

Introduction to **elegant** and Summary of CSR Benchmarking Results

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Outline of Presentation

- Capabilities of **elegant** (14.6Beta4 and later)
- CSR algorithm used by **elegant**
- Basic CSR tests with gaussian beams
- CSR benchmarking results

Physics capabilities of elegant

- 6-D tracking with various methods
 - 1st and 2nd order matrices
 - 4th-order symplectic integration with exact energy dependence
- Rf elements with exact time dependence
- Transverse and longitudinal wakes
- Internal beam generation using Halton sequences (quiet start) or random numbers
- Lacks space-charge

Some Other Capabilities of **elegant**

- Output of matrices, twiss parameters, beam moments, slice analysis, and floor coordinates vs distance
- Optimization of matrices, twiss parameters, floor coordinates, and tracking results
- Errors (internally- or externally-generated)
- Trajectory/orbit correction
- SDDS compliant

Availability/Support of elegant

- Supported platforms
 - LINUX, Solaris, etc.
 - Microsoft Windows (98 or later).
 - Got a C compiler?
- Binaries, source, documentation, and examples available at
<http://www.aps.anl.gov/asd/oag/oaghome.shtml>
- New versions released about twice a year.
- Automated regression testing prior to release to reduce chance of bugs.

CSR Algorithm in elegant

- Use line-charge treatment of Saldin *et al.* as extended by Stupakov.
- For example, inside a dipole Saldin *et al.* give

$$\frac{dE(s, \phi)}{d(ct)} = \frac{-2e^2}{(3R^2)^{1/3}} \left\{ s_l^{1/3} [\lambda(s - s_l) - \lambda(s - 4s_l)] + \int_{s-s_l}^s \frac{dz}{(s-z)^{1/3}} \frac{d\lambda(z)}{dz} \right\}$$

where $s_l = R \phi^3 / 24$ is the slippage length.

- The difficulty in using this results from the appearance of $\frac{d\lambda(z)}{dz}$ in the integrand

CSR Implementation in **elegant**

- Dipoles and drifts are divided into a user-selectable number of pieces.
- Between pieces, CSR wakes are computed and energy kicks are applied
- Dipole piece tracking
 - Symplectic integrator with exact energy dependence
 - Thin-edge effects (linear and second-order)
 - Field terms up to 4th order in x and y
 - Incoherent SR option
- Drifts use exact calculation of path-length effects

CSR Wake Computation in **elegant**

- *Binning*: macroparticles are pointlike, so perform a straight-forward histogram.
- *Smoothing*: Savitzky-Golay smoothing of variable degree may be used.
- *Differentiation*: performed using a three-point Savitzky-Golay filter.
- *Integration*: performed using trapezoid₁ rule plus analytical integration up to the $1/(s-z)^{\frac{1}{3}}$ singularity.

CSR Output Features

- Inside dipoles
 - particle coordinates
 - linear density and its derivative
 - CSR wake, including individual components
- Inside drifts
 - linear density and its derivative
 - CSR wake

Basic Tests of CSR in elegant

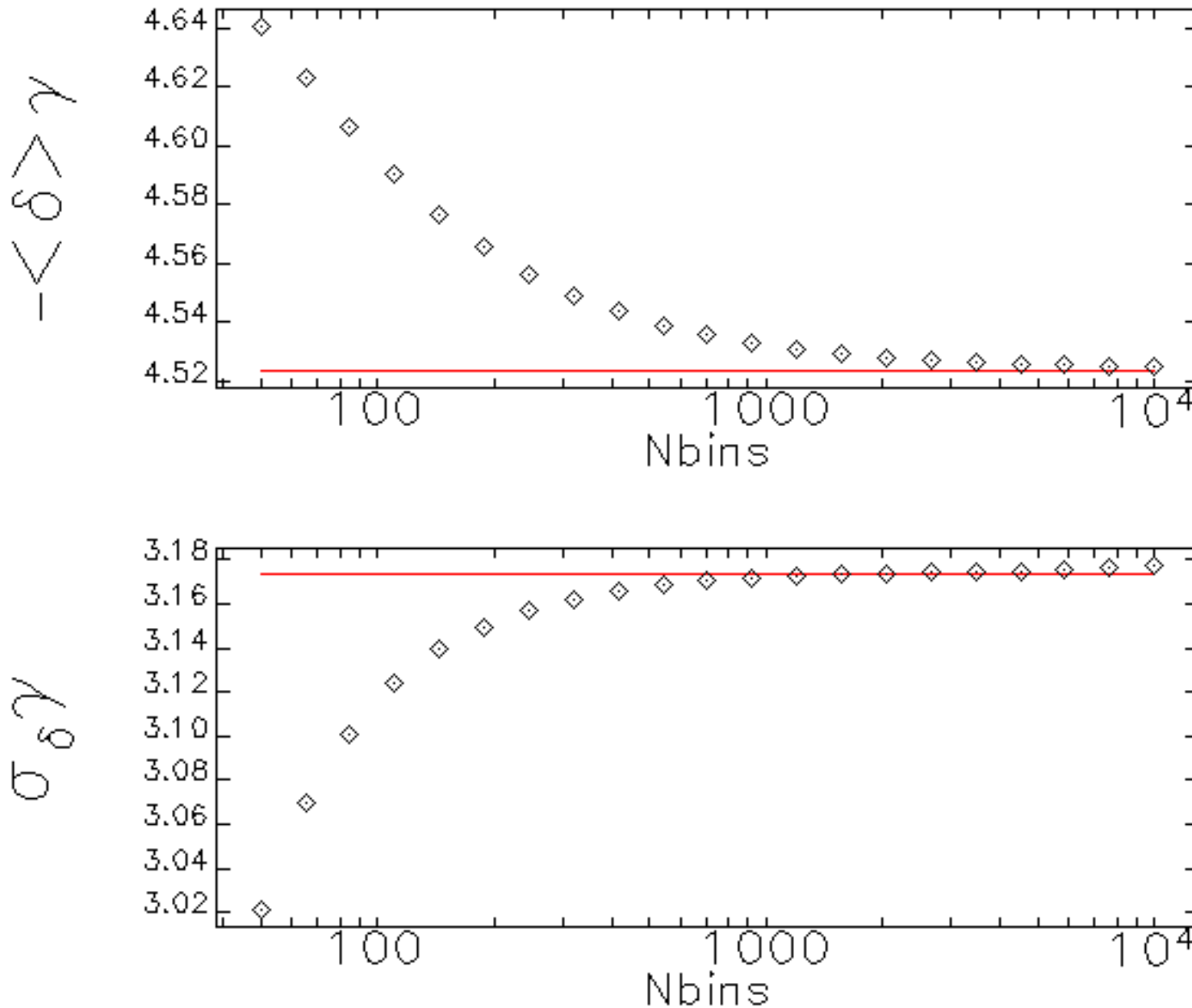
- For gaussian beam and steady-state CSR, the mean and standard deviation of the fractional momentum change are, respectively

$$\langle \delta \rangle = -0.3505 \frac{r_e Q L_b}{e \gamma (R^2 \sigma_s^4)^{1/3}}$$

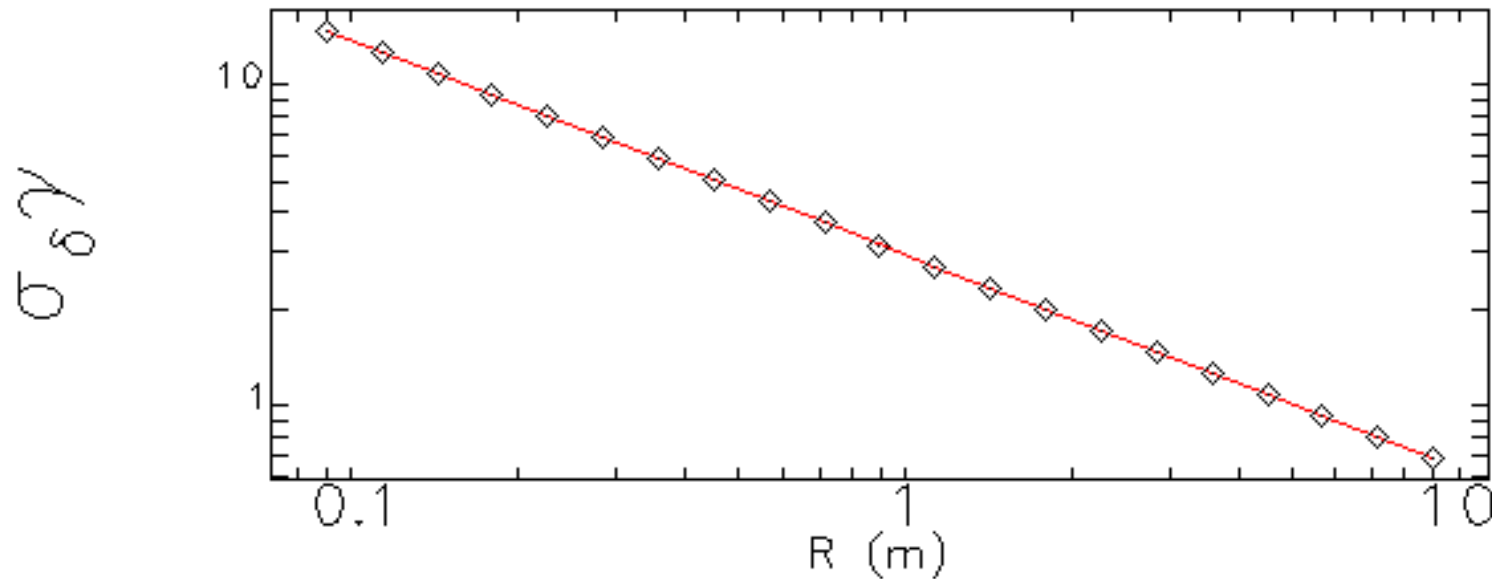
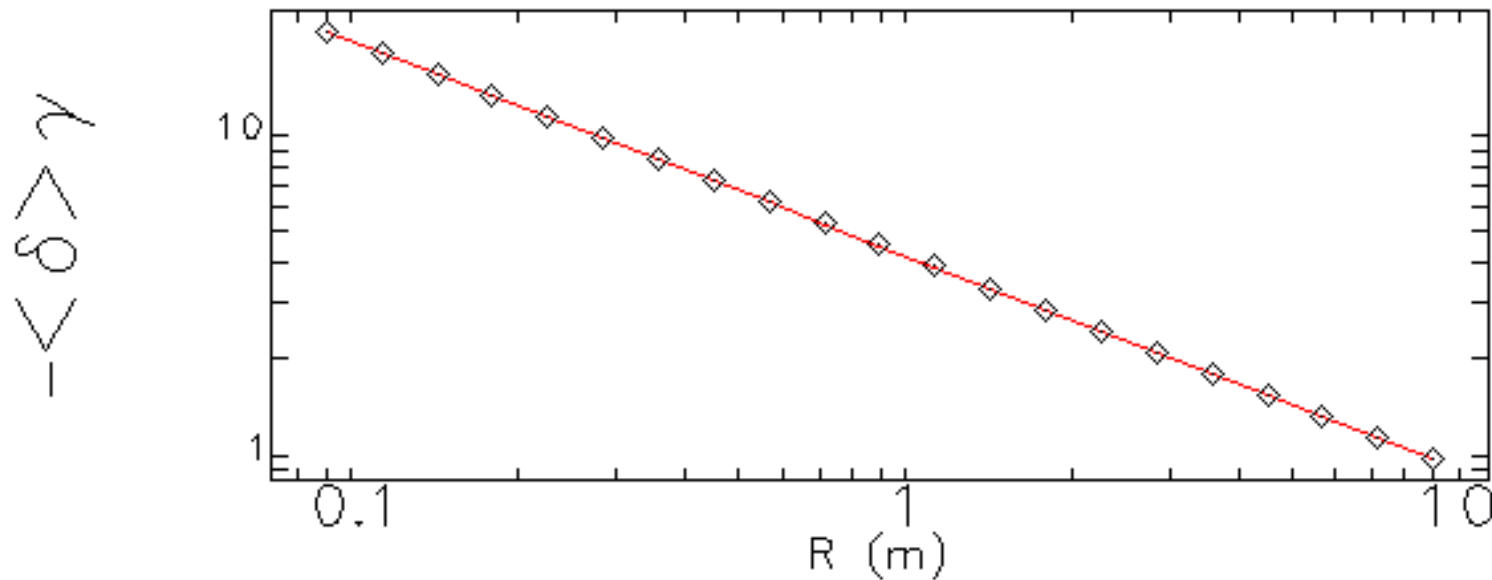
$$(\delta)_{s.d.} = 0.2459 \frac{r_e Q L_b}{e \gamma (R^2 \sigma_s^4)^{1/3}}$$

- Default values: $L_b=0.6$ m, $R=0.9$ m, $Q=2.1$ nC, $\sigma_s=50$ μm , $\gamma=3.9 \times 10^{10}$, with 100 pieces per dipole, 1000 bins, no smoothing, and 0.5M particles.

