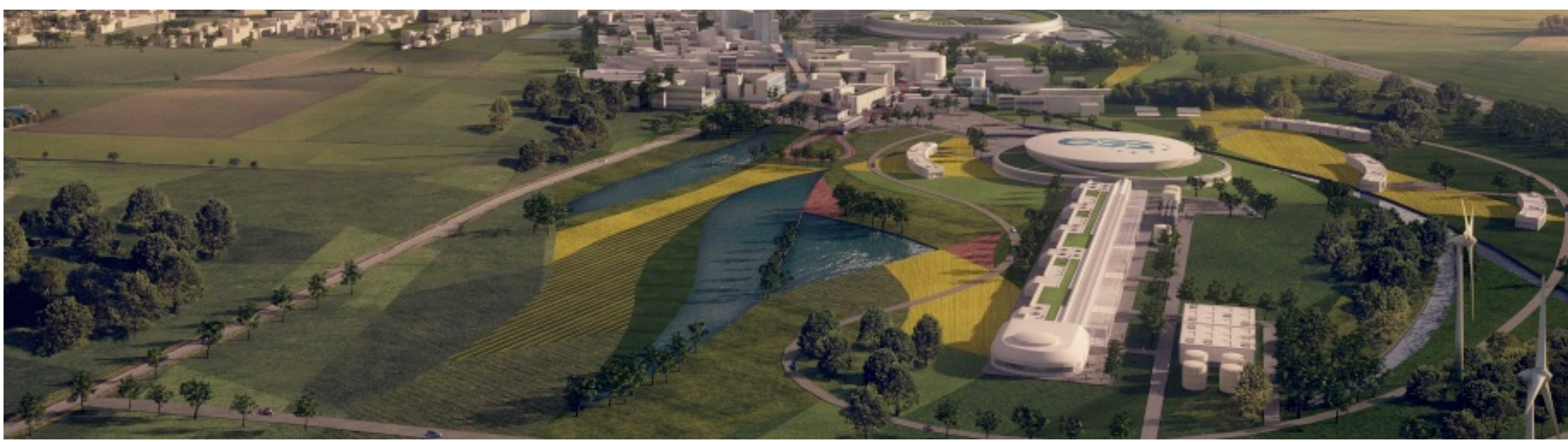
Space Charge 2013

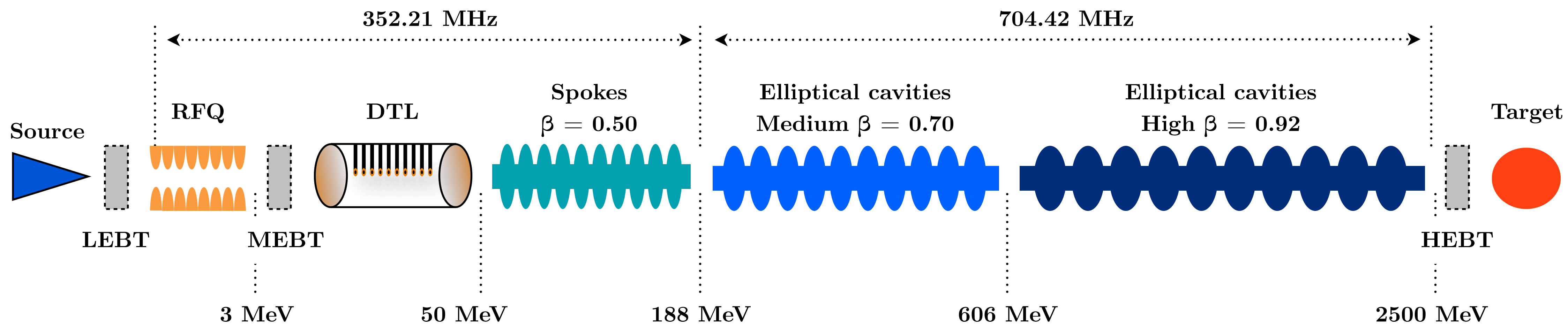
CERN, April 18th 2013

Space Charge studies in the ESS Linac

Emanuele Laface
Physicist
Accelerator Department



ESS Linac Simulator (ELS) Parameters



	TDR 2012	Proposal 2013
Power	5 MW	5 MW
Peak Power	125 MW	125 MW
Peak Current	50 mA	61 mA
Protons per Bunch	$8.87 \cdot 10^8$	$1.08 \cdot 10^9$
Energy	2500 MeV	2077 MeV
Pulse Length	2.86 ms	2.86 ms
Duty Cycle	4%	4%
Transversal Emittance	$0.21 \cdot 10^{-6}$ m·rad	$0.21 \cdot 10^{-6}$ m·rad
Longitudinal Emittance	$0.28 \cdot 10^{-6}$ m·rad	$0.28 \cdot 10^{-6}$ m·rad
Cavities	208	148
Gradient	40 MV/m	44 MV/m
Length	600 m	500 m

