STATUS OF XFEL SIMULATIONS

Barbara Marchetti

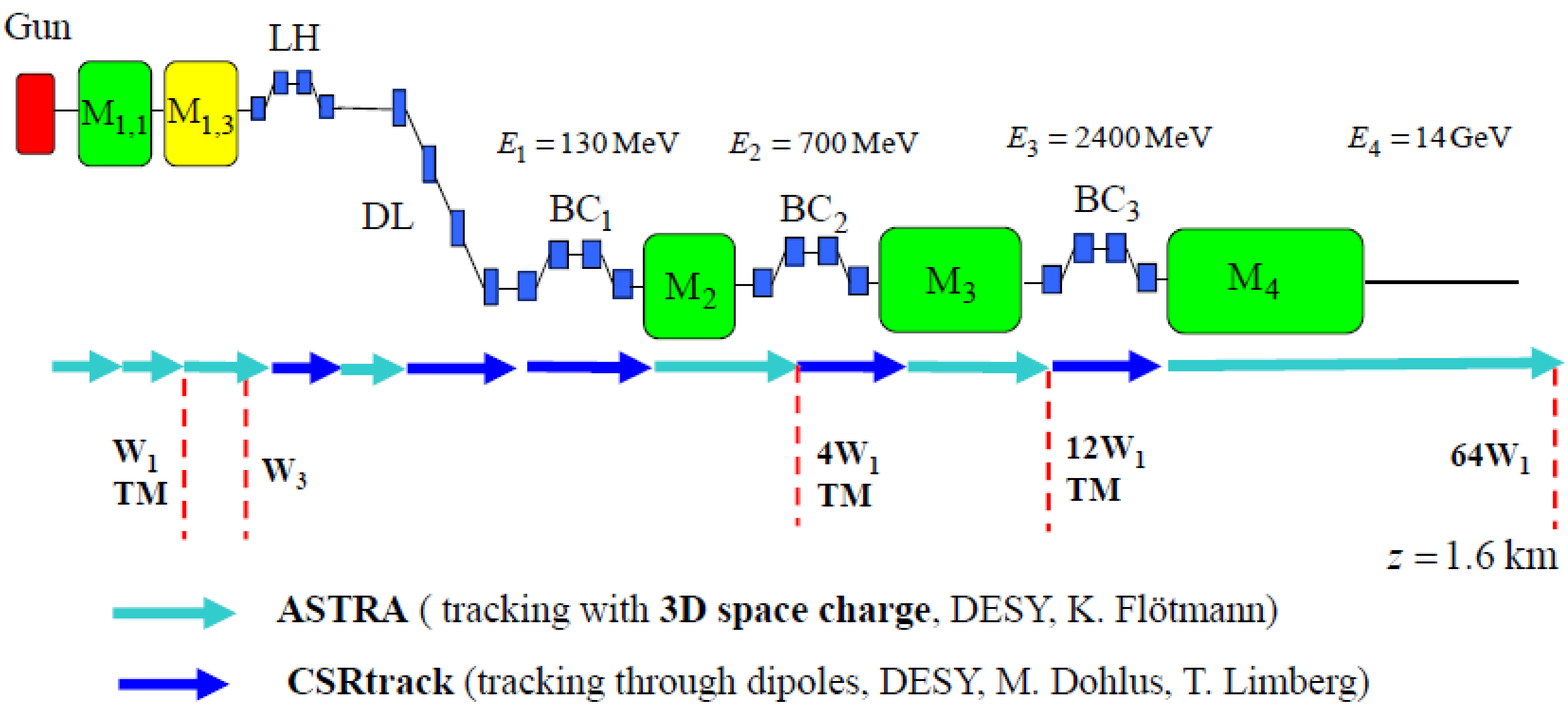
Thank you to : Igor Zagorodnov, Mikhail Krasilnikov

Introduction

- <u>Final goal</u>: S2E simulations for the single spike laser production at the XFEL.
- <u>Short term goal n.1</u> : understand the method to optimize the bunch compression in the Xfel used by the community working on this topic (e.g.Igor Zagorodnov, Martin Dohlus…). -> I got from them a big amount of Matlab routines and two practical examples of simulations from which be able to start.
- <u>Short term goal n.2</u> : make some estimation of the properties of e-bunch needed for single spike lasering, optimize the emission using Genesis.

XFEL LAYOUT

I. Zagorodnov talk
01.01.2011
DESY



W1 -TESLA cryomodule wake (TESLA Report 2003-19, DESY, 2003)

W3 - ACC39 wake (TESLA Report 2004-01, DESY, 2004)

TM - transverse matching to the design optics

Wakefield are added using Matlab routines .

OPTIMIZE THE TRANSPORT MEANS…

- Find the machine parameters (RF max amplitude, phase, R_{56} for the magnetic compressors) that allow maximum compression of the bunch and stable run (e. g. tolerance to phase jitter). I. Zagorodnov, M. Dohlus, DESY 10-102, 2010
- Study the result of the compression for different charges of the e-bunch, laser shapes …
- Since all these simulations are VERY time consuming some "tricks" are necessary, for example, to avoid the re-calculation of beam matching at each run, or the re-set of RF phases when wakefields are included…

Starting my simulation

- In order to get familiar with the e-bunch transport and compression I have got from Xfel dynamics group the optimized simulation they did for 1 nC e-bunch.
- I have slightly changed the initial parameter of the run into the Pitz optimized starting point (calculated by Mikhail) and run the compression again in order to compare the final result.

COMPARISON BETWEEN STARTING PARAMETERS

Optimized machine setup
(ASTRA simulations)

	parameter	unit	value
cathode laser	temporal	profile	flat-top
	transverse	distribution	rad.homogen
	rt/FWHM\ft	ps	2\21.5/2
	XYrms	mm	0,401
	Ek	eV	0,55
	th.emit.	mm mrad	0,34

Pitz

Optimized machine setup
(ASTRA simulations)

	parameter	unit	value
cathode laser	temporal	profile	flat-top
	transverse	distribution	rad.homogen
	rt/FWHM\ft	ps	2\20/2
	XYrms	mm	0,401
	Ek	eV	0,55
	th.emit.	mm mrad	0,34

Xfel

While doing the simulations I wanted also to check the impact of the different parameters used for SC calculation…

Space charge parameters comparison:
(in parenthesis values found in the xfel):

