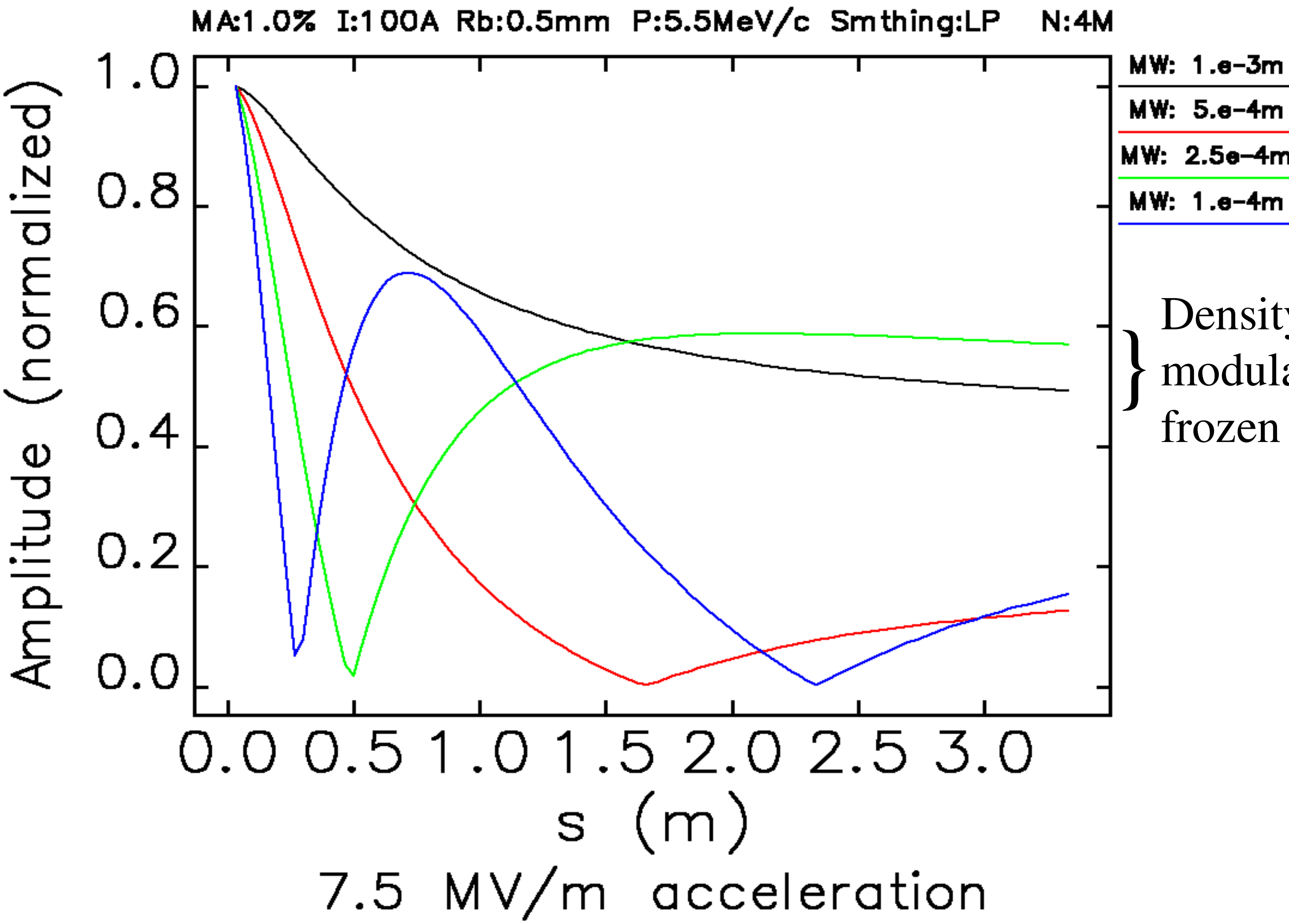




Results for Various Wavelengths



Results with Acceleration



} Density modulation frozen in

LCLS Simulations

- Used 10JUN03 Design from P. Emma
- Started at 135 MeV with PARMELA output from C. Limborg
- Created smoothed distribution with density modulation and more particles
- Included LSC in linac structures only, with 2000 bins and low-pass at 0.4 Nyquist
- Included wakes, CSR, ISR, etc.

