Beam Profile Broadening in PSR due to Transverse Space Charge: Simulation and Comparison with Experiment

SNS/ORNL/AP TECHNICAL NOTE

Number 009

J. D. Galambos
S. Danilov
D. Jeon
J. A. Holmes
D. K. Olsen
Oak Ridge National Laboratory

F. Neri
M. Plum
Los Alamos National Laboratory

December 13, 1998

Spallation Neutron Source Project
Oak Ridge National laboratory
PO Box 2009 MS 8218
Oak Ridge TN 37831

Beam Profile Broadening in PSR due to Transverse Space Charge: Simulation and Comparison with Experiment

J. Galambos, S. Danilov, D. Jeon, J.A. Holmes, D. K. Olsen Oak Ridge National Laboratory; F. Neri, M. Plum, Los Alamos National Laboratory

The effect of space charge in broadening the transverse beam profile with increasing beam intensity is examined in this note. A series of experimental measurements of transverse beam profiles was performed on the PSR facility [1] for different injected particle intensities, but otherwise similar conditions. Transverse broadening of the beam was observed with increasing injected particle intensity. The experimental measurements were simulated using an injection and tracking code, both with and without a transverse space charge model. Comparison of these calculations shows that the effect of transverse space charge forces is to smooth and broaden the calculated beam profiles. When the transverse space charge model is employed, the calculated beam profiles reproduce the experimental beam profiles well.

1 The experiment

Experimental beam profiles were obtained from the Proton Storage Ring [1] (PSR) at the Los Alamos Neutron Science Center (LANSCE). The PSR is a storage ring, with injection from an 800 MeV linac. Injection was carried out for a duration of 825 μsec for three cases. Subsequently, the beam was extracted in a single turn and transported to a wire scanner beam profile diagnostic. These cases were identical except for the accumulated particle intensity, which was varied by injecting the linac beam (a) every turn (count down = 1), (b) every-other turn (countdown = 2), and (c) every fourth turn (countdown = 4). The runs were performed on Sept. 8, 1998, and the beam profile measurements used here were taken from the ROWS02 wire scanner diagnostic.

2 The simulation

The aim of this note is to compare calculated and experimentally observed emittances in PSR. The SAMBA tracking code was used to perform the calculations while simulating the actual injection scheme. The injection parameters are described in Table 1. Both transverse and longitudinal space charge effects are included in the simulations. The space charge calculation involves a Particle-in-Cell (PIC) method, which includes distributing the macro-particles to the nodes of a rectangular grid and then using an FFT method on that grid to approximate the full nonlinear space charge force [2]. The beam is tracked for the full injection cycle, with the parameters described in Table 1. After 2305 injection turns (or 825 μsec) the beam is tracked from the injection foil to the ROWS02 wire scanner, and then distributed to a transverse grid with number and spacing chosen to match ROWS02, which was used to make the measurements.

In the calculations, 50 macro-particles per turn were injected, resulting in 115,250 macro-particles at the end of injection. A 128x128 grid in the transverse plane for the PIC binning was used, and 197 space charge kicks per turn (~ 45 cm longitudinal distance per kick) were used. This step size was found to be small enough for convergence in previous studies.

3. The comparison

The experimental data for comparison were taken from ROWS02 of the PSR. Because the transverse location of the wire scanner is not precisely known, the center of the calculated distribution was assumed to match that of the experimental data. Also the vertical scale of the calculated distribution is a free parameter and is adjusted so that the calculated centroid height matches that from the wire scanner data. The width and shape of the calculated distribution were not adjusted. Measurements were made for two injection scenarios, both with and without vertical bump painting. No closed orbit bump was used in the horizontal direction.

3.1 Injection with Vertical Bump Painting

Figure 1 shows the comparison of the horizontal beam profiles for three beam intensities, for the case with a painted vertical bump. The calculated profiles are in good agreement with the measured profiles, and the effect of increasing beam intensity on the shape of the distribution is small. Figure 2 shows the comparison for the vertical distributions for the same case. The vertical beam profiles are observed to broaden and to fill in, becoming less "hollow", with increasing intensity, for both the calculated and experimental distributions. While the agreement is extremely good at low intensities, at the level of $3x10^{13}$ particles the experimental distribution shows more broadening. There is still a slight hollowness in the calculated distribution, whereas the experimental profile is centrally peaked at the full intensity. The measured distributions are broader than the calculated distributions.

The inclusion of transverse space charge effects in these calculations contributes significantly to the goodness of the profile comparisons shown in Fig. 2. For example, Fig. 3 shows the comparison of the experimental and calculated data at full intensity, both with and without transverse space charge effects. The vertical beam profile calculated without space charge is significantly different from that observed experimentally.

The discrepancy between the calculated and experimental vertical size broadening with intensity is more evident when a logarithmic scale is used, as shown in Fig. 4. This figure shows the horizontal and vertical distributions at the lowest and highest intensities. The experimentally observed broadening of the vertical beam size with increasing beam intensity, and the underestimate of this effect by the calculation are evident. Because this discrepancy occurs at both low and high intensity, it may be caused by other effects, such as magnet errors or wall impedance effects, that are not included in the present calculations. Because accurate calculation of the growth of the beam tails is important for predicting beam halo, these effects are being incorporated into SAMBA.

3.2 Injection with No Vertical Painting

The cases described above were repeated without vertical bump painting, resulting in more hollow distributions. Figure 5 shows the horizontal profile comparison for the three intensities. As before, the agreement is good, but there is not a dramatic dependence of the profile shape on intensity. The calculated profile underestimates slightly the broadening at high intensities. Figure 6 shows the vertical profile comparisons for these cases. The beam profile fills in noticeably with increasing intensity for both the measured and calculated distributions. However, the calculated profiles are again slightly less broad than the experimental distributions.

Figure 7 shows the results at full intensity, calculated both with and without space charge. It is obvious that, although it does not fully account for the amount of beam broadening, transverse space charge does explain most of this effect.

