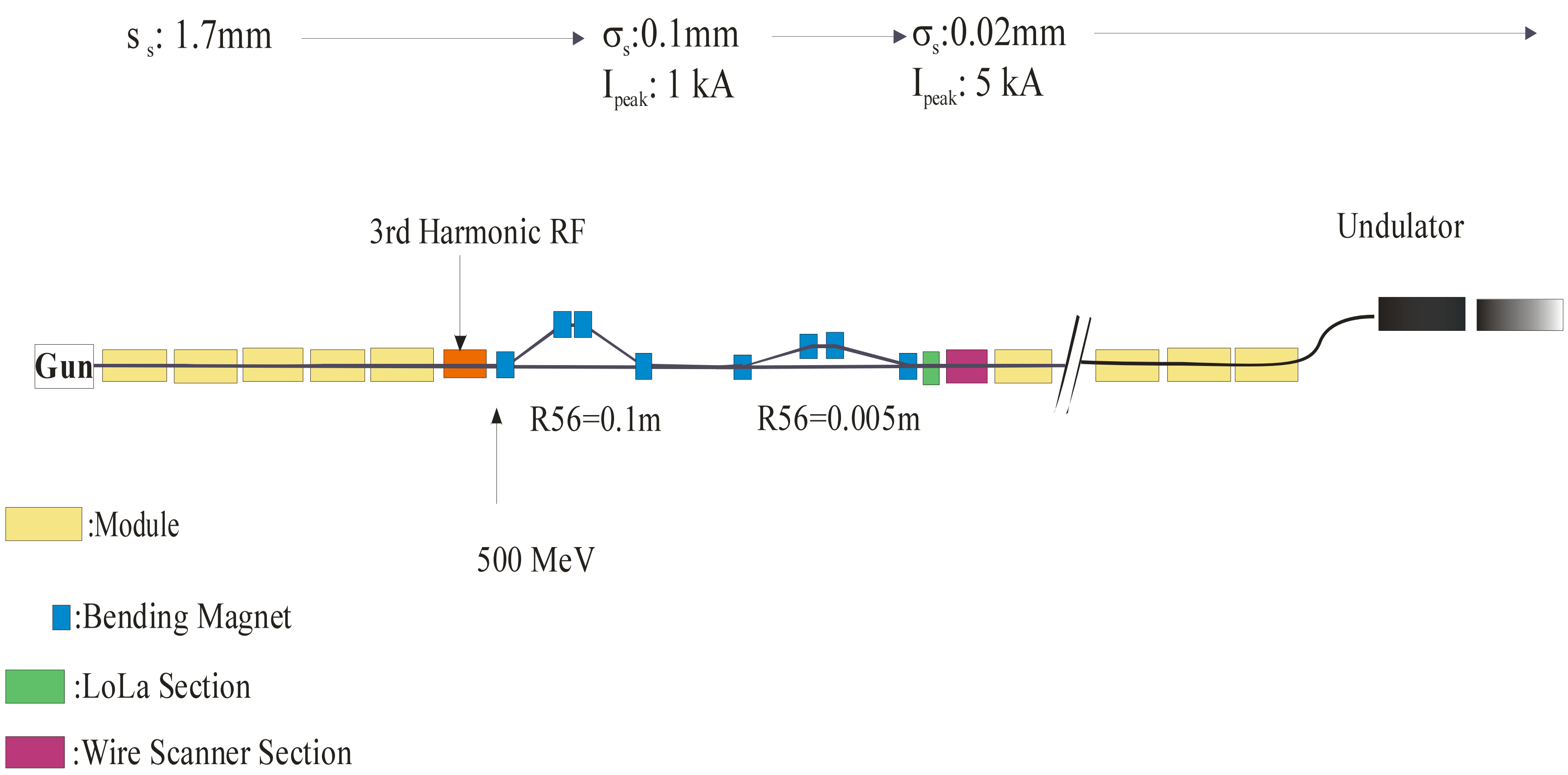
XFEL
X-Ray Free-Electron Laser

Status of the XFEL Bunch Compression System

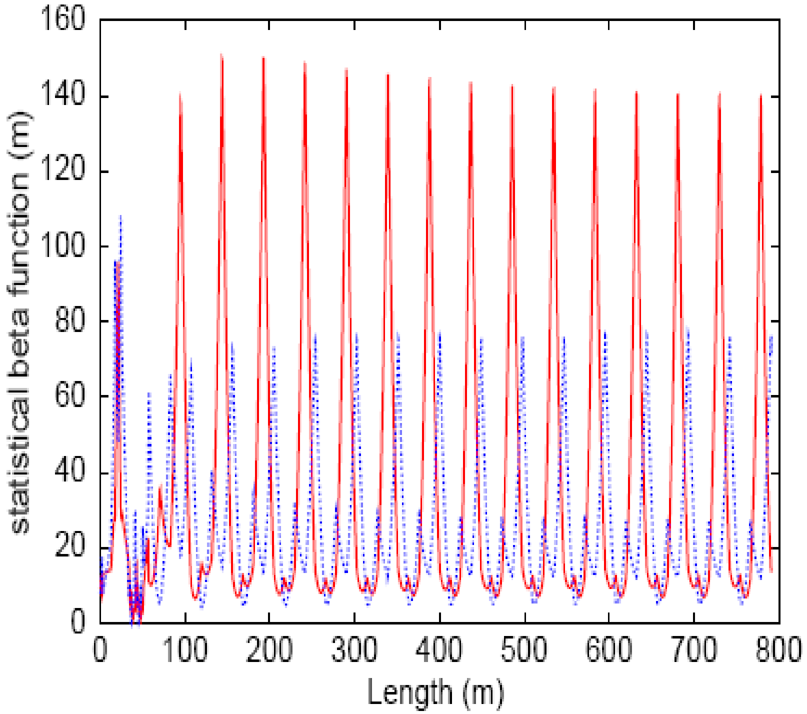
XFEL Meeting 26.1.2005

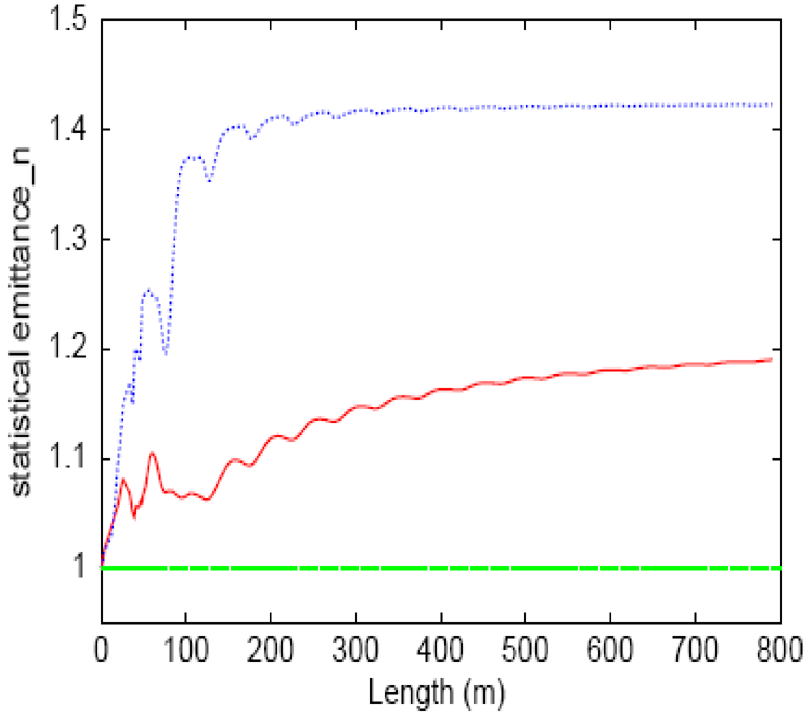
W. Decking, M. Dohlus, N. Golubeva and T. Limberg
for the XFEL Beam Dynamics Group

2004 Working Model for European XFEL Bunch Compression



Impact of Space Charge Effects in the Instrumentation Section and Main Linac on Optics and Emittance





From 'Transverse Space Charge Forces after Final Compression', V. Balandin, N. Golubeva, December 13, 2004

Adapt BC Lay Out for Design Parameters and Further Optimization

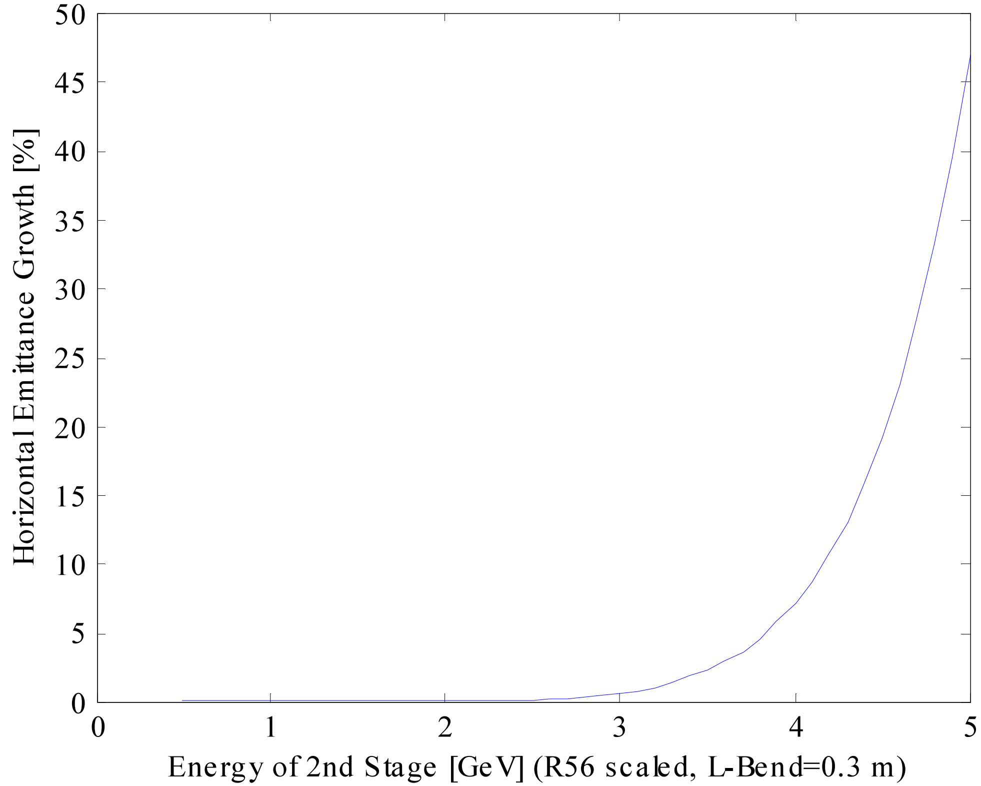
To avoid space charge effects and to gain head room for current densities beyond design or, respectively, a bigger safety margin at design parameters:

- Shift 2nd BC stage to higher energy
  - To reach the same sensitivity as downstream of 1st BC stage, a factor 2.2 in beam energy would be needed. For our lattice to do a parameter study we chose 2.5 GeV which would, from this point of view, allow for up to 25 kA peak current.
- Leave 1st BC Stage as is
  - The chirp (~2% @ 500 MeV = 10 MeV) just about compensates the longitudinal wake fields of the structures
  - No changes for 3rd harmonic RF system necessary

