Transverse Beam Optics of the FLASH Facility

(current status and possible updates)

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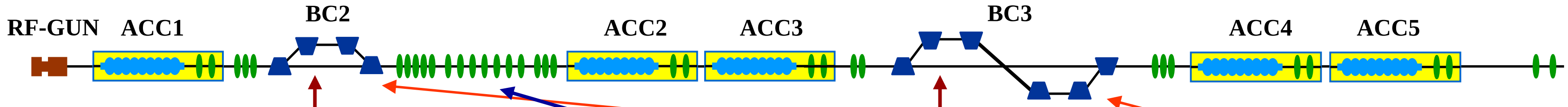
XFEL Beam Dynamics Group Meeting, 18 June 2007

Outline

- Different optics solutions developed before start of the commissioning
  - Two variants for the linac optics
  - Several variants for focusing in the undulator
- Usage of quadrupole settings corresponding to different optics solutions in real operations
- Shutdown 2007: adaptation of the optics solutions to the accelerator upgrade and possible optional improvements in the transverse optics
- Some remarks about bypass operations
- New version of the online toolbox for FLASH optics
- Summary

Lattice Constraints Used for the Optics Design



18° **3.8°**

Bunch compressor angles proposed for the start of the commissioning

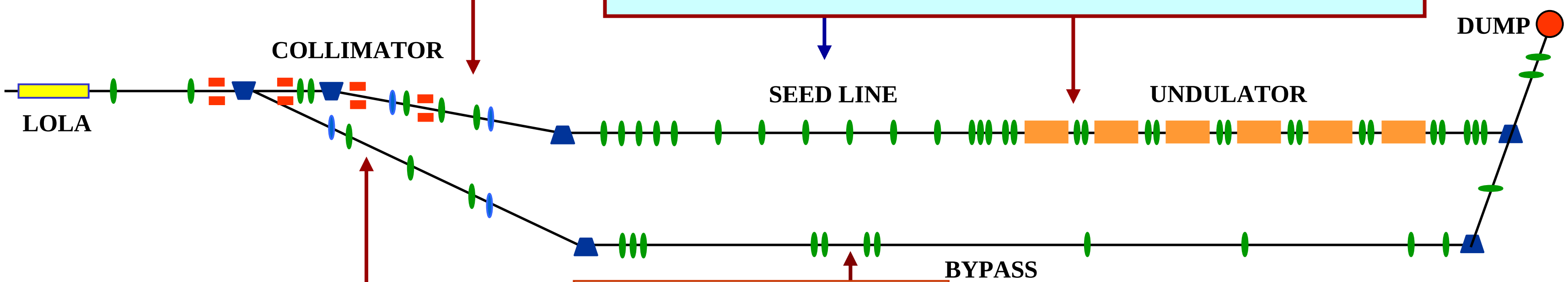
Bunch compressors: special beta functions reduce emittance growth due to coherent synchrotron radiation (CSR)

Collimator: the selection of optical functions in the dogleg of this section are almost completely determined by the need to suppress dispersion and to shape a beam envelop suitable for collimation purposes

Diagnostic sections: FODO lattice with periodic Twiss functions (DBC2 and SEED sections)

Dump: beam spot size should be not smaller than the safety limit

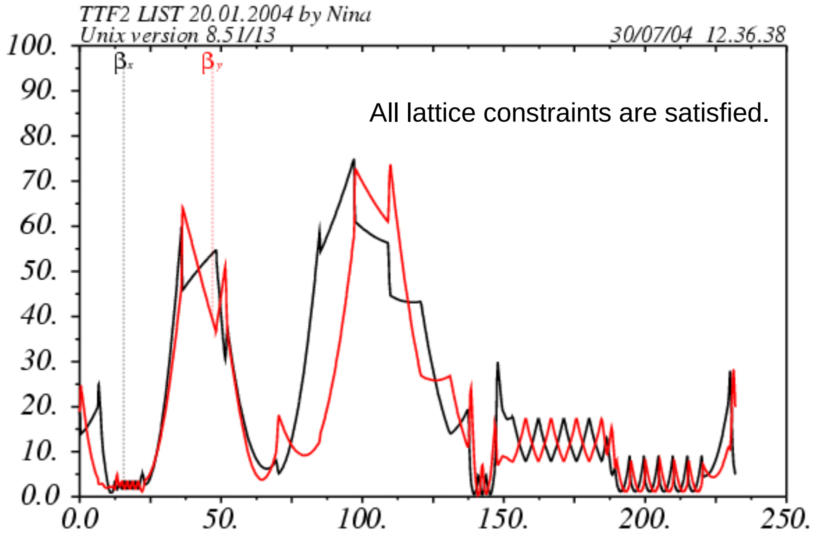
Undulator: the quadrupole strength has to be optimized to provide good FEL performance



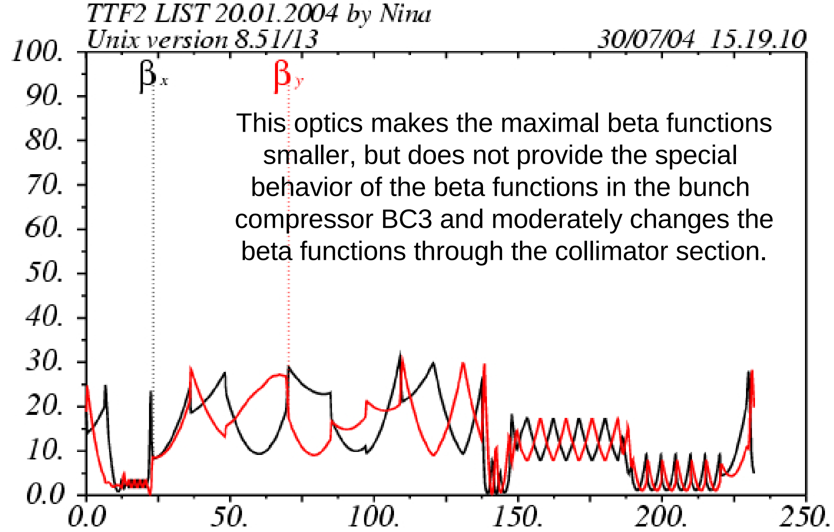
Material test facility

Bypass: this line starts with a section which is tilted with respect to the principal linac planes

Two Options Developed for the FLASH Linac Optics

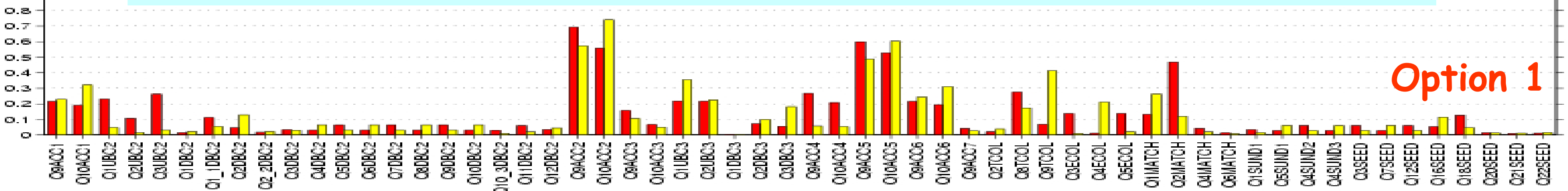


Optics Option 1



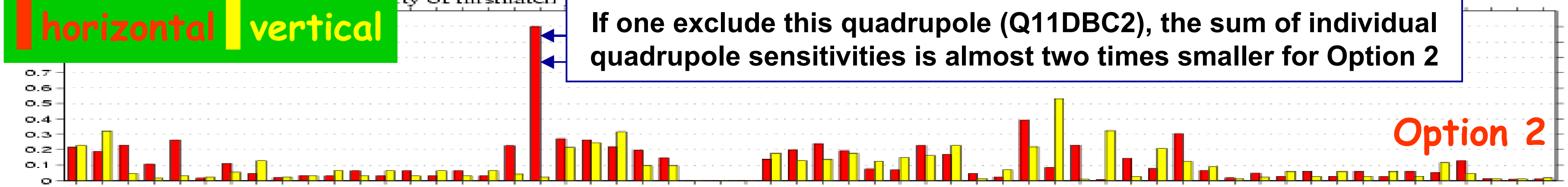
Optics Option 2

Sensitivity to individual quadrupole errors: relative errors in k-values



horizontal vertical

If one exclude this quadrupole (Q11DBC2), the sum of individual quadrupole sensitivities is almost two times smaller for Option 2



Roughly speaking, these errors are proportional to the product of the quadrupole k-value and of the betatron function at the quadrupole location

Why Second Optics Option was Developed?

The operations of the FLASH facility started with many important components missing (in particular, without 3rd harmonic accelerating section, without electronics for the part of the beam position monitors and etc.).

In these conditions the only possible operational mode is the femtosecond mode with creation of a short high-current leading peak (spike) in the bunch density distribution.

Due to strong collective effects the parameters of the spike could be quite different from the parameters of the rest of the bunch. As most of the available diagnostics tools (wire scanners, OTR screens, beam position monitors) are only able to determine integral properties of the total bunch, it is thus almost impossible to control the orbit and the optics match of the lasing spike.

So it looks useful to have an optics solution as much insensitive as possible to uncertainties in the knowledge of the beam energy, to magnet setting errors and to at least some of collective effects.

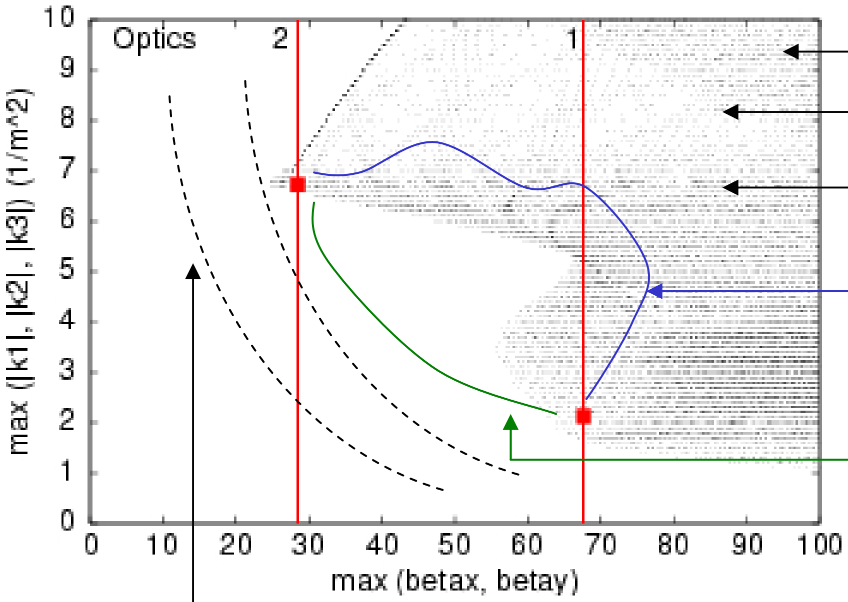
Why not a whole set of optics, but exactly two optics were suggested?

It is a result of extensive studies which led us to the conclusion which, very roughly speaking, can be formulated as follows:

If one will keep the 45° FODO lattice with periodic Twiss functions in the DBC2 section*, then all reasonable optics for the FLASH linac operations could be divided into two classes. Optics within each class demonstrate similar properties, and there is "no continuous transition" between these two classes. So we have chosen one "good representative" (representative, which satisfies some additional optimality constraints) from each class and obtained two different optics.

* **In the beginning of facility commissioning the ability to have (constantly, during operations) good conditions for measurement of the parameters of the beam coming from injector (i.e. 45° FODO with periodic Twiss functions in the DBC2 section) was considered as having primary importance with respect to the possibility of reduction of optics sensitivity. Now the point of view on this subject did change, and the possible optics improvements will be discussed later during this talk.**

An example which illustrates this “two class separation”

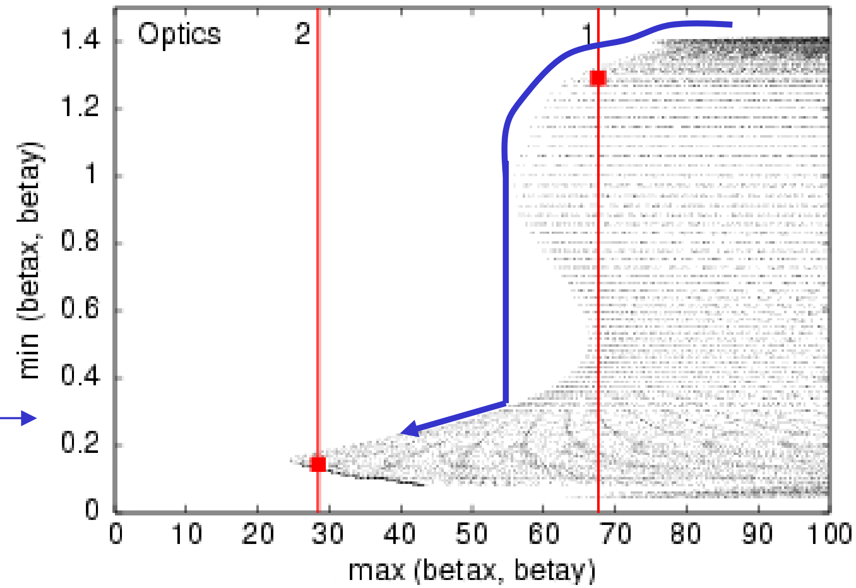


The transition from DBC2 diagnostic section into accelerating module ACC2. Scan over all possible strengths of 3 quadrupoles downstream of DBC2 FODO (Q10.3DBC2, Q11DBC2, Q12DBC2). Each point corresponds to different qudrupole settings (i.e. to different optics).

