Optimized matching strategy for laser driven plasma booster

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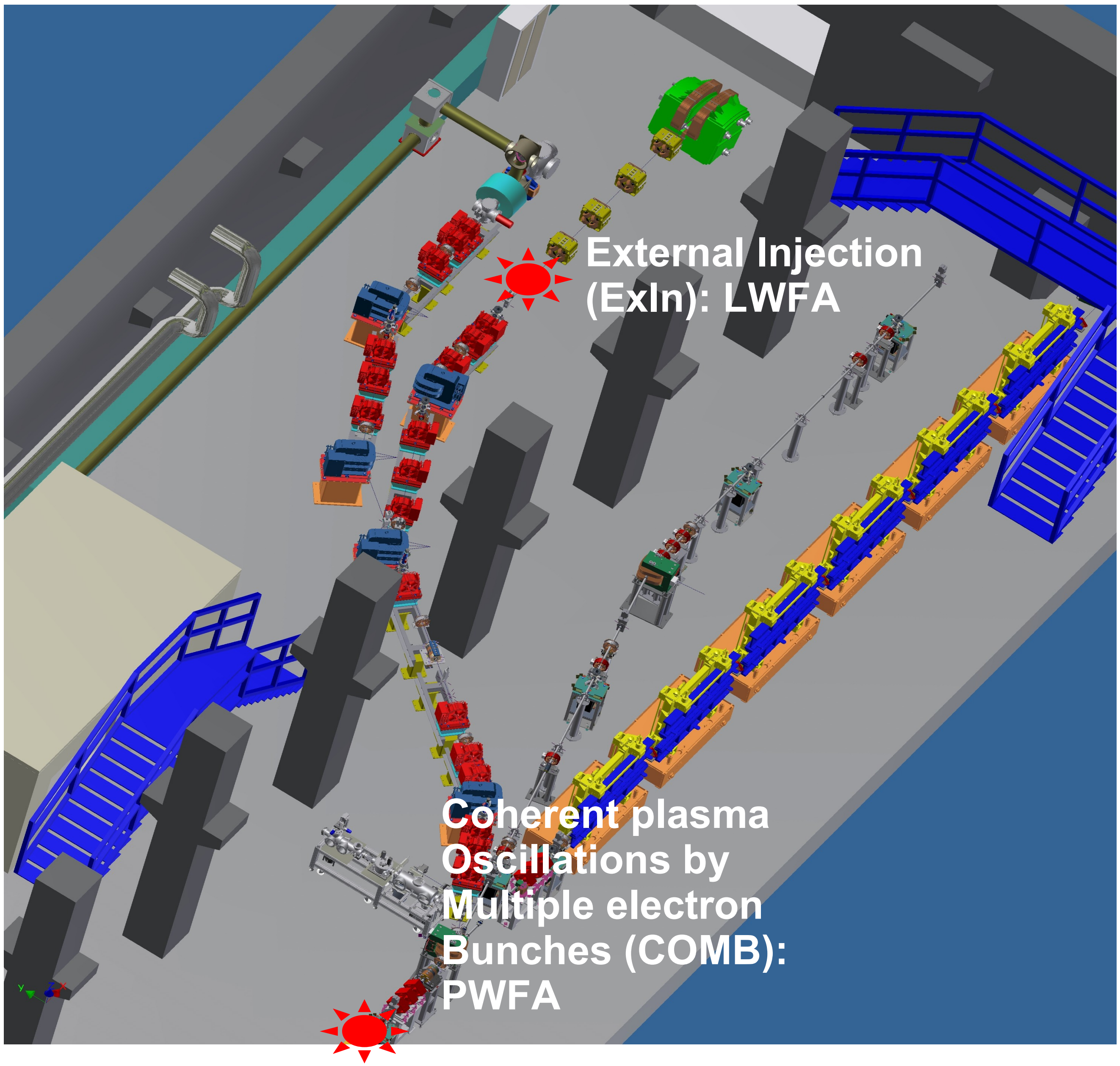
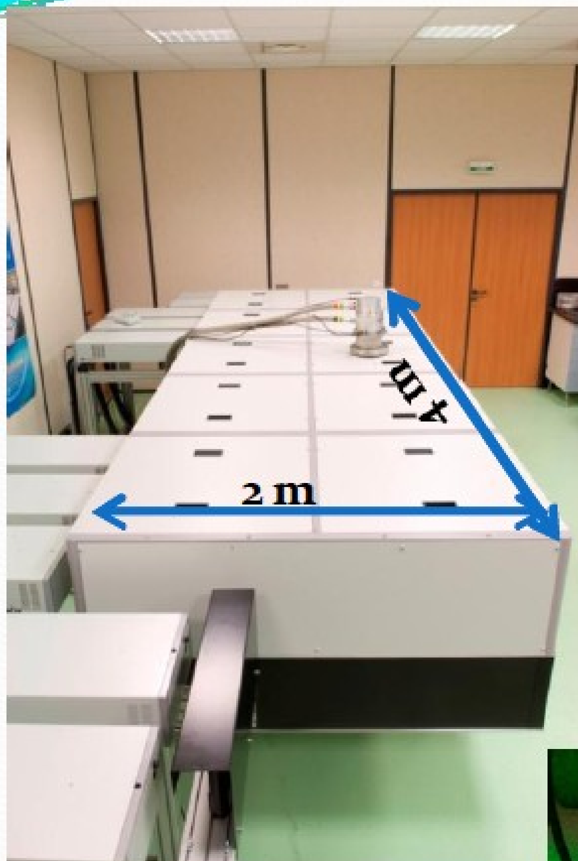
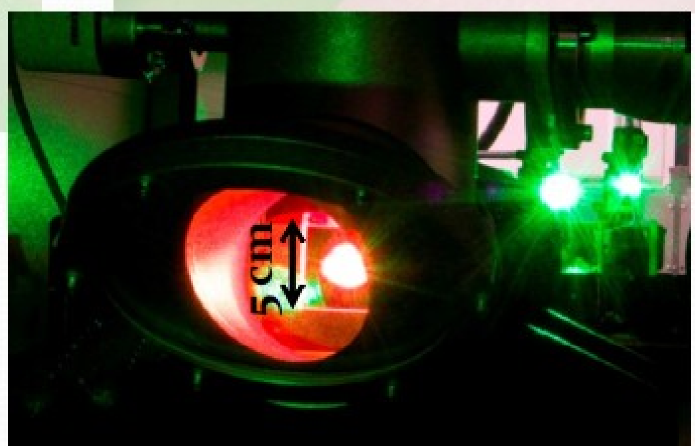
Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams

External injection experiment @ SPARC_LAB



ExIn: the FLAME laser





Energia massima: 7J

Energia massima sul target: ~5J

Durata minima: 23 fs

Lunghezza d'onda: 800 nm

Larghezza di banda: 60/80 nm

Spot-size @ focus: 10 μm

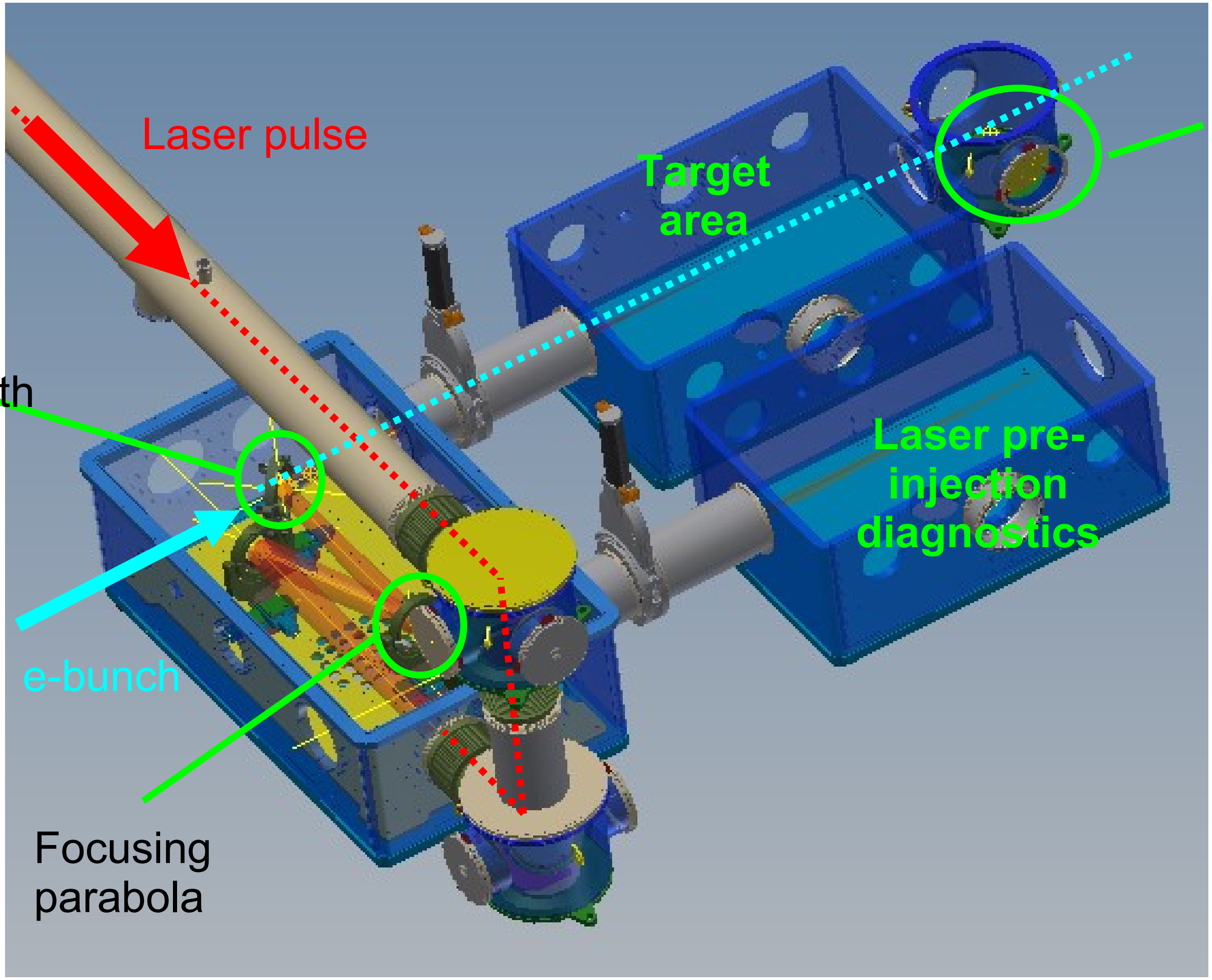
Potenza massima: ~300 TW

Contrasto: 10^{10}

ExIn goals

- Demonstrate GV/m acceleration fields
- Stability.
- Reproducibility.
- Preserve beam brightness

ExIn interaction chamber



Laser extraction (to diagnostics)

Moving mirror with hole

Focusing parabola

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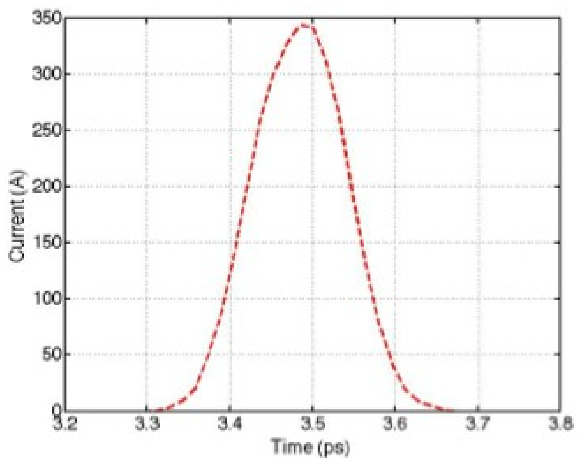
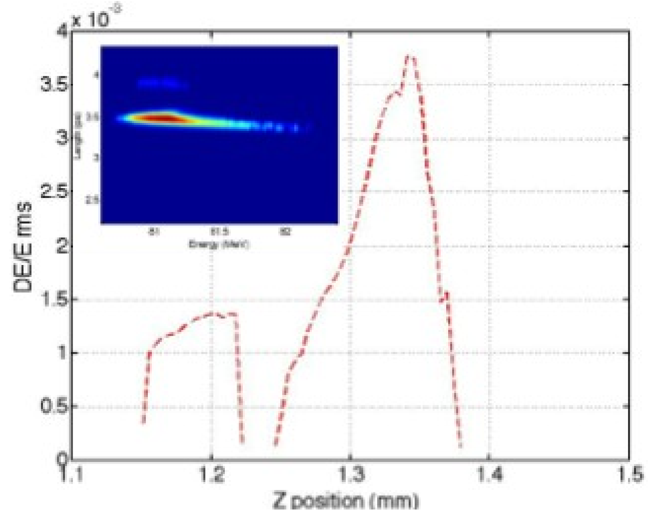
ExIn experimental parameters

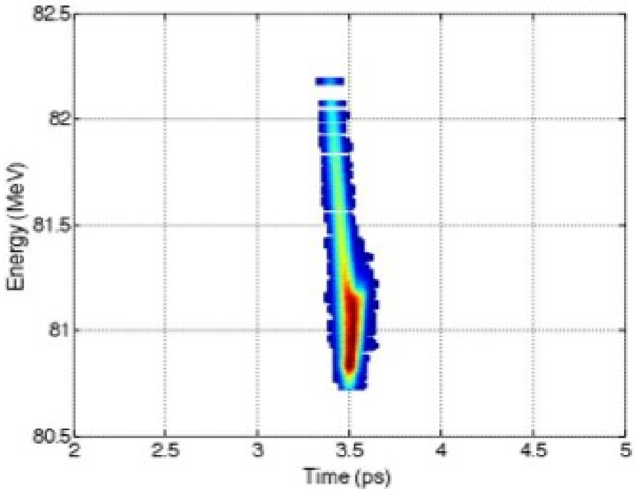
- Acceleration by LWFA of an electron beam produced by the SPARC photoinjector.
- Incoming bunch properties: E = 70 - 110 MeV; L_{FWHM}: 20 – 30 fs; ε_{nt}: few μm; σ_{tr}: down to 4 μm with permanent magnet quads; δE/E: some 10^{-3}; charge: 5 – 30 pC.
- Plasma wave in quasi-linear regime for best compromise between fields strength, acceleration length (pump depletion), de-phasing, tolerances to jitters, ecc...
- Laser is guided by dielectric capillaries exploited as hollow waveguide*, though first preparatory runs will be performed with larger laser waist size and without any guiding.
- Assuming $E_{laser} \approx 3.5$ J and q ≈ 20 pC the working point is chosen to be with **R_{cap} = 60 μm** and **$n_0 = 10^{17}$cm^{-3}** **, with average accelerating field around 7 GV/m.
- Expected performances: E_f = 300 – 800 MeV, $\varepsilon_f < 1.2\ \varepsilon_0$, δE/E < 10^{-2}.

