Transverse Focusing in FLASH: Theory and Last Experimental Results

KW02-06, 07.01-10.02.2008

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FLASH seminar, 1 April 2008

4.5 optics shifts in KW02-06

Original schedule:

09.01.2008	optics for material test stand with BC2 and BC3 off
11.01.2008	optics for ODR + setup with BC2 on
15.01.2008	test of ODR optics (4h)
26.01.2008	optics for SASE 13.5 nm
07.02.2008	optics for SASE 26 nm

In fact, no shifts for studies optics itself !!!
Nevertheless, we tried to do some studies in all available free time spots.

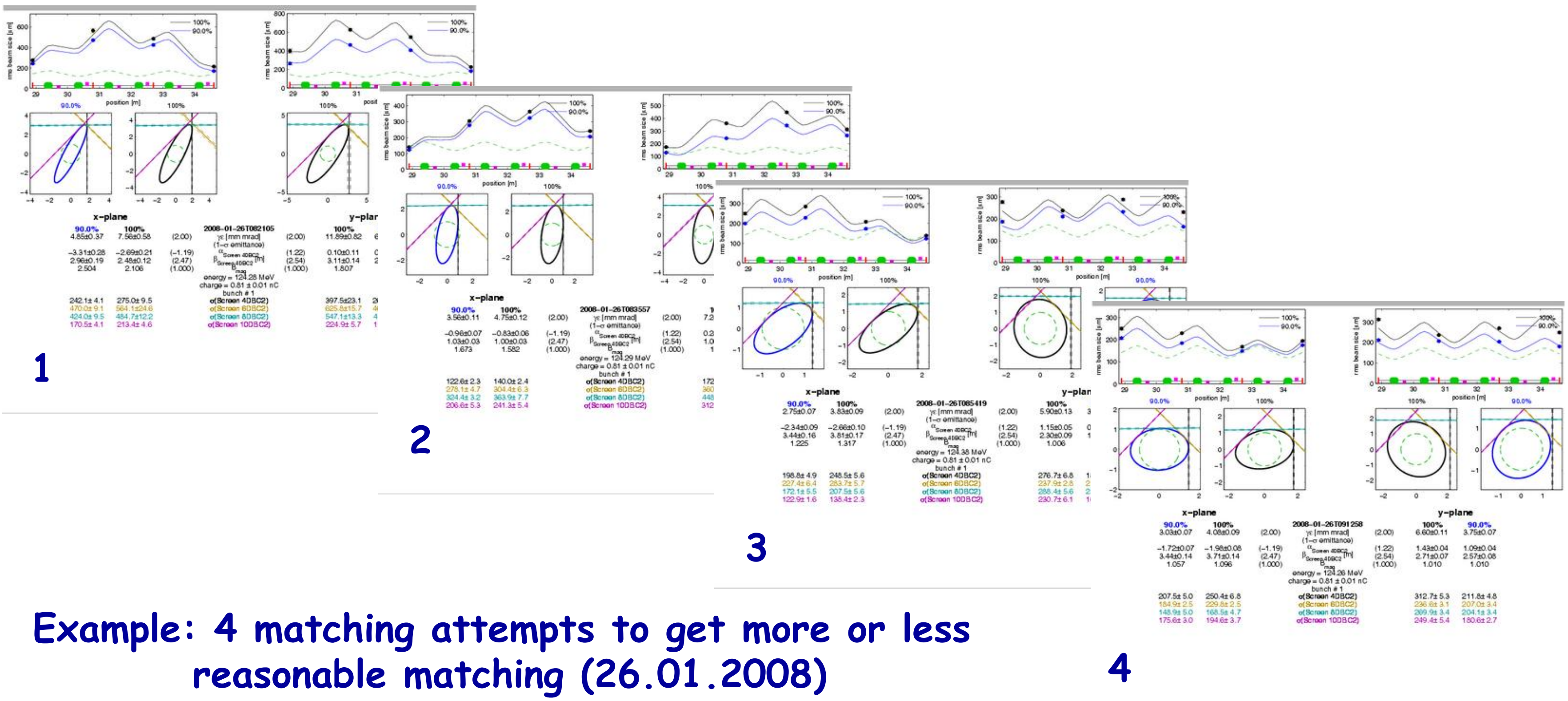
Topics to be discussed:

- **Optics in the linac:**
  - Matching in DBC2 section using 5 quadrupoles Q9ACC1-Q3UBC2
  - Switching BC2 on and off
  - Beam behaviour in BC3 section and switching BC3 on and off
- **FEL mode:**
  - Optics Option 2+
- **Bypass mode:**
  - New optics for transporting beam through bypass
  - Optics for ODR experiment: small vertical beam size at 57BYP (beam through 0.5 mm slit)
  - Special optics for material test stand

Matching to BC2 entrance using 5 upstream quadrupoles

Works good using one measurement in DBC2 section in ~60-70% of the cases.
The rest can be divided in two approximately equal groups:

1. To achieve more or less good matching several measurement attempts (attempts, not iterations) are required.
2. Even theoretical matching solution can not be found (mismatch of estimated beam parameters is outside of the matching section capabilities).



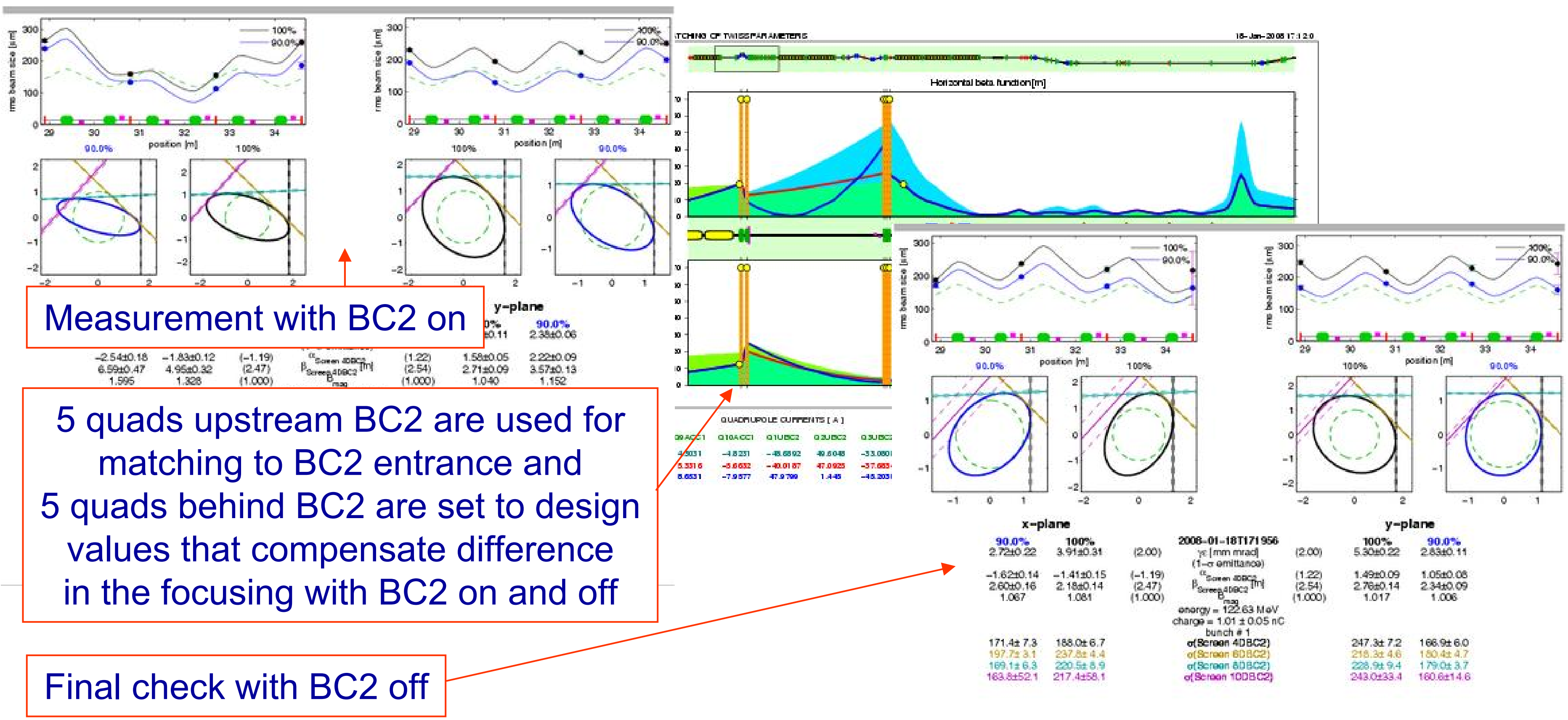
1 2 3 4

Example: 4 matching attempts to get more or less reasonable matching (26.01.2008)

Switching BC2 off

This procedure was tested several times and now can be considered as well established. One measurement in DBC2 section with BC2 on is, in most cases, not only sufficient for switching BC2 off, but also allows to make simultaneously improvement of the matching.

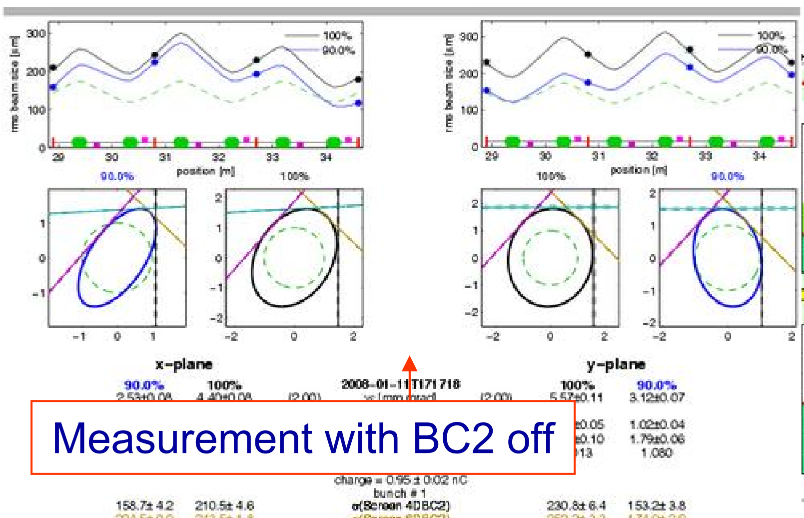
Example (18.01.2008):



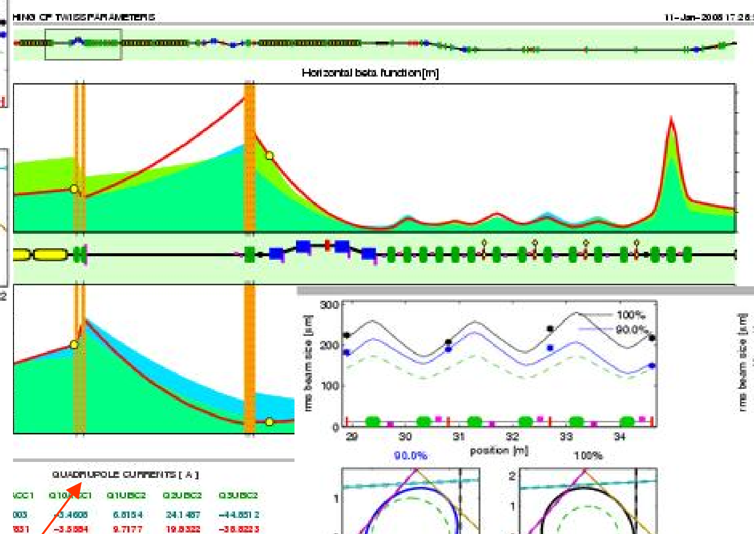
Switching BC2 on

This procedure was also tested several times and works as good as switching BC2 off.