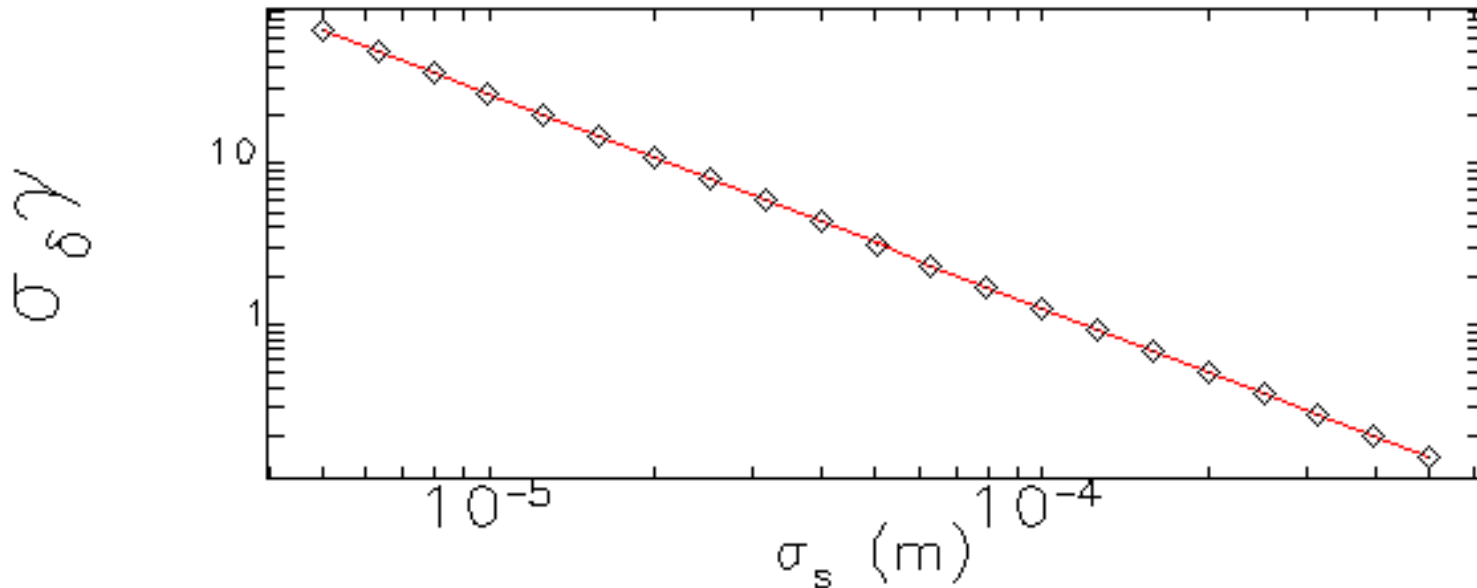
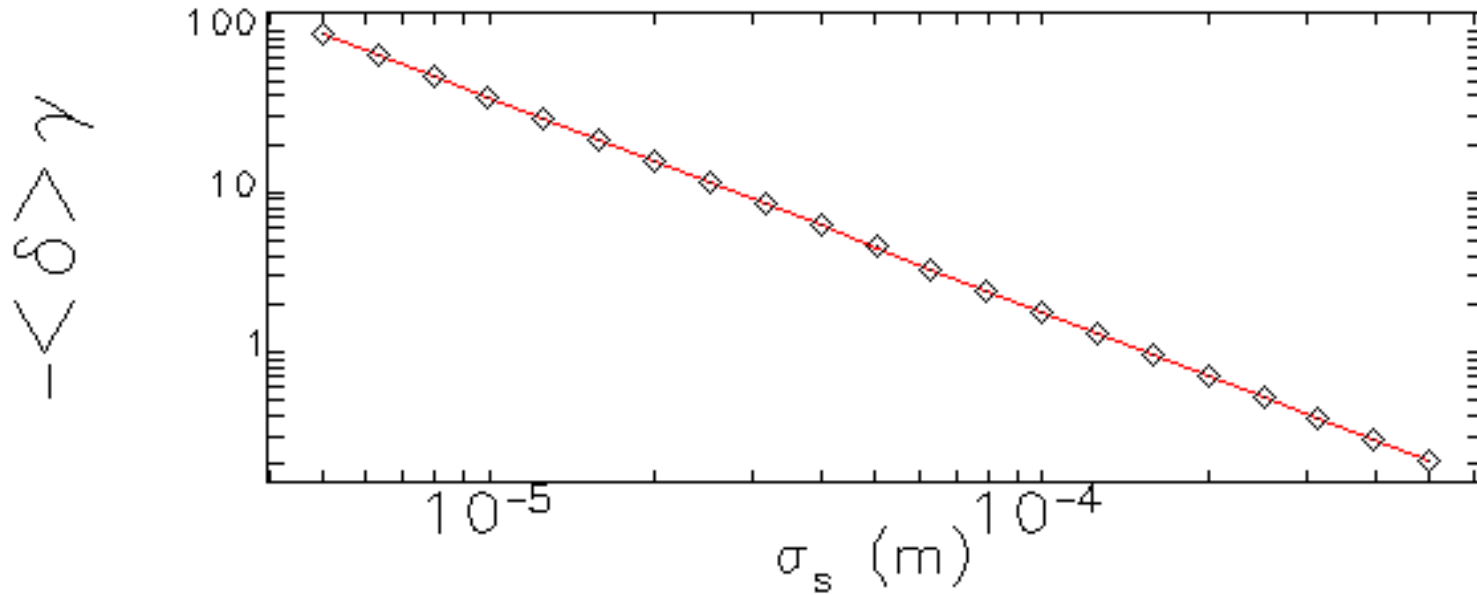
Effect of Number of Bins



Dependence on Bending Radius



Dependence on Bunch Length



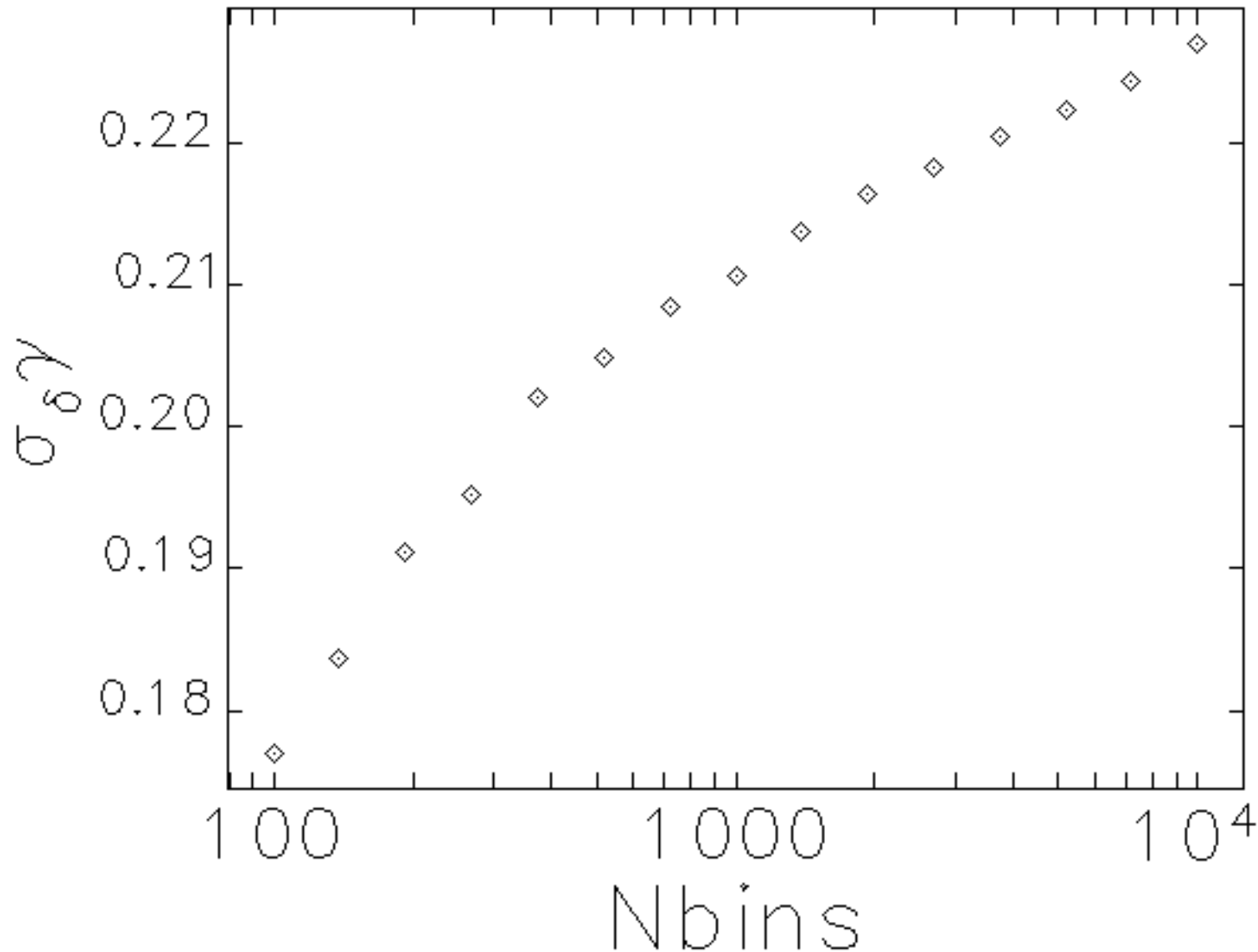
Discussion of Test

- This test is potential misleading!
- It shows that the basic numerics are right, but may provide poor guidance for other runs
 - large number of particles
 - extremely smooth distribution with gentle derivatives
 - distribution doesn't change or develop features or noise
 - steady-state CSR

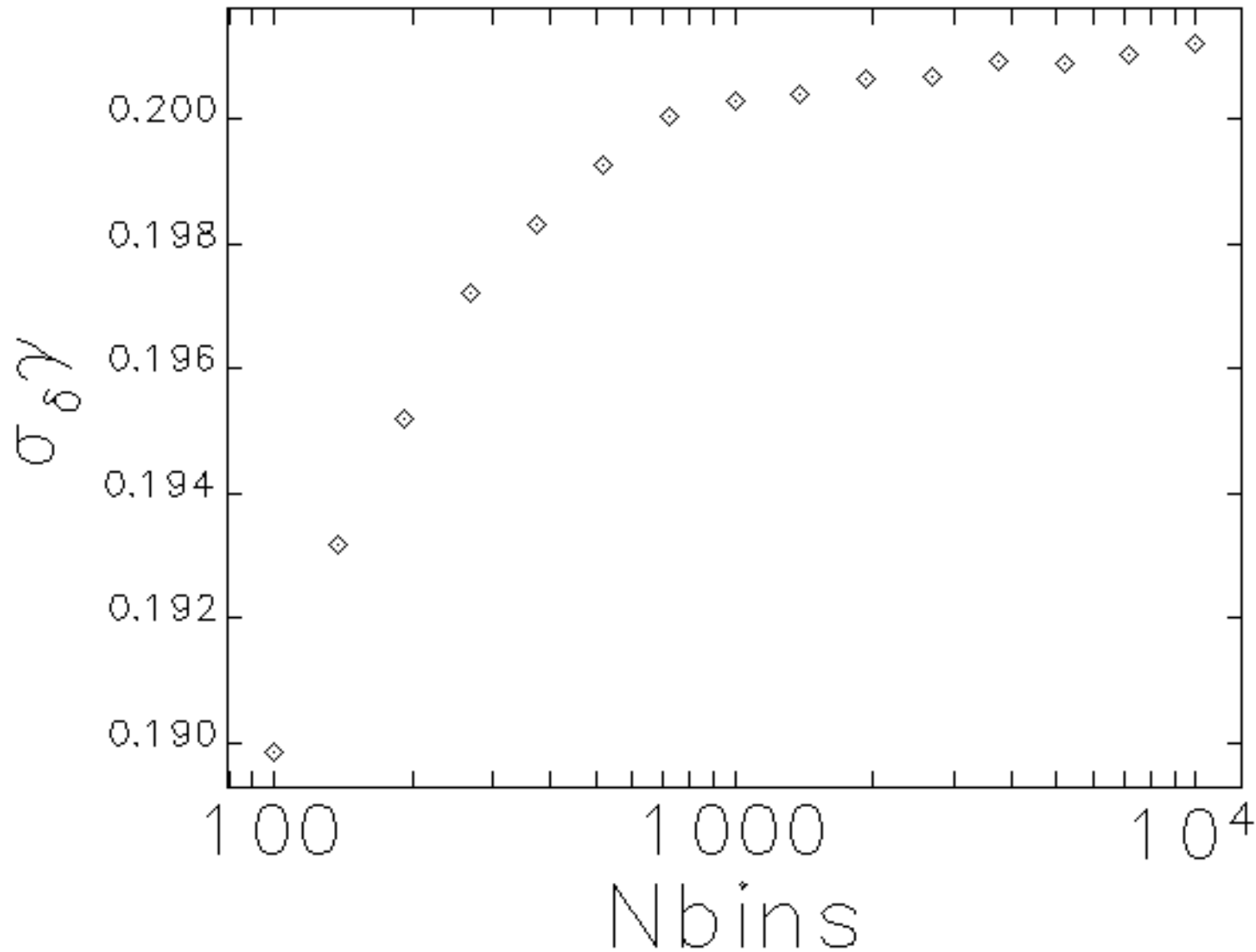
Problem with Uniform Distribution

- The uniform distribution has infinite values of λ' .
- The more bins one uses, the more the numerical derivative at the ends increases and the more particles are needed to control noise.
- There is no point at which things can be expected to converge as the number of bins and particles is increased.
- Single-dipole transient CSR example: use benchmark dipole and beam parameters (except $\gamma=3.9\times 10^{10}$) with 0.5M particles.