*B. Cross *et al.*, PRE 65, 026405 (2002). **A.R. Rossi *et al*, PRSTB 740, 60 (2014).

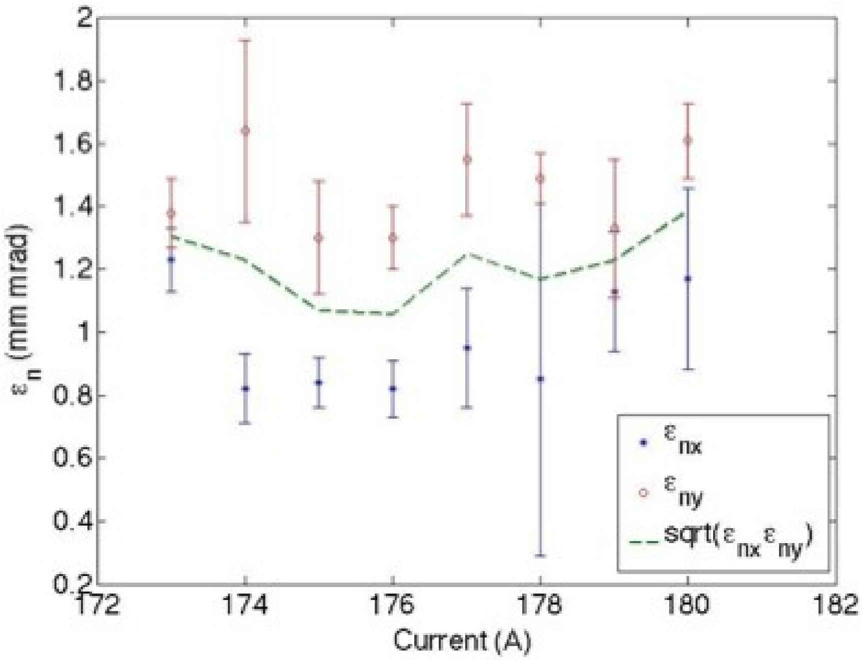
Beam dynamics experimental results: EXIN setting







Energy (MeV)	81.23(0.03)
Energy spread (%)	0.35(0.03)
Bunch duration (ps)	0.048(0.001)
TransvEmit (mm mrad)	1.06(0.13)
Charge (pC)	55(4)
LongEmit (keV*mm)	3.37(0.29)



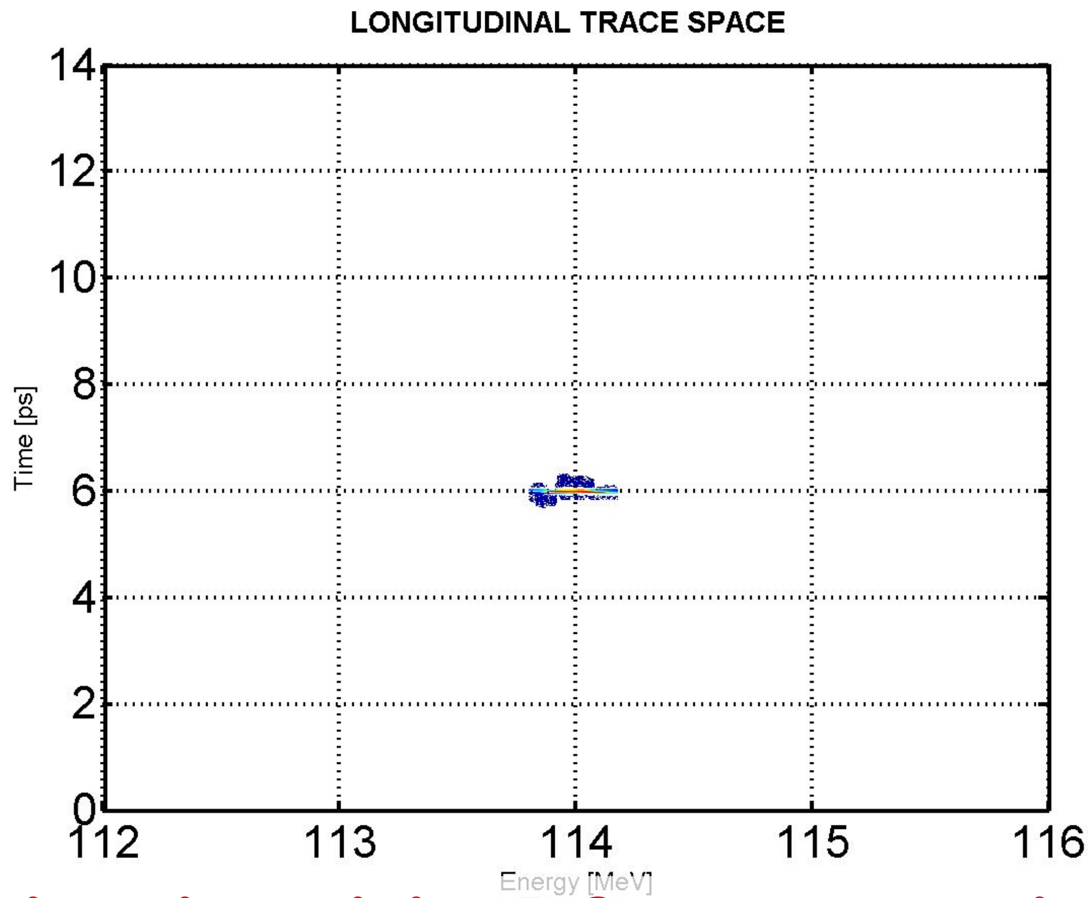
Beam dynamics experimental results: EXIN setting

$$\sigma_t = 26\,fs$$

$$\varepsilon_{nx} = 1.2um$$

$$\sigma_E = 0.1\%$$

$$I = 400A$$



Beam matching is critical for preserving beam brightness!!

Matching strategies

- Matching is critical for preserving beam quality, both when the bunch enters the plasma and when it leaves the interaction area.

- Up to now we know how the focusing strength should vary for adiabatic matching [1] and the theory is checked with simulations avoiding beam loading; a possible practical implementation consists in using plasma lenses [2].

- Plasma lenses are very effective but add to the overall complexity of the system if considered as stand alone optical elements; tapering is a collateral, unavoidable feature, that may act as a plasma lens. It is difficult but not impossible to control. However it may fail to have some needed degree of freedom (e.g. for compensating longitudinal fields variations, beam loading, etc...)

- Matching conditions are analytically established only in bubble regime (and linear regime, which is not so appealing).

- In our setting, simulations show that the matched transverse size is < 2 μm, while the focusing with permanent magnets quads reaches a size > 4 μm.

[1] K. Floettmann, PRSTAB 17, 054402 (2014); I. Dornmair et al., PRSTAB 18, 041302 (2015).
[2] R. Lehe *et al.*, PRSTAB 17, 121301 (2014).

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Our proposal for ExIn is to exploit tapering while the plasma wave regime is varying due to laser focusing. This adds a degree of freedom that can be fruitfully exploited to preserve beam quality. The need for guiding also allows to somehow control the tapering.

[1] K. Floettmann, PRSTAB 17, 054402 (2014); I Dornmair et al., PRSTAB 18, 041302 (2015).
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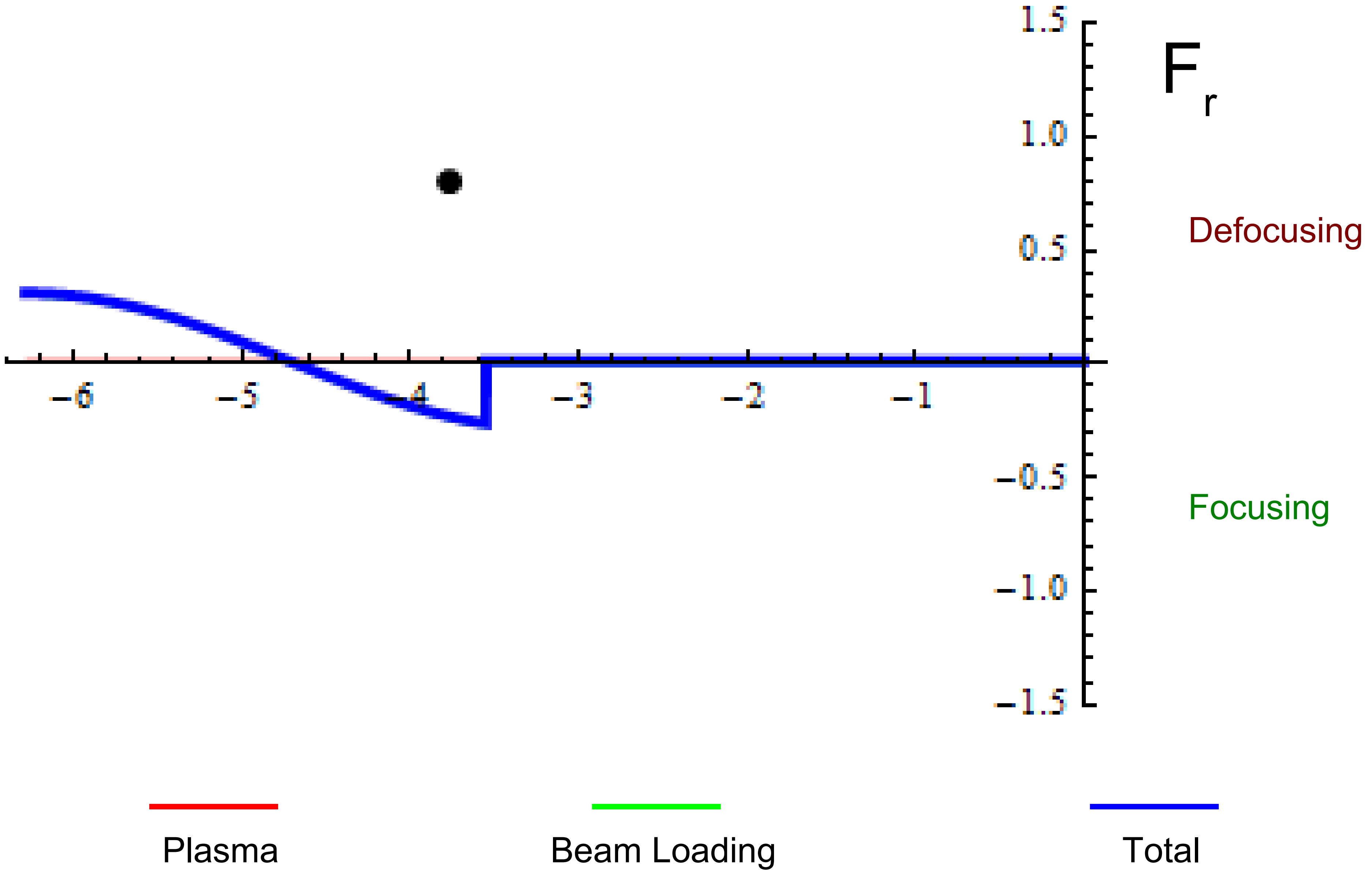
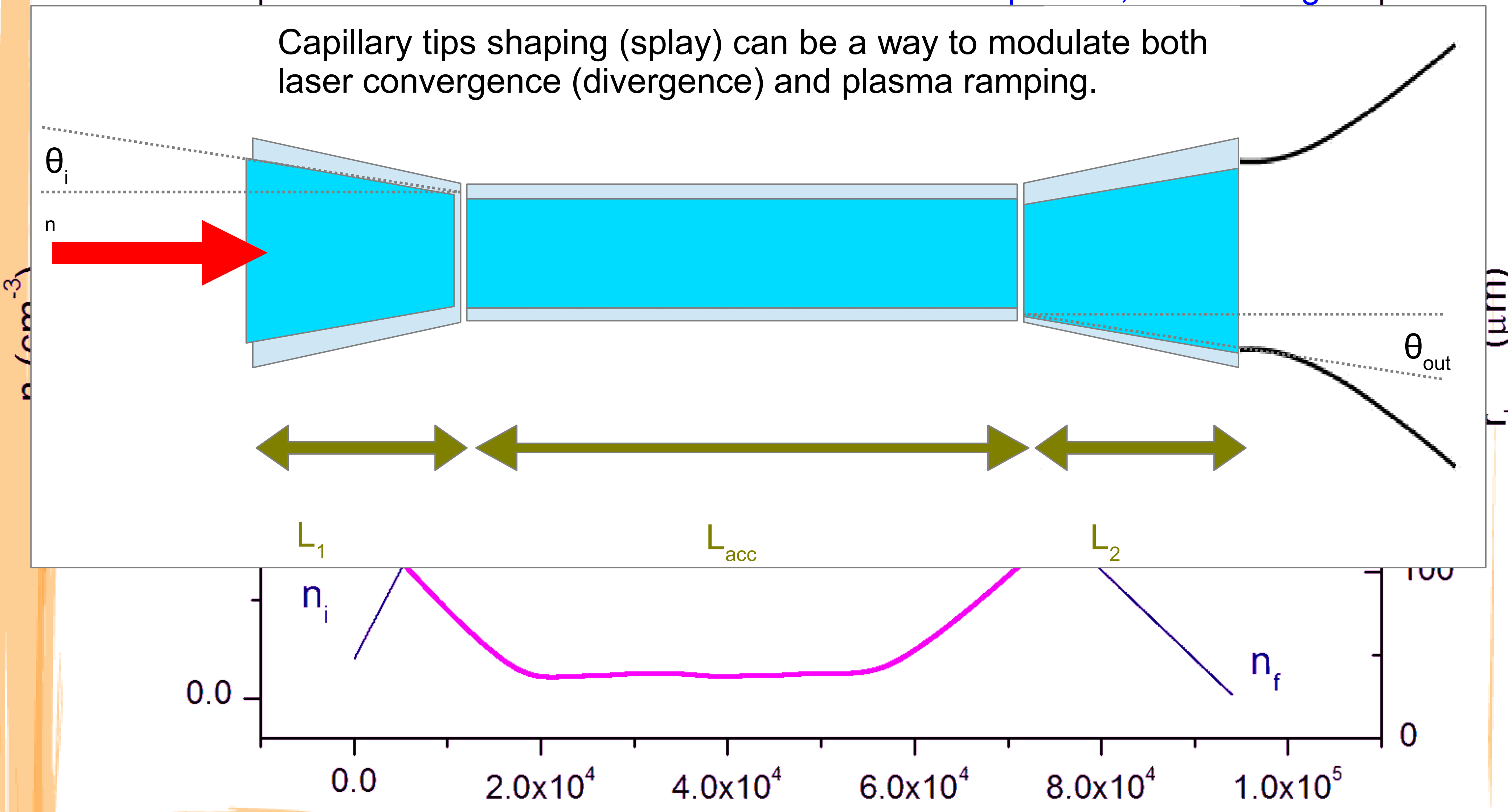
Matching strategy: the idea