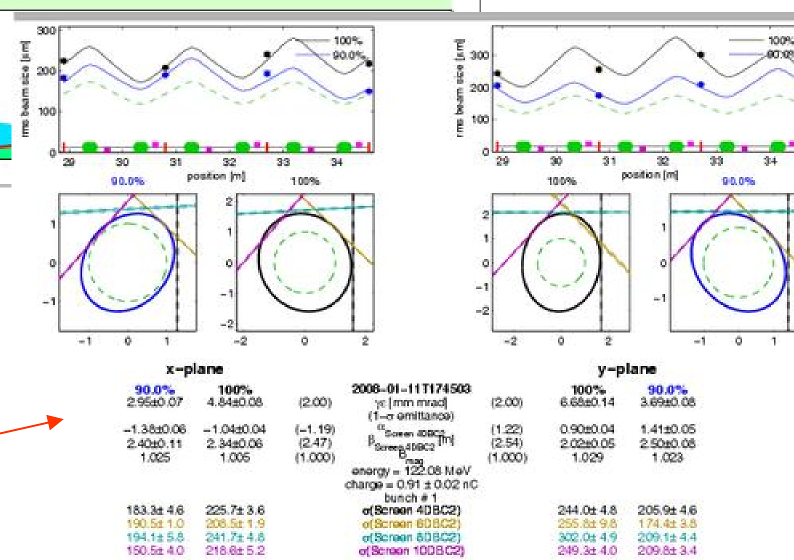
Example (11.01.2008):



Measurement with BC2 off



5 quads upstream BC2 are used for matching to BC2 entrance and
5 quads behind BC2 are set to design values that compensate difference in the focusing with BC2 on and off



Final check with BC2 on

Beam behaviour in BC3 area

As beam behaviour in the region from ACC1 exit to DBC2 exit seems to be well controlled, in the BC3 regions we observe disagreement with theoretical expectations.

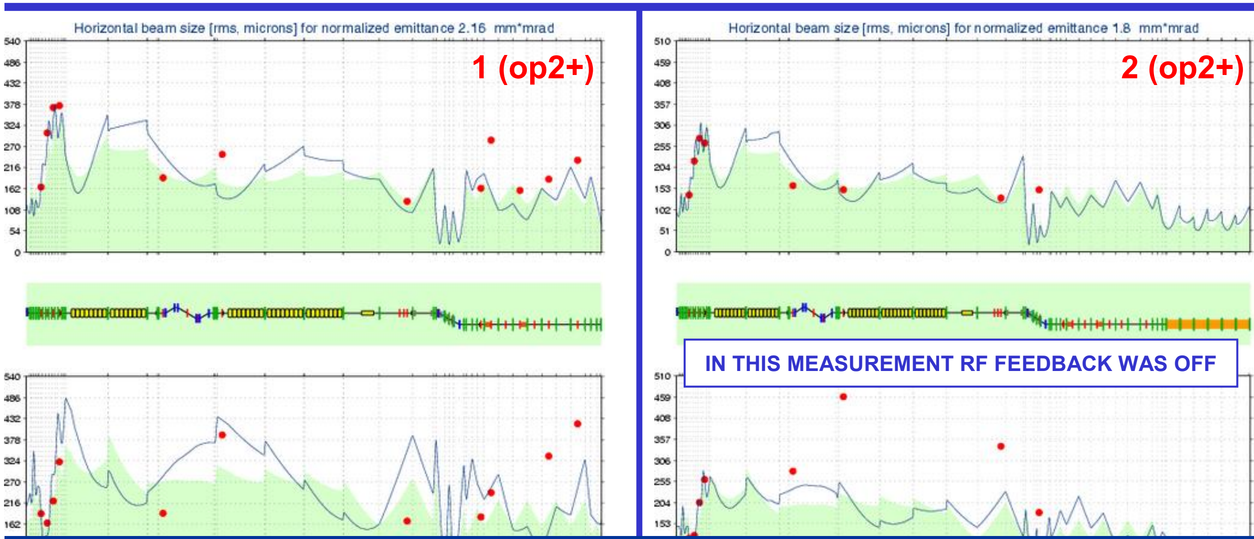
The main suspects are quadrupoles of the types TQD and TQF for which we do not have measured (or/and calculated) field profiles yet.

Special optics with switching off all or part of these quadrupoles were developed to check this, but, unfortunately, due to lack of time this test was not done during this accelerator studies block.

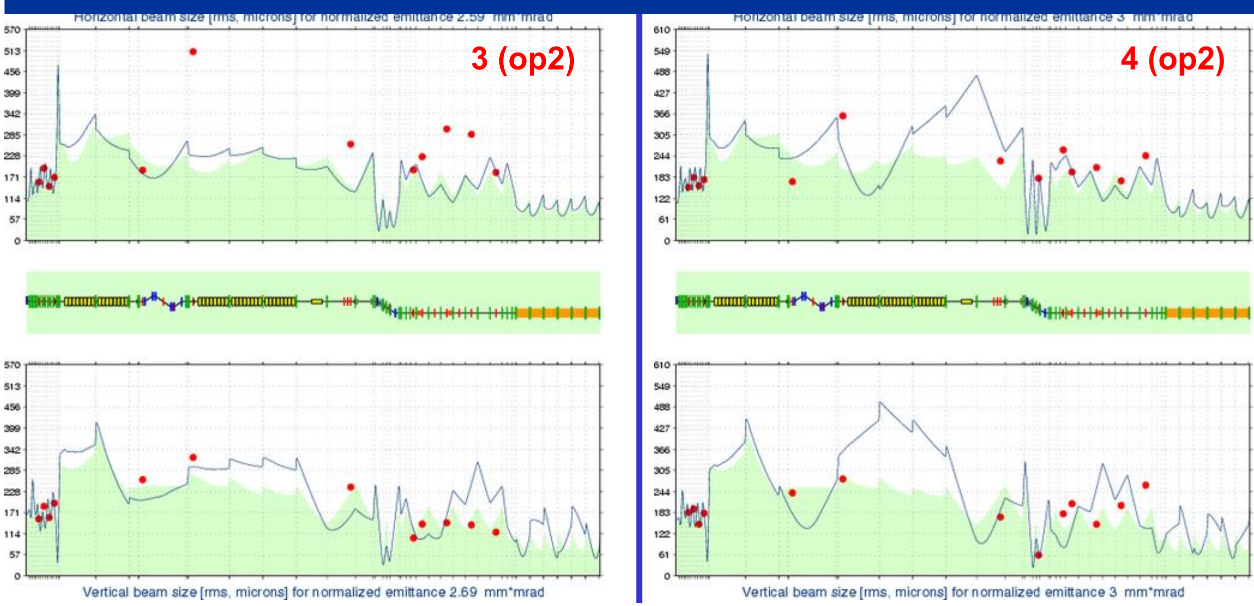
But at least we found time to look at dependence of beam sizes at OTR 3UBC3 and 5DBC3 from the beam position (one of the secondary suspicions).

Switching BC3 on and off was also done and it works more or less satisfactory taking into account mentioned above problems.

Measured beam sizes along the linac (OTR screens, red dots) compared with theoretical prediction (green areas) and with beam sizes reconstructed using measurements in DBC2 section (blue lines).



OLD MEASUREMENTS: OCTOBER 2007



Four optics installations (from scratch)

1. 12 October 2007, Afternoon
2. 13 October 2007, Night
3. 14 October 2007, Morning
4. 15 October 2007, Afternoon

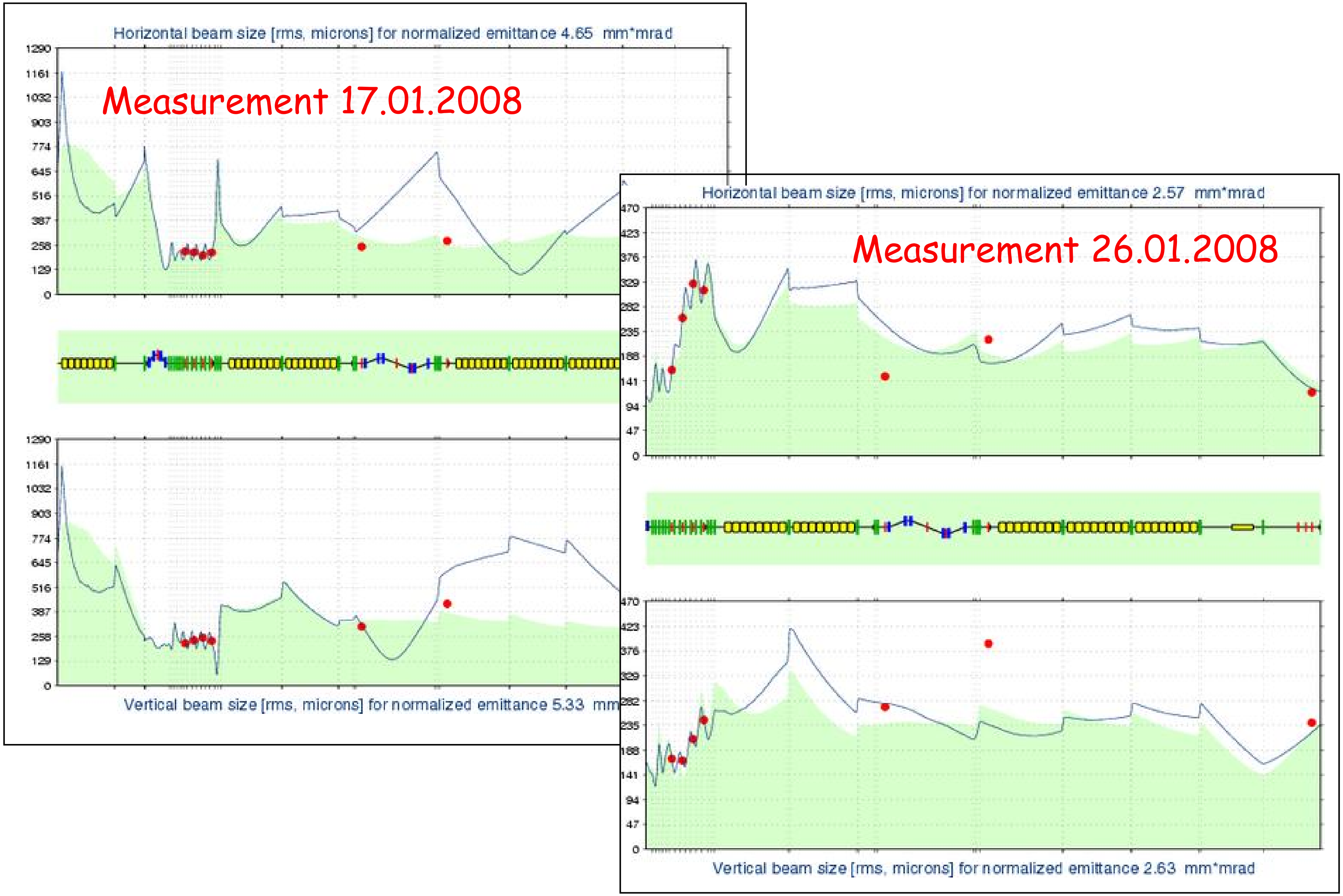
In the beginning of every new installation of the transverse focusing energy profile along the linac was different with about the same final

Procedure:

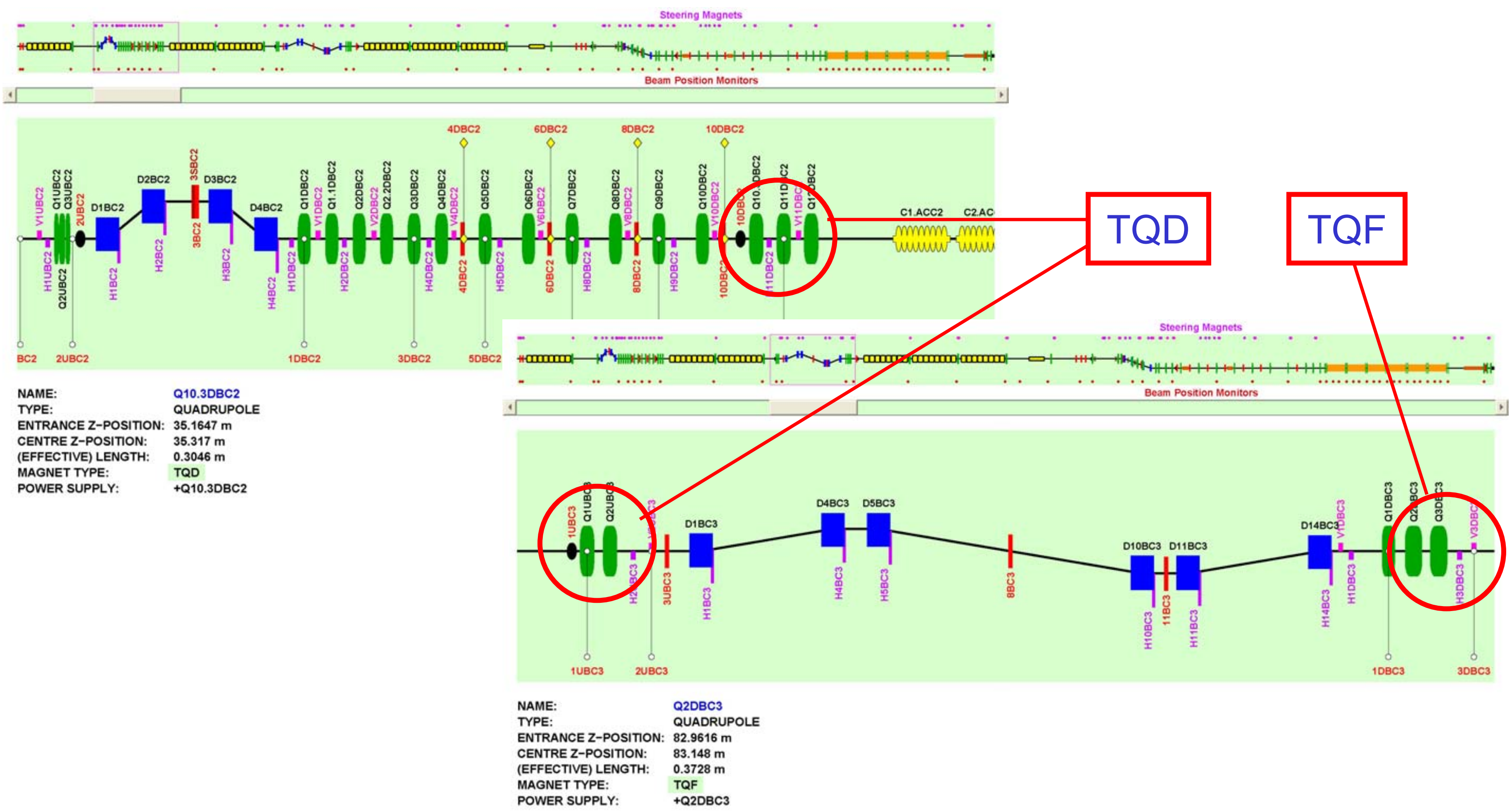
Matching to the BC2 entrance and, after that, loading of theoretical quadrupole currents calculated by Optics Toolbox for all downstream quadrupoles.

Measurements were done after some steering and without touching quadrupoles (except for the variant 4, where quadrupoles in ACC3 and ACC5 were slightly tuned and beam was matched in the SEED section, because this optics was then used for establishing SASE operation).

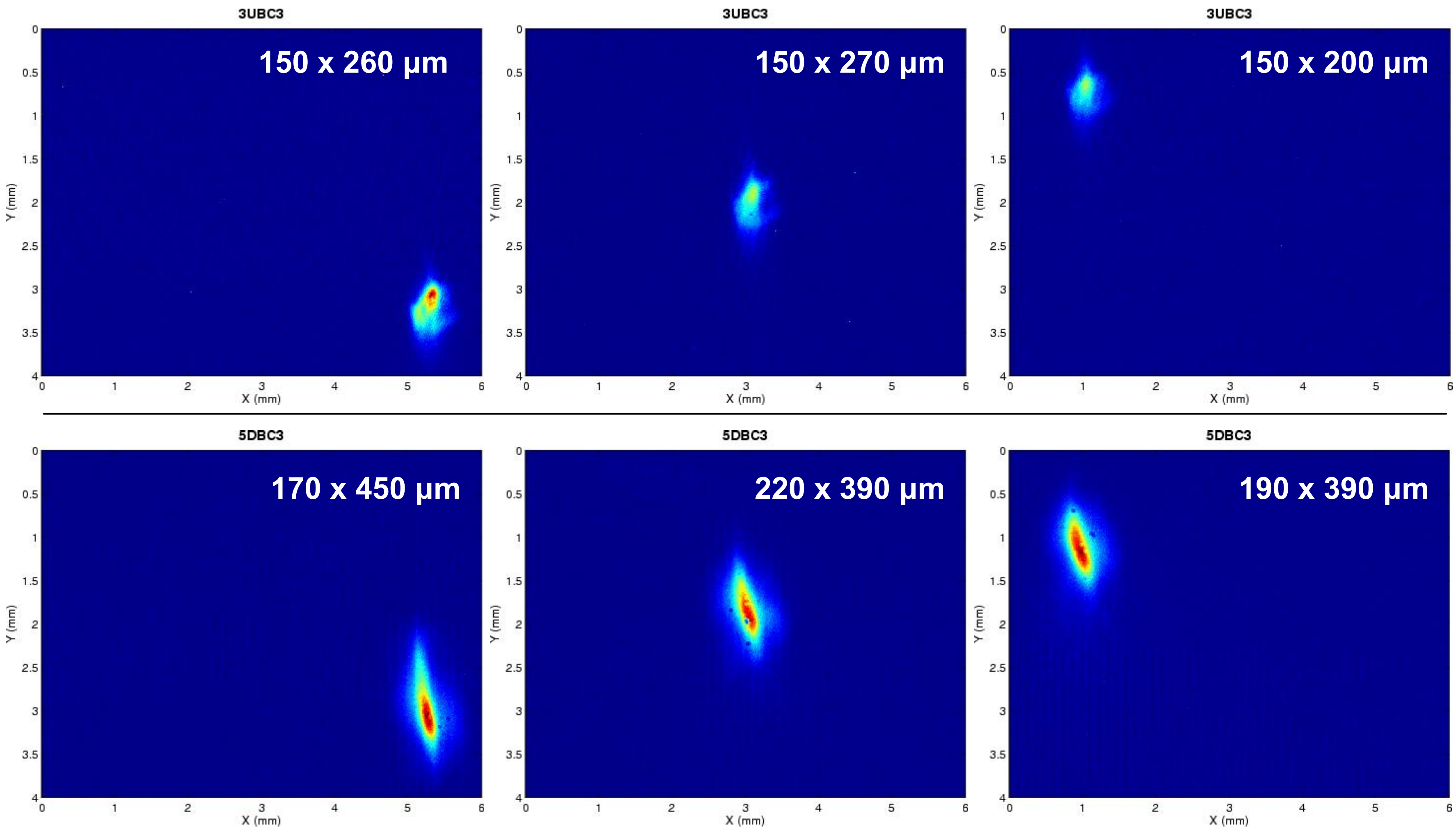
SITUATION DID NOT BECOME BETTER “BY ITSELF”



Unfortunately, for these quadrupoles we do not have measured or calculated field profiles yet !



Beam at screens 3UBC3 and 5DBC3

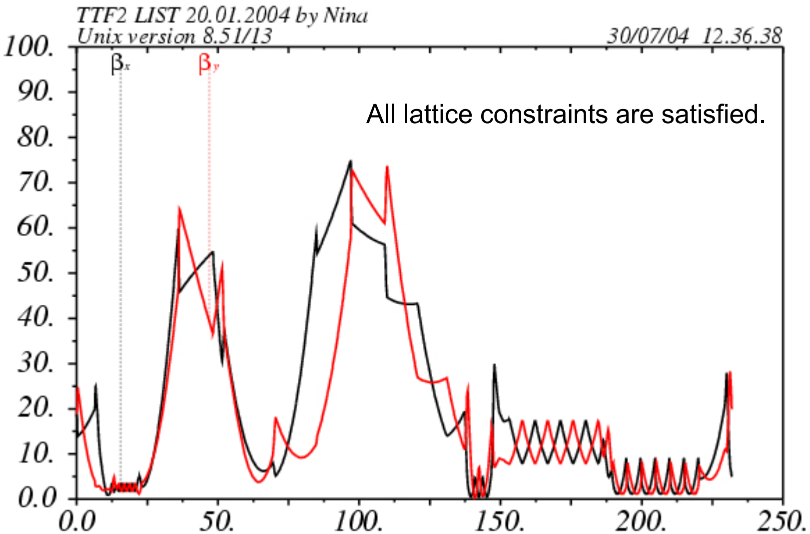


As concerning the beam images at screens 3UBC3 and 5DBC3, we have seen some dependence of rms beam sizes on the beam position, but not as large as needed to explain disagreement with theoretical predictions. So the new magnetic measurements for quadrupoles around BC3 (types TQD and TQF) are still desirable.

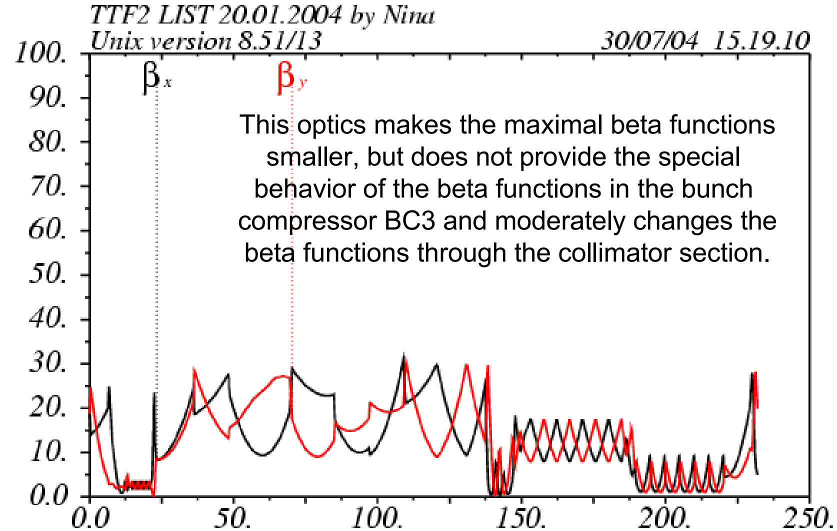
Optics Option 2+

- Commissioning started (September 2004) with quadrupole settings corresponding to Optics Option 1.
- On 21 April 2006 the optics of the accelerator was switched to Optics Option 2.
- Optics Option 2+ offers some additional improvements to optics option 2. Original plan was to make first try of this optics during last accelerator and FEL studies weeks, but actually it is already in use since 19.11.2007.