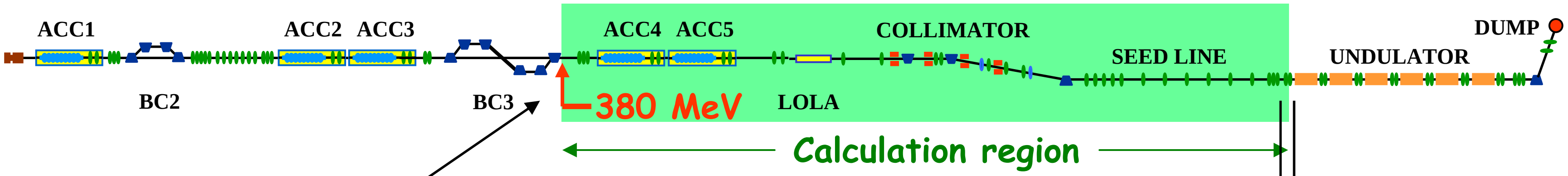
The absence of continuous transition between two optics means that moving along this curve we only loosing in sensitivity, and move along that curve is not possible.

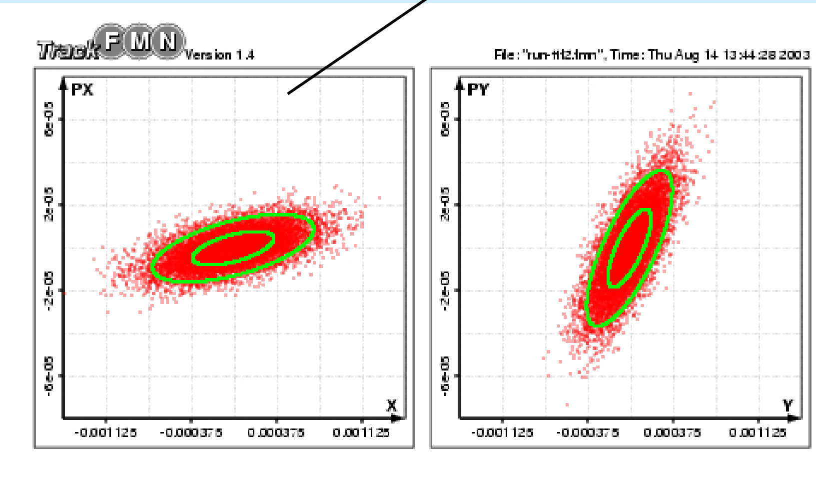
Approximate behaviour of level surfaces of “sensitivity function” (sensitivity to relative errors)

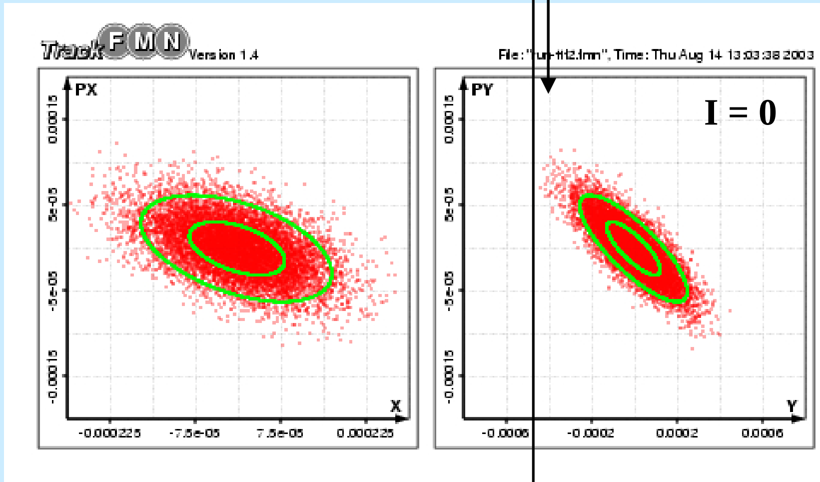
One more example: at the reducing of max(βx, βy) (inside accelerating modules ACC2 and ACC3) there is a sudden jump in the maximum of min(βx, βy).



Transverse Space Charge Effects



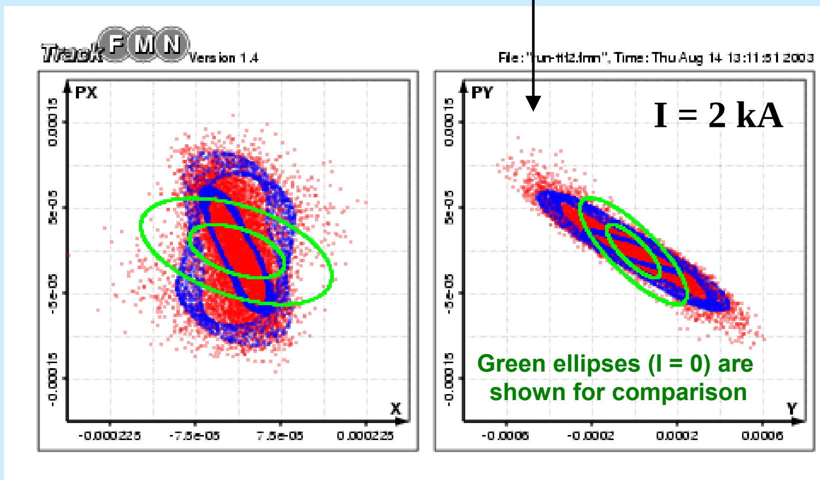




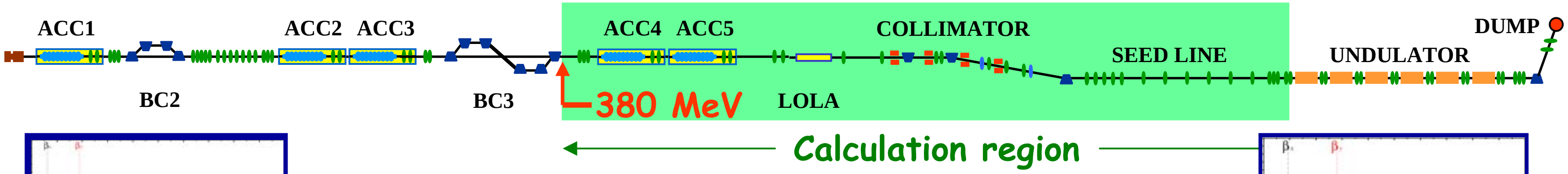
Red - beam of particles.

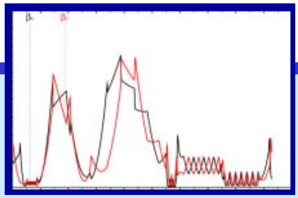
Green and Blue are test particles, which do not contribute in the space charge forces, but see the space charge field of the main beam.

(Optics Option 1)

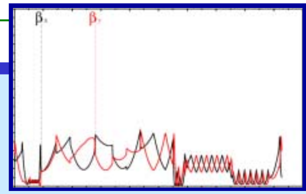


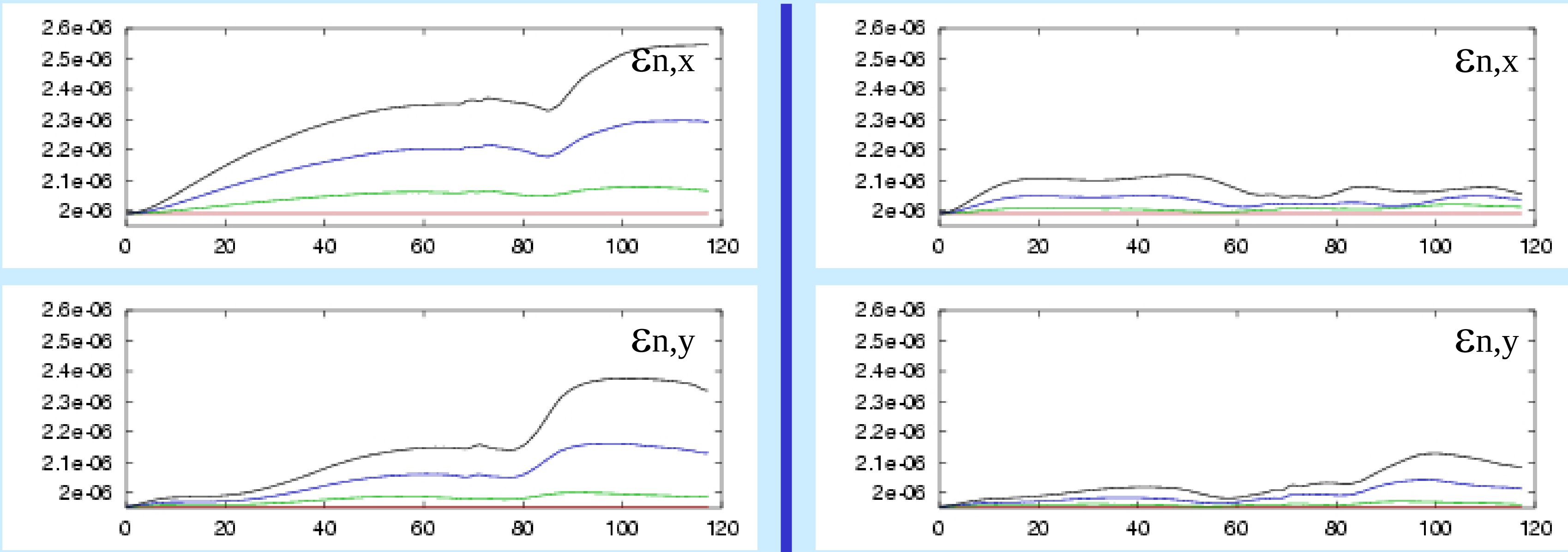
Transverse Space Charge Effects





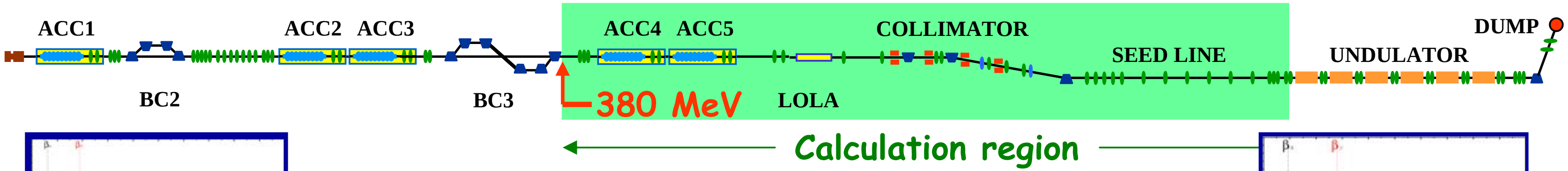
$\varepsilon_{n,\,\text{initial}}$ = 2 mm mrad. I = 0, 1, 2, 3 kA

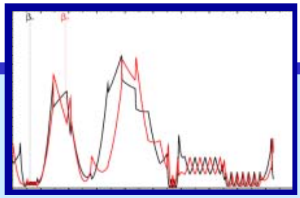




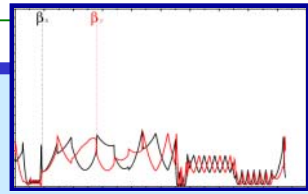
Remark: calculations presented in this talk were made with the MAD program (betatron functions) and TrackFMN code (V.Balandin, N.Golubeva: 1993-2006) (nonlinear tracking, transverse space charge effects, sensitivities, Taylor maps).