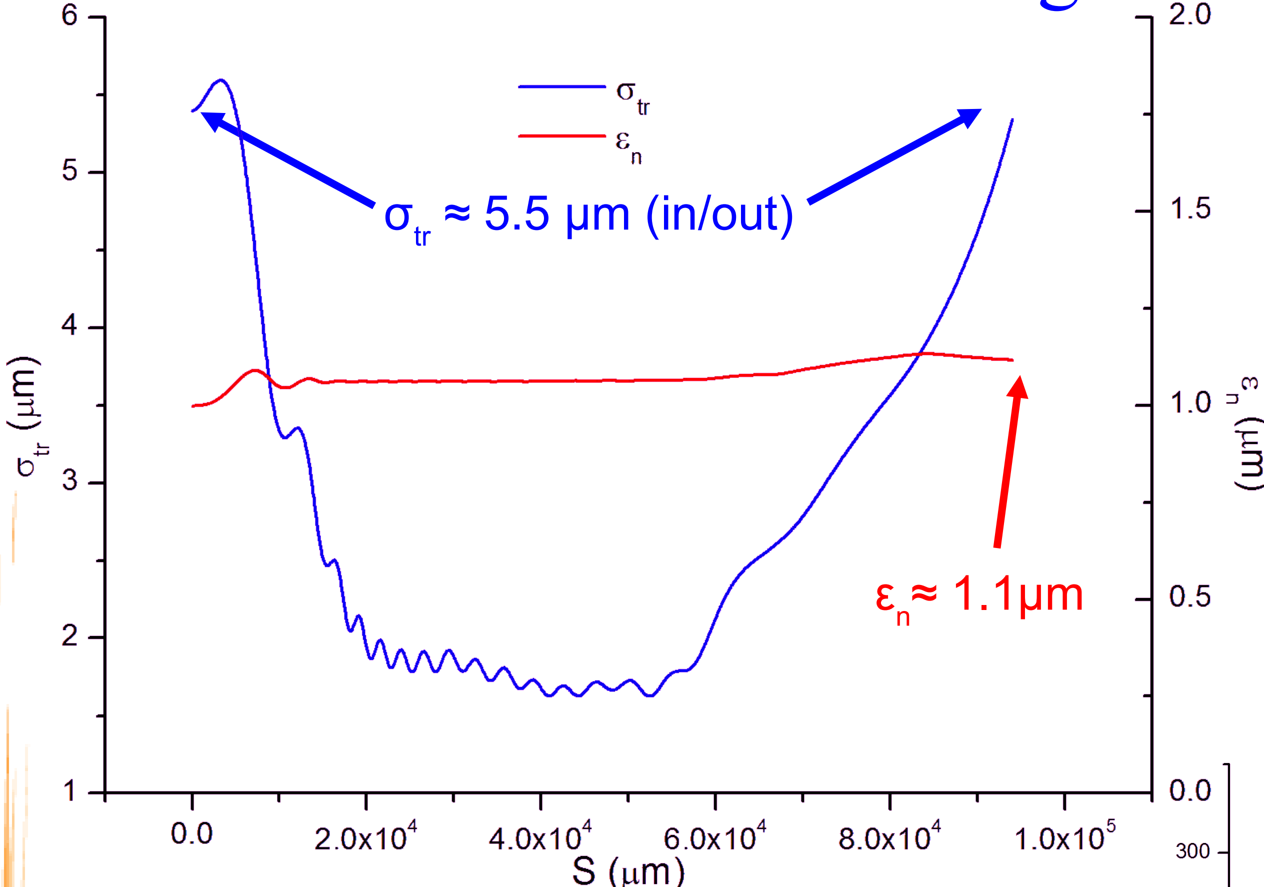


Simulation settings

We assume linear tapering for sake of simplicity. The incoming bunch is an **ideal** one with bi-Gaussian profiles, 17 fs long



Simulation results: matching and focusing/defocusing



Energy gain is in excess of 200 MeV in a 3 cm acceleration length, which means an average electric field in excess of

7 GV/m

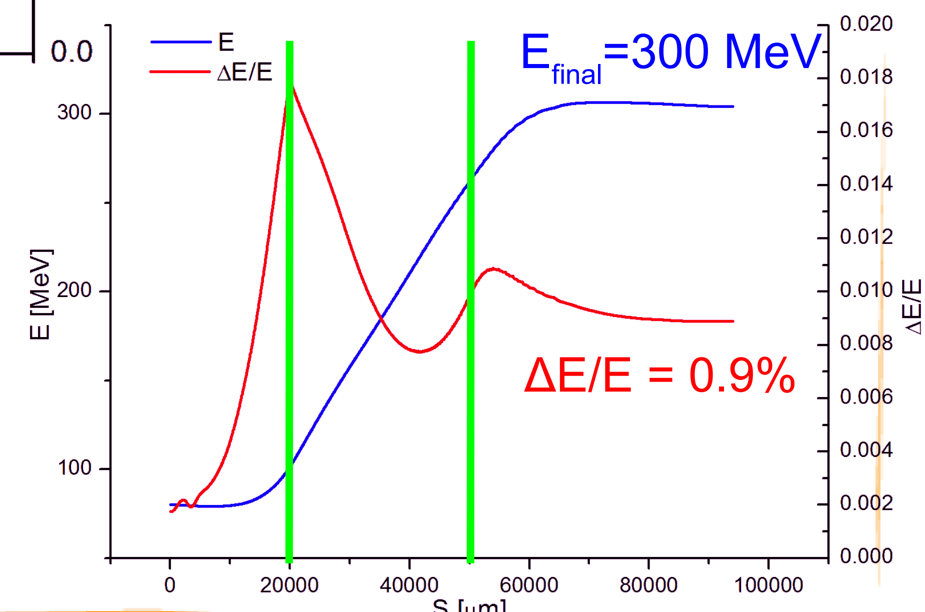
Energy spread is within 1% (a safe threshold for subsequent transport*) and REDUCED IN THE FINAL RAMP due to beam loading and plasma wavelength increase.

* P. Antici et al., J. App. Phys. 112, 044902 (2012).

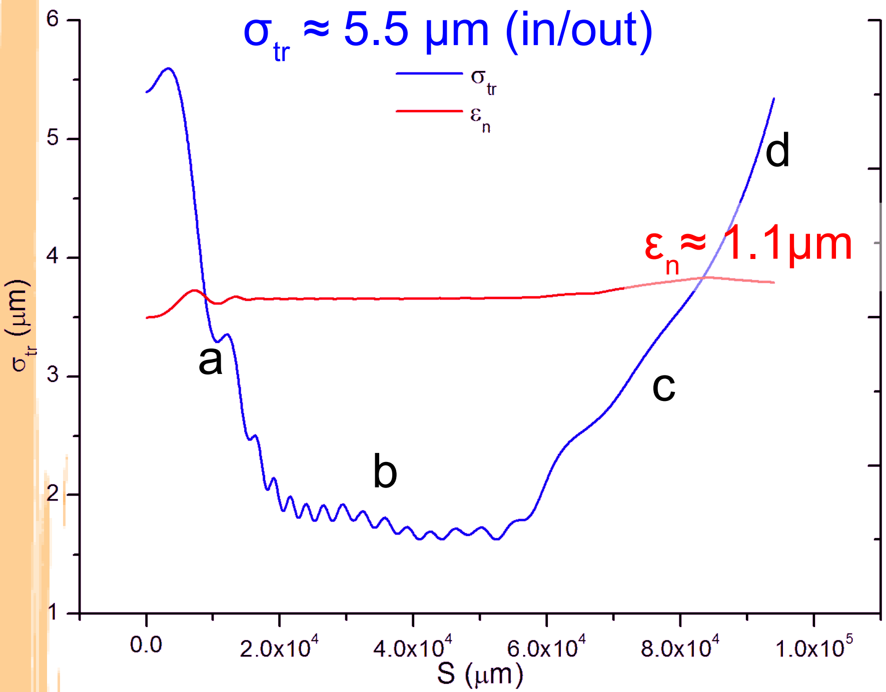
A very nice matching is obtained by laser focusing method.

Beam size is reduced to matched size and then increased back to initial value in a quasi-adiabatic transformation.

Both initial and final sizes seems to be within manageability of permanent magnet quads.