Optics Options 1 and 2

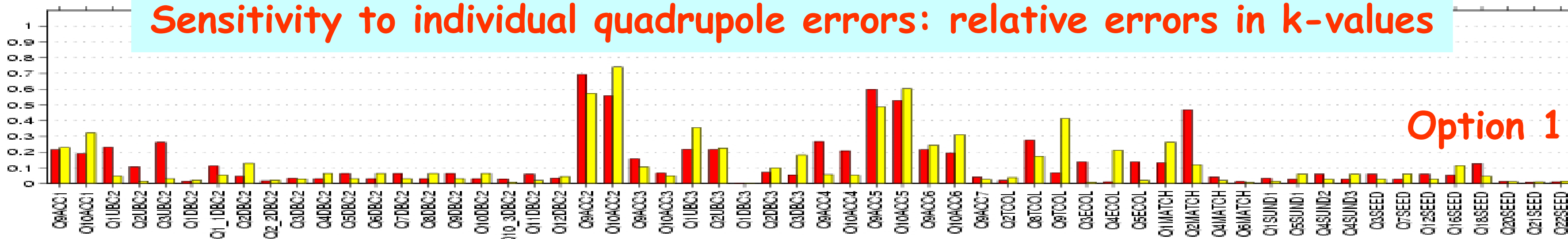


Optics Option 1

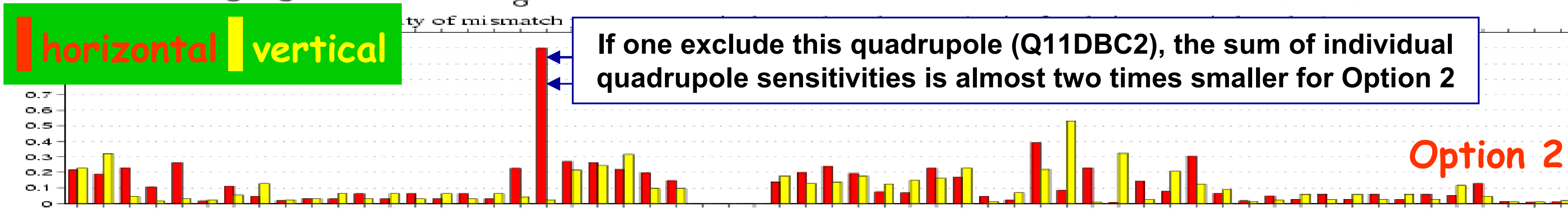


Optics Option 2

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



horizontal vertical

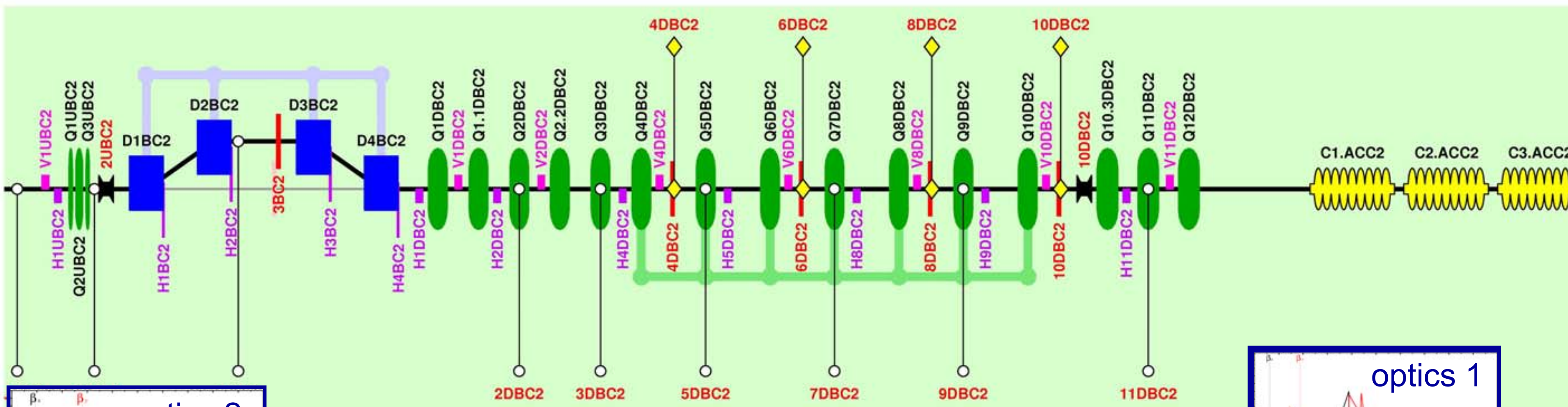


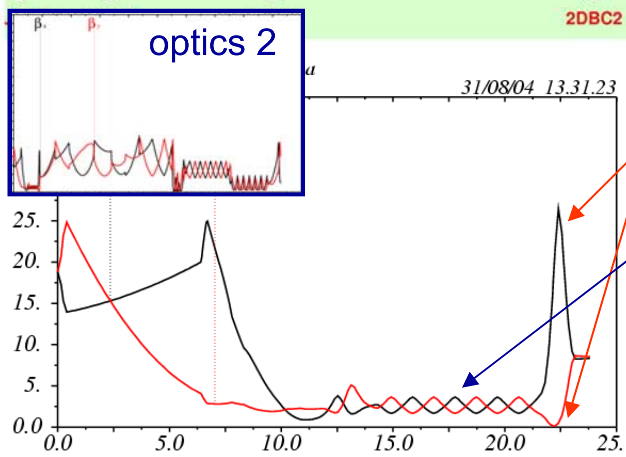
If one exclude this quadrupole (Q11DBC2), the sum of individual quadrupole sensitivities is almost two times smaller for Option 2

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

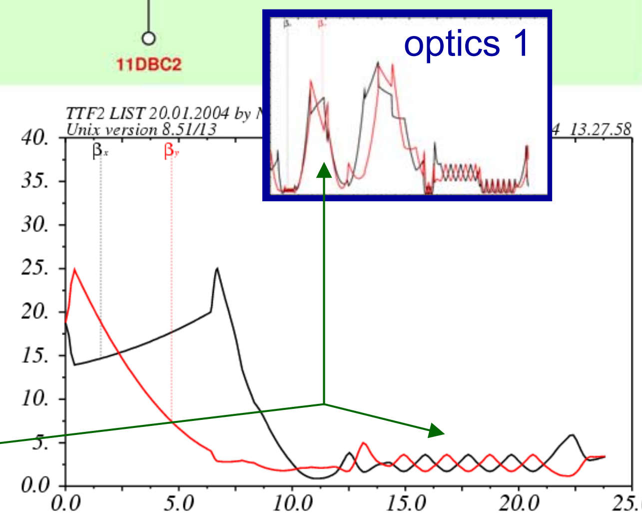
What can be improved in Optics 2 ?

1: Transition into ACC2 accelerating module



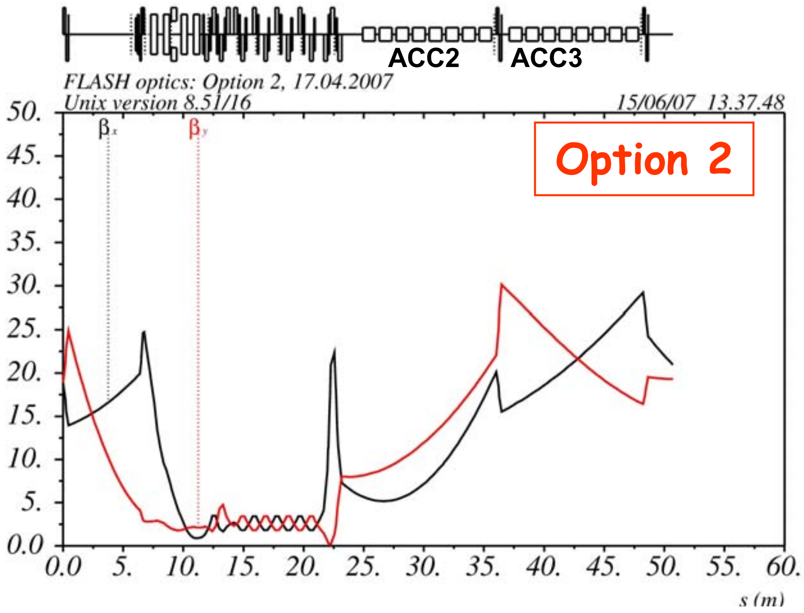


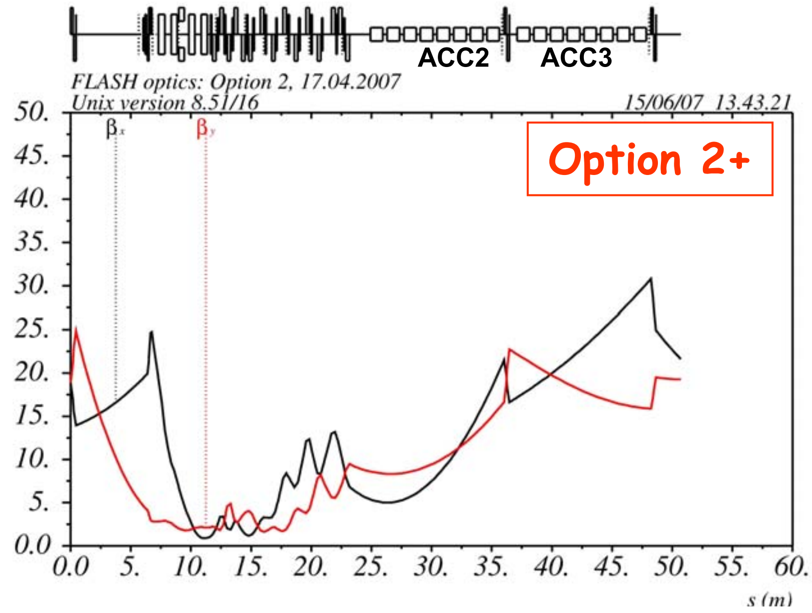
If one will try to remove the main source of troubles while keeping 45° FODO with periodic Twiss functions and without large increase in sensitivity to quadrupole errors, the result (with necessity) will be similar to the optics 1.