Other Considerations when Shifting 2nd Stage to Higher Energy

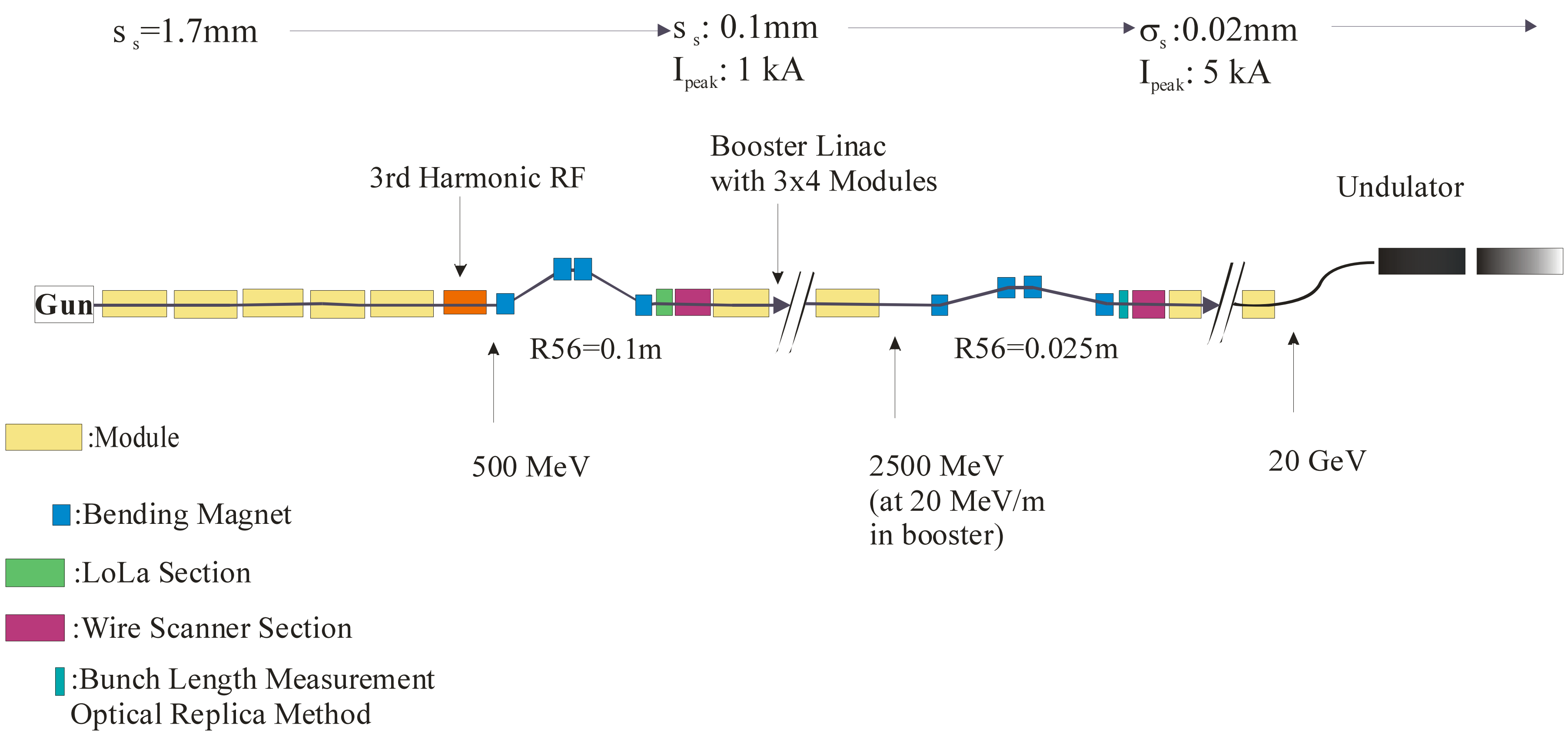
- Scale R56 to preserve the compensation of energy correlations induced by:
  - RF for bunch compression
  - Longitudinal wake fields of linac structures
- Magnet Strength Limit for 30 cm Length: ~ 2 GeV

Limit of Incoherent Synchrotron Radiation Emittance Growth in BC 2nd stage (scaled R56, fixed magnet length)



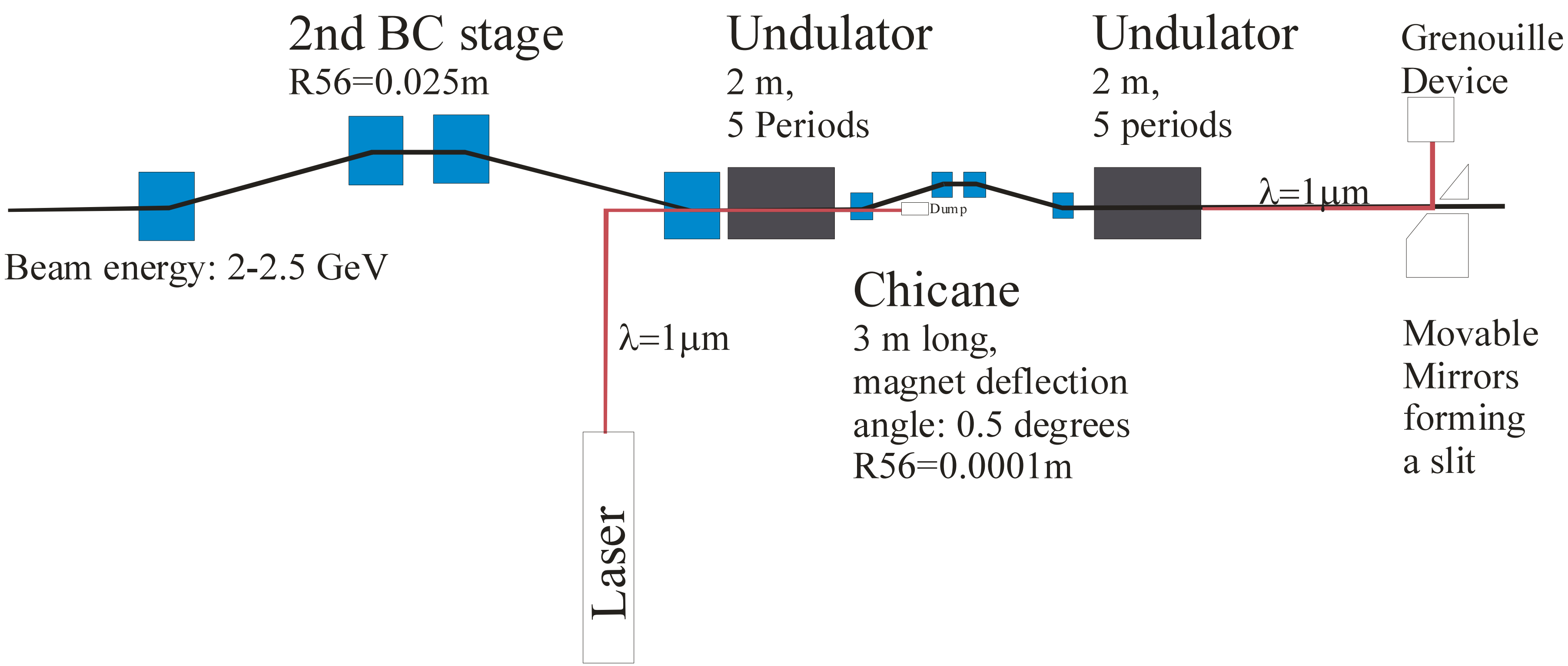
=> For our studies we can use the old geometry of the 2nd BC stage at 2.5 GeV

Working Model for European XFEL Bunch Compression for Further Optimization with the 2nd BC Stage at 2.5 GeV



Preliminary Lay Out of Bunch Length Measurement Downstream 2nd BC Stage

Optical Replica Method (E. Saldin, E. Scheidmiller, M. Yurkov)



Presented Studies with 2nd BC Stage @ 2.5 GeV

W. Decking: Lattice Lay Out and Impact of Wake-Fields

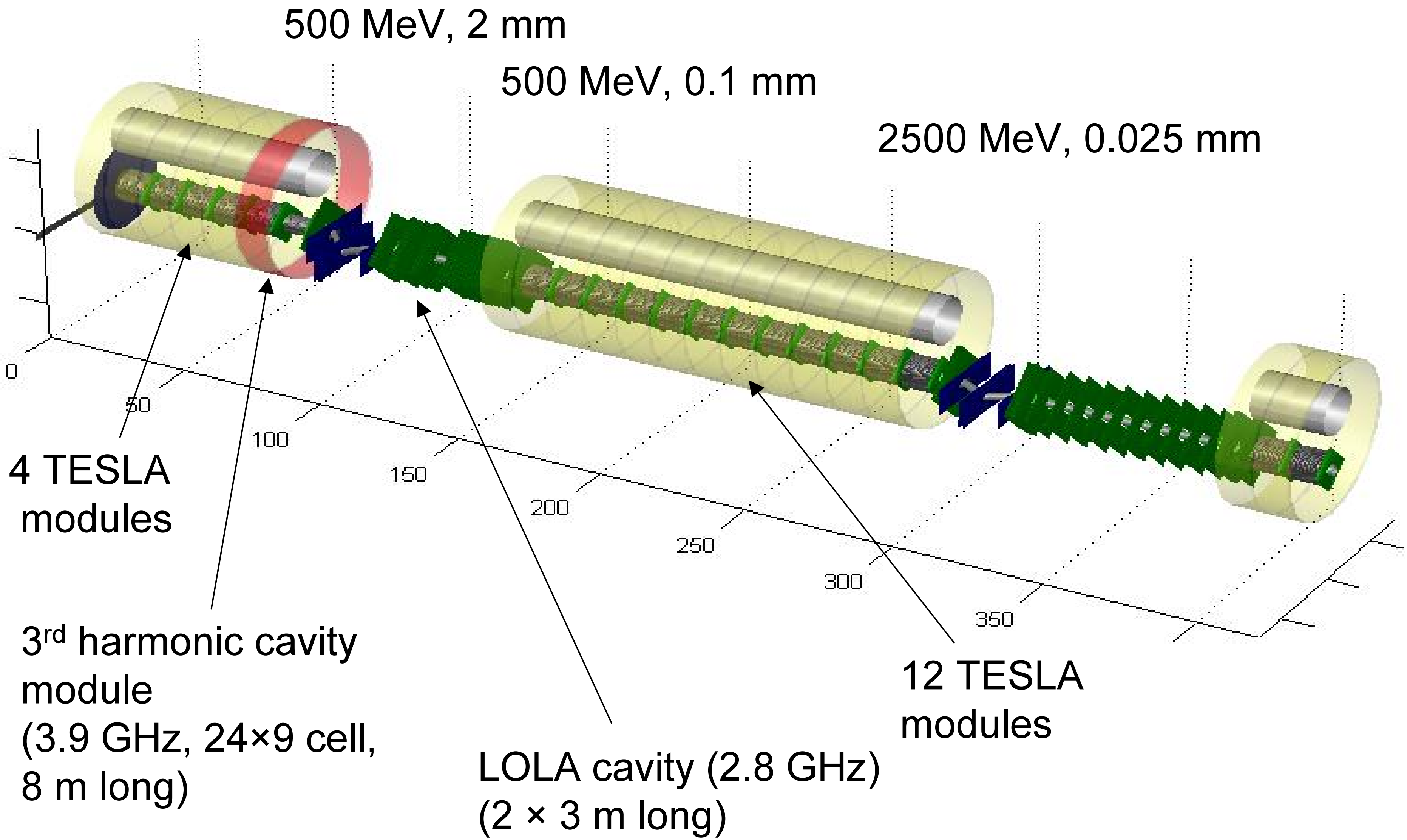
N. Golubeva: Space Charge Calculations with transverse SC code TrackFMN (V. Balandin)