Simulation results: effects of beam loading

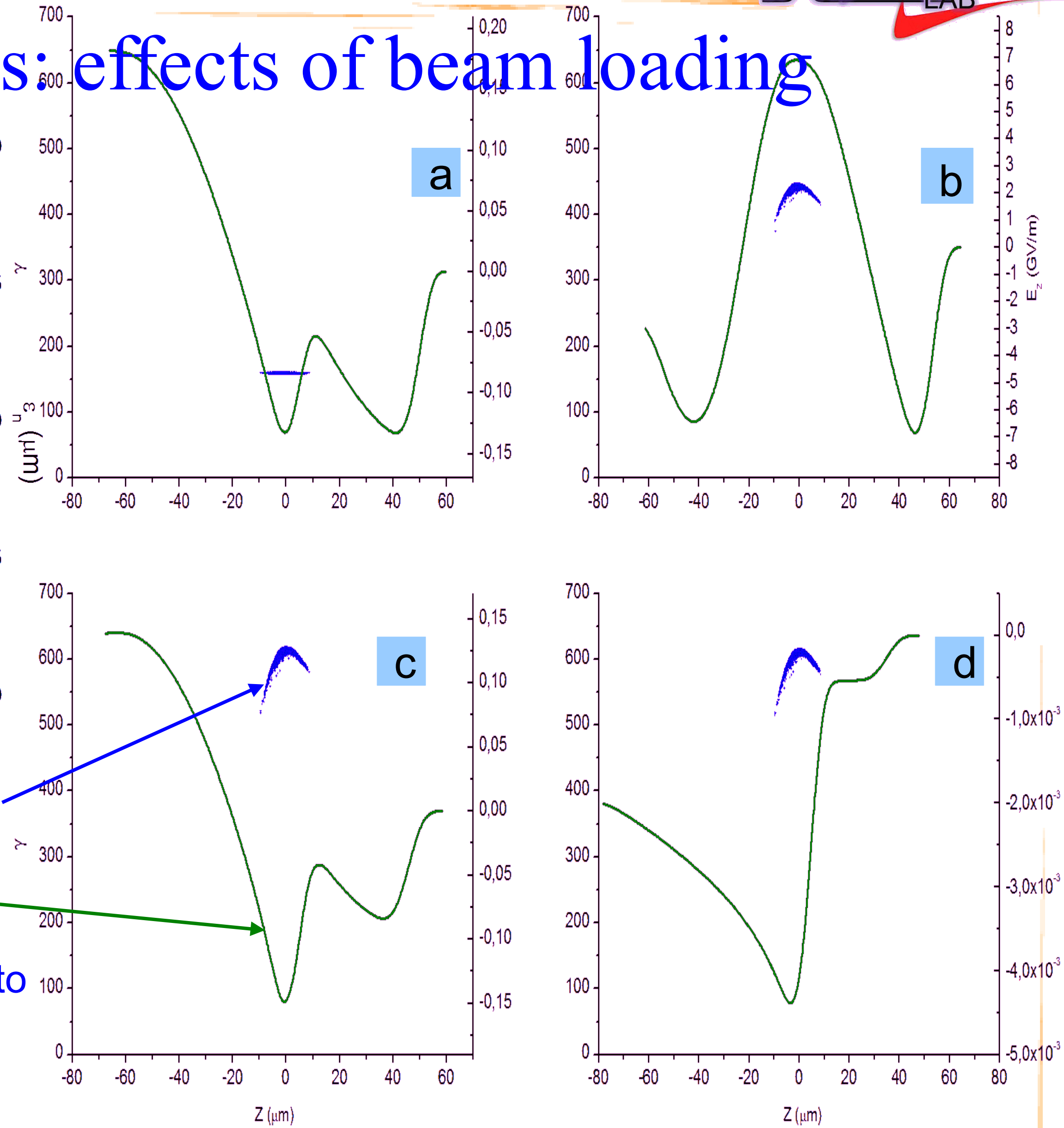


E_{final}=300 MeV

$\Delta E/E$ < 1%

Long. phase space

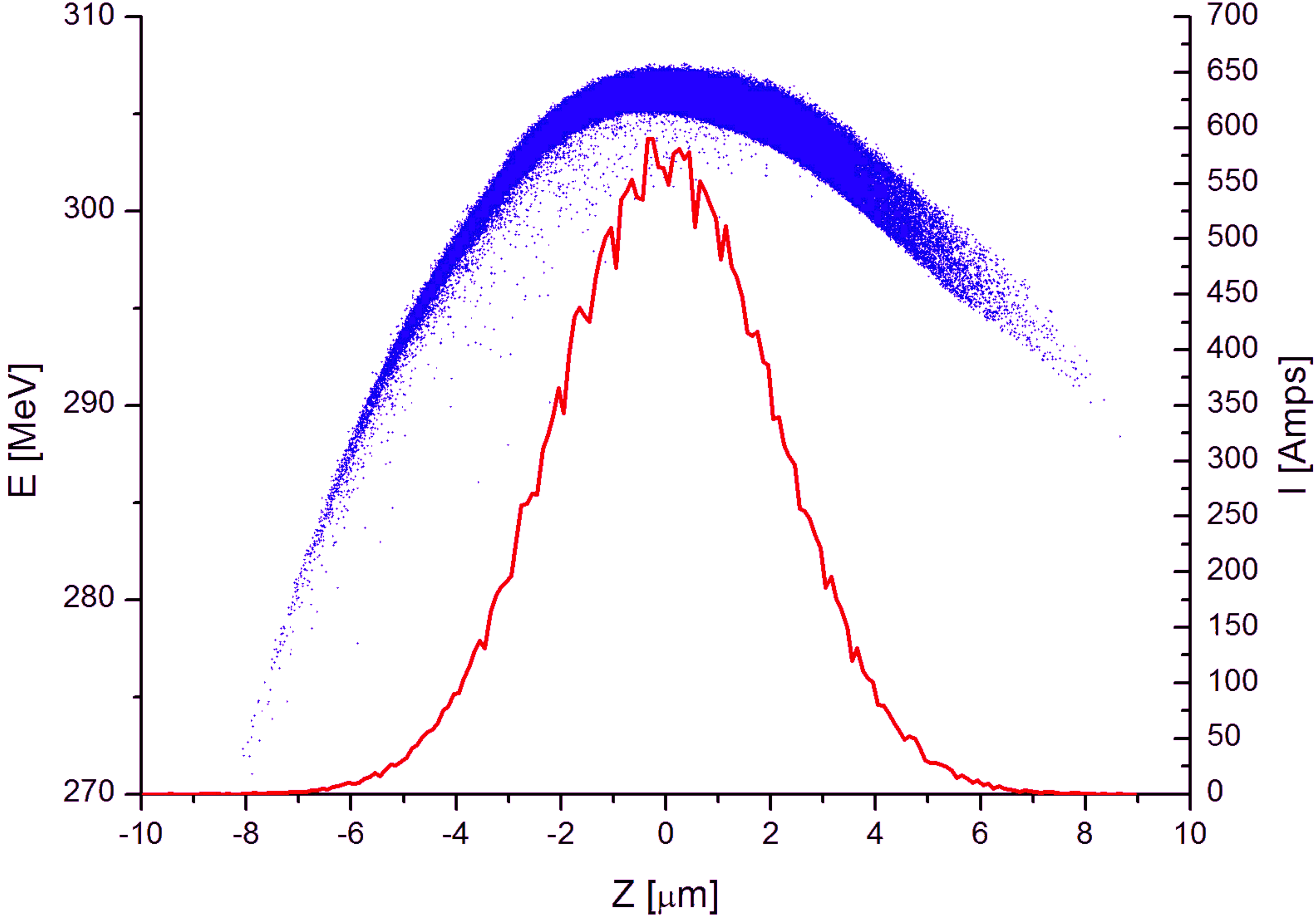
E_z



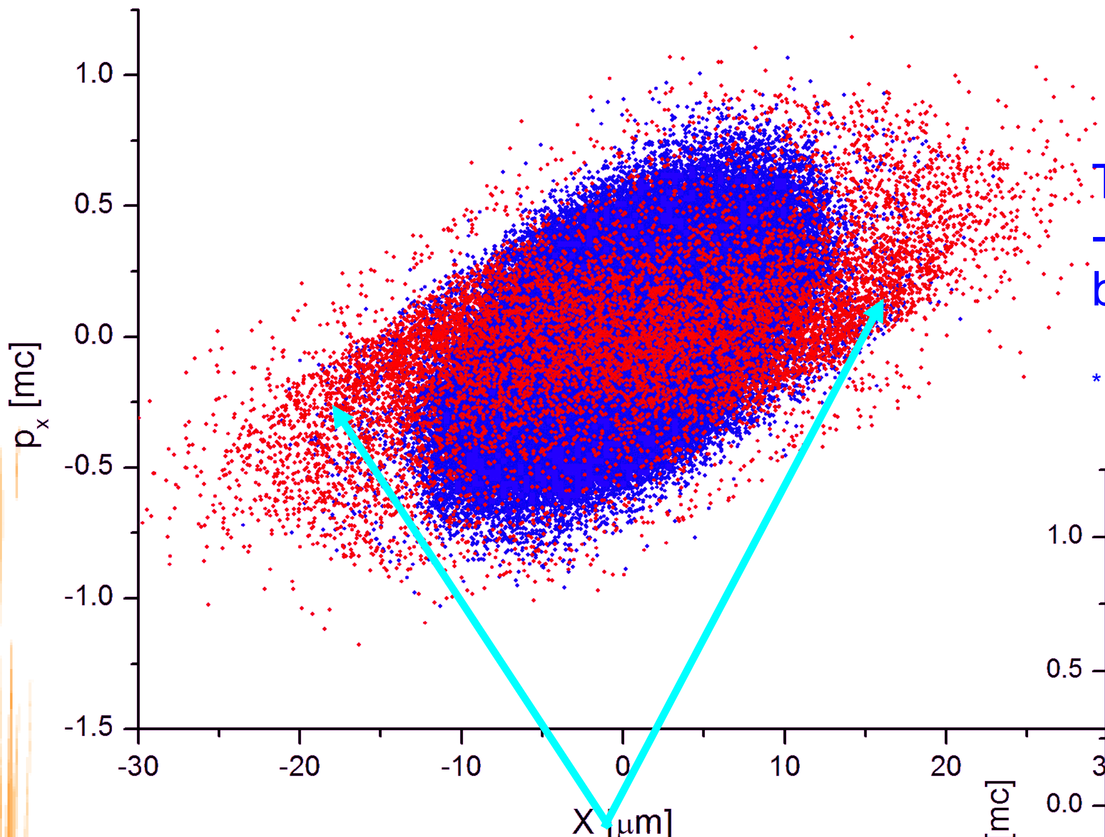
The plasma wave regime goes from linear to quasi linear and back to linear.

Beam loading has a varying impact on beam dynamics and helps to reduce final emittance and energy spread, being relevant when the plasma wavelength is such that the bunch would experience defocusing fields.

Simulation results: final beam

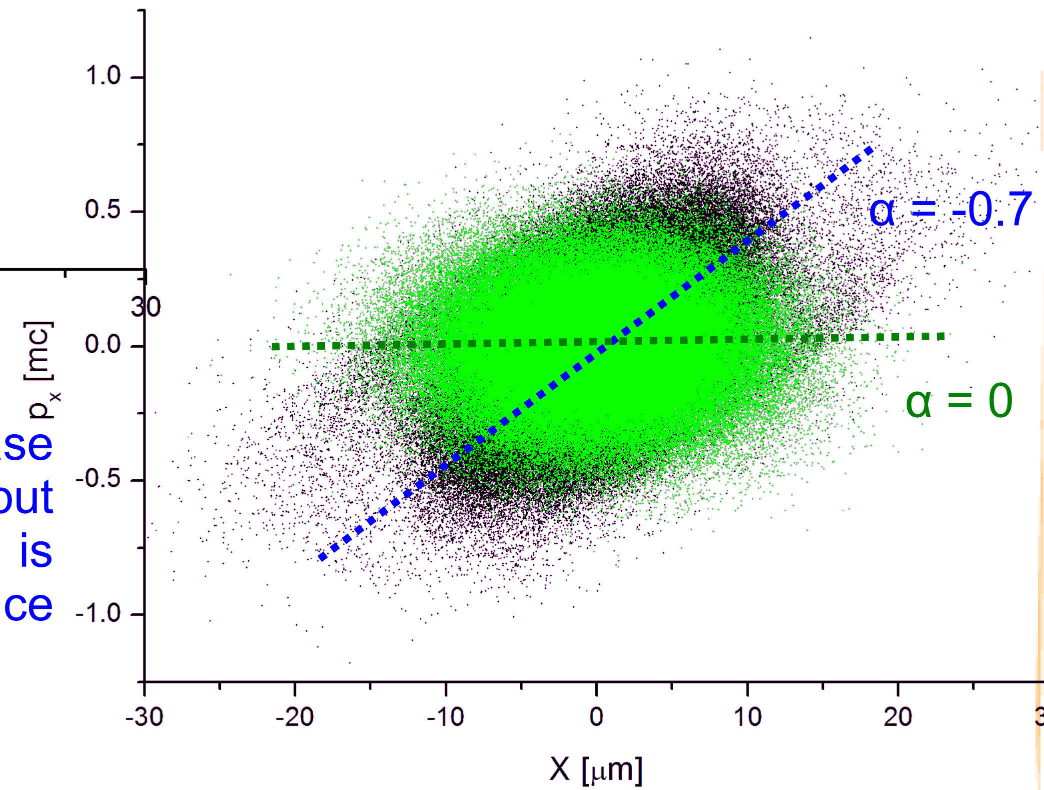


Simulation results: final beam



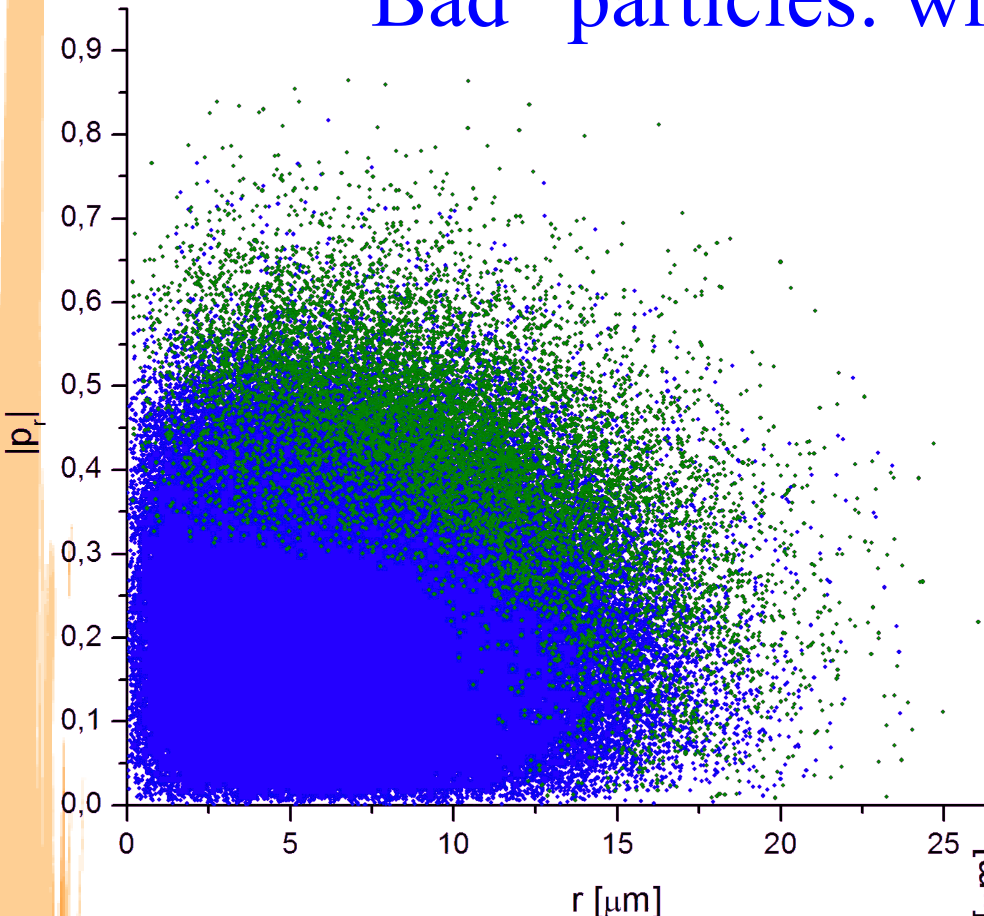
The final Twiss parameter α has a value of -0.7. With a little more effort should be brought to -1*

* K. Floettmann, PRSTAB 17, 054402 (2014).

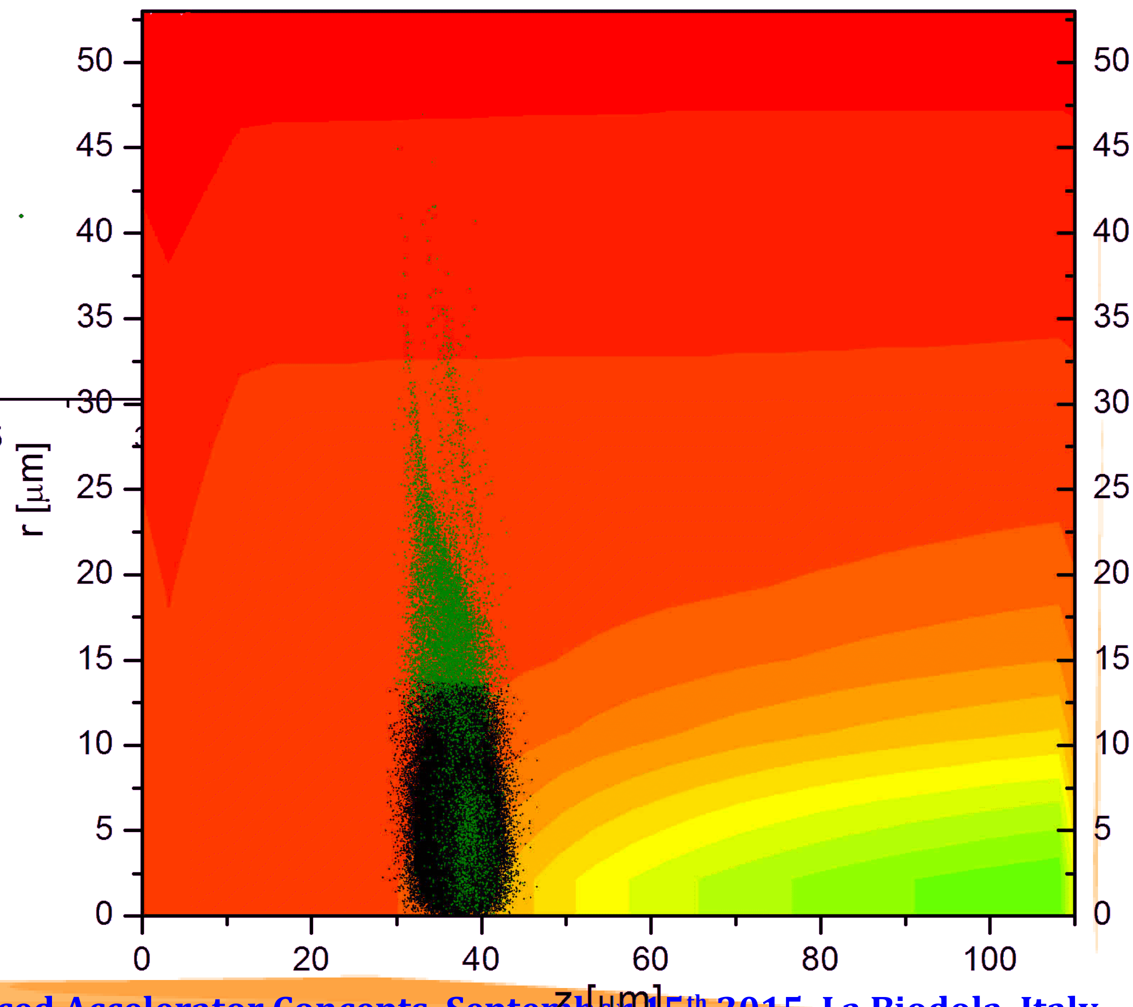


A slight non-linearity in transverse phase space builds up since initial focusing, but only 5% of charge is involved, even if it is responsible for most of the emittance increase.

“Bad” particles: where do they come from?