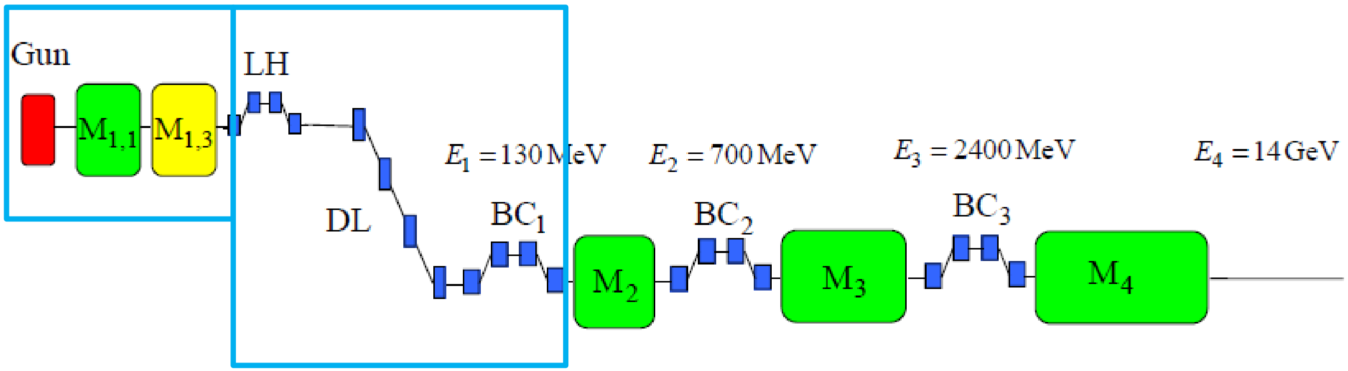
Cell_var 1 (2) (variation of the radial grid height over the bunch radius)

MaxScale 0.05 (0.5) (SC fields scale with energy: scaling factor up to which SC is scaled instead of recalculated)

Max_cont 40 (50) (max number of scaling steps after which SC field are recalculated)

Nrad 40 (35) (# of rings for SC grid)

Nlong_in 100 (65) (# of slices for SC grid)

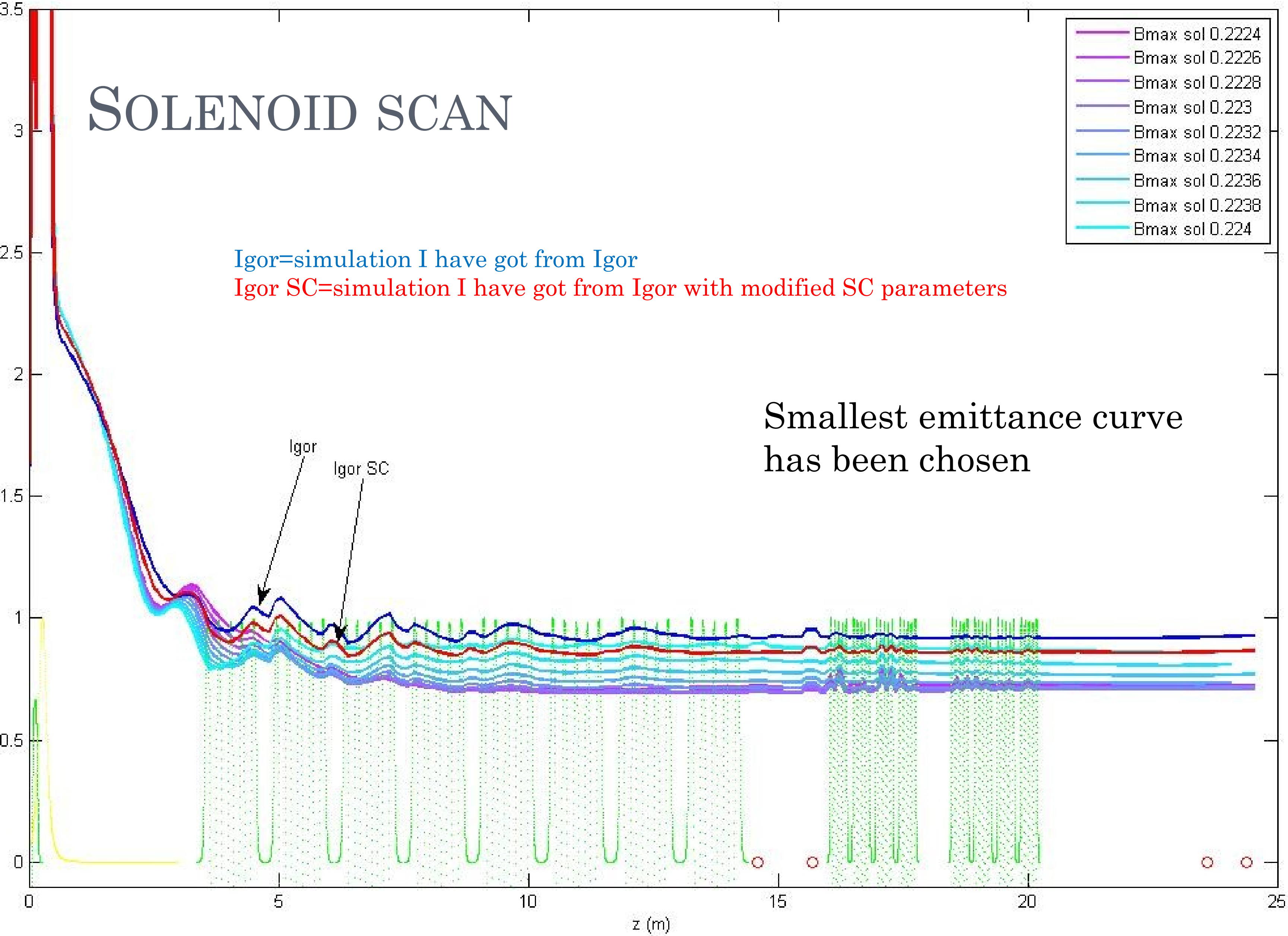


Injector (0-24.75 m), 1 run ~ 1 day + Laser heater, dogleg and first magnetic compressor (24.75 - 76.73 m), 1 run ~ 15 h