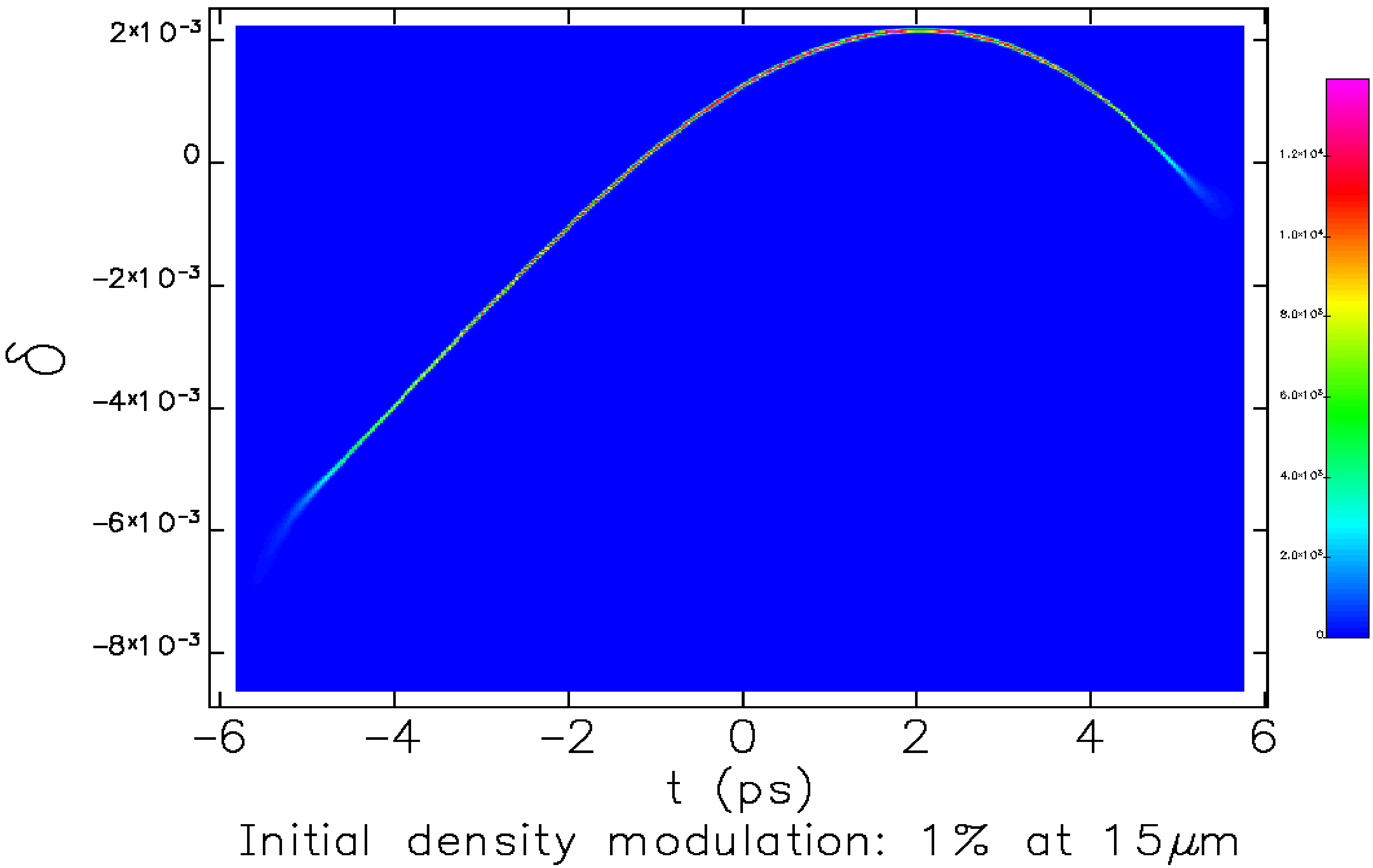
Beam Preparation

- PARMELA-generated beam has
  - Only 200k particles
  - Numerical noise that will drive instability
  - Need to increase the number of particles and remove the noise
- Time distribution
  - Make histogram of t and smooth heavily
  - Multiply by sinusoidal density modulation (±1%)
  - Sample using quiet-start sequence to generate 8M values of t

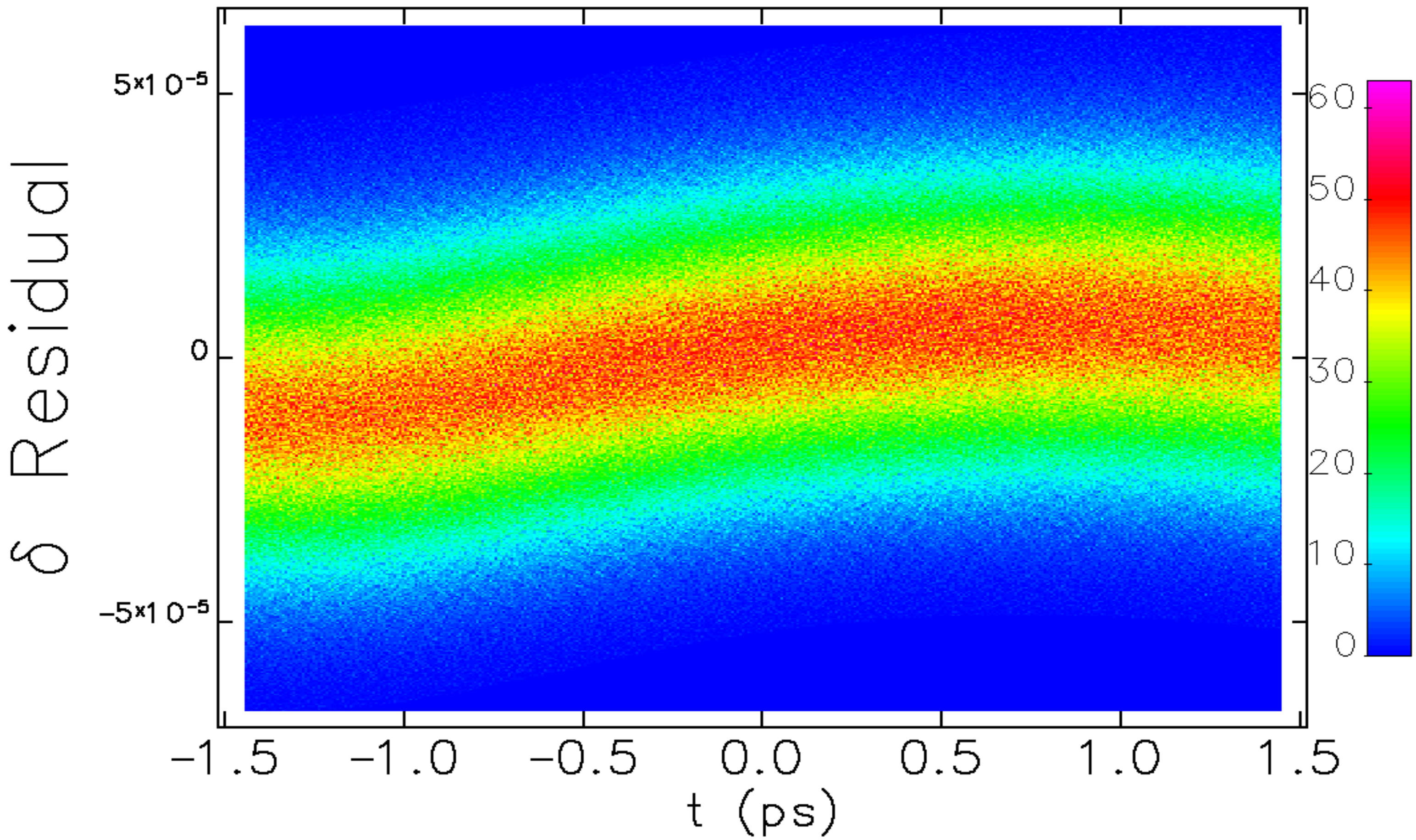
Beam Preparation

- Make fits to PARMELA data to get p(t) and $\sigma_p(t)$
  - Evaluate p for each new particle t
  - Quiet-sample $\sigma_p(t)$ to create local momentum spread
- For transverse
  - Compute projected rms parameters
  - Quiet-sample for each new particle
  - Should eventually try using local beam moments