Emanuele.Laface@esss.se

Space Charge Model

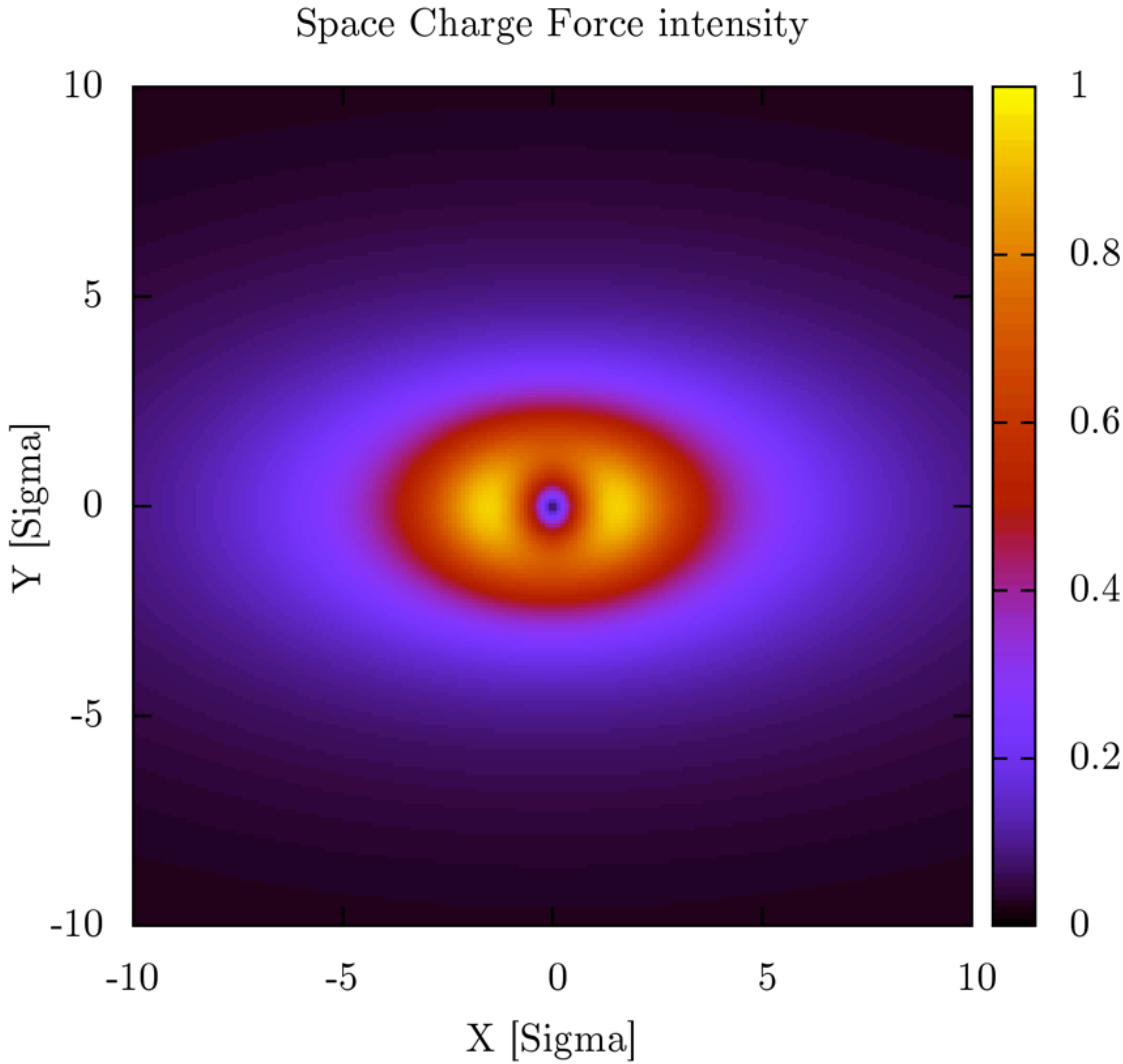
in the laboratory frame

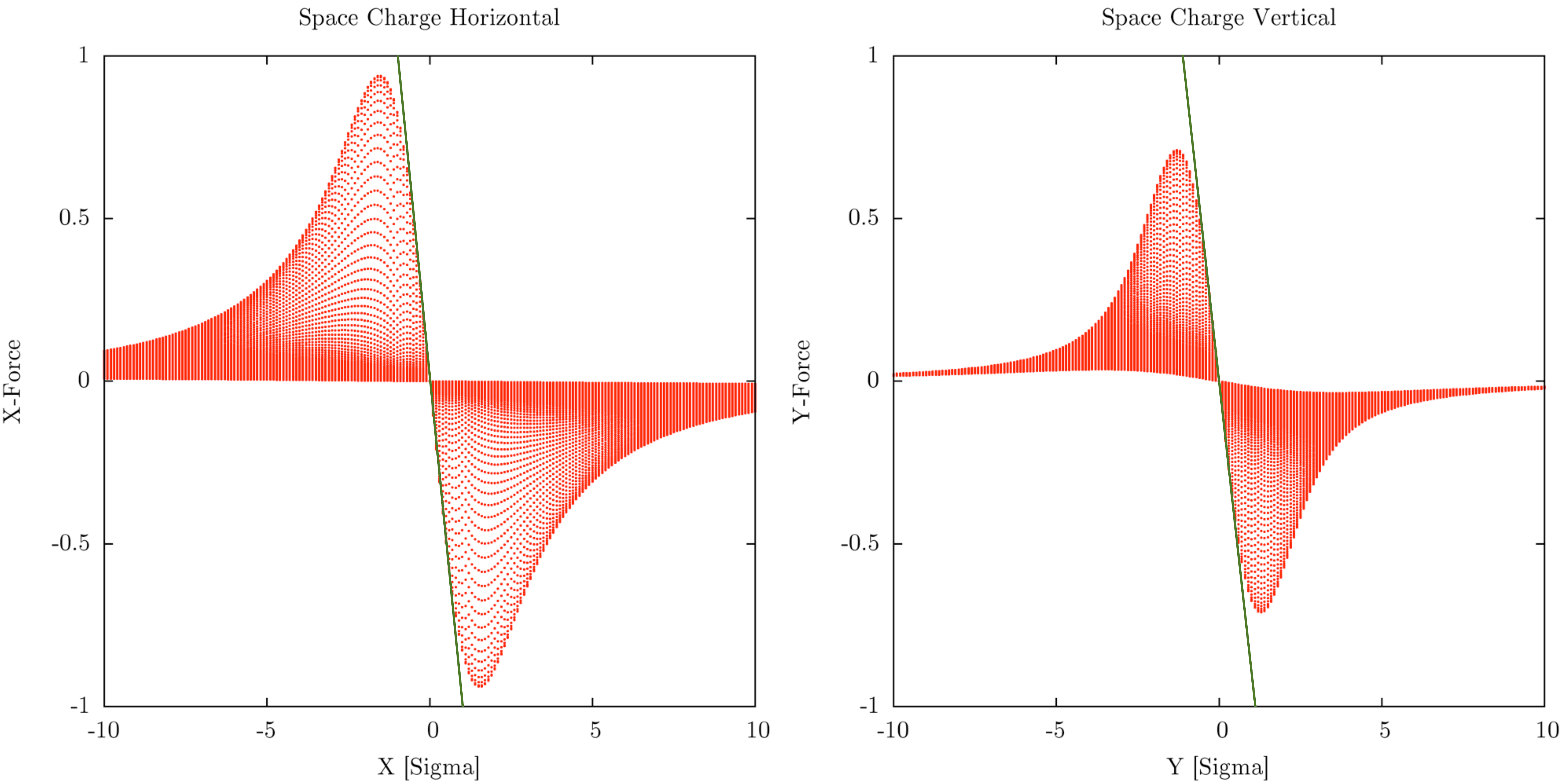
$$U_{sc}(x,y,z) = \frac{eN}{4\sqrt{\pi^3}\epsilon_0\gamma^2}\int_0^\infty \frac{e^{-\frac{x^2}{2\sigma_x{}^2+t}-\frac{y^2}{2\sigma_y{}^2+t}-\frac{z^2}{2\sigma_z{}^2+t}}-1}{\sqrt{(2\sigma_x{}^2+t)(2\sigma_y{}^2+t)(2\sigma_z{}^2+t)}}dt$$

$$F_x = \frac{e^2N}{2\sqrt{\pi^3}\epsilon_0\gamma^2}x\int_0^\infty \frac{e^{-\frac{x^2}{2\sigma_x{}^2+t}-\frac{y^2}{2\sigma_y{}^2+t}-\frac{z^2}{2\sigma_z{}^2+t}}}{\sqrt{(2\sigma_x{}^2+t)^3(2\sigma_y{}^2+t)(2\sigma_z{}^2+t)}}dt$$

$$F_y = \frac{e^2N}{2\sqrt{\pi^3}\epsilon_0\gamma^2}y\int_0^\infty \frac{e^{-\frac{x^2}{2\sigma_x{}^2+t}-\frac{y^2}{2\sigma_y{}^2+t}-\frac{z^2}{2\sigma_z{}^2+t}}}{\sqrt{(2\sigma_x{}^2+t)(2\sigma_y{}^2+t)^3(2\sigma_z{}^2+t)}}dt$$

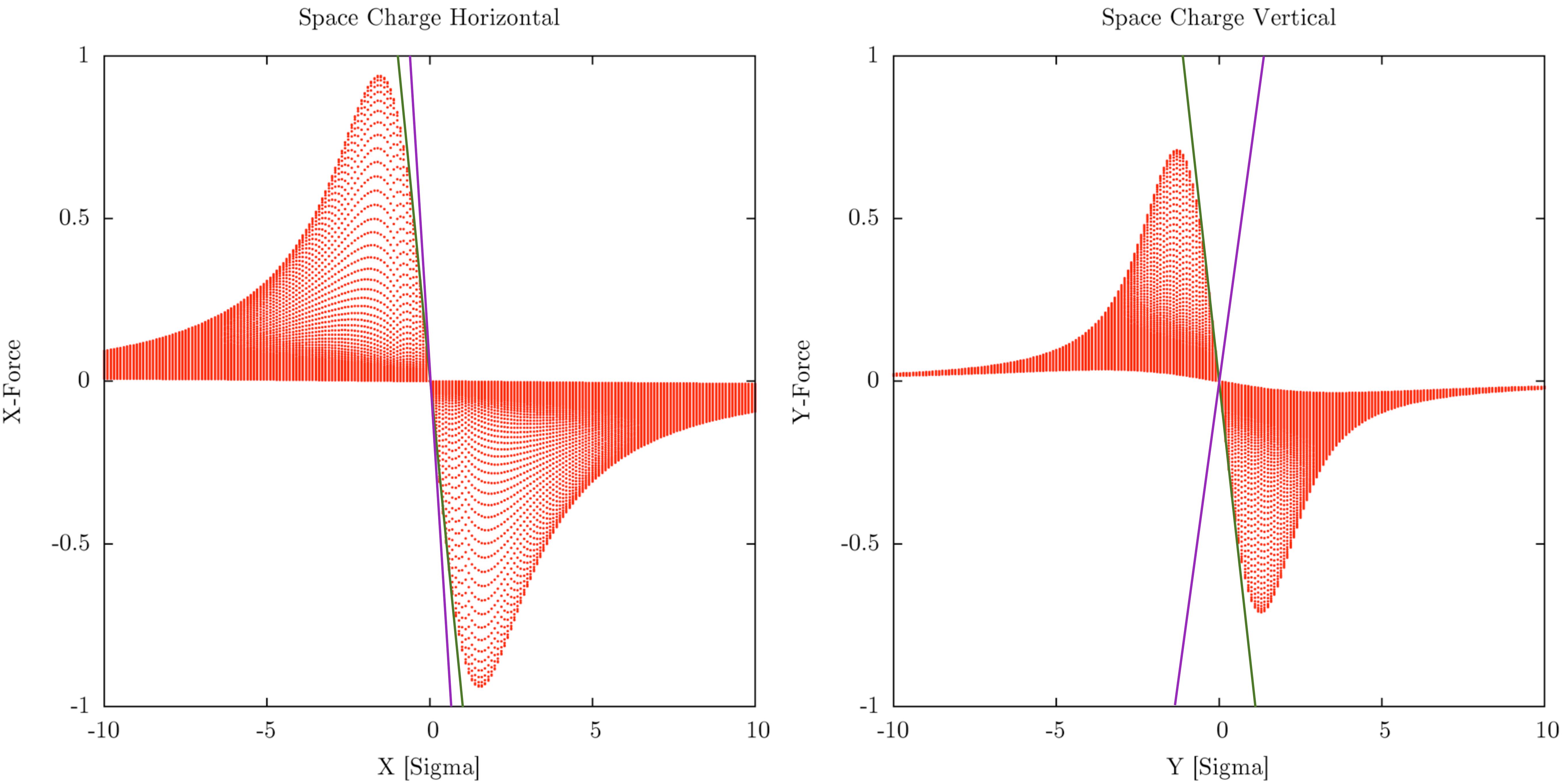
$$F_z = \frac{e^2N}{2\sqrt{\pi^3}\epsilon_0\gamma^2}z\int_0^\infty \frac{e^{-\frac{x^2}{2\sigma_x{}^2+t}-\frac{y^2}{2\sigma_y{}^2+t}-\frac{z^2}{2\sigma_z{}^2+t}}}{\sqrt{(2\sigma_x{}^2+t)(2\sigma_y{}^2+t)(2\sigma_z{}^2+t)^3}}dt$$


Space Charge Force intensity
10
5
0
-5
-10
-10
-5
0
5
10
X [Sigma]
Y [Sigma]
1
0.8
0.6
0.4
0.2
0



Space Charge Horizontal
X-Force
X [Sigma]
1
0.5
0
-0.5
-1
-10
-5
0
5
10
Space Charge Vertical
Y-Force
Y [Sigma]
1
0.5
0
-0.5
-1
-10
-5
0
5
10

Space Charge force can be, in the normal conducting linac, up to 80% of the force of the quadrupoles.

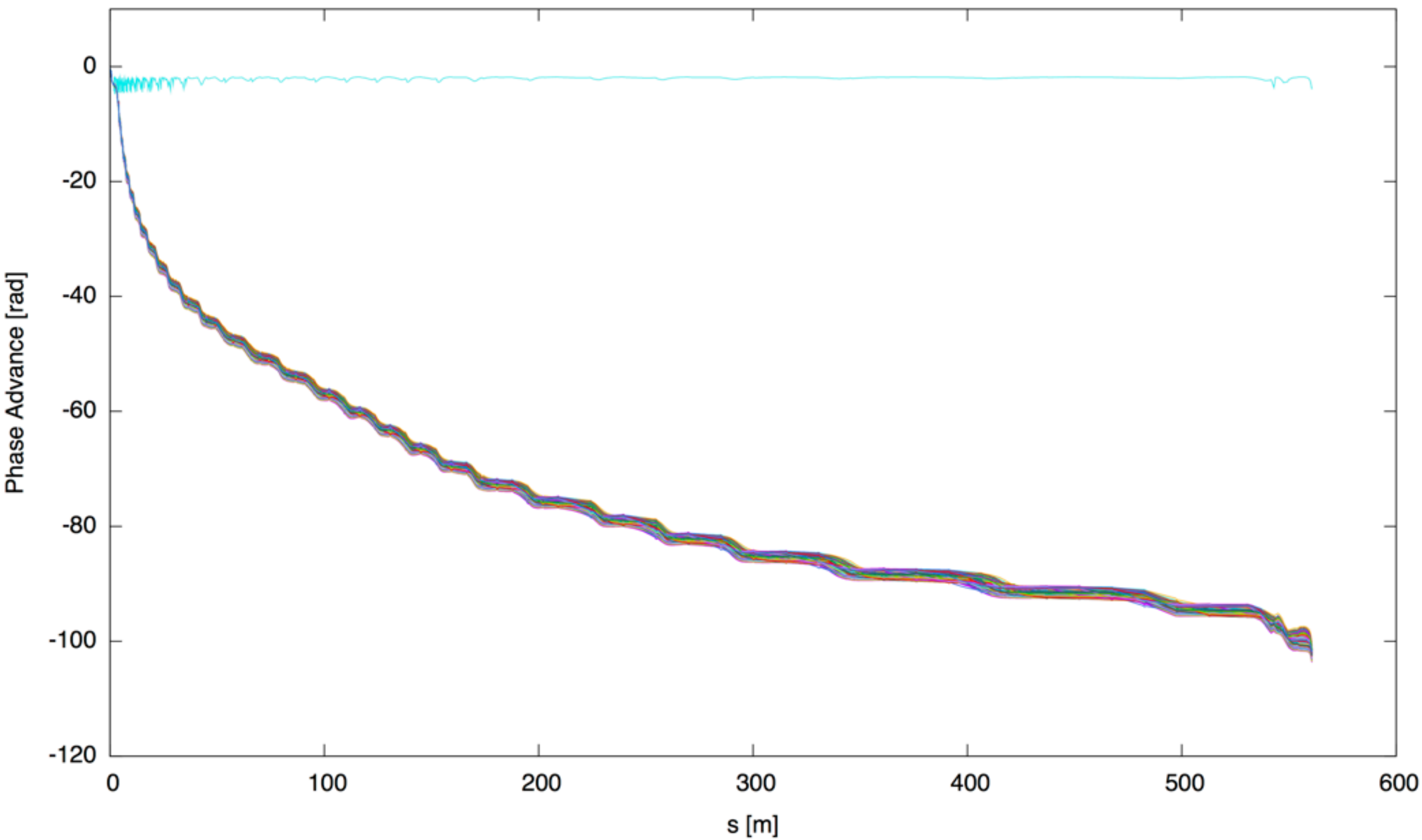


Space Charge force can be, in the normal conducting linac, up to 80% of the force of the quadrupoles.