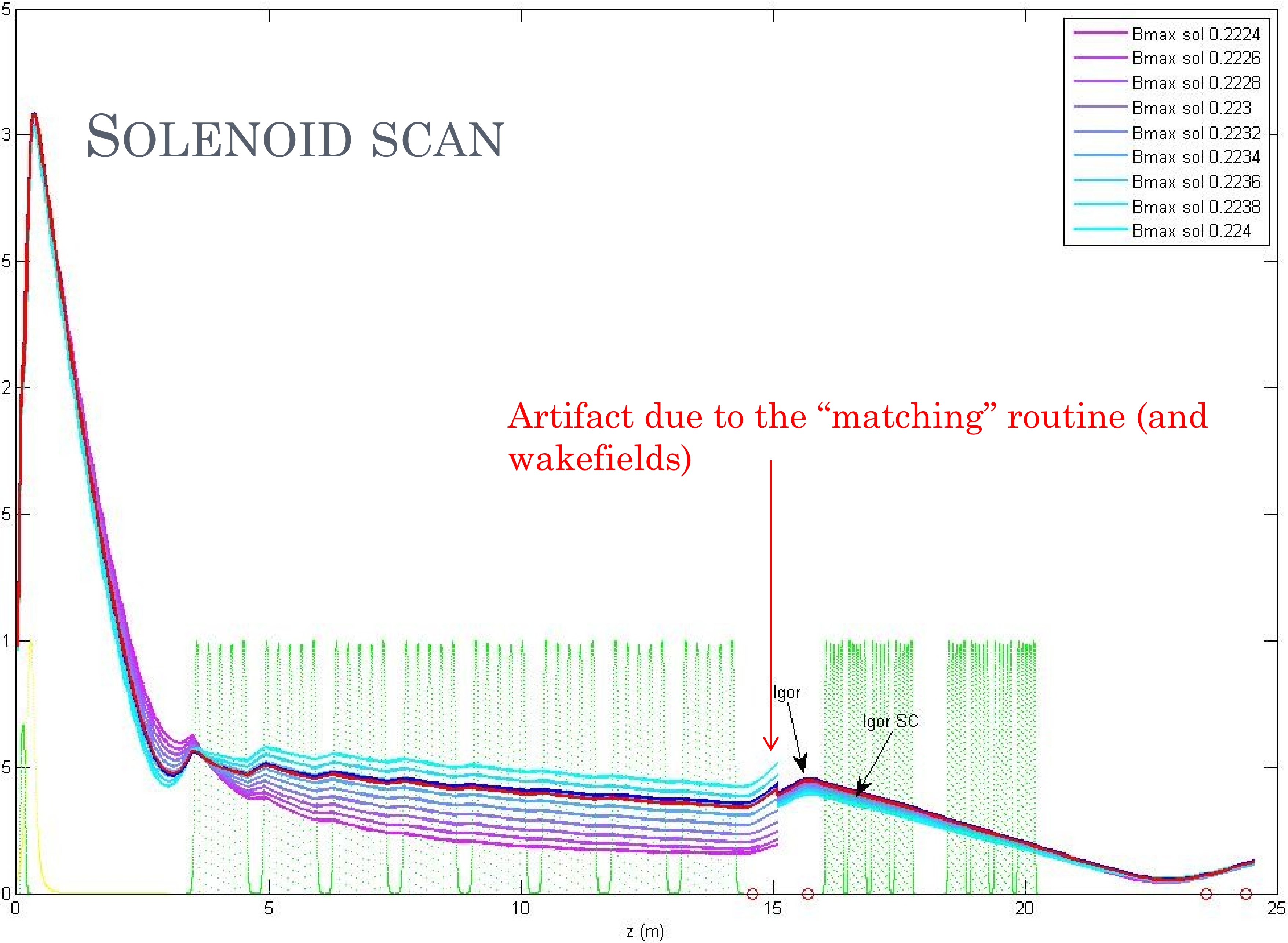
Solenoid scan

Igor=simulation I have got from Igor
Igor SC=simulation I have got from Igor with modified SC parameters

Smallest emittance curve has been chosen

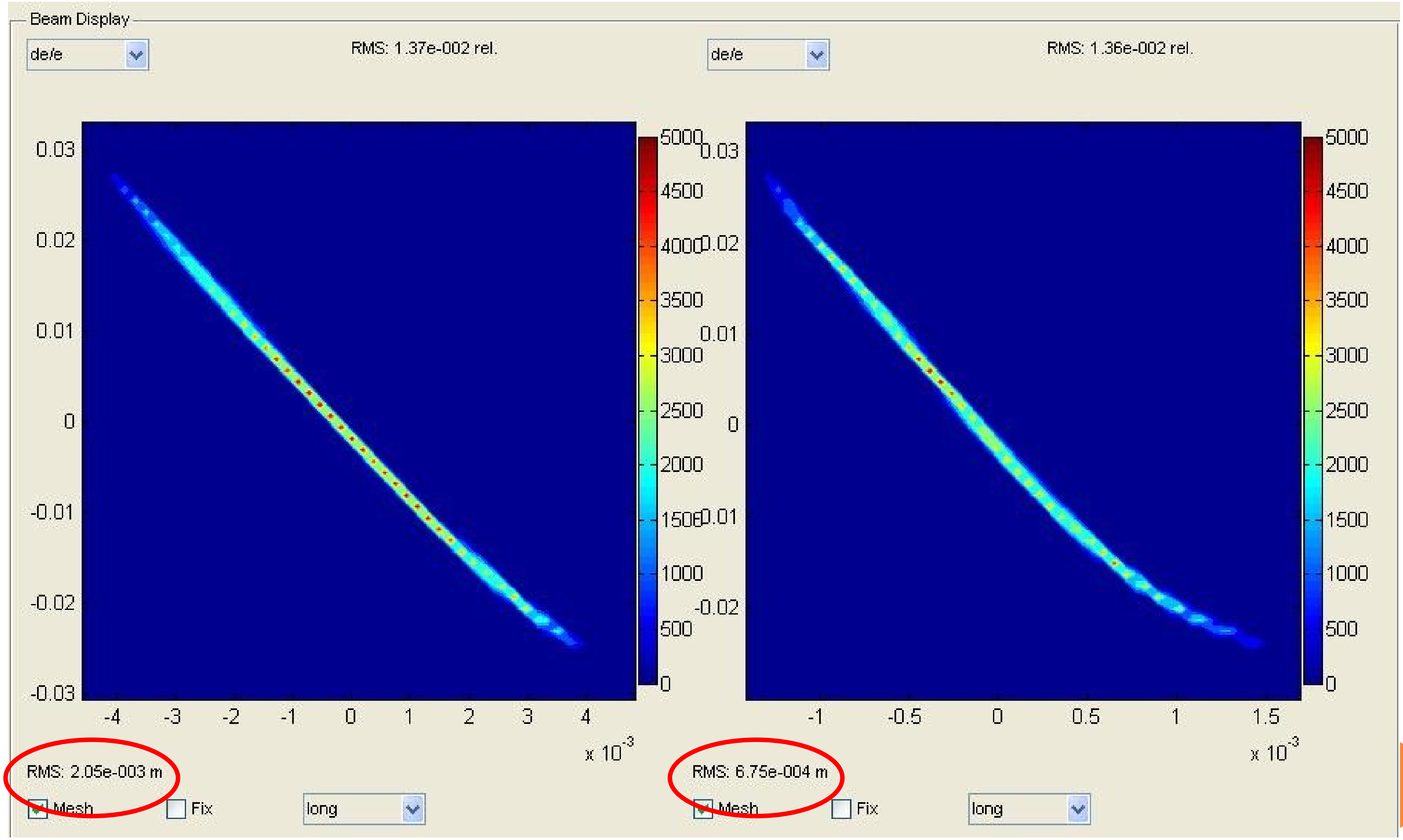


Solenoid scan



First compression

Before BC1 After BC1



E=130 MeV

Compression factor ~ 3.04 -> **This part is OK**

Space charge observations

- Let’s introduce the Laminarity Parameter in order to quantify the impact of SC in a position z of the accelerator
- It represents the ratio between the space charge term and the emittance term in the transverse envelope equation and it is defined as:

Accelerator physics: basic principles on beam focusing and transport

Massimo Ferrario

INFN-LNF, Frascati (Roma), Italy

SPARC-BD-12/01
2 January 2012

$\rho >> 1$
SC term dominates

$\rho << 1$
Emittance term dominates

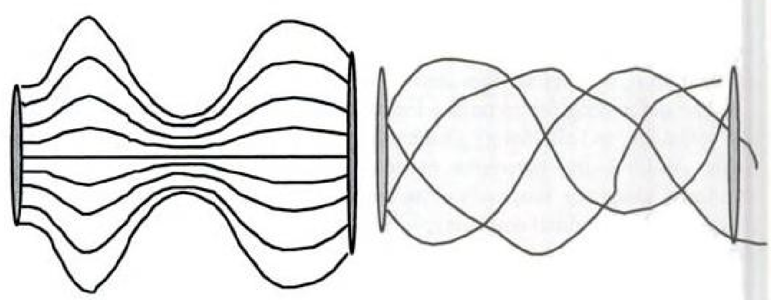


Figure. 2. Schematic representation of a quasi-laminar beam trajectories (left plot) and of an emittance dominated beam trajectories (right plot).