λ=15μm: Initial Distribution

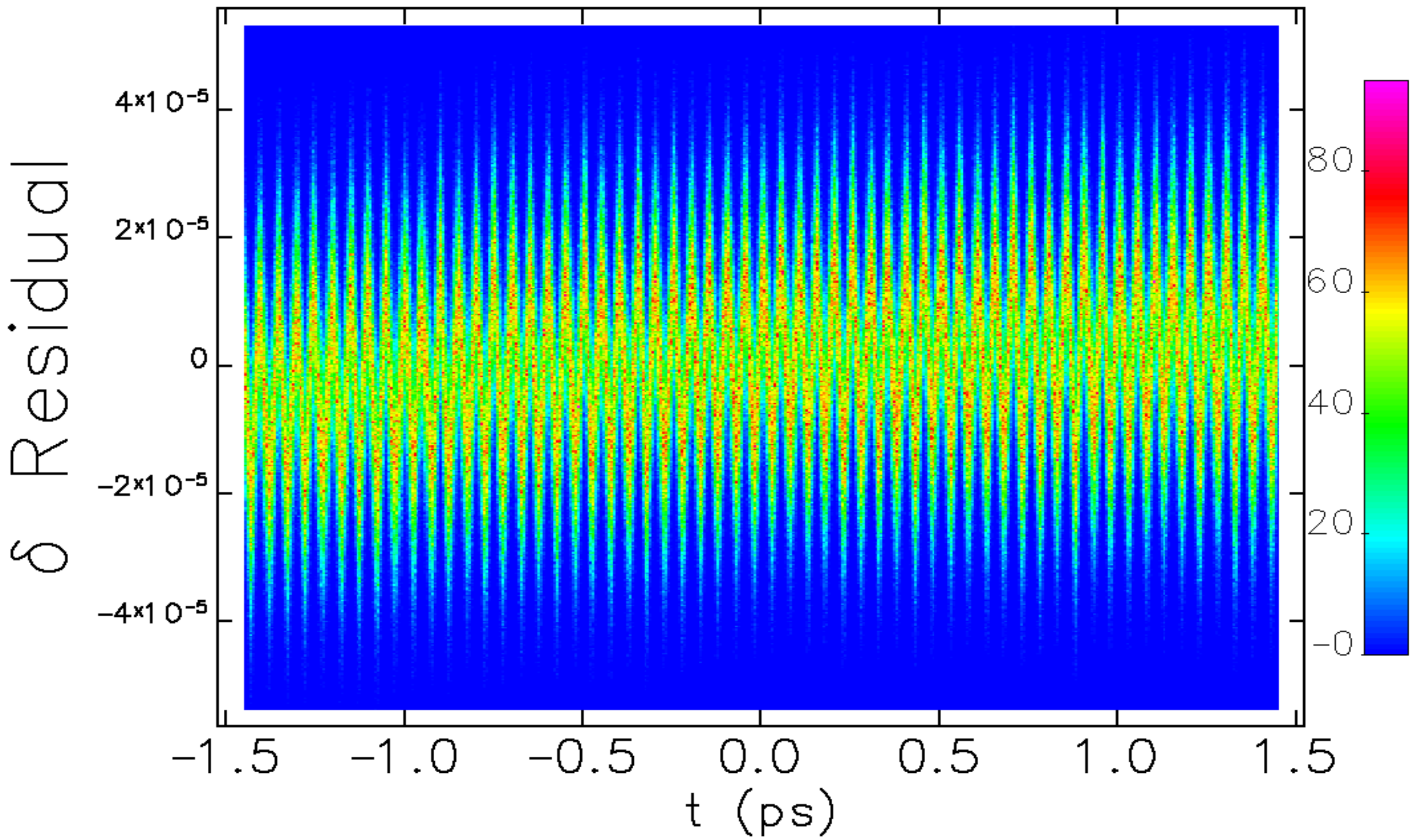


λ=15μm: Initial Distribution

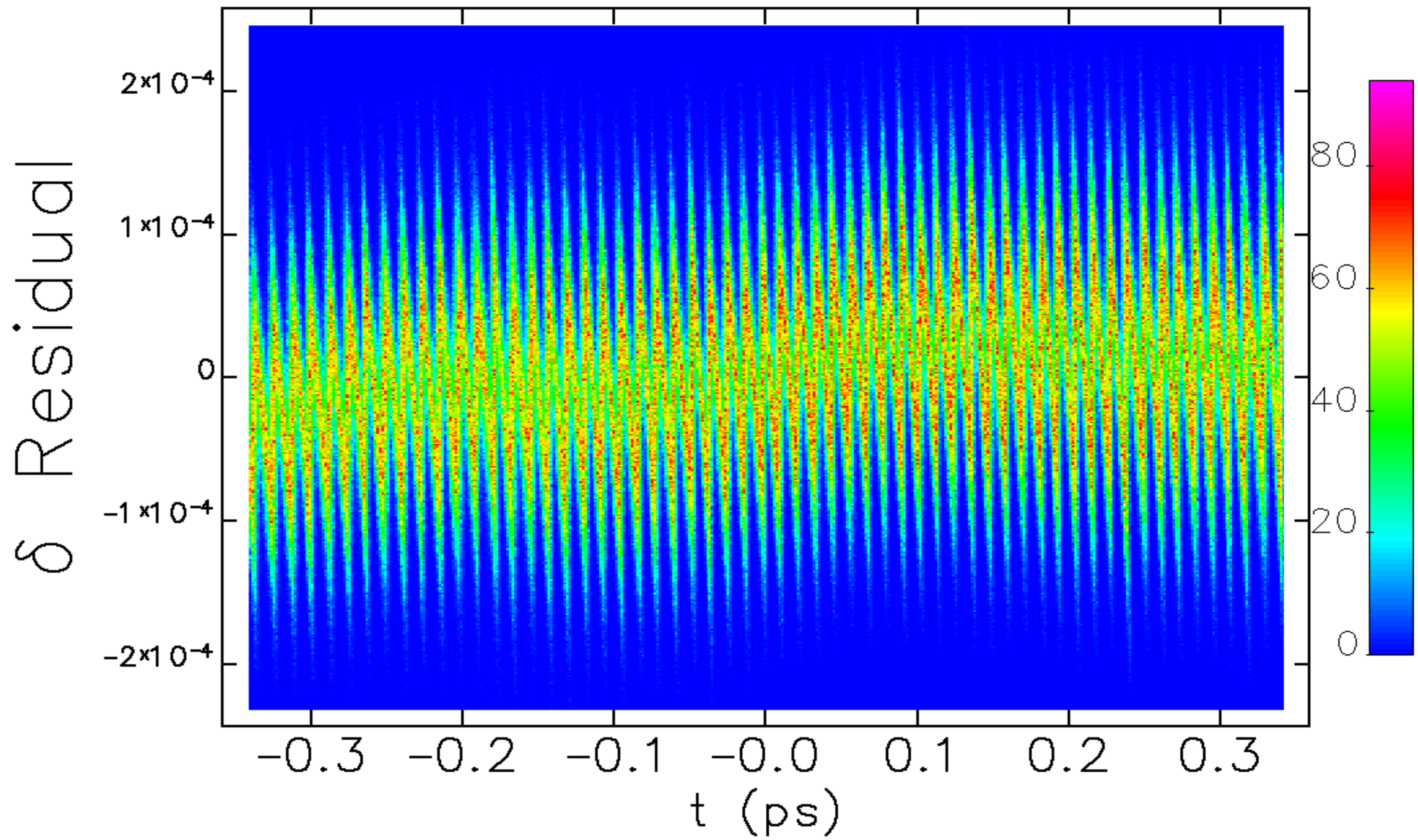


Residual of fit for central 25% of beam