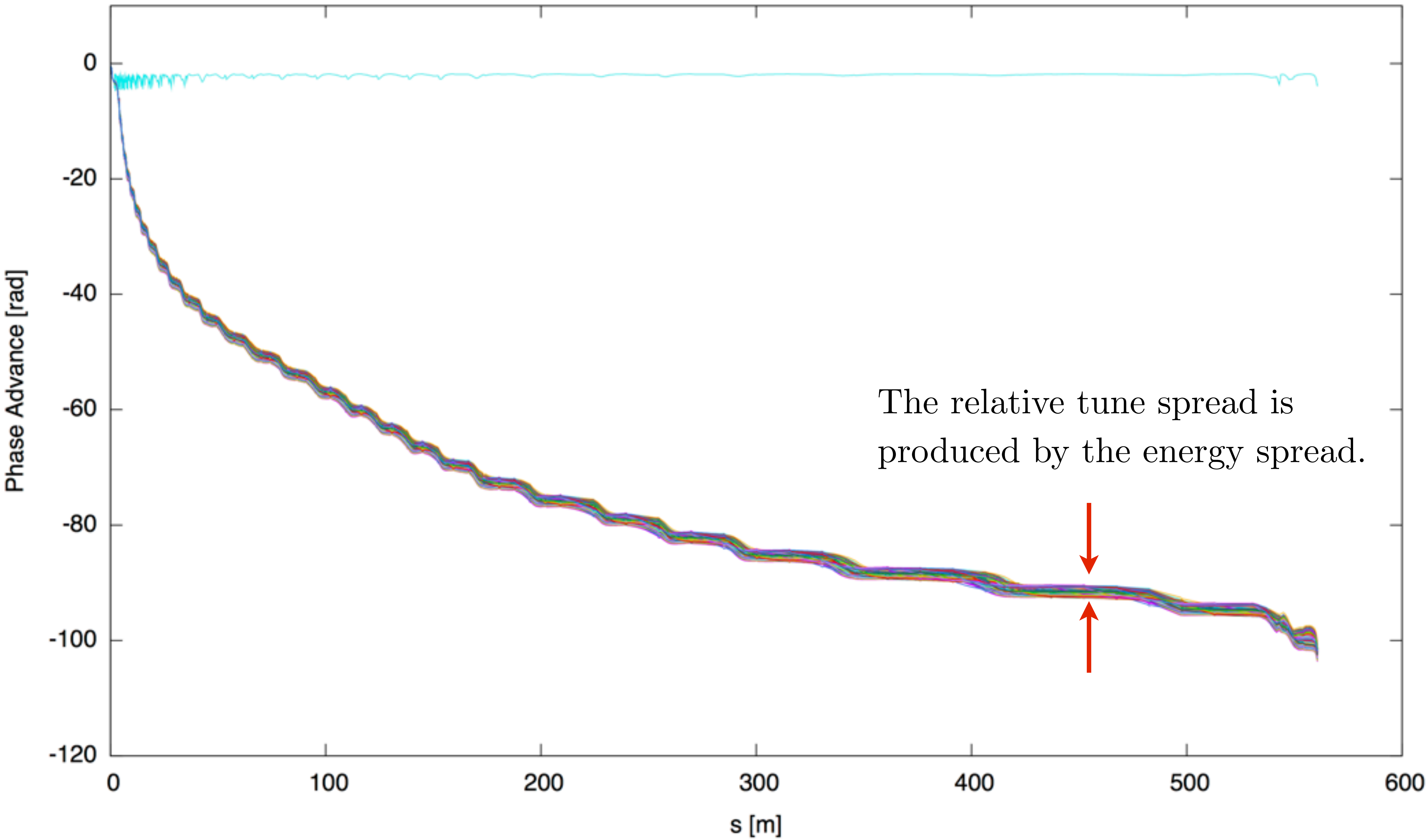
This force induces a tune shift in the whole beam.

It produces also a tune spread based on the different forces applied at different distances from the center of the beam.

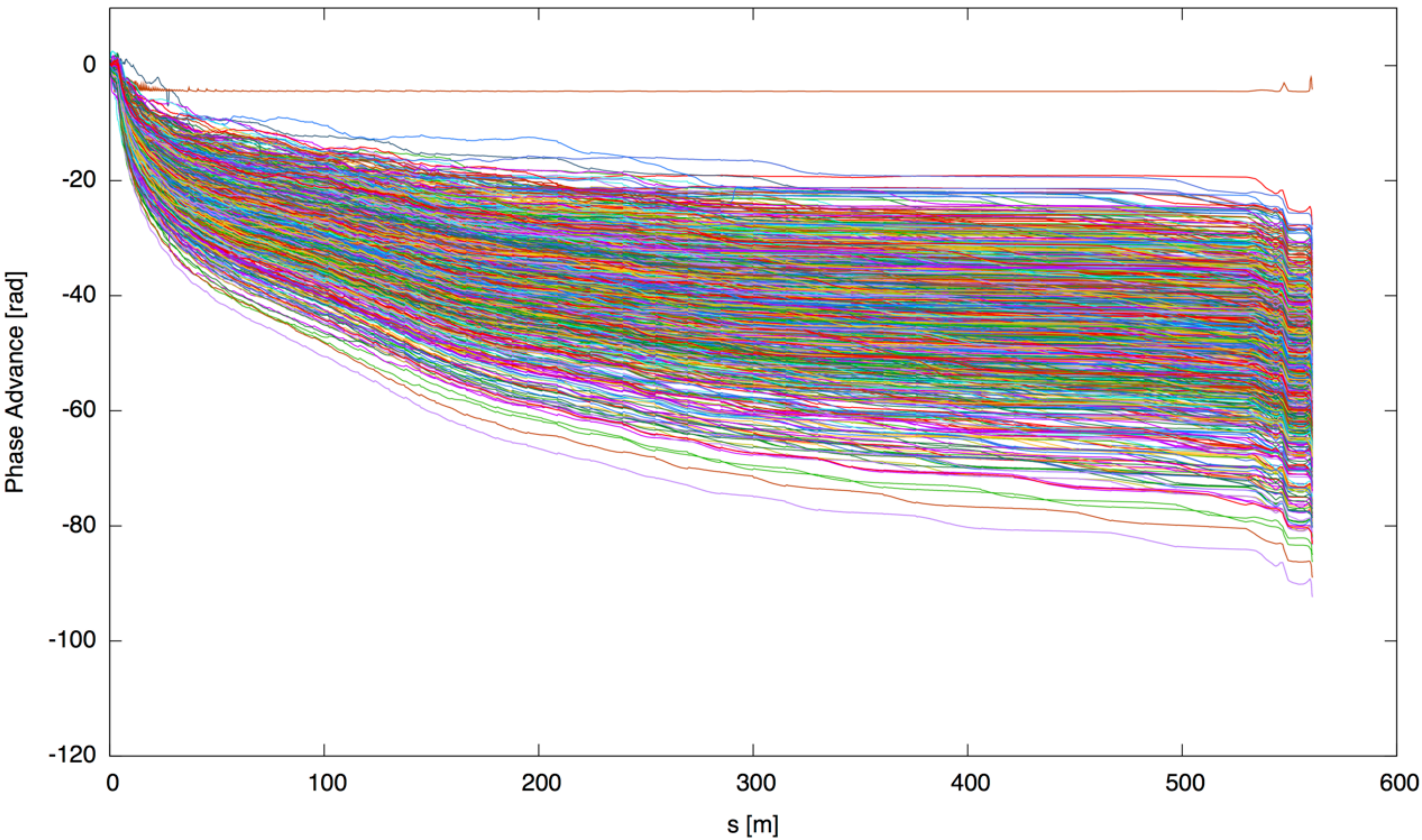
Phase advance in the ESS Linac without Space Charge