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

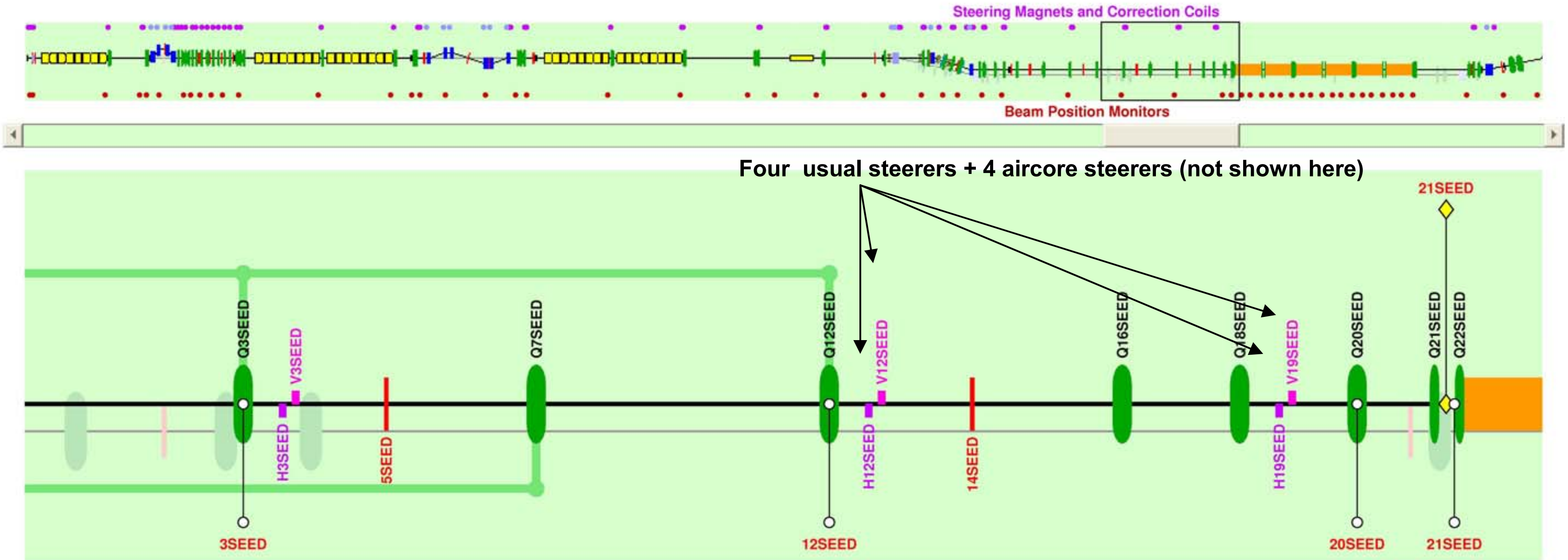




Original solution of the optics option 2

- Non-periodic Twiss functions
- Setting of Q4DBC2-Q10DBC2 quadrupoles corresponding to ~30° phase advances.

What can be improved in Optics 2 ?
2: Matching to the undulator entrance



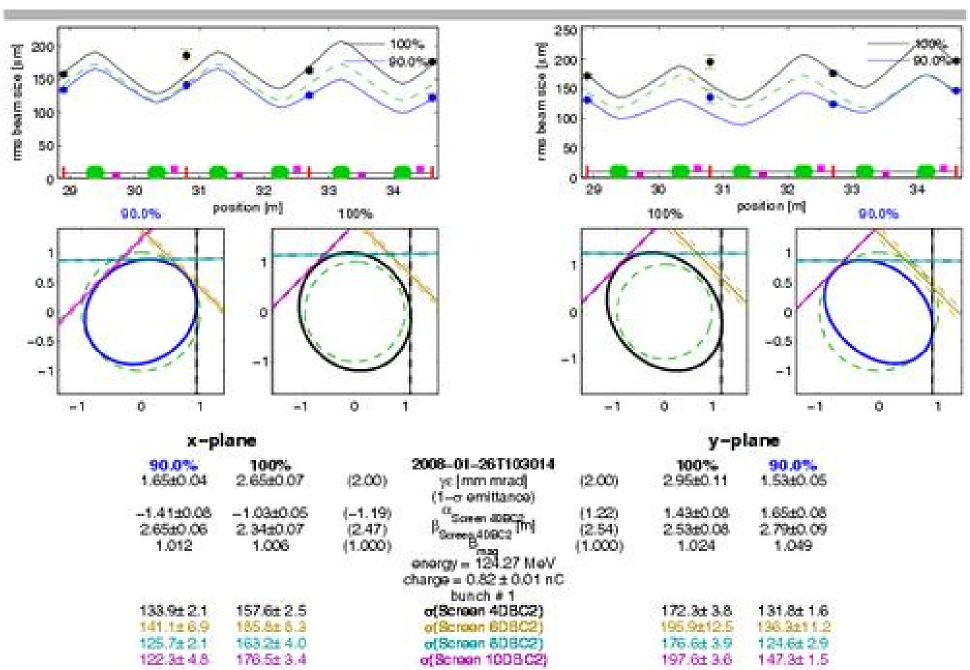
Two quadrupoles at the undulator entrance (Q21SEED and Q22SEED) do not contribute significantly into matching to the undulator unless their strengths are high (which could produce strong kicks due to offsets of these quadrupoles with respect to the beam). Of course, these quadrupoles could be used as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

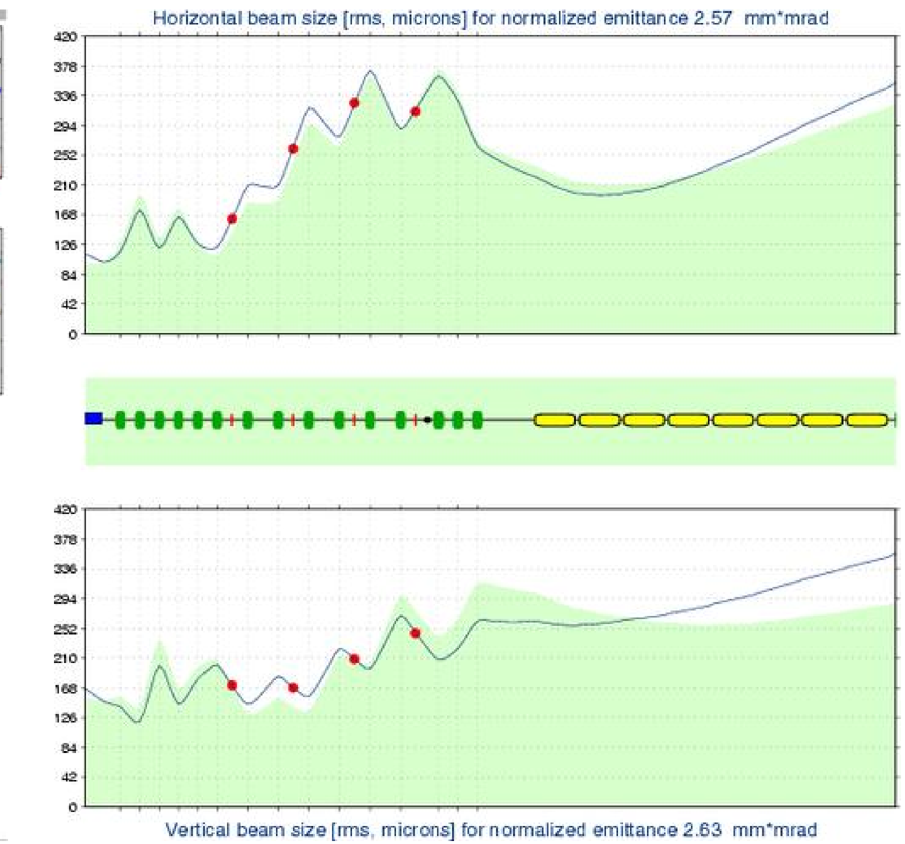
So it looks beneficial to degauss these two quadrupoles and switch them off without any serious reduction of the matching flexibility (especially, if quadrupoles in the seeding line will have separate power supplies).

Setup of transition into ACC2 accelerating module for optics option 2+

Measurement in DBC2
with 45° phase advance

Comparison of design (green), estimated (blue) and measured (red) beam sizes after switching to optics option 2+ in DBC2 section

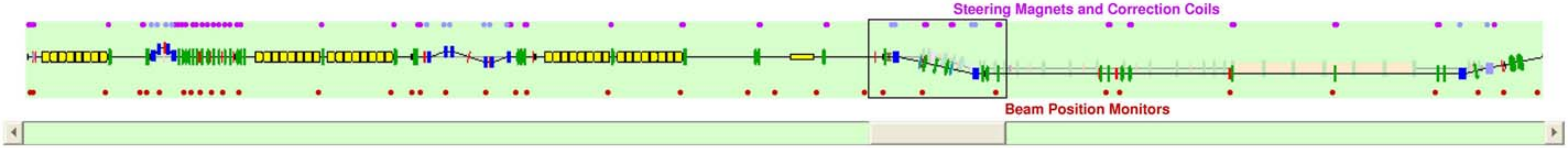


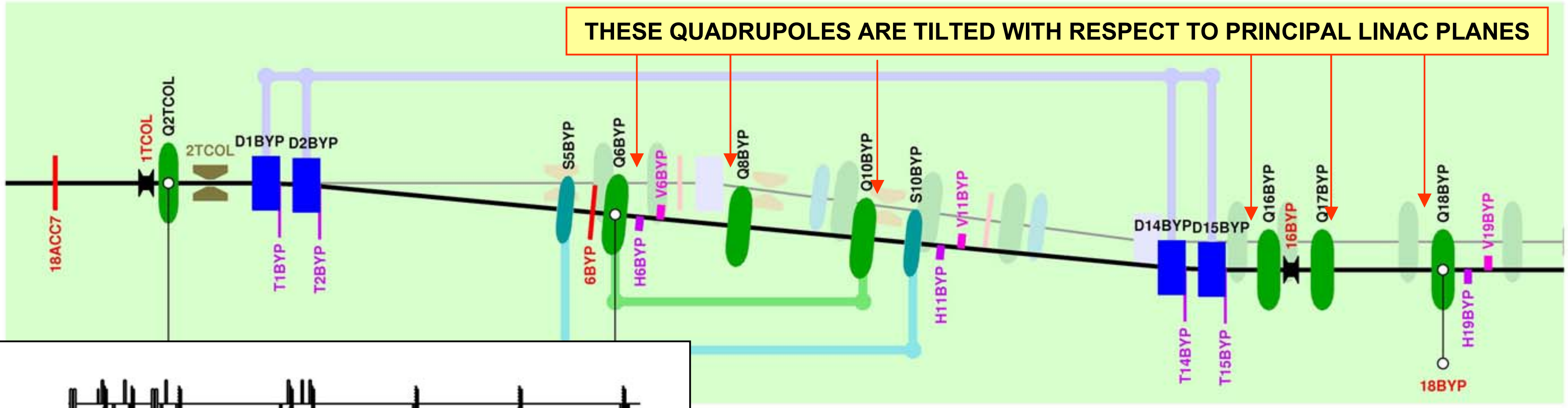


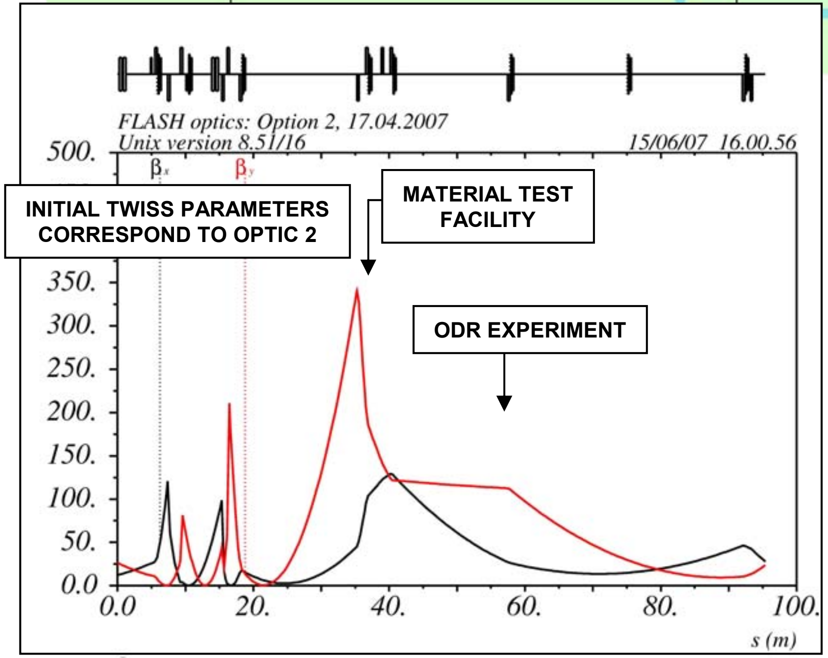
Optics for different modes of bypass operations

Before the start of bypass optics setup, polarity of bypass quadrupoles was, once more, checked with Hall probe: nothing wrong was found.