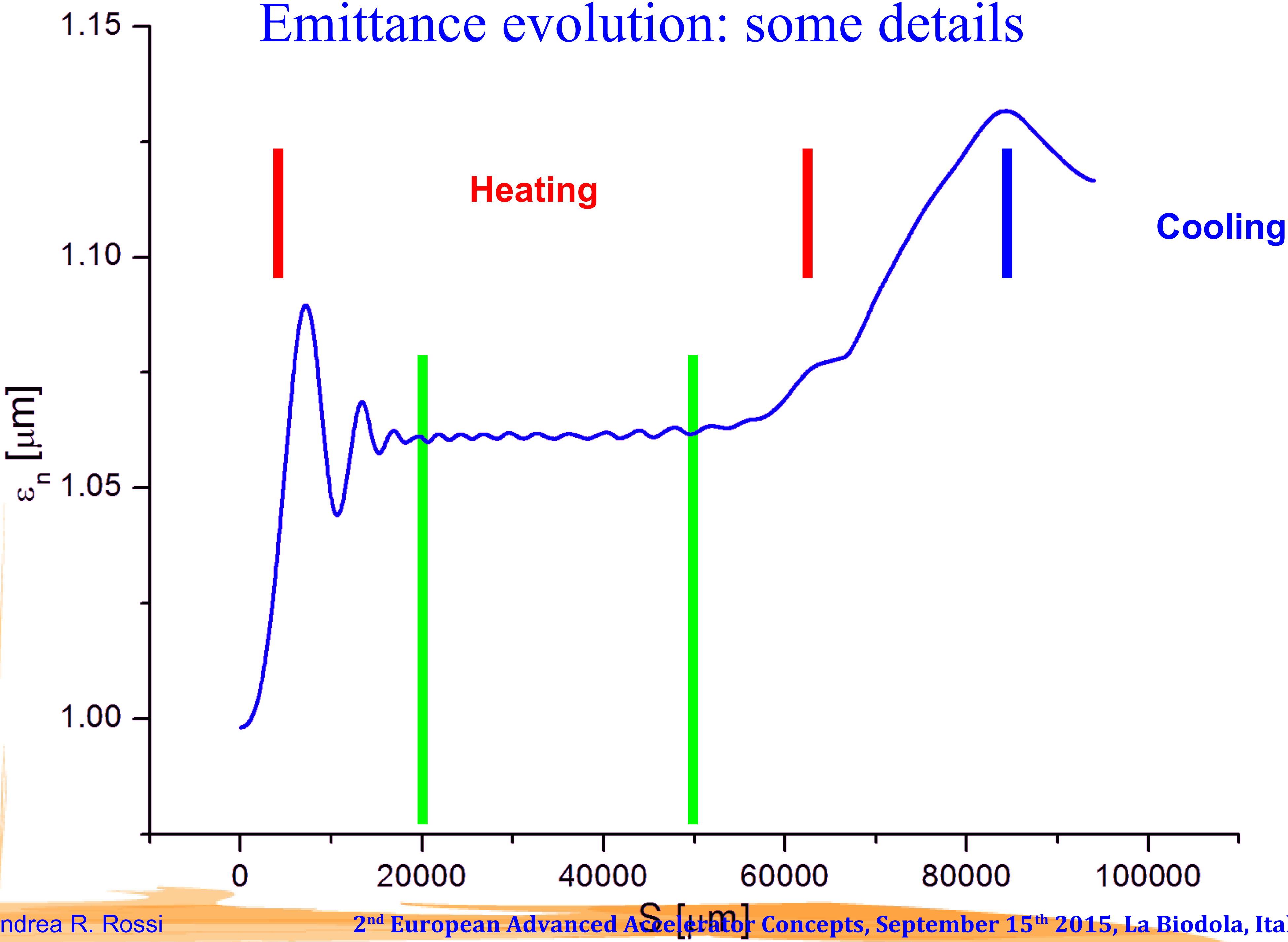


Why are they bad? Because, when beam loading dominates the plasma wave, they are eventually expelled from the (beam-driven) wave and start to drift in the neutral plasma.

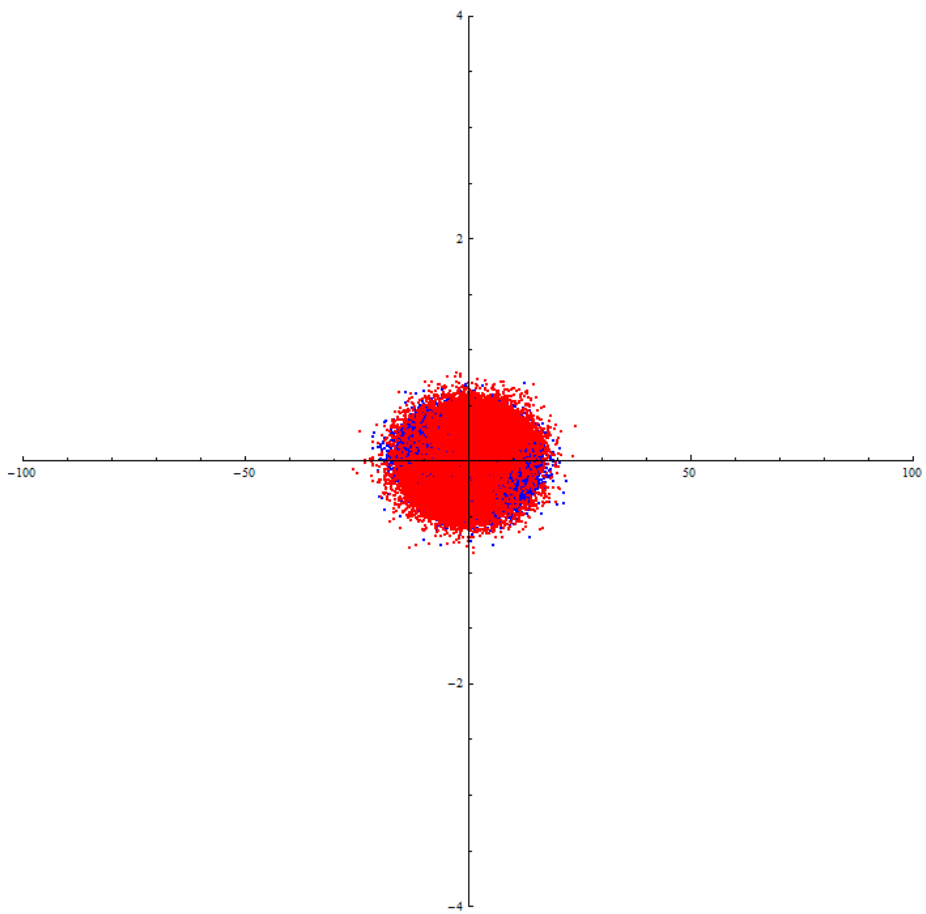


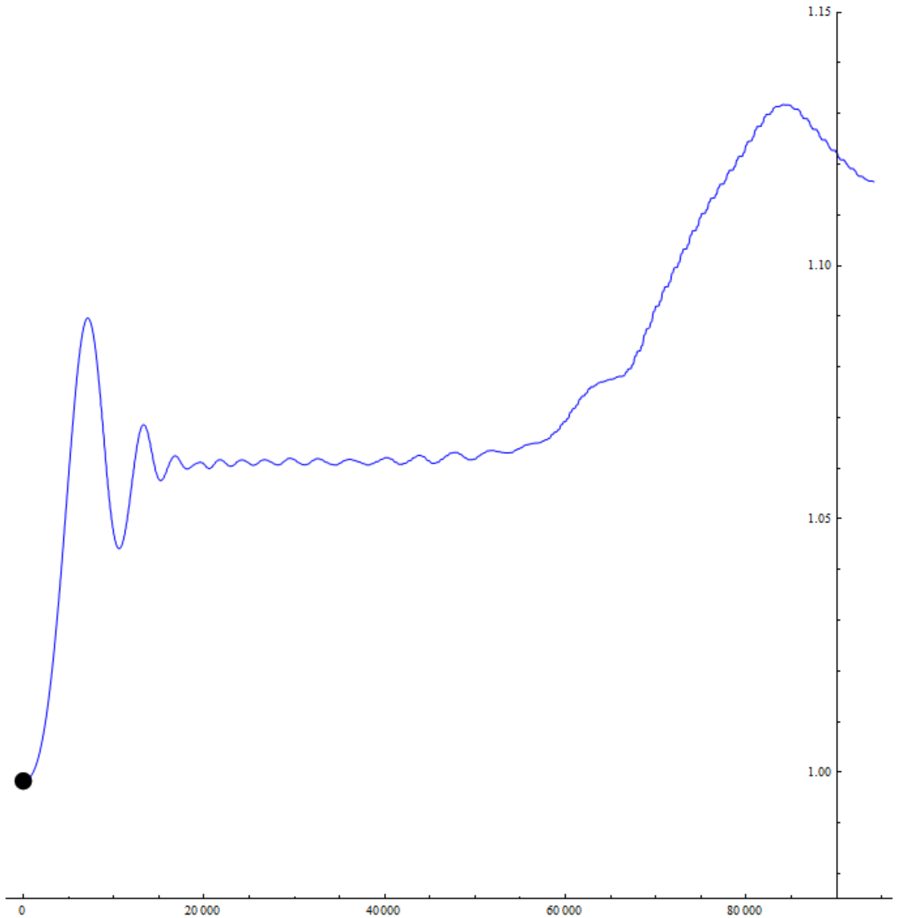
The “bad” particles, in the initial r-$|p_r|$ phase space, are around the outer edge of the distribution, i.e. large transverse position and/or transverse momentum.

Emittance evolution: some details

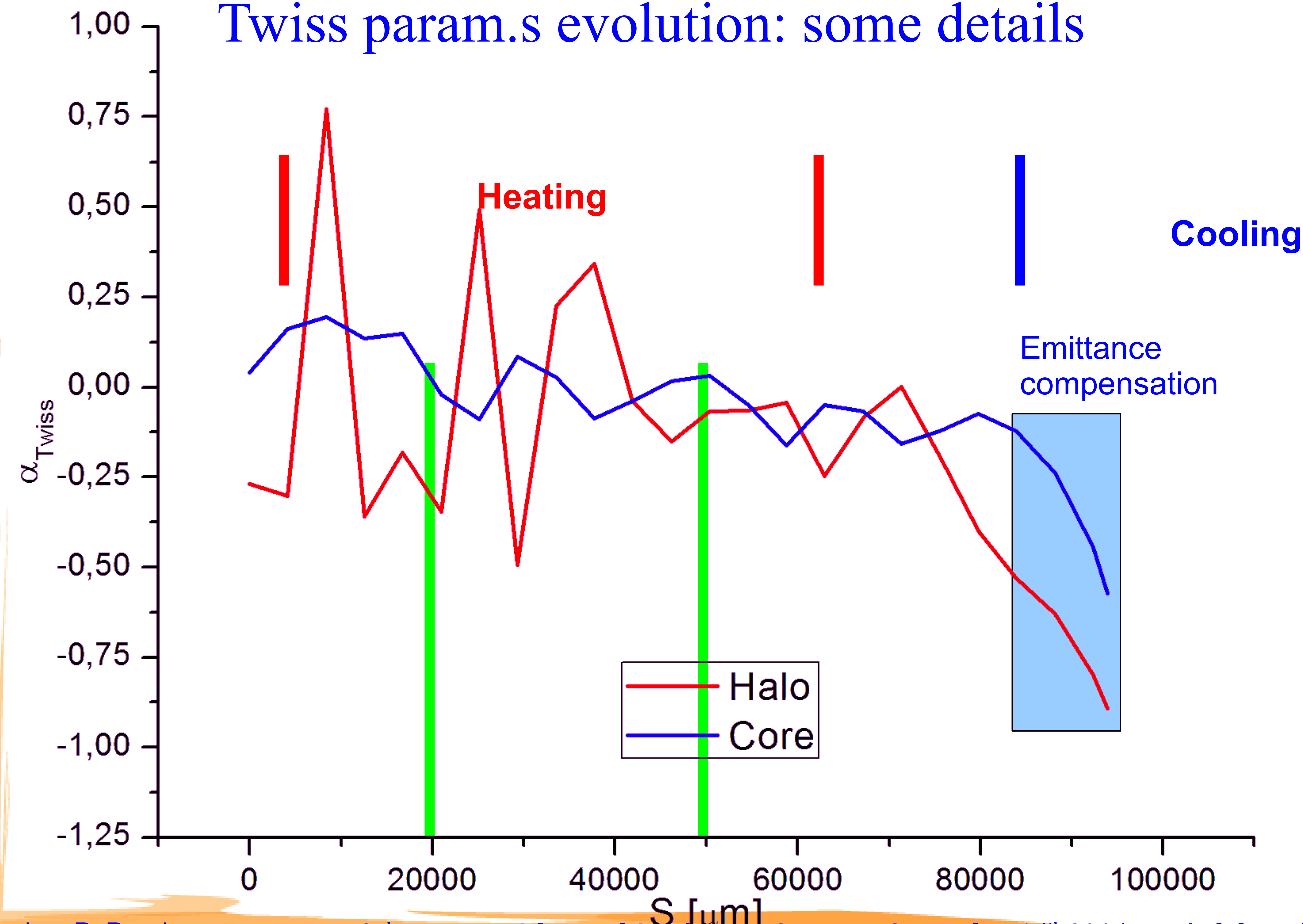


Emittance evolution: what's going on?





Twiss param.s evolution: some details



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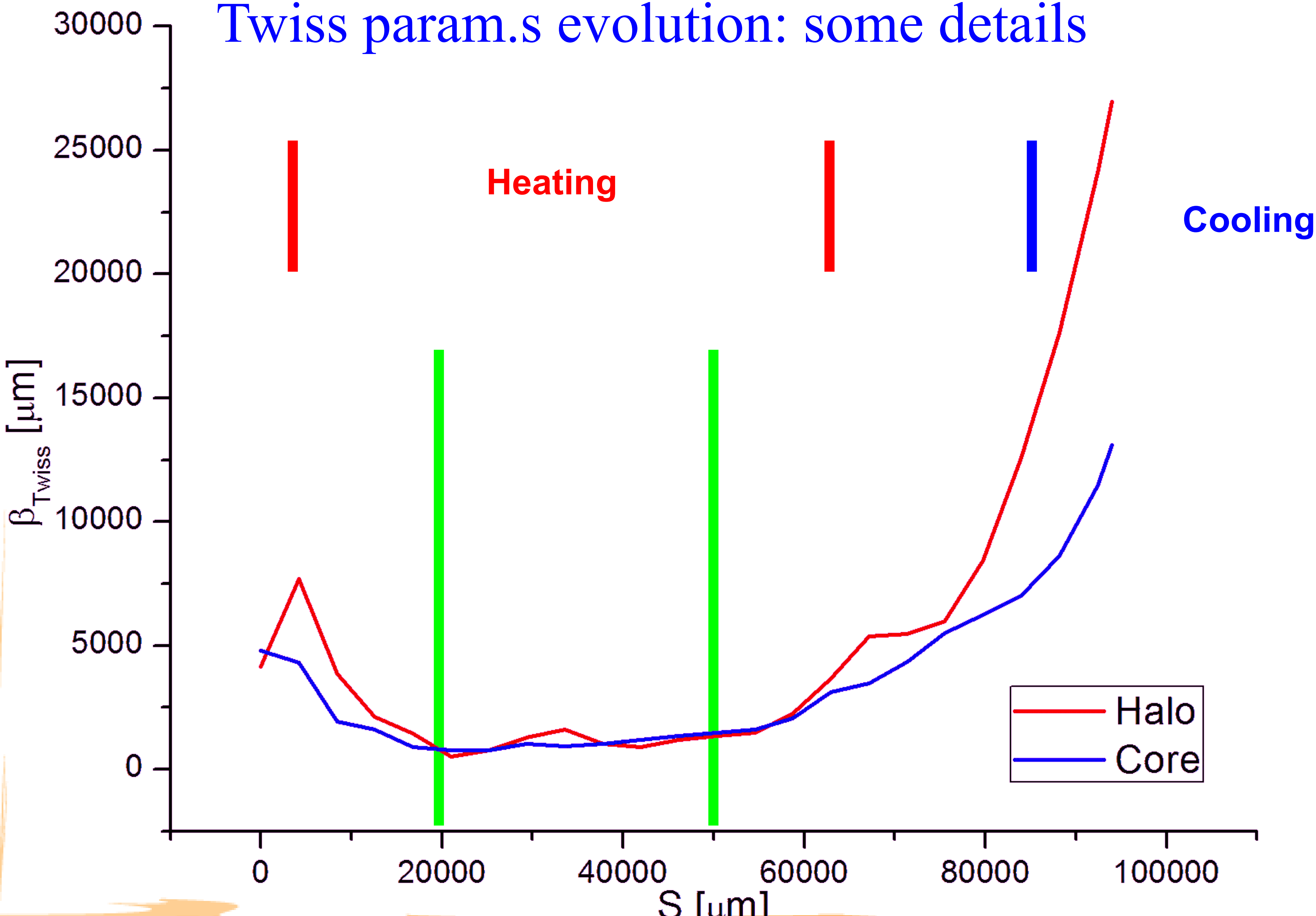