At the exit of BC1, I have calculated
$\rho = 1.1852$

COMPARISON @ BC1 EXIT:

My run

Number of Particles: 200000 Charge: 1 nC
Position: 6.5491 m Beam Energy: 130 MeV

FWHM (distance between green bars): 2.15e+003 µm
Charge within FWHM: 89.6 %
Projected Emittance: $\gamma\varepsilon_x$ = 1.5e-006 m $\gamma\varepsilon_y$ = 7.32e-007 m
Optics @ I_{peak}: α_x = -9.13 β_x = 69m α_y = 0.0194 β_y = 9.3

RMS Values for all Particles:

x = 4.17e-004 m x' = 5.64e-005
y = 1.98e-004 m y' = 1.52e-005
z = 6.75e-004 m δ = 1.36e-002

RMS Values within FWHM:

x = 4.03e-004 m x' = 5.51e-005
y = 1.86e-004 m y' = 1.50e-005
z = 5.73e-004 m δ = 1.20e-002

Igor 's run

Number of Particles: 200000 Charge: 1 nC
Position: 6.5491 m Beam Energy: 130 MeV

FWHM (distance between green bars): 2.14e+003 µm (7.13
Charge within FWHM: 89.7 %
Projected Emittance: $\gamma\varepsilon_x$ = 1.85e-006 m $\gamma\varepsilon_y$ = 9.63e-007 m
Optics @ I_{peak}: α_x = -8.19 β_x = 60.3m α_y = 0.232 β_y = 9.69m

RMS Values for all Particles:

x = 4.86e-004 m x' = 6.40e-005
y = 2.34e-004 m y' = 1.71e-005
z = 6.70e-004 m δ = 1.34e-002

RMS Values within FWHM:

x = 4.63e-004 m x' = 6.22e-005
y = 2.04e-004 m y' = 1.62e-005
z = 5.70e-004 m δ = 1.20e-002

Run using Igor's input and Mikhail's SC parameters

Number of Particles: 200000 Charge: 1 nC
Position: 6.5491 m Beam Energy: 130 MeV

FWHM (distance between green bars): 2.13e+003 µm (7.1 p
Charge within FWHM: 89.7 %
Projected Emittance: $\gamma\varepsilon_x$ = 1.77e-006 m $\gamma\varepsilon_y$ = 9.01e-007 m
Optics @ I_{peak}: α_x = -8.86 β_x = 65m α_y = 0.206 β_y = 9.52m

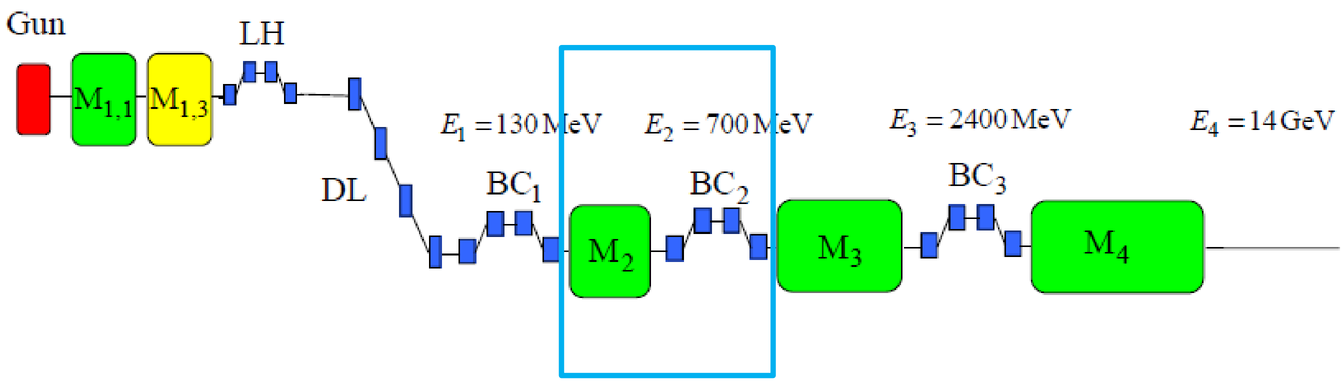
RMS Values for all Particles:

x = 4.69e-004 m x' = 6.22e-005
y = 2.27e-004 m y' = 1.65e-005
z = 6.67e-004 m δ = 1.33e-002

RMS Values within FWHM:

x = 4.51e-004 m x' = 6.09e-005
y = 2.00e-004 m y' = 1.60e-005
z = 5.67e-004 m δ = 1.19e-002

Difference in ex= 0.08 e-006 m (4.3 %)
Difference in ey= 0.035 e-006 m (3.7 %)
Difference in RMSx= 0.17 e-004 m (3.5 %)
Difference in RMSy= 0.07 e-004 m (3 %)
Difference in RMSz= 0.03 e-004 m (0.4 %)