3.3 Numerical Sensitivities

Sensitivity of the calculated beam profiles to the number of transverse grid points and the number of macro-particles is shown in Fig. 8. Typically, about 10 macro-particles per grid cell are used, and we compare results with different grid sizes. Although increasing the number of grid points helps resolve the beam shape in the center of the distribution, even with a smaller number of grid points there is general agreement between the calculated and experimental bean profile data.

All the calculations shown in Fig. 8 included a smoothing parameter of length equal to one grid size in the PIC force calculation[2]. This parameter was intended to smooth out any non-physical interaction of near-neighbor macro-particles. Figure 9 shows the sensitivity of the results to the value of the smoothing parameter as it is progressively decreased to zero. There is little impact of setting the smoothing parameter to zero. When a sufficient number of particles (at least 10) per PIC cell is used, additional smoothing is not necessary. All the cases in sections 3.1 and 3.2 were calculated with the smoothing parameter set to zero.

4 Observations on the Comparison

Overall, the agreement between the measured and calculated transverse profiles is quite good. There is a noticeable broadening of the vertical distribution with increasing beam intensity in both the experimental data and calculated profiles. There is much less impact on the horizontal profiles with increasing intensity, both for the experimental and calculated profiles. While the experimentally observed beam broadening is well reproduced, the calculated profiles underestimate the amount of edge profile broadening at higher intensities, particularly in the vertical direction. This may be due to uncertainties in the experimental setup. For example, the Linac intensity could be 10-20% larger than assumed in the simulation, or the closed orbit offset of 16.6mm assumed here could be higher. The difference may also be attributable to effects not included in the model, for example magnet errors and wall impedance effects.

References

1. D. Fitzgerald et.al. “Overview and Status of the Los Alamos PSR Injection Upgrade Project”, PAC conference proceedings, Vancouver CA, 1997, http://www.triumf.ca/pac97/papers/pdf/9W021.PDF

2 J. A. Holmes, J. D. Galambos, D. Jeon, D. K. Olsen, J. W. Cobb, “Dynamic Space Charge Calculations for High Intensity Beams in Rings”, Proceedings of the ICAP conference, Monterey CA, Sept. 1998.

Table 1. Input parameters for the simulation.

Injection period	825 μsec
Injection turns	2305
Injected particles/turn	1.3×10^{10}
Linac beam location relative to closed orbit	Horizontal: 3.85mm , -0.95 mrad Vertical: 16.64mm, 2.68 mrad
Horizontal closed orbit bump at foil	None
Vertical closed orbit bump at foil	None, or $12 \rightarrow 0$ mm and $1.65 \rightarrow 0$ mrad
RF	Single harmonic, ramped from 8 to 17 kV during injection
Ring Injection β_x, α_x, D_x	2.77 m, 0.63, 1.42m
β_y, α_y	10.93 m, -1.43
Linac β_x, α_x	1.25 m, 0.
β_y, α_y	3.20, 0.
Linac horizontal distribution:	Bi-gaussian, 30% with $\varepsilon_{2\sigma} = 0.33\ \pi$ mm-mrad 70% with $\varepsilon_{2\sigma} = 1.0\ \pi$ mm-mrad
Linac vertical distribution:	Bi-gaussian, 40% with $\varepsilon_{2\sigma} = 0.33\ \pi$ mm-mrad 60% with $\varepsilon_{2\sigma} = 1.0\ \pi$ mm-mrad
Linac longitudinal distribution:	50 Bi-uniform bunches separated by 4.969 degrees each. Each bunch has: 70% within .025 degrees and 8 MeV 30% within 1.0 degree and 32 MeV

Figure 1. Comparison of the calculated and measured horizontal distributions, for three beam intensities and injection with vertical painting.