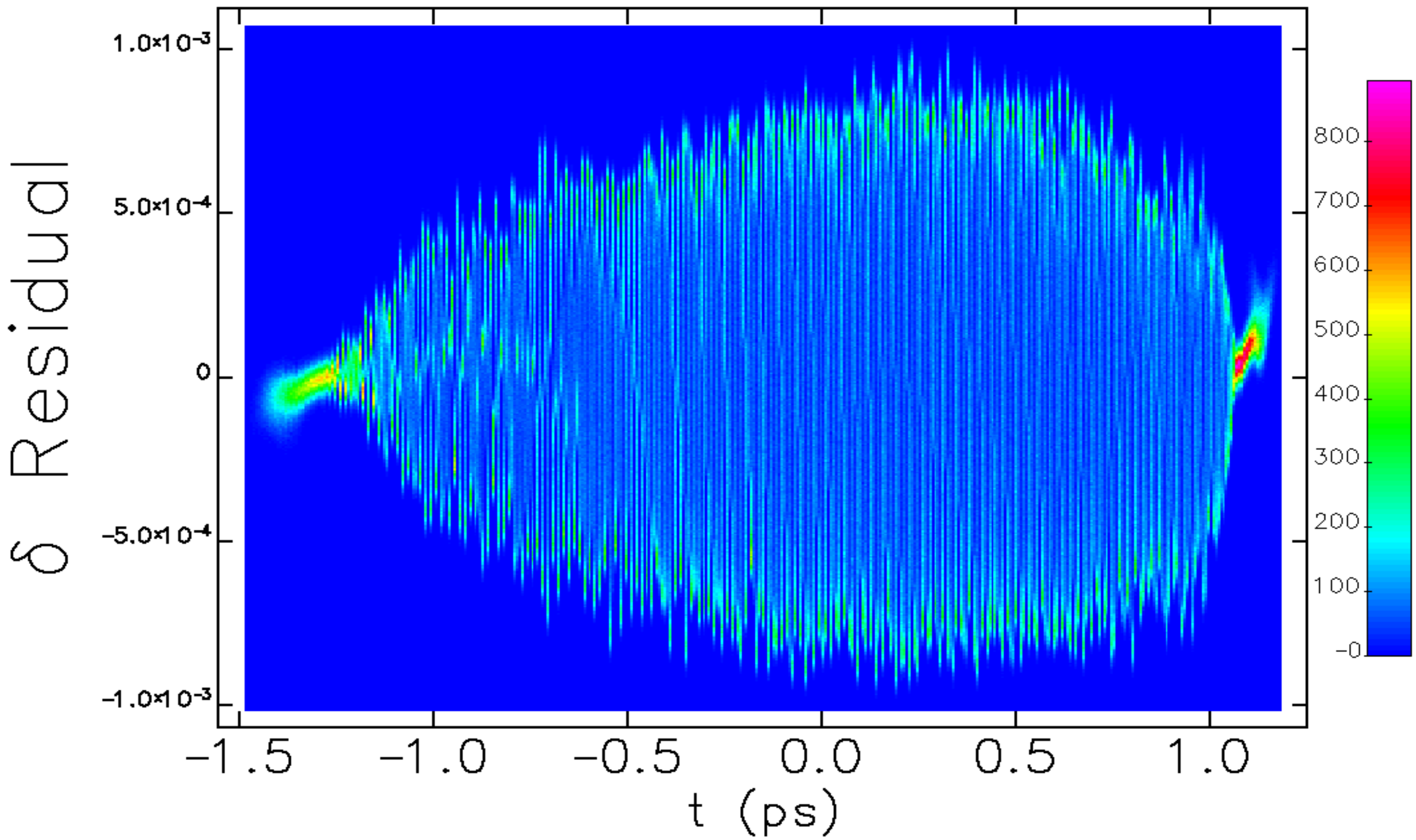
λ=15μm: BC1 Entrance



λ=15μm: BC1 Exit

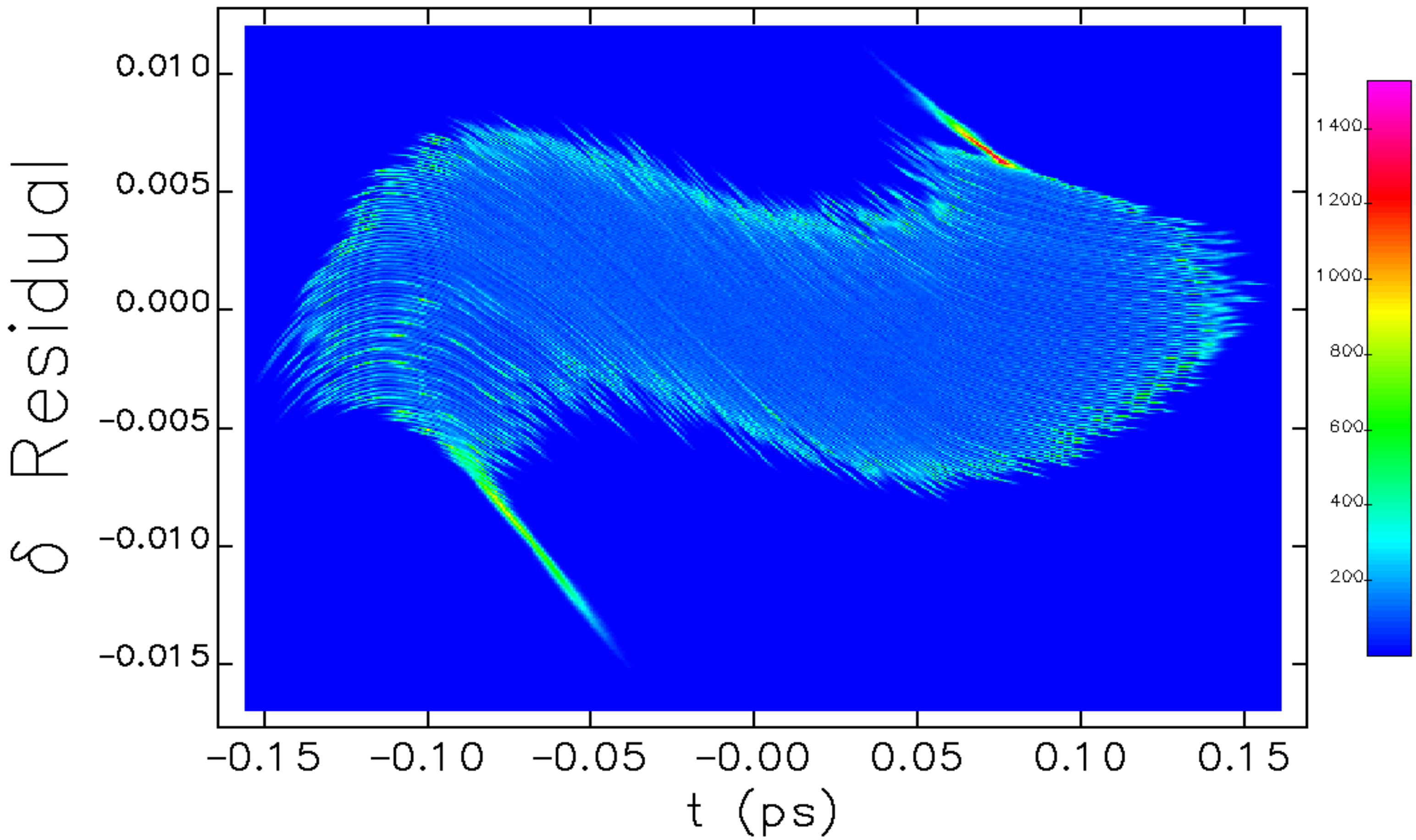


λ=15μm: BC2 Entrance

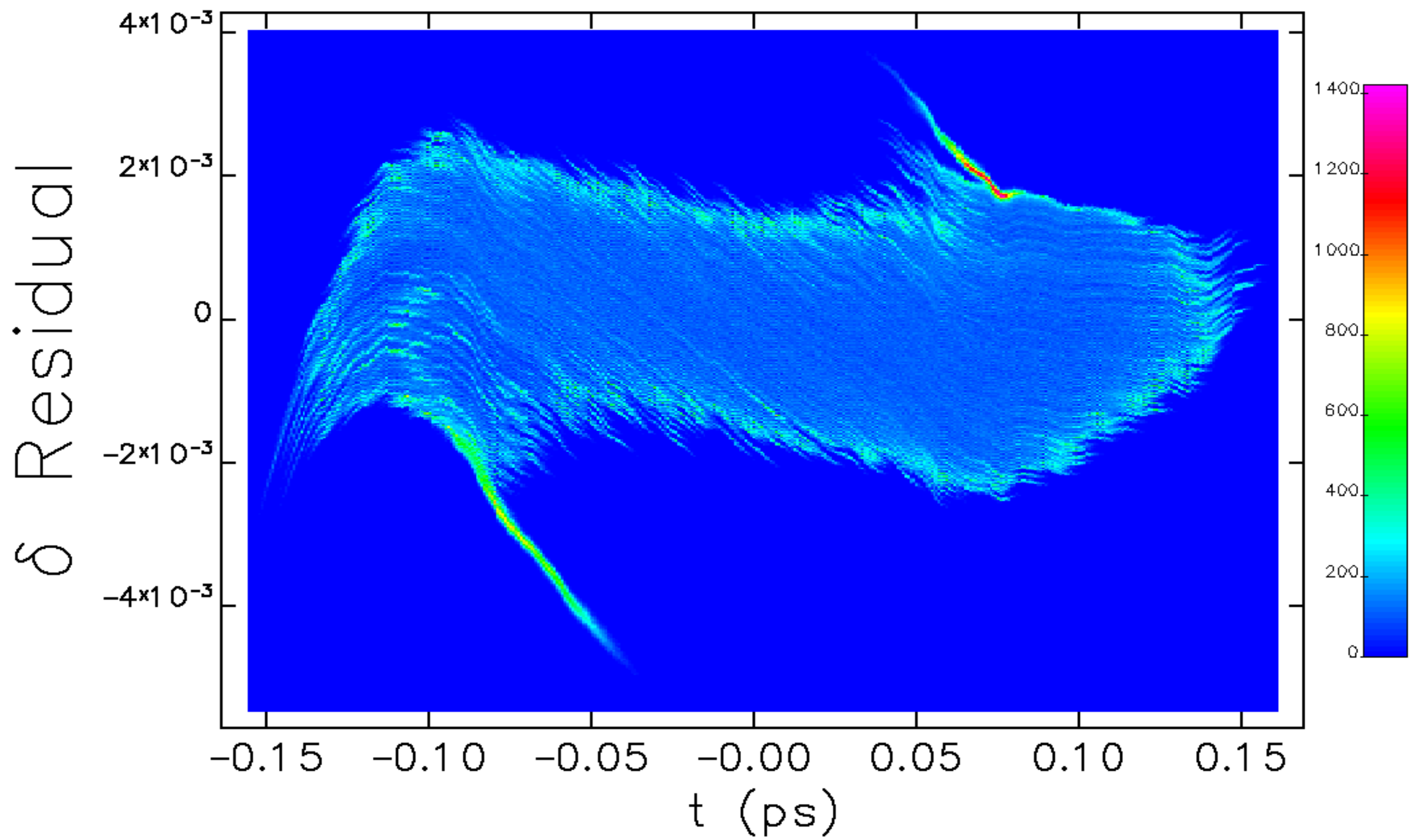


Residual of fit for entire beam