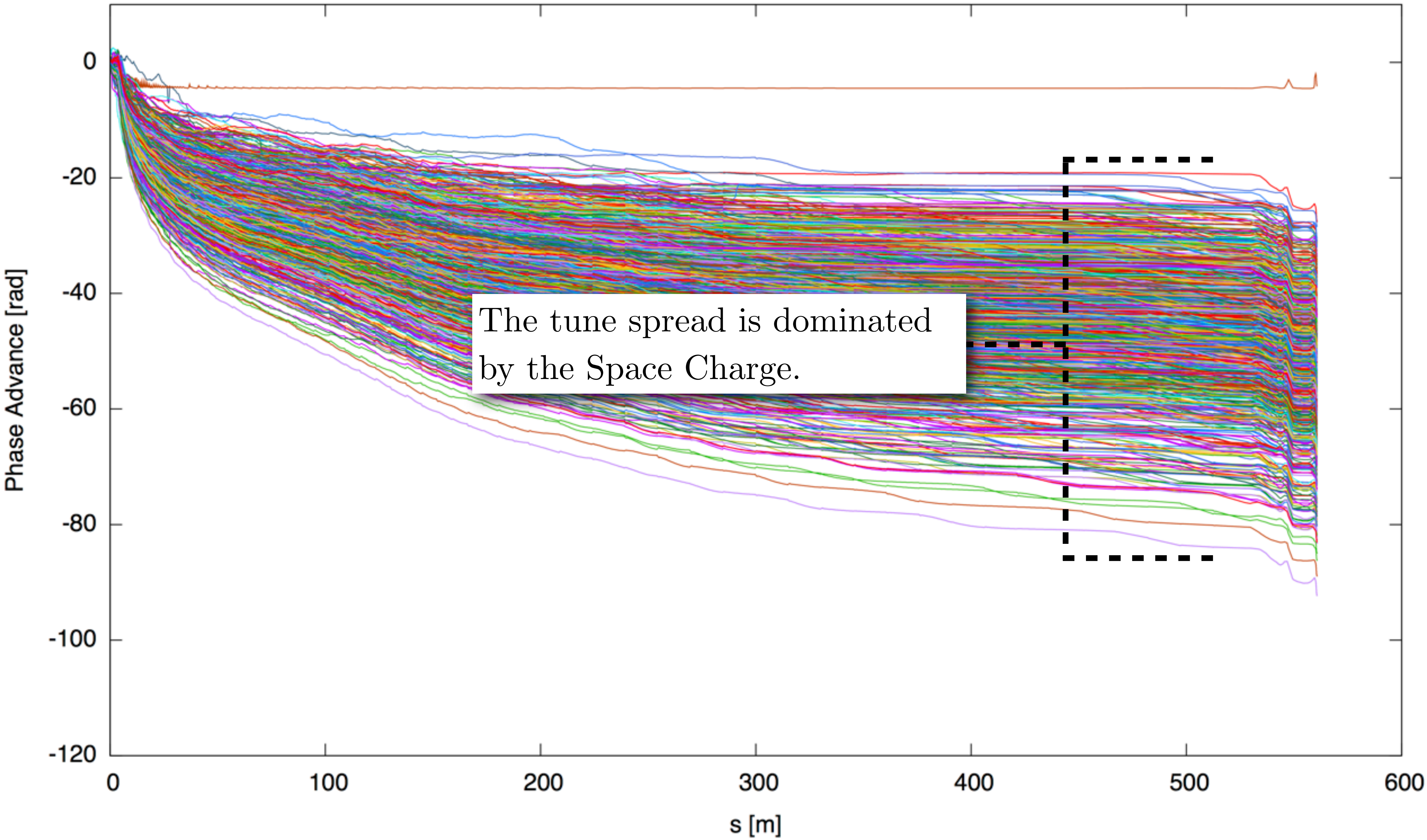
Phase advance in the ESS Linac without Space Charge



Phase advance in the ESS Linac with Space Charge



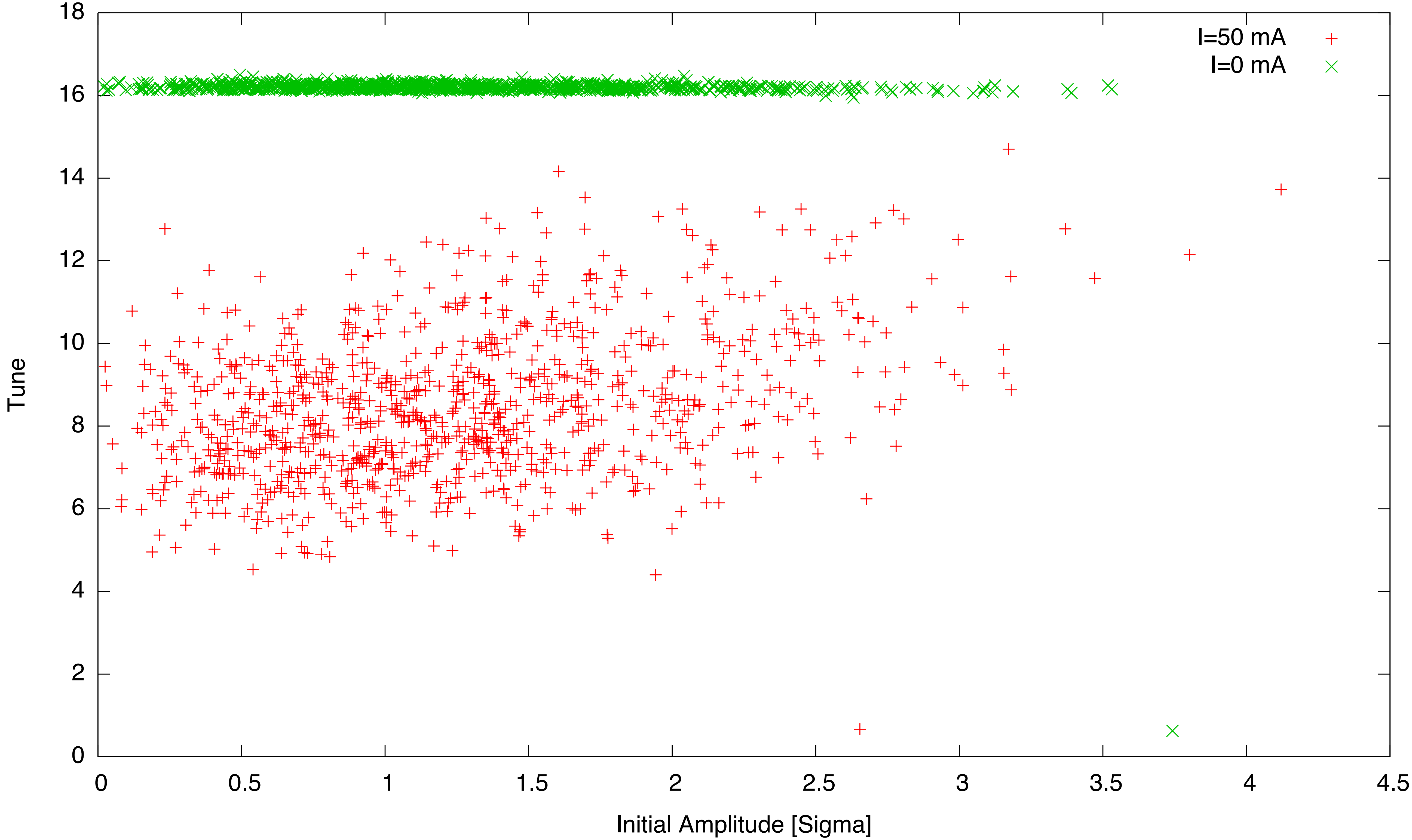
Phase advance in the ESS Linac with Space Charge



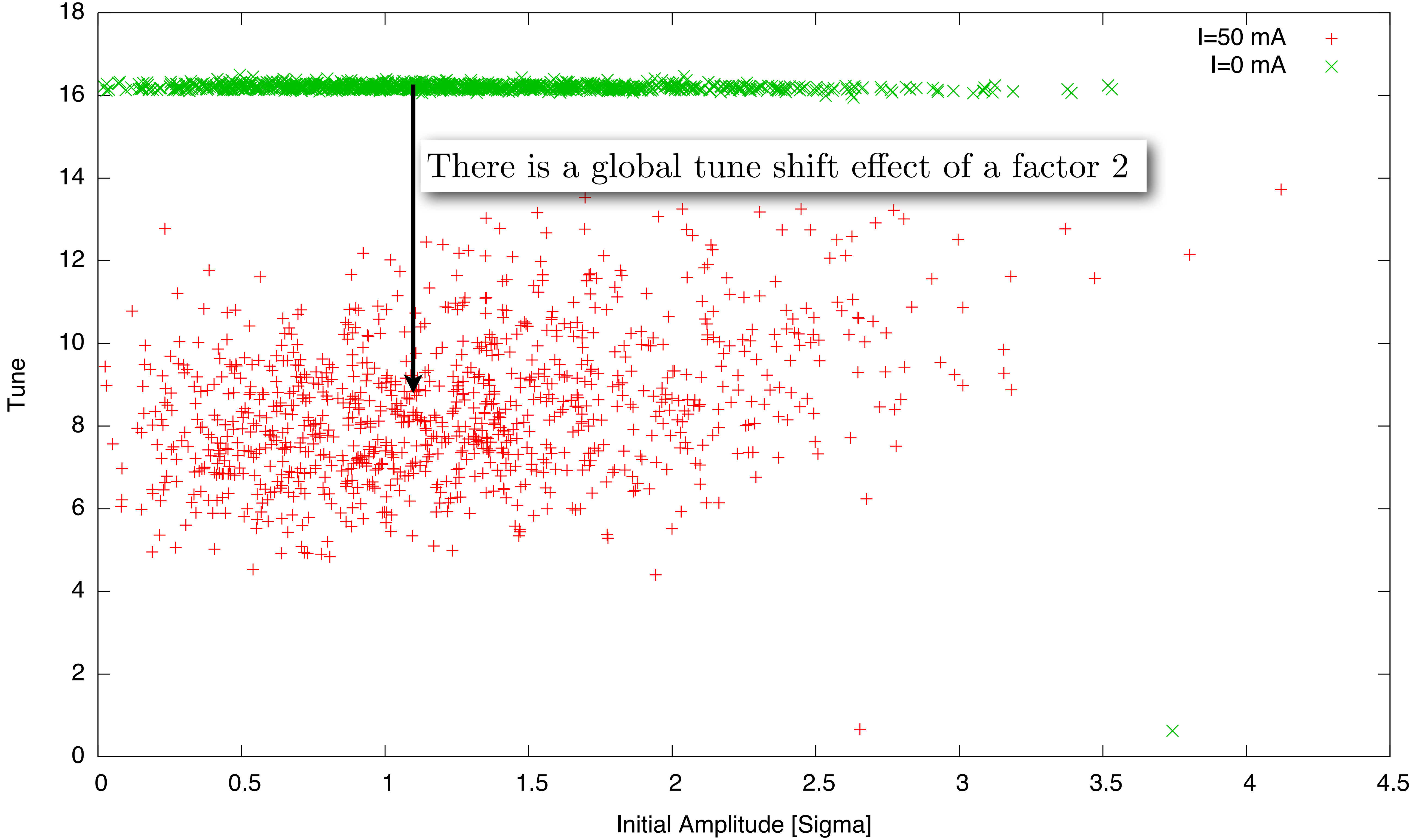
What is the dependence from the initial amplitude of the particles?

Or, in other words: is it possible to identify a stable region?