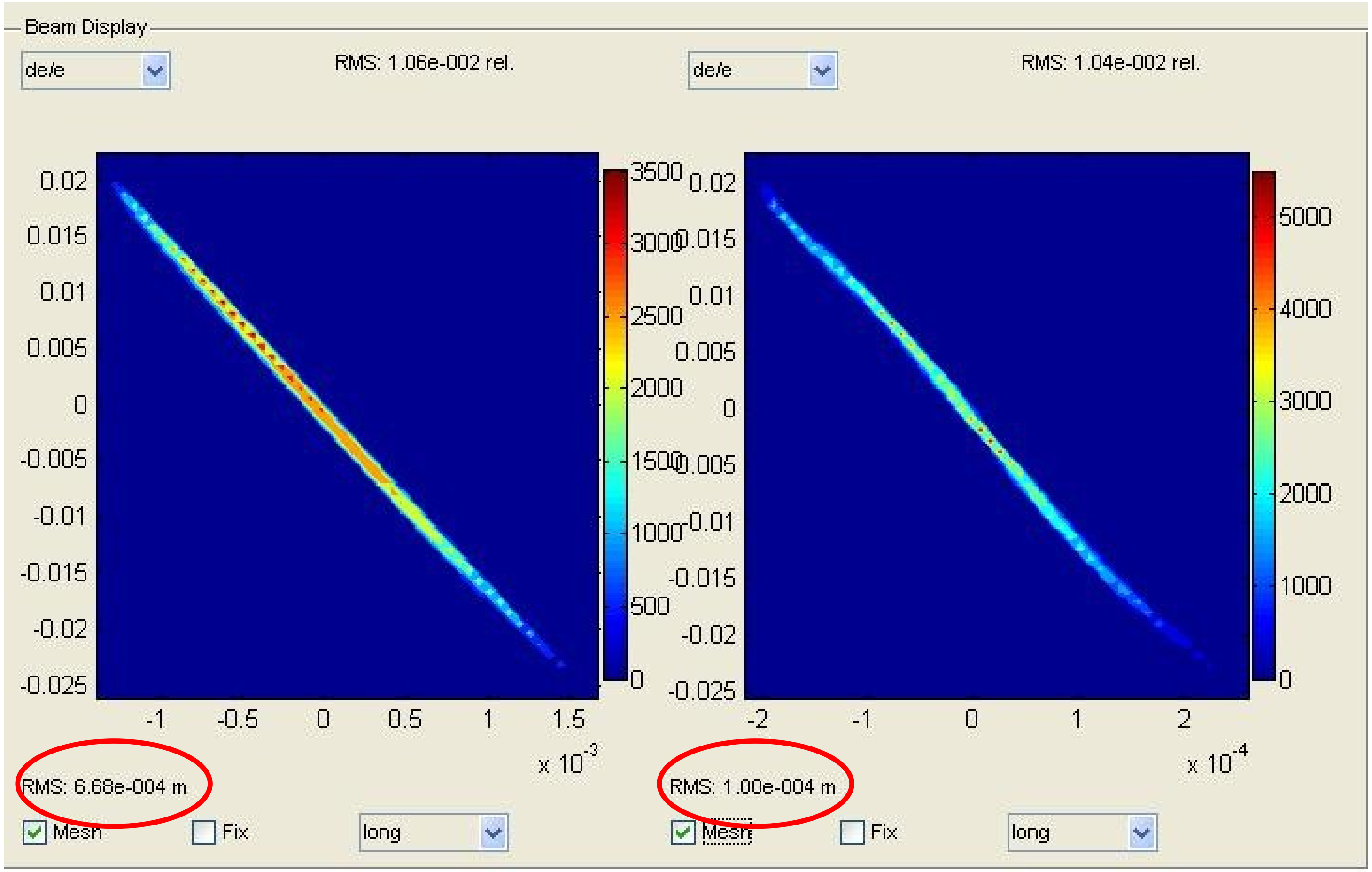
LINAC 2, SECOND MAGNETIC COMPRESSOR (76.73 – 178.89 M)

1 RUN ~ 3 DAYS

SECOND COMPRESSION

= 0.0888

Before BC2 After BC2



Compression factor ~ 6.68 (too small? In Igor files it is higher than 7)

Comparison between output file obtained for SC switched on and off in linac 2

ρ from 1.1852 (at BC1) to 0.0888 (at BC2)

SC on linac exit

Number of Particles: 200000 Charge: 1 nC
Position: -0.1 m Beam Energy: 700 MeV

FWHM (distance between green bars): 2.13e+003 μm (7.12
Charge within FWHM: 89.7 %
Projected Emittance: $\gamma\varepsilon_x$ = 1.48e-006 m $\gamma\varepsilon_y$ = 7.26e-007 m
Optics @ I_{peak}: α_x = 2.72 β_x = 62.9m α_y = 1.61 β_y = 51.6m

RMS Values for all Particles:

```
x = 2.25e-004 m   x' = 1.15e-005
y = 1.35e-004 m   y' = 6.13e-006
s = 6.68e-004 m   δ  = 1.06e-002
```

RMS Values within FWHM:

```
x = 2.10e-004 m   x' = 1.00e-005
y = 1.32e-004 m   y' = 6.04e-006
s = 5.68e-004 m   δ  = 9.05e-003
```

SC off linac exit

Number of Particles: 200000 Charge: 1 nC
Position: -0.1 m Beam Energy: 700 MeV

FWHM (distance between green bars): 2.13e+003 μm (7.12
Charge within FWHM: 89.7 %
Projected Emittance: $\gamma\varepsilon_x$ = 1.4e-006 m $\gamma\varepsilon_y$ = 7.43e-007 m
Optics @ I_{peak}: α_x = 3.03 β_x = 60.4m α_y = 1.64 β_y = 45.4m

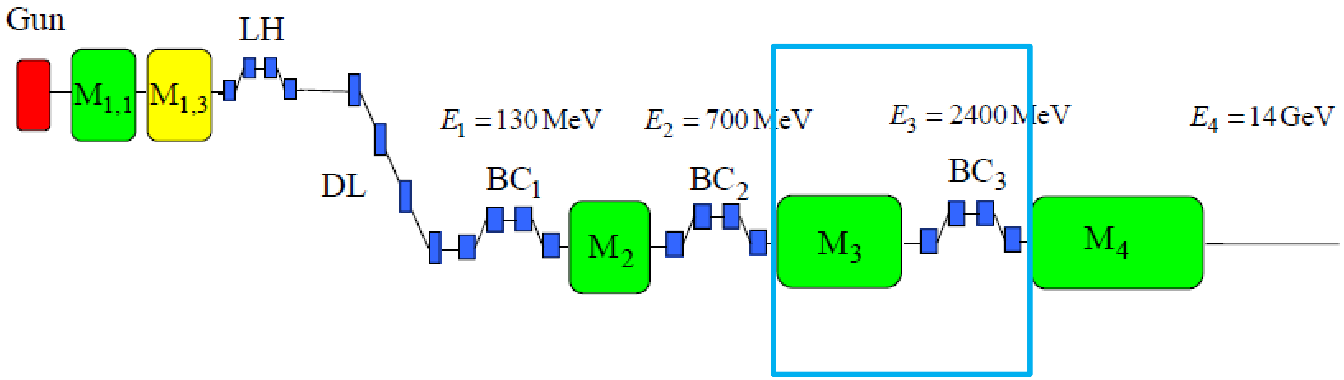
RMS Values for all Particles:

```
x = 2.49e-004 m   x' = 1.01e-005
y = 1.38e-004 m   y' = 6.00e-006
s = 6.68e-004 m   δ  = 1.06e-002
```

RMS Values within FWHM:

```
x = 2.18e-004 m   x' = 9.32e-006
y = 1.31e-004 m   y' = 5.84e-006
s = 5.68e-004 m   δ  = 9.06e-003
```

Difference in ex= 0.08 e-006 m (5.4%)
Difference in ey= 0.017 e-006 m (2.3 %)
Difference in RMSx= 0.24 e-004 m (10.7 %)
Difference in RMSy= 0.03 e-004 m (2.2 %)
Difference in RMSz= 0