M. Dohlus: Calculation of CSR effects with CSRtrack to explore BC parameter range

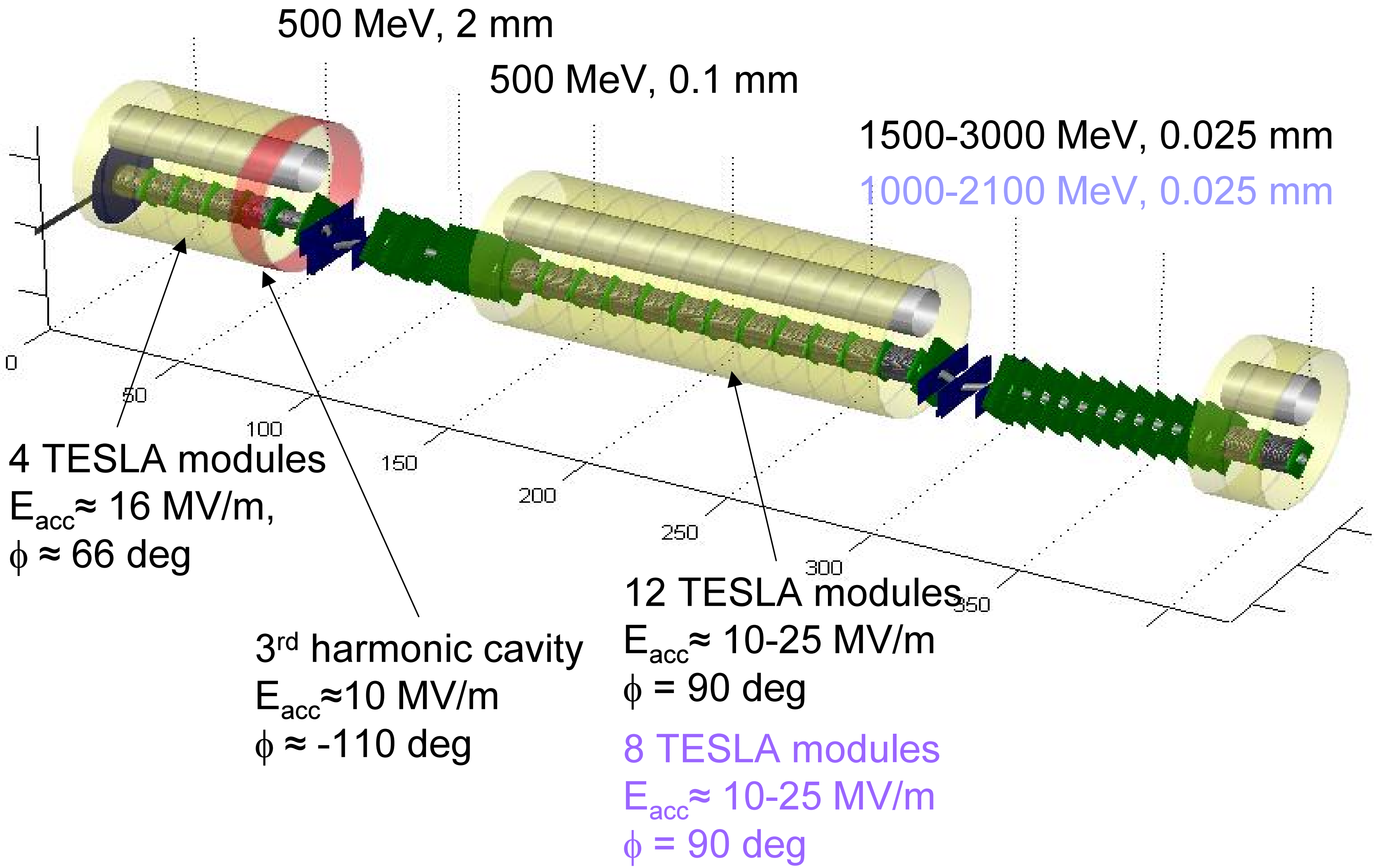
Lattice Lay Out for Bunch Compression Parameter Studies

Impact of Wake Fields on Compression

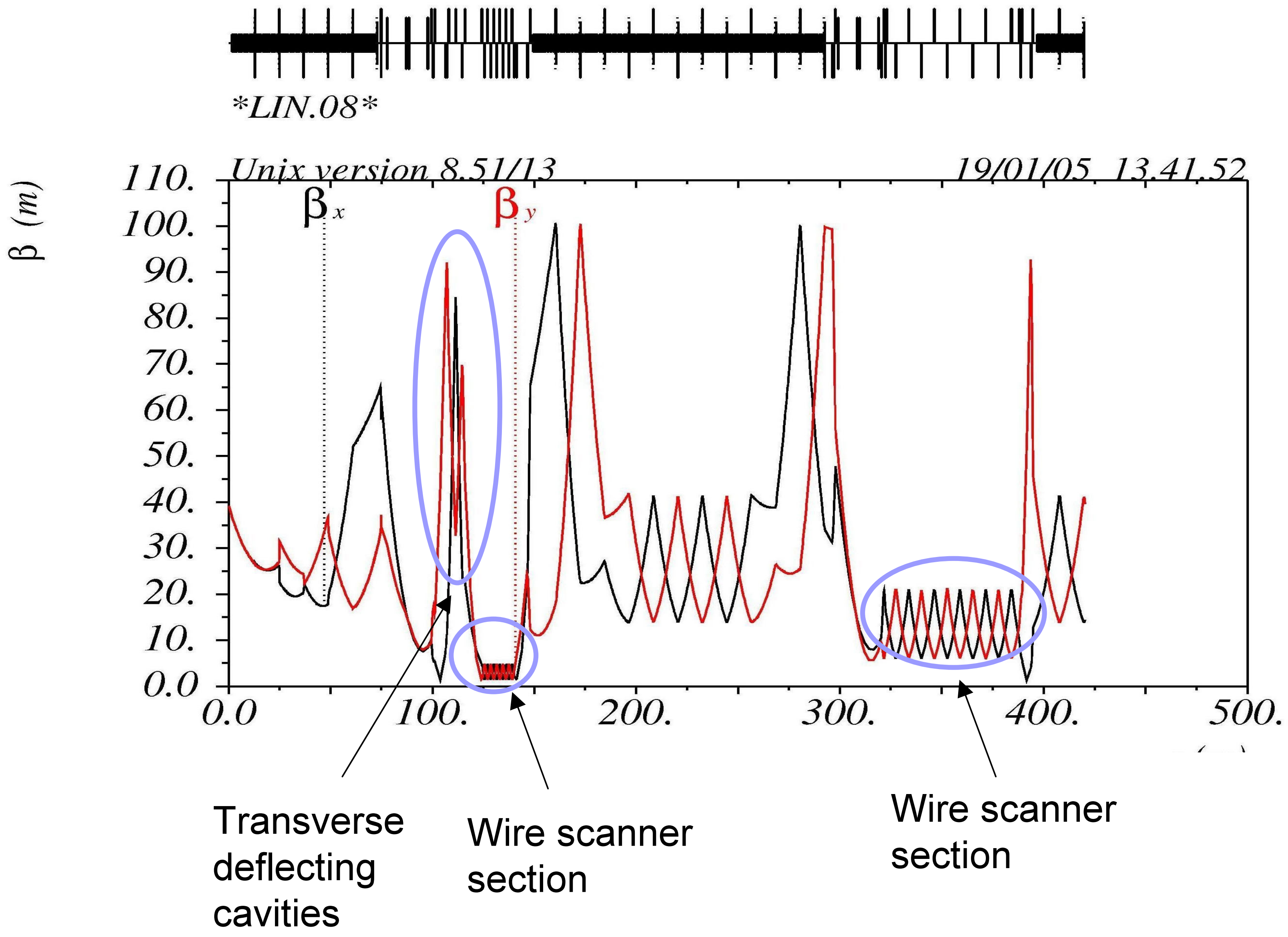
BC Layout for Parameter Studies



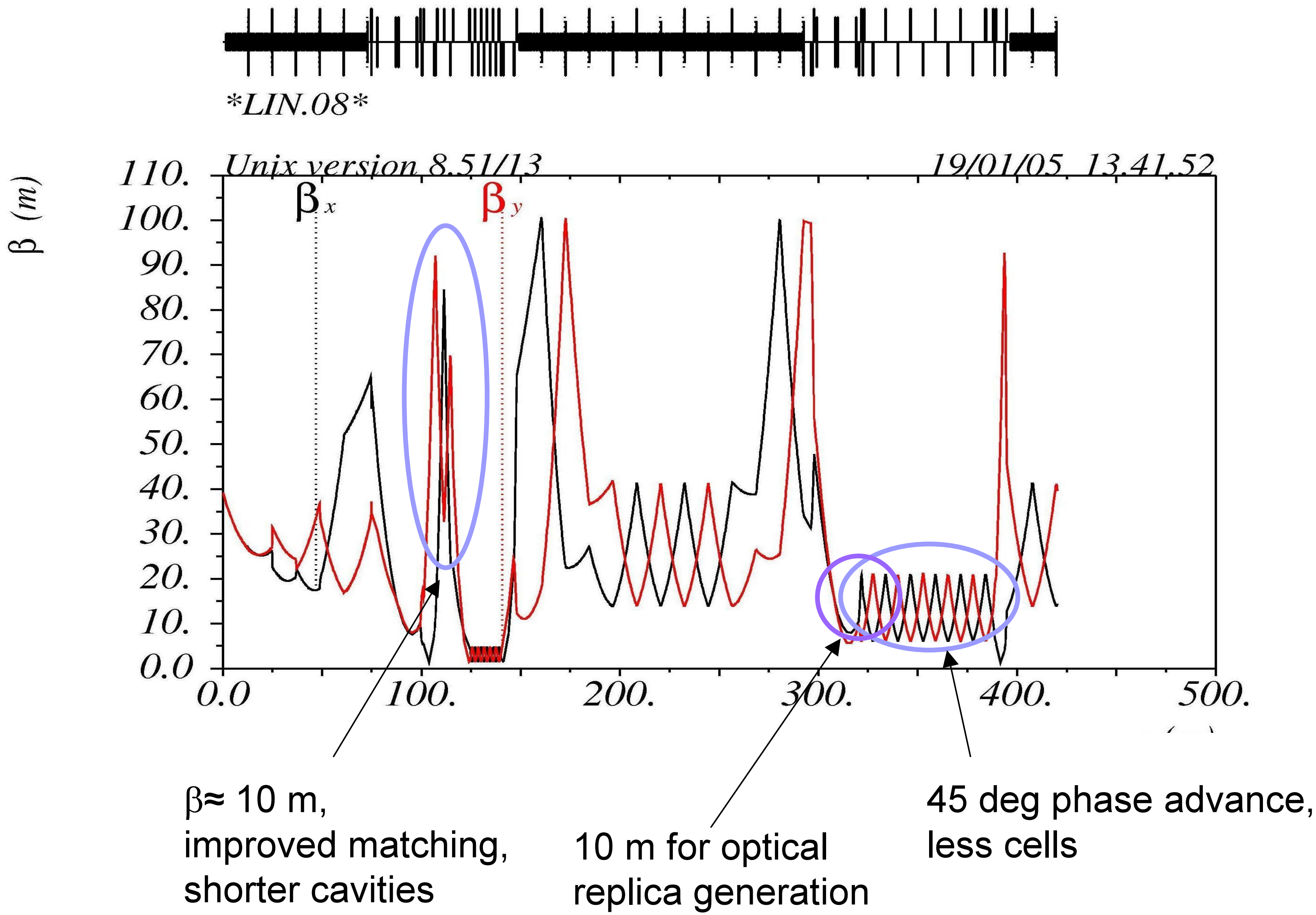
Energy Management



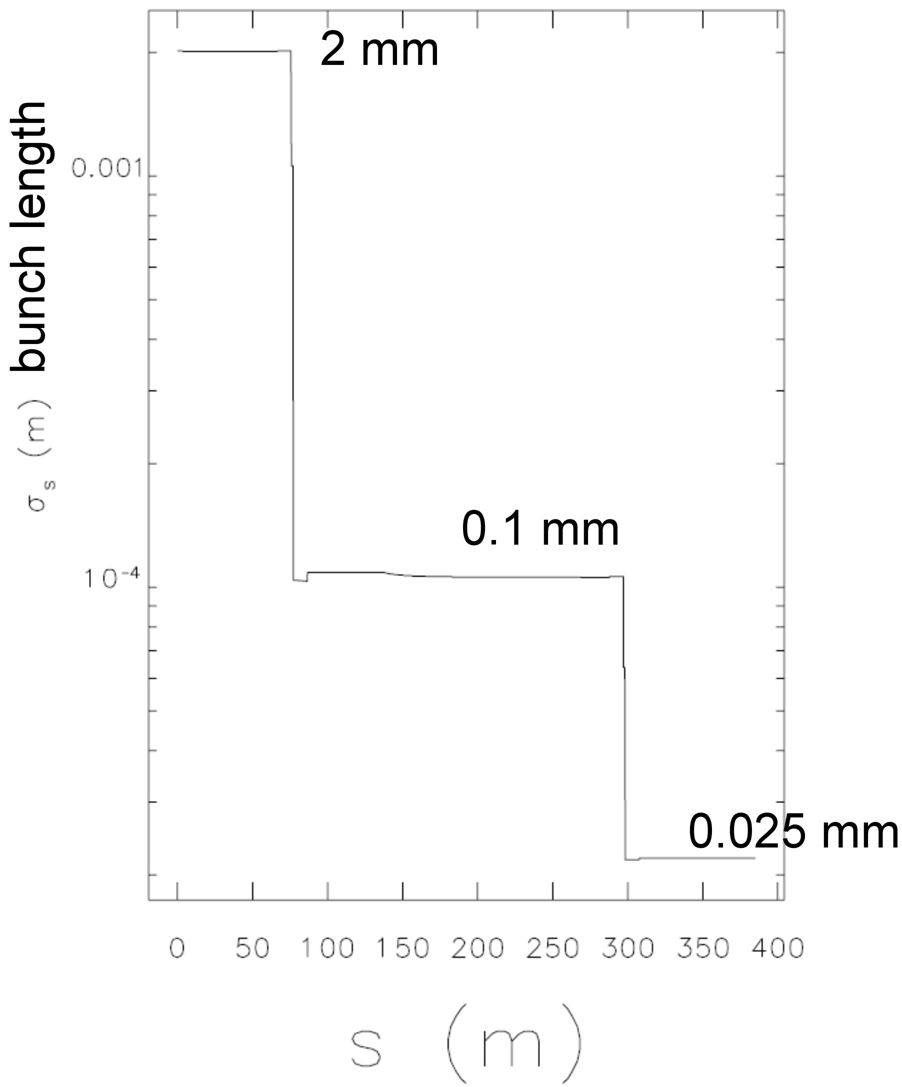
BC Parameter Study Optics for Parameter Study