Bypass beam line





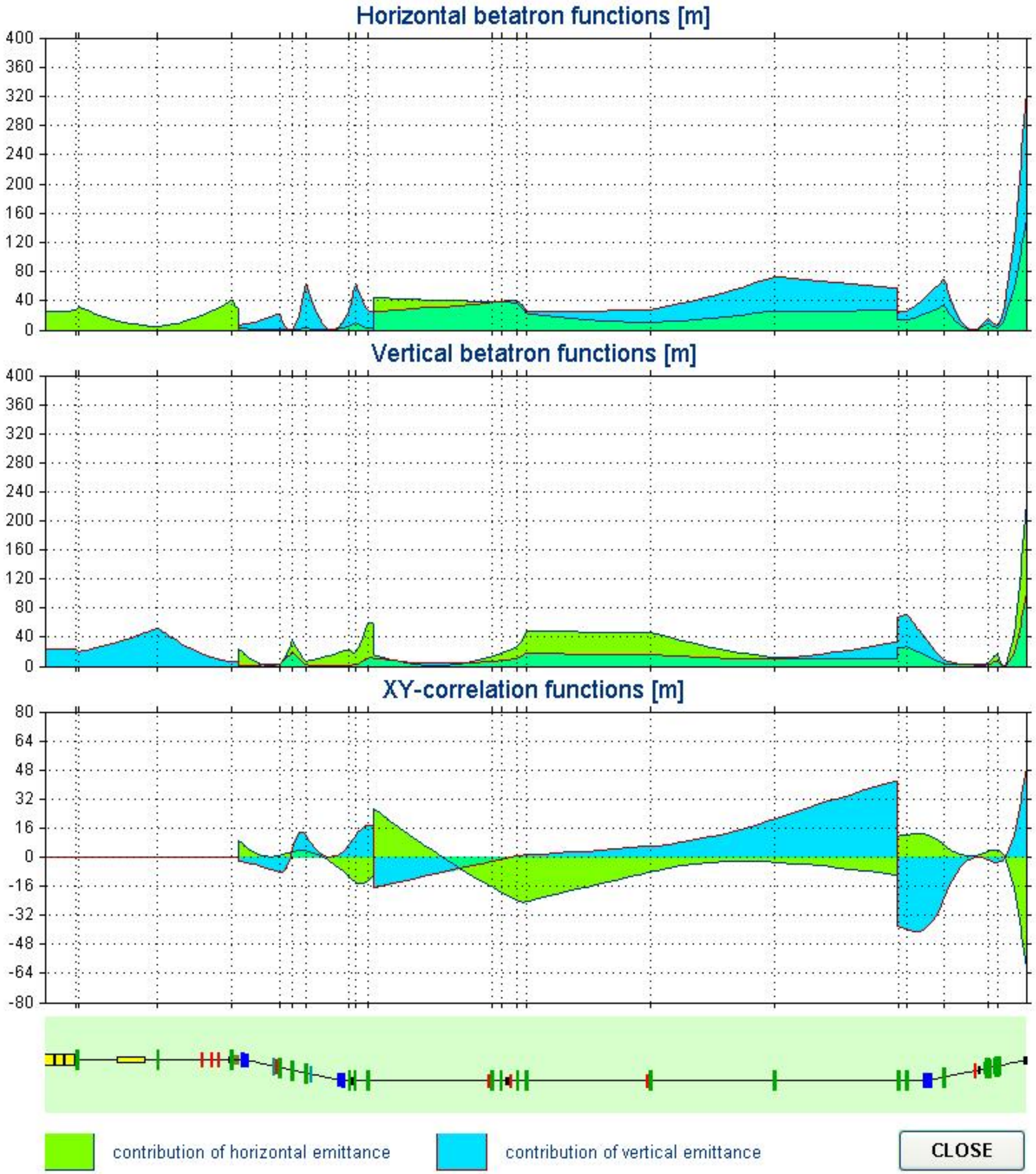


According to original design (G. HOFFSTAETTER):
- quadrupoles Q6BYP, Q8BYP AND Q10BYP are used for dispersion suppression (only one degree of freedom is left),
- and quadrupoles Q16BYP, Q17BYP and Q18BYP are used for the coupling removal (practically, no freedom is left).

To focus beam at the location of the material test facility the usage of only quadrupole doublet (Q36BYP, Q37BYP) is insufficient.

Possible ways:
- 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.
- to work with coupled optics, that allows to use quadrupoles Q16/17/18BYP not for the coupling removing, but for manipulations with beam.

Optics for "simple beam transport" through bypass

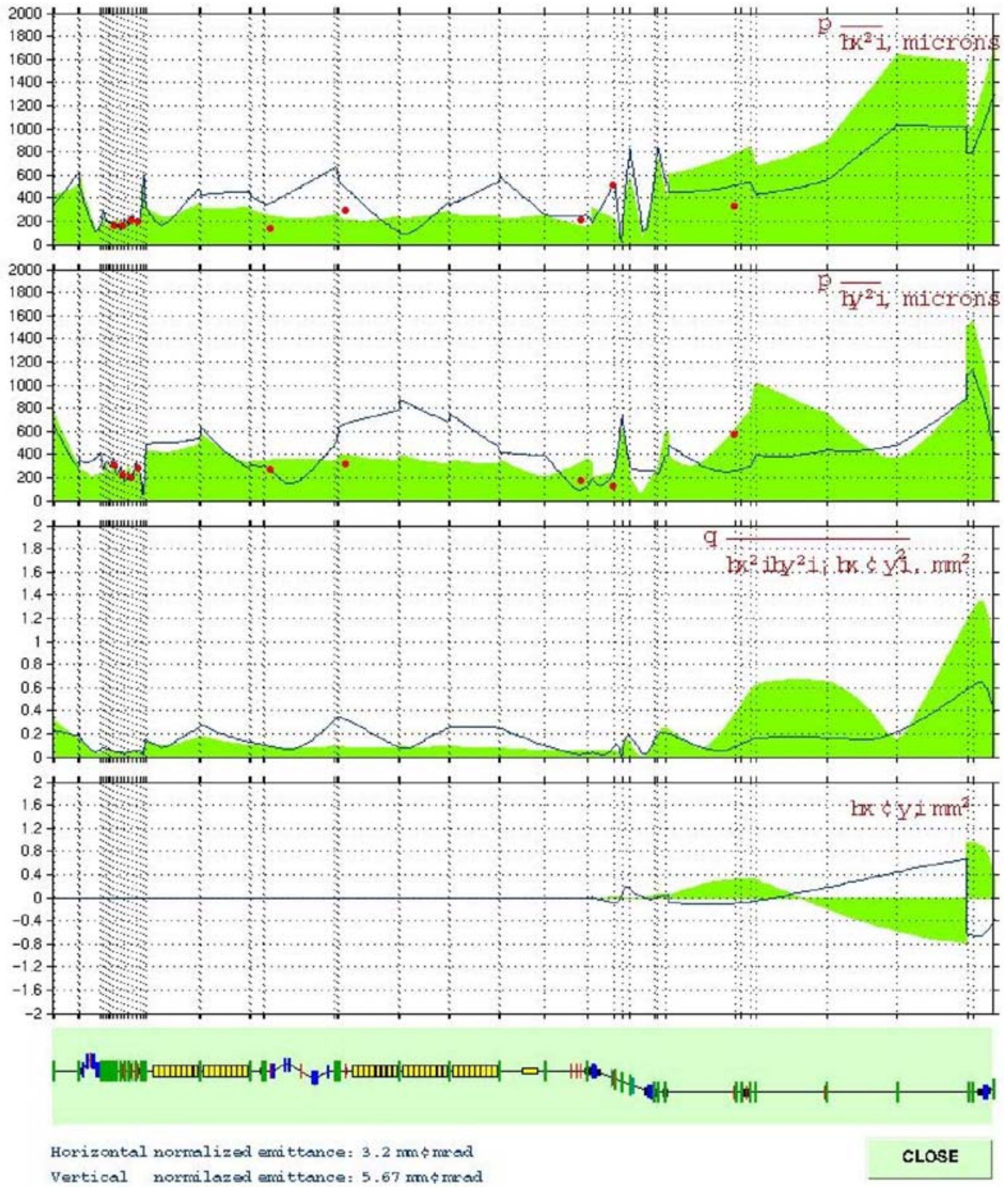


Special feature is that this optics minimizes the maximal beam size (for equal emittances).

The price paid for that is that in this optics transverse beam motion is coupled (two betatron functions for each plane) starting from bypass entrance up to beam dump, and that this optics requires different setting of some linac quadrupoles as compared to FEL operations.

At first time this optics was tested 09.01.2008.

Theory compared with experiment: 10.01.2008



Design (green areas), estimated (blue lines), and measured (red dots) beam sizes (energy ~700MeV).

Optics for ODR experiment

- **Purpose:** Create beam size at the location of the OTR 57BYP as small as to allow the beam passage through 0.5 mm vertical slit (i.e. about 80-90 microns rms).
- **Problems to be solved:** Create theoretical optics with extremely small beam size at the location of the OTR 57BYP is not a problem.

  The problems are:

  a) To keep beam relatively small in the upstream beam line, because beam with 2-3 cm rms transverse size will not fit good into vacuum pipe (4 cm diameter) and will create large unwanted background for the experiment.

  b) Due to somewhat unavoidable mismatch between real and theoretical optics to find practical way to move beam waist position close to the slit location.