Problem with Uniform Distribution in Transient Simulation



Comparable Results for Gaussian Distribution



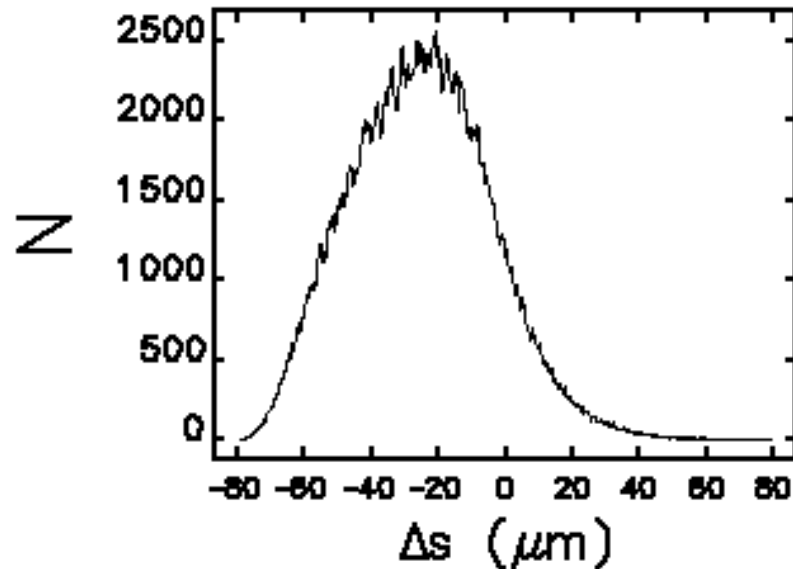
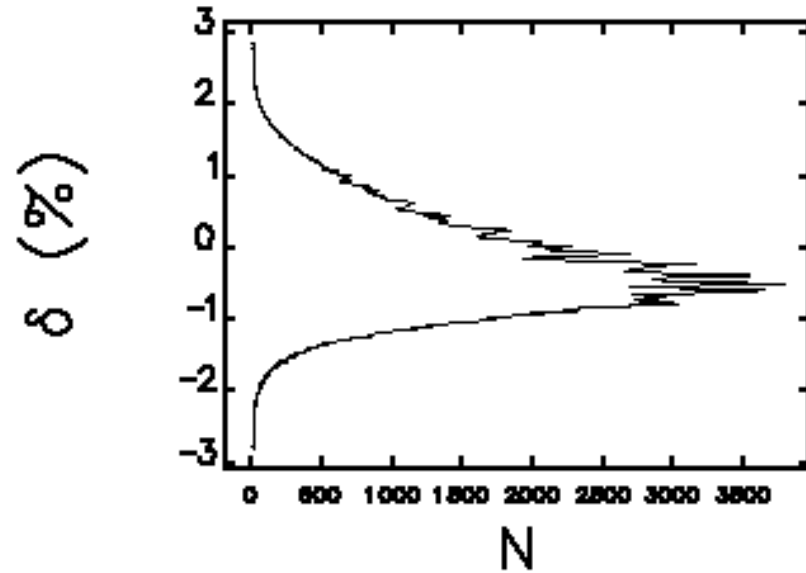
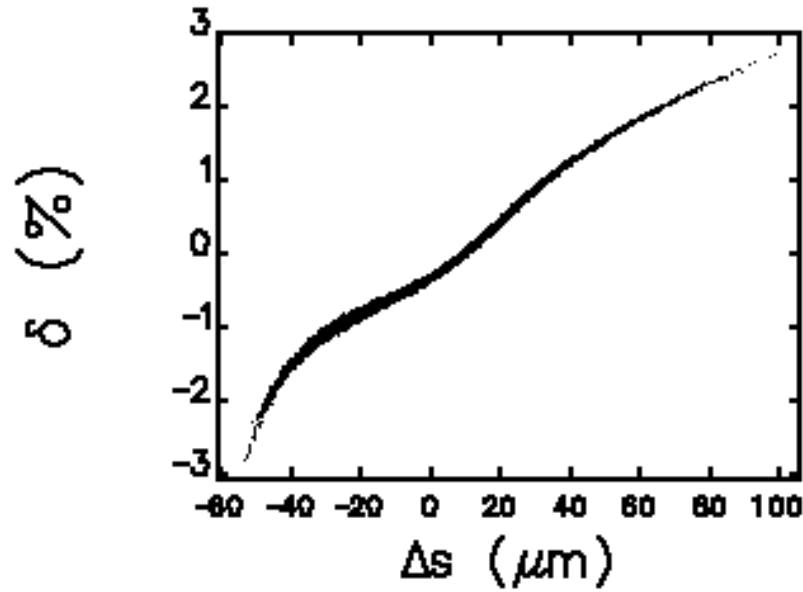
Parameters for Benchmark Runs

- 0.5 M particles
- Dipoles divided into 100 pieces
- 2nd order edge effects included
- Drifts divided into 0.01m pieces
- CSR computations use 600 bins and no smoothing

Plots for Benchmark Runs

- Plots generally show projected beam properties
 - fractional momentum spread
 - fractional momentum deviation
 - corrected horizontal normalized emittance
 - 20-slice-averaged corrected horizontal normalized emittance

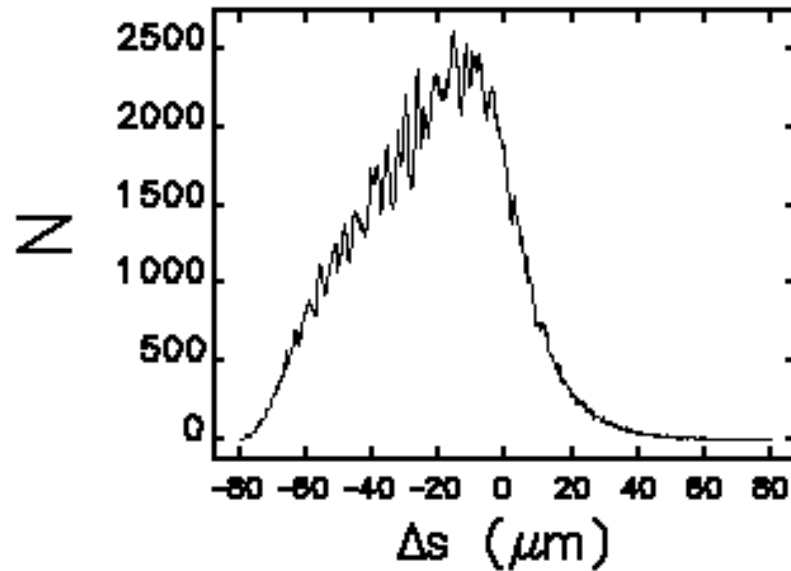
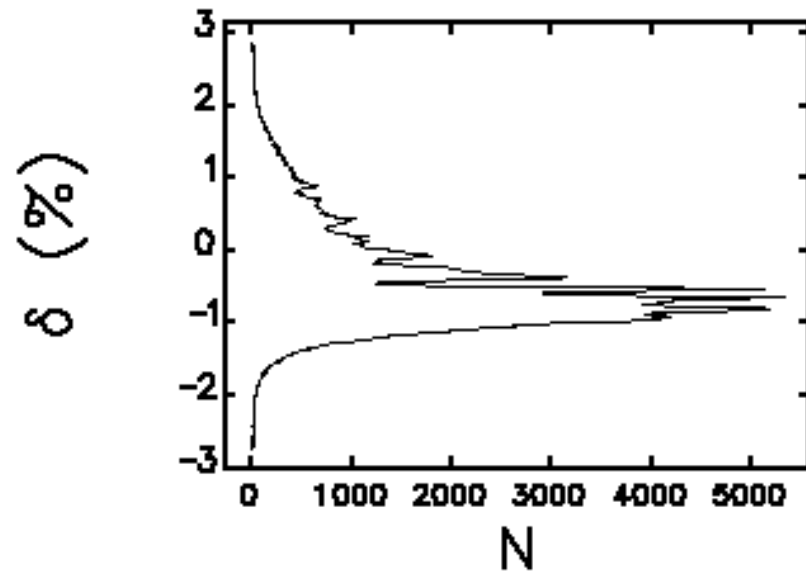
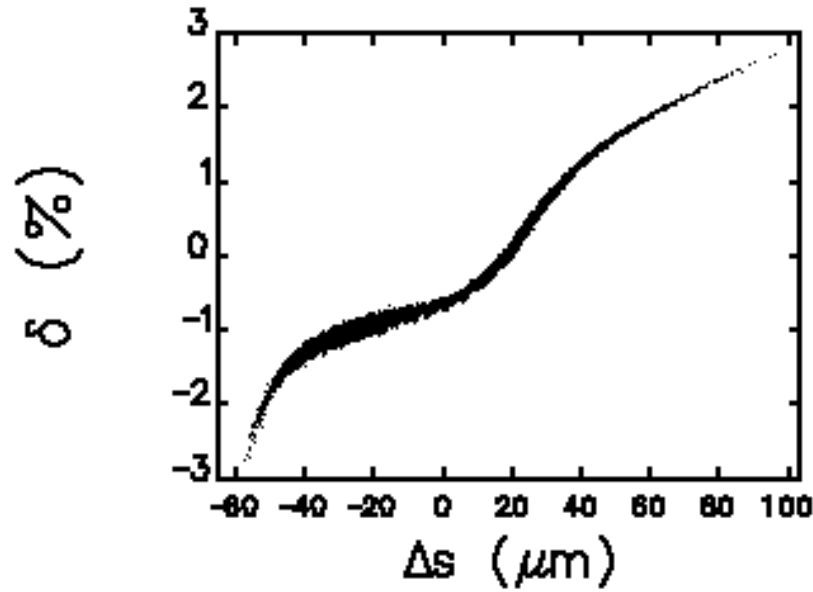
0.5-nC Gaussian Beam at 0.5GeV



Case: withCSR-0.5GeV-GC-0.5nC
Location: end
 $\langle \delta \rangle = -0.2144\%$
 $SD(\delta) = 0.6930\%$
 $SD(\Delta s) = 20.8715 \mu\text{m}$



1.0-nC Gaussian Beam at 0.5GeV



Case: withCSR-0.5GeV-GC-1.0nC

Location: end

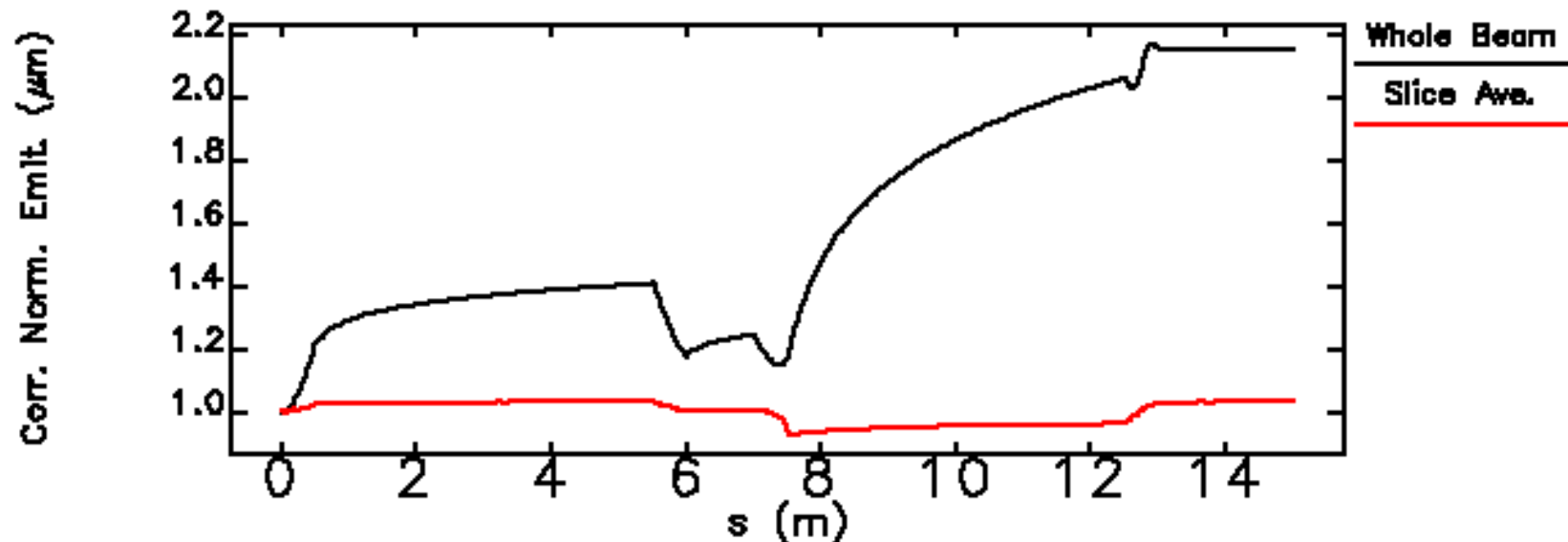
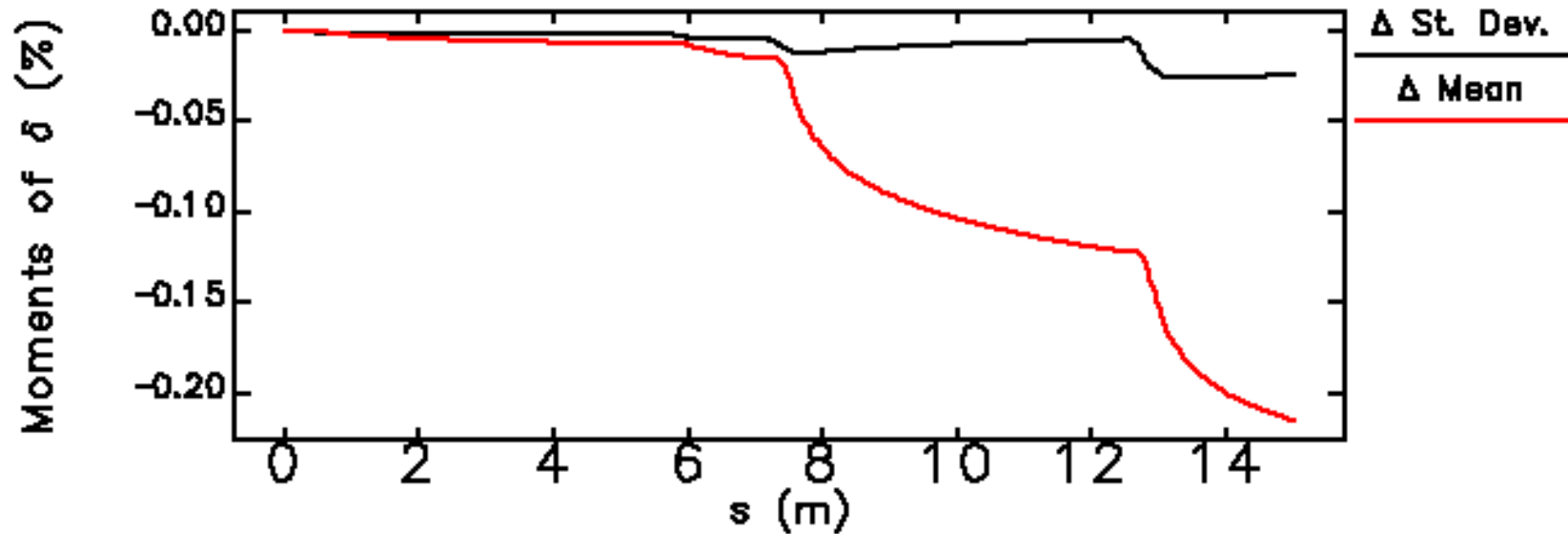
$\langle \delta \rangle = -0.4215\%$