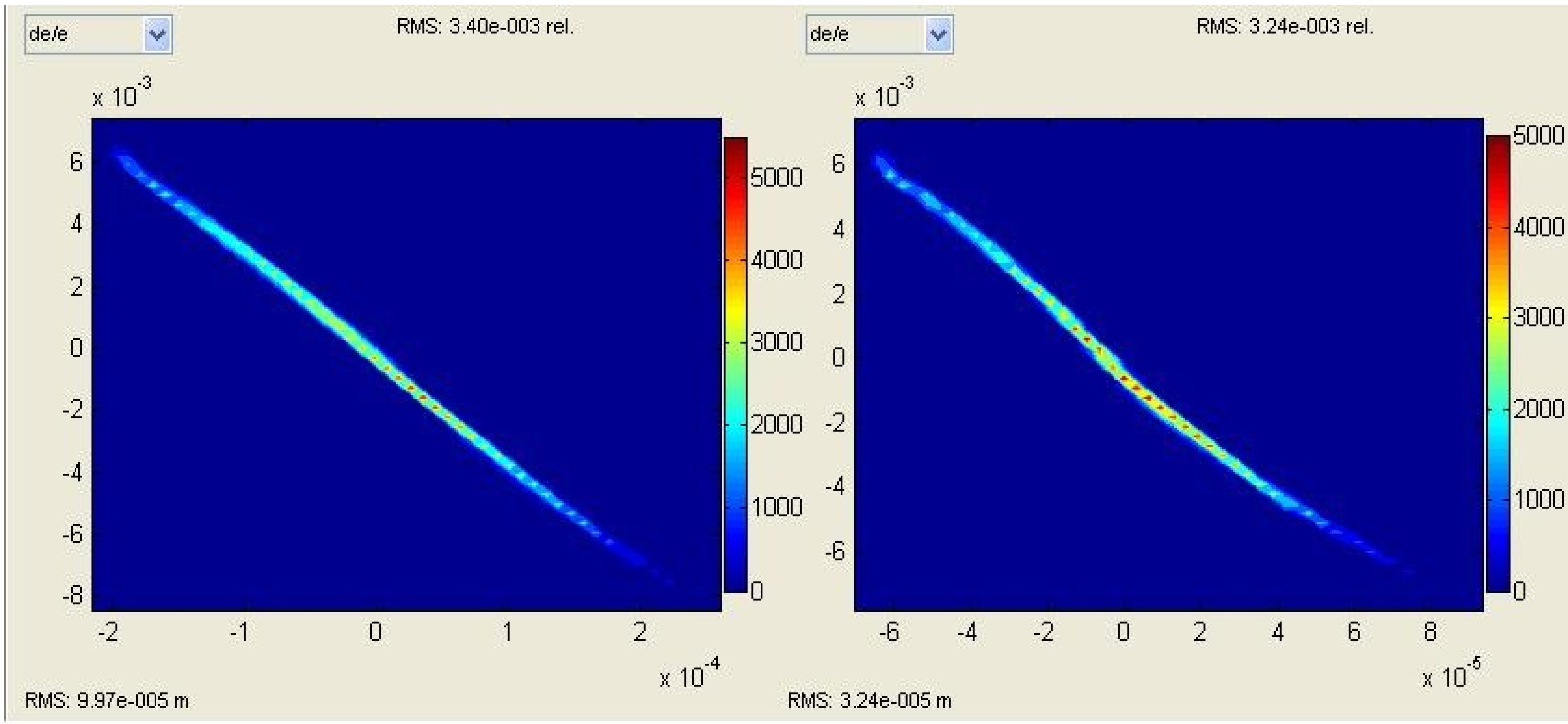


Linac 3, third magnetic compressor (178.89 - 389.50 m)

1 run ~ 6 days

Last Compression

Before BC3 After BC3



Compression factor ~ 3 (again too small! In Igor's files it is 3.6)

Situation at BC3 exit

Parameter	Unit		
Bunch charge	nC	1	
Peak current (gun)	A	43	
Bunch length (gun, FWHM)	ps	25	
Slice emittance (gun)	µm	0.8	
Projected emittance (gun)	µm	1	
Compression		114	
Peak current	kA	**4.9**	3.6 kA
Bunch length (FWHM)	fs	178	32.9 ps
Slice emittance	µm	**1**	0.8 µm
Projected emittance	µm	3.5	2.49 µm
Slice energy spread **(laser heater off)**	MeV	0.45	0.2 MeV

Before starting the transport in linac 4, better optimization of RF-phases of linac 2 and 3 is needed!

… work in progress.

I. Zagorodnov talk
01.01.2011
DESY

Summary of SC impact in Linac2 and Linac3

Linac2 Length = 81.6 m

ρ from 1.1852 (at BC1) to 0.0888 (at BC2)

Difference in ex= 0.08 e-006 m (5.4%)
Difference in ey= 0.017 e-006 m (2.3 %)
Difference in RMSx= 0.24 e-004 m (10.7 %)
Difference in RMSy= 0.03 e-004 m (2.2 %)
Difference in RMSz= 0

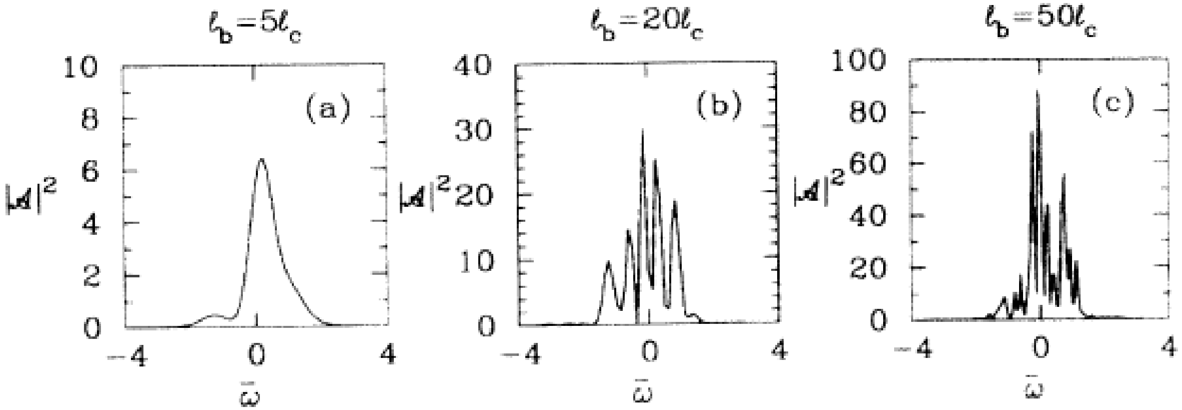
Linac3 Length = 190 m

ρ from 0.0888 (at BC2) to 0.0445 (at linac 3 exit)

Difference in ex= 0.0101 pi mrad mm, 0.03 e-006 m (1.37%)
Difference in ey= 0.0449 pi mrad mm, 0.14 e-006 m (4.7 %)
Difference in RMSx= 0.002 mm (1.5 %)
Difference in RMSy= 0.002 mm (4.3 %)
Difference in RMSz= 0

Preliminary calculations for single spike simulations

WHAT SINGLE SPIKE OPERATION IS



The problem under study is characterized by several characteristic scale lengths: the electron bunch length, the gain length, and the cooperation length. An important parameter determining the evolution of the system is the ratio of ℓ_b to ℓ_c. When this ratio is larger than 2π, long bunch case, we recover the results of the previous authors for the undulator saturation length and linewidth, and we also have new results: the evaluation of the saturation length fluctuations and the intensity fluctuations, as well as the study of the temporal and frequency structure of the radiated pulse. In particular we show that although the linewidth at saturation is of the order of the FEL parameter, ρ, or the inverse of the number of undulator periods [3,5], the radiation pulse contains many spikes, each one having a maximum duration corresponding to about $2\pi\ell_c$, with large intensity fluctuations. If the ratio of ℓ_b to ℓ_c is smaller than 2π, short bunch case, the saturation length tends to be somewhat longer than in the long bunch case. One single radiation pulse is present in this case, with no inner spikes.