Optics for ODR experiment

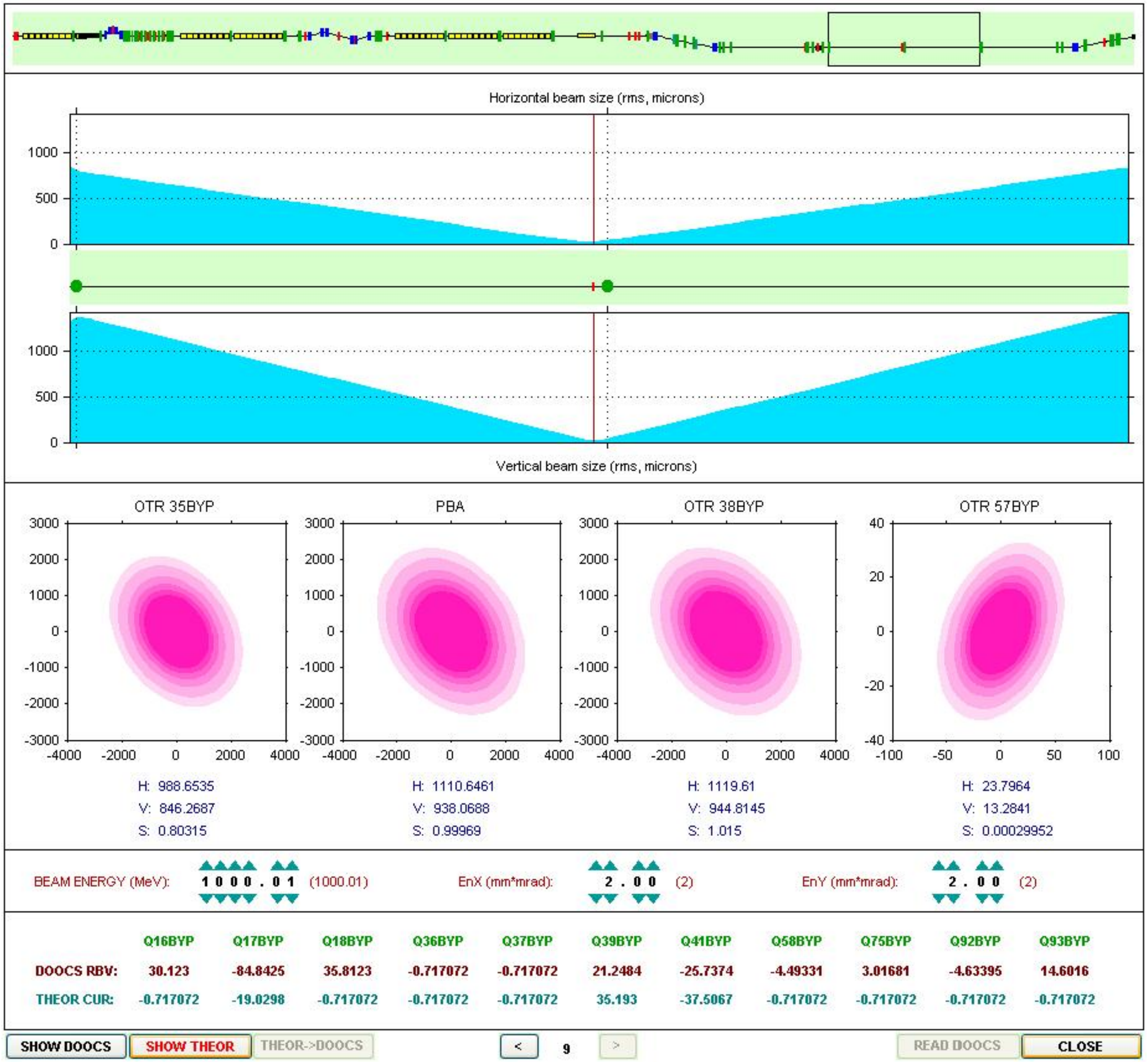
Solutions:

1. Tuning table: smooth, step by step, reduction of the theoretical beam size at the OTR 57BYP while keeping upstream theoretical beam size below 0.5 cm rms. Can solve the problem if beam emittances and mismatch are not too large. Allows also to make test of our understanding of the bypass coupled optics.

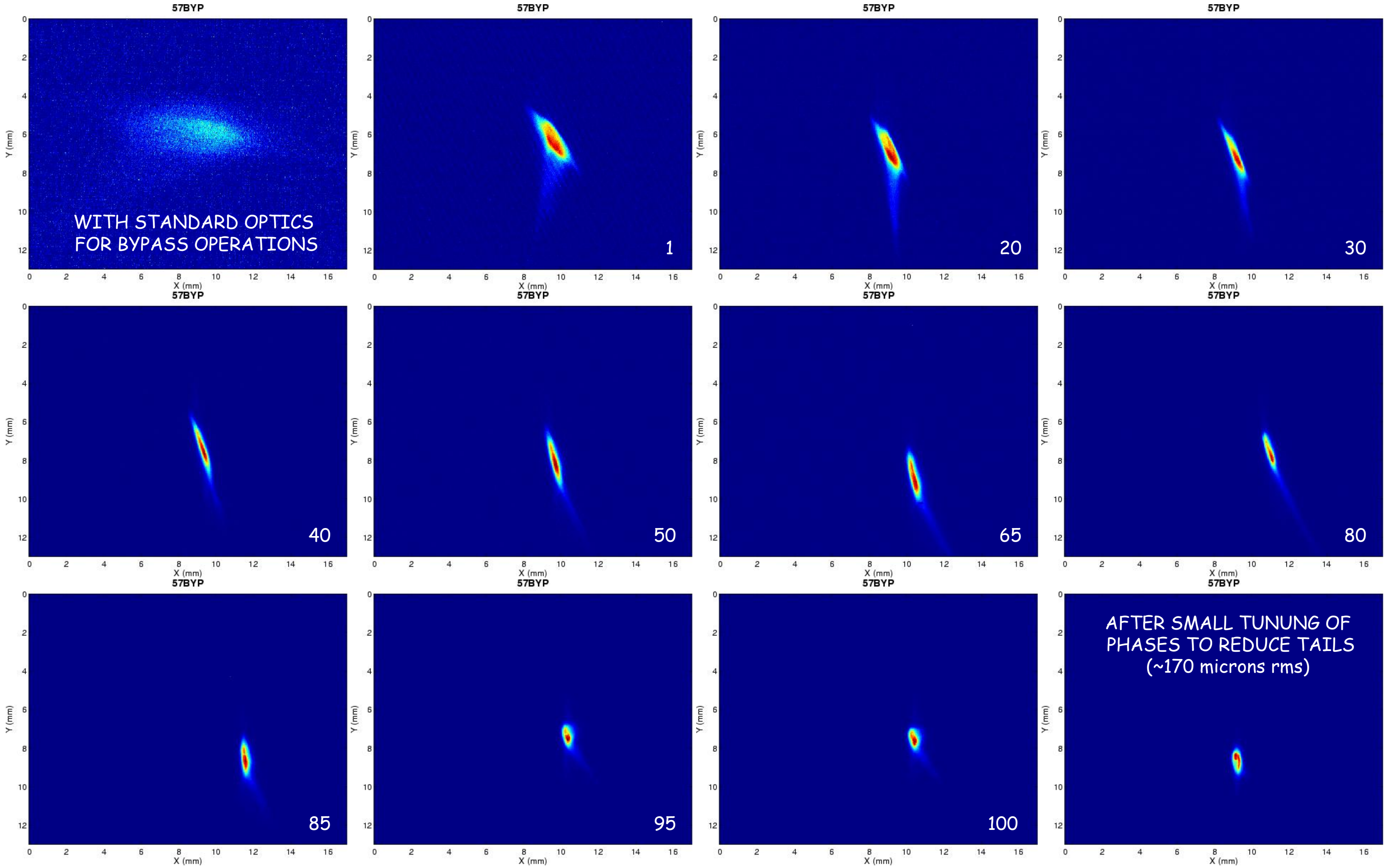
2. Solution which uses only three from seven quadrupoles available between last bypass dogleg dipole and OTR 57BYP. For this solution the upstream beam size is larger than for tuning table solution, but still reasonably small for emittances below 4 mm mrad. The advantage is that due to small number of quadrupoles involved empirical tuning of the beam waist position can be done easier.

3. For the possible case when the previous two solutions will not solve the problem, solution with extreme beam squeezing was developed (as last hope).

Special software for working with tuning table solution

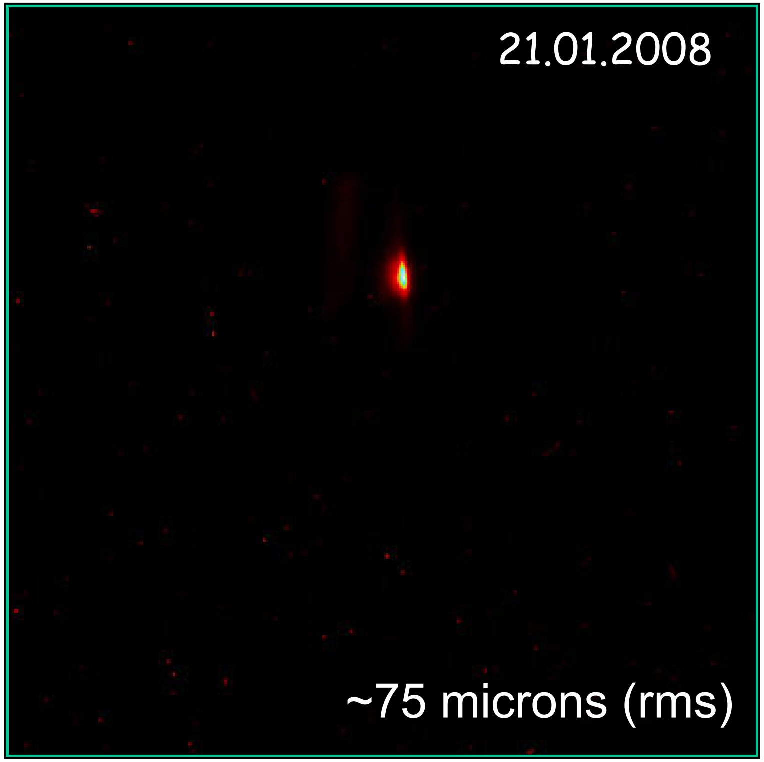


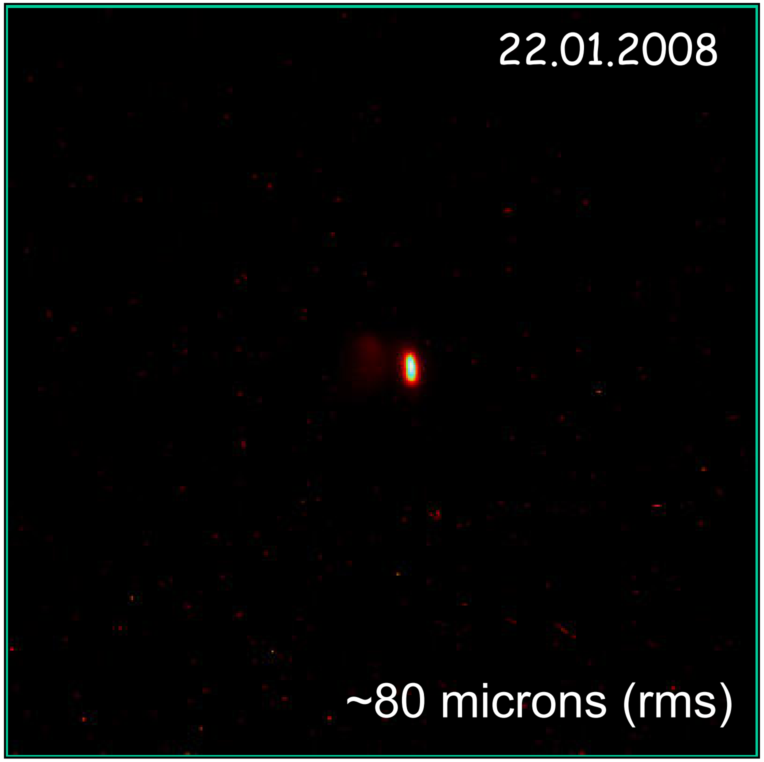
First test of the tuning table for the ODR optics