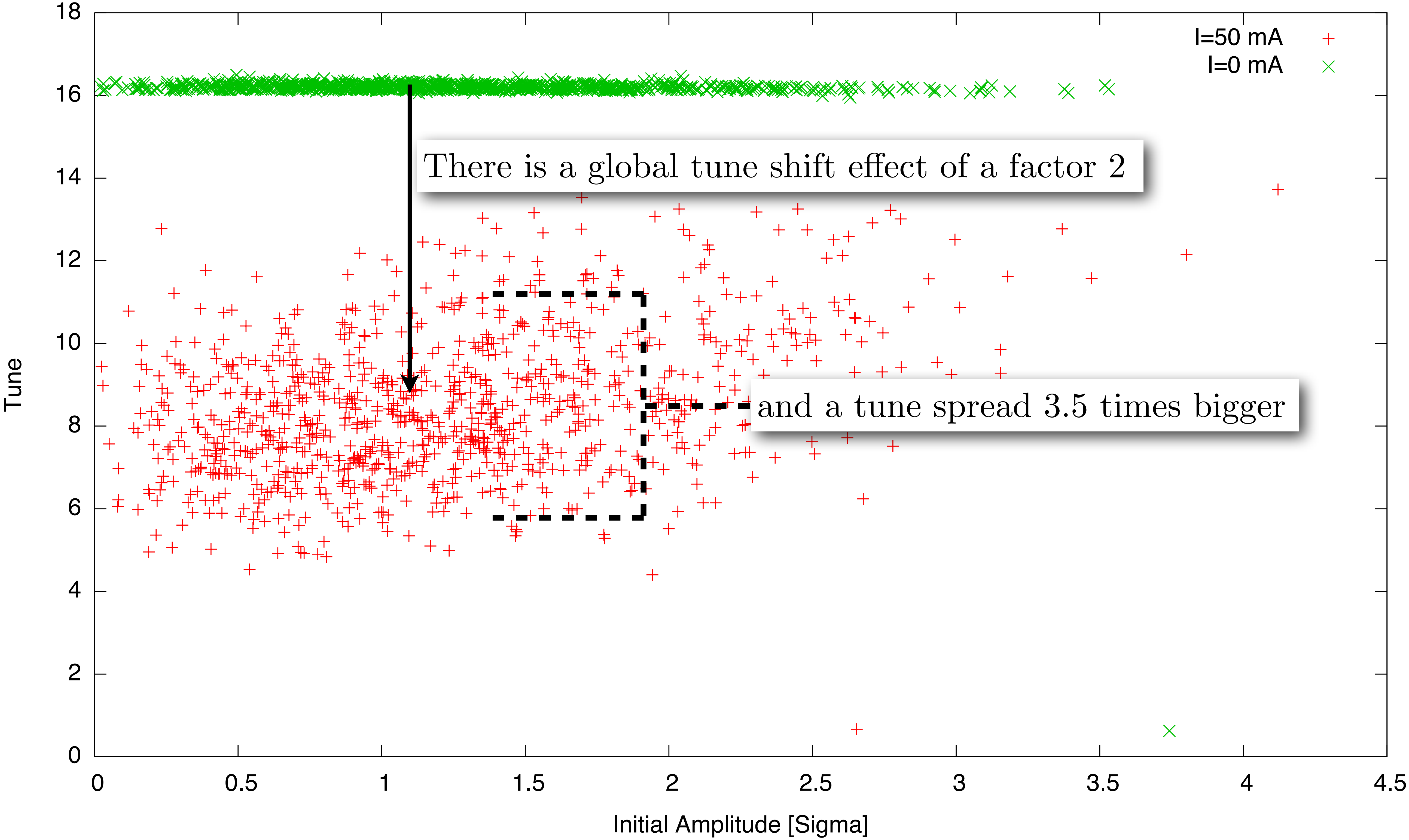
Number of oscillations of the particles at the end of the Linac, with and without the Space Charge, versus the initial amplitude.



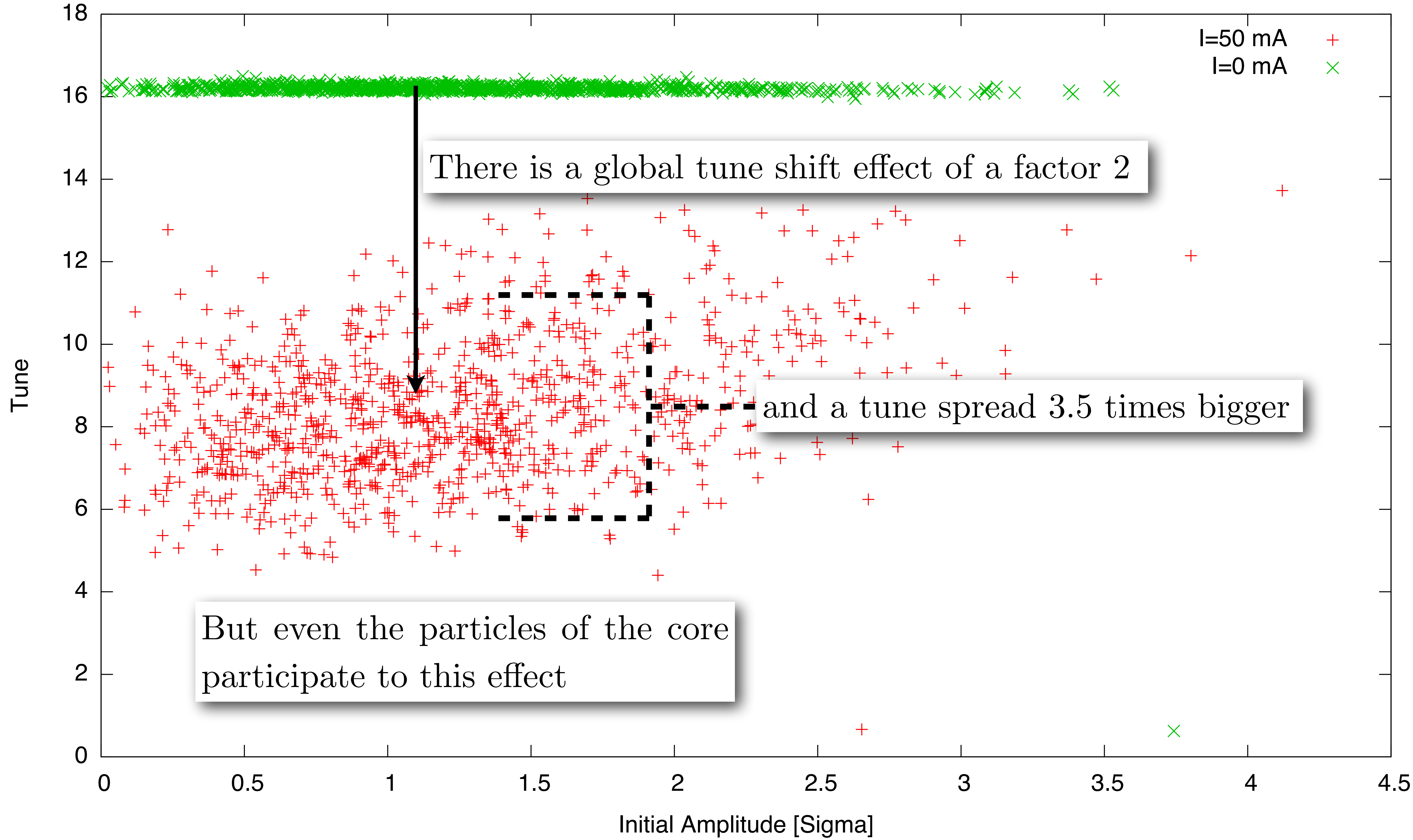
Number of oscillations of the particles at the end of the Linac, with and without the Space Charge, versus the initial amplitude.



Number of oscillations of the particles at the end of the Linac, with and without the Space Charge, versus the initial amplitude.



Number of oscillations of the particles at the end of the Linac, with and without the Space Charge, versus the initial amplitude.



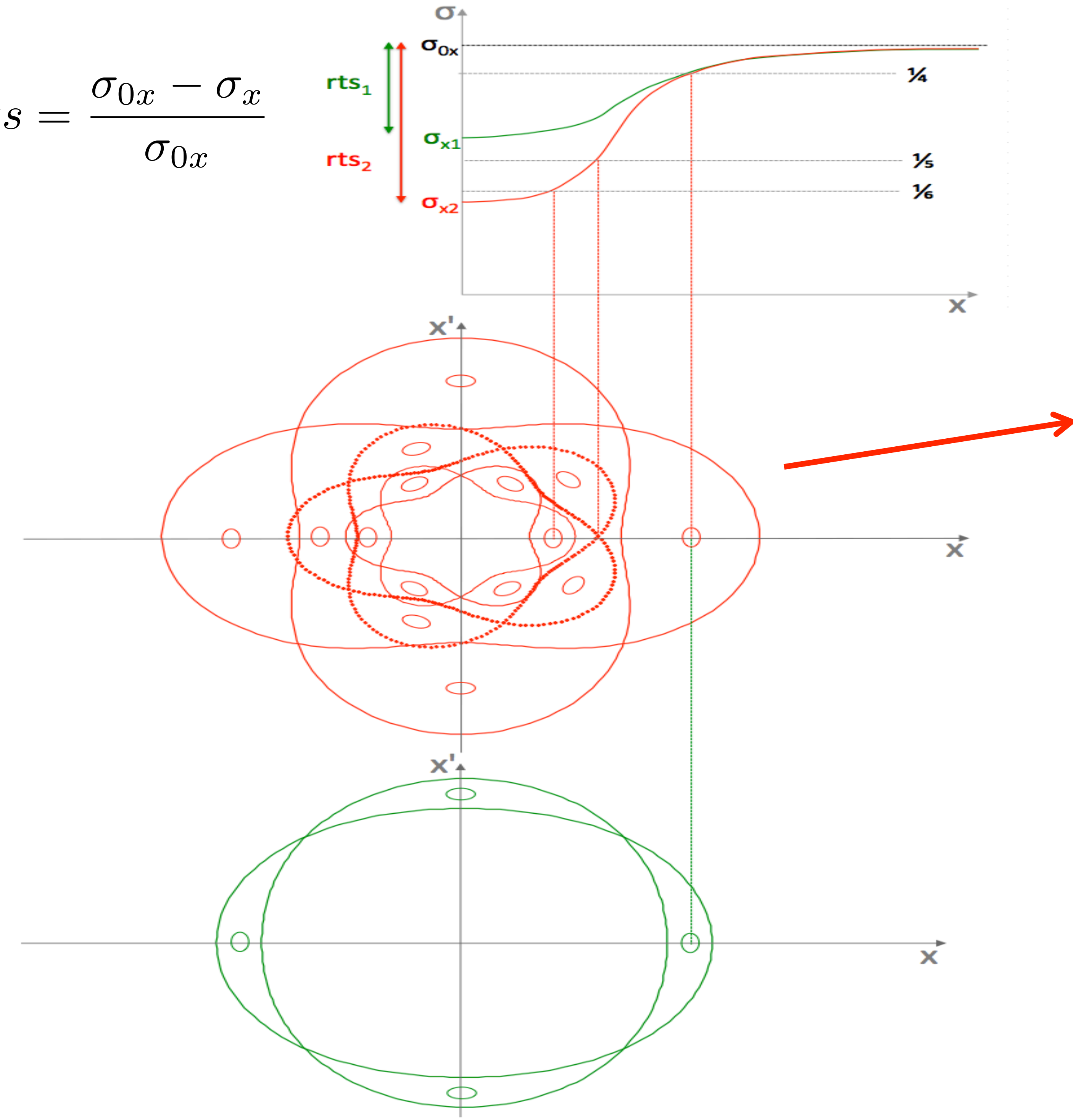
Emanuele.Laface@esss.se

The Space Charge excites the particles at any amplitude (but more on the core of the bunch) allowing the particles to cross resonances.