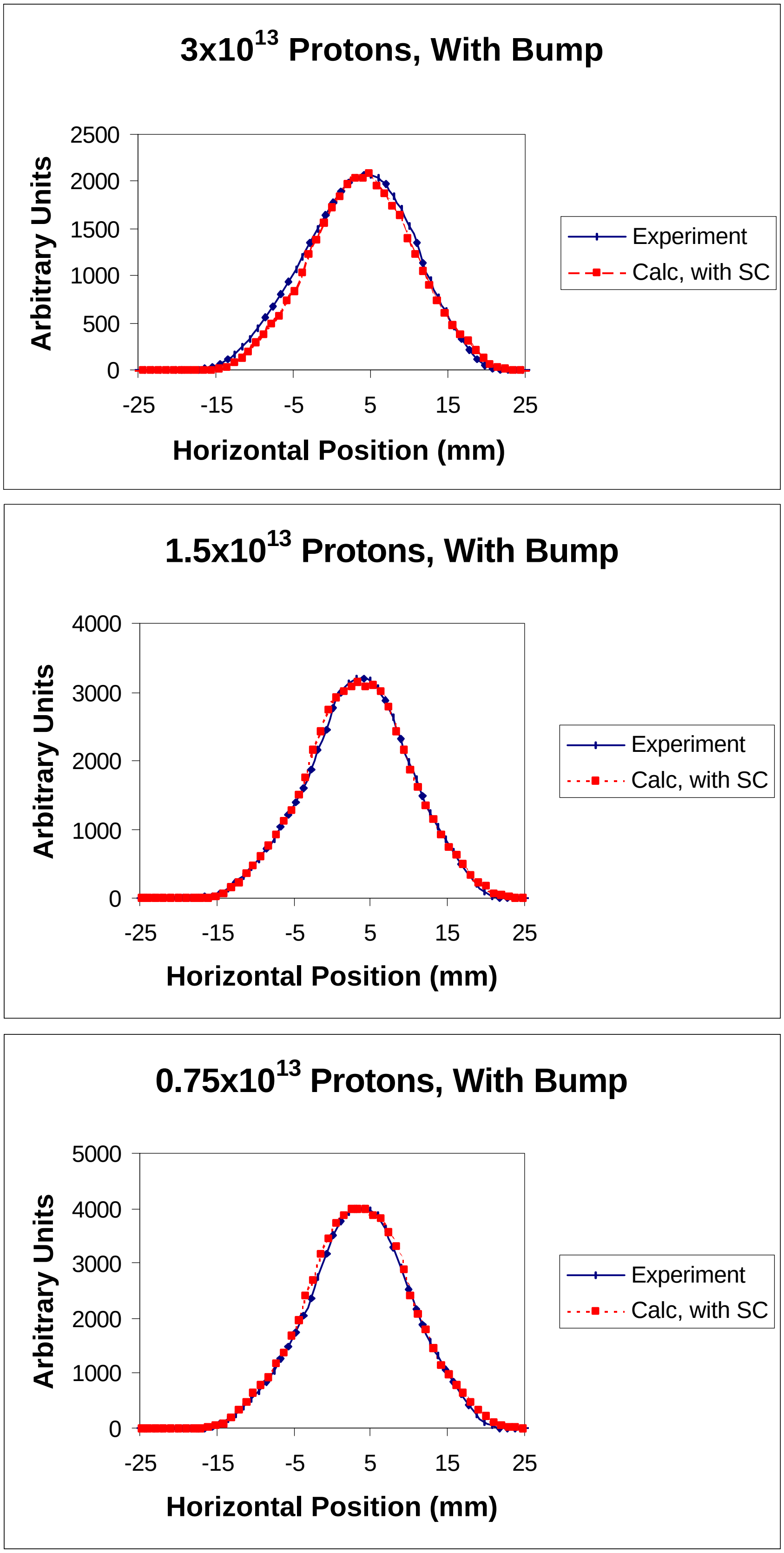


Figure 2. Comparison of the calculated and measured vertical distributions, for three beam intensities and injection with vertical painting.

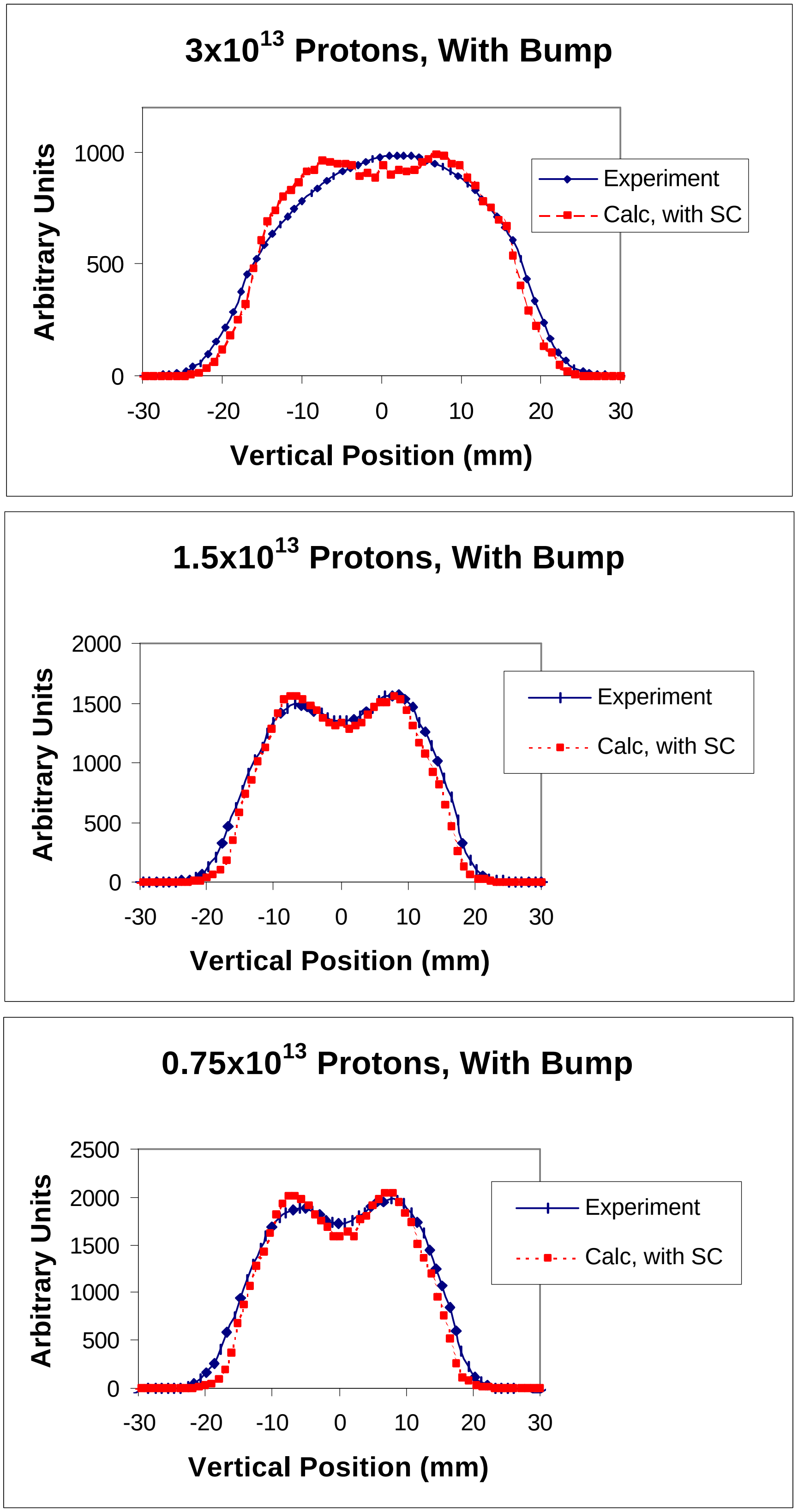
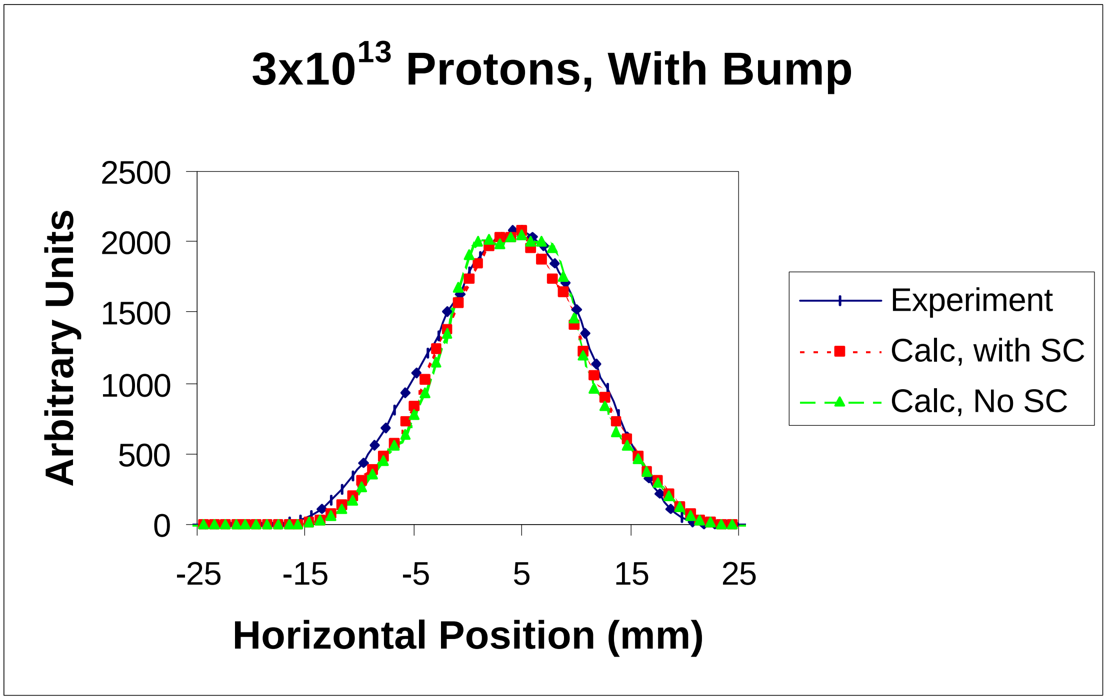