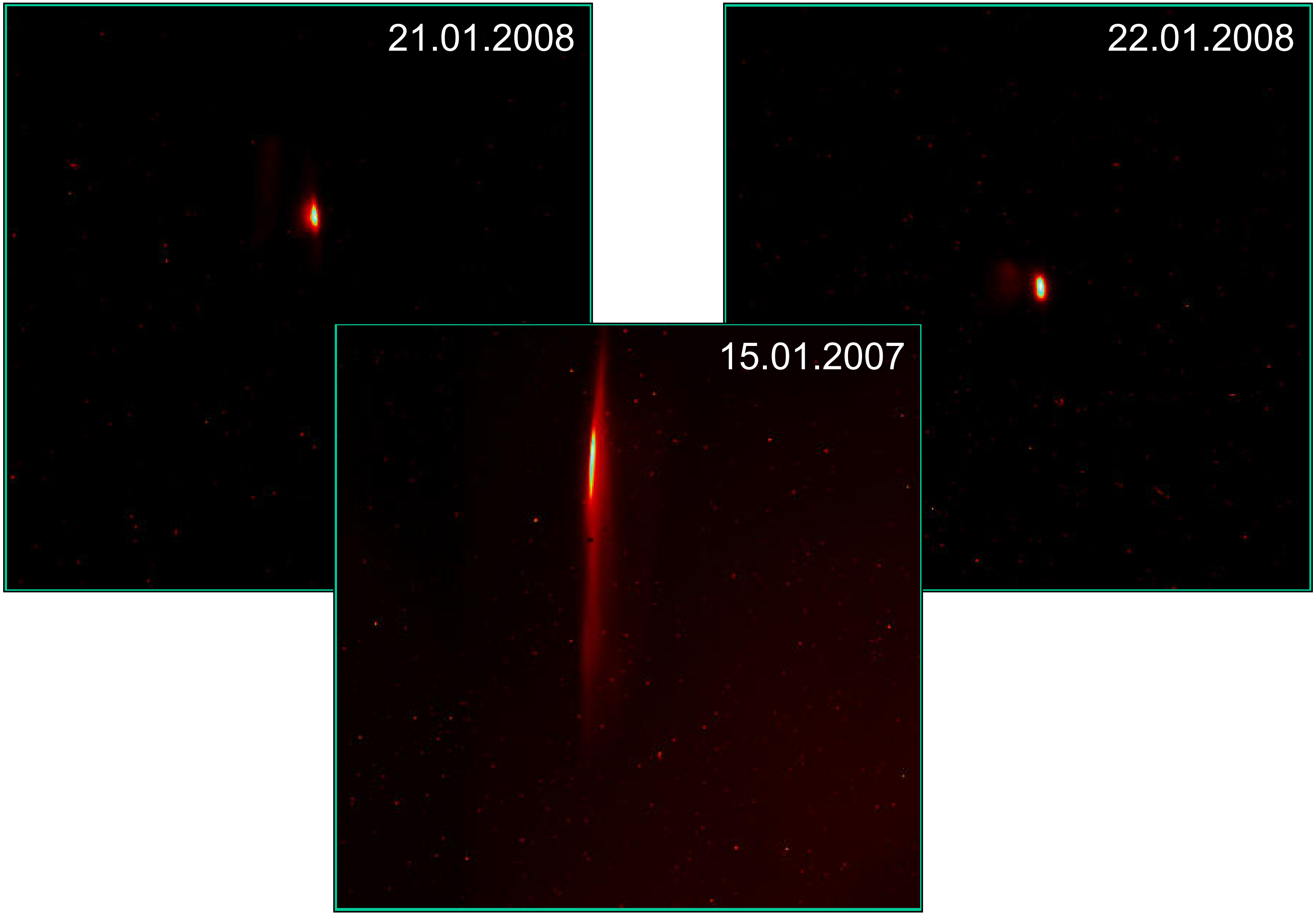
Measured emittances in DBC2 (100%): enx ≈ 3 mm·mrad, eny ≈ 4 mm·mrad. Energy ≈ 700 MeV

Beam tuned for the ODR experiment (solution 2 + small empirical tuning)

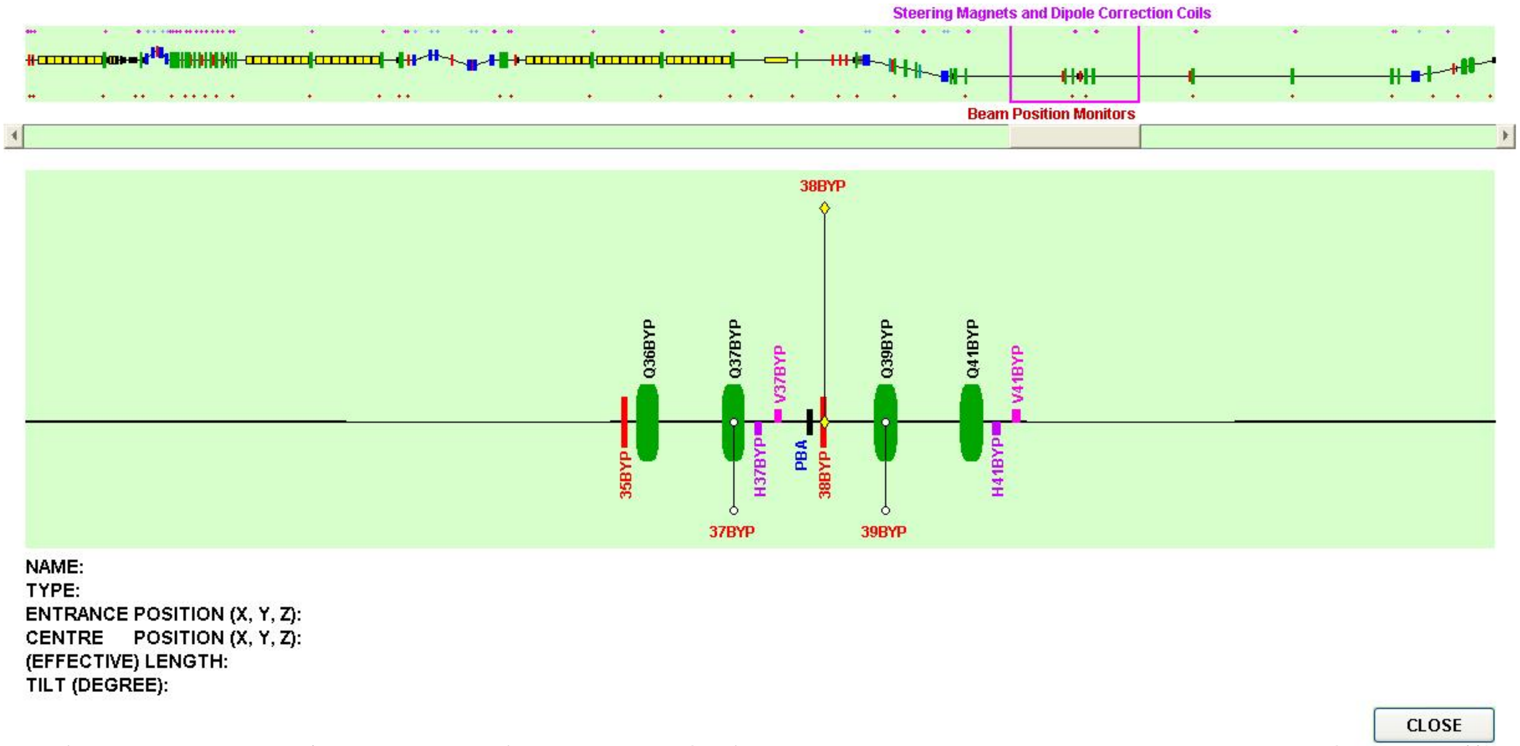




Measured emittances in DBC2 (100%): enx ≈ 4 mm·mrad, eny ≈ 4 mm·mrad. Energy ≈ 920 MeV


21.01.2008
22.01.2008
15.01.2007

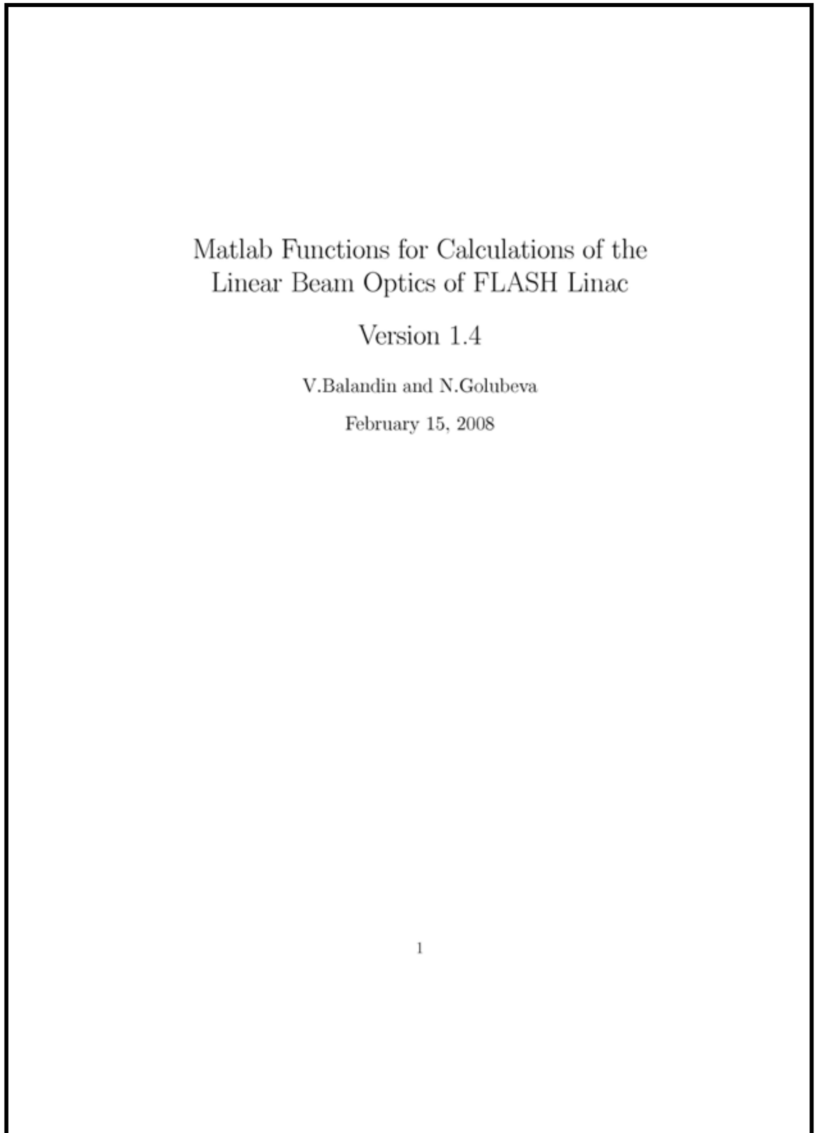
Optics for Material Test Stand



It is the same problem as in the case of the ODR experiment: Creation of a small beam spot size at the location of the material sample (smaller (40 μm)² is required, M. Schmitz), but more complicated since unfortunately, there is no possibility to measure the beam size exactly at the position of the sample. One may measure only ~3m upstream at OTR 35 BYP and 20.5 cm downstream at OTR 38BYP.

The same approach to the optics development as for the ODR experiment was used (tuning tables, extreme beam squeezing), but unfortunately due to lack of time and unsatisfactory functionality of the beam profile diagnostic the experiment, namely the exposing of the material sample, has not been performed.

MatLab Based Online Toolbox for FLASH Optics



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

Version 1.4

V.Balandin and N.Golubeva

February 15, 2008

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The next version (Version 1.4) of the matlab functions for calculation of the linear beam optics of the FLASH linac was tested during this accelerator studies period and released on 15 February 2008.

This new version includes dump line and bypass descriptions and possibility to work with coupled linear optics.

Version 1.0 – July 28, 2006
Version 1.1 – October 20, 2006
Version 1.2 – December 11, 2006
Version 1.3 – July 18, 2007
Version 1.35 – September 25, 2007
Version 1.4 – February 15, 2008

Manual in FLASH-eLogBook: doc/Physics/Optics

Our understanding of the linear optics in FLASH
seems to be quite satisfactory
and is continuously improved.

Shifts
<u>specially dedicated to beam optics studies</u>
are very desirable
in the next accelerator studies periods.

Many thanks to shift crews for the help and support!