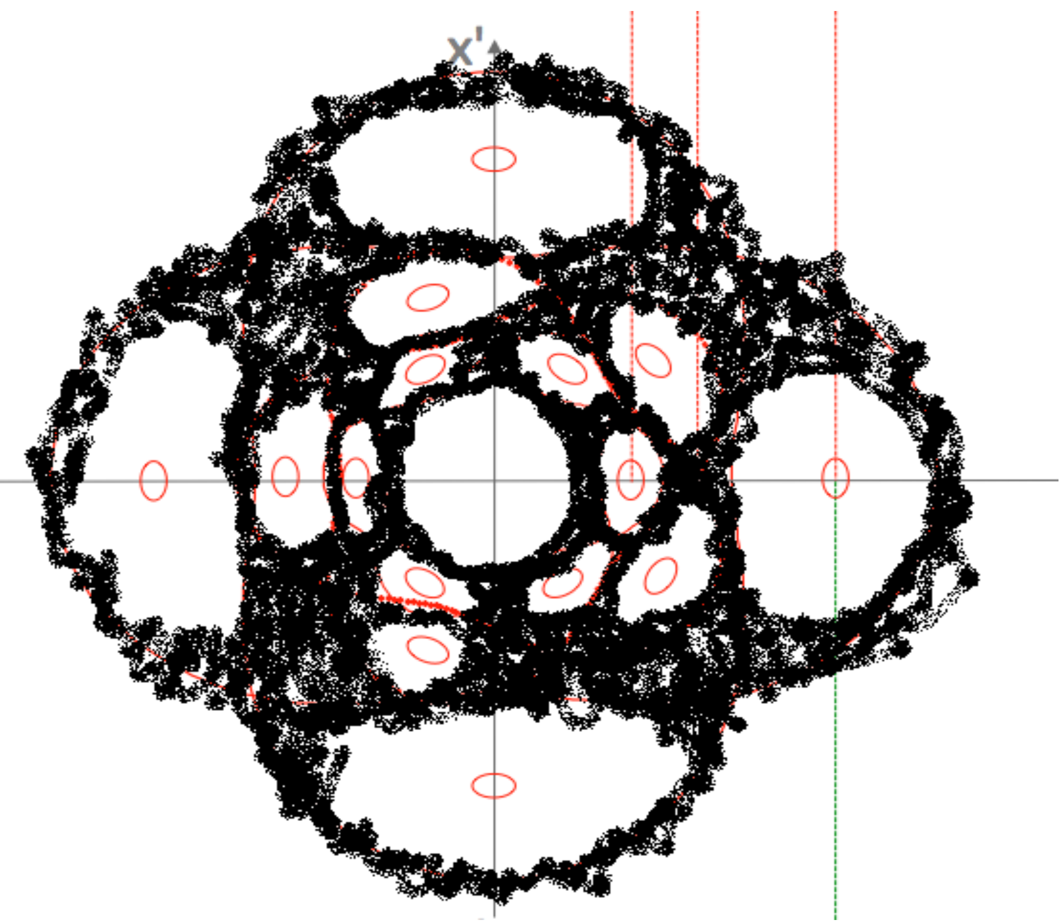
The more resonances the particle crosses the bigger is the change in the tune of that particle.

The resonance overlap mechanism

$$rts = \frac{\sigma_{0x} - \sigma_x}{\sigma_{0x}}$$



Courtesy of M. Eshraqi and J.-M. Lagniel, 2013



The particle of the core that crosses the chaotic layer jumps to a large amplitude.

Considerations

The dynamic of ESS is dominated by the Space Charge.

Considerations

The dynamic of ESS is dominated by the Space Charge.

Two elements are required in order to keep the Space Charge under control:

Considerations

The dynamic of ESS is dominated by the Space Charge.

Two elements are required in order to keep the Space Charge under control:

an accurate model of the Space Charge;

Considerations

The dynamic of ESS is dominated by the Space Charge.

Two elements are required in order to keep the Space Charge under control:

an accurate model of the Space Charge;

a tune of the parameters of the machine to minimize the relative tune spread in the early region of the Linac reducing the number of crossed resonances.

References

E. Laface et al., “Space Charge and Cavity Modeling for the ESS Linac Simulator”, IPAC 2013, Shanghai, China.

M. Eshraqi et al., “On the Choice of Linac Parameters for Minimal Beam Losses”, IPAC 2013, Shanghai, China.

P.M. Lapostolle, “Effets de la charge d’espace dans un accelerateur lineaire a protons”, CERN AR/Int. SG/65-15, 15 Juillet 1965.

K.Y. Ng, “The transverse Space-Charge force in tri-gaussian distribution”, Fermilab-TM-2331-AD, 2007.

R. Pissens et al., “QUADPACK, A Subroutine Package for Automatic Integration”, Berlin : Springer, 1983.

P. Gonnet, “Increasing the Reliability of Adaptive Quadrature Using Explicit Interpolants”, ACM Trans. on Math. Soft. Vol. 33, Issue 3, Article 26 (2010).

B.V. Chirkov, “A universal instability of many-dimensional oscillator system”, Phys. Rep. 52: 263 (1979)

T.P. Wangler, “RF Linear Accelerators”, Wiley, Physics textbook, 2008.

L. Groening et al., “Experimental observation of Space Charge driven resonances in a linac”, Linac 2010, Tsukuba, Japan

Thank You.

Emanuele.Laface@esss.se

Backup Slides

ESS Linac vs. Linac 4

	TDR 2012	Linac 4
Power	5 MW	5.1 kW
Peak Power	125 MW	6.3 MW
Peak Current	50 mA	65 mA
Protons per Bunch	$8.87 \cdot 10^{8}$	$1.14 \cdot 10^{9}$
Energy	2500 MeV	160 MeV
Pulse Length	2.86 ms	0.4 ms
Duty Cycle	4%	0.08%
Transversal Emittance	$0.21 \cdot 10^{-6}$ m·rad	$0.4 \cdot 10^{-6}$ m·rad
Longitudinal Emittance	$0.28 \cdot 10^{-6}$ m·rad	$0.45 \cdot 10^{-6}$ m·rad
Cavities	208	
Gradient	40 MV/m	3.3 MV/m
Length	600 m	76.33 m

Common strategies adopted to solve it:

$$\int_0^\infty \frac{e^{-\frac{x^2}{2\sigma_x{}^2+t}-\frac{y^2}{2\sigma_y{}^2+t}-\frac{z^2}{2\sigma_z{}^2+t}}}{\sqrt{(2\sigma_x{}^2+t)^3(2\sigma_y{}^2+t)(2\sigma_z{}^2+t)}}dt$$

- Linear approximation and long bunch: $x \to 0, y \to 0, \sigma_z \gg \sigma_x, \sigma_y$

K.Y. Ng, "The transverse Space-Charge force in tri-gaussian distribution", Fermilab-TM-2331-AD, 2007.

- Elliptical uniform bunch: $U_{sc}(x,y,z) = V_0 - \frac{\tau}{2\epsilon_0}\left[\frac{x^2+y^2}{2} + a^2\frac{z-\frac{x^2+y^2}{2}}{b^2-a^2}\left(1-\frac{\mathrm{acosh}(\frac{\mathrm{b}}{\mathrm{a}})\mathrm{b}}{\sqrt{b^2-a^2}}\right)\right].$

P.M. Lapostolle, "Effets de la charge d'espace dans un accelerateur lineaire a protons", CERN AR/Int. SG/65-15, 15 Juillet 1965.

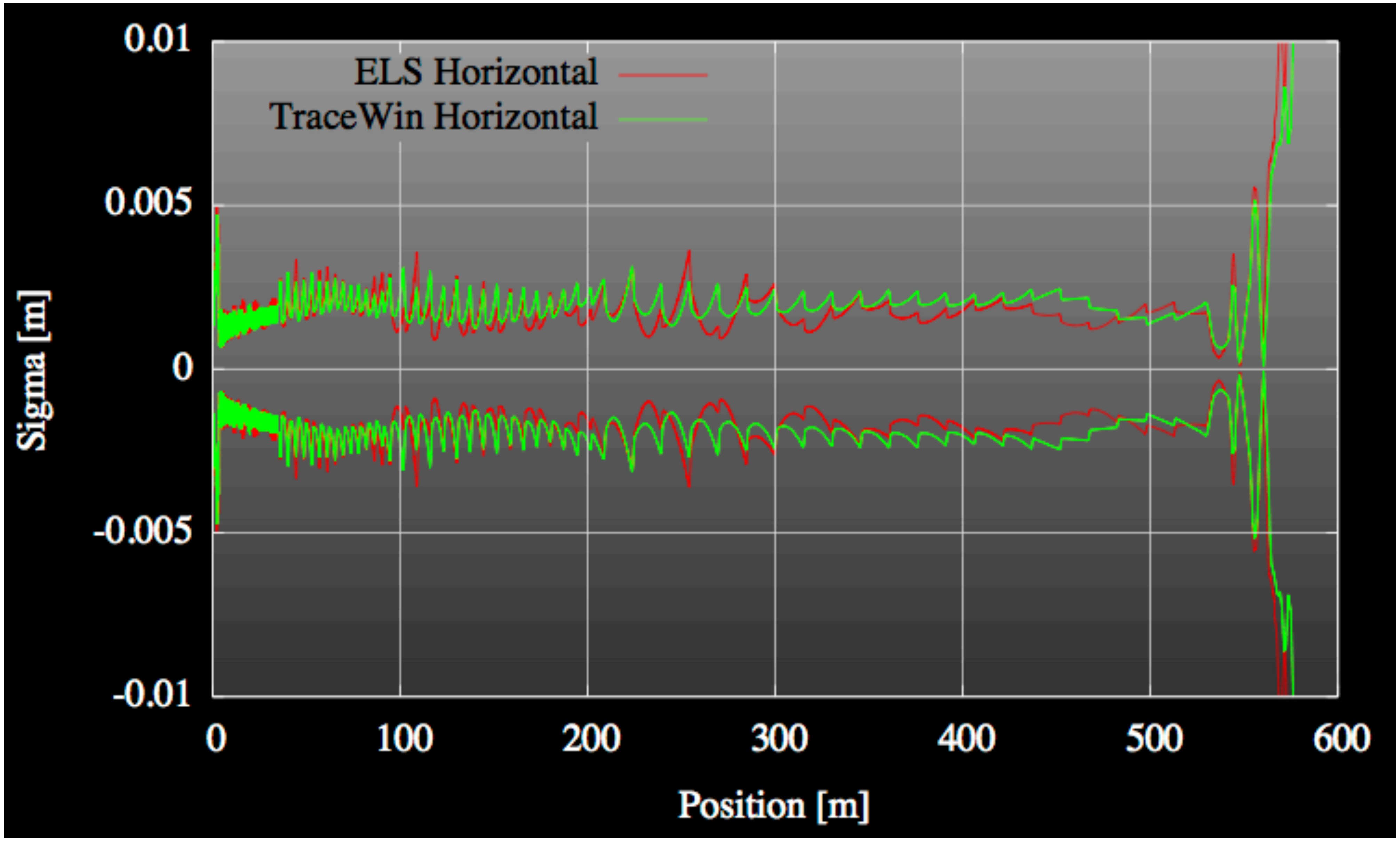
- Numerical integration: I adopted this solution using an adaptive algorithm for the Gaussian quadrature.