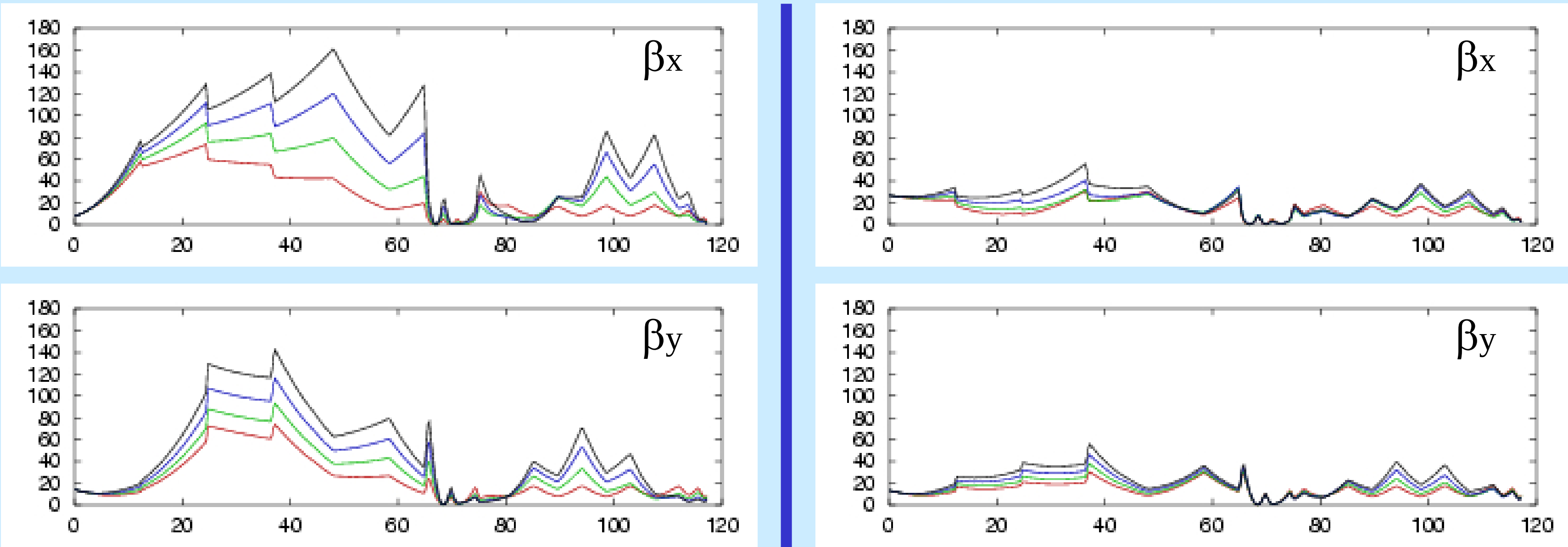
Transverse Space Charge Effects





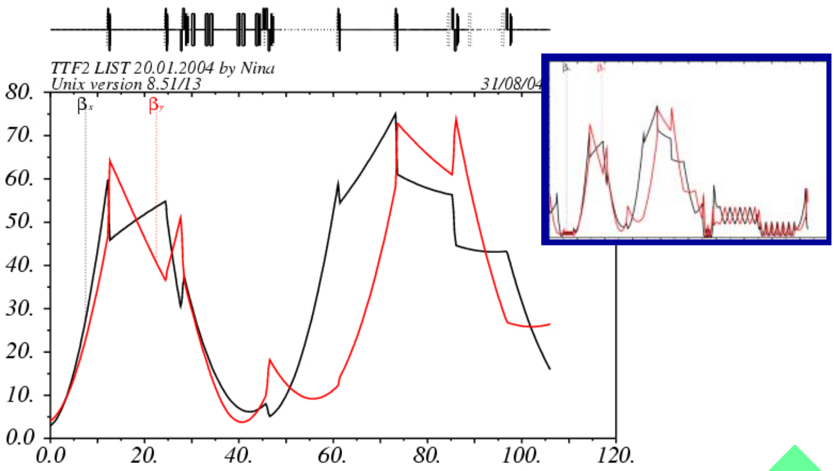
$\varepsilon_{n,\ \mathrm{initial}} = 2$ mm mrad. I = 0, 1, 2, 3 kA

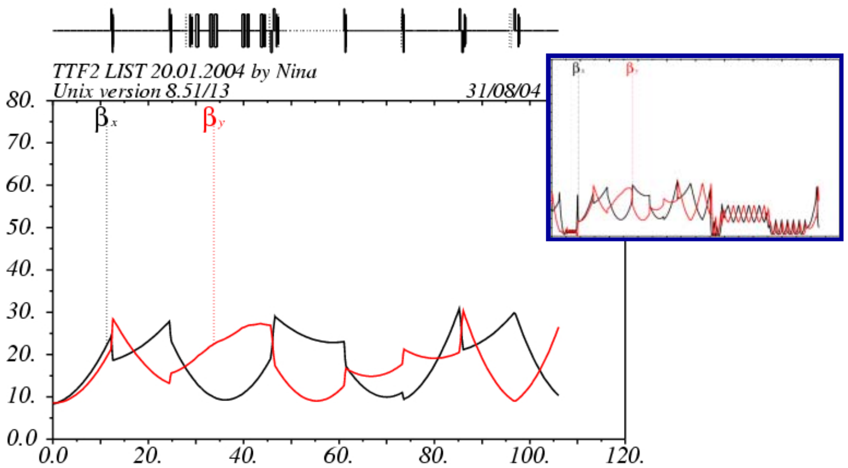


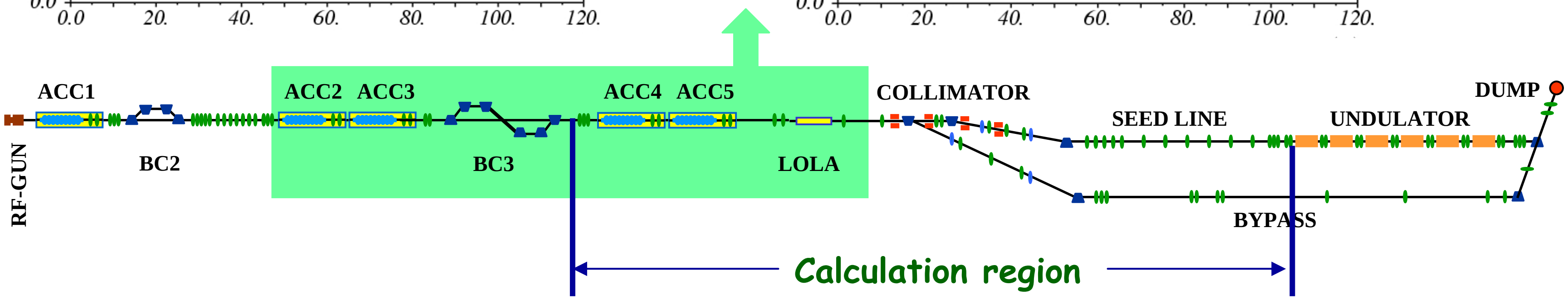


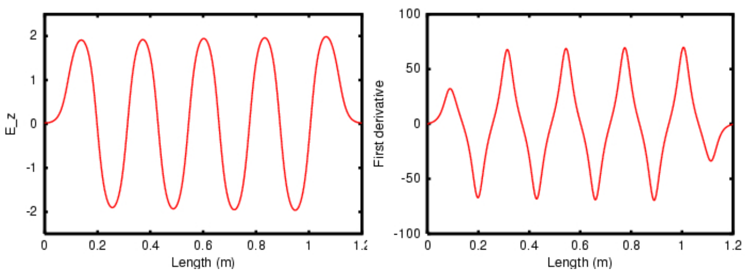
$$\beta_x = \frac{\langle x^2 \rangle}{\sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x\, p_x \rangle^2}}$$

Transverse Space Charge Effects: Optics Difference in the Calculation Region





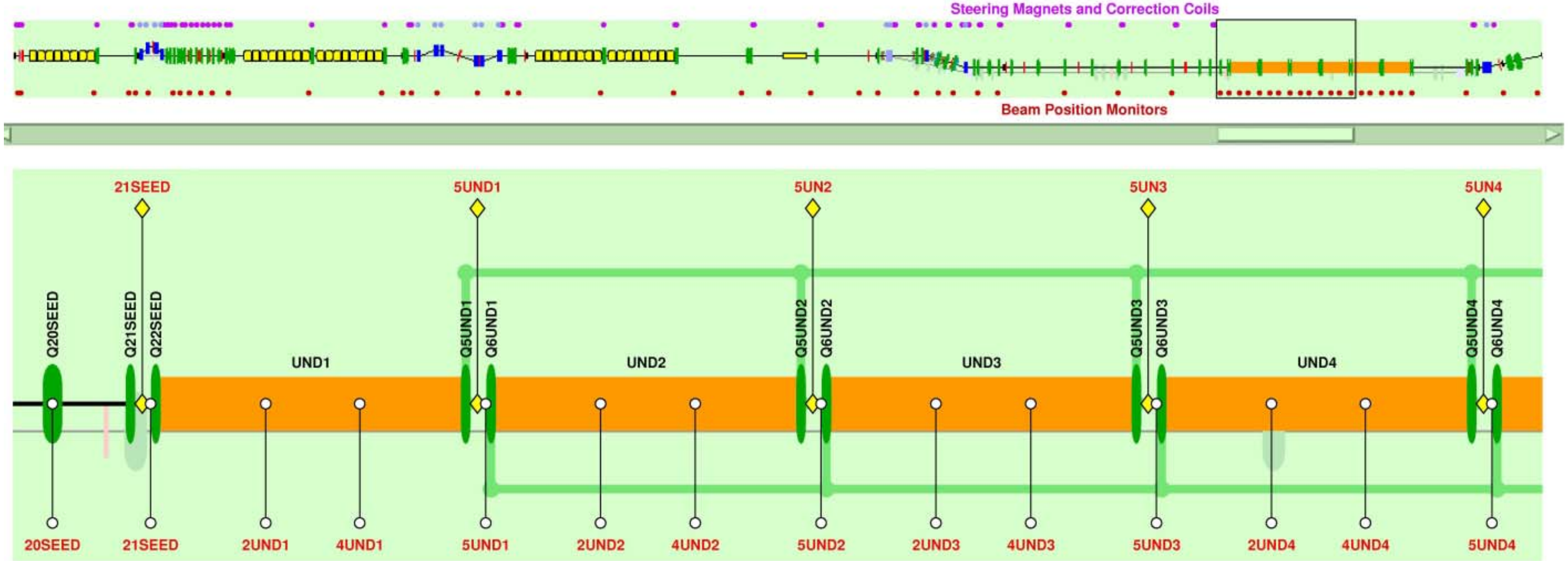


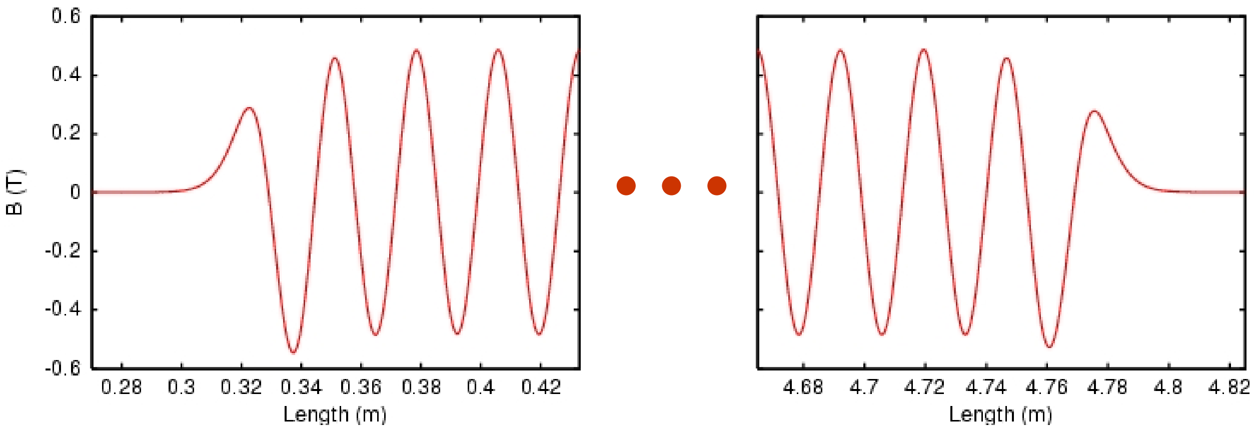


Accelerating field amplitude and its first derivative along the axis of the TESLA cavity (arbitrary units)

RF Radial Focusing: The transport matrices corresponding to the passage through an RF cavity were calculated using the knowledge of on-axis accelerating field profile and beam injection phase and energy. This focusing is not of principal importance, but the change in quadrupole settings for recovering optical functions calculated initially without RF focusing is up to 15%.