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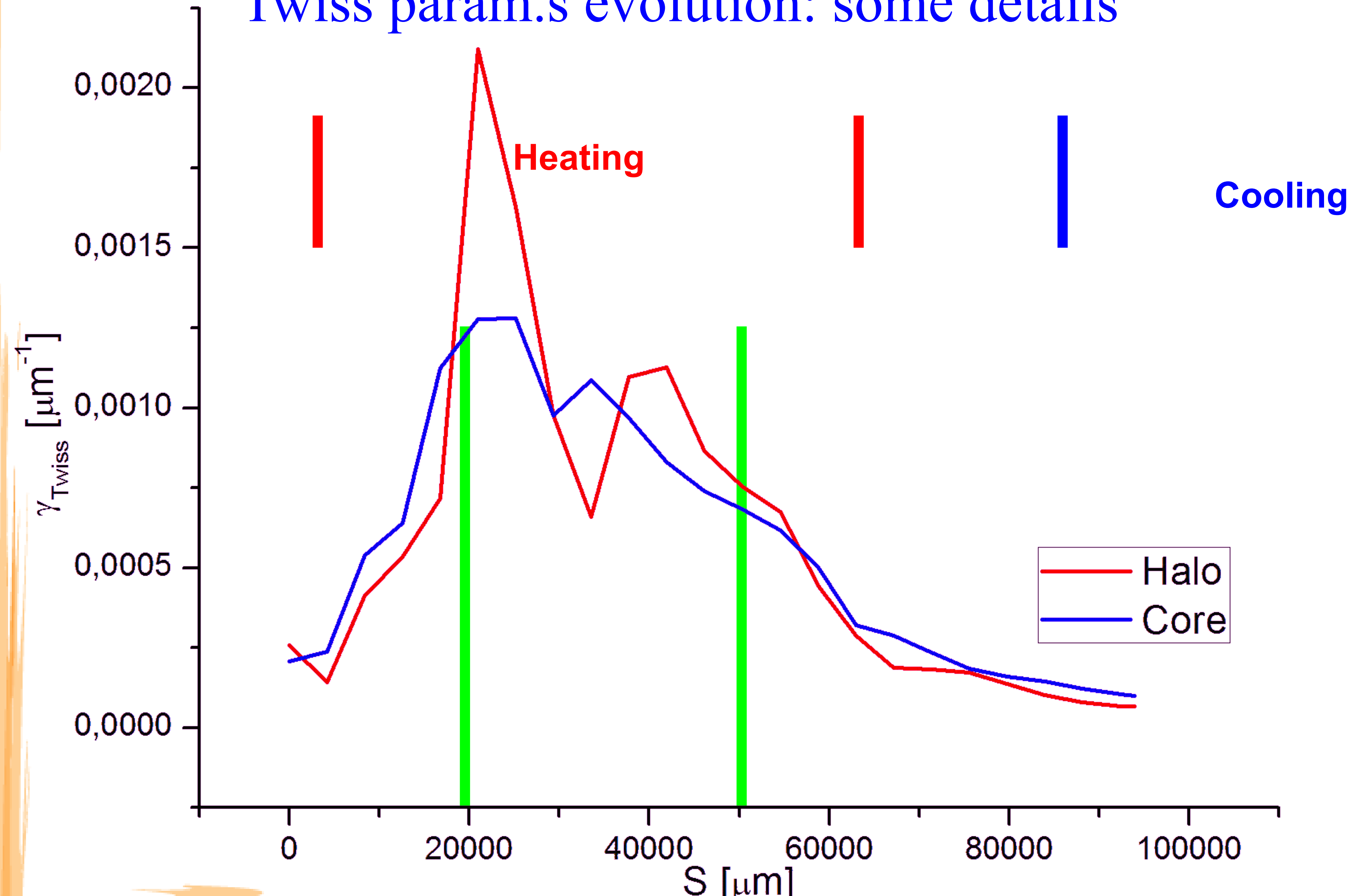
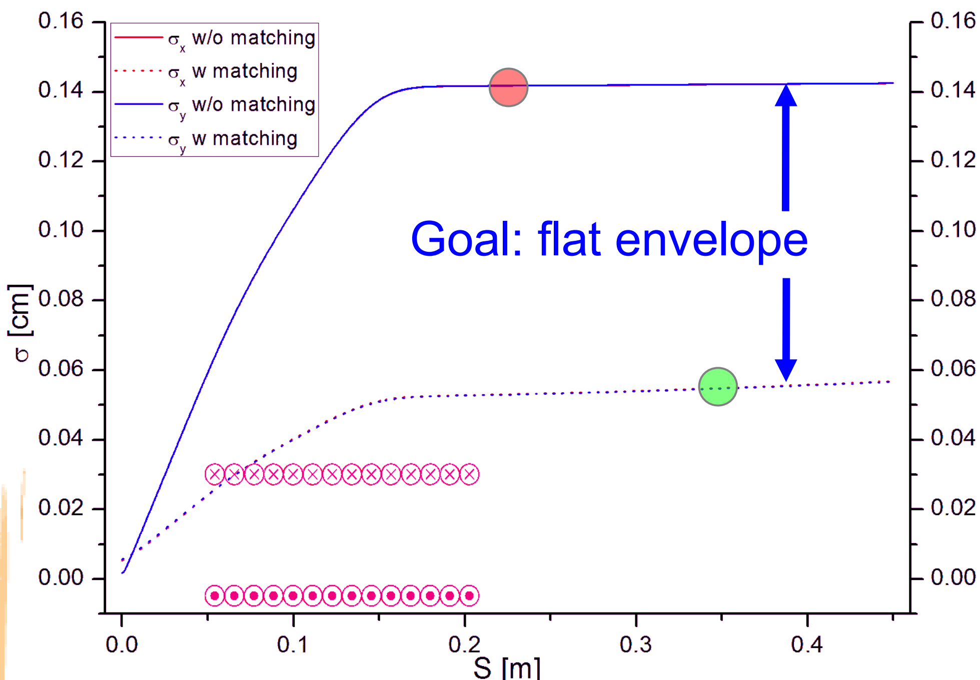
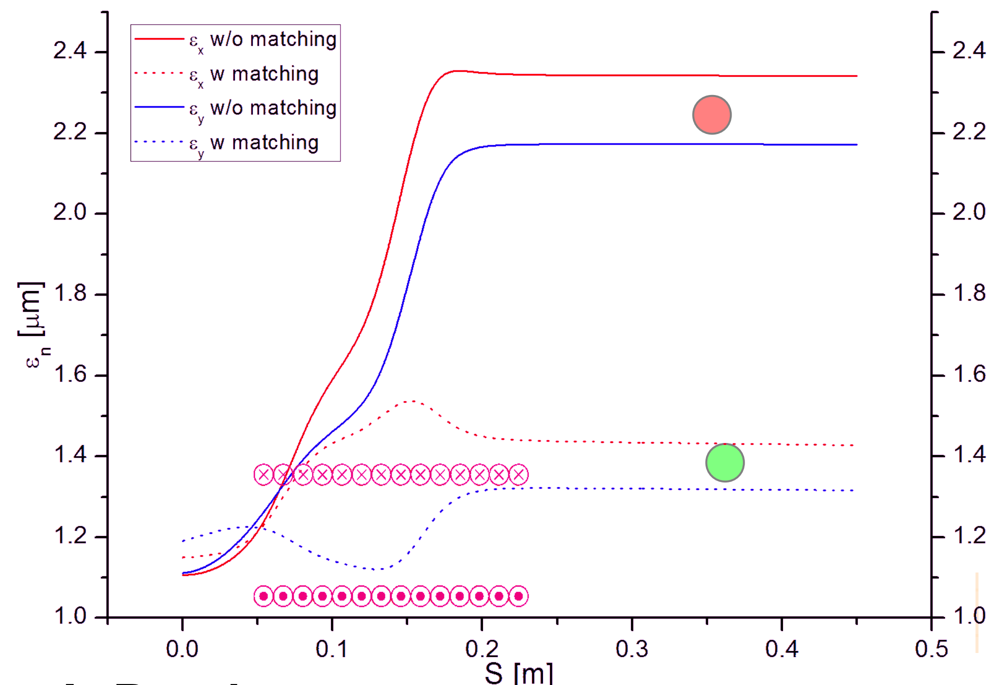


Simulation results: post acceleration transport

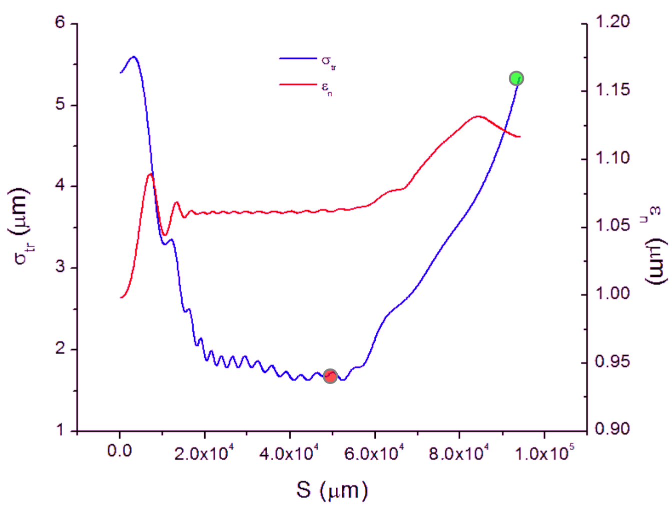


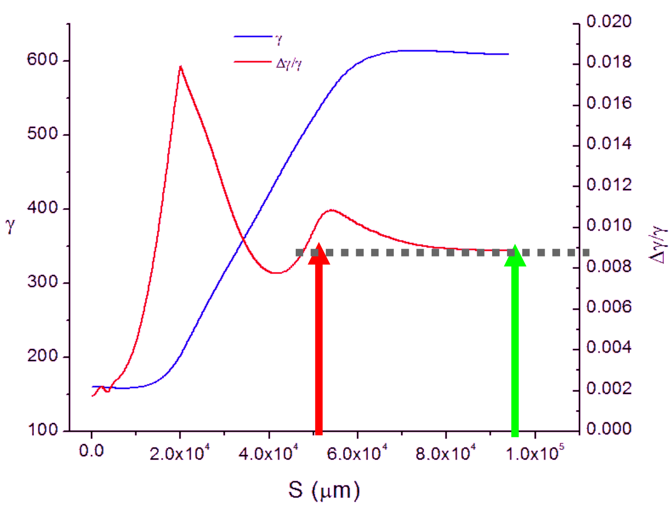


Simulations by A. Bacci

Focusing is performed with a 18 cm long solenoid (same focusing as PMQ). The solenoid is ≈ 5 cm from plasma.

Both beams start with about the same energy spread. The **matched** one behaves in a much better way than the **unmatched**





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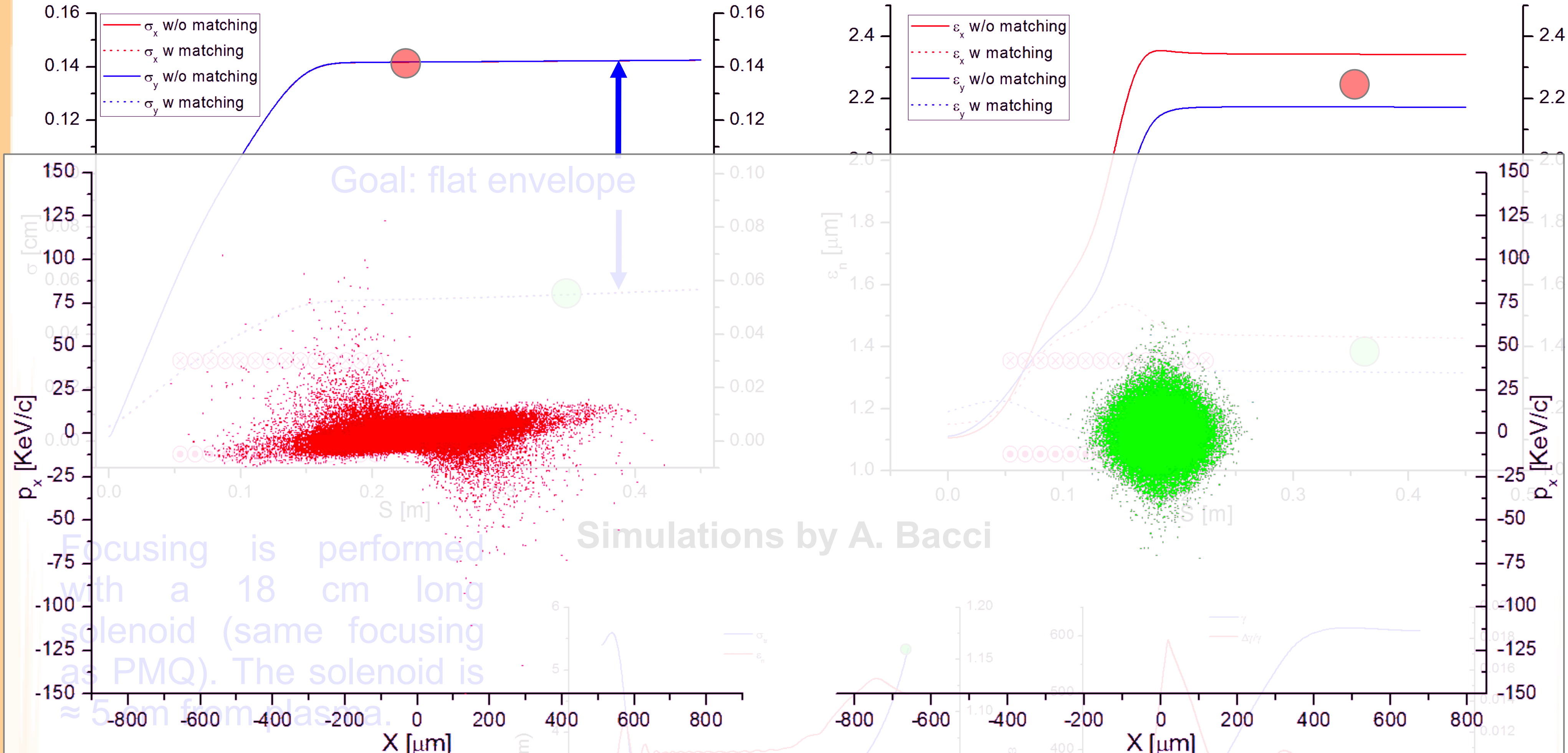