R. Pissens et al., "QUADPACK, A Subroutine Package for Automatic Integration", Berlin : Springer, 1983.

P. Gonnet, "Increasing the Reliability of Adaptive Quadrature Using Explicit Interpolants", ACM Trans. on Math. Soft. Vol. 33, Issue 3, Article 26 (2010).

Some results

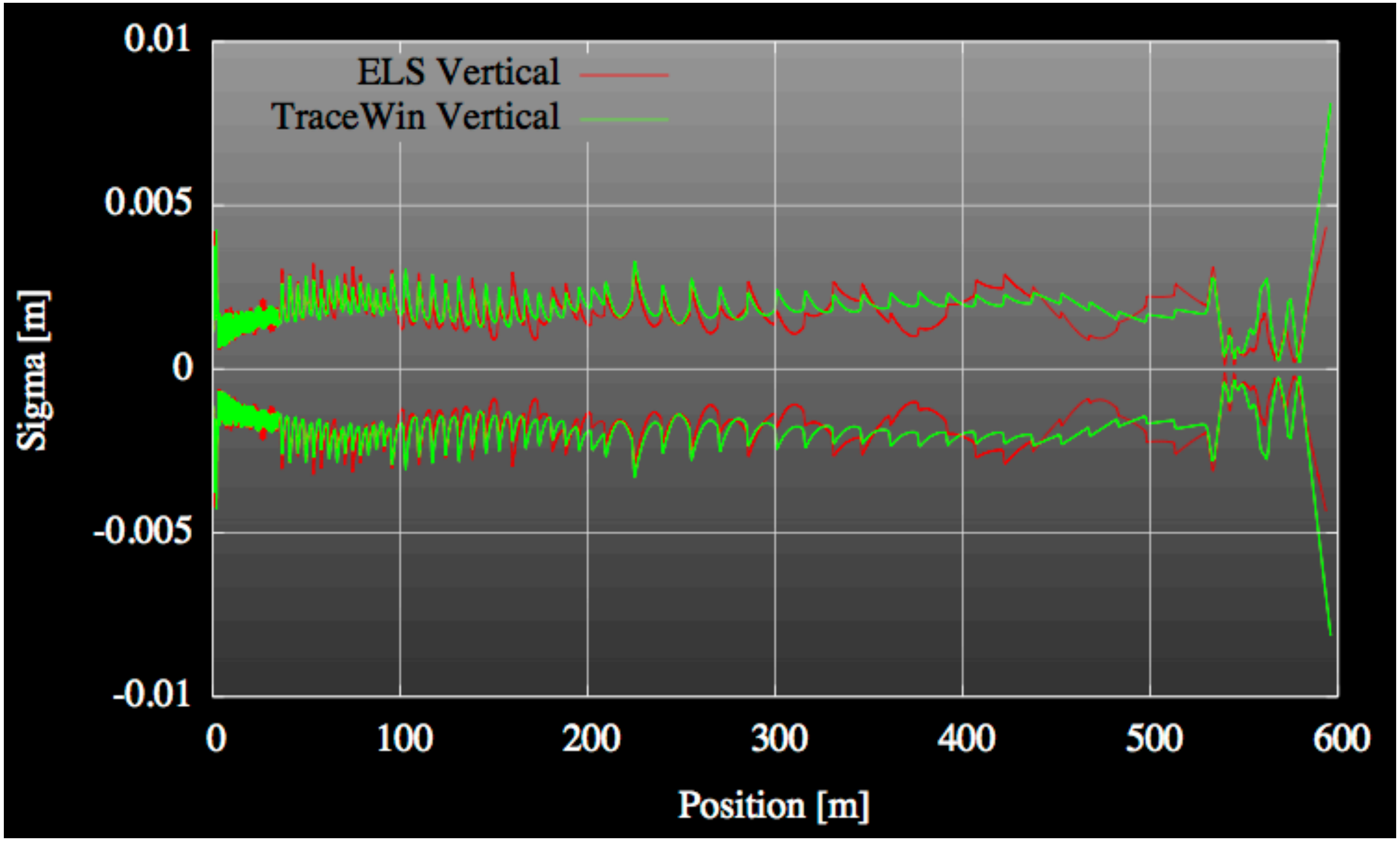
DTL to Target October 2012 Lattice



I=50 mA, Horizontal plane

Some results

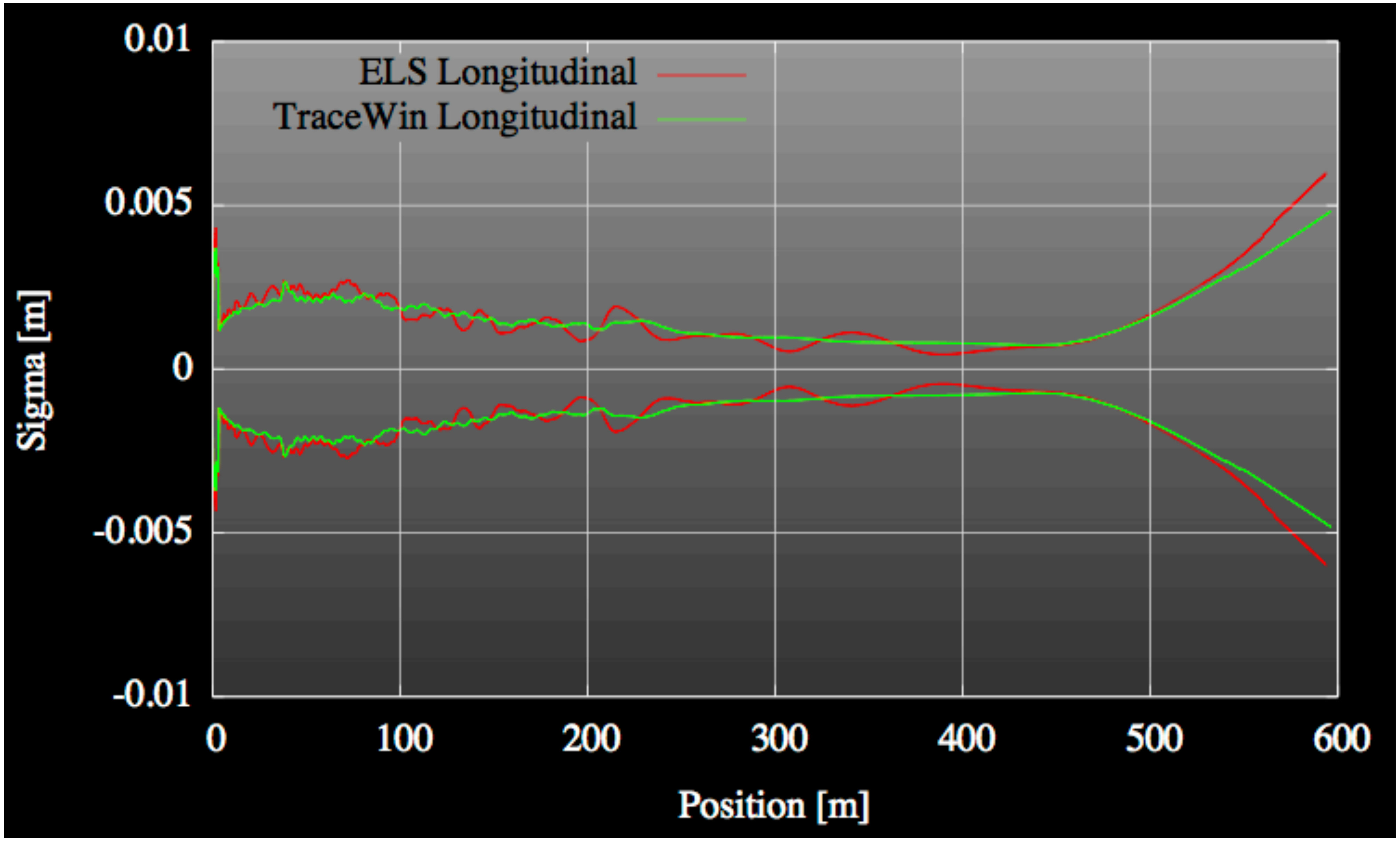
DTL to Target October 2012 Lattice



I=50 mA, Vertical plane