Undulator Section of the FLASH Facility

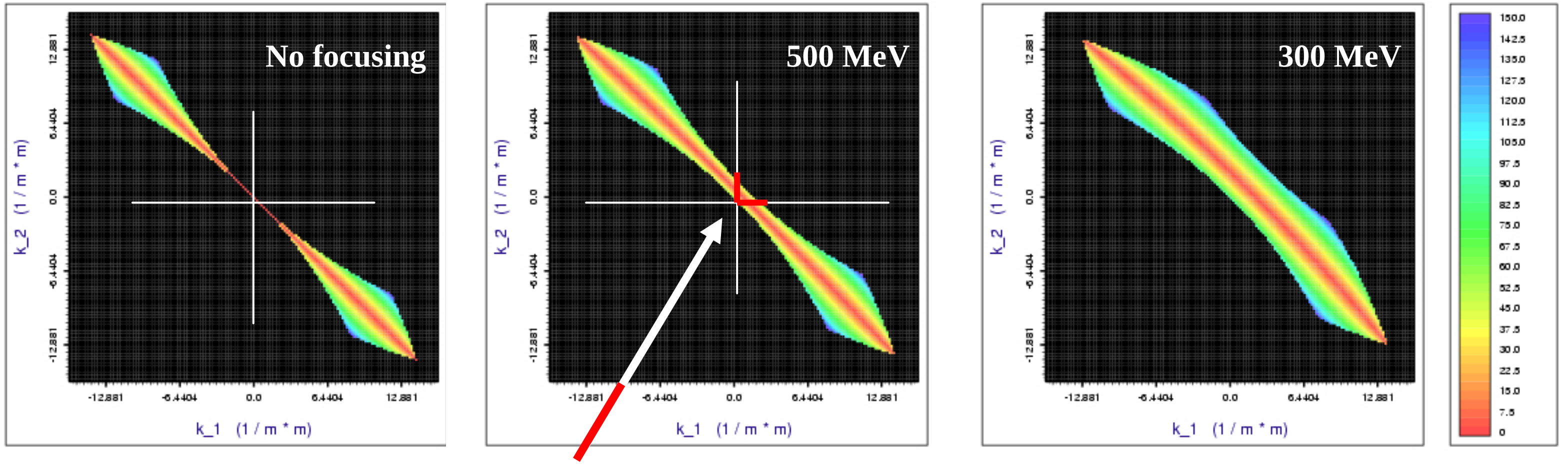




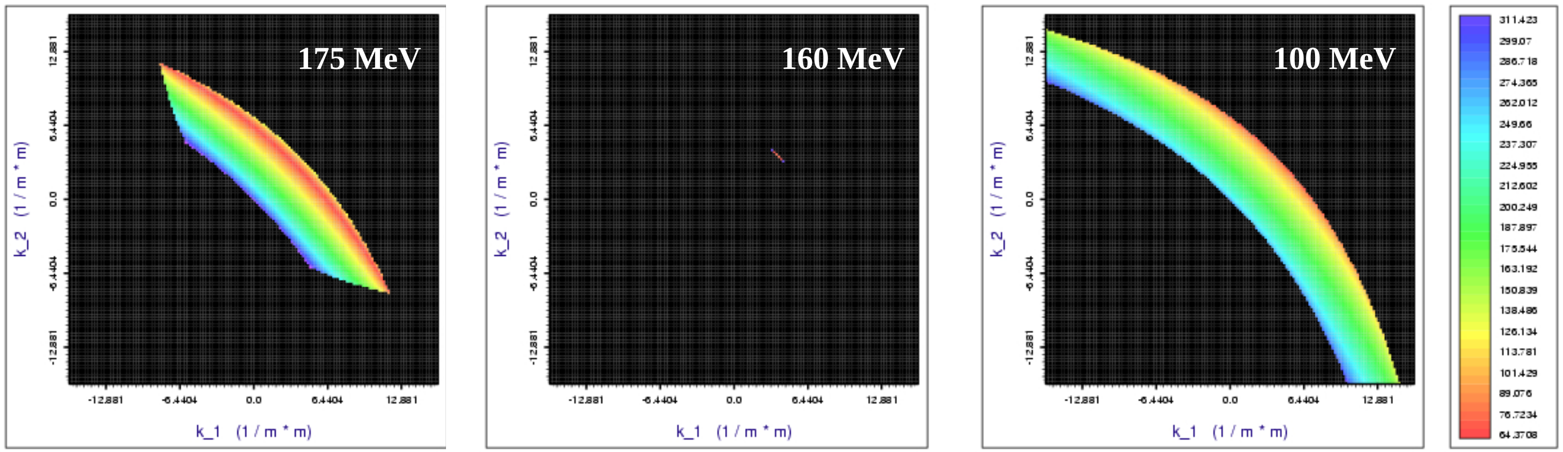
Measured field data, which was used for the calculations of natural undulator focusing. Peak magnetic field is 0.48 T, The period is 27.3 mm.

Effect of natural focusing on periodic beam transport: stability regions for undulator cell

(inside stability region the difference $|\mu_x - \mu_y|$ is shown)

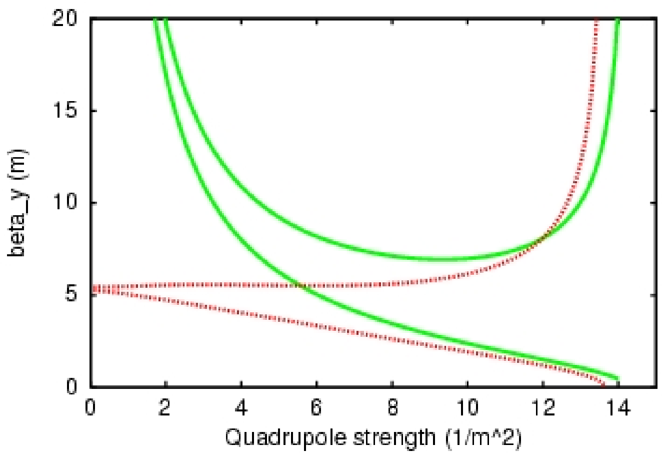


These intervals (effect of natural focusing) allow to have periodic solution even with one quadrupole off !!!

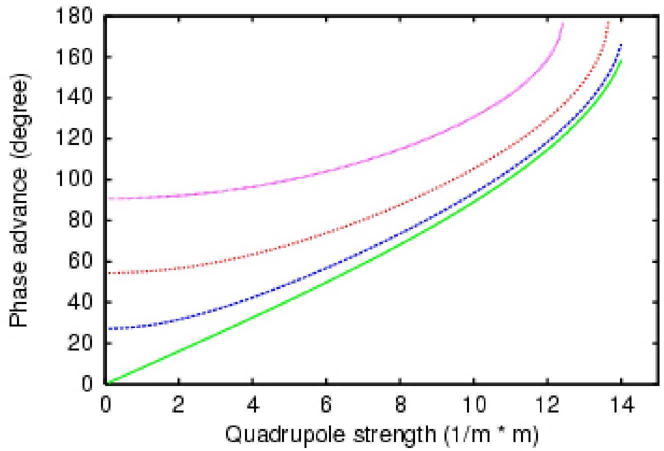


Undulator cell is a periodic unit of undulator system and contains one undulator segment followed by two quadrupoles

Effect of natural focusing on periodic betatron functions and phase advances



Minimal and maximal values of horizontal (green) and vertical (brown) periodic betatron functions achievable within the undulator cell as a function of the quadrupole strength k (with doublet setting k1 = -k2 = k).



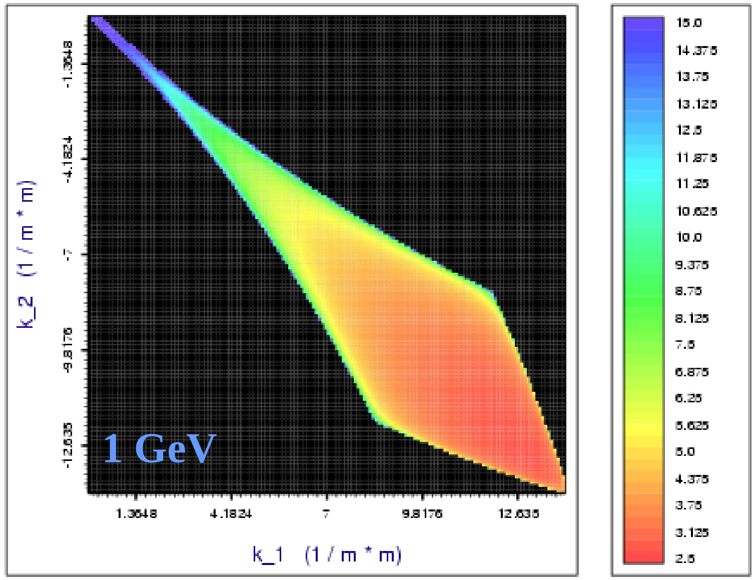
Phase advance in the vertical plane as a function of the quadrupole strength k (with doublet setting k1 = -k2 = k).

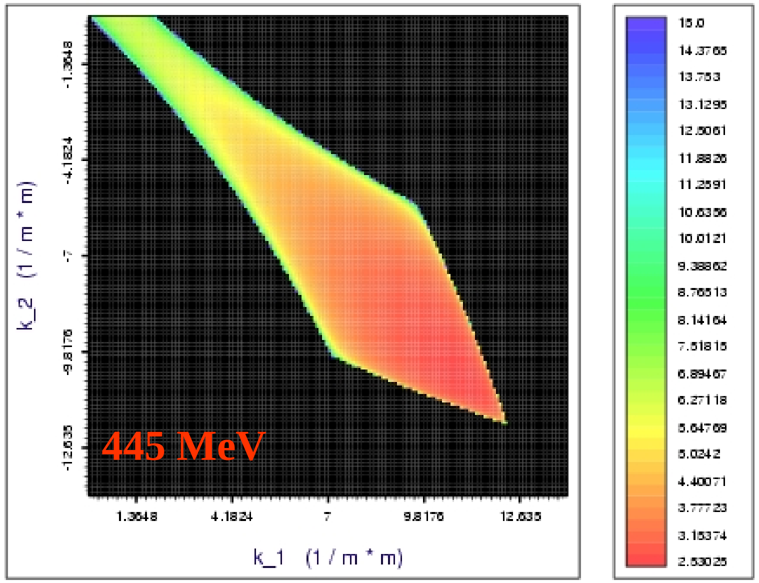
Curves: no focusing, 1 GeV, 500 MeV, 300 MeV

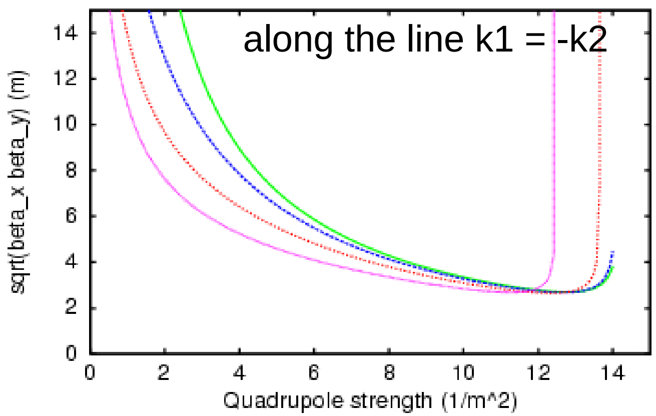
(without natural undulator focusing all curves must coincide)

Average Beam Spot Size inside Undulator Segment as Criterion for Choosing the Working point for Quadrupoles.

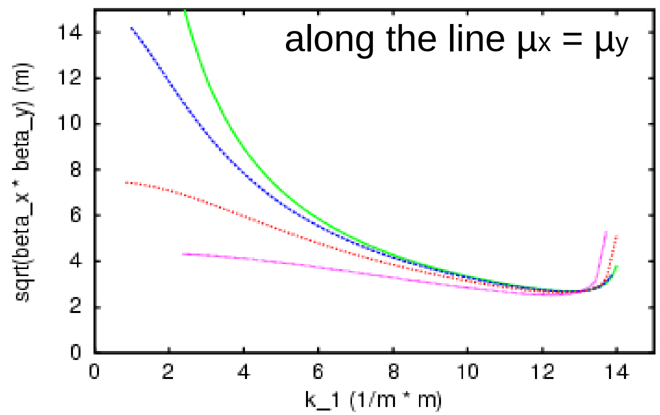
$$ABS = (1 / L_{seg}) \int (\beta_x \, \beta_y)^{\frac{1}{2}} dz$$



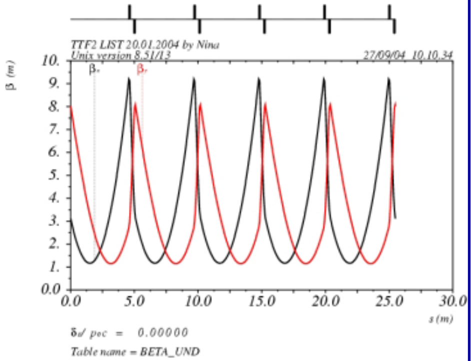




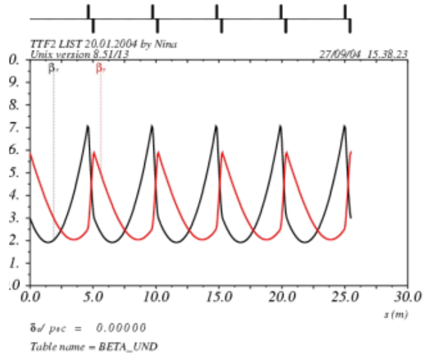
Curves:
no focusing
1 GeV
500 MeV
300 MeV



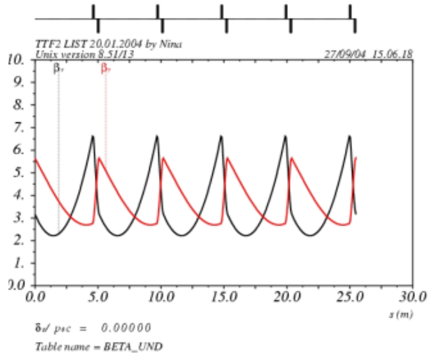
Different Variants for Beam Optics in the Undulator Section (445 MeV)



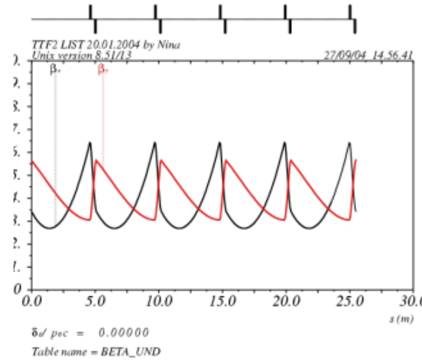
Variant 1, ABS = 2.6
(smallest ABS possible, but strongest kicks due to quadrupole offsets)



Variant 2, ABS = 2.9

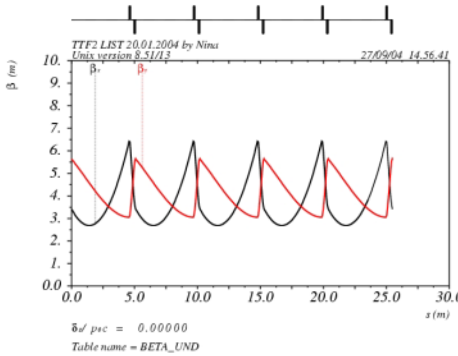


Variant 3, ABS = 3.3

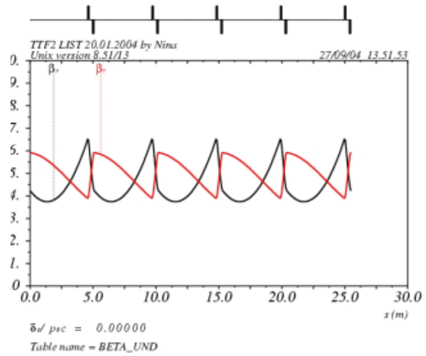


Variant 4, ABS = 3.6

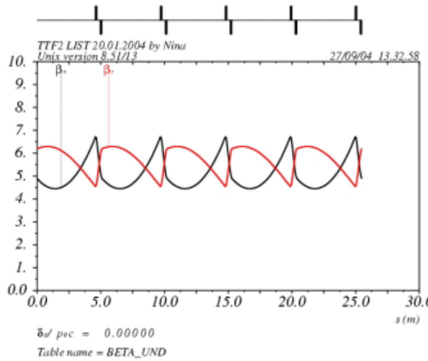
$$ABS = (1 / L_{seg}) \int (\beta_x \beta_y)^{\frac{1}{2}} dz$$