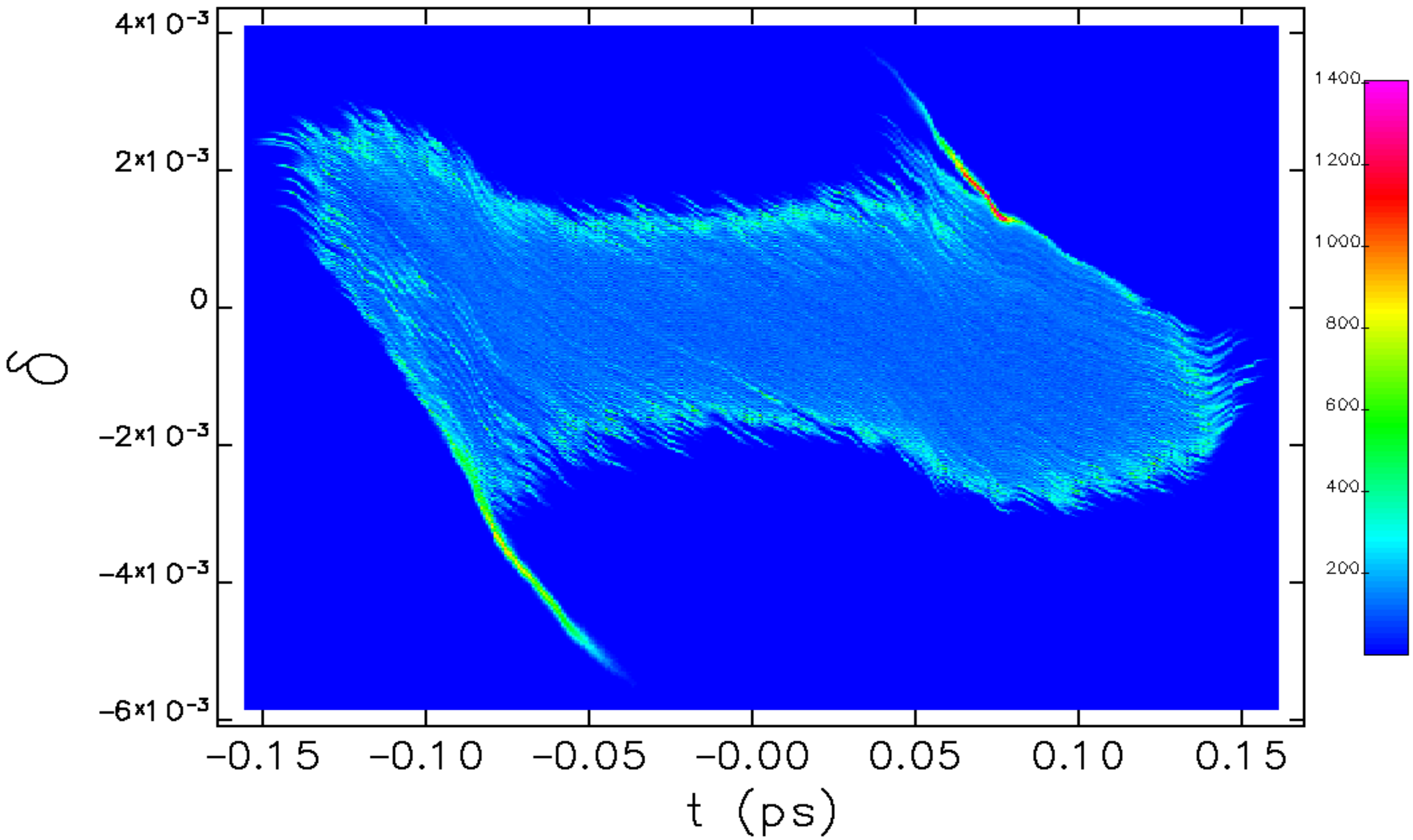
λ=15μm: BC2 Exit



λ=15μm: DL2 Exit

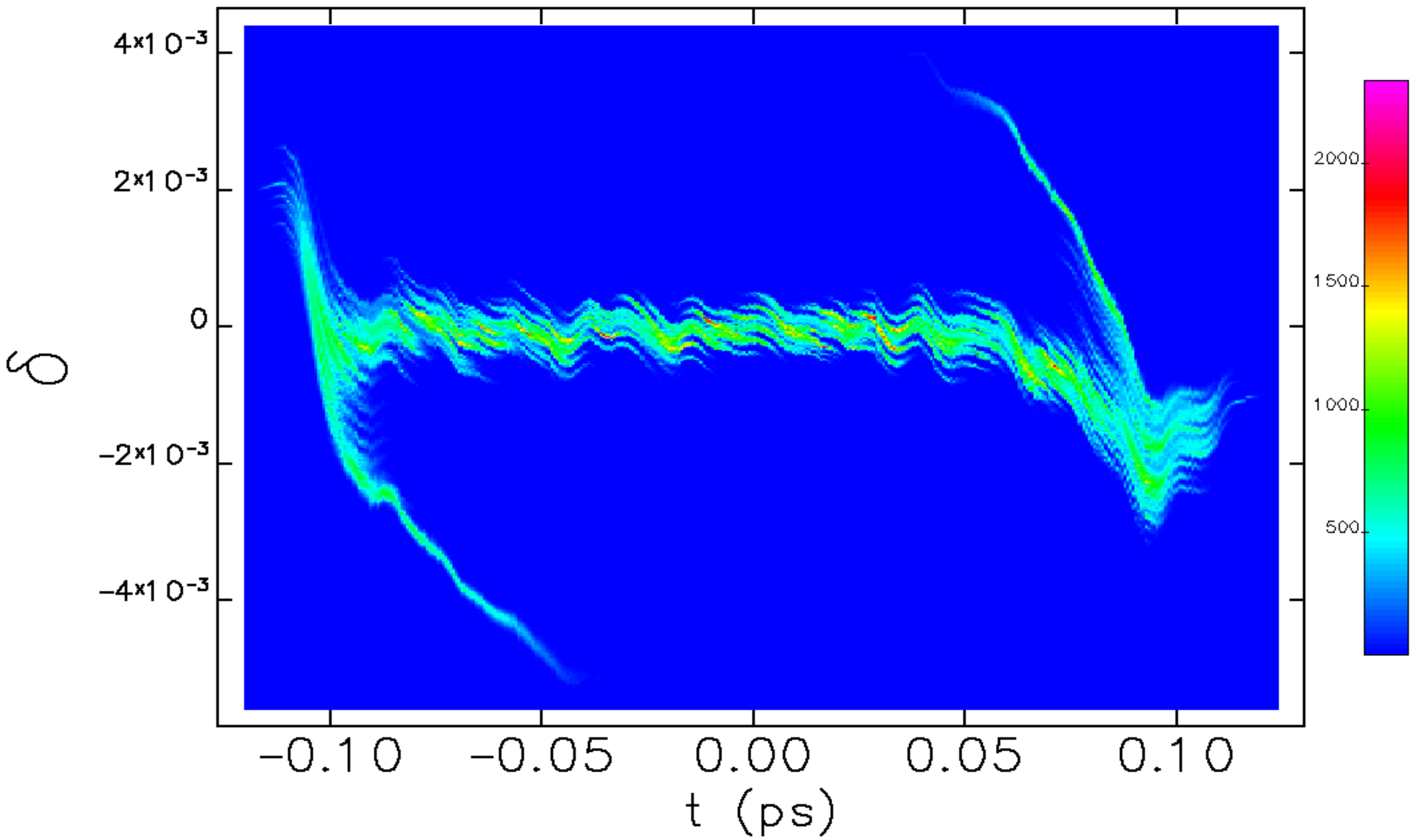


λ=15μm: DL2 Exit

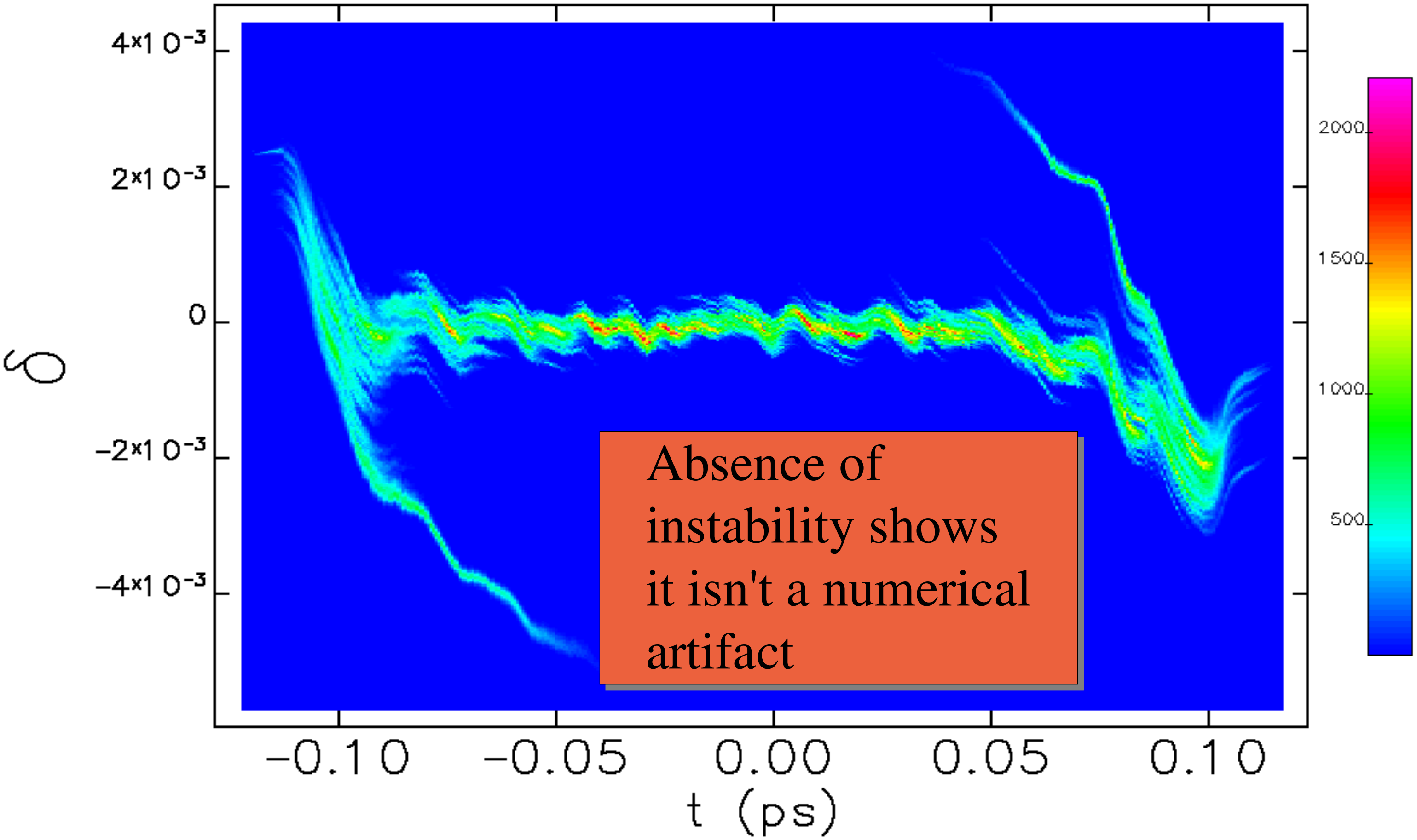


Normal phase-space view