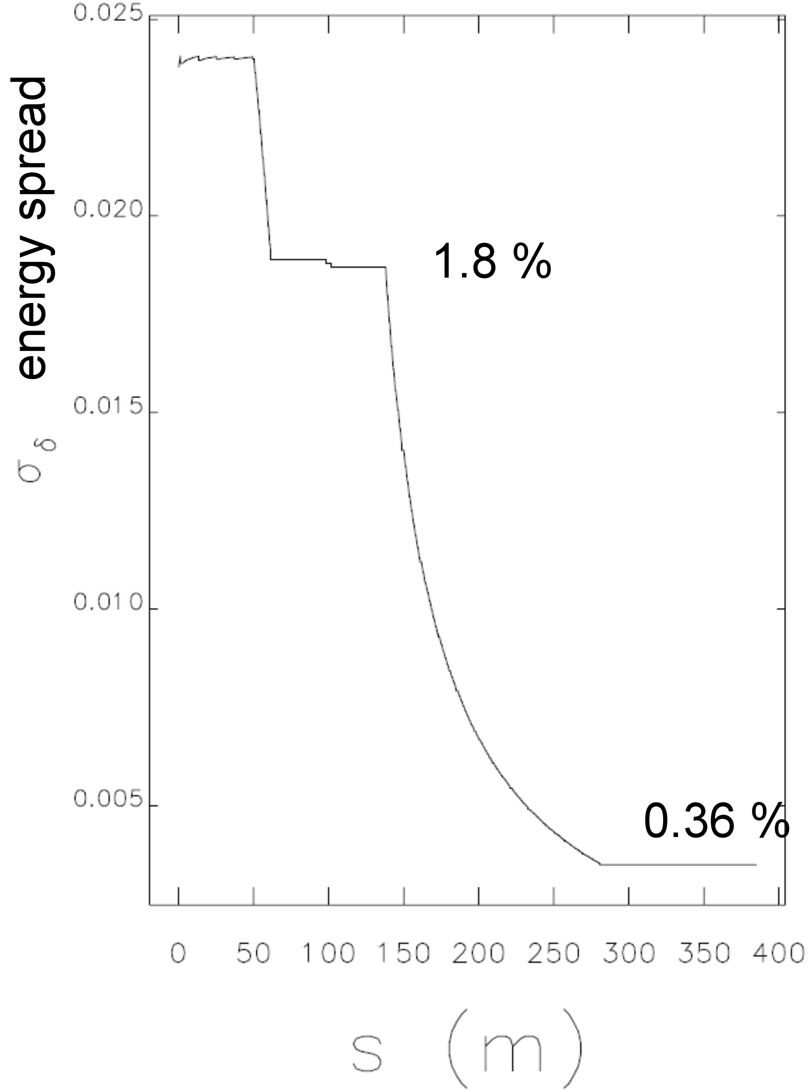


Optics Improvements

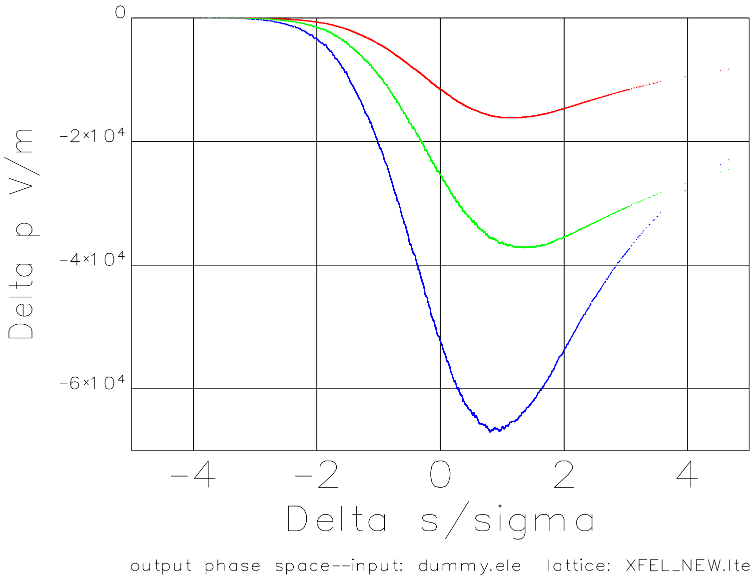


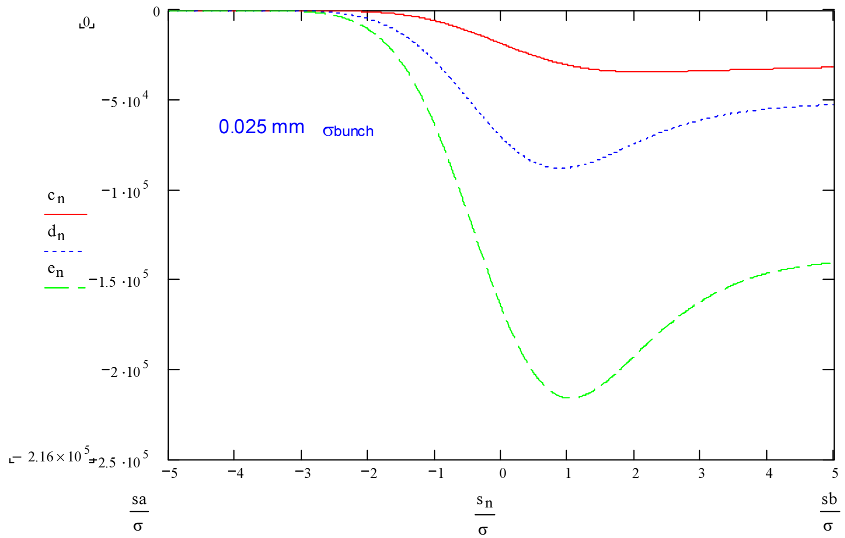
Compression

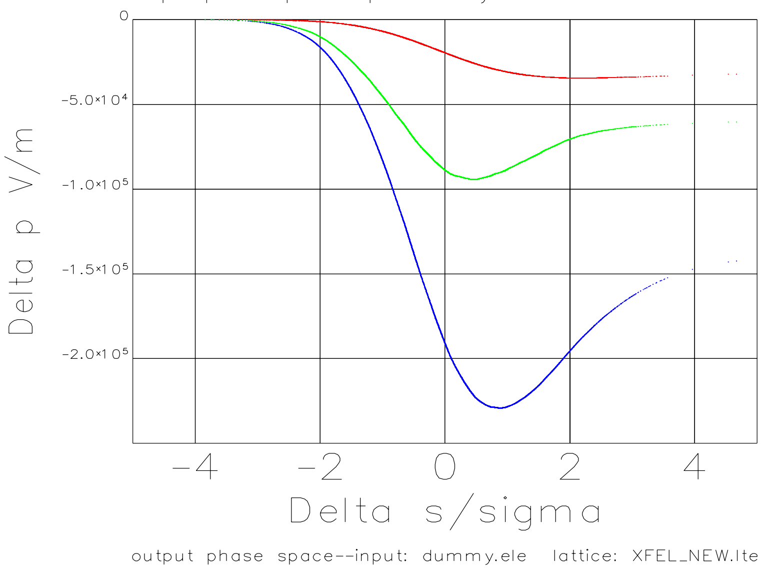


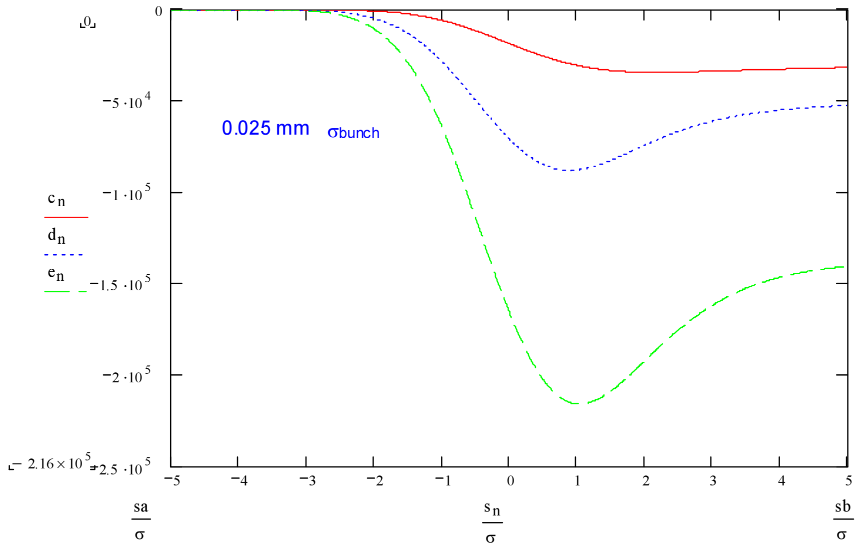


Geometric Wakes







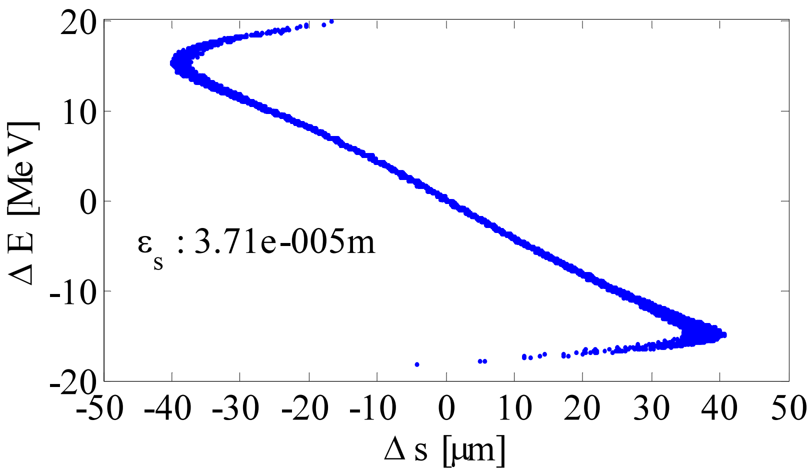


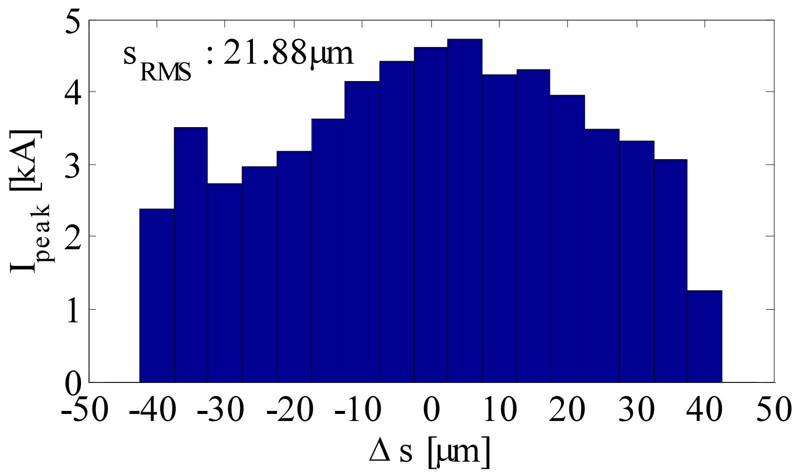
XFEL
X-Ray Free-Electron Laser

All Wakes Included

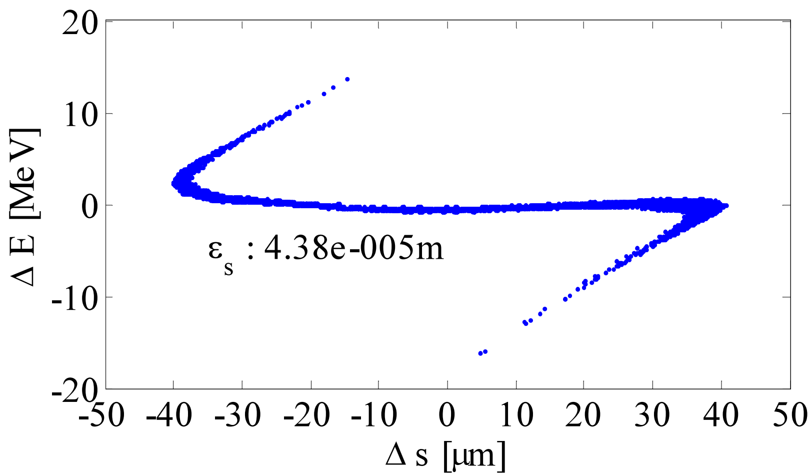
DESY

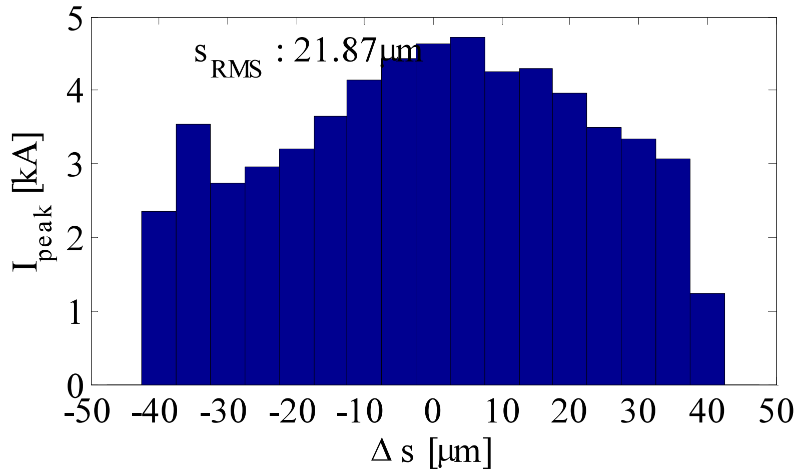
After Bunch Compression



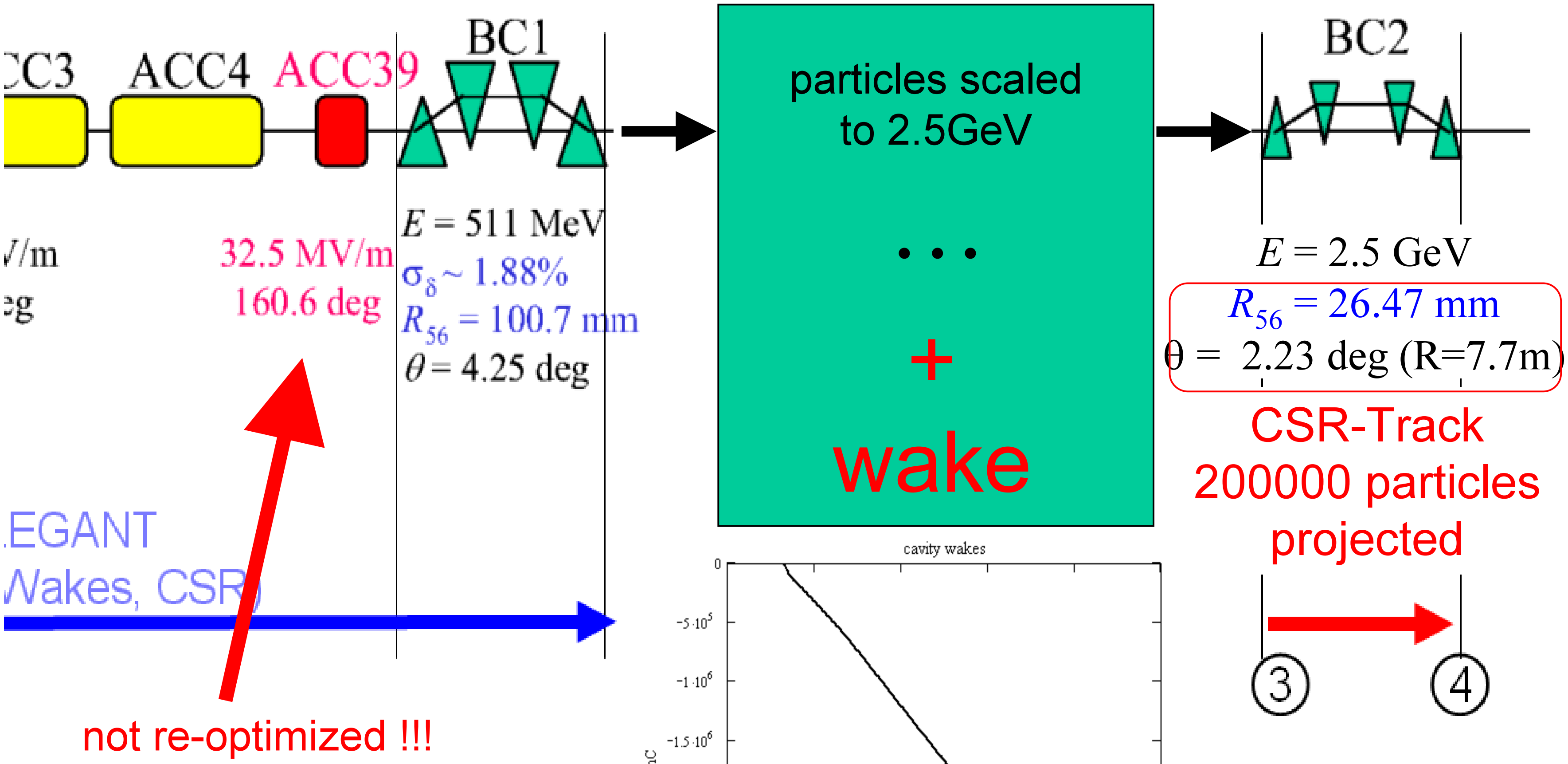


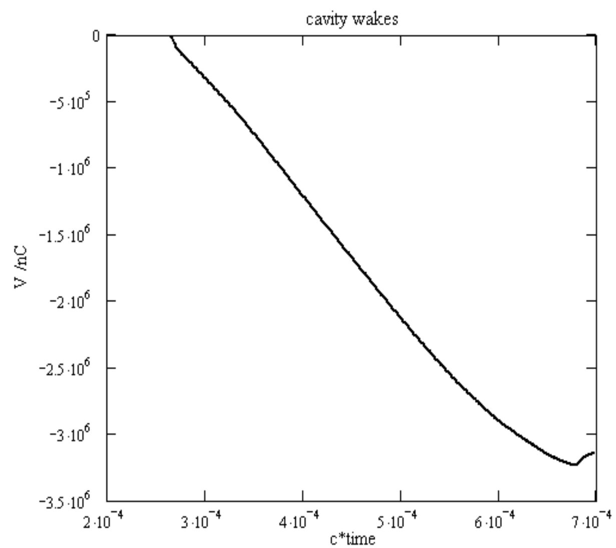
End of LINAC





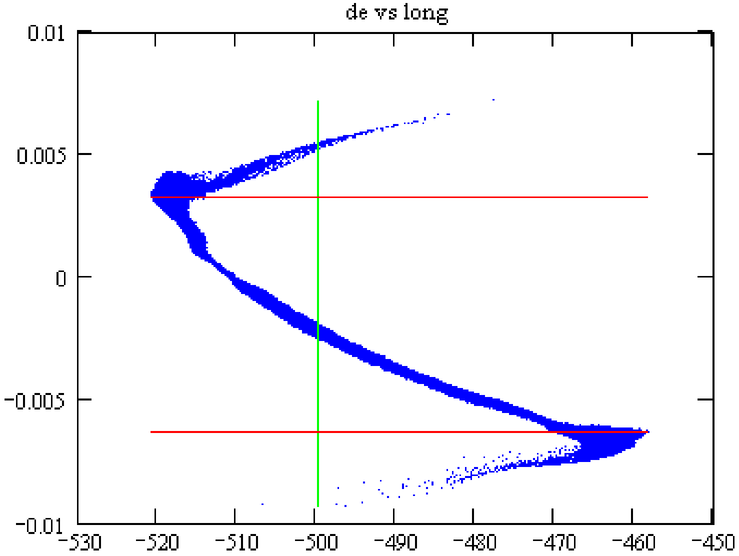
Wake fields + CSR: Simulation Set Up

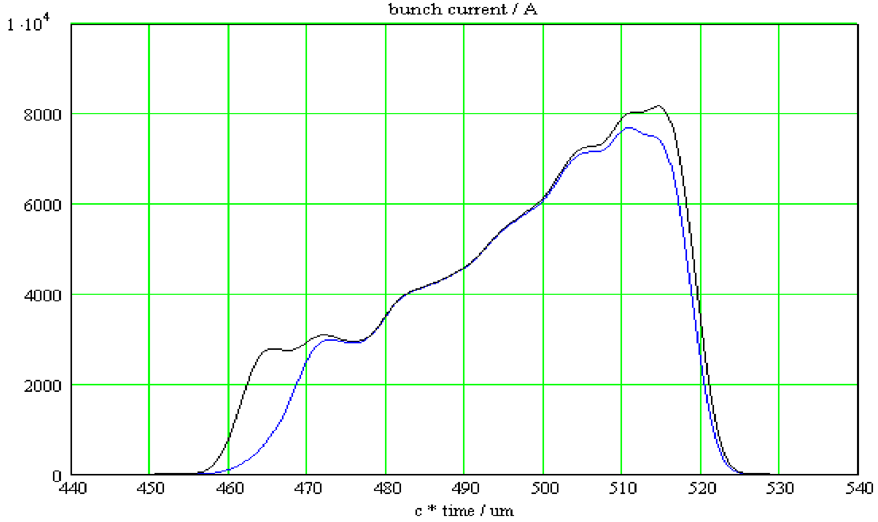




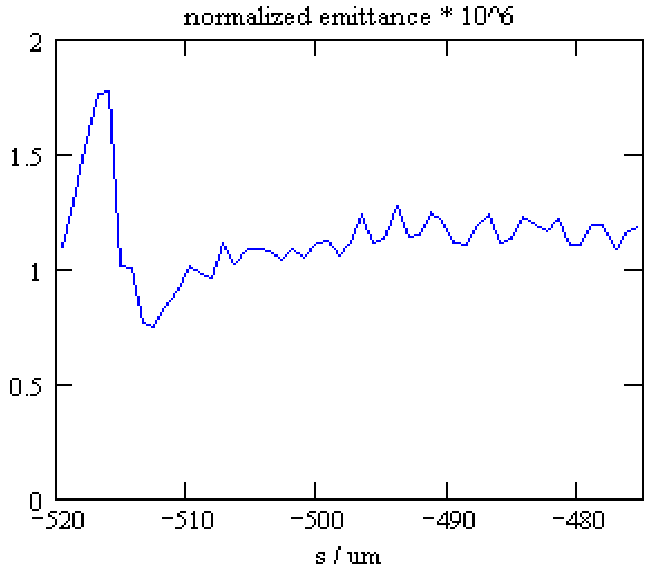
Wake fields + CSR: Results

Longitudinal





Transversal



Transverse Space Charge Effects

Numerical method (TrackFMN code, 1993, V.Balandin) :

Cloud-In-Cell (CIC) scheme (rectangular clouds).
Symplectic integration of Hamiltonian equations of motion (split-operator method). $H = H_{ext} + H_{sc}$, where H_{sc} is proportional to the scalar potential φ, which satisfies the Poisson's equation. The 2D Poisson's equation can be solved using finite difference approximation or FFT method.

RF Radial Focusing:

The transport of particles through an RF cavity is calculated using the on-axis accelerating field profile and its derivatives up to forth order (it was found that it is sufficient to use only the first derivative).

Number of "space charge kicks":

Up to 1-2 'space charge kicks' per 5 centimeter. Number of macroparticles: up to 10^6. Number of grid points: up to 512×512.