$SD(\delta) = 0.6709\%$

$SD(\Delta s) = 21.9233 \mu\text{m}$

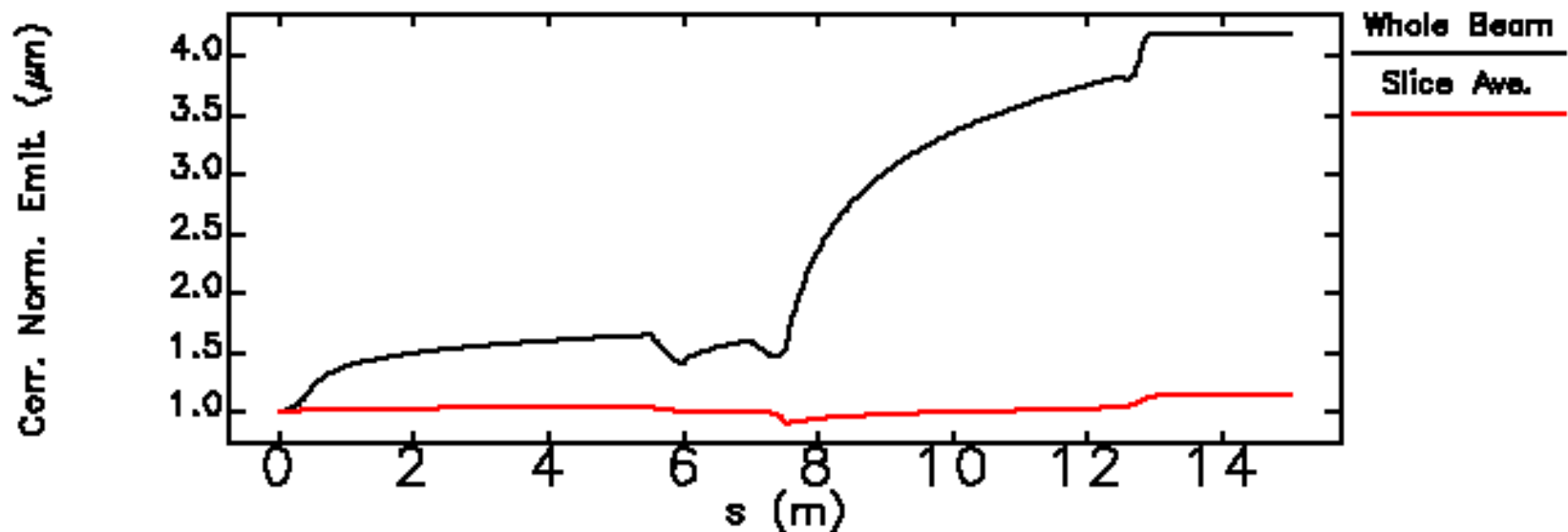
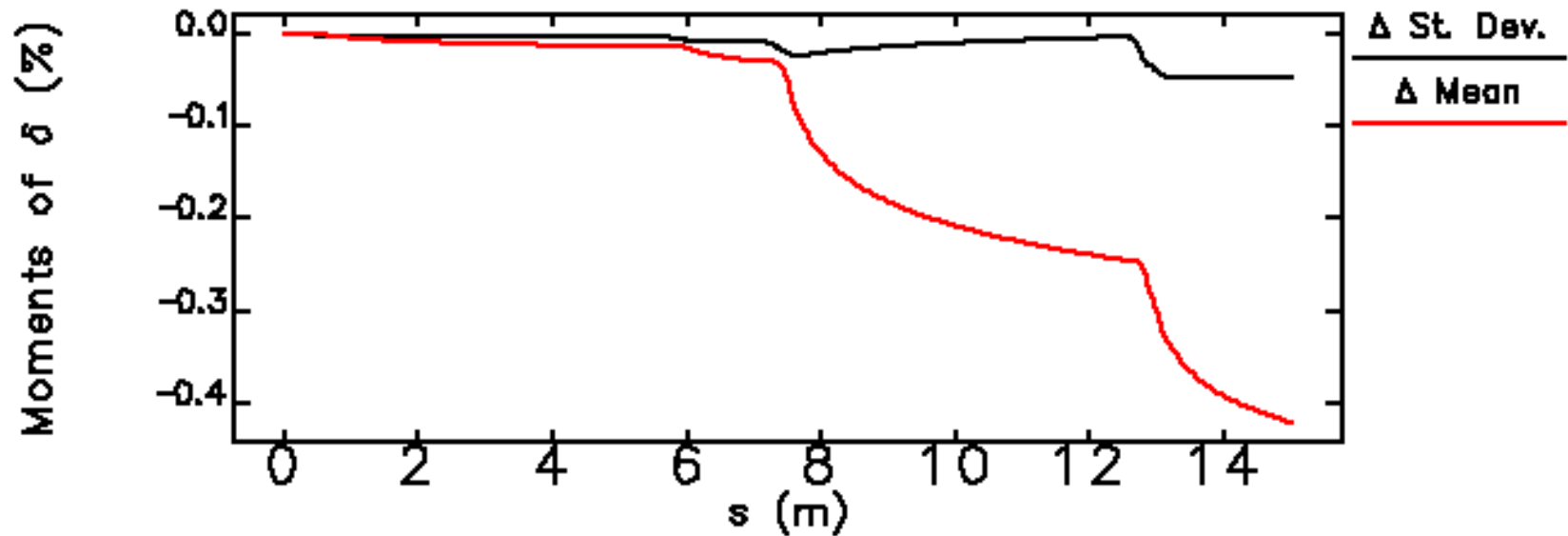