Figure 3. Comparison of the experimental data with the simulation, with and without space charge for injection with vertical painting.



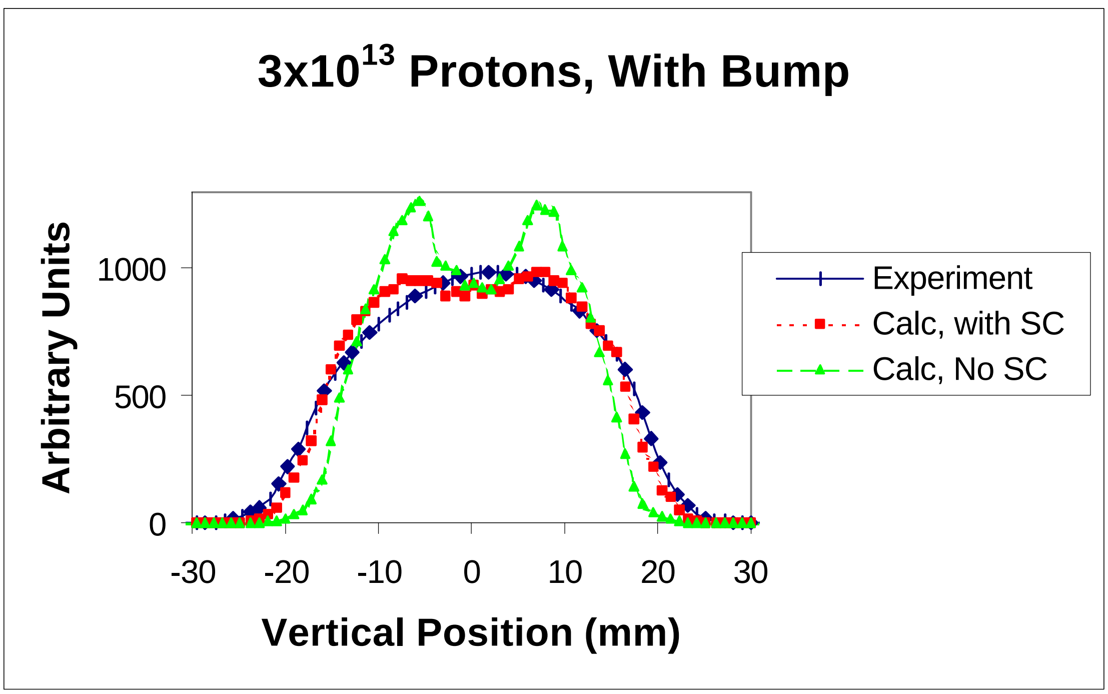


Figure 4. Horizontal and vertical distributions for injection with vertical bump painting at high and low intensities.