Quantities which will be shown

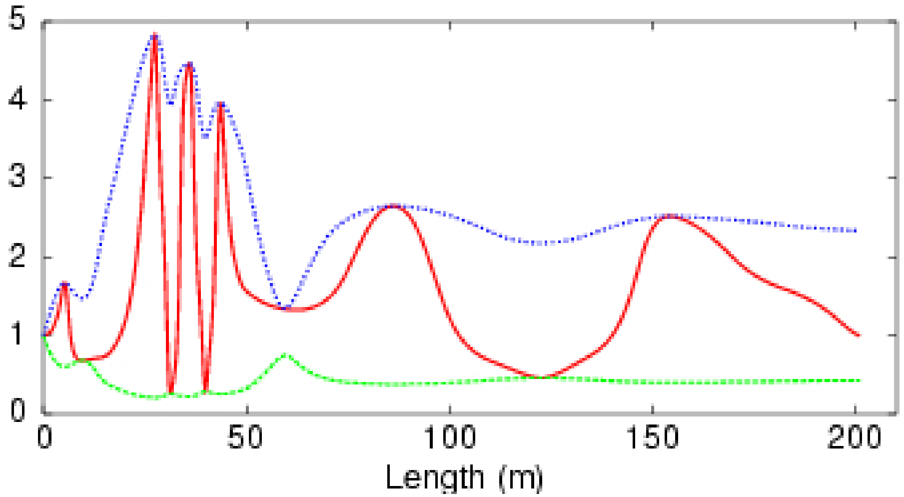
- **Emittance:** $\varepsilon_x = \sqrt{\langle x^2\rangle \langle p_x{}^2\rangle - \langle x\, p_x\rangle^2}$,
  where p_x is particle transverse momentum divided by design momentum

  Normalized emittance: $\varepsilon_{nx} = \beta_0 \gamma_0 \varepsilon_x$

- **β-function:** $\beta_x = \langle x^2\rangle / \varepsilon_x$

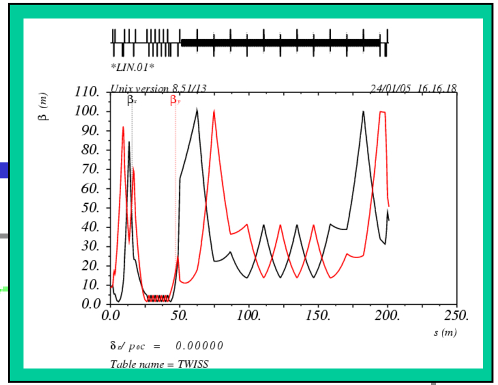
  Mismatch parameter: $\lambda_x = M_x + \sqrt{M_x{}^2 - 1}$

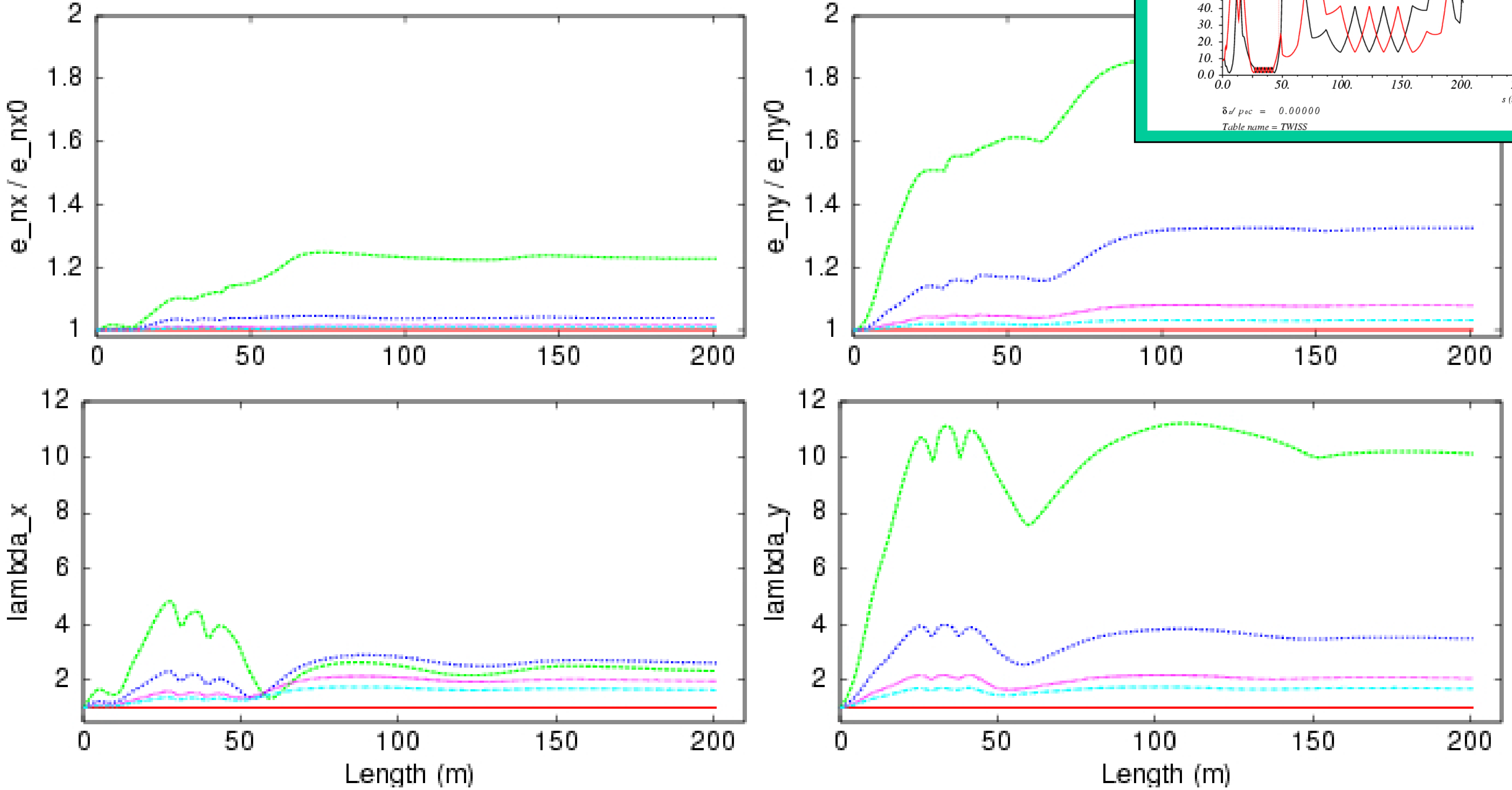
$$M_x = 0.5 \times (\beta_x \tilde{\gamma}_x - 2\, \alpha_x \tilde{\alpha}_x + \tilde{\beta}_x \gamma_x)$$



$$\frac{1}{\lambda_x} \le \frac{\beta_{x,\ \text{space charge}}}{\beta_{x,\ \text{design}}} \le \lambda_x$$

Section between BC1 and BC2

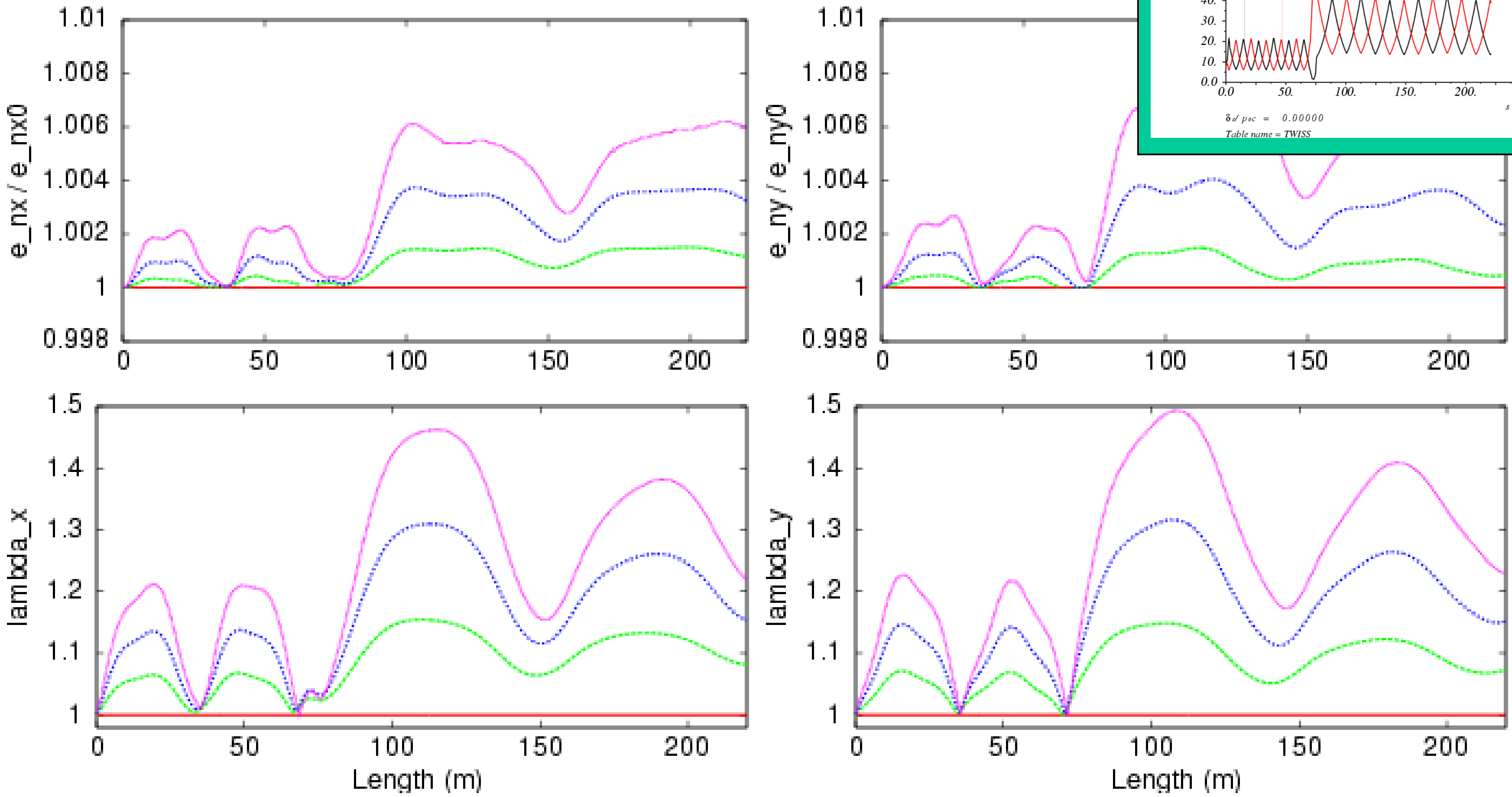


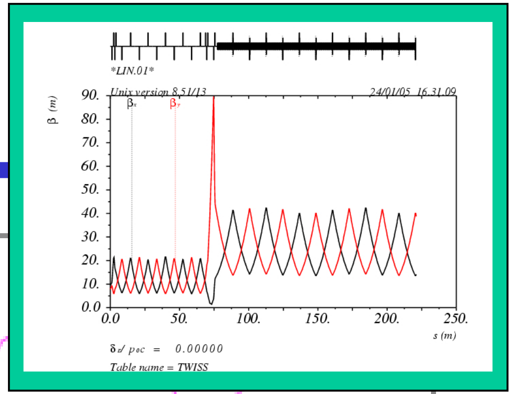


Beam parameters: E_{in} = 500 MeV, $E_f \approx$ 2.5 GeV, I = 1 kA

$\varepsilon_{nx,ny}$ = 0.2, 0.5, 1.0, 1.5 mm mrad

After final compression (BC2)

