

DESY Beam Dynamics Meeting

Simulation of Longitudinal Beam Dynamics

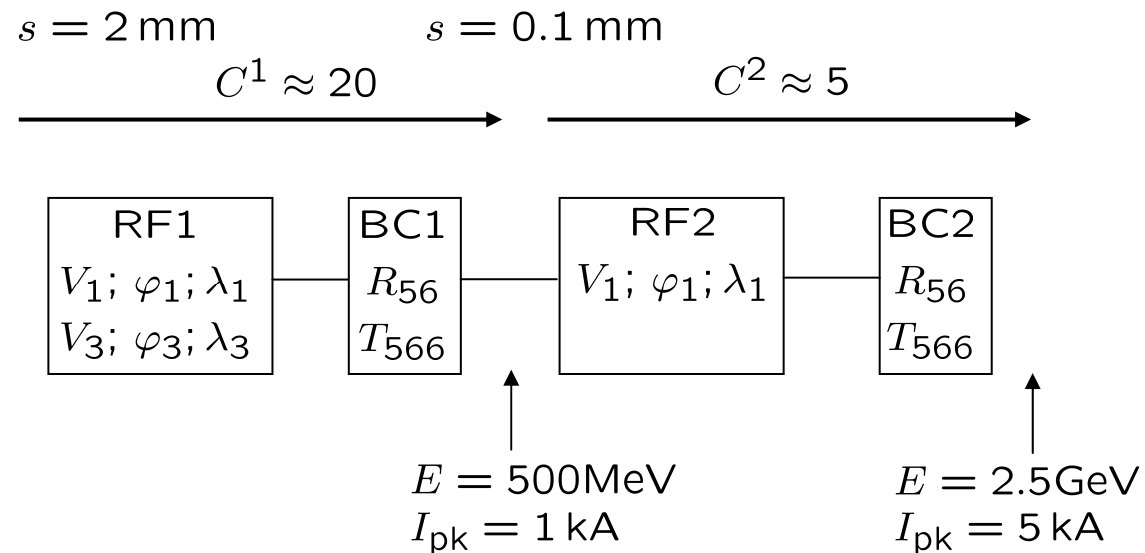
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- **Introduction**
- Overview LiTrack
- Optimization
- State of LSC Impedance Extension
- Summary and Next Steps

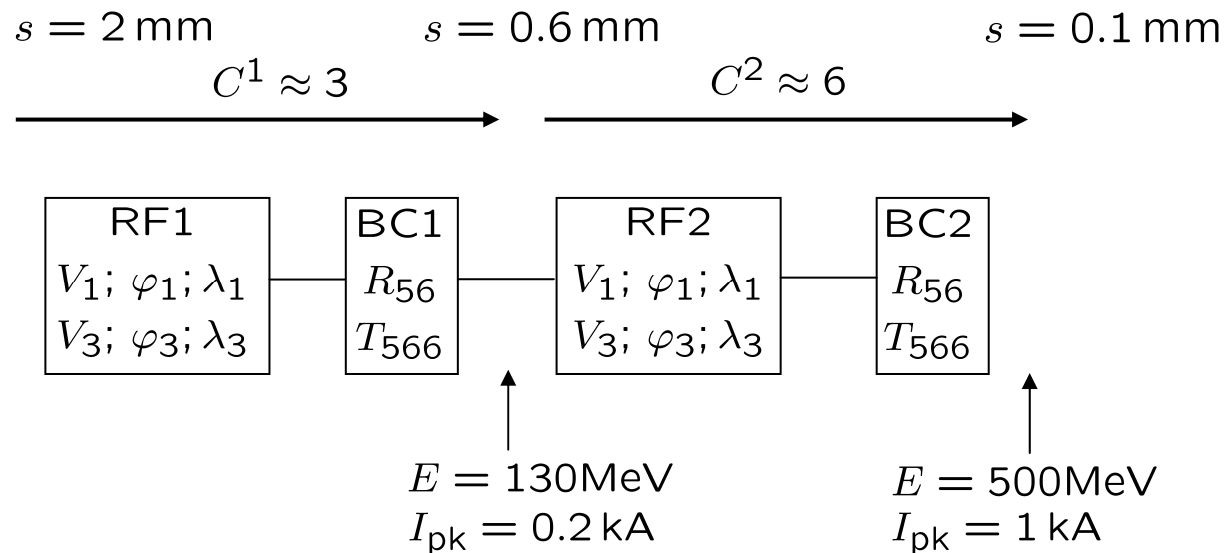
Introduction

Example 1



Introduction

Example 2



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Attributes of Original LiTrack Code

- Longitudinal phase space single bunch tracker
- RF acceleration
- Bunch compression up to 3rd order
- Cavity wakes
- Random distributions

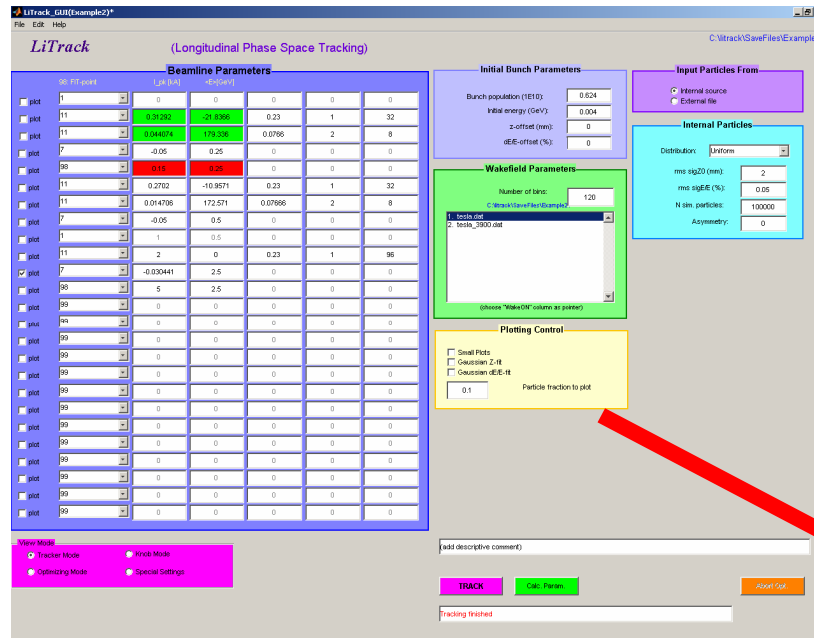
Original Reference:

P. Emma and K.L.F. Bane, *LiTrack: A FAST LONGITUDINAL PHASE SPACE TRACKING CODE WITH GRAPHICAL USER INTERFACE*, PAC '05 / SLAC-PUB-11035

Extensions to LiTrack

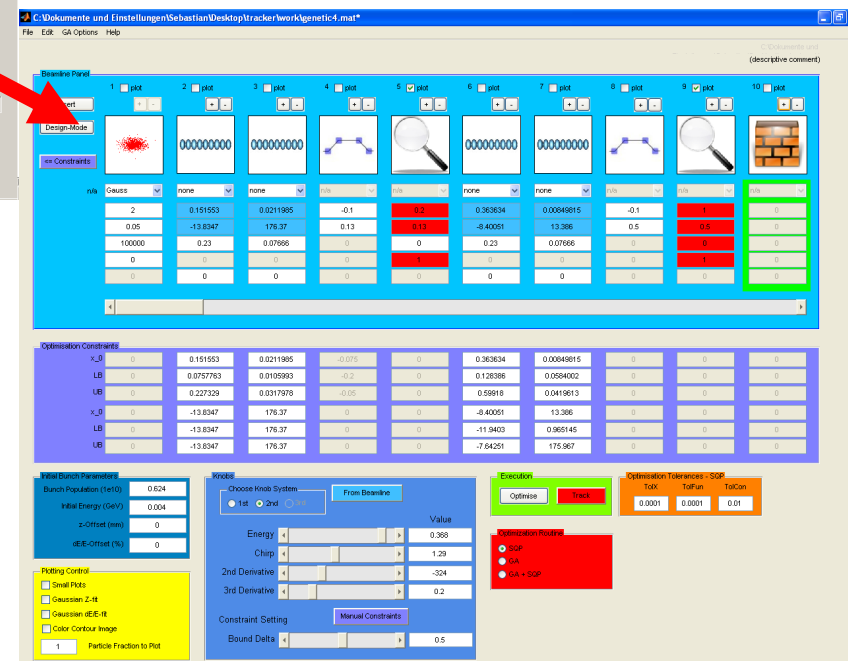
- Set up by energy and momentum derivatives (“knobs”)
- Minimization of the longitudinal rms emittance
 - Constrained minimization of the longitudinal rms emittance (SQP- local convergent)
 - Penalty emittance minimization (GA - global convergent)
 - Hybridization of both algorithms
- Systematic distribution
- Longitudinal space charge impedance (in the works)
- Manual / Documentation (draft available / under construction)

The New GUI



- Linac definitions by pics
- Clearly arranged panels
- New introduced menu bar
- Parameter/target choice

- Optimization for more than one BC system.

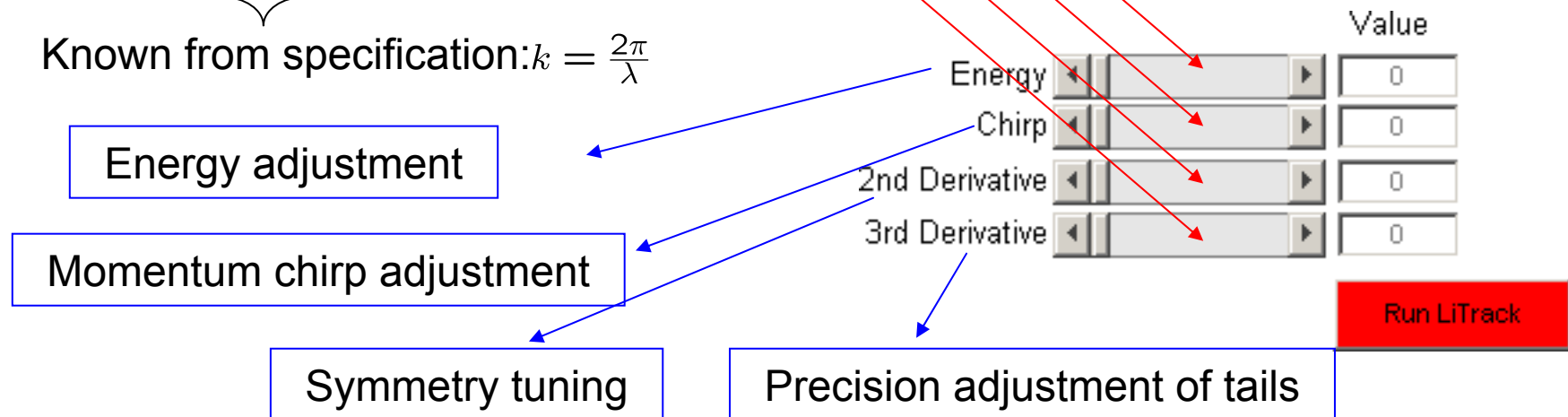


The Knob Panel

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & -k & 0 & -(nk) \\ -k^2 & 0 & -(nk)^2 & 0 \\ 0 & k^3 & 0 & (nk)^3 \end{bmatrix} \cdot \begin{bmatrix} a_1 \cos \varphi_1 \\ a_1 \sin \varphi_1 \\ a_n \cos \varphi_n \\ a_n \sin \varphi_n \end{bmatrix} = \begin{bmatrix} 1 \\ p_0' \\ p_0'' \\ p_0''' \end{bmatrix}$$

k wavenumber
 n n-th harmonic
 a normalized amplitude – RF
 φ phase – RF

Known from specification: $k = \frac{2\pi}{\lambda}$



Reference:

M. Dohlus and T. Limberg, BUNCH COMPRESSION STABILITY DEPENDENCE ON RF PARAMETERS

The GUI Pictograms



Mark, no action



General Bunch Compression R_{56} T_{566} U_{5666}

Chicane (low angle approx.) R_{56} $T_{566} \approx -\frac{3}{2}R_{56}$ $U_{5666} \approx 2R_{56}$



RF Linac



FIT-point (Peak current, energy, skewness,
correlation coefficient and rms emittance)



End of track

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General Problem Description

Optimization aims:

- Minimal longitudinal rms emittance

$$\min_x \varepsilon(\mathbf{x}) \quad \varepsilon(\mathbf{x}) = 4\sigma_\delta\sigma_z\sqrt{1 - r_{\delta,\sigma}^2}$$

subject to requirements

- Peak current
- Energy
- Symmetric current profile
- Positive correlation in phase space
- Bounds on the design variable

$$\left. \begin{aligned} I_{pk} - I_{pk,t} &= 0 \\ E - E_t &= 0 \\ \mathbf{a} &= \frac{1}{N} \sum_{j=1}^N \left(\frac{x_j - \bar{x}}{\sigma} \right) = 0 \\ -r_{\delta,z} &\leq 0 \\ b_l &< x < b_u \end{aligned} \right\} \begin{aligned} c_{eq}(\mathbf{x}) &= 0 \\ c_{ieq}(\mathbf{x}) &\leq 0 \end{aligned}$$



- Nonlinear Constrained Optimization
- Nonlinear Constraints



Approximation of the start values



SQP

Start Values by Genetic Algorithms

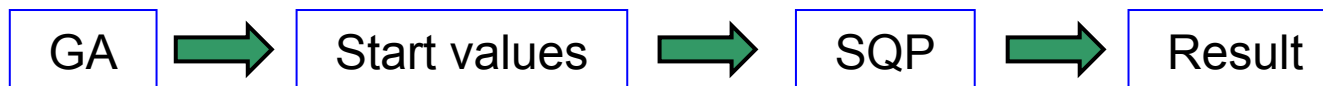
Determination of start values:

- Global optimization (GA)

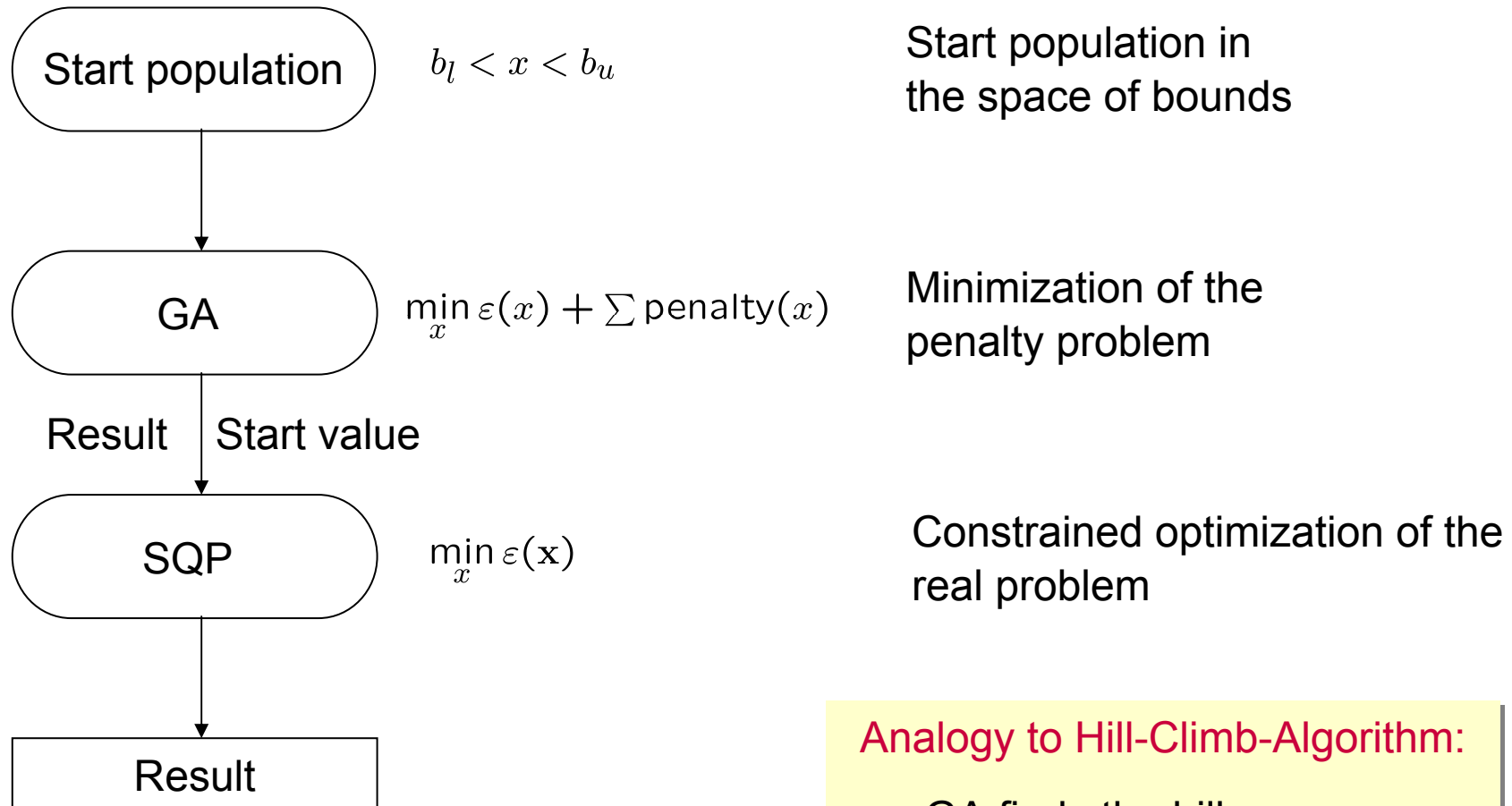
$$\min_x \varepsilon(x) + \left| \sum_{\lambda} I_{pk_{\lambda}}(x) - I_{t_{\lambda}} \right| + \left| \sum_{\mu} \bar{E}_{\mu}(x) - E_{t_{\mu}} \right| + \left| \sum_{\mu} a_{\mu}(x) \right|$$

Subject to **Constraints**

- Positive correlation, else $-r_{\delta,z}(x) < 0 \rightarrow f(x) = \text{penalty value}$
- Bounds on the design variable $b_l < x < b_u$