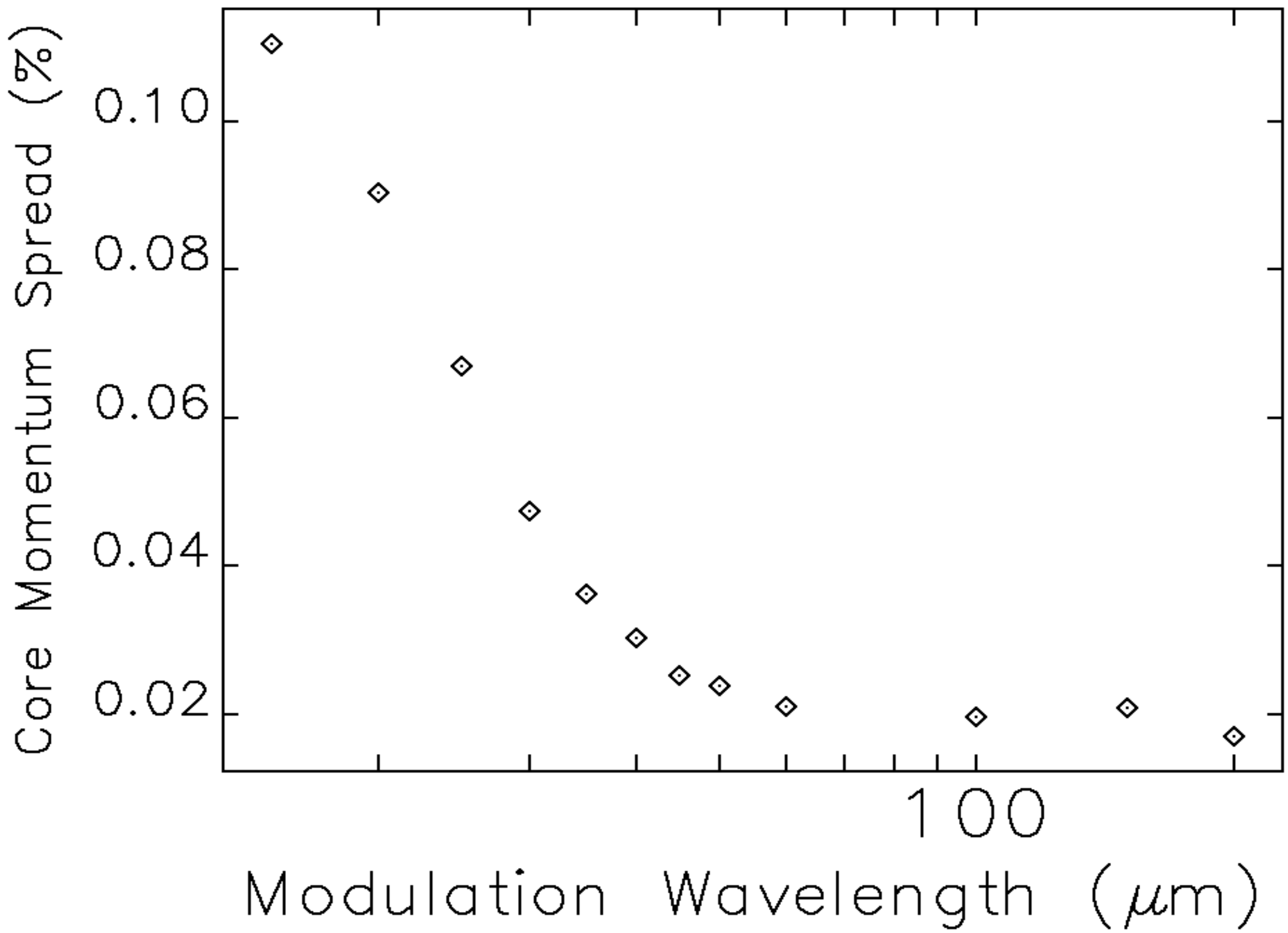
λ=60μm: DL2 Exit



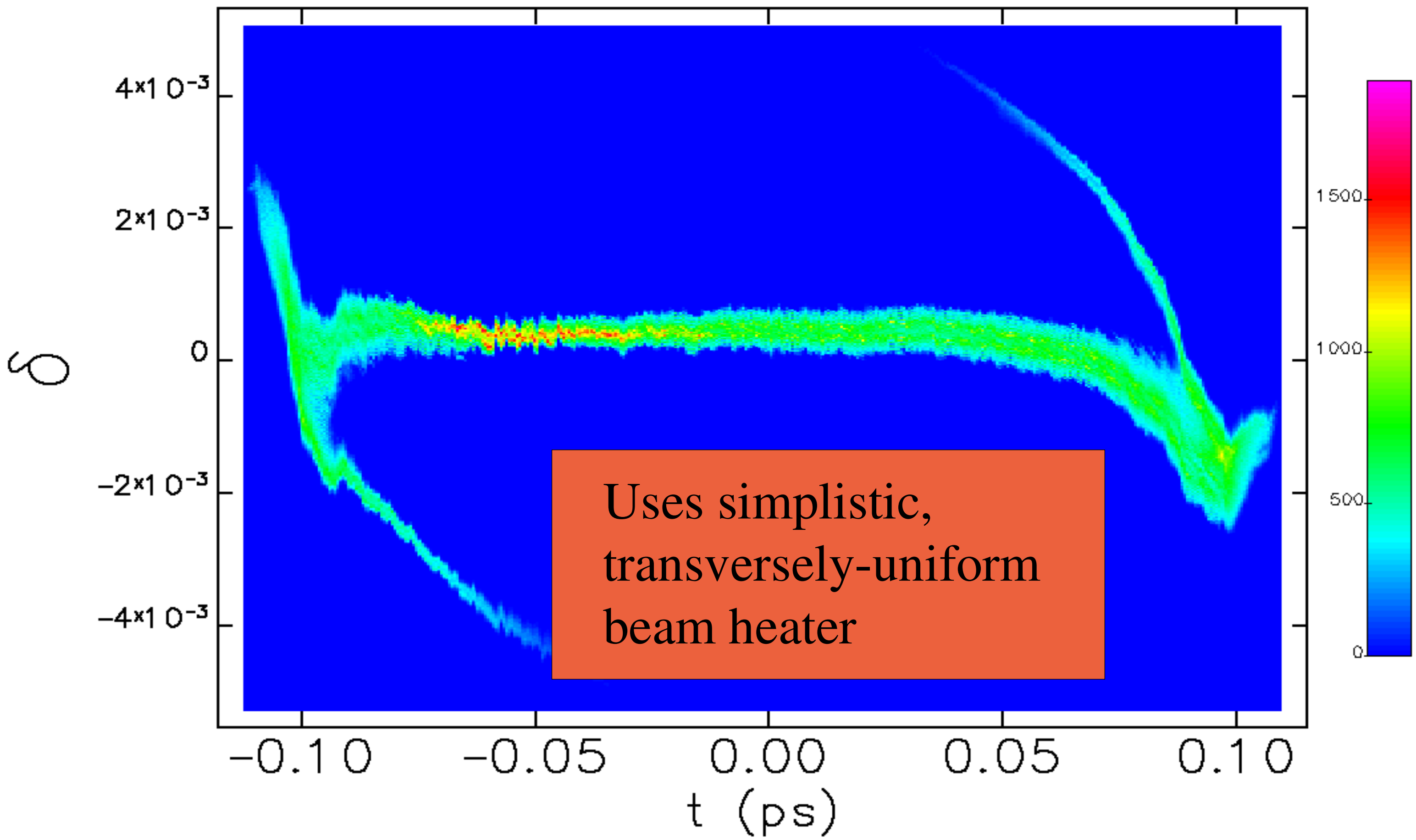
λ=200μm: DL2 Exit



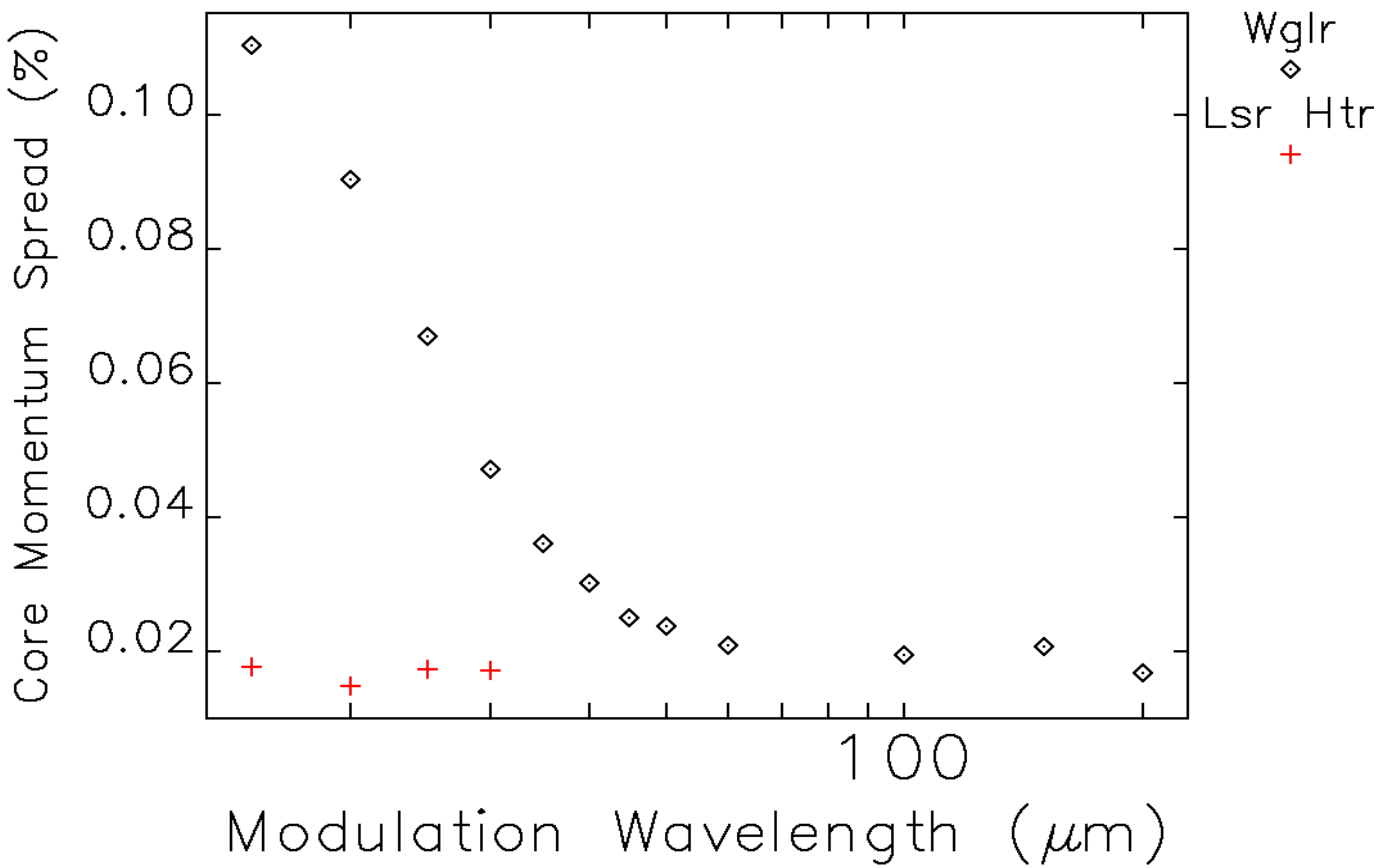
Core Momentum Spread vs Wavelength



Effect of “Beam Heater”: 15μm with ±0.04% Energy Modulation



Comparison of Wiggler with Heater Case



Conclusions

- The model provides a plausible simulation of longitudinal space charge
  - Noise is controlled
  - Oscillations have expected behavior
- Execution is reasonably fast
- LCLS simulations
  - Predict a potentially serious problem
  - Indicate that beam-heater is a likely solution