Some results

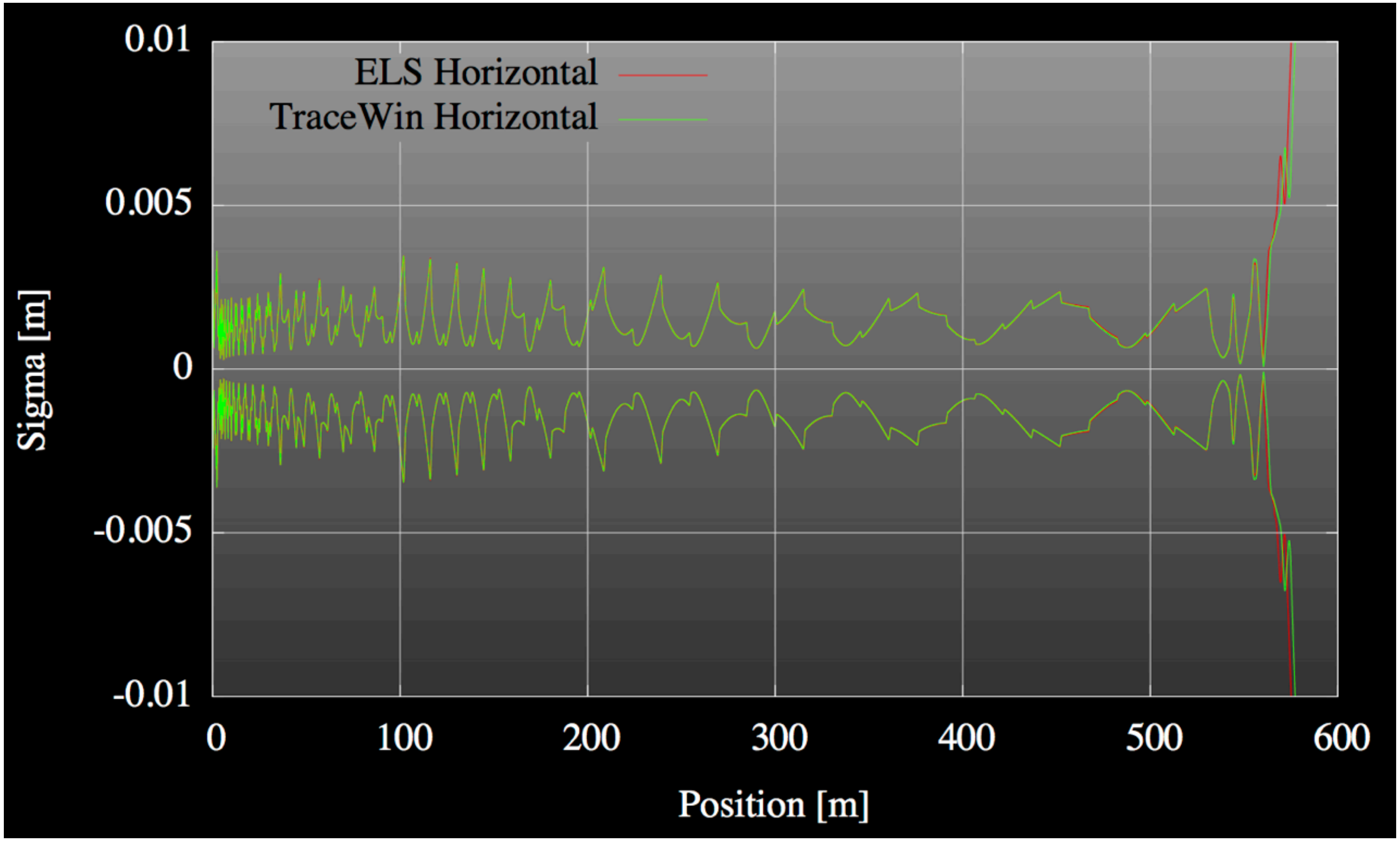
DTL to Target October 2012 Lattice



I=50 mA, Longitudinal plane

Some results

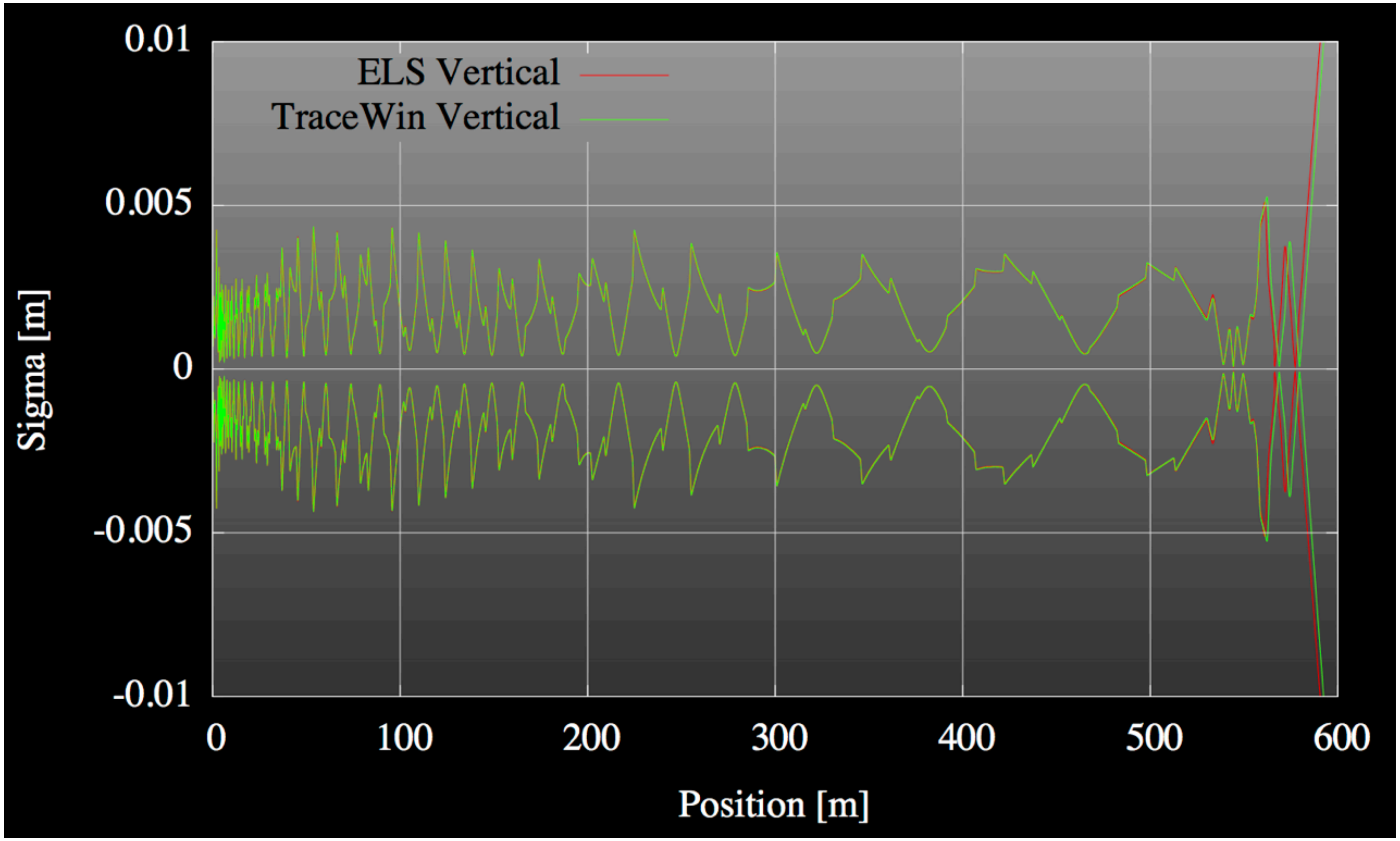
DTL to Target October 2012 Lattice



I=0, No Space Charge, Horizontal plane

Some results

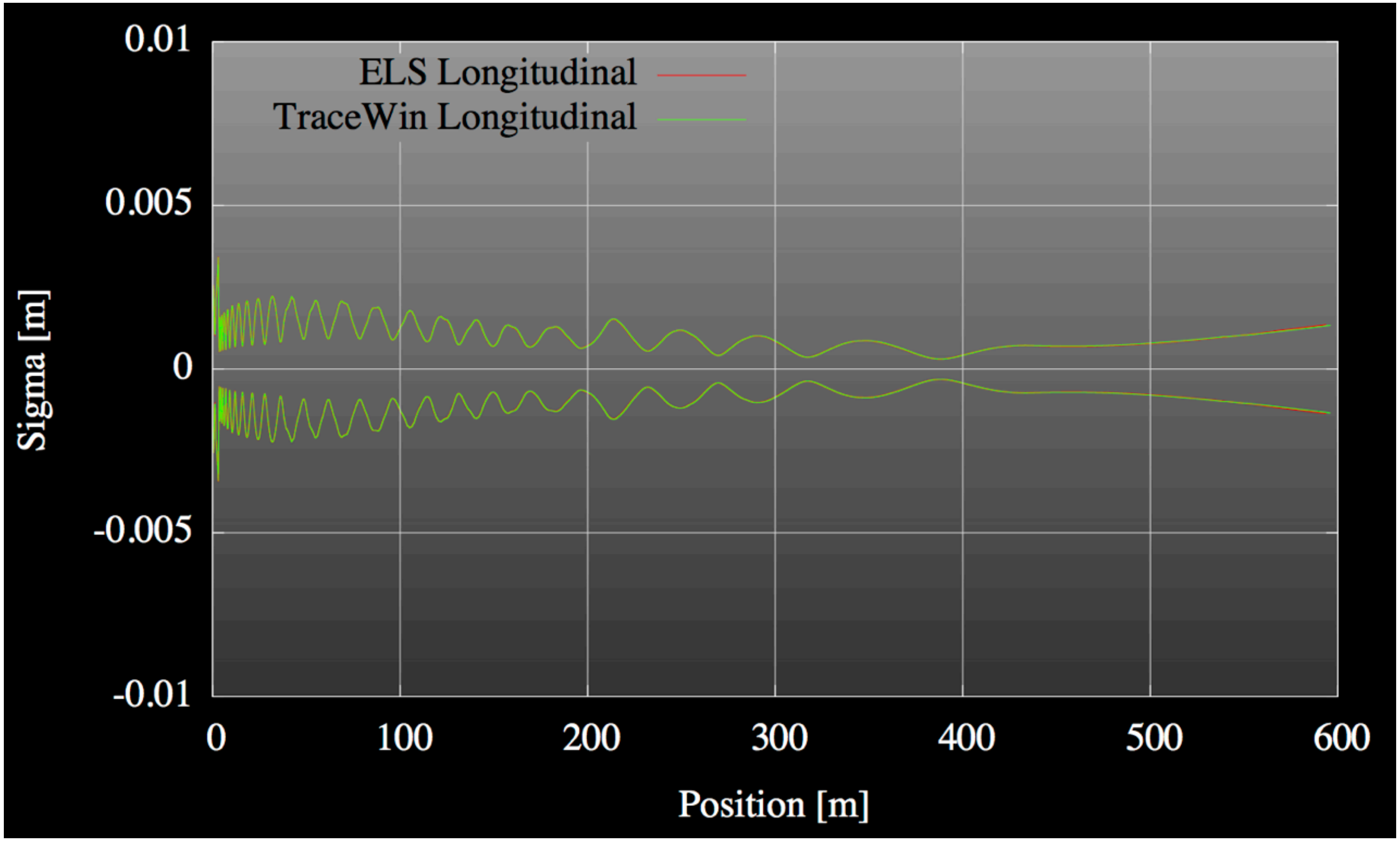
DTL to Target October 2012 Lattice



I=0, No Space Charge, Vertical plane

Some results

DTL to Target October 2012 Lattice



I=0, No Space Charge, Longitudinal plane