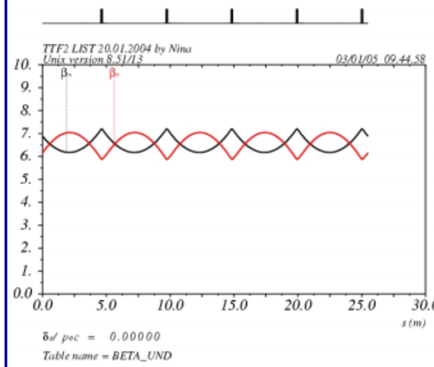
Variant 5, ABS = 4.1



Variant 6, ABS = 4.6



Variant 7, ABS = 5.2



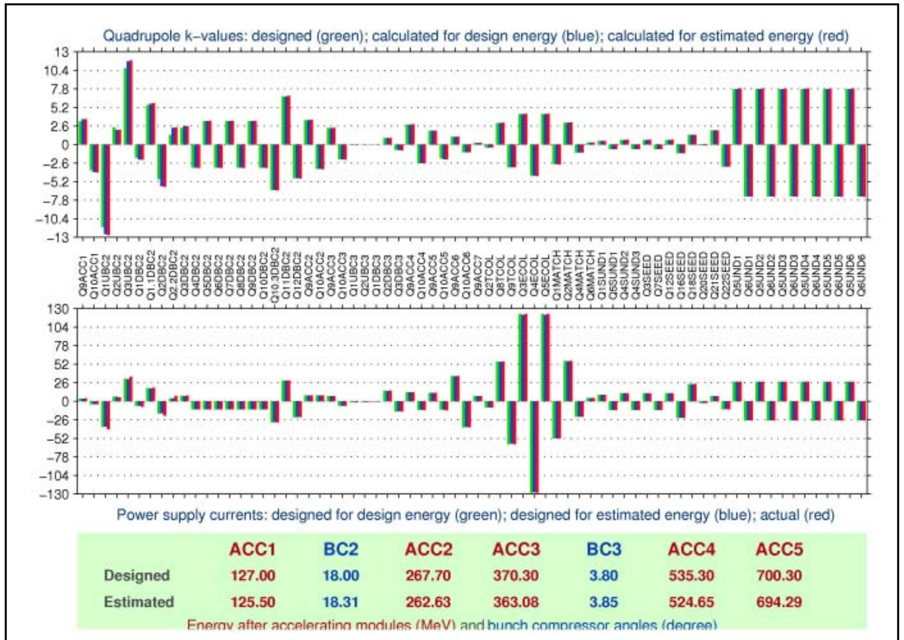
Variant FOFO
(one quadrupole is off, weakest quadrupole kicks)

Usage of Different Optics in Real Operations

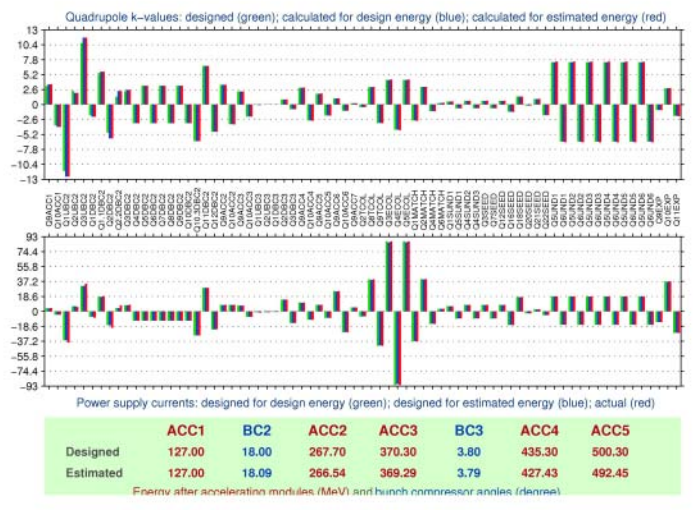
Because Twiss parameters and orbit of the lasing spike are, in general, unknown, as usage of different optics in real operations we will understand the following procedure: setting of theoretical quadrupole currents corresponding to chosen optics solution with following empirical tuning during SASE search.

The final difference between actual and theoretical quadrupole settings depends on operator experience and his wish to do (or not) certain changes.

Nevertheless, several times SASE was obtained (and improved) practically without touching theoretical quadrupole settings (even without matching in the DBC2 section), especially in the beginning of the work with optics option 2 (see examples from FLASH eLogBook shown at this page).

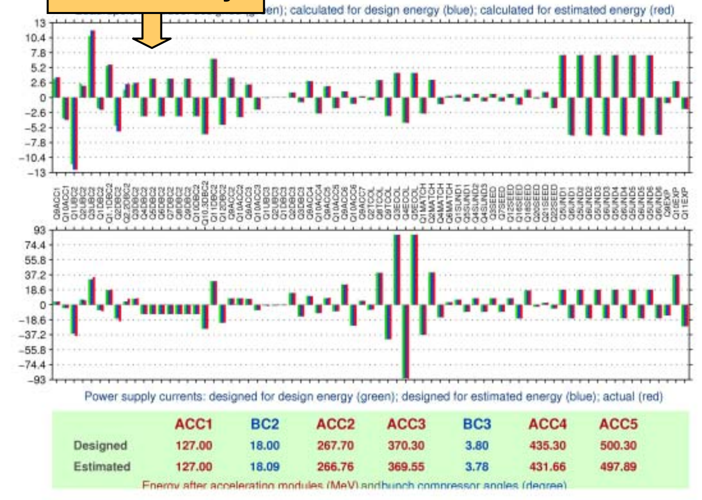


27.04.06, SASE: 13 nm, 6 uJ peak, 2 uJ average.



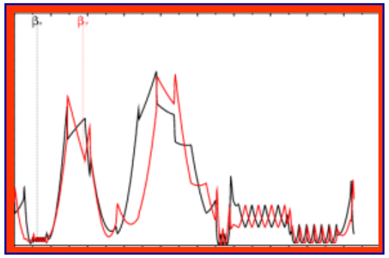
4.05.06, SASE: 25.5 nm, 14 uJ peak, 5 uJ average.

After one day.

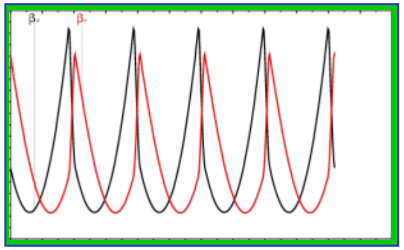


5.05.06, SASE: 25.5 nm, 33 uJ peak, 13 uJ average.

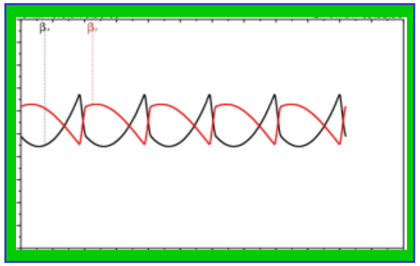
Usage of Different Optics in Real Operations



- Commissioning started (September 2004) with quadrupole settings corresponding to Optics Option 1 in accelerator and with focusing Variant 1 for the undulator section.



- After empirical tuning (mainly in ACC4/ACC5 area and in the front of the undulator) the beam was transported to the undulator entrance (in November 2004).

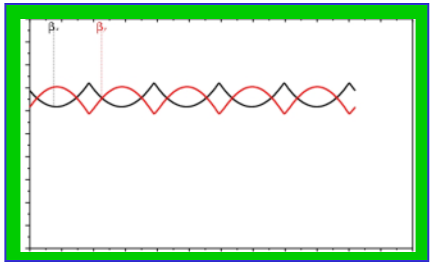


- Without automatic procedure for alignment of undulator quadrupoles, it was difficult to get the beam through the undulator with large kicks due to offsets of strong quadrupoles in optics Variant 1. So focusing was reduced to Variant 7.

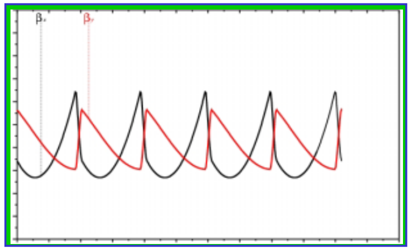
- First beam through the undulator was obtained with Variant 7 in the middle of December 2004.

Usage of Different Optics in Real Operations

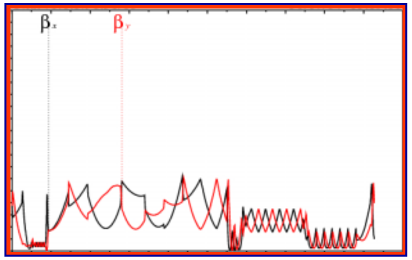
- Losses in the undulator were still too high to allow systematic SASE search and one of the reasons for that were large orbit kicks due to quadrupole offsets. So focusing was further reduced to the Variant FOFO and the FIRST LASING was obtained in the middle of January 2005 (~32nm).



- With increased experience of operators and with empirical alignment of undulator quadrupoles, focusing in undulator section was made stronger and the last operational variant for the undulator optics (before current shutdown) was Variant 4.



- On 21 April 2006 the optics of the accelerator was switched to Optics Option 2 with undulator Variant 4. The optics change was done within one shift and the FIRST LASING at ~13nm was obtained already during the first shift dedicated to SASE search (26 April 2006).



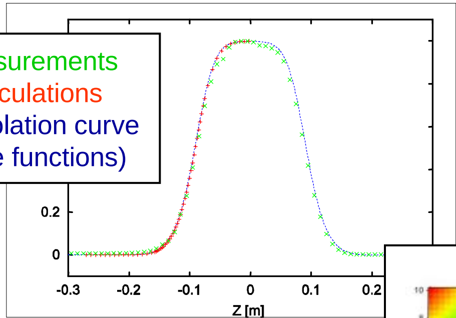
Why Usage of Optics 2 was more Successful ?

- Of course, the increased experience of people since start of the facility operations played very important (and some times, probably, even dominant) role.
- Magnet setting corresponding to the Optics 1, probably, never was correctly established (shortcuts, wrong polarities, correct information about some magnets missing, …).
- Since start of operations and before switching to Optics 2, a lot of information about magnets was collected and analyzed, and, as a result, the beam dynamical model of the FLASH linac was essentially improved.
- Nevertheless, it seems that concept of sensitivity reduction was very useful and additional steps in this direction could also be helpful.

Effective Parameters of Quadrupole Magnets in FLASH

Quad name	$\int(Bdz)/B_{max}$		Steffen-type approximation		Data used	
	L_{eff}, m	k_{corr}	L_{steff}, m	k_{corr}		
TQA	0.2702	1	0.2768	0.9757	Efr.Inst.,meas.,2002	Jan 2004
TQB	0.3207	1	0.3286	0.9759	Efr.Inst.,meas.,2002	Jan 2004
TQG	0.1248	1	0.12716	0.9813	Efr.Inst.,meas.,2002	Jan 2004
QA (cold)	0.1860	1	0.2096	0.8877	M.Marx,calc.,Apr 2006	20 Apr 2006
QTS.EXT	0.0707	1	0.0932	0.7592	Y.Holler, meas.,1996	05 Dec 2006
QTS.INT (S-Band Triplet)	0.1200	1	0.1312	0.9144	M.Marx,calc.,Nov 2006	05 Dec 2006
TQD (Danfysik)						
TQF (Protvino)						
QMN						
QC						

V.Balandin, N.Golubeva
28 December 2006



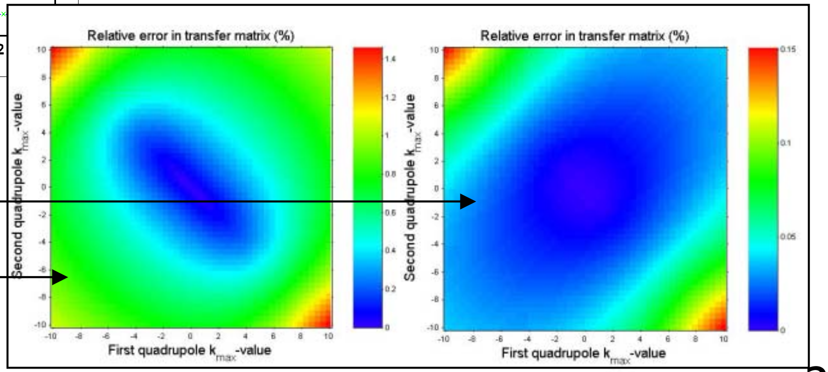
Measurements
Calculations
Interpolation curve
(Enge functions)