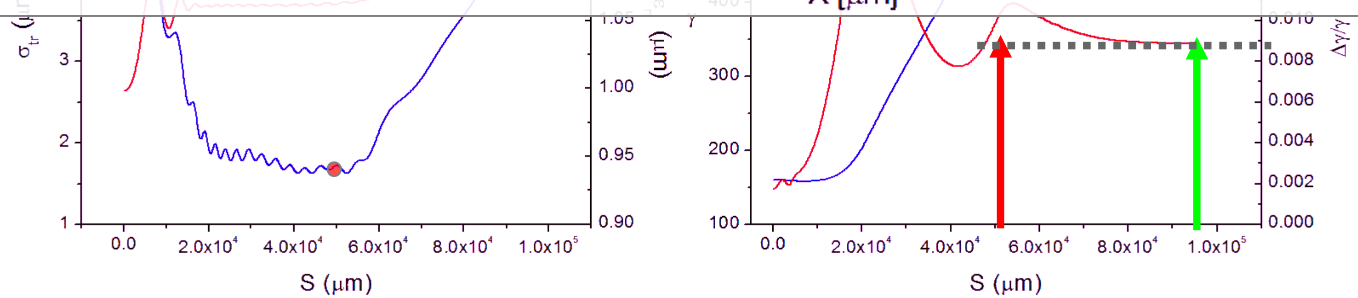

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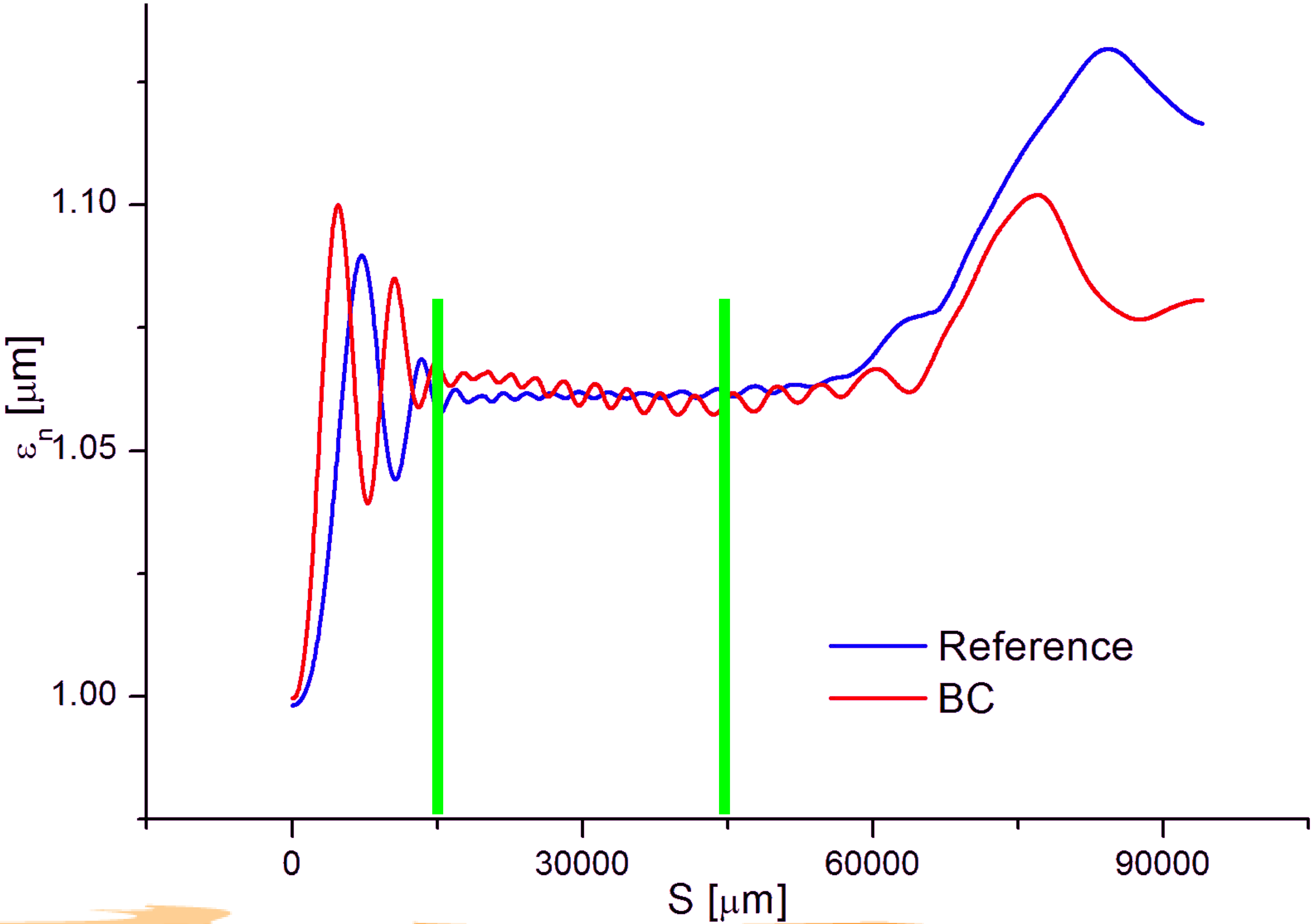
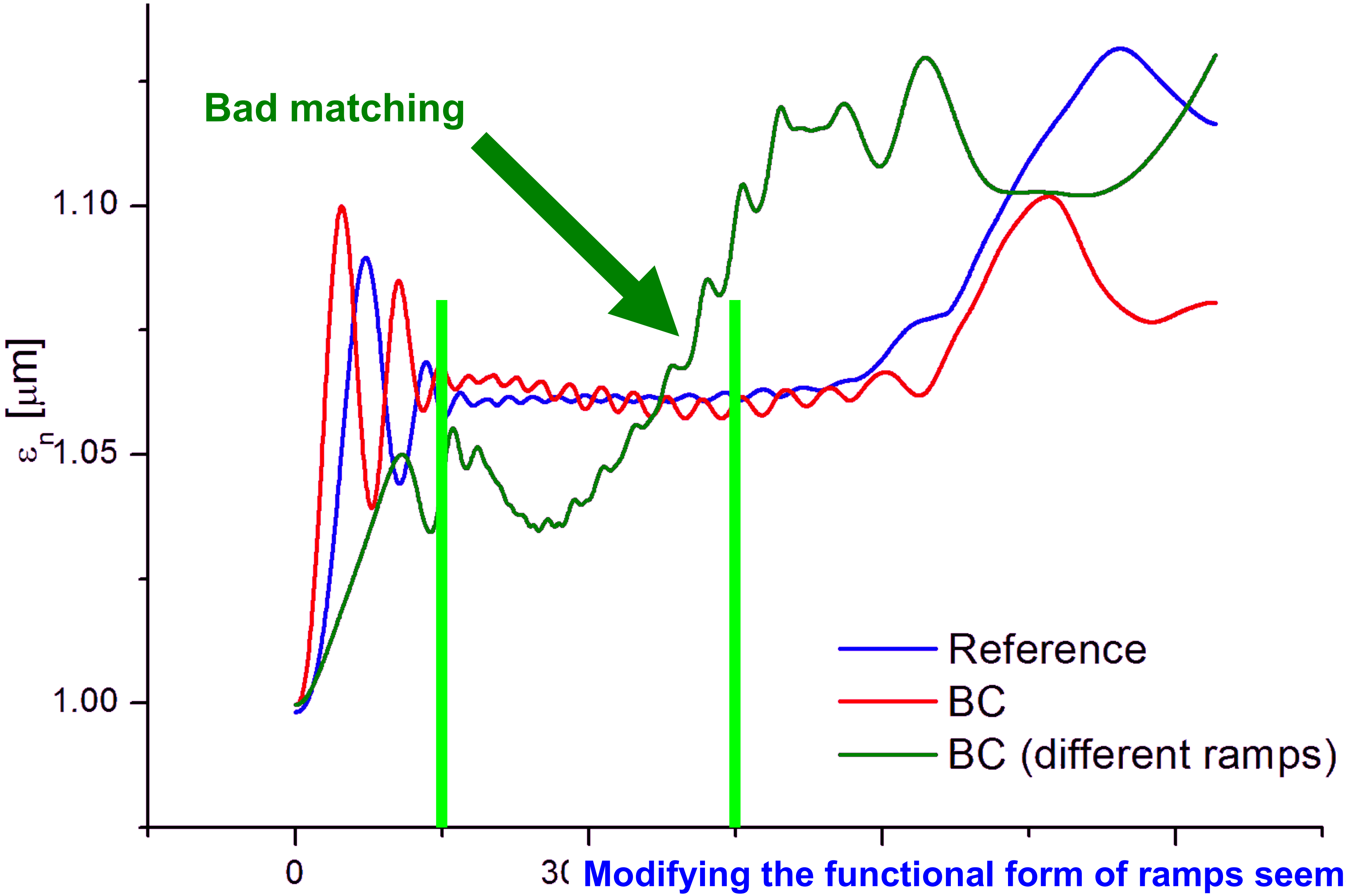
Stability: Reference vs Beer Can (BC, *ceteris paribus*)

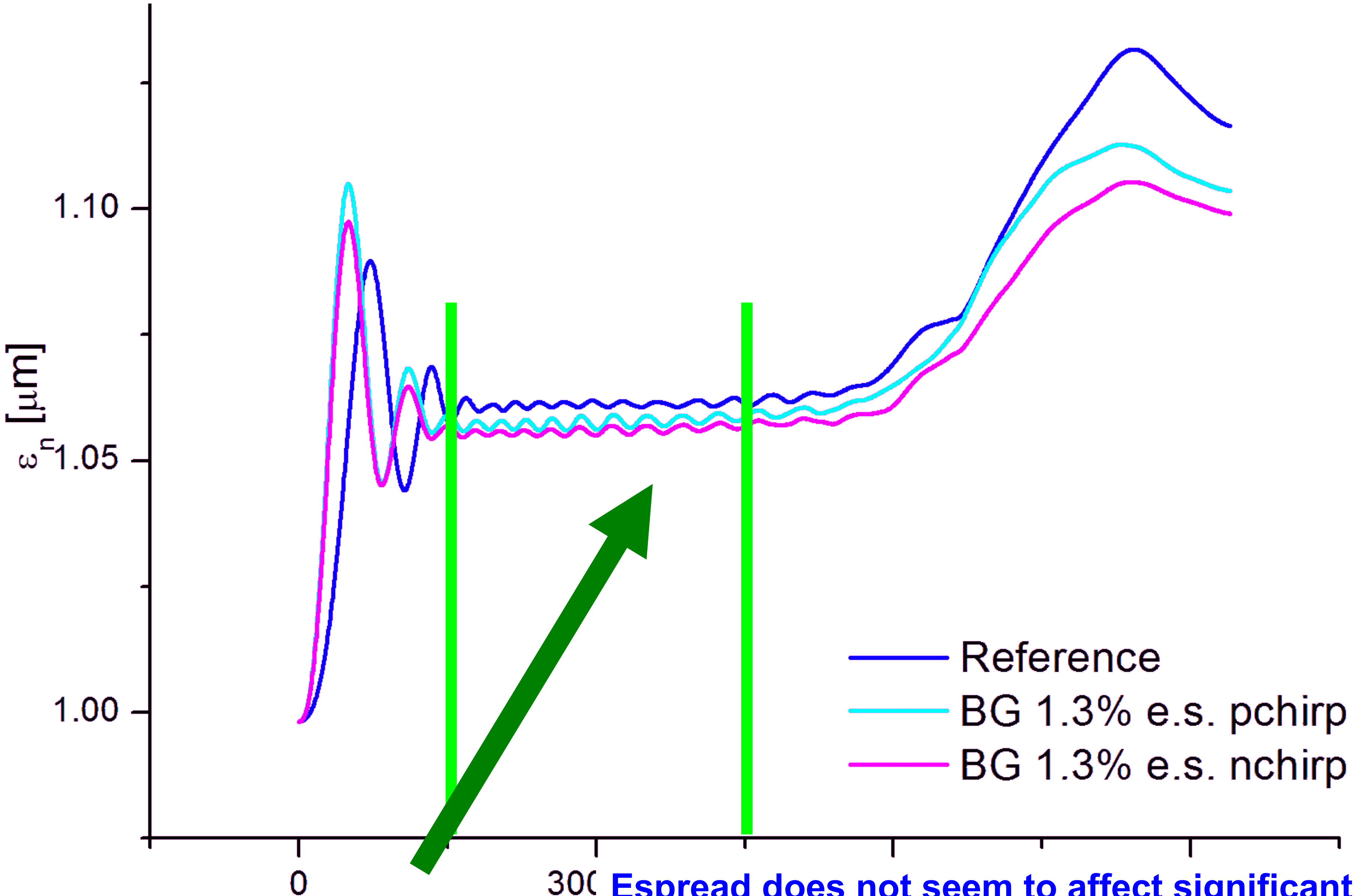


Stability: Reference vs BC vs BC with different ramps



Modifying the functional form of ramps seems to be a way to improve results, as expected