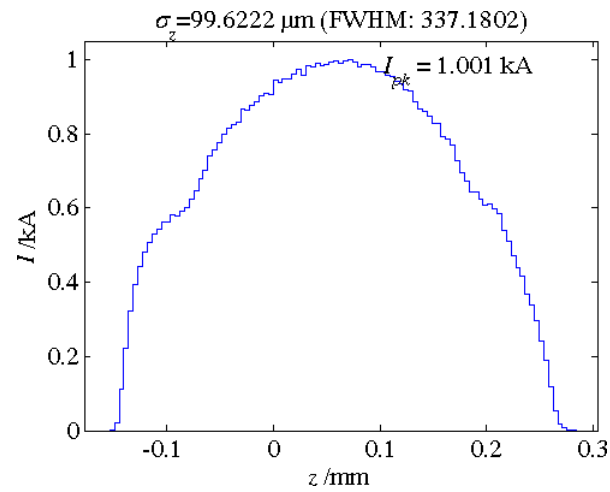
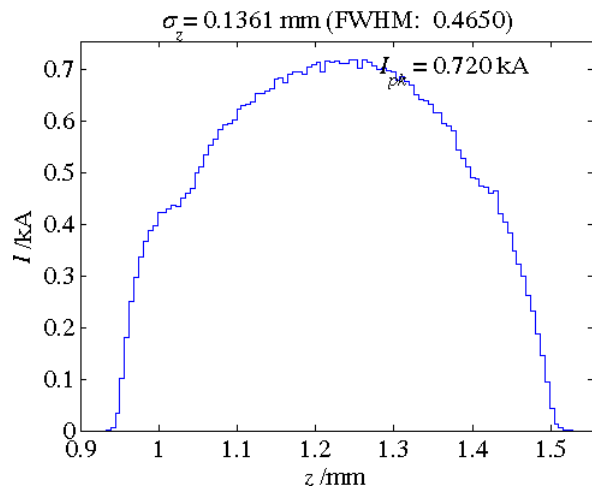
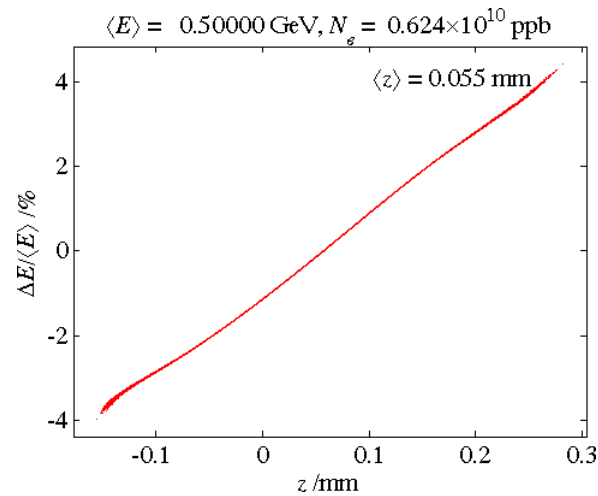
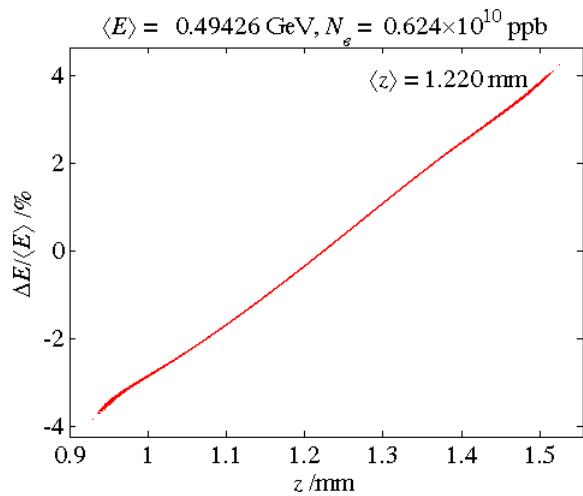
Schema of Hybridization



Analogy to Hill-Climb-Algorithm:

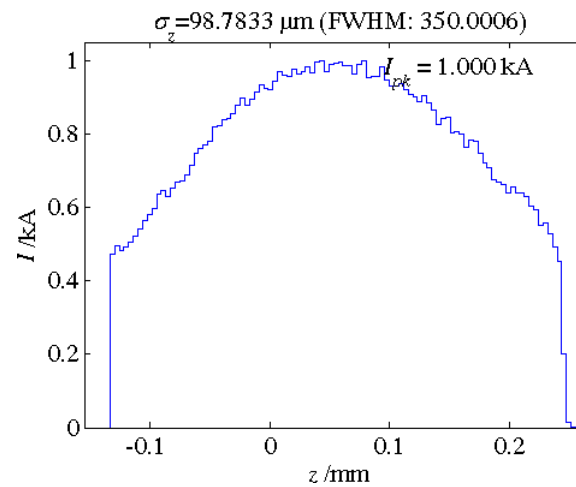
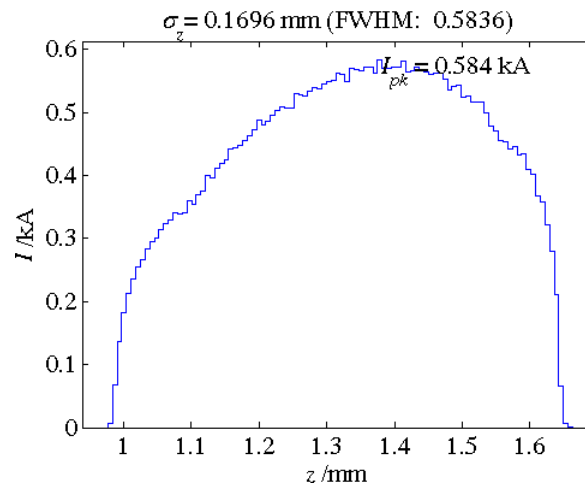
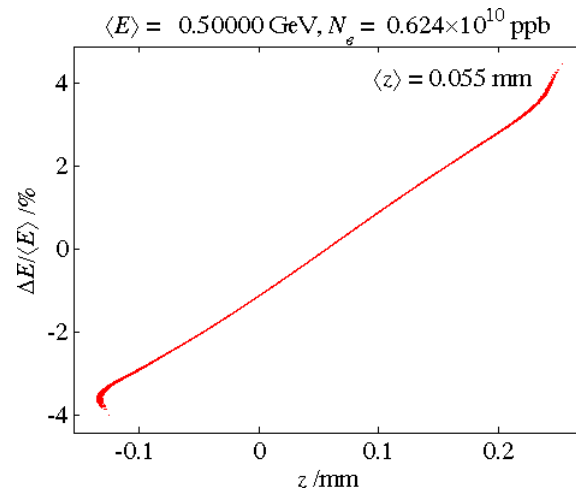
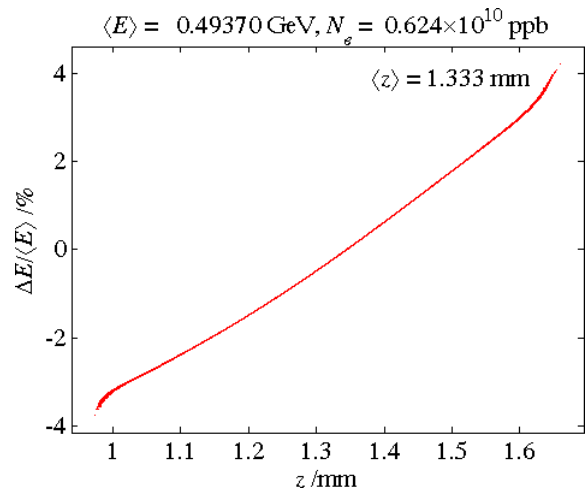
- GA finds the hill
- SQP searches the crest