Cold Doublet: comparison of "soft edged" and "hard edged" doublet models

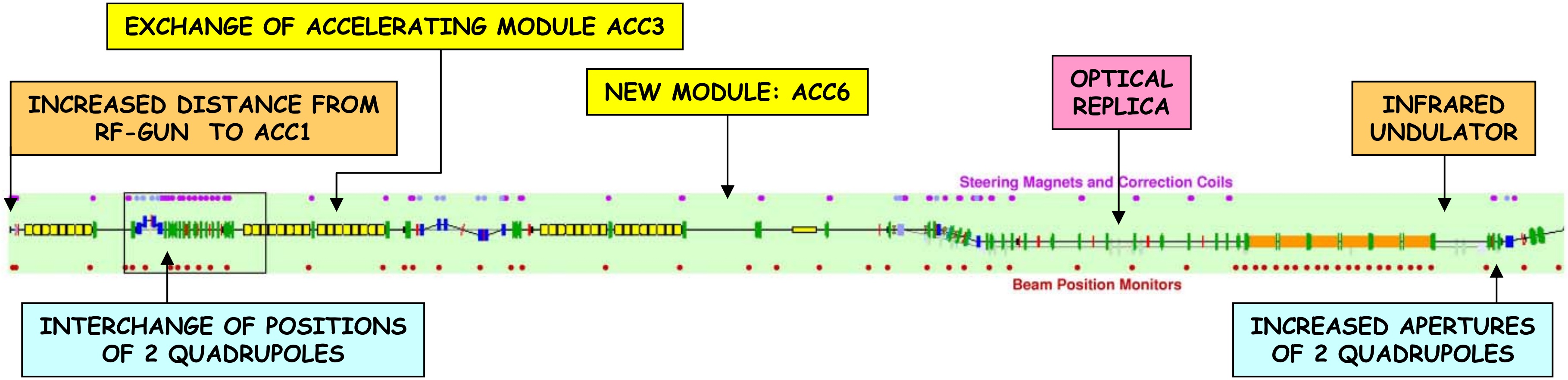
$$\text{relative error} = \frac{|M_{exact} - M_{approx}|}{|M_{exact}|}$$

Effective length is defined as a result of the Steffen-type approximation procedure

Effective length is defined as a field integral divided by the maximal field value



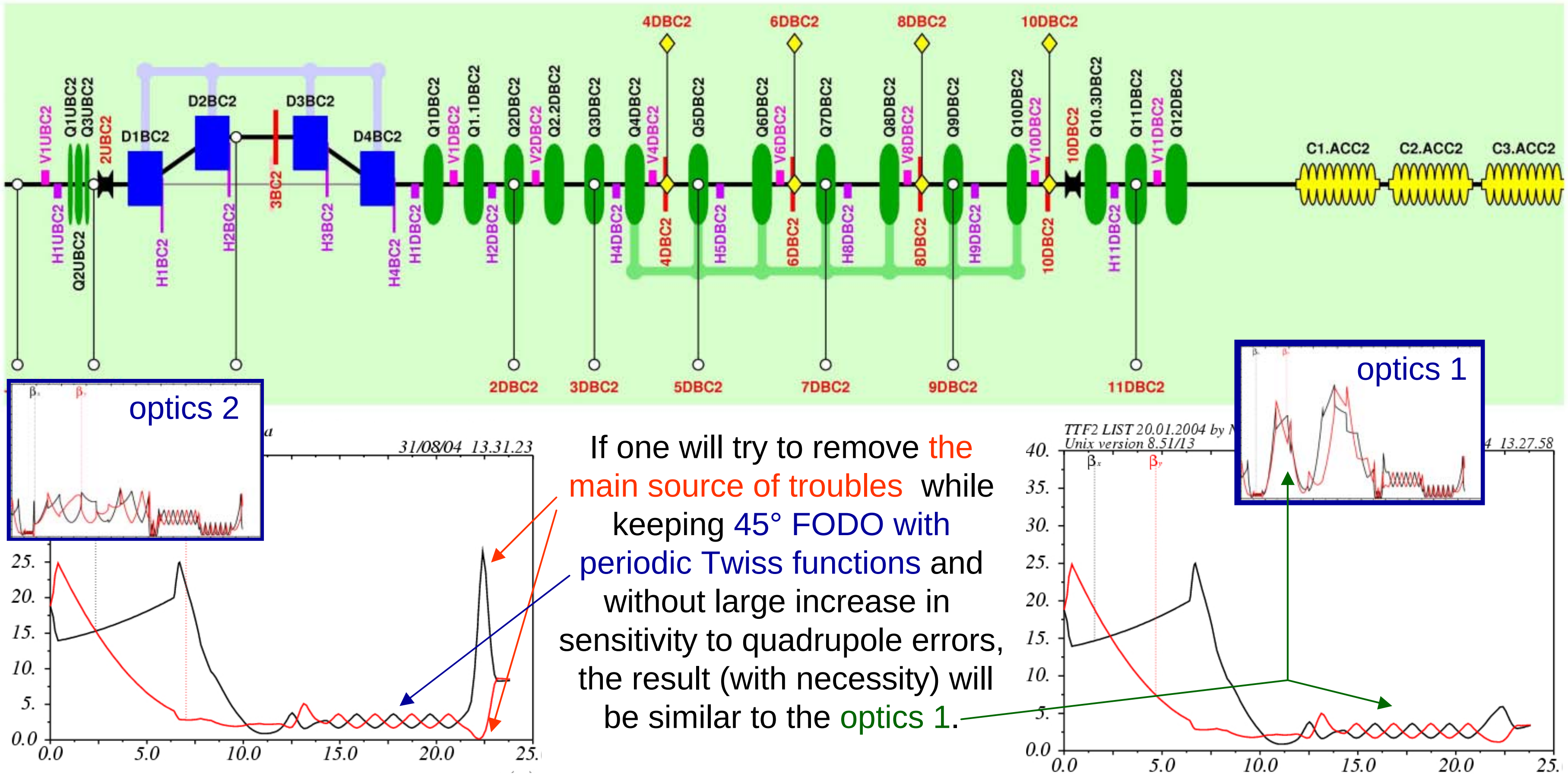
Shutdown 2007



There is no problem to adapt optics 2 to updated accelerator structure. Automatic procedure (which will allow to calculate needed currents for magnet power supplies as a function of accelerating regime and desired bunch compressor angles) is under development and will be included in Optics Toolbox version 1.3.

But it seems that there are some possibilities for further improvement of optics 2 (optics 2+), which we would like to discuss .

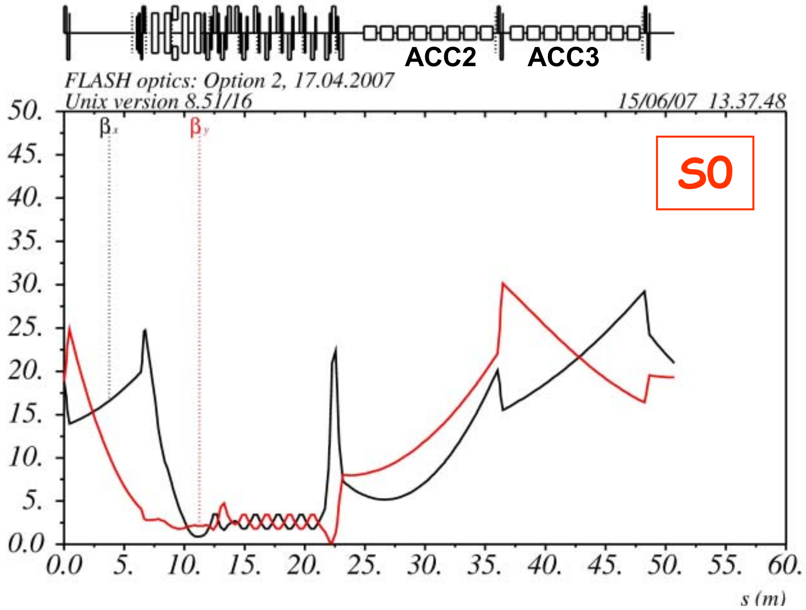
Transition into ACC2 accelerating module: What can be improved in Optics 2 ?



If one will try to remove the main source of troubles while keeping 45° FODO with periodic Twiss functions and without large increase in sensitivity to quadrupole errors, the result (with necessity) will be similar to the optics 1.

Possible solutions: usage of non periodic Twiss functions or/and reduction of the focusing strengths of quadrupoles Q4DBC2-Q10DBC2 (powered in series).

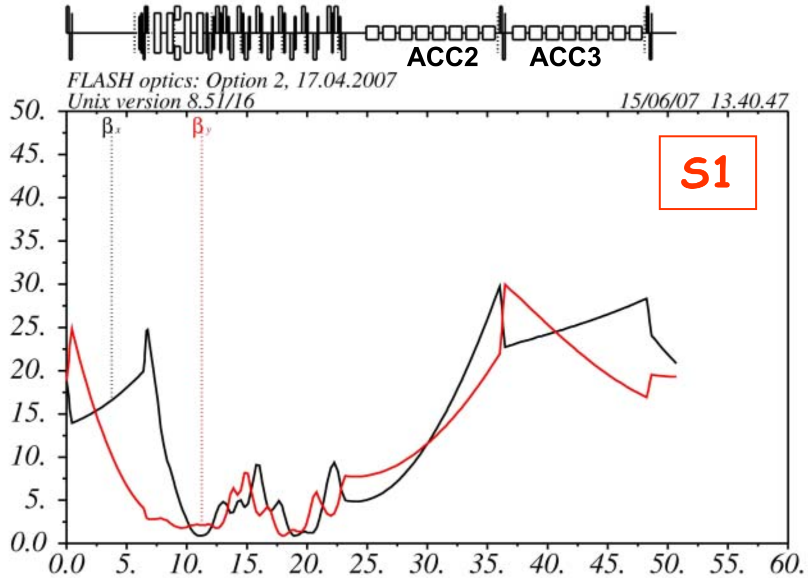
Transition into ACC2 accelerating module

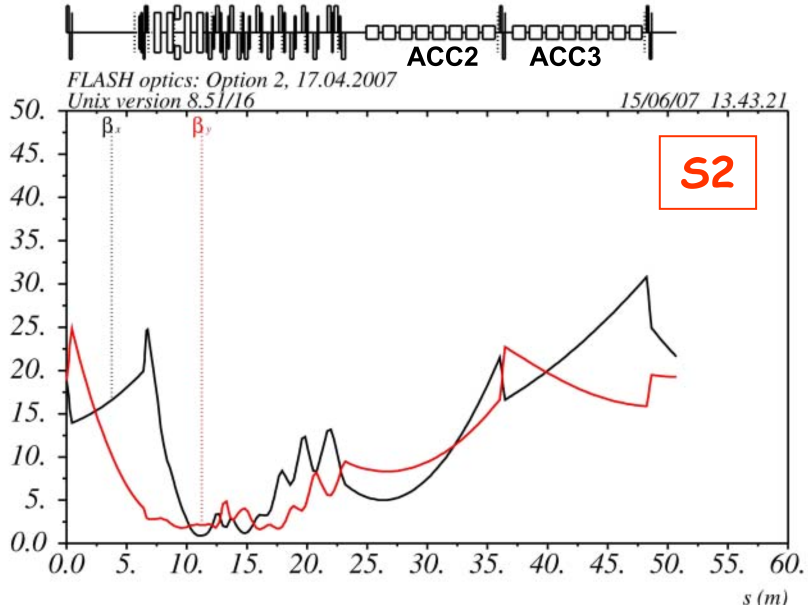


➡ Original solution of the optics option 2 (**S0**).

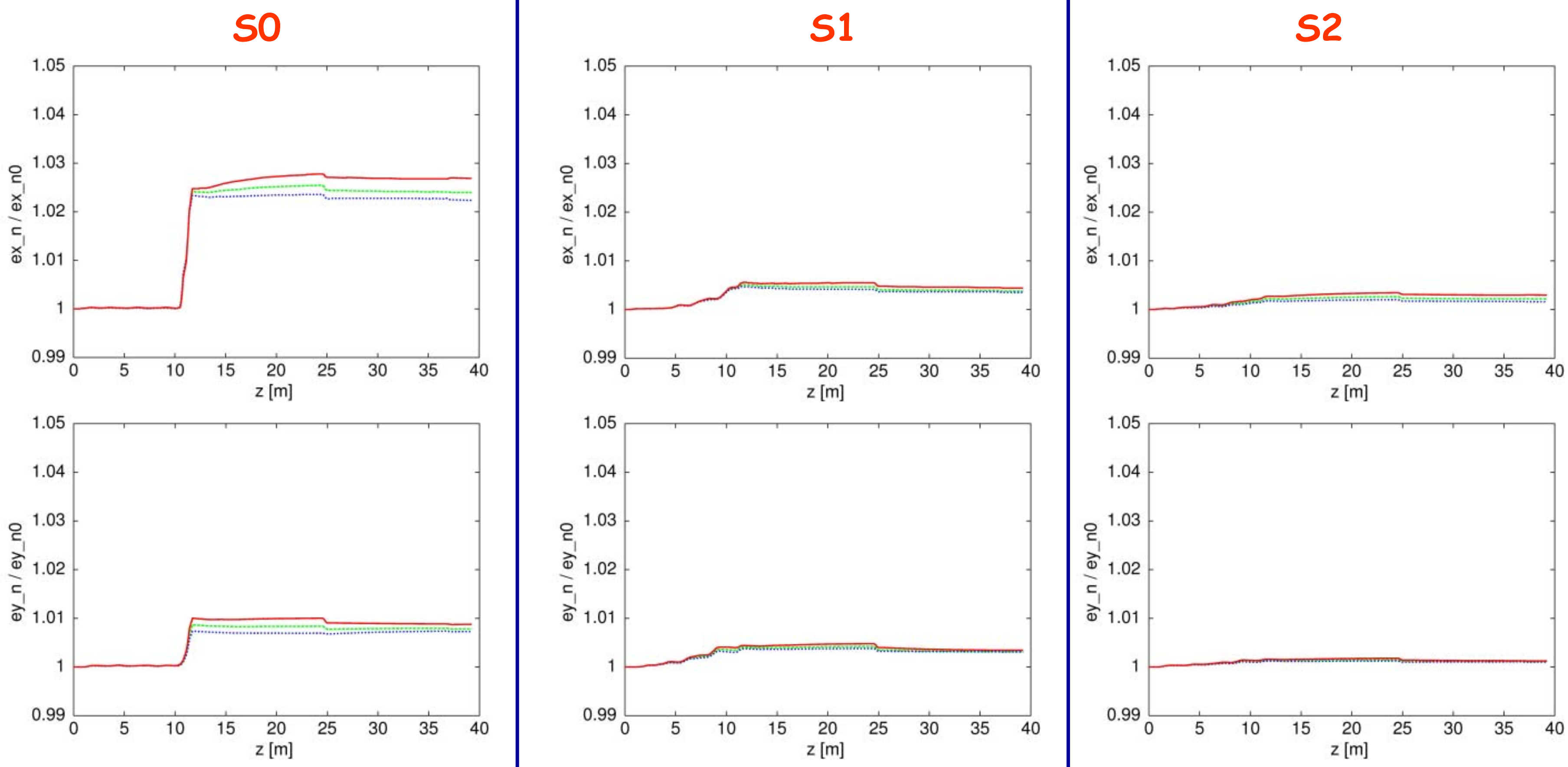
➡ Non-periodic Twiss functions in the DBC2 section, but setting of quadrupoles Q4DBC2-Q10DBC2 still corresponds to 45° phase advances (**S1**).