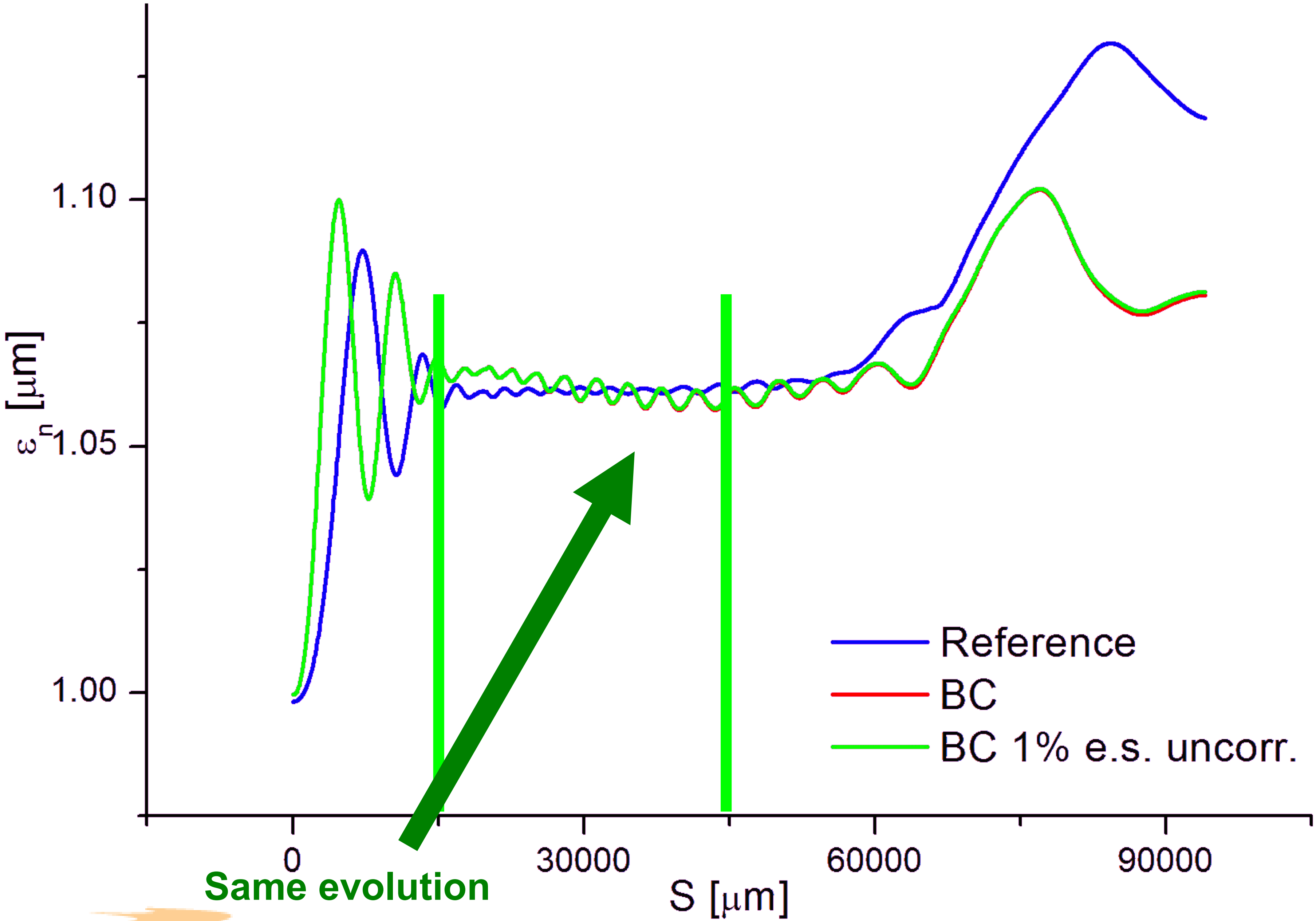
Stability: Reference vs BG with 1.3% e.s. pchirp/nchirp



Almost same *emittance* evolution

Espread does not seem to affect significantly matching and *emittance* evolution

Stability: Reference vs BC vs BC 1% uncorr. e.s.



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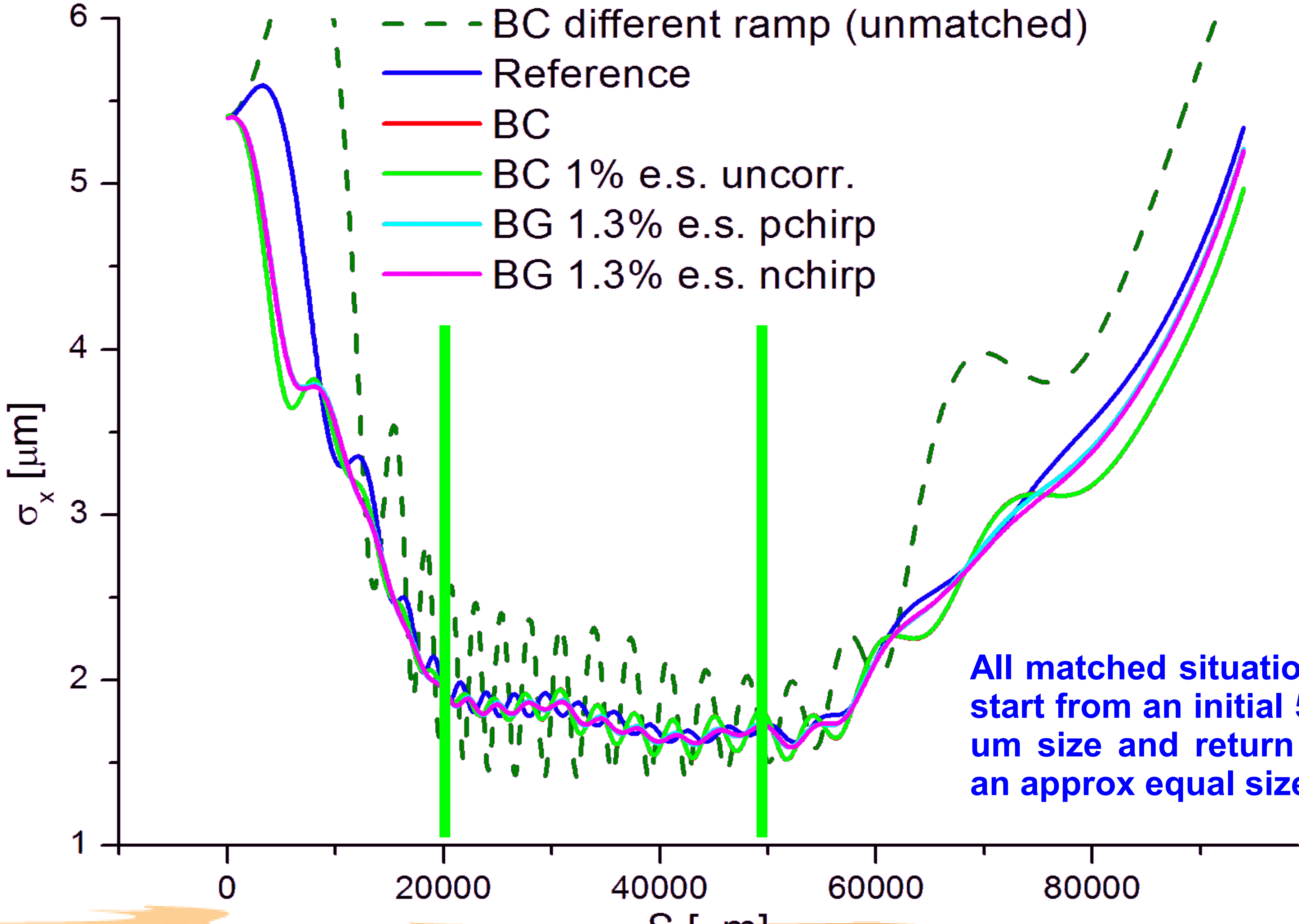
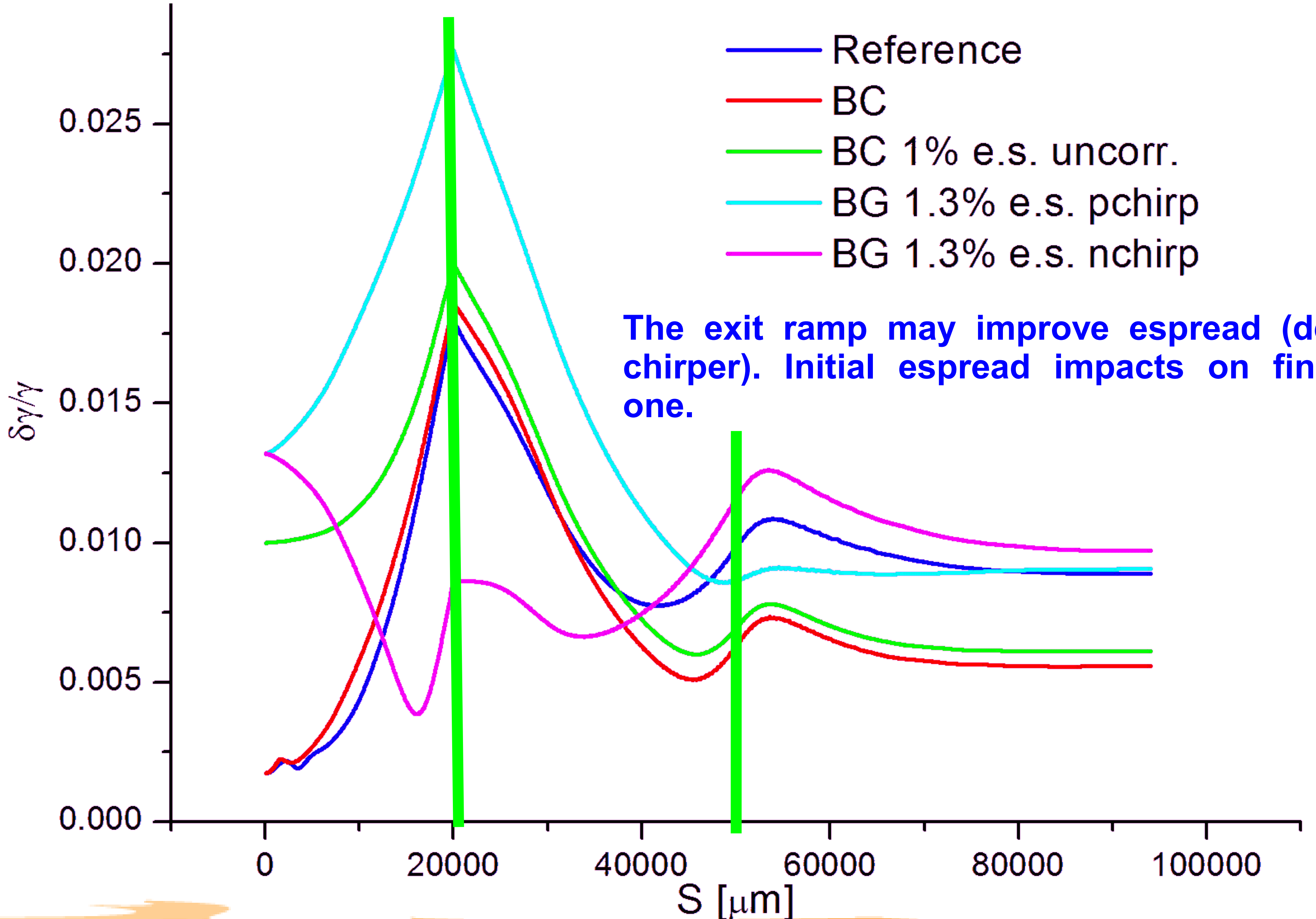
Transverse size evolution



All matched situations start from an initial 5.5 um size and return to an approx equal size

Espread evolution



The exit ramp may improve espread (de-chirper). Initial espread impacts on final one.

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Conclusions

- We showed a method to match an electron beam in/out a laser driven plasma accelerating stage.
- The method consist in exploiting both plasma density ramps and laser (de)focusing switching from a beam driven wave to a laser driven wave and back to a beam driven wave; this allows to avoid problems from varying plasma wavelength at density ramps.
- The method, applied to an ideal beam, showed to be effective and robust against some changes in beam distribution and allows to relax requirements on conventional focusing devices.
- The whole process can be further optimized by changing splay angles and/or shapes.
- The effect of the splays and their shape on plasma ramps profiles must be checked by dedicated simulations.

Thanks for your attention!

Backup slides

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S2E simulation: plasma acceleration

Simulation tool: QFLUID2 by P. Tomassini and A.R. Rossi

- 2D cylindrical.
- Fluid approximation for plasma.
- Bunch macroparticles are fully kinetic.
- Supports quasi linear regimes.
- Laser evolution is self consistent and uses envelope approximation.
- Beam loading effects are included.

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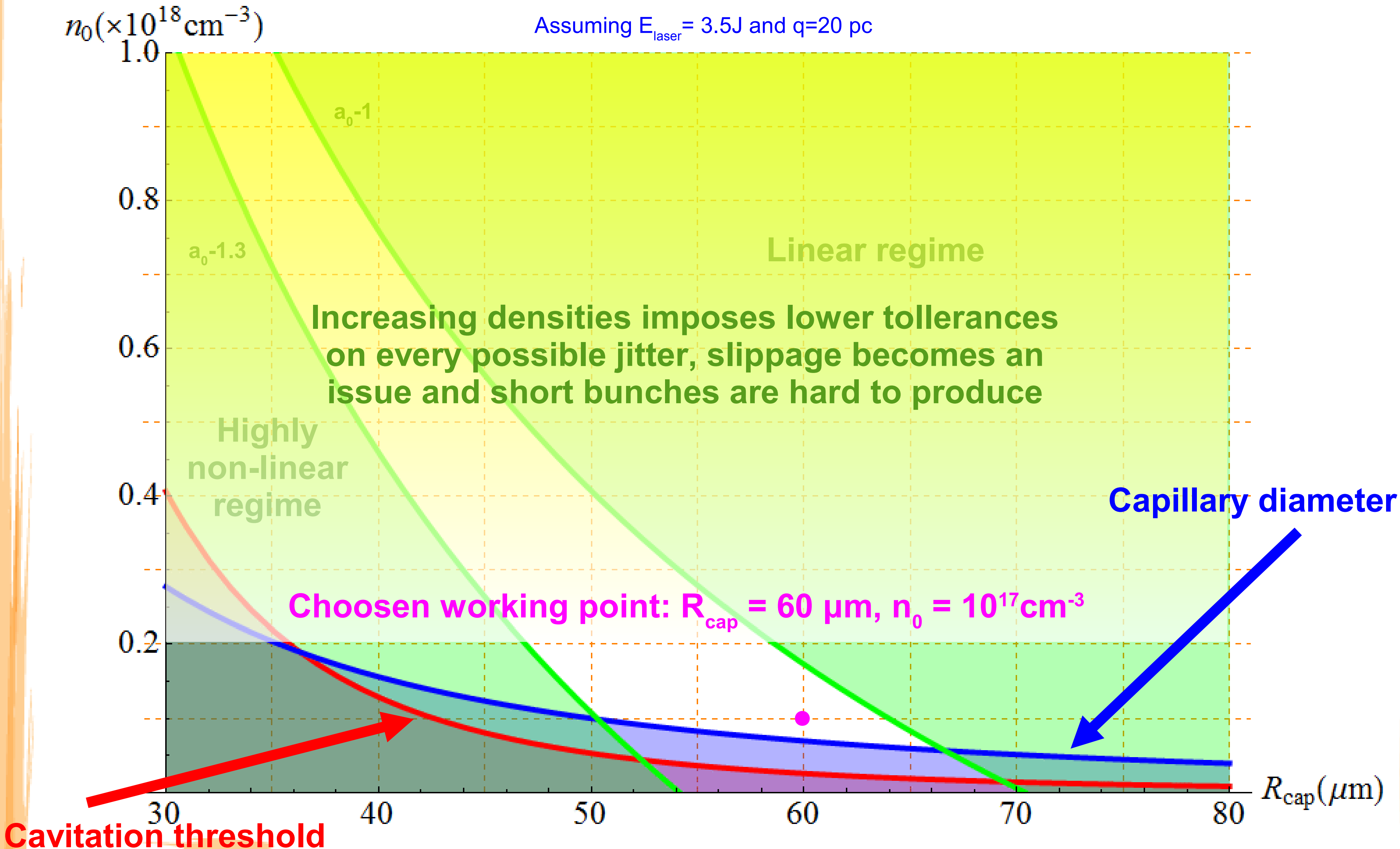
Choice of parameters: physical and practical constraints



Random particle trajectory