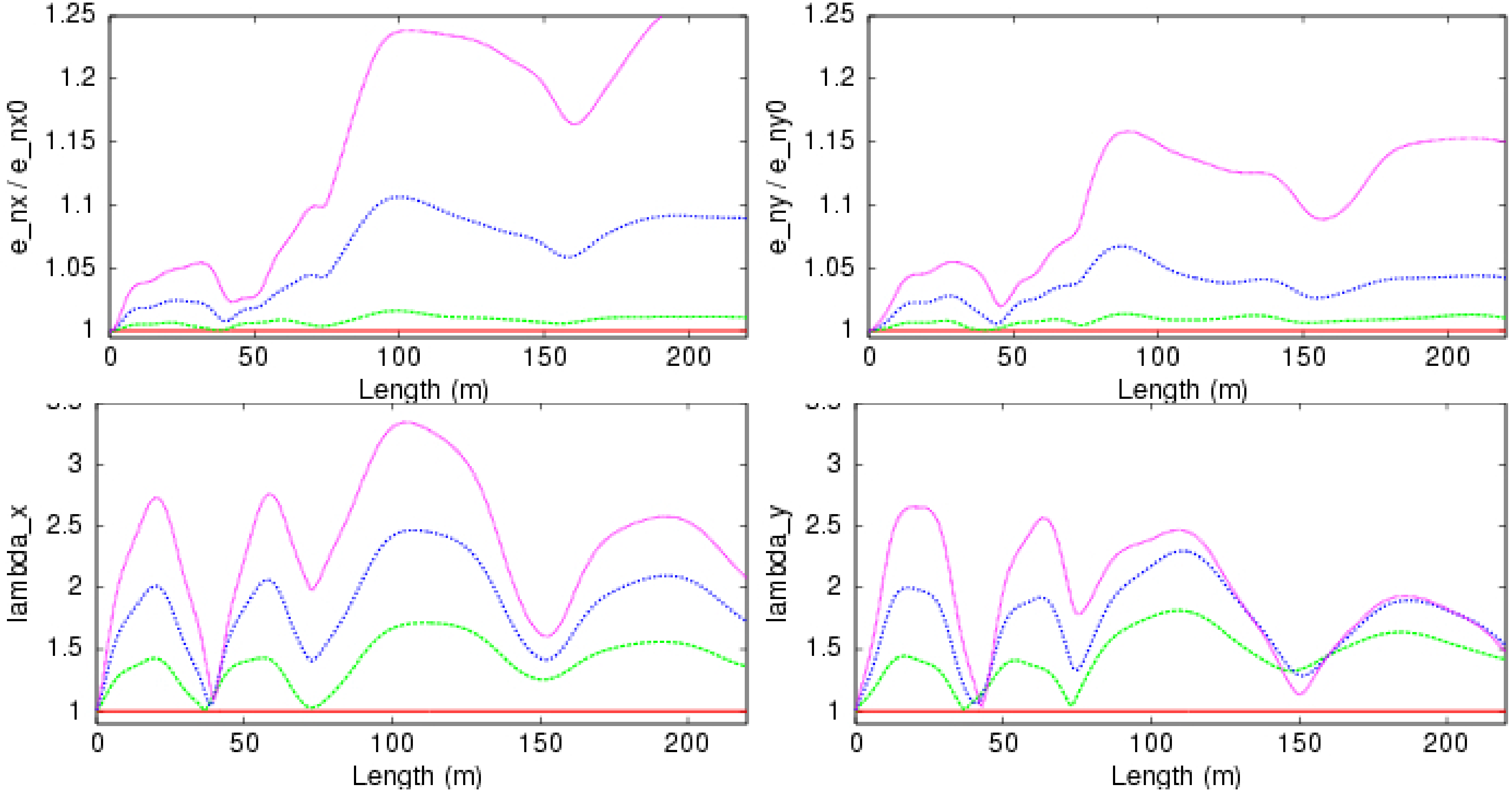




Beam parameters: E_{in} =2.5 GeV, $E_f \approx$ 4.5 GeV,

$\varepsilon_{nx,ny}$ = 1.0 mm mrad I = 0, 5, 10, 15 kA

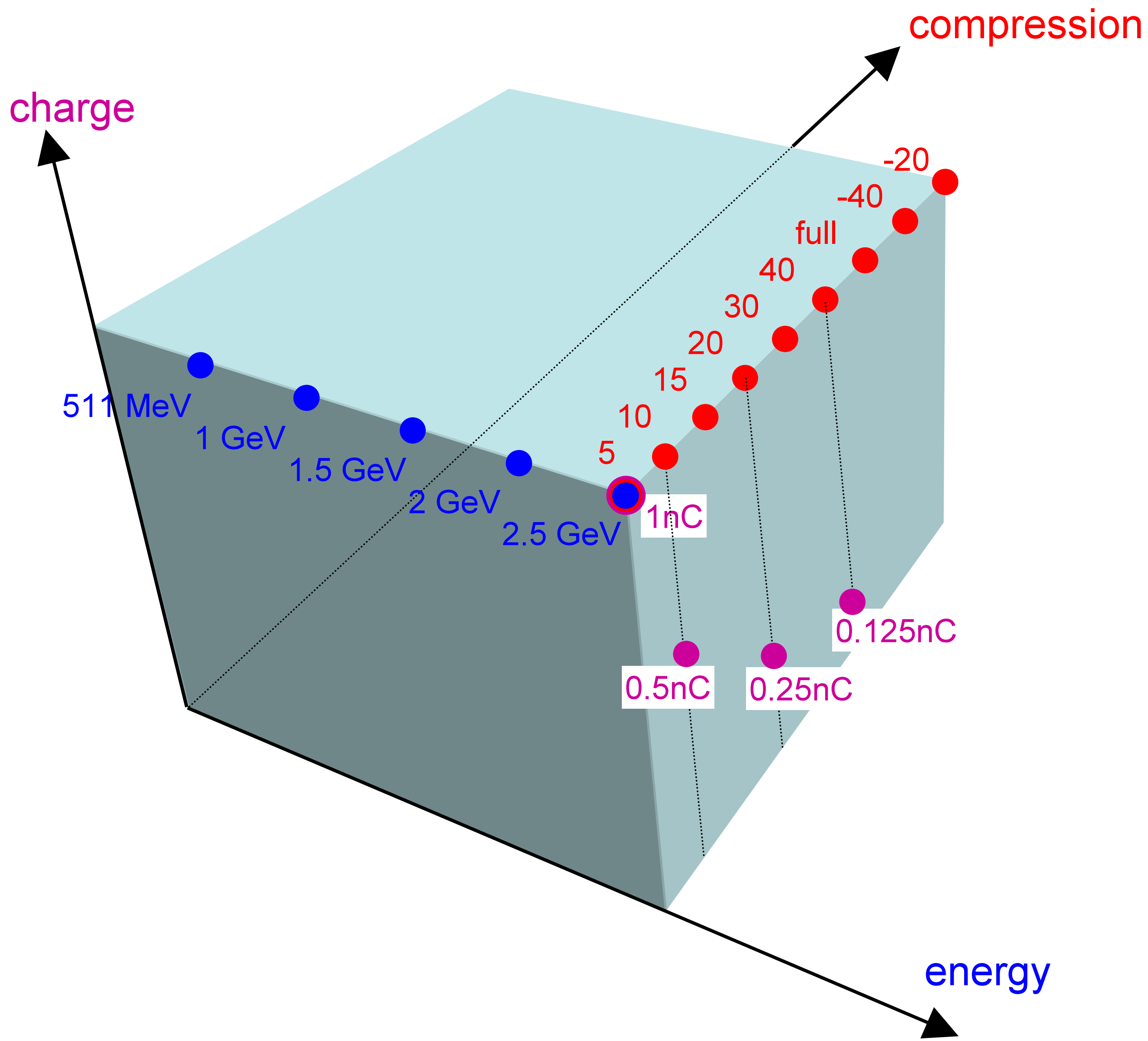
After final compression (BC2): smaller emittance and smaller energy

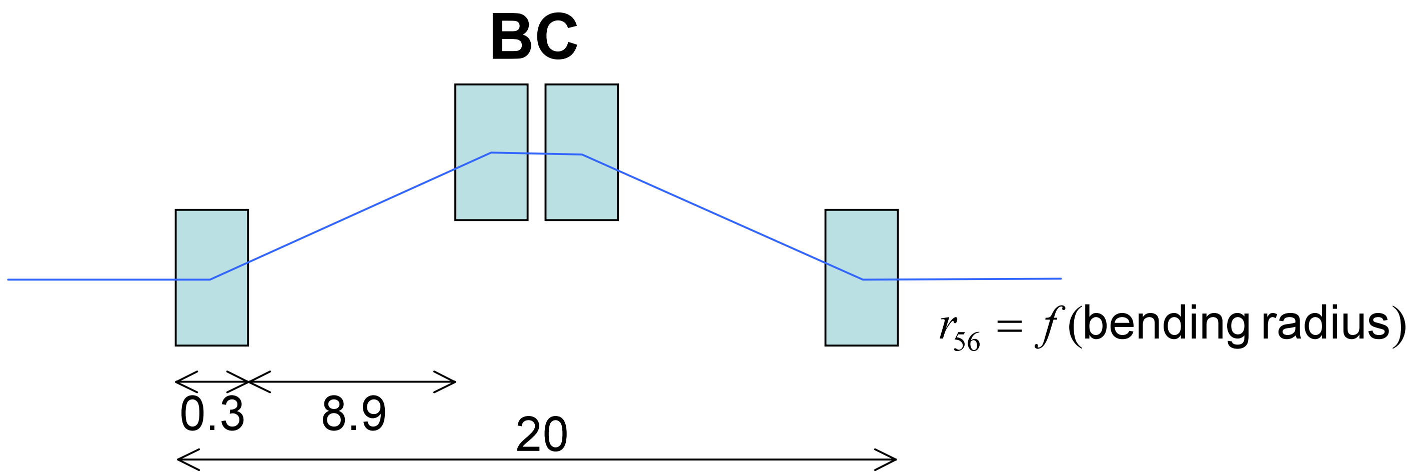


Beam parameters: E_{in} =1.5 GeV, $E_f \approx$ 3.5 GeV, $\varepsilon_{nx,ny}$ = 0.5 mm mrad

I = 0, 5, 10, 15 kA

parameter scan & CSR effects





source distribution

ideal gaussian
linear chirp = 9.634 MeV/100µm = const !!!
rms-length = 100 µm
slice energy spread = 0.1 MeV (~ 4keV@50A)
Twiss, horizontal: $\varepsilon_{nx} = 10^{-6}$, $\beta_x = 47.5$ m, $\alpha_x = 2.3$

compression factor

$$\text{compr.} = \frac{1}{\left|1 + r_{56} \cdot \frac{\text{linear chirp}}{\text{energy}}\right|}$$

E = 511 MeV Q = 1nC compr. = 5

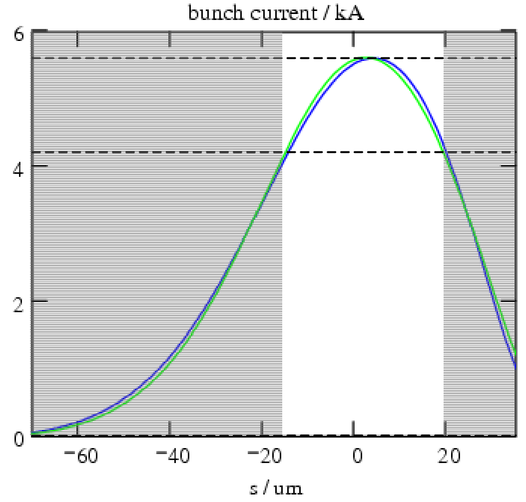
R_{bend} = 19.65 m, r_{56} = -4.24 mm

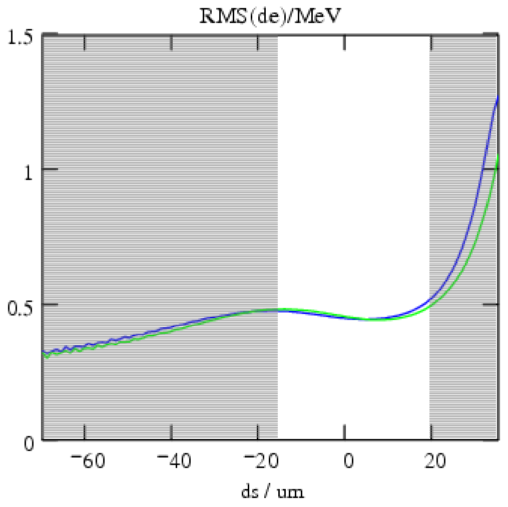
calculation method: green's, projected

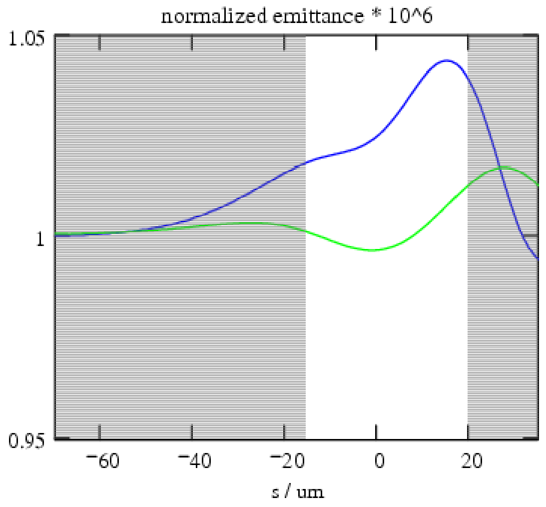
emittance:

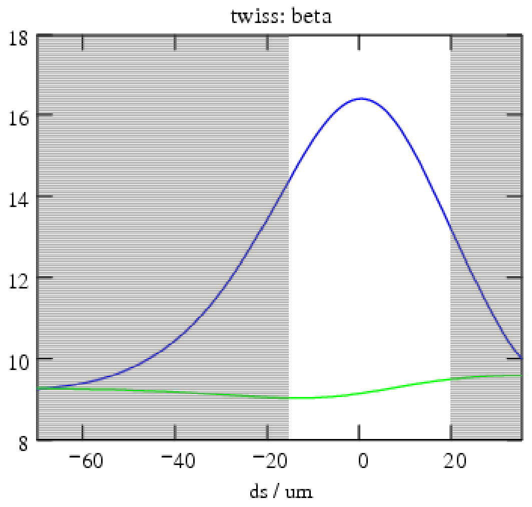
slice with I_peak: $1.031 \cdot 10^{-6}$
$0.998 \cdot 10^{-6}$

projected: $2.147 \cdot 10^{-6}$
$1.555 \cdot 10^{-6}$









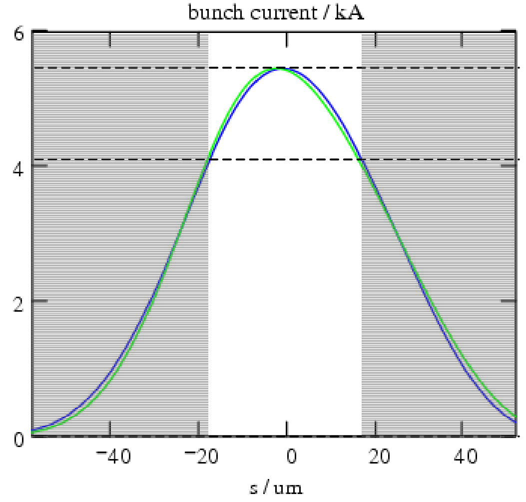
E = 2500 MeV   Q = 1nC   compr. = 5

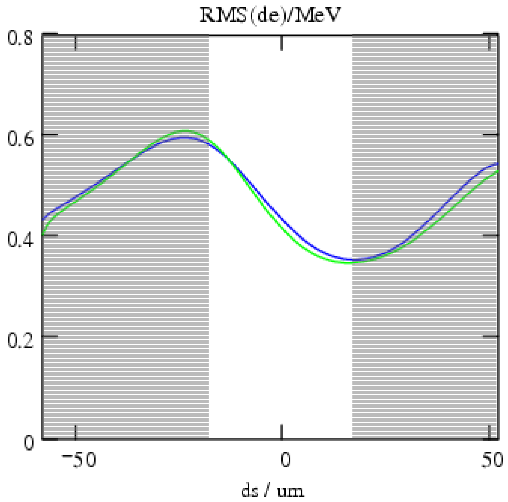
R_{bend} = 8.89 m, r_{56} = -20.76 mm

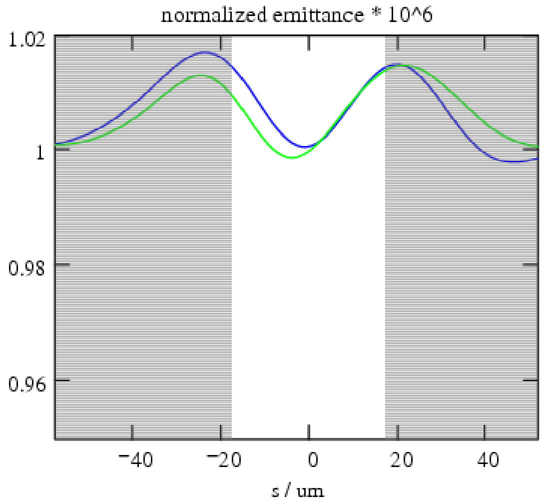
calculation method: green's, projected

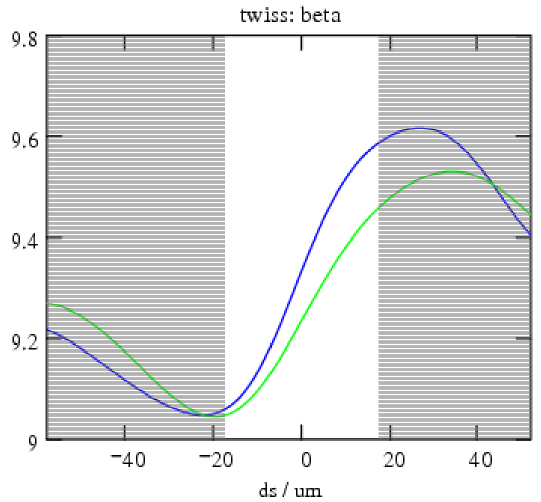
emittance:
slice with I_peak: $1.001 \cdot 10^{-6}$
$1.000 \cdot 10^{-6}$

projected: $2.010 \cdot 10^{-6}$
$1.951 \cdot 10^{-6}$









energy scan

compr. = 5 Q = 1nC

E/MeV	Ipeak/kA	(slice) emitt.	(proj) emitt.	beta/m	(slice) RMS(E)/MeV
511	5.5	1.03/1.01	2.15/1.56	13..17/9.1..9.5	0.46
1000	~	1.01	1.89/1.76	10..10.6/9.1..9.5	0.44
1500	~	1.01	1.92/1.84	9.6..9.8/9.1..9.5	0.45
2000	~	1.01	1.96/1.90	9.1..9.6/9.1..9.5	0.45
2500	~	1.01	2.01/1.95	9.1..9.6/9.1..9.5	0.46

green's, projected method
numbers: from plots by eye

compression

energy = 2.5 GeV   Q = 1nC

compr.	Ipeak/kA	(slice) emitt.	(proj) emitt.	beta/m	(slice) RMS(E)/MeV
5	5.5	1.01/1.01	2.0/1.95	9.1..9.6/9.1..9.5	0.46
9.1	9.7	1.02/1.01	3.5/3.3	7.5..9.5/7.5..9.5	0.8
13.6	14.8	/1.18	/5.4	/4.6..8.5	1.2
18.2	19.1	1.8 /1.6	8 /7	2.7..5.8/2.7..7.1	2
27.3	31.9	/3.1	/12	/0.6..2.8	4
36.4	41.3	/6	/16	/0.5..2	5
full	68.1	/16	/27	/4..5	7.5
-36.4	76	/14	/19	/1..2	7
-18.2	43	/3.1	/11	/2..3.5	4

green's, projected method
numbers: from plots by eye

compression & charge

energy = 2.5 GeV

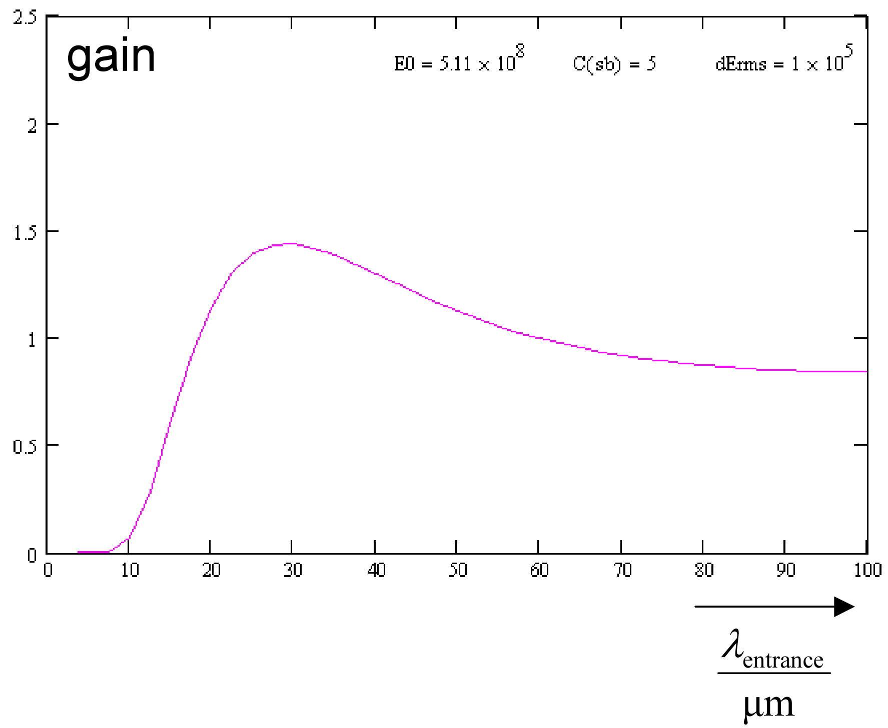
compr. Q/nC	Ipeak/kA	(slice) emitt.	(proj) emitt.	beta/m	(slice) RMS(E)/MeV
5 , 1.0	5.5	1.01/1.01	2.0/1.95	9.1..9.6/9.1..9.5	0.46
9.1, 0.5	4.9	1.01/1.01	1.9/1.8	9.1..9.7/8.5..9.6	0.8
18.2, 0.25	4.9	1.06/1.05	1.9/1.8	7.5..9.2/7.6..9.6	1.6
36.4, 0.125	4.9	/1.35	/1.82	/6.4..8.9	3.2

green's, projected method
numbers: from plots by eye

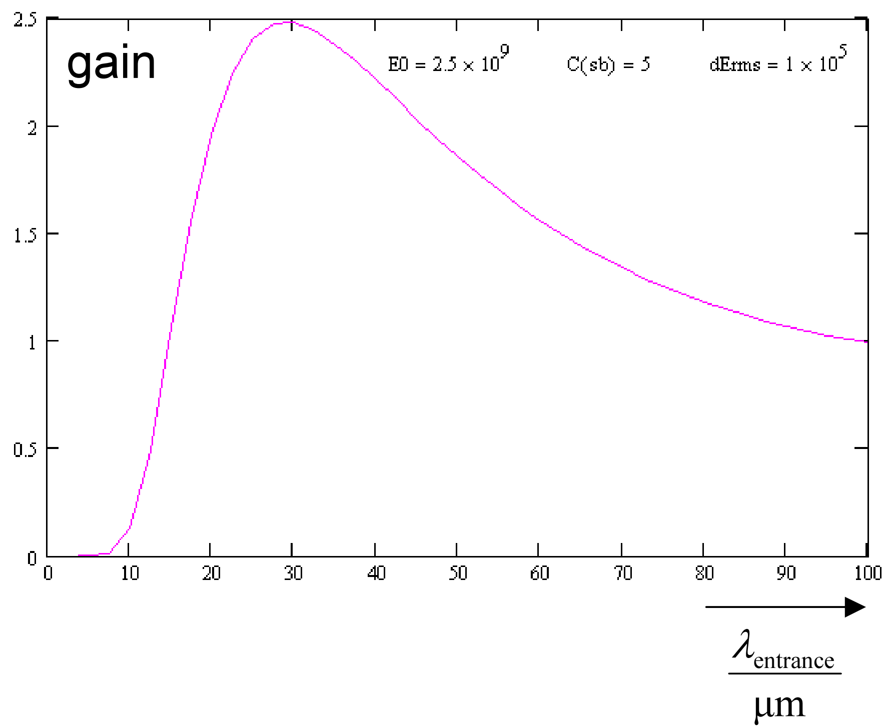
modulation gain

only bc2, integral equation theory

E = 511 MeV
Q = 1nC
compr. = 5



E = 2.5 GeV
Q = 1nC
compr. = 5



Summary

With the 2nd BC stage at higher energy (2-2.5 GeV)

- Space charge effects at design parameters (5 kA) are negligible. Some beta-beating between 1st and 2nd stage, can most likely be remedied with
  - Optimized optics
  - Slightly increased energy of 1st stage
  - Slightly longer bunch

  Head room: lower emittances (at least to 0.5 mm-mrad) can be preserved, peak current up to 15 kA managable
- CSR effects:

  No Problem at design parameters. Nearly independent of the beam energy at the 2nd BC stage. Head room (less than 25% slice emittance increase in core, needs S2E for more precise evaluation):
  - for fixed bunch charge of 1 nC, up to 15 kA
  - For fixed peak current of 5 kA, bunch lengths down to 5 μm RMS (at 0.25 nC)
  - Do not over-compress!
- Wake Fields:
  - of booster linac, 3rd harmonic RF and transverse deflecting cavity slightly change settings for phase and amplitude of RF, but do not disturb the bunch compression.

Conclusion

- 1st BC stage after 5 Modules at 500 MeV beam energy
- 2nd BC stage after another 12 Modules.
  - Beam energy for safe and stable running will be 2 GeV (RF gradient of 15 MeV/m)
  - Beam energy can be increased to 2.5 GeV and higher when running with peak currents way beyond design
- For Beam Diagnostic:
  - Downstream 1st BC stage:
    - Transverse deflecting cavity (Measures bunch length and slice emittance)
    - Wire scanner section
  - Downstream 2nd BC stage:
    - Bunch length measurement with ‘optical replica’ method
    - wire scanner section