➡ Non-periodic Twiss functions and setting of Q4DBC2-Q10DBC2 quadrupoles corresponding to 30° phase advances (**S2**)





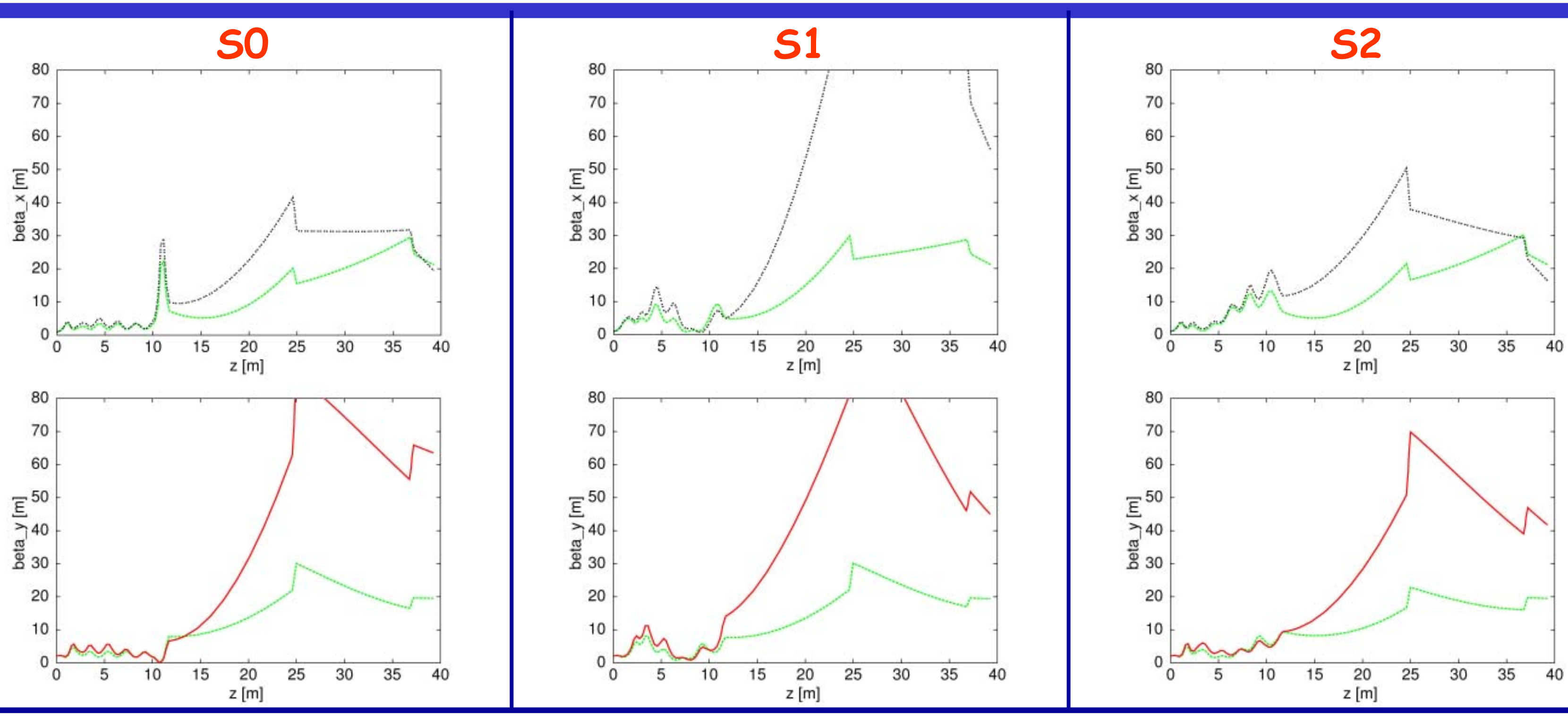
Transition into ACC2 accelerating module: growth of emittances due to chromatic effects

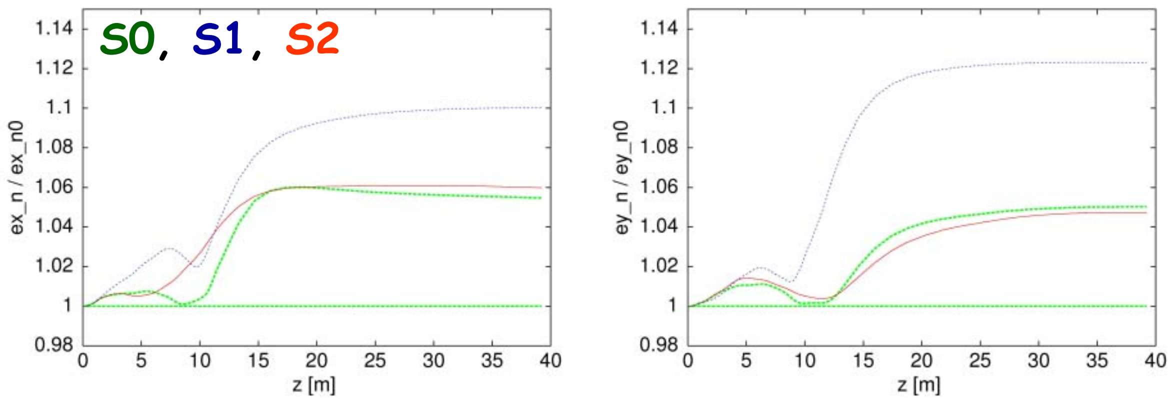


Matched gaussian beam at the exit of BC2 with normalized emittances 1 mm·mrad and 1% rms energy spread.
Tracking up to ACC3 exit . No magnet misalignments and quadrupole gradient errors.

— beam with nominal energy, — +2% coherent energy shift, — -2% coherent energy shift.

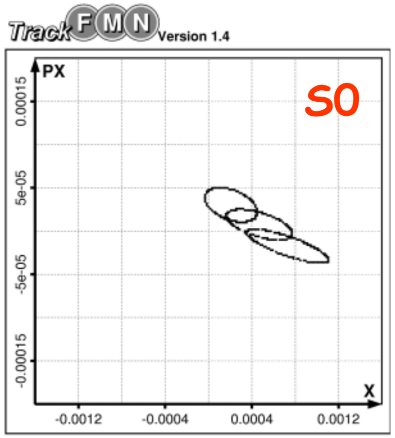
Transition into ACC2 accelerating module: transverse space charge effect

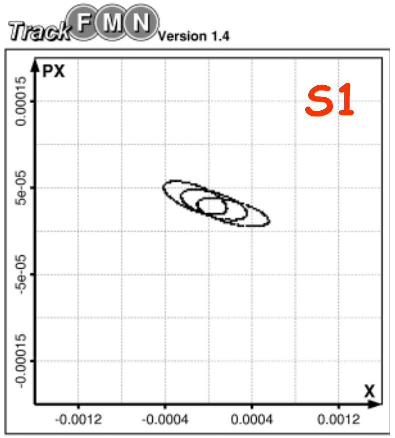


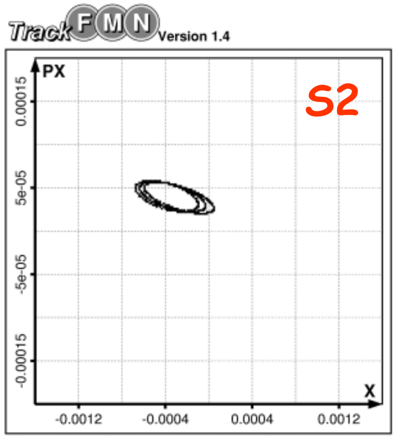


Monochromatic matched gaussian beam at the exit of BC2 with normalized emittances 1 mm·mrad. I = 400 A.

Transition into ACC2 accelerating module: beam steering due to manipulations with beam energy in RF-Gun and ACC1 module



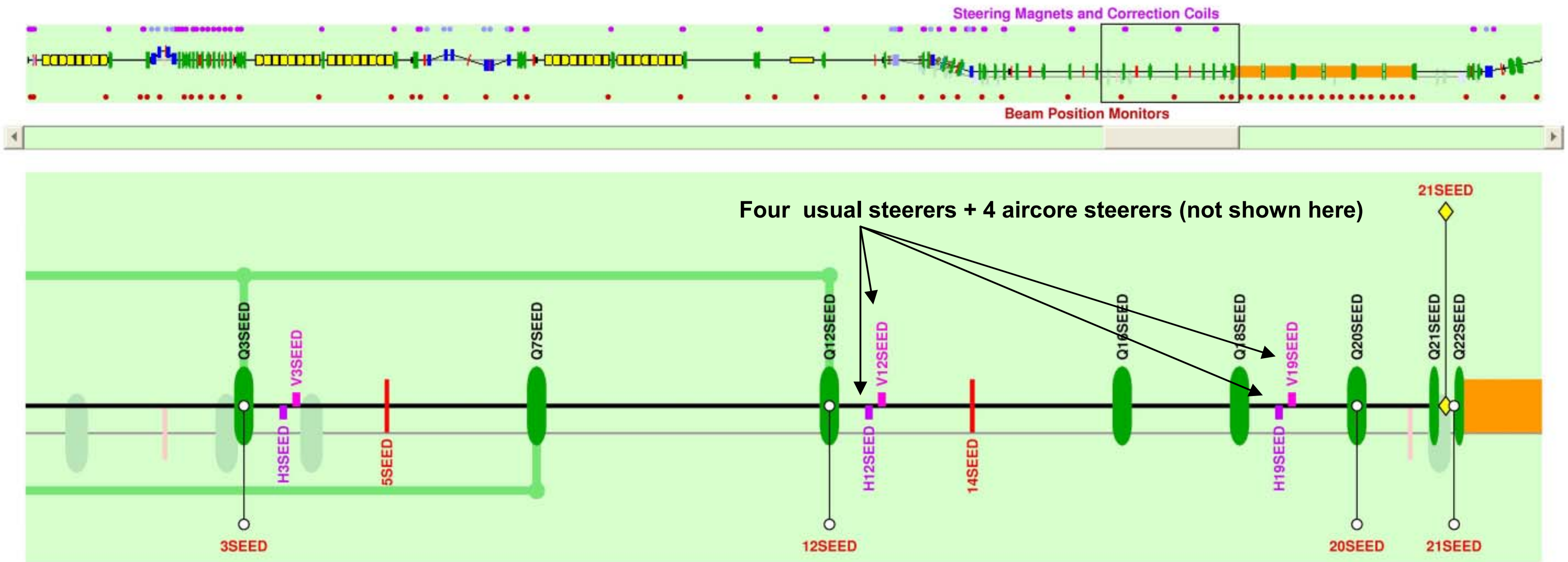




Monochromatic 2σ ellipses with -2%, 0, +2% energy offsets at the BC2 exit. Coherent deflection angle in the horizontal plane is set to 0.3 mrad (the resulting trajectory offsets nowhere exceeds the value of about 1 mm).

It seems that switch from optics solution S0 to optics solution S2 could be beneficial.

Matching to the undulator entrance



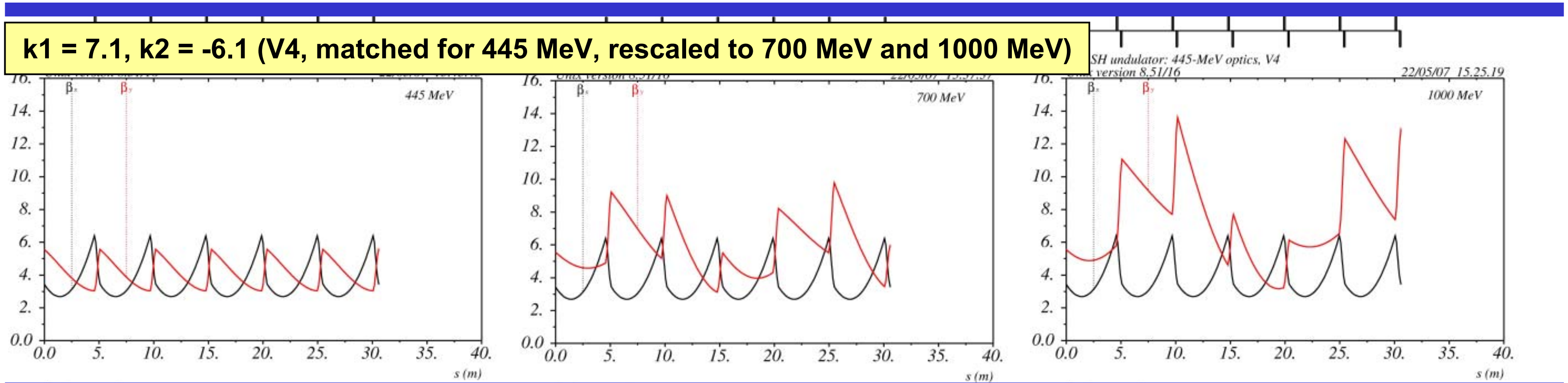
Two quadrupoles at the undulator entrance (Q21SEED and Q22SEED) do not contribute significantly into matching to the undulator unless their strengths are high (which could produce strong kicks due to offsets of these quadrupoles with respect to the beam). Of course, these quadrupoles could be used as additional steerers, but it looks better to use "real" steerers (four pairs of which are placed in the front of undulator entrance).