Spectrum, Temporal Structure, and Fluctuations in a High-Gain Free-Electron Laser Starting from Noise

R. Bonifacio,[1,2] L. De Salvo,[1] P. Pierini,[2] N. Piovella,[1] and C. Pellegrini[3]
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(Received 14 July 1993)

L_b = bunch length
L_c = cooperation length (length spanned by the radiation in one undulator passage, in its slippage over the e-bunch-> radiation emitted by one slice of the bunch having this length is coherent)
$L_b \leq 2\pi L_c \rightarrow$ single spike regime

LOOKING FOR A STARTING POINT…

$$L_{c,1D} = \frac{\lambda_r}{4\pi\sqrt{3}\rho_{1D}}$$

$$\rho_{1D} = \left[\frac{JJ(K_{rms})K_{rms}k_p}{4k_u}\right]^{2/3}$$

$$\sigma_{b,SS} < 2\pi L_{c,1D} = \frac{\lambda_r}{2\sqrt{3}\rho_{1D}}$$

Estimation of ρ value is critical for a starting point …

… but ρ depends on the bunch charge!

Beam parameters from S2E simulations

I. Zagorodnov talk
01.01.2011
DESY

Parameter	Unit					
Bunch charge	nC	1	0.5	0.25	0.1	0.02
Peak current (gun)	A	43	24	13.5	5.7	1.2
Bunch length (gun, FWHM)	ps	25	22	20	17	17
Slice emittance (gun)	µm	0.8	0.5	0.3	0.21	0.09
Projected emittance (gun)	µm	1	0.7	0.6	0.3	0.1
Compression		114	233	363	877	3833
Peak current	kA	**4.9**	**5.6**	**4.9**	**5**	**4.6**
Bunch length (FWHM)	fs	178	72	39	12	2.2
Slice emittance	µm	**1**	**0.7**	**0.5**	**0.3**	**0.17**
Projected emittance	µm	3.5	2.2	1.5	0.84	0.26
Slice energy spread (**laser heater off**)	MeV	0.45	0.44	0.6	0.6	0.8

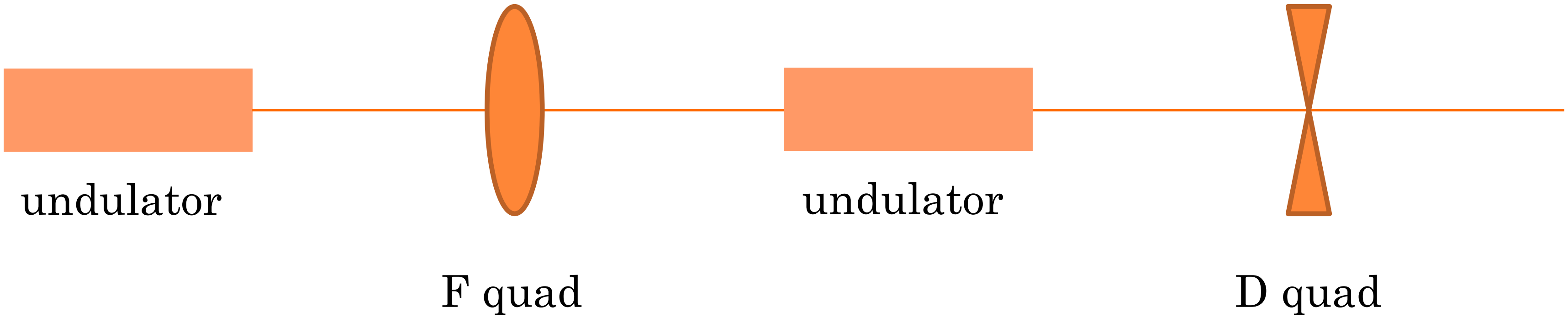
Radiation diffraction, emittance and energy spread neglected!

CALCULATION OF THE # OF SPIKES

Assuming beta lattice 32 m

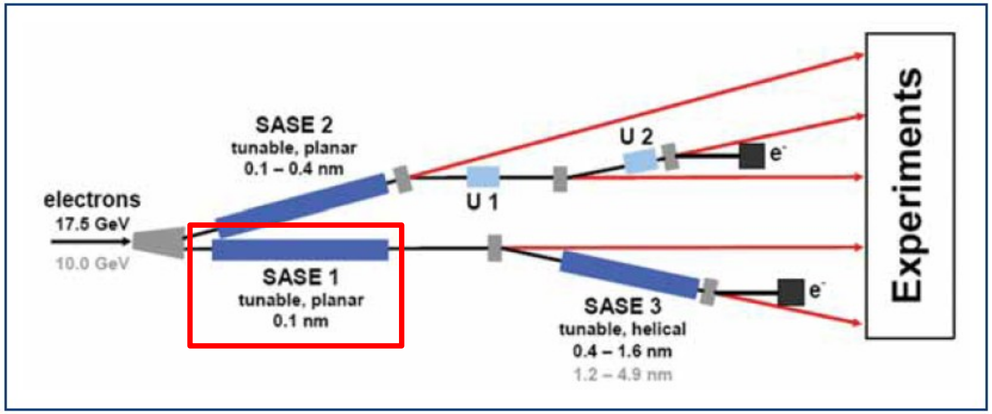
Q	1	0.5	0.25	0.1	0.02
ρ	$0.5*10^{-3}$	$0.7*10^{-3}$	$0.7*10^{-3}$	$0.9*10^{-3}$	$1.3*10^{-3}$
L_c [m]	$0.4204*10^{-7}$	$0.3444*10^{-7}$	$0.3169*10^{-7}$	$0.2595*10^{-7}$	$0.1805*10^{-7}$
$2\pi L_c$ [m]	$0.2641*10^{-6}$	$0.2164*10^{-6}$	$0.1991*10^{-6}$	$0.1630*10^{-6}$	$0.1134*10^{-6}$
FWHM in previous simulations [m]	$0.5336*10^{-4}$ (200 spikes)	$0.2159*10^{-4}$ (100 spikes)	$0.1169*10^{-4}$ (59 spikes)	$0.1643*10^{-4}$ (100 spikes)	$0.66*10^{-6}$ (6 spikes)

Implementation of XFEL layout in Genesis: matching problem.