Result 1 - Without Cavity Wakes



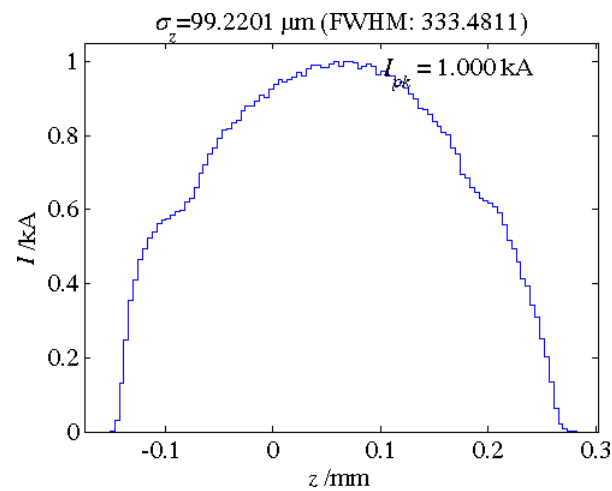
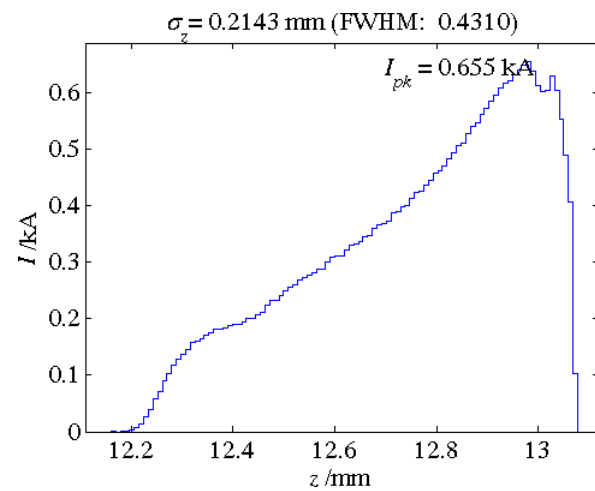
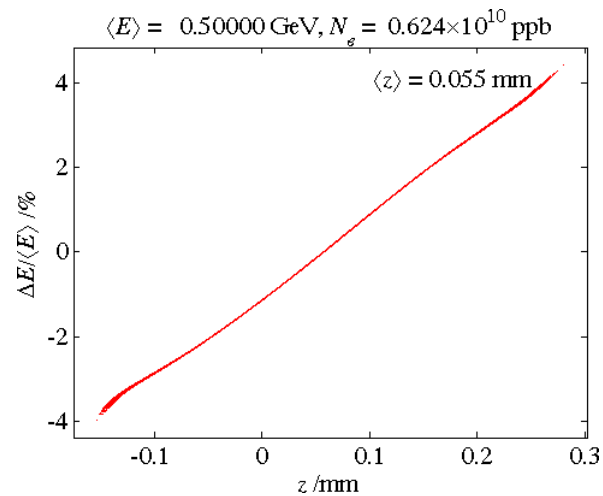
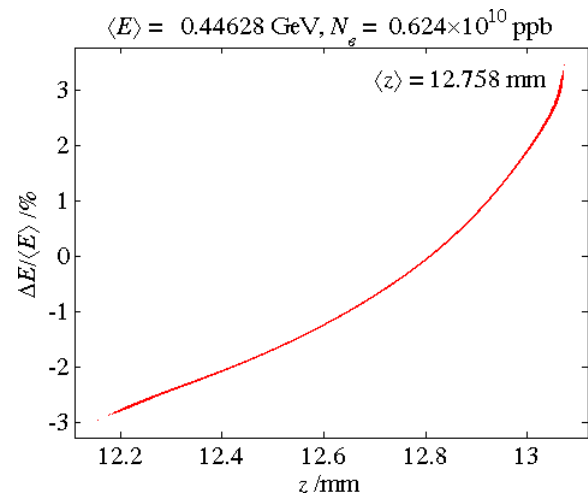
Time needed:
6.8 s