So it looks beneficial to degauss these two quadrupoles and switch them off without any serious reduction of the matching flexibility (especially, if quadrupoles in the seeding line will have separate power supplies).

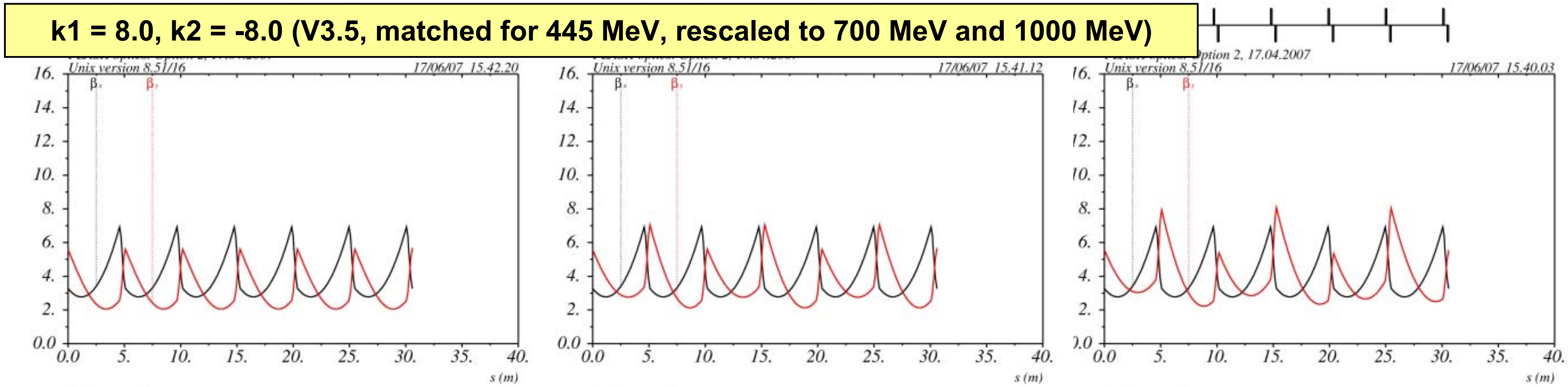
Focusing inside the undulator

In perfect situation (ideally aligned quadrupoles and perfect matching) a stronger focusing inside the undulator is, of course, beneficial. Without automatic procedure for quadrupole alignment and with unknown Twiss parameters of the lasing spike the efficiency of the focusing increase is limited by success of empirical tuning. The current focusing variant is V4. Nevertheless, small increase in the quadrupole focusing strengths could be beneficial, especially if one will simply rescale the quadrupole settings with changing beam energy, as it sometimes was done before (without natural undulator focusing taken into account).

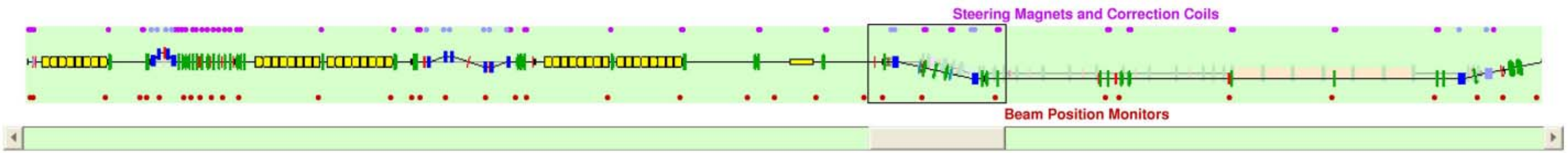
k1 = 7.1, k2 = -6.1 (V4, matched for 445 MeV, rescaled to 700 MeV and 1000 MeV)

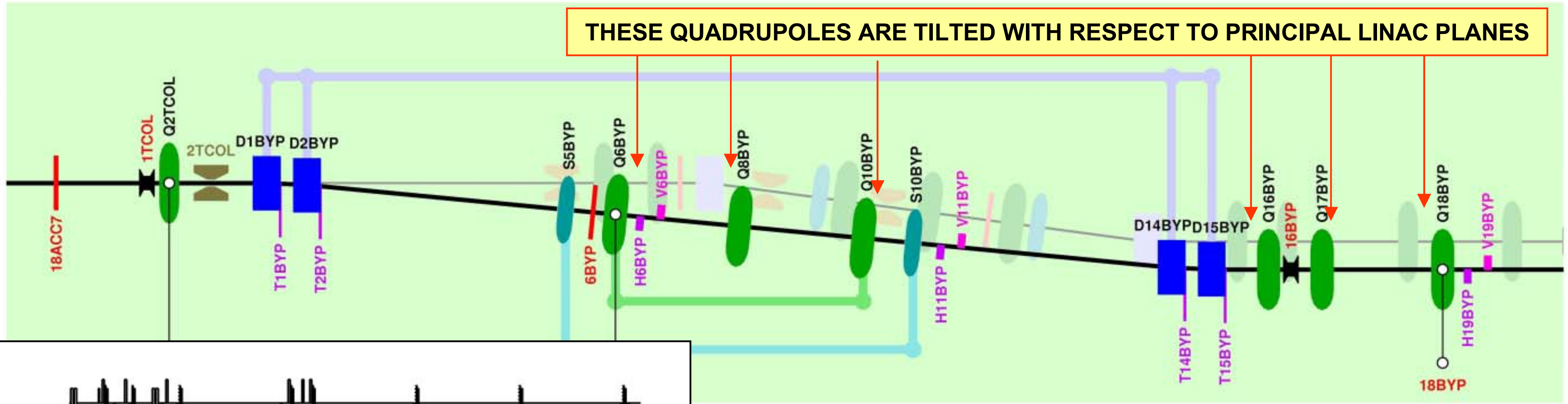


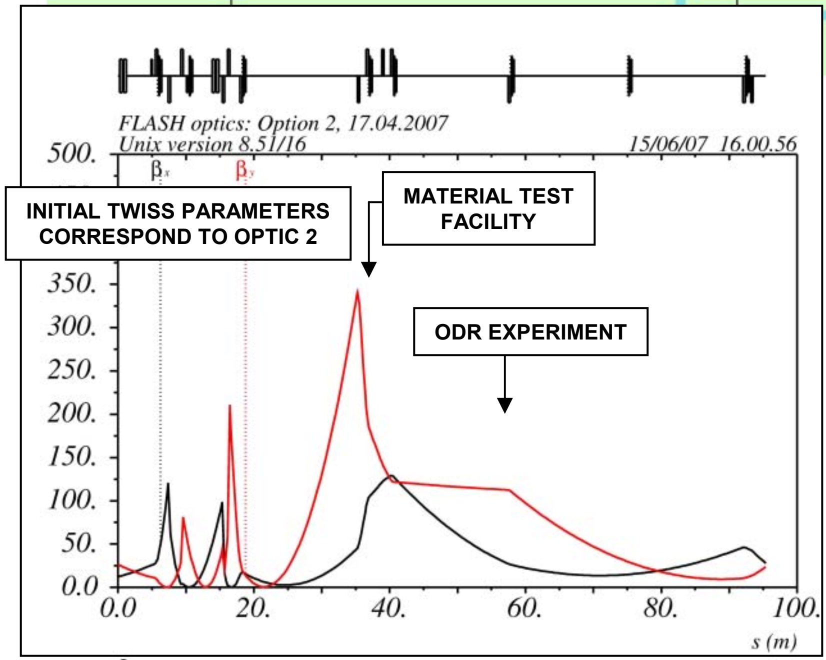
k1 = 8.0, k2 = -8.0 (V3.5, matched for 445 MeV, rescaled to 700 MeV and 1000 MeV)



Some remarks about bypass operations







ACCORDING TO ORIGINAL DESIGN (G. HOFFSTAETTER) QUADRUPOLES Q6BYP, Q8BYP AND Q10BYP ARE USED FOR DISPERSION SUPPRESSION (ONLY ONE DEGREE OF FREEDOM IS LEFT), AND QUADRUPOLES Q16BYP, Q17BYP AND Q18BYP ARE USED FOR THE COUPLING REMOVAL (NO FREEDOM IS LEFT). TO FOCUS BEAM AT THE LOCATION OF THE MATERIAL TEST FACILITY THE USAGE OF QUADRUPOLE DOUBLET (Q36BYP, Q37BYP) ALONE IS INSUFFICIENT. ADDITIONALLY, THE SPECIAL INITIAL CONDITIONS AT THE BYPASS ENTRANCE HAVE TO BE CREATED. THIS MEANS THE USAGE OF LINAC QUADRUPOLES STARTING, AT LEAST, FROM ACC6 DOUBLET. THE BETTER APROACH COULD BE TO WORK WITH COUPLED BEAM, THAT ALLOWS TO USE QUADRUPOLES Q16/17/18BYP NOT FOR THE COUPLING REMOVING BUT FOR MANIPULATIONS WITH BEAM AND COULD ALLOW TO KEEP SETTING OF LINAC QUADRUPOLES UNCHANGED (WORK IN PROGRESS).

MatLab Based Online Toolbox for FLASH Optics

Matlab Functions for Calculations of the
Linear Beam Optics of FLASH Linac

Version 1.2

V.Balandin and N.Golubeva

December 11, 2006

1

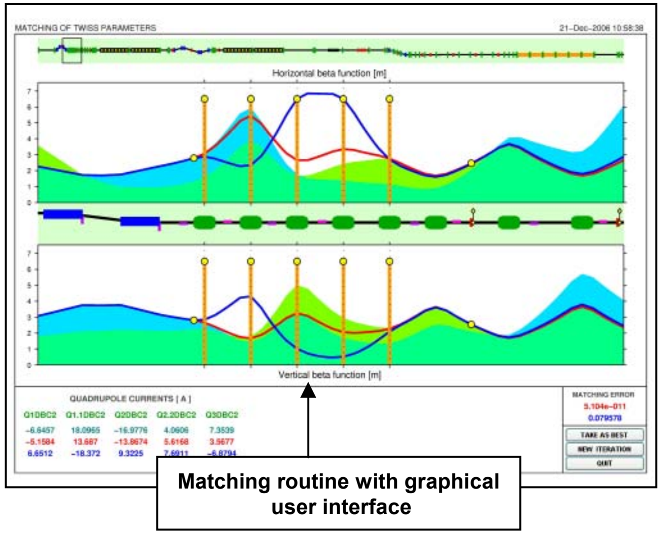
(6 + 2)D motion is implemented, including rf-focusing (based on usage of on-axis accelerating field profile) and natural undulator focusing (based on usage of measured undulator field).

+2)D means dynamics of reference energy and reference time of flight (although time of flight is not in usage yet).

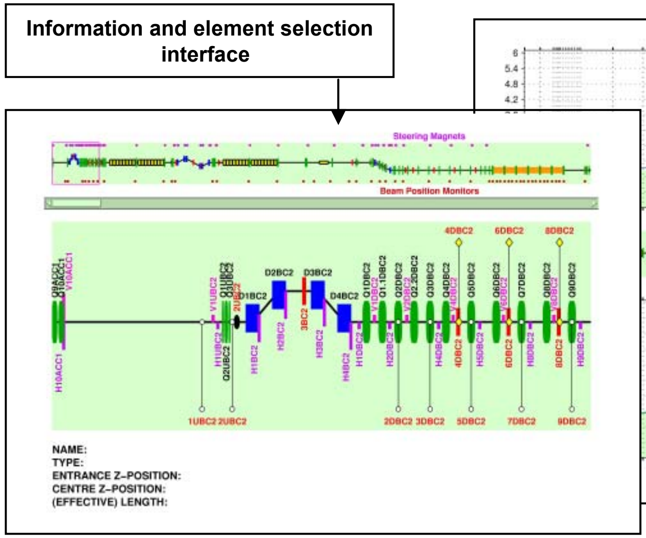
Version 1.0 – July 28, 2006
Version 1.1 – October 20, 2006
Version 1.2 – December 11, 2006
Version 1.3 – coming soon

Manual (110 pages for current version)
in FLASH-eLogBook: doc/Physics/Optics

MatLab Based Online Toolbox for FLASH Optics



Many functions are already available including among others …



Summary

- There is no problem to adapt optics 2 to updated accelerator structure

- Automatic procedure (which will allow to calculate needed currents for magnet power supplies as a function of accelerating regime and desired bunch compressor angles) is under development and will be included in Optics Toolbox

- It seems that there are some possibilities for further improvement of the optics option 2

- Version 1.3 of Optics Toolbox will be ready in 2-3 weeks