0.5-nC Gaussian Beam at 0.5GeV



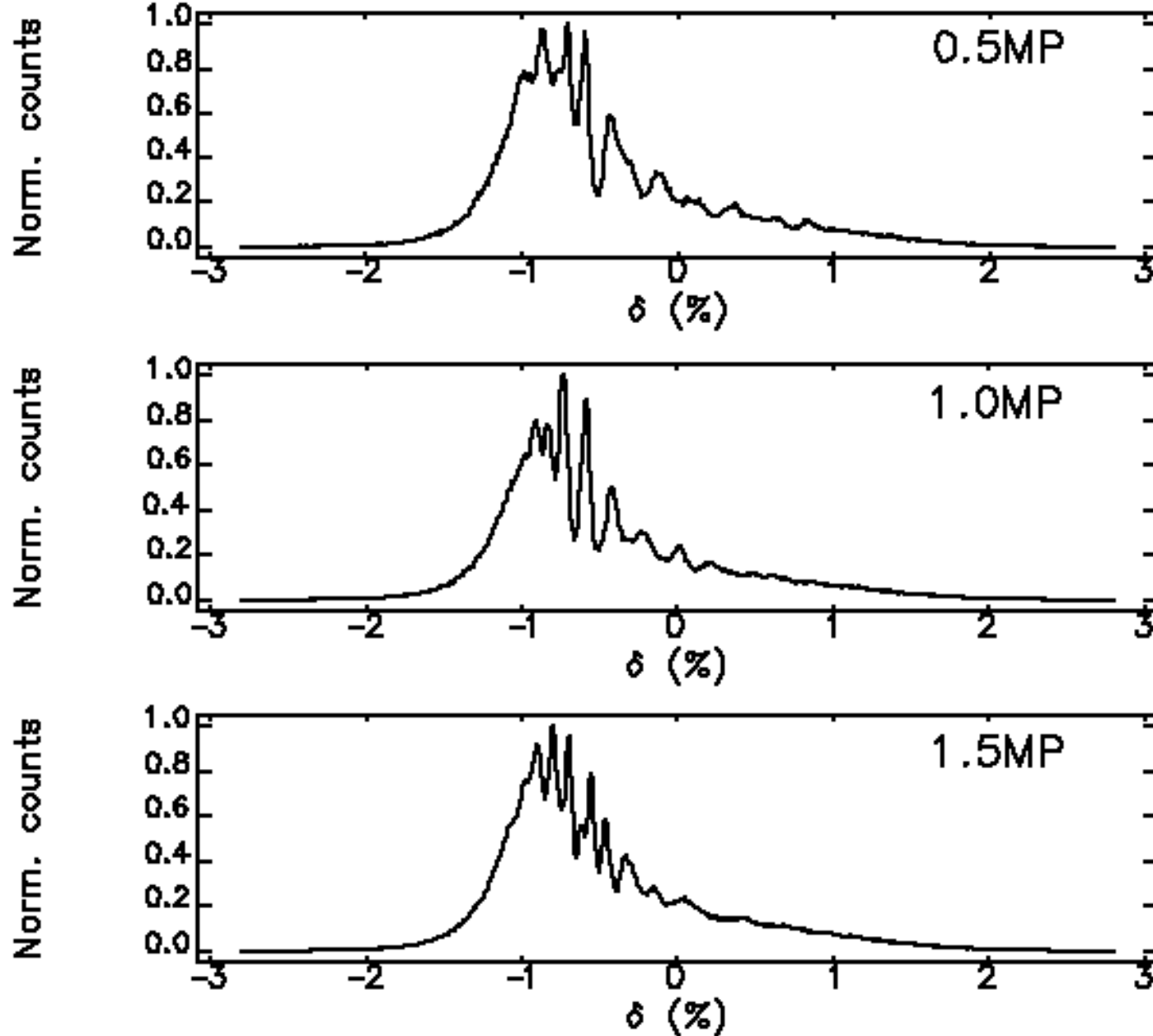
Case with CSR-0.5GeV-GC-0.5nC

1.0-nC Gaussian Beam at 0.5GeV

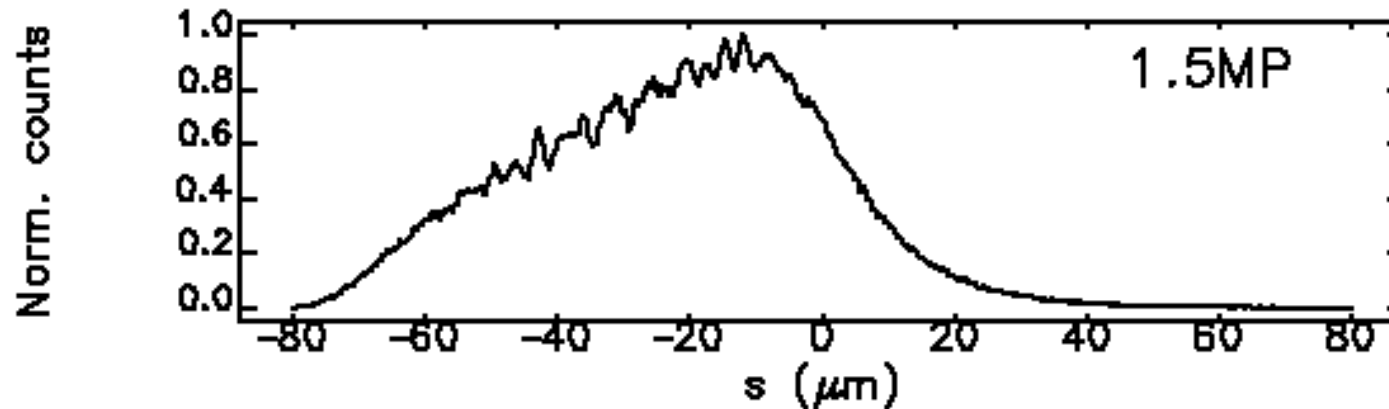
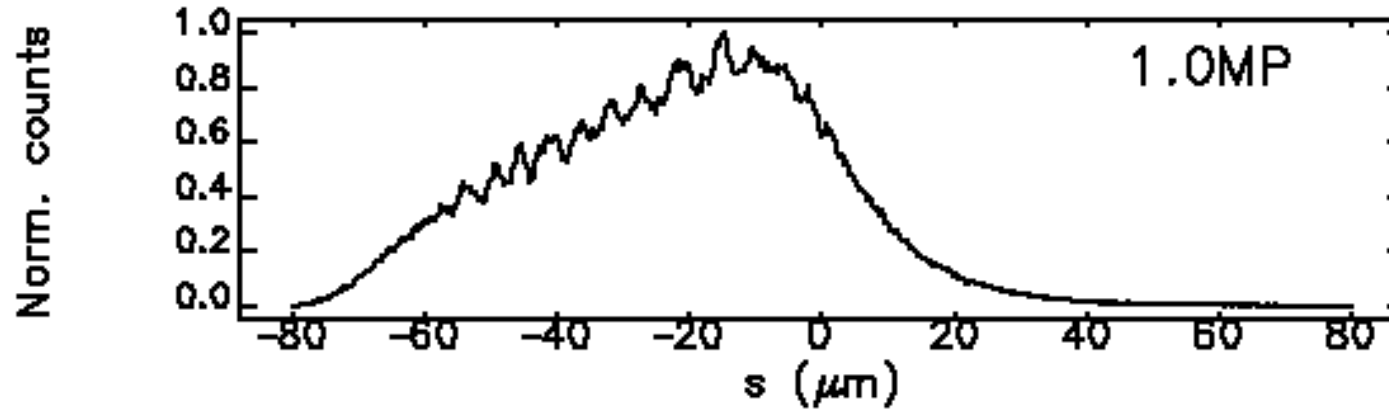
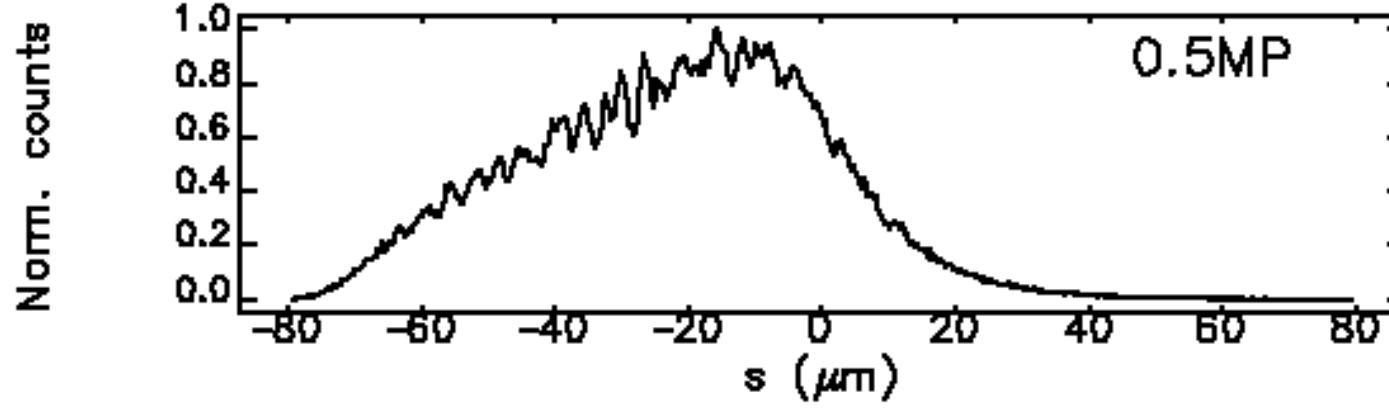


Case with CSR-0.5GeV-GC-1.0nC

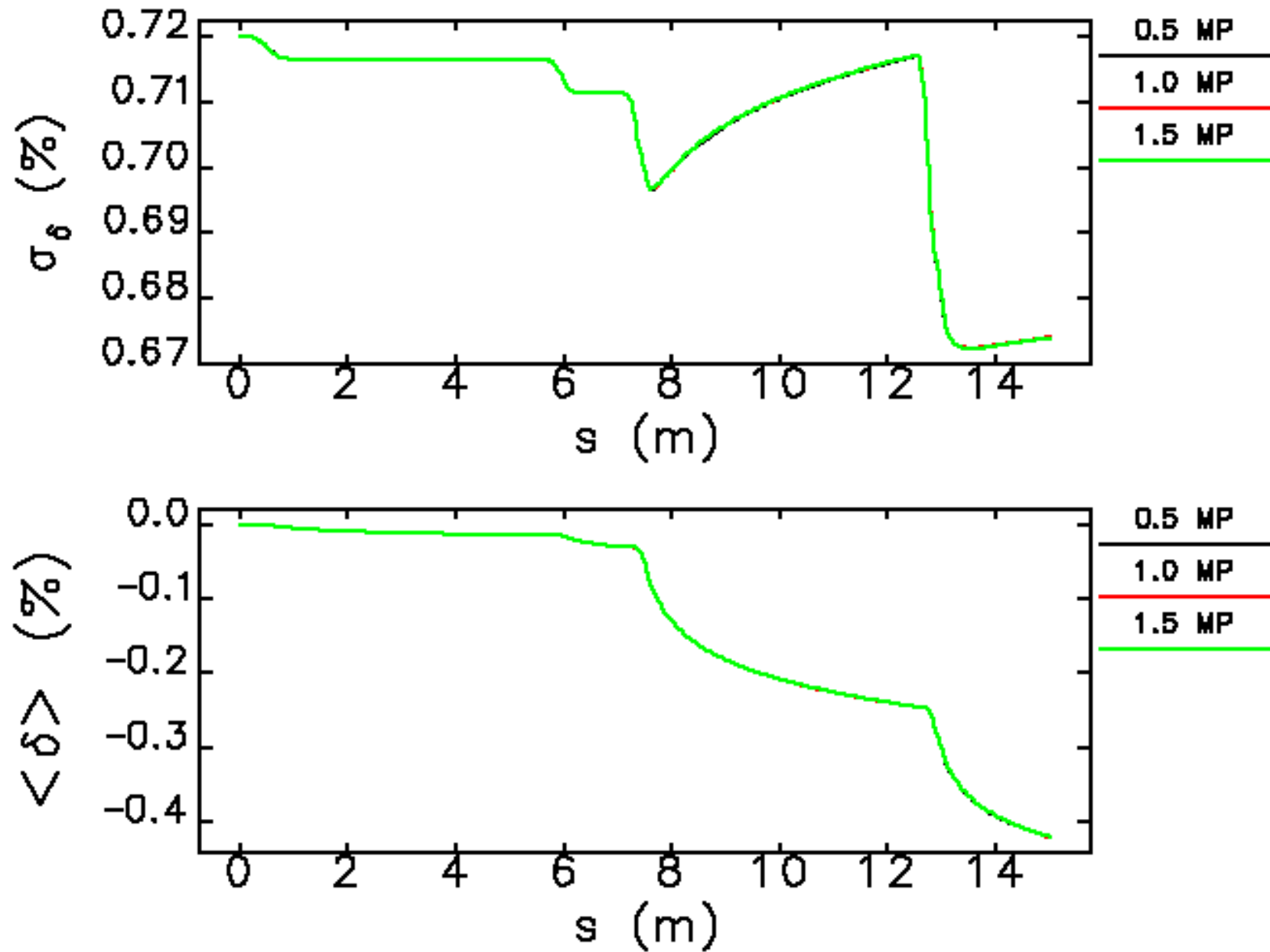
Reality Check: Effect of More Particles



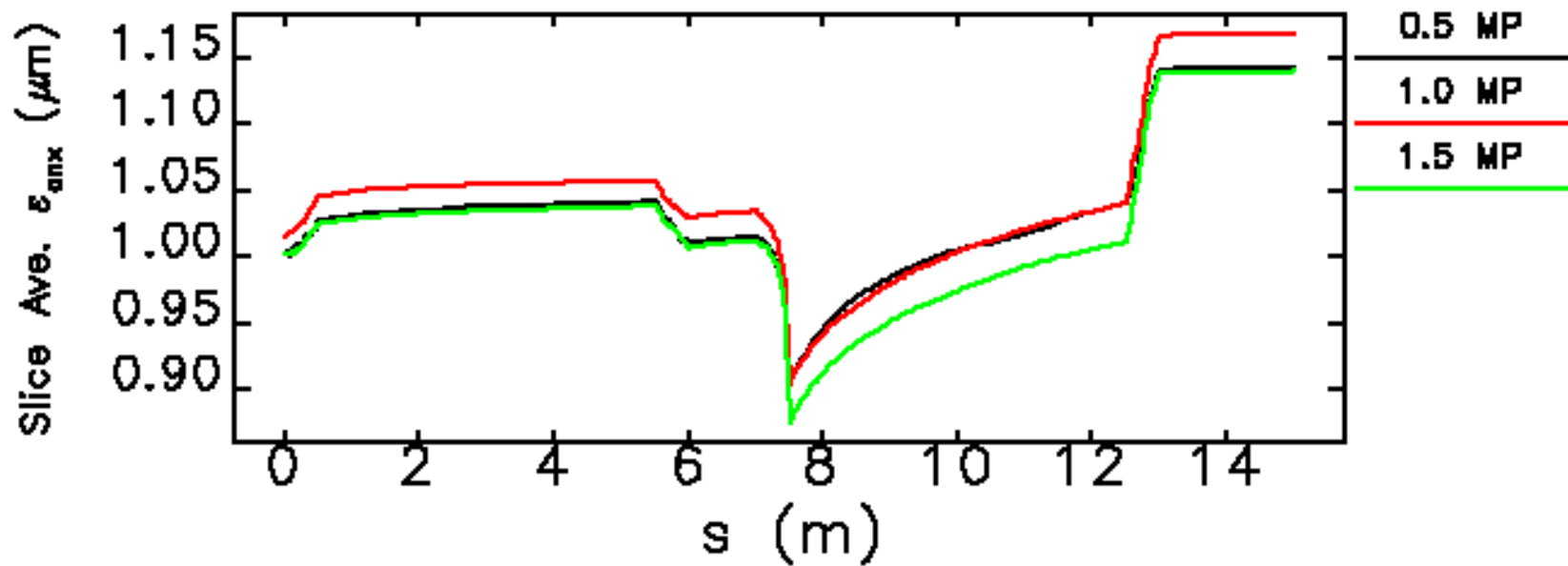
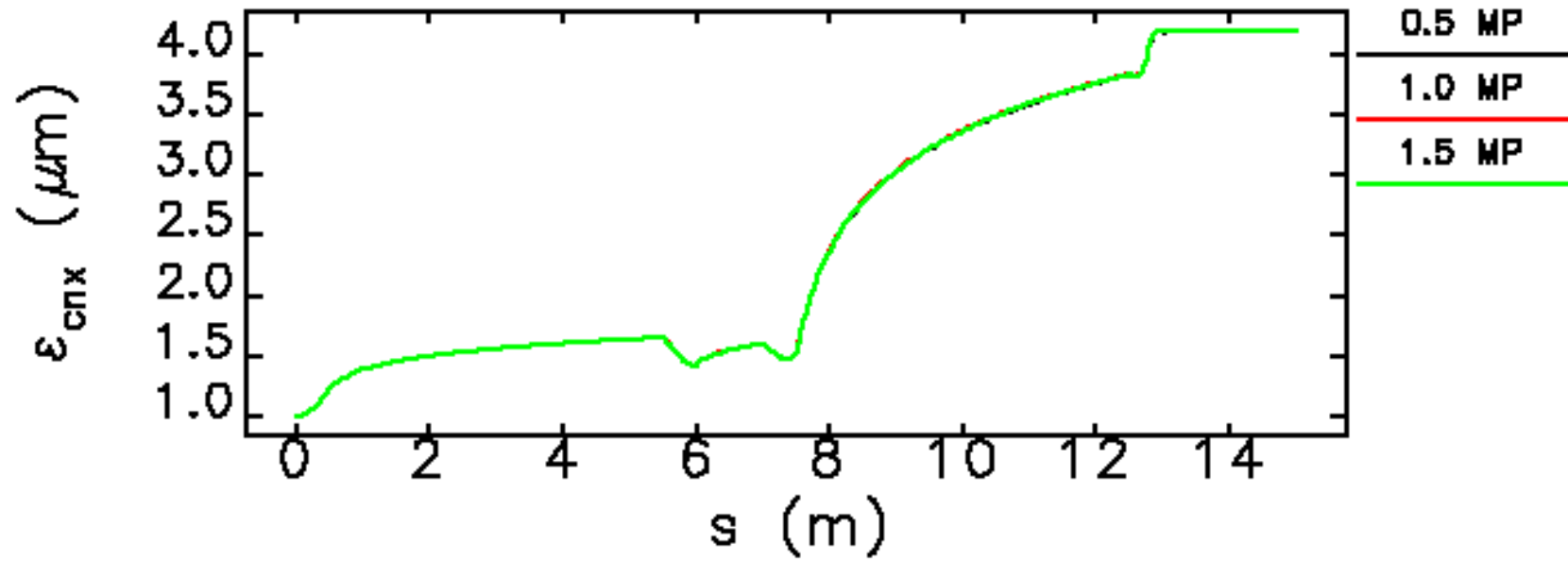
Reality Check: Effect of More Particles