Result 1- With Cavity Wakes



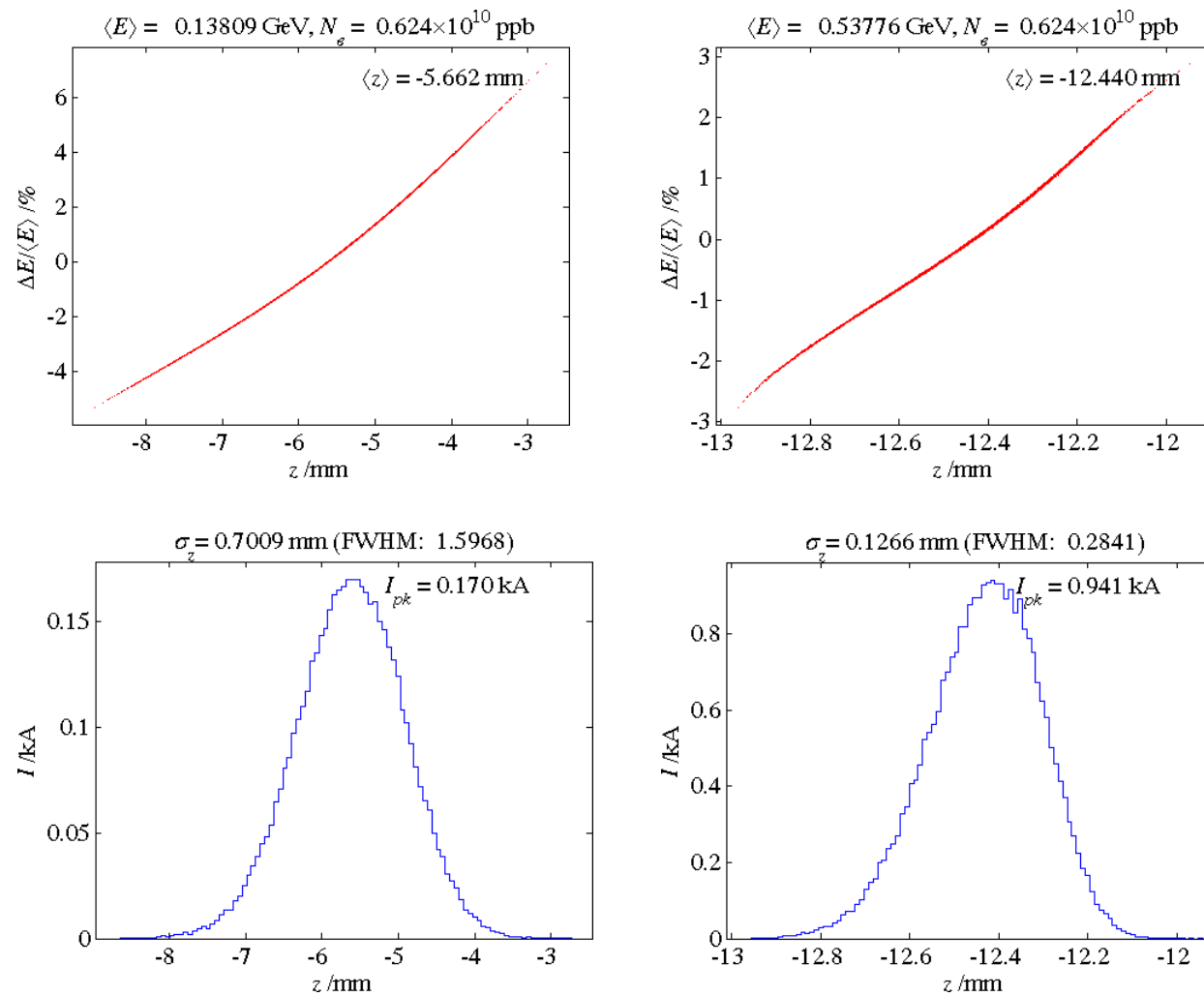
Time needed:
79.3 s

Result 1 – Start Values by GA Without Wakes

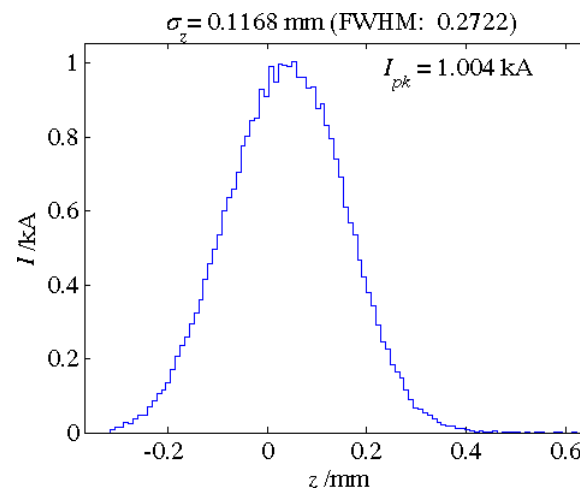
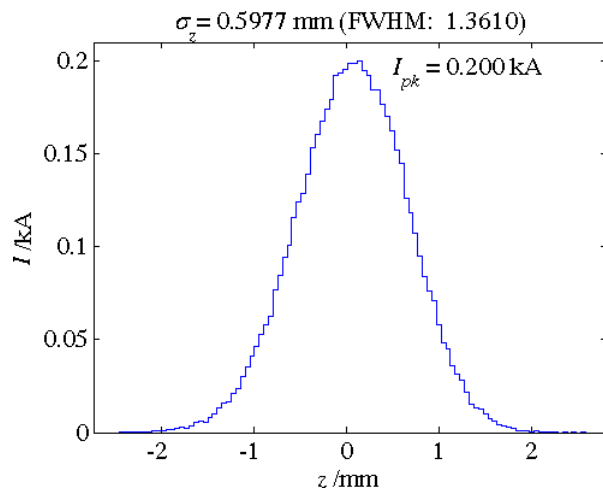
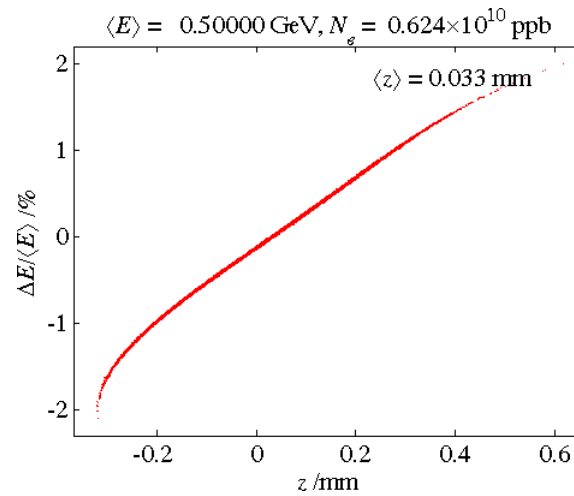
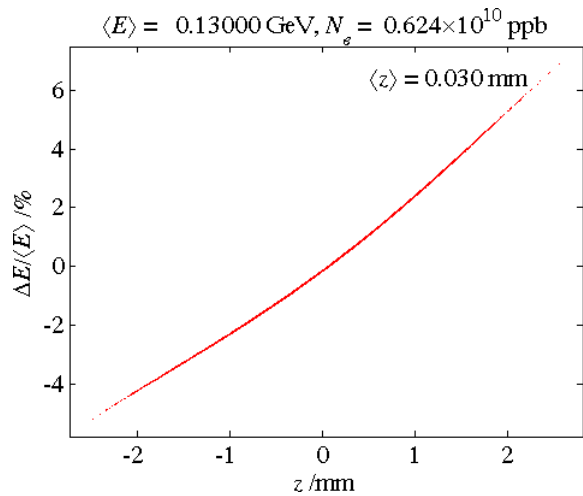