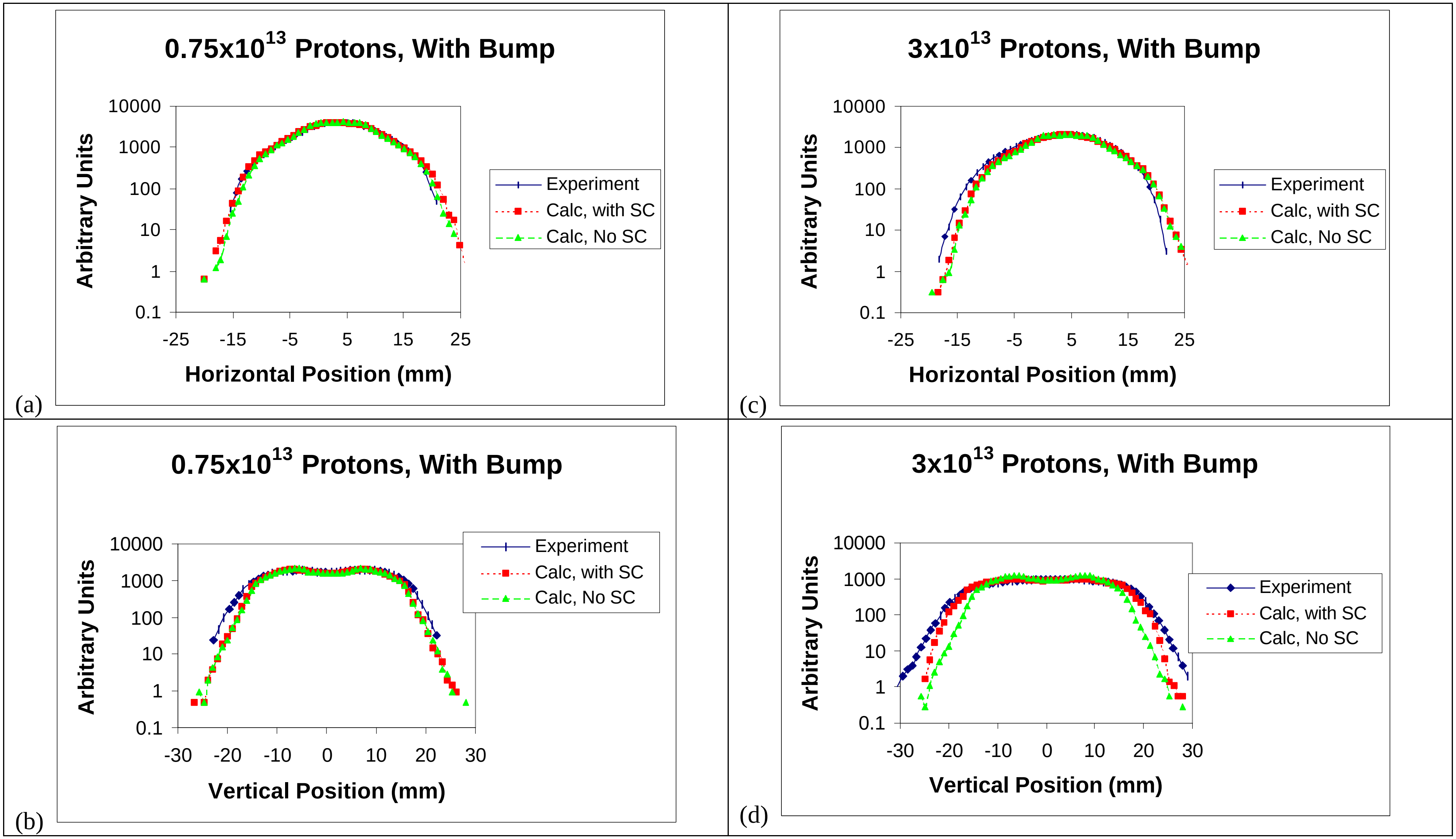


Figure 5. Comparison of calculated and measured horizontal distributions, for three beam intensities and injection without vertical bump painting.