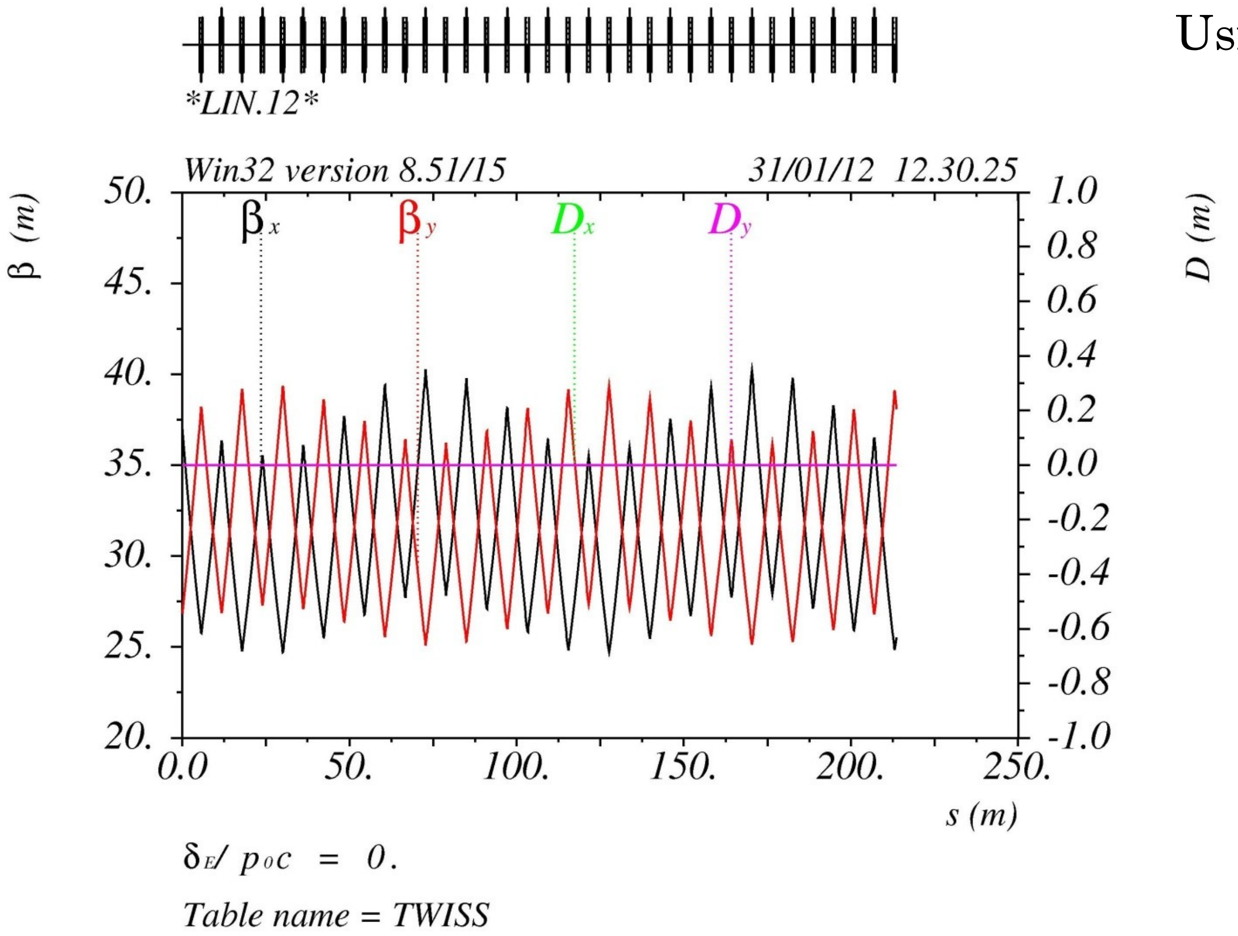
SASE1 consists in 17 cells like this one plus one final undulator section:

Total: 35 undulator sections.



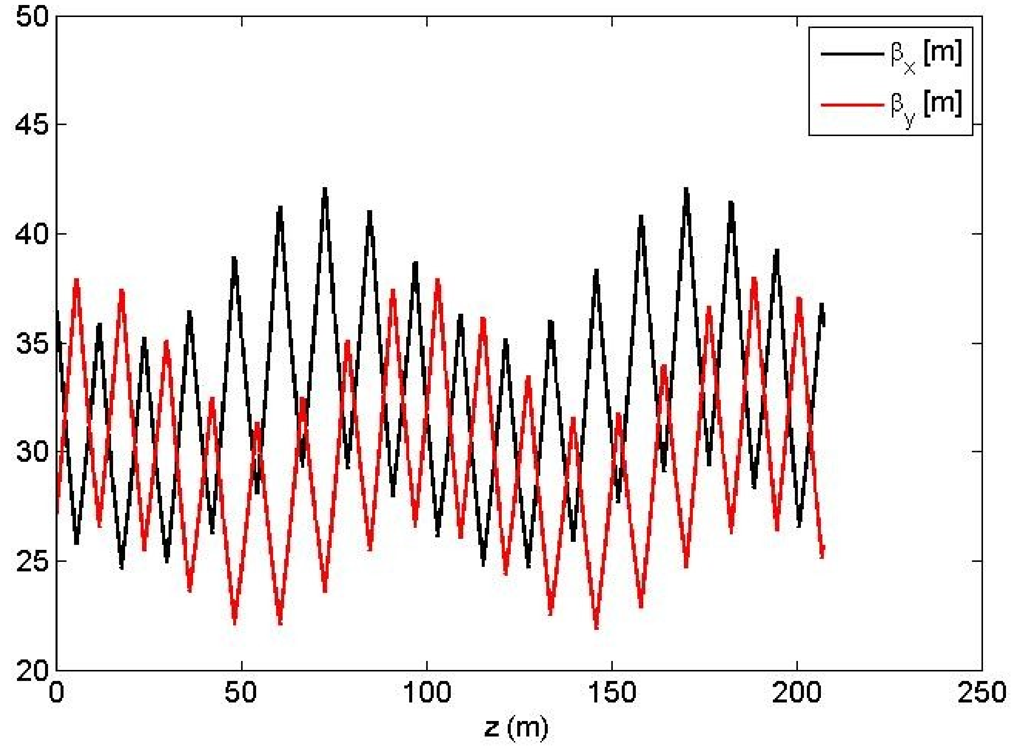
MATCHING AVAILABLE ON XFEL S2E SIMULATION WEBSITE (WWW.DESY.DE/XFEL-BEAM/INDEX.HTML)

Using MAD



CORRESPONDENT MATCHING IN GENESIS

- In Genesis the lengths of the optics elements have to be a multiple of the undulator period (mismatch due to approximation)
- The field of the quadrupoles has to be scaled according to the change of length from Mad to Genesis.



Additional fine tuning needed: work in progress...

Thank you to:

Igor Zagorodnov
Mikhail Krasilnikov

The End