Time needed:
4.5 min

Result 2 – Without Wakes - GA Results



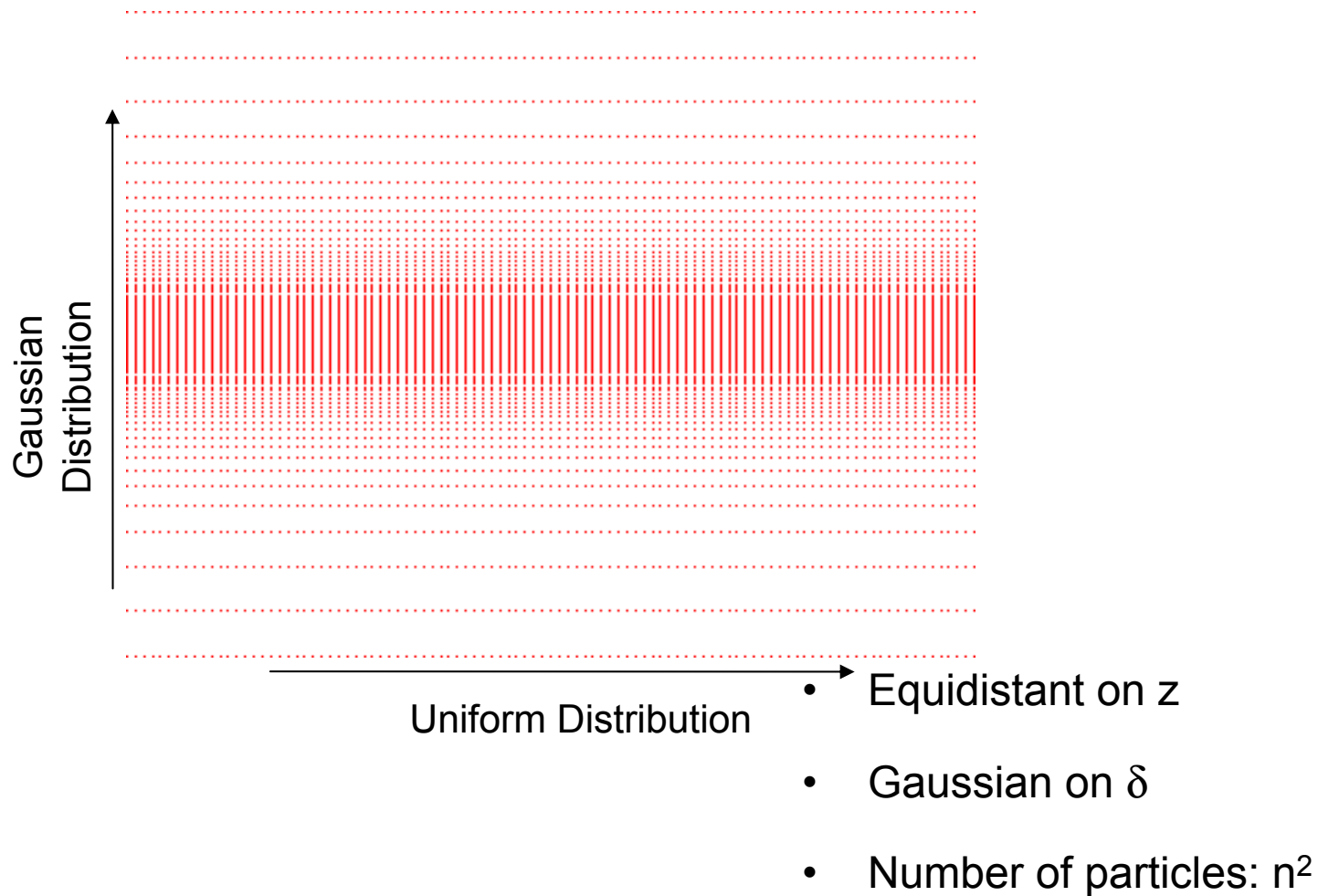
Result 2 – Without Wakes - SQP Results



Time needed:
7.6 min

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New Standardized Distribution



Model Assumptions

- RF-Sections

Constant energy gradient

$$E(z) = \frac{E_{\text{end}} - E_0}{z_{\text{end}} - z_0} z + E_0$$

- Compressors / Drifts

Constant energy

$$E(z) = E_0$$

- Beta function

from component list

in sections constant

$$\beta_{\text{TWISS}} = \sqrt{\frac{\beta_x^2 + \beta_y^2}{2}}$$

- Beam size

$$\sigma_r(z) = \sqrt{\frac{\varepsilon_n}{\gamma(z)} \beta_{\text{twiss}}(z)}$$

Analytical Modes of LSC

$$Z'_{SC}(k, z) \approx \frac{jZ_0 k}{4\pi\gamma(z)^2} \left(a + 2 \ln \frac{\gamma(z)}{\sigma_r(z)k} \right) \quad \frac{k\sigma_r}{\gamma} \ll 1$$