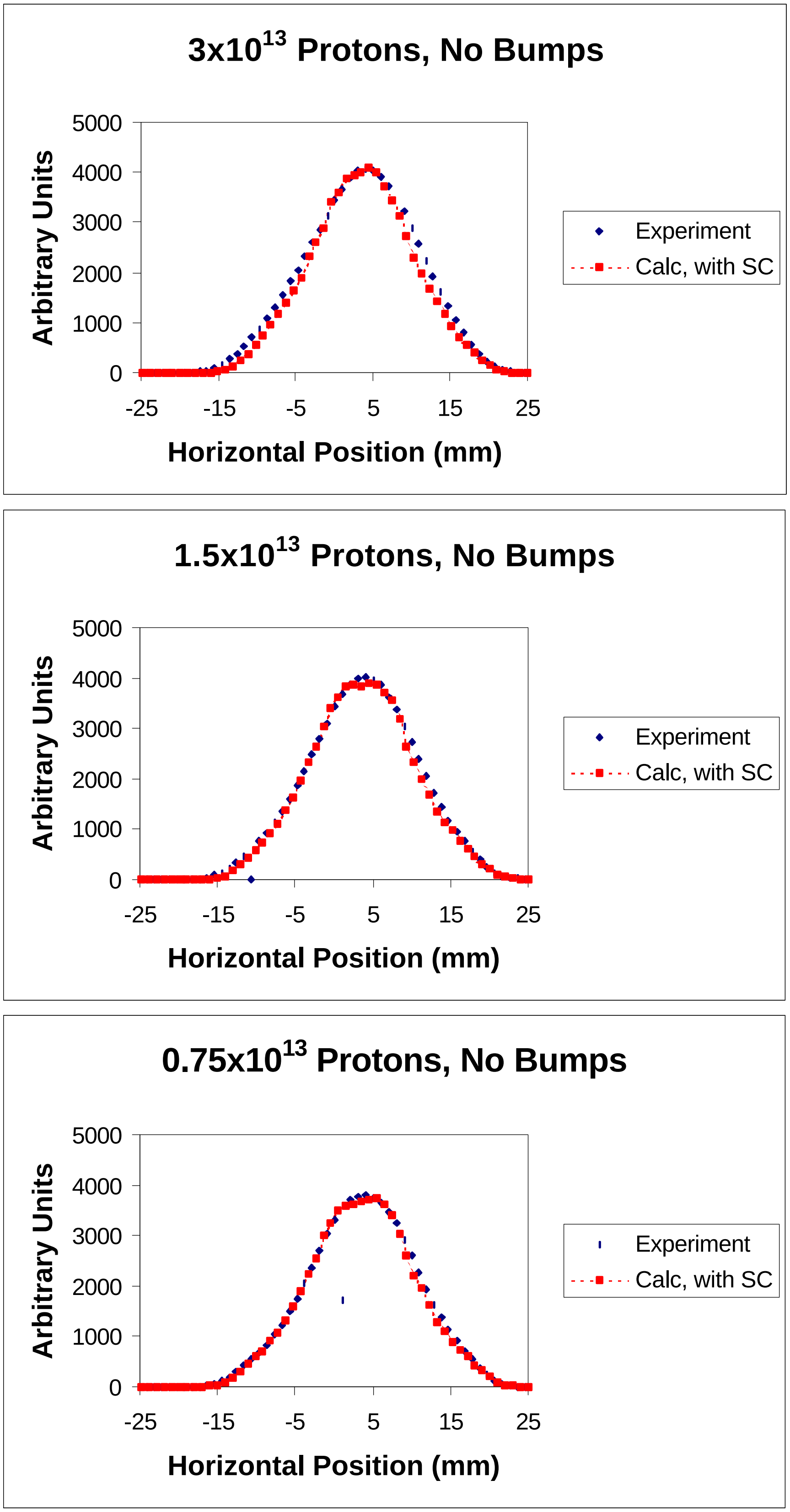


Figure 6. Comparison of calculated and measured vertical distributions, for three beam intensities and injection without vertical bump painting.

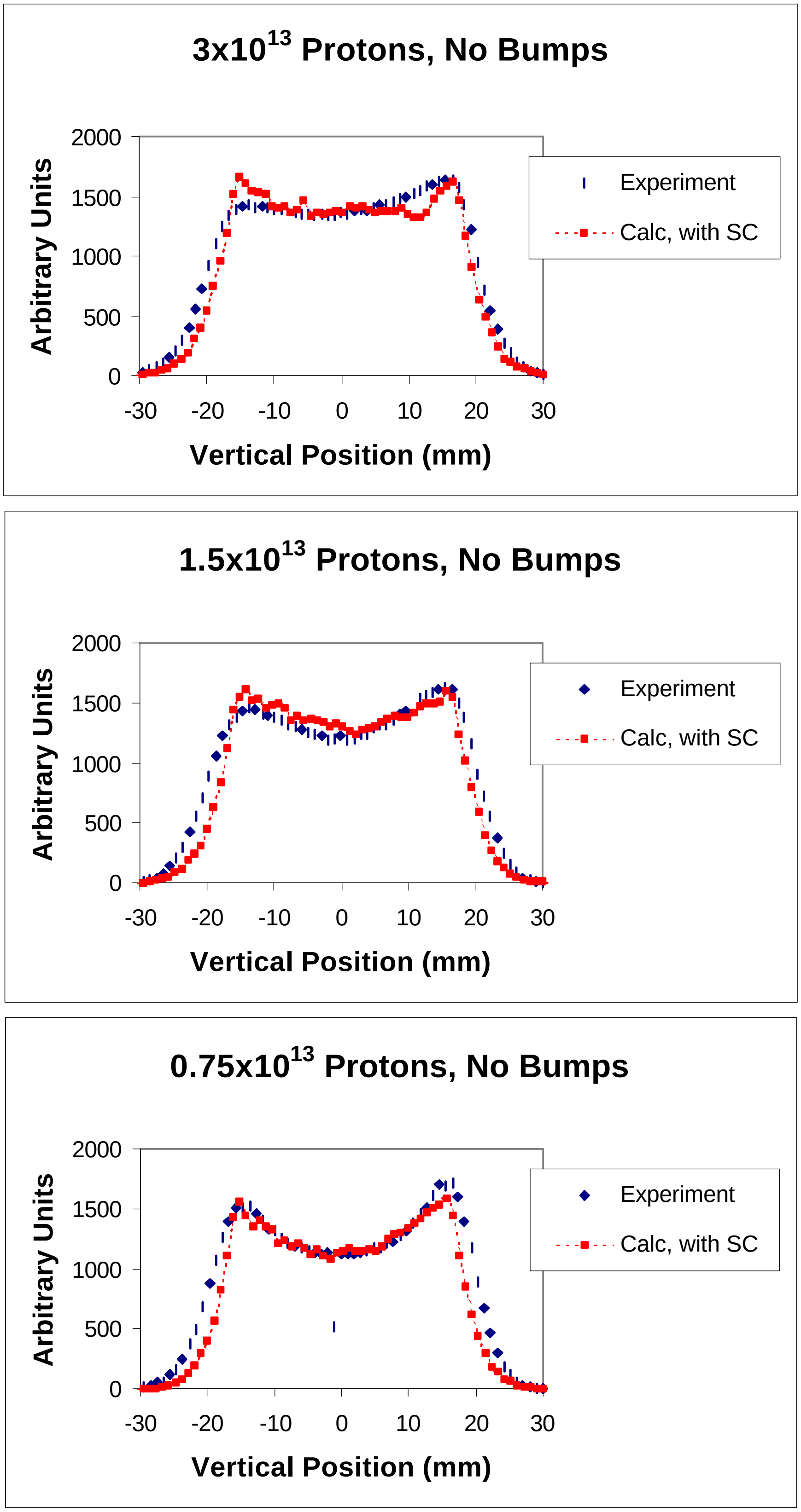


Figure 7. Comparison of the experimental data with the simulation, with and without space charge for injection without vertical painting.