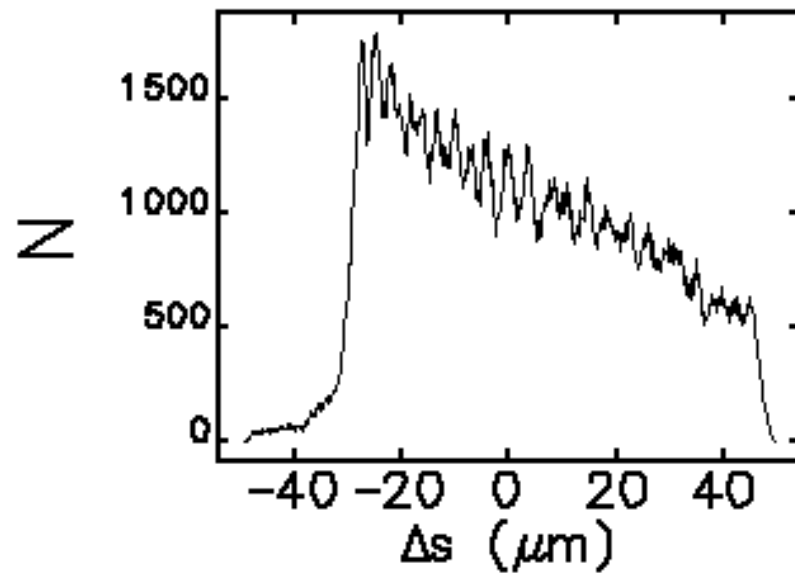
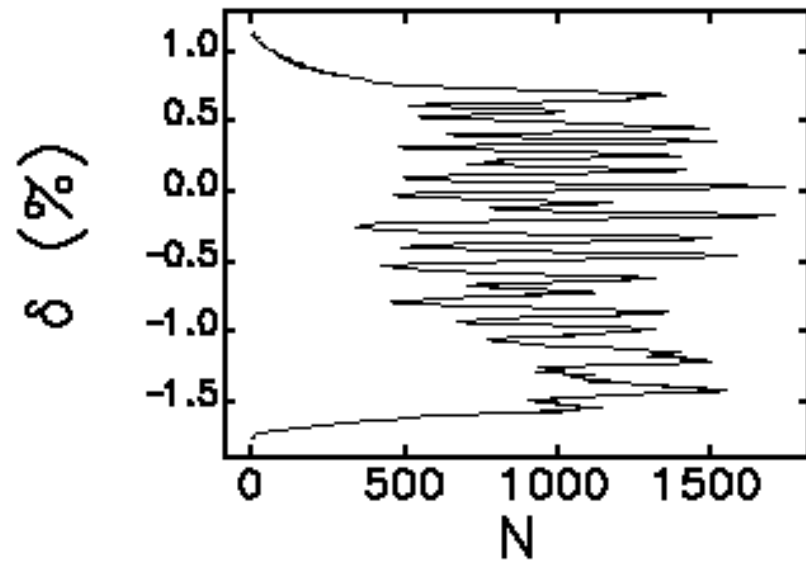
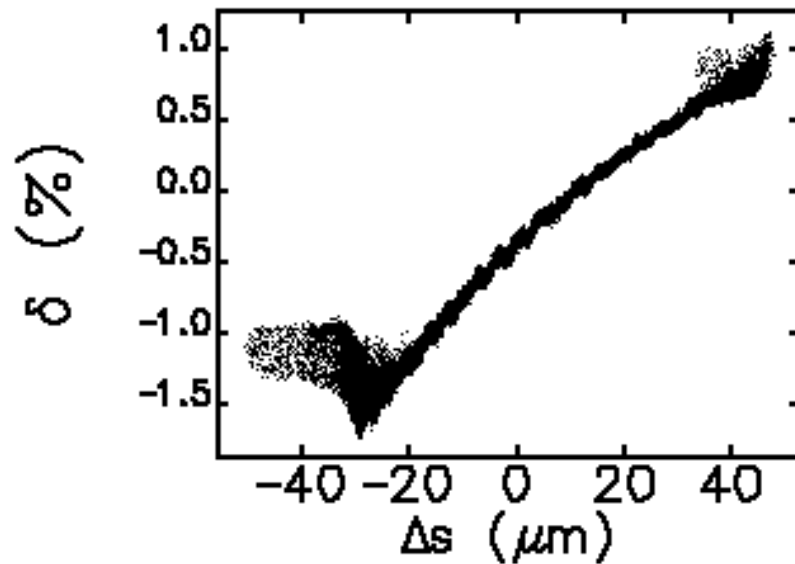
Reality Check: Effect of More Particles



Reality Check: Effect of More Particles



1.0nC Uniform Beam at 0.5GeV



Case: withCSR-0.5GeV-UC-1.0nC

Location: end

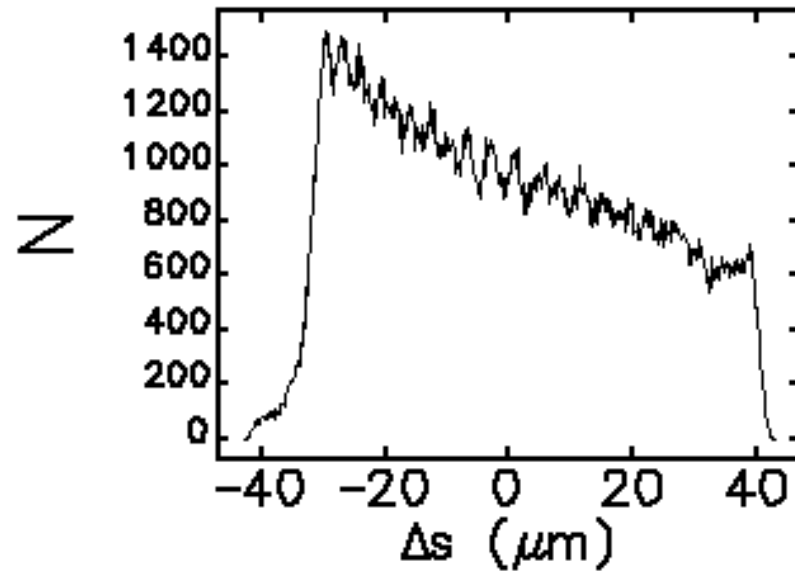
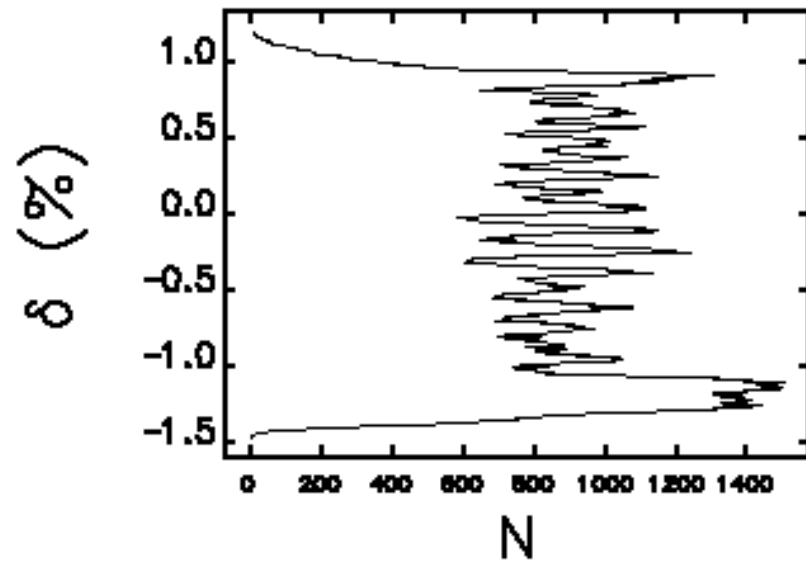
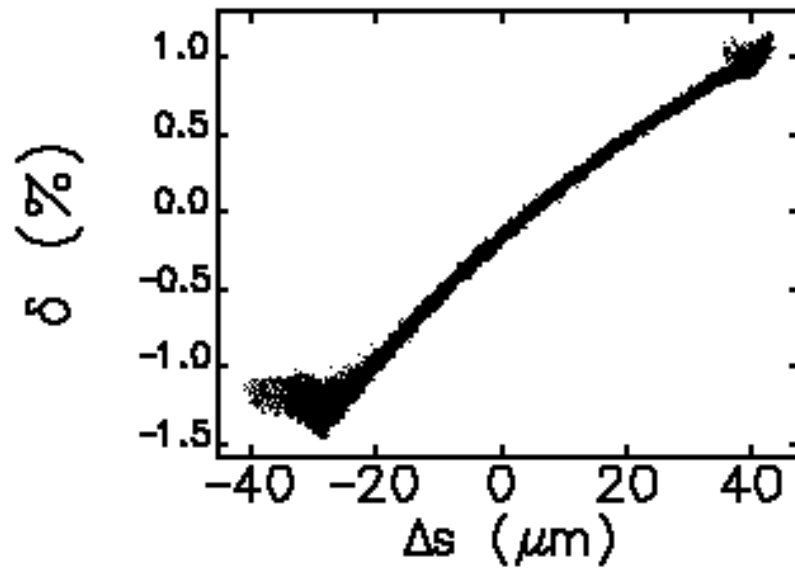
$\langle \delta \rangle = -0.4341\%$

$SD(\delta) = 0.7210\%$

$SD(\Delta s) = 21.9225 \mu\text{m}$



0.5nC Uniform Beam at 0.5GeV



Case: withCSR-0.5GeV-UC-0.5nC

Location: end

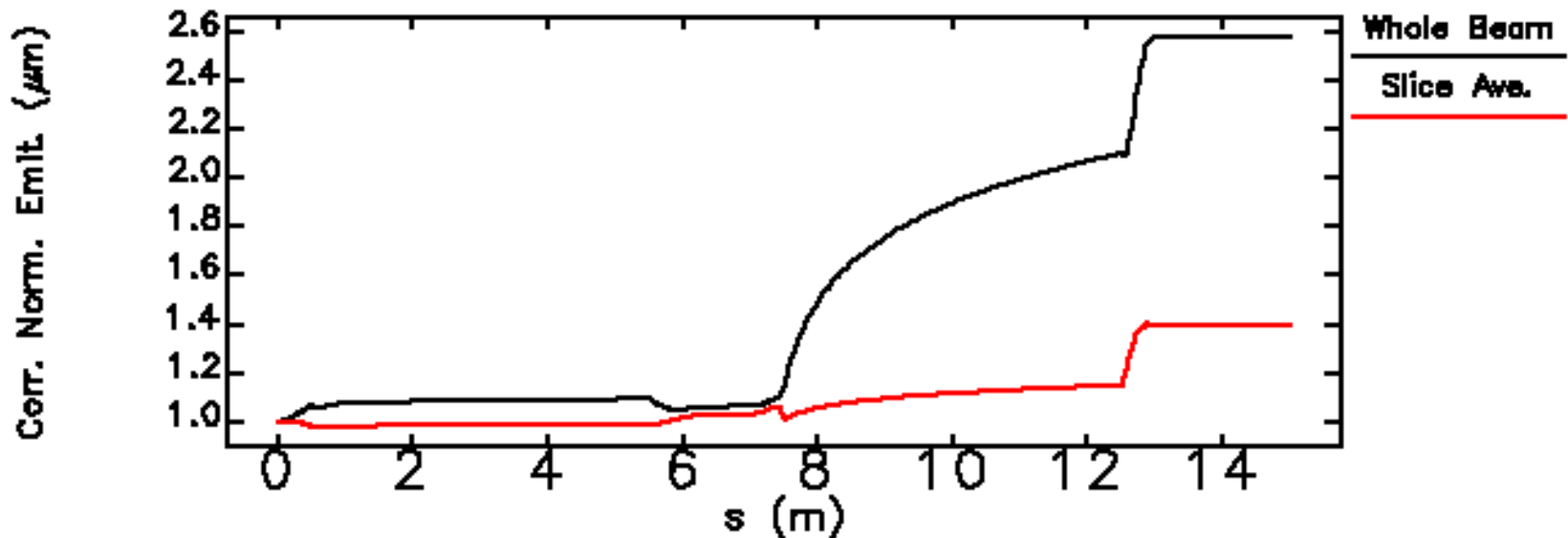
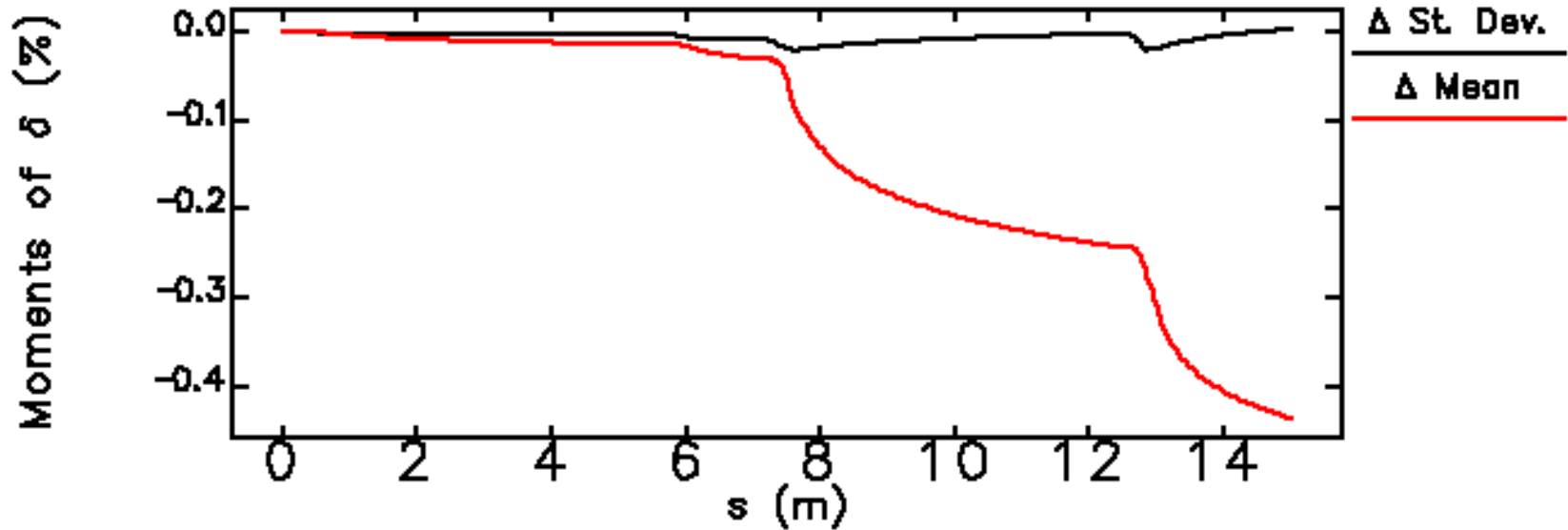
$\langle \delta \rangle = -0.2205\%$

$SD(\delta) = 0.7148\%$

$SD(\Delta s) = 20.9035 \mu\text{m}$

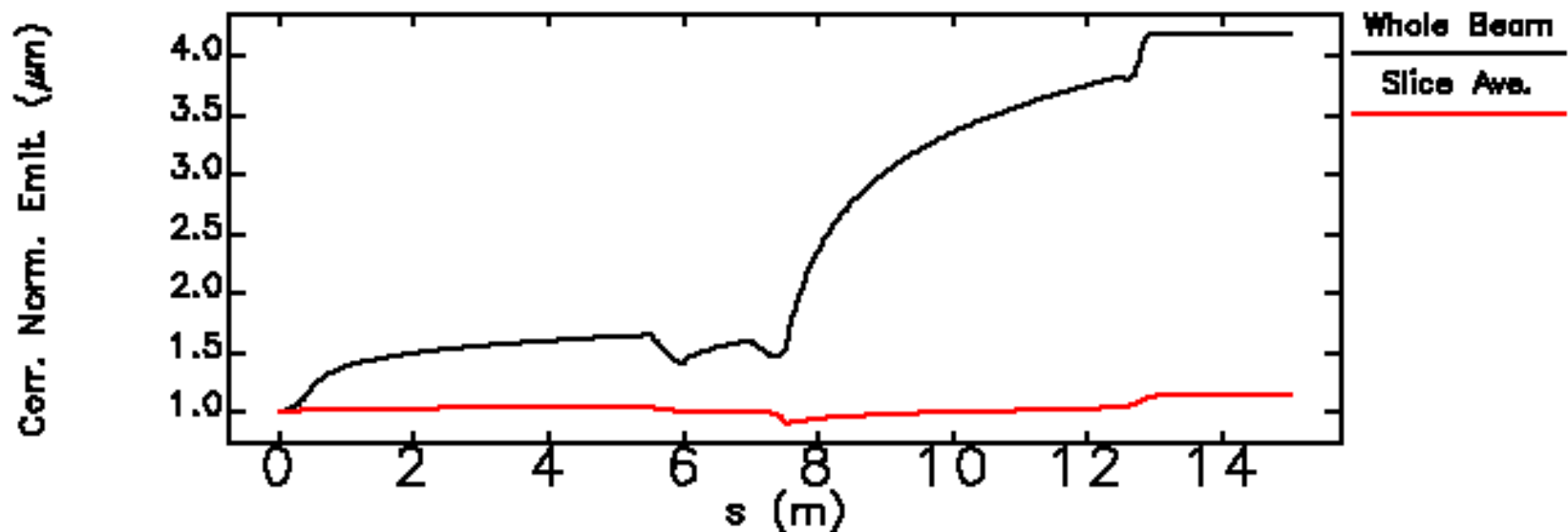
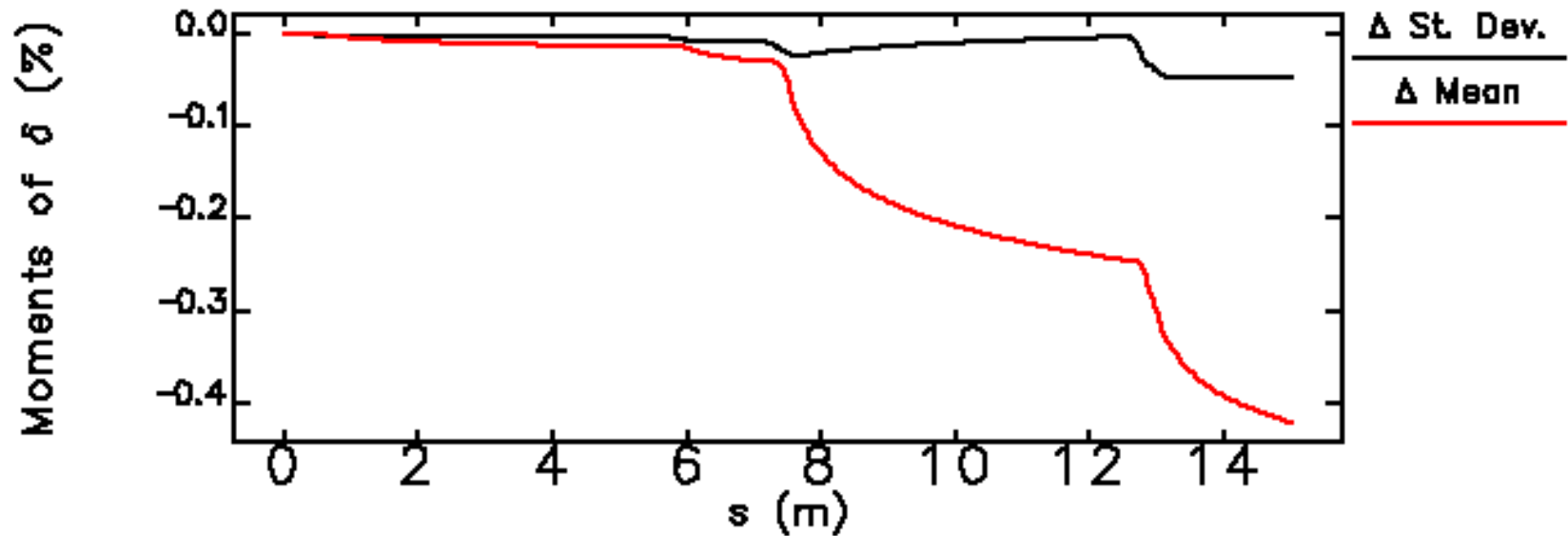


1.0nC Uniform Beam at 0.5GeV



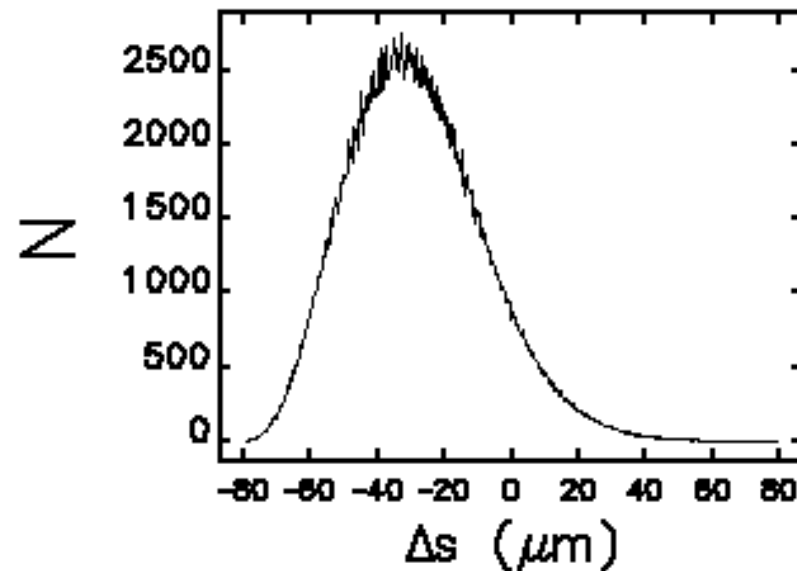
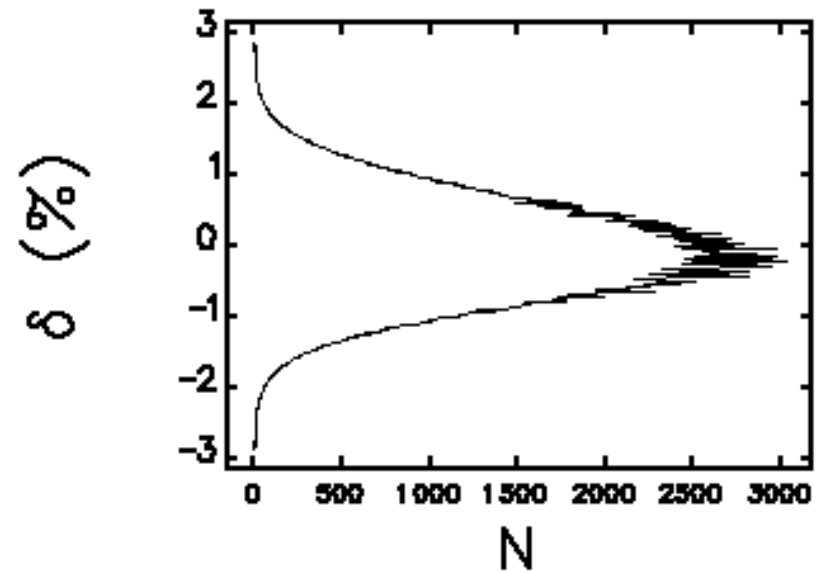
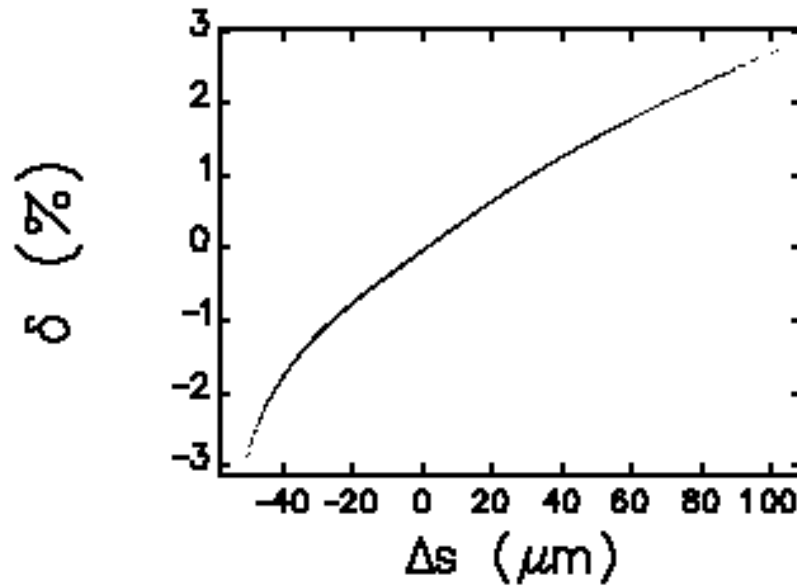
Case with CSR-0.5GeV-UC-1.0nC

1.0-nC Gaussian Beam at 0.5GeV (again)



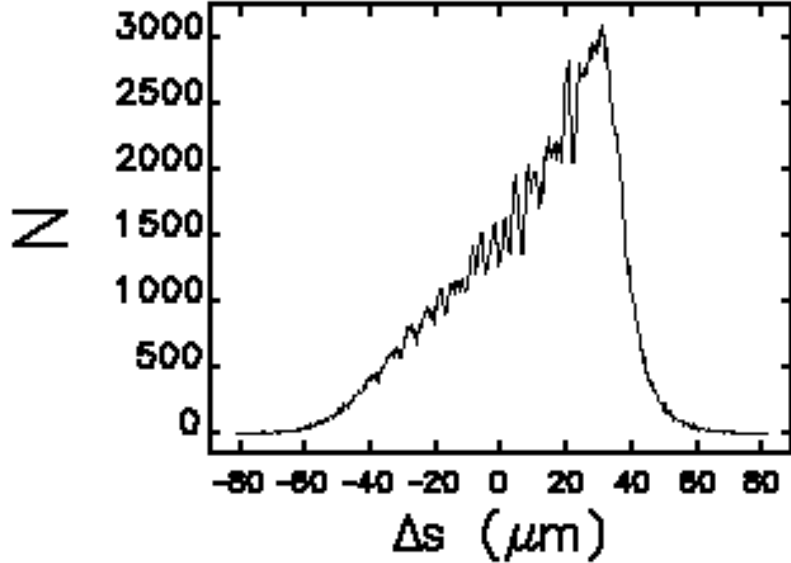
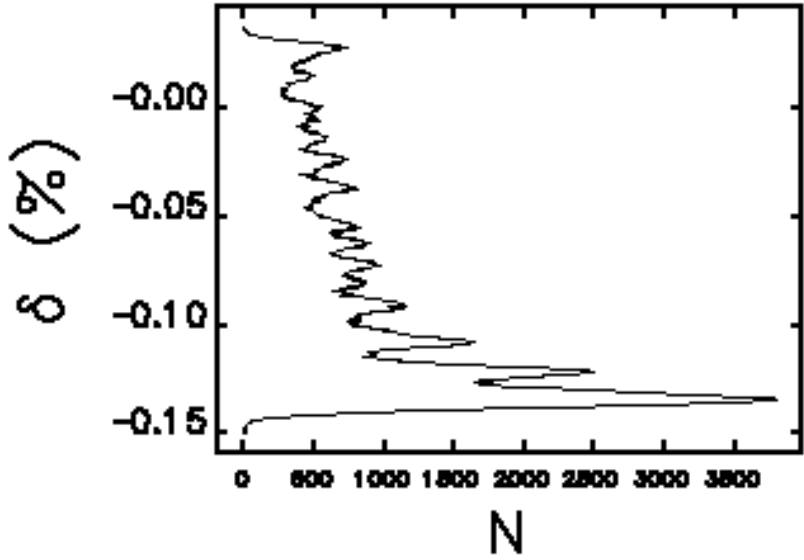
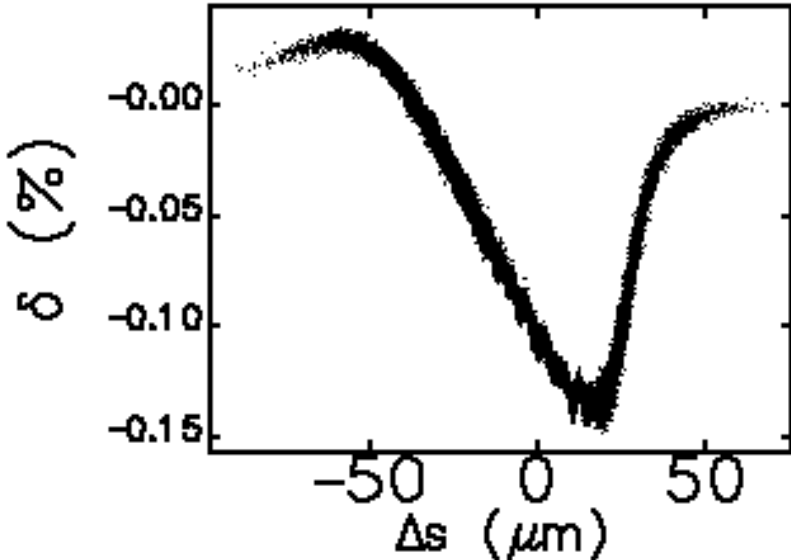
Case with CSR-0.5GeV-GC-1.0nC

1.0-nC Gaussian Beam at 5 GeV



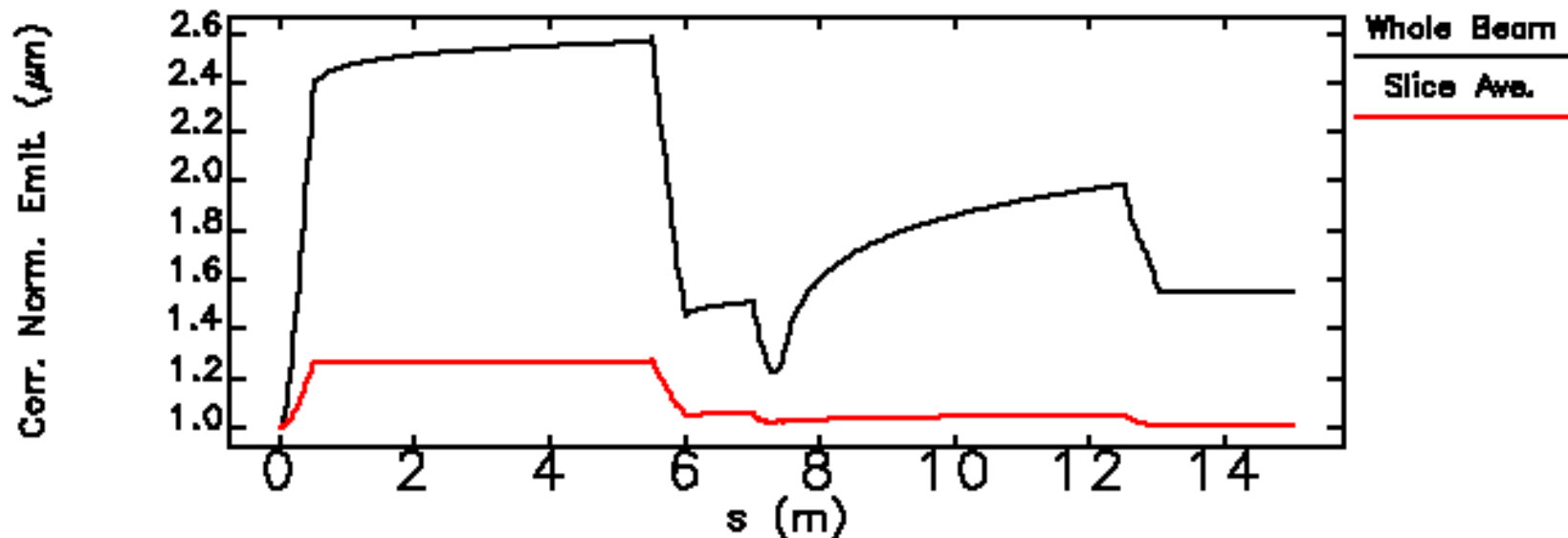
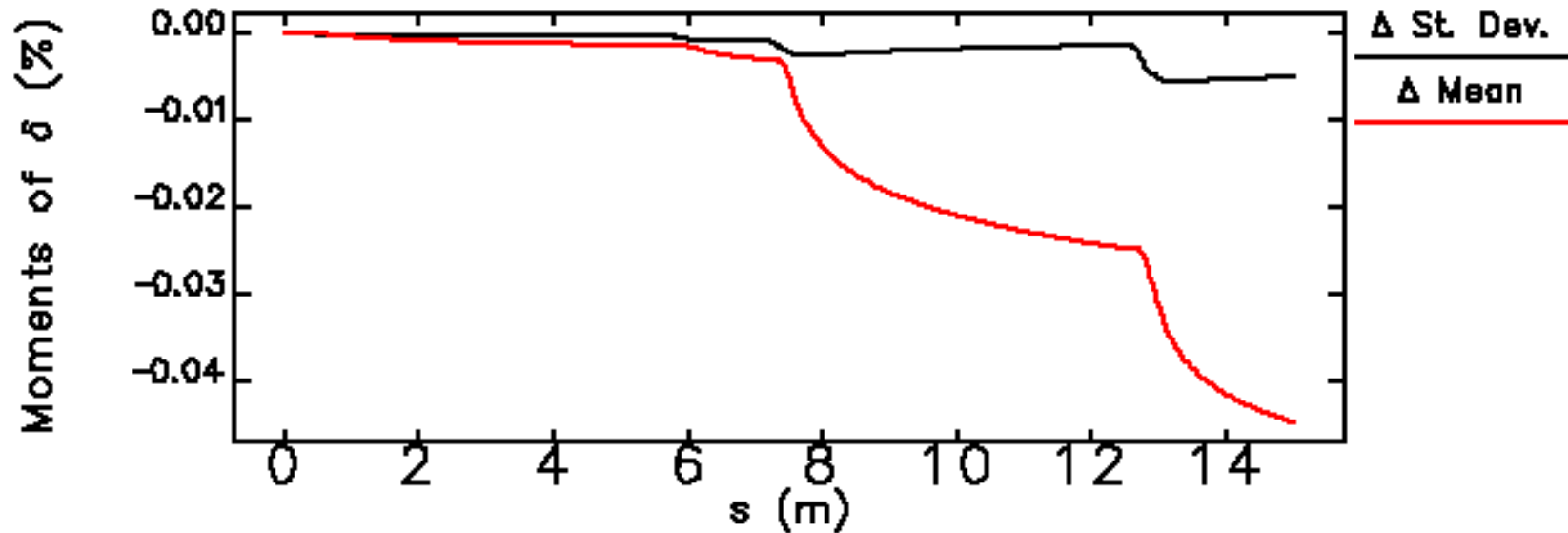
Case: withCSR-5.0GeV-GC-1.0nC
Location: end
 $\langle \delta \rangle = -0.0431\%$
 $SD(\delta) = 0.7124\%$
 $SD(\Delta s) = 20.2323 \mu\text{m}$

1.0-nC Gaussian Beam at 5 GeV w/o Chirp



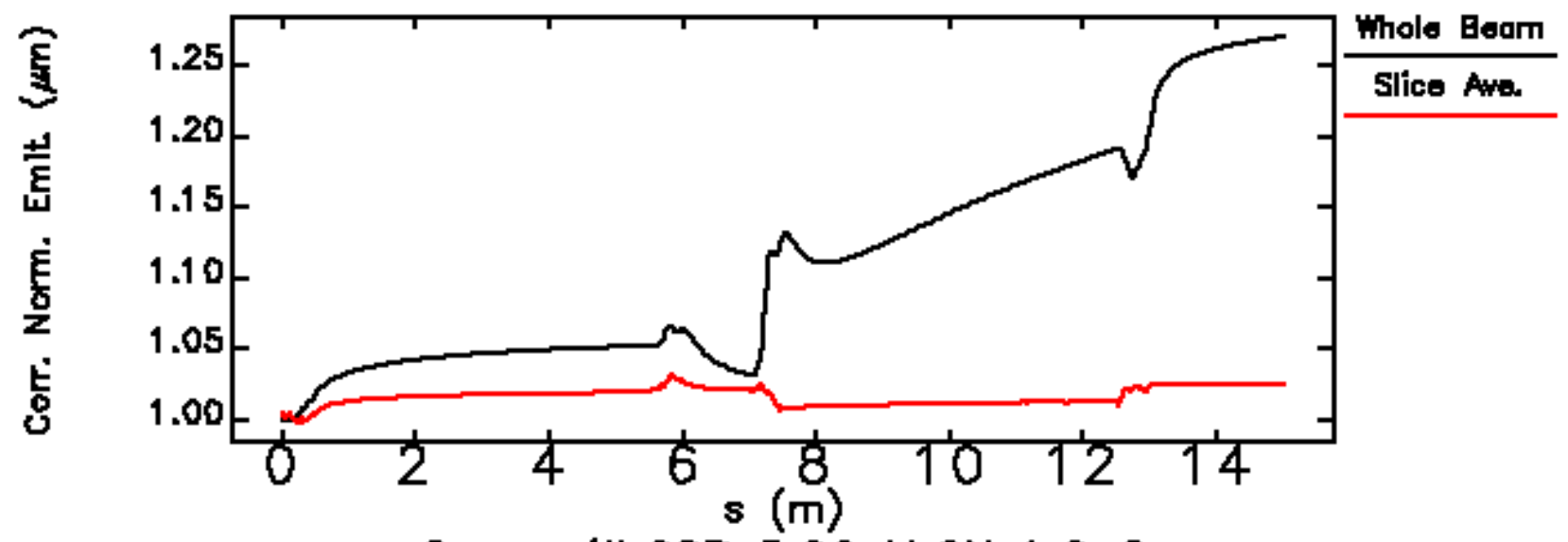
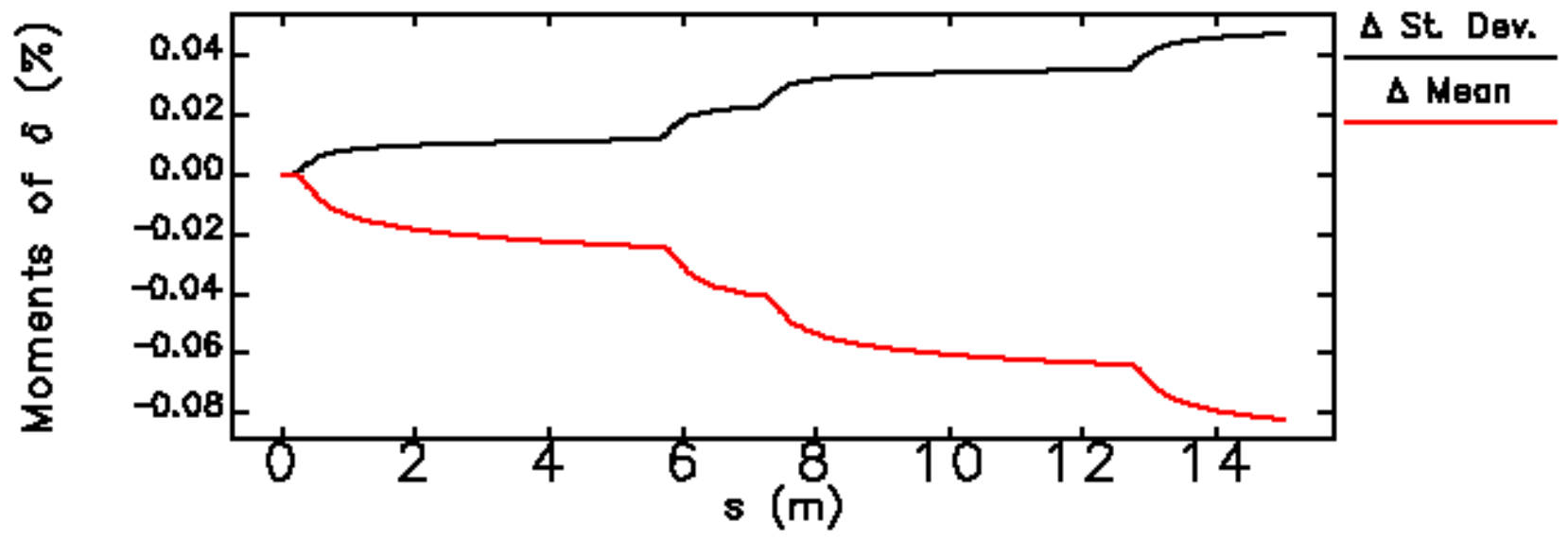
Case: withCSR-5.0GeV-GN-1.0nC
Location: end
 $\langle \delta \rangle = -0.0826\%$
 $SD(\delta) = 0.0495\%$
 $SD(\Delta s) = 23.1829 \mu\text{m}$

1.0-nC Gaussian Beam at 5 GeV



Case with CSR-5.0GeV-GC-1.0nC

1.0-nC Gaussian Beam at 5 GeV w/o Chirp



Case with CSR-5.0GeV-GN-1.0nC

Summary

- Relevant features of **elegant** were reviewed
- Simple test with steady-state CSR and gaussian beam looks good
- About 600 bins for 0.5 million particles gives reliable results
- Comparisons among different cases generally make sense
- Uniform-beam benchmark case is ill-defined