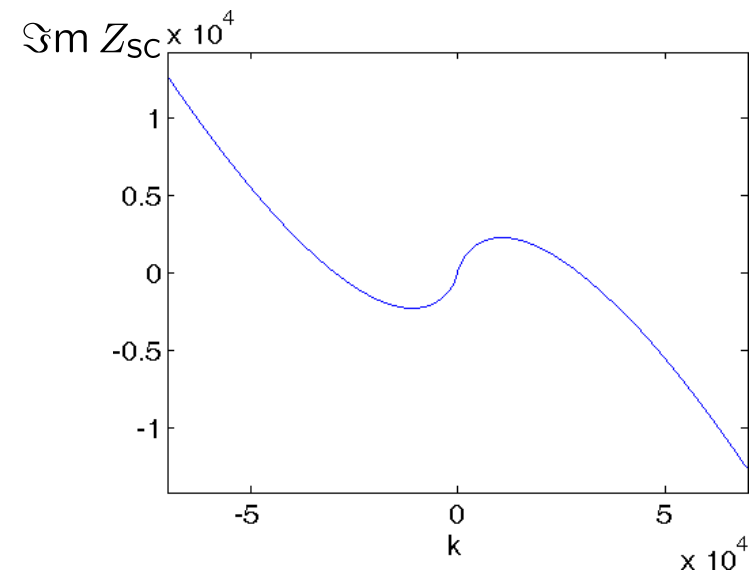
$$\bar{\beta}_{\text{twiss}} \approx 10 \text{ m}; \quad \varepsilon_n = 1 \text{ } \mu\text{m}; \quad E(z) = \frac{E_{\text{end}} - E_0}{z_{\text{end}} - z_0} z + E_0$$

$$Z_{SC}(k, a \rightarrow b) = \int_a^b Z'_{SC}(k, z) dz$$

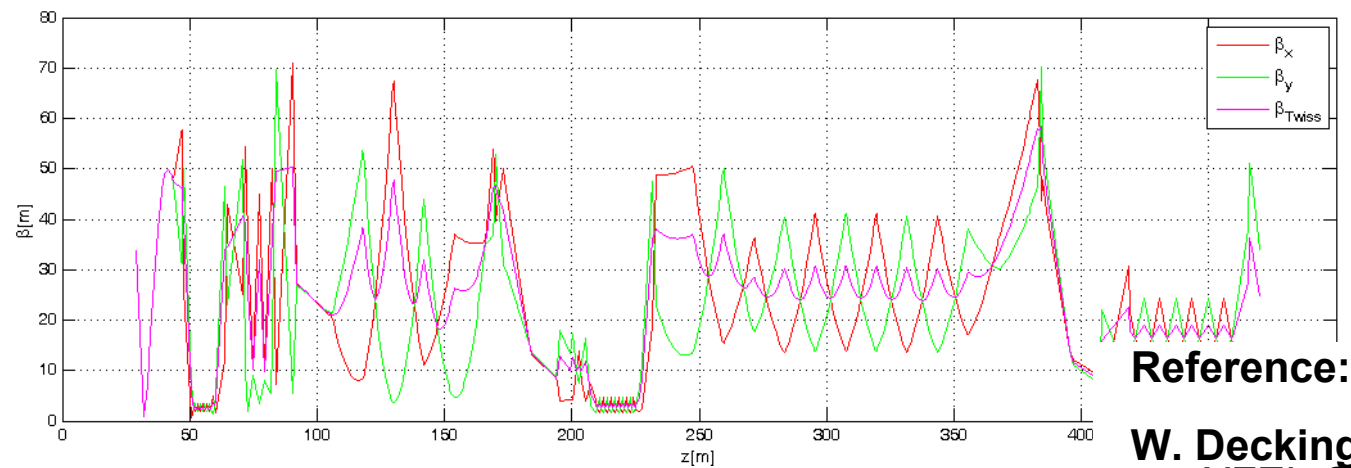
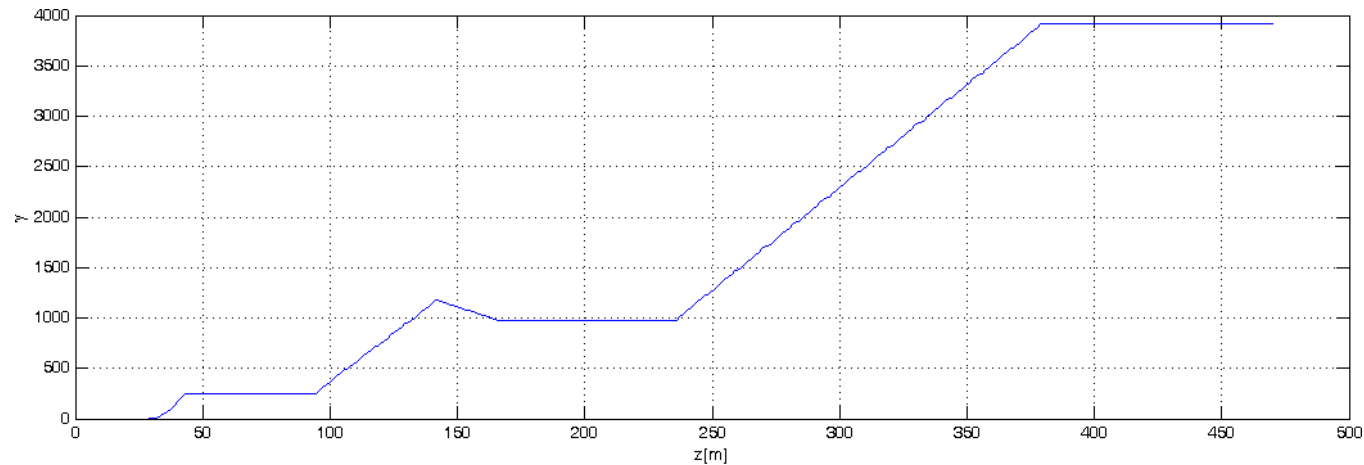
Analytical Integration

Possible alternatives to analytical model :

- Numerical Integration
- Adaptive Simpson quadrature
- Adaptive Lobatto quadrature



Beta Function



Reference:

W. Decking
XFEL Componentlist 3.3

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Summary and Next Steps

Summary

- Extension by knobs
- Optimization of bunch compression system
- New convenient GUI
- Implementation of systematic distribution
- Implementation of LSC impedance (in the works)
- Documentation ((permanently) under construction)

Future Work

- Implementation of LSC impedances and wakes
- Sensitivity analysis and search for insensitive working points
- Improvement of the actual optimization design

Acknowledgement to Martin Dohlus and Torsten Limberg for guidance and many helpful discussions!