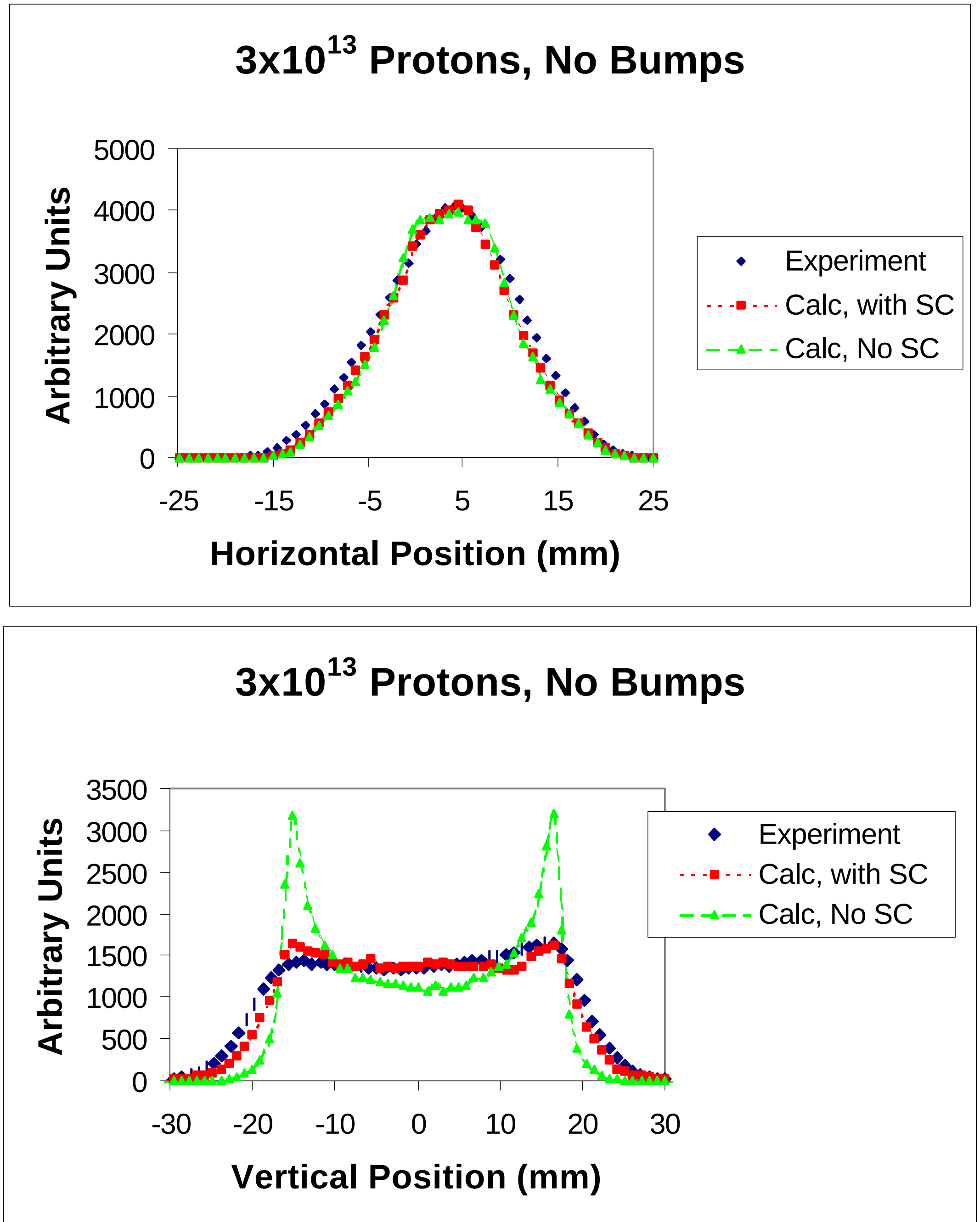


Figure 8. Comparison of calculated and experimental vertical beam profiles for various numerical resolutions: (a) 23,050 macro-particles and a 32x32 grid, (b) 46,100 macro-particles and a 64x64 grid, and (c) 115,250 macro-particles and a 128x128 grid. A smoothing parameter equal one grid size was used in all cases. The calculations are for injection with vertical painting.

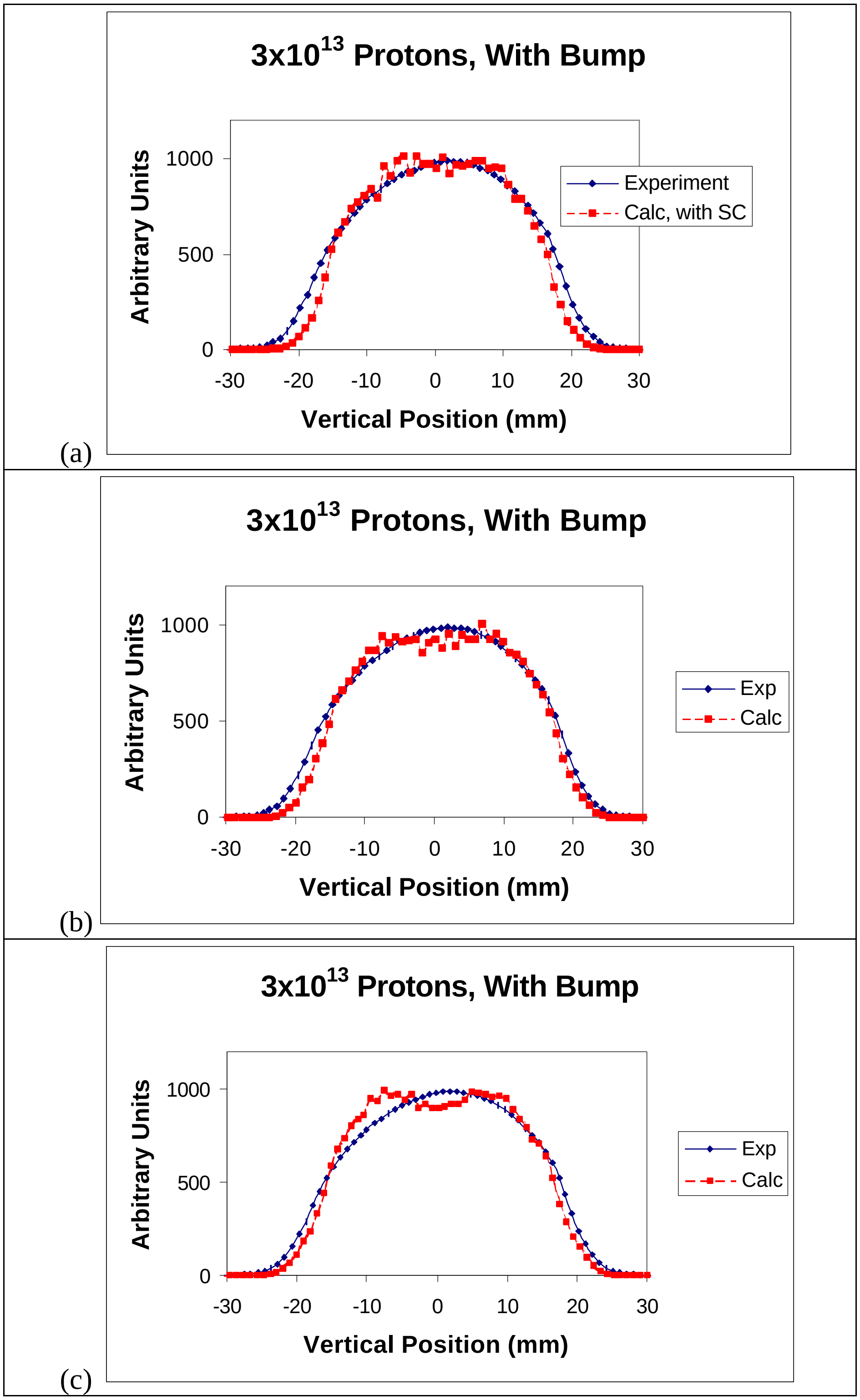
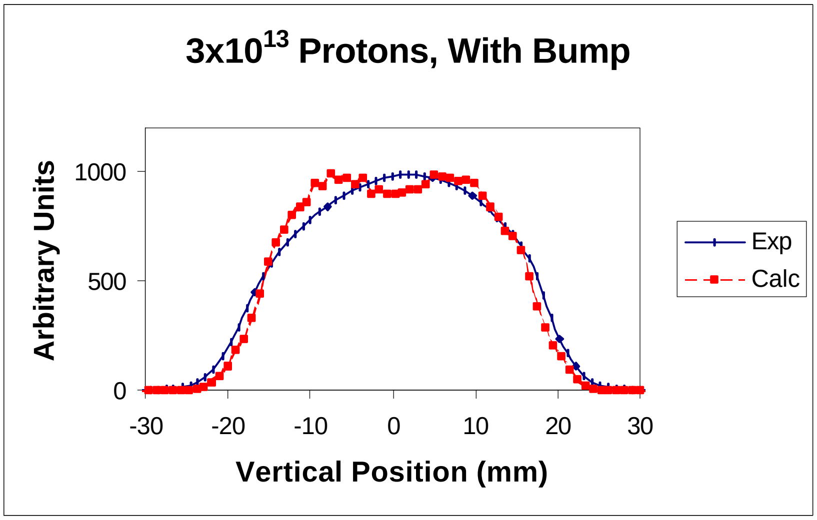
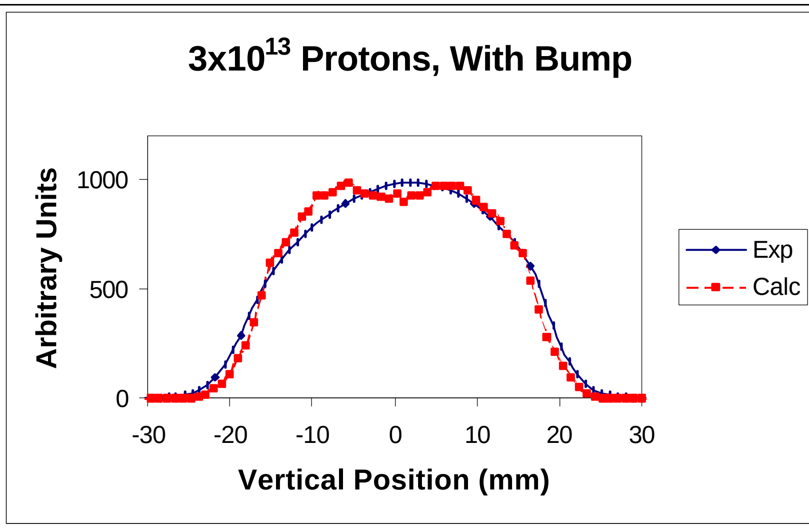


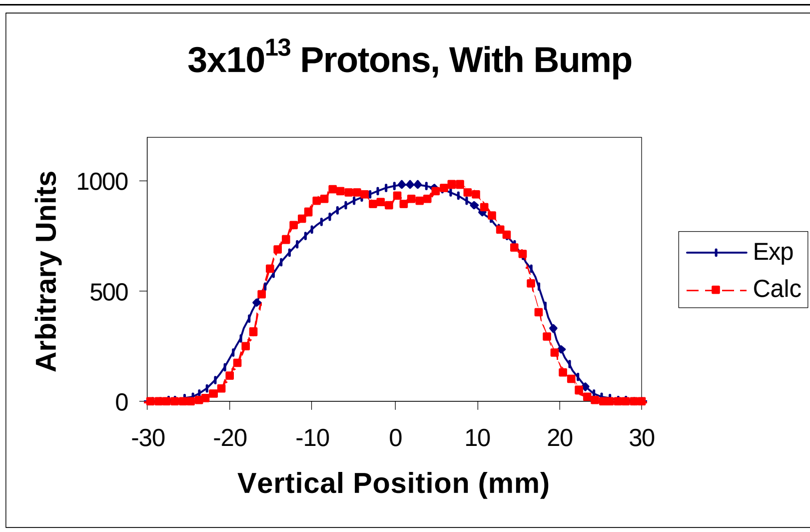
Figure 9. Comparison of calculated and experimental vertical beam profiles for different smoothing parameter values. All cases are for 115,250 macro-particles and a 128 x 128 grid. (a) smoothing parameter = 1 grid size, (b) smoothing parameter = 1/2 grid size, (c) smoothing parameter = 0. Calculations are for injection with vertical painting and $3x10^{13}$ particles.



(a